LANAI WATER SUPPLY

JOHN F. MINK
Hydrologist

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Summary and Conclusions

1. High level groundwater underlies a total area of about 24 square miles in east central Lanai. In approximately 14 square miles the water table lies higher than 500 feet above sea level; in the other ten square miles it drops to about ten feet above sea level. Except in Palawai Basin, the high level water is potable.

2. Basal groundwater underlies the rest of the island. It occurs as a thin lens of brackish water floating on salt water. Virtually none of it is potable, but some may be acceptable for salt-tolerant plants.

3. The principal recharge zone covers 2.5 square miles of the leeward sector and 2.0 square miles of the windward sector. Essentially all reliable recharge takes place in this zone. Average principal recharge to leeward is 3.8 mgd and to windward is 3.0 mgd. Subsidiary recharge averages 1.2 mgd and 1.3 mgd, respectively.

4. The high level aquifers occur in the rift zones and at the margin of the caldera of the original volcano constituting the entire island. Dikes and other poorly permeable rocks impede the movement of the groundwater. Transmissivity is low (average 2500 sq. ft./day from

pump tests), and hydraulic conductivity is on the order of only ten ft./day. These parameters limit allowable pump rates to less than about 700 gpm.

5. Although the high level resource consists of many small aquifers, the composite of these aquifers behaves as a regional aquifer because of hydraulic connections between the discrete units.

6. Groundwater was first developed in the windward sector, and for many years a yield averaging nearly 500,000 gallons per day was obtained. Free flowing tunnels at the head of Maunalei Valley accounted for 290,000 gpd of this total, but today less than 20,000 gpd is diverted from them. The other windward source, Shaft 2, yields an average of 190,000 gpd. The water table in Shaft 2 is at the same level today as it was when pumping started in 1936.

7. The leeward system, all of which was constructed after the second world war, consists of five wells and a horizontal dike-tunnel. The average yield today is 1.41 mgd (1979-83), but an average of 1.83 mgd was pumped from 1969 through 1978. Since the start of pumping more than 30 years ago, the average draft has been 1.26 mgd. Over that period the regional water level dropped approximately 50 feet.

8. The sustainable yield of the leeward system as presently constructed is 1.4 mgd, about equal to current draft. Combined with the windward contribution, total present draft is 1.6 mgd.

9. Sustainable yields at steady state conditions for eight scenarios of development were calculated to determine system output in excess of present and projected plantation - Lanai City demand. The scenarios range from the system as it exists today to full development of both leeward and windward high level water. The following development opportunities were considered:
   a. Improve the windward system to return production to 500,000 gpd.
   b. Lower the pump settings in the leeward wells to add 500,000 gpd to the system yield.
   c. Install a larger pump in Shaft 2 (windward) to increase production by 200,000 gpd.
   d. Drill a new well at Kaiholena to add 400,000 gpd.
   e. Redevelop the windward and leeward systems to achieve full permissible production of 6.0 mgd (3.3 mgd leeward, 2.7 mgd windward).

10. A decision not to make any change in the leeward system, but to return the windward system to its proven capacity, would provide a surplus of 300,000 gpd over current demand but none over the projected ultimate demand of

1.9 mgd.

11. The sustainable yields listed in the scenarios are for steady state conditions that will not come about for many years. Decisions to enhance yield do not have to be made immediately.

12. However, the expected eventual demand of about 1.0 mgd generated by new ventures will require changes and additions to the system as it now is configured.

Recommendations

Although enough high level water can be produced by the present system to supply plantation - Lani City needs plus some new ventures for several years, eventually expansion of the water supply will be necessary. The expansion may be accomplished in the following ways (listed in order of ease of implementation):

1. Improve the diversion system at the free flowing Maunalei Tunnels. The yield should be returned to an average of at least 250,000 gpd.
2. Increase production from Shaft 2 by pumping more continuously and, later, installing a larger capacity pump.

3. Continue to pump the leeward system at 1.4 mgd. Higher rates can be tolerated for years at a time, but ultimately the water table will reach pump level at an average of 1.4 mgd.
4. Drill a new well at T-6 in Kaiholena. The well should reach to sea level. Expected yield would be 400,000 gpd.
5. As the water table continues to fall toward its equilibrium level in the leeward sector, plan to lower the pumps in those wells where it is feasible.
6. Should the projected demand for potable water exceed 4.0 mgd, full development of the leeward aquifer will have to be undertaken.
7. Over the next five years, scenario 3 (leeward system as it exists, enhanced windward production) would be relatively easy to accomplish. The increase in output over present production would be 500,000 gpd. Over eventual plantation - Lanai City demand it would be 200,000 gpd.

In conclusion, it is worth mentioning that the boundaries of the high level aquifers are not well known. A finer resolution of their position could be achieved by conducting a resistivity survey in central Lanai.

LANAI WATER SUPPLY

INTRODUCTION

Lanai has prospered for more than half a century as a major producer of pineapple even though earlier attempts at agriculture failed because of the difficulty of supplying water. Providing a reliable water supply to sustain plantation activities has not been easy, however; in the beginning fresh water had to be laboriously collected from free flowing tunnels in Maunalei Gulch and pumped across the mountain crest to the cultivated and populated areas. Only much later, about 1950, was water successfully produced from wells on the leeward slopes. Today water is obtained from both Maunalei and the leeward wells.

The high level groundwater resources of leeward Lanai have yielded a reliable water supply for the last three decades. Average annual average demand has fluctuated between less than 1.0 mgd to about 2.5 mgd, and during the decade of most intensive use (1969-1978) it averaged 1.83 mgd. The water levels in the aquifers have decayed less than 100 feet from original elevations of 800 to 1600 feet. In view of the fact that additional water supplies are desirable to enhance present operations and will be needed for future expansion of the economy, the ability of these aquifers to sustain production requires continuing assessment. Can more water be pumped from the present system configuration without causing unacceptable reductions in the water levels? Can new producing stations be constructed to yield an additional supply without seriously interfering with the operating system? Can more potable water be obtained from windward Lanai? These questions serve as principal objectives of the evaluations presented in this report.

Emphasis is placed on potable water, which is virtually restricted to high level groundwater aquifers of east central Lanai (see Figure 1). High level water fills the pores of normal basaltic lavas between dikes and is normally beyond the reach of sea water intrusion. Only about fifteen percent of the island is underlain with high level water. Elsewhere the groundwater is "basal", that is, it occurs as a fresh to brackish lens floating on sea water. In some areas the basal water may be acceptable for salt-tolerant agriculture, but nowhere is it likely to be fresh enough under the stress of pumping to be usable as a potable supply.

Although the goal of this report is to assess the probability of successfully expanding the fresh water supply, summaries of the hydrological and geological factors controlling the occurrence and developability of the groundwater resources and their current exploitation are included. In passing, it should be mentioned that surface water is not a feasible alternative to groundwater on Lanai.

Inevitably, parts of the evaluations overlap and even repeat the work of Anderson, who recently (April, 1983) submitted a review of the present water supply system as a follow on to an original investigation done in 1961. This report may be viewed as complementary to Anderson's work, but differences exist that are significant enough to affect final conclusions about the total high level water supply and how it might be developed.

SUMMARY OF PREVIOUS INVESTIGATIONS

Shortly after Hawaiian Pineapple Company purchased most of Lanai, Harold S. Palmer of the University of Hawaii and Chester K. Wentworth of the Bishop Museum made geological and hydrological surveys of the island. Palmer (1924) was specifically interested in groundwater conditions and Wentworth (1925) directed most of his attention to geology. Palmer noted the presence of a remnant volcanic caldera in Palawai Basin and the faulting associated with it. He also mapped dikes in upper Maunalei Gulch.

Wentworth (1925) recognized that Lanai consists of the remainder of a single volcano with its caldera in Palawai and a major rift zone extending to the northwest. He called the volcanic formation the Lanai basalt. He reported extensive faulting but observed only a few dikes. Like Palmer, he did not believe that high level aquifers exist and, in fact, assigned no importance to dikes as controls on groundwater movement. Wentworth recommended the construction of a basal infiltration gallery reaching to sea level from the northeast corner of Palawai Basin. Had this project been implemented, the leeward high level water would have been encountered at an elevation above 1000 feet, about 500 feet below ground level. He estimated a potential freshwater yield of 0.5 mgd from the island.

The most extensive and complete study of the geology and water resources of Lanai was made by H. T. Stearns (1940). Stearns did field work in the summer of 1936, and his investigation was expanded to include a resistivity survey by Joel Swartz, also of the U.S. Geological Survey. The survey was designed to detect depth to salt water along a transect across the island from Kaumalapau on the south to the mouth of Maunalei on the north. The approximate western boundary of the high level aquifers was identified. The survey was one of the first successful applications of this variety of geophysics in water exploration in the United States.

Stearns elaborated on Palmer's and Wentworth's observations and refined the relationship among the caldera, faulting and the rift zones. He identified a single caldera and three rifts, one each to the northwest, southwest and south. He noted the absence of secondary eruptions and concluded that the Lanai volcano ceased activity in its most primitive stage. He mapped more than 100 faults and at least 275 dikes. In contrast to Palmer and Wentworth, he stated that the dikes effectively hold groundwater at high elevations. On his recommendation, an inclined shaft (Shaft 2) was driven in the middle part of Maunalei from elevation 851 feet. The water table was struck at elevation 735 feet, and construction was terminated. The groundwater was subsequently developed by means of a well drilled below an excavated chamber at the base of the shaft. Stearns continued to contribute advice about water development on Lanai for many years afterwards.

Water development employing wells located leeward of the crest started after the end of the second world war. Five wells were drilled and a shaft-high level tunnel was completed by 1954. The results of these activities were monitored by Hawaiian Pineapple Company personnel, in particular J. T. Munro and V. T. Thalman who, in addition to maintaining a data file, made numerous hydrological analyses. They attempted to determine rates of infiltration by relating head changes to draft and rainfall, but variations in drawdown and recovery were too small to permit accurate calculations. In addition, their analyses lacked a variable for natural leakage from the high level groundwater system.

In 1961, K. E. Anderson reviewed the water development activities of the preceding 15 years and submitted his conclusions concerning yields based on field observations and analyses of the head-draft-rainfall measurements that had been collected. He allocated an area of 11.3 square miles to high level water occurrence. Anderson estimated the ultimate available supply of high level water to be 4.85 mgd, equivalent to the infiltration rate he computed in a water balance. This value applies to the combined windward and leeward high level systems. Of the ultimate yield, he stated that 3.63 mgd was recoverable at contemporary costs, but placed the safe yield at 2.34 mgd, of which 1.85 mgd was available on the leeward side.

Anderson's most recent review (1983) concludes that 2.07 mgd is available on a sustained basis from the present system in leeward Lanai and in excess of 0.49 mgd from Shaft 2 and the free flowing tunnels of the windward side for a total yield in excess of 2.56 mgd. These values relate to the operating system; he believes the entire high level water resource is capable of supplying 4.1 to 5.5 mgd. To achieve this production, the present system would have to be revised and new wells drilled.

Anderson's water balance model assumes maintenance of a high water table without permanent loss of head. In this respect it resemble the Munro-Thalman models in ignoring natural leakage. Once leakage is admitted into the model, the equations become non-linear. An inescapable conclusion of the non-linearity is that a steady state cannot be achieved if draft equals or exceeds recharge.

Following Anderson's initial work, S. P. Bowles conducted investigations aimed at establishing a management plan for water production on Lanai. His conclusion about sustainable yield was more optimistic than Anderson's. In his water balance, infiltration amounts to 6.5 mgd in contrast to Anderson's 4.1 to 5.5 mgd. By implication he assumed ultimate sustainable yield to be the same as average infiltration, ignoring natural leakage as had Anderson.

A gravity survey was made on Lanai by H. L. Krivoy and M. P. Lane (1965) in which closure of the gravity contours confirmed the existence of the caldera in Palawai. The gravity high is 250 milligals, and the closure gradient is 50 milligals. In 1973, W. H. Adams and R. D. Huber studied groundwater conditions on the north and northeast coasts of the island. Only basal water, highly brackish to saline, occurs there.

A very important aspect of the continuing evaluation of the behavior of the high level groundwater resources of Lanai has been the careful collection and maintenance of hydrologic data by the Dole Company. Without these data- rainfall, draft, water levels- no sensible hydrologic models could be fashioned.

LANAI ENVIRONMENT

Lanai rises as the remnant of a volcanic shield from an arid, dramatic coastline to cool, verdant, highlands. At Kaumalapau Harbor the average annual temperature is 76°F but in Lanai City, 1620 feet higher, it is only 68.5°F. On the maximum elevation of the island, Lanaihale at 3370 feet, the average is probably 60°F. The moderate temperature on the plateau, and the even cooler temperature in the small mountain range, significantly depresses evaporation and transpiration rates.

As portrayed on the isohyetal map, all of Lanai should be dry to the point of desolation, yet in the east central part of the island about 20 square miles of forest and humid scrub land exist. Here the meager rainfall of 35 to 40 inches per year is augmented by frequent fogs, providing a total moisture flux that in combination with the moderately cool temperature encourages vegetative growth. The maximum average annual rainfall is only 40 inches, but a forest characteristic of 60 inches or more drapes the inland mountains. At the leeward coast the annual average is less than 20 inches. About 85 percent of the island's area of 141 square miles is a semi arid to arid terrain.

The rain gage site having the highest long term average is on Hii Bench, approximately one mile leeward of the crest of the island at an elevation of 1845 feet (Gage 540). The average annual rainfall is 40.9 inches, though the median is smaller, 36.7 inches. If annual rainfall followed a normal distribution, as it typically does in Hawaii, the mean and median would be identical. A site on Soule's Bench (Gage 555), similarly located and at the same elevation, has an annual average of 40.1 inches. A gage on Lanaihale, the peak of the island, has averaged 39.3 inches per year. On a ridge of Hauola Gulch on the windward slope of the crest the annual average is 40.1 inches (Gage R-12).

A very long rainfall record exists for Lanai City, which at elevation 1620 feet lies about on the margin of the moisture envelope covering the central mountains. At Lanai City the average for the period 1930 through 1982 was 37.2 inches and the median, 33.4 inches. Annual rainfall at Lanai City has ranged from a minimum of 16.0 inches (1953) to a maximum of 66.9 inches (1968). The most phenomenal run of wet years took place over the seven year period from 1962 through 1968 during which 360.4 inches of rain fell, an average of 51.5 inches per year, nearly 40 percent above normal. In contrast, the next seven year period (1969 through 1975) averaged only 32.9 inches per year. In 1982, a wet year throughout the State, Lanai City recorded 57.4 inches of rain. Thus far in 1983, rainfall is considerably below average. The most recently drawn isohyetal map of Lanai is given in the publication, 'Median Rainfall, State of Hawaii; Circular C88, Department of Land and Natural Resources State of Hawaii, 1982."

The geology of Lanai was effectively described by Stearns (1940), and all subsequent geological discussions have leaned heavily on his work. The island is a volcanic dome whose focus of eruptive activity, the caldera, collapsed to form Palawai Basin. Volcanic activity was restricted to the effusion of primitive basalt, the first stage in an eruptive history. No secondary flows followed, and pyroclastic activity leading to cinder, ash and tuff deposition was neither extensive nor voluminous. The only major geological rock unit is the Lanai basalt. Sedimentary accumulations produced by erosion of the dormant volcano lie chiefly in the lower reaches of valleys and in the Palawai depression. Marine sands in protected locations along the coast form attractive beaches.

Three rift zones radiate from the caldera, the principal one to the northwest and subsidiary ones to the south and southwest. Dikes are associated with rift zones and Stearns identified at least 275 of them. Faulting occurred along the margin of the caldera, but most traces are difficult, if not impossible, to detect. Suggestions have been offered that the faults may be responsible for impounding water at high elevations. Nowhere else in Hawaii has this been demonstrated, however; the likely cause of the high water tables is containment of groundwater in small aquifers bounded by dikes.

The surface and subsurface rocks of the island are permeable to infiltration from rainfall to the extent that surface runoff infrequently reaches the sea. No perennial streams exist on Lanai, nor did any when Hawaiian Pineapple Company secured the island in 1922 (see Palmer, 1924; and Wentworth, 1925). Weak springs caused by local perching conditions exist in gulches leeward of the crest and perhaps at one time were more productive than now, but they were never reliable enough to serve as a water supply. In windward Lanai in upper Maunalei Gulch, perennial springs flowed but eventually were diverted by tunnels. Under pre-development conditions, Maunalei Stream may have reached the sea for appreciable periods each year.

The simple geology of Lanai is reflected in the occurrence of its water resources. Potential surface water supplies are essentially absent because of the perviousness of the rocks, while fresh to brackish groundwater underlies the entire island. Fortunately, the subsurface complexities of the caldera and the rift zones provide an environment for the accumulation of high level groundwater. Aquifers of normal basaltic lava lying between nearly impermeable dikes and other equally dense caldera rocks contain fresh water to elevations in excess of 1500 feet. The extent of the favorable conditions is limited to less than 25 square miles, however. Under the remainder of the island basal water occurs, virtually all of it brackish except adjacent to the high level boundaries.

THE WATER BALANCE OF LANAI

The yield of the fresh groundwater resources of Lanai depend on the volume of water in the high level aquifers, the rate of which these aquifers are replenished, and the rate of leakage from them. The area underlain by high level water has been estimated to be 11.3 square miles by Anderson and 15.5 square miles by Stearns, and later by Bowles. A recalculation for this study sets the maximum area at 24 square miles with a primary inner area of 14 square miles equally apportioned to the windward and leeward sides of the crest (see Figure 1). The primary area is comparable to the earlier estimates. In the primary area the water table is higher than 500 feet above sea level; in the secondary area of ten square miles it descends to a low of 25 feet above sea level and approaches being basal at its boundaries.

Stearns (1940) computed a water balance which allocated total average daily infiltration of 6.46 mgd to the high level aquifers. Anderson (1961) was more conservative, assigning an average infiltration of 4.85 mgd. The smaller high level area of Anderson was mainly responsible for the lower infiltration estimate. Bowles (1973) agreed with Stearns. An obviously understated guess of only 1.55 mgd was proffered by Adams and Huber (1973) who employed an unrealistic evapotranspiration rate for the high region of the island. For the basal sector, Stearns estimated total infiltration to average only 14.81 mgd over 127 square miles. This value, even if doubled or tripled, is insufficient to maintain a fresh water lens having a signficant development potential.

In the water balance computations noted above consideration was not given to the moisture contribution of fog. Ekern (1964) proved that fog drip increases the total moisture flux by a substantial margin in central Lanai. Three years of moisture collection at elevation 2750 feet (rain Gage R-10) yielded a rainfall catch totalling 104 inches and fog drip, calibrated to correspond to direct catch, of 71 inches, or 68 percent of direct rainfall. The fog and the moisture it brings to the principal recharge zone explains why a montane rain forest is able to thrive on Lanai.

The favorable moisture environment also explains why measured evaporation is low in the mountain area. The results of 19 months of pan evaporation measurements from January, 1957, through July, 1958, indicate annual evaporation at 2750 feet elevation to be slightly more than 25 inches. The year 1957 had below average rainfall while 1958 was about average. This modest evaporation loss is a third of what it is below an elevation of 1000 feet in most other regions of Hawaii.

The principal recharge zone in the high level groundwater region is an envelope of 4.5 square miles about equally divided between the windward and leeward slopes. The subsidiary recharge zone includes the remaining 9.5 square miles of the primary high level groundwater area (see Figure 1). In the water balance equation, employing annual averages of 38 inches for rainfall, 60 percent of that for fog drip, 20 inches for evapotranspiration (which is based on the evapotranspiration/evaporation ratio of 0.8 that is characteristic of mature sugar and grasses in Hawaii), and direct surface runoff out of the recharge zone as 15 percent of rainfall, the average infiltration to the principal recharge zone becomes 3.8 mgd to the leeward slope and 3.0 mgd to the windward slope, a total of 6.8 mgd. In the subsidiary recharge zone, assigning a value of 32 inches for rainfall, fog drip at 30 percent of rainfall, direct surface runoff at ten percent of rainfall, and evapotranspiration as 33 inches, infiltration to the leeward sector is 1.2 mgd and to the windward sector, 1.5 mgd. Thus total average recharge to the combined primary and secondary high level aquifers on the leeward side is 5.0 mgd, and on the windward side it is 4.3 mgd, a grand total of 9.3 mgd. In Appendix A details of the water balance computations are given.

A water balance is rarely accurate because the hydrologic cycle is too complex to portray with simple linear equations in which the variables are long period averages. Nevertheless, a balance is a necessary first step in creating groundwater flow models. The total infiltration value given above is nearly twice as great as Anderson's estimate and almost one and a half time more than the Stearns-Bowles guess. However it is still the same order of magnitude as the lower estimates. A groundwater flow model, which is discussed later, suggests that the higher infiltration value is more realistic.

AQUIFER CHARACTERISTICS AND BEHAVIOR

Groundwater is developed on both sides of the crestline of the island, but about 75 percent of the total supply is taken from the leeward aquifers. The high level resource is continuous from leeward to windward, yet it is convenient to differentiate between the sectors because of differences in topography, feasibility of development, and cost of producing and transporting water. In both sectors the groundwater is trapped in the dike-caldera complex, and techniques for exploiting the resource are essentially the same. Windward high level groundwater was developed first, starting as far back as 1910-1911 when the upper Maunalei tunnels were driven, but after 1945 every new venture took place in the leeward sector within more favorable reach of the plantation and its population.

High level groundwater is contained in aquifers that over the short term behave as discrete units but which are hydraulically continuous with each other through fractures and other structural imperfections in the dike barriers. The maximum known water table elevation is approximately 1600 feet above sea level. On the leeward side the water table descends from 1500 to 800 feet above sea level along a northeast-southwest direction over a distance of one mile. A similar descent occurs in Maunalei on the windward side. The minimum width of the zone where the water table exceeds elevation 1000 feet is approximately two miles, equally apportioned to either side of the crest. The maximum length of this zone along the crest line is about three miles.

The resistivity survey included in Stearns indicates that on the northwest the water table falls to basal conditions where the Maunalei Road starts its slope to the north coast (see Figure 1). This boundary is about one mile from the water table lying at elevation 1000 feet. Basal conditions also prevail about one mile southeast of Kaiakeakua. In Maunalei the basal aquifer likely starts less than a mile north of Shaft 3. On the southern leeward slopes the resistivity survey suggested the presence of basal water at the southwestern edge of the Palawai depression.

Groundwater seeps from aquifers with higher heads to those with lower heads, and ultimately it seeps through the last restraining structure into the basal lens. Over a long time period, therefore, the high level aquifers behave as a single regional unit displaying local peculiarities. Too great a fall in head in one aquifer will induce leakage from an adjacent aquifer with a higher head until eventually equilibrium is approached. This dependency among aquifers is suggested by linear correlations of annual maximum heads between pairs of the leeward wells over the historical range of head changes of 40 to 80 feet. In all cases the correlation coefficients are .66 or greater and in most they exceed .75. The linear correlations are not extrapolatable beyond the head range considered, however; non-linear equations describe behavior over the full range.

Because the aquifers are not homogeneously continuous, the intrinsic characteristics of each formation composing them are not as important as in monolithologic extensive aquifers. In calderas and rift zones a variety of rock types hold and transmit water. How the combination of rocks affect hydraulic flow is more pertinent than the characteristics of individual units. Normal basaltic lavas are extremely permeable, but where they are intersected by dikes or are layered with impermeable breccias and similar caldera rocks, their high hydraulic conductivity is subsumed into a much less permeable mass. The usual way to assess aquifer characteristics is by means of pumping tests.

A record exists of lengthy pumping tests conducted on Wells 3, 4 and 5 in 1950 before they were fitted with permanent pumps. The results of the tests indicate the nature of the aquifers serving each well. The tests are described, the results graphed, and relevant hydrologic parameters are derived in Appendix B. Also included in the appendix are specific capacities of the wells as obtained from both old data and examination of recent pumping charts.

Transmissivities of the aquifers as they currently are being exploited average about 2500 sq. ft./day, only one hundredth of that of an extensive basal lens with a moderate head. In no test was a transmissivity of more than 6500 sq. ft./day indicated. Transmissivity is converted to hydraulic conductivity through division by the depth of water flowing to the well. Assuming depth of flow to be equal to depth of penetration of the bore below the water table, hydraulic conductivity ranges from 6 to 11 ft./day, quite low in comparison with the typical value of basaltic rocks free of dikes. Because drawdown is inversely proportional to transmissivity or hydraulic conductivity and directly proportional to pumping rate, head can be lost rapidly when pumping rates are high and transmissivity is meager. In the high level aquifers the low hydraulic conductivity values confirm what has been learned through experience, that the rate of pumping at each well should not be greater than about one mgd (694 gpm).

Transmissivity is the fundamental characteristic of an aquifer, specific capacity of the well itself. For the Lanai wells, specific capacity is defined as the rate of pumpage per foot of drawdown due to head losses caused by change in the flow pattern from laminar in the aquifer to turbulent at the well face. It varies logarithmically with the log of the pumping rate. Each well has a unique specific capacity curve. The head loss suffered at the well face must be added to aquifer drawdown to give total drawdown at a given pumping rate.

Specific capacity due only to well effects ranges from 16 gpm to 35 gpm per foot of drawdown (see Appendix B). These values are considerably poorer than in a good basal well for which a common value might be 1000 gpm/ft. Dividing the specific capacity by the length of penetration of the well below the water table gives the unit specific capacity. This parameter is an indicator of the kind of aquifer being pumped. Unit specific capacities associated with aquifer types are as follows (Mink, J. F., 1978):

Aquifer	Unit Specific Acpacity (gpm/ft./ft.)
Caldera	.001
Dike complex	.01
Marginal dike zone	.1

Unit specific capacities in the central Lanai aquifers vary from .02 to .06, corresponding to dike complex-marginal dike zone conditions. In the dike complex the close spacing of dikes reduces well efficiency; in the marginal dike zone the dikes are farther apart and have less effect on well behavior.

In Appendix B the value for the average specific yield (effective porosity) of the aquifers is given as ten percent. This value is based on the drawdown curve generated at Test Hole T-2 while Well 5, 40 feet away, was being pumped. It is typical of Hawaiian basalts but may be on the high side for aquifers in the caldera-rift zone environment. A conservative value of five percent will be employed in predicting aquifer behavior.

The volume of groundwater stored in the aquifers before development commenced can be roughly calculated by assigning a specific yield of .05 to the primary high level zone. For the seven square miles of the leeward portion over an average depth of 1000 feet to sea level, the original volume of water was 73 billion gallons. The same quantity occurred in the windard sector. This compares with the value of 50 billion gallons suggested by Bowles. Anderson estimated a usable volume of seven billion gallons at present pump settings, which average about 220 feet below the water table. Adjusted for depth of saturation of 1000 feet to sea level, his value would be 32 billion gallons. Although the above storage volumes are approximate, they are of an order of magnitude which centers around 50 billion gallons in each of the leeward and windward sectors. This total volume, however, would be available for exploitation only if the pumps were set at about sea level. Since 1950 when pumping on the leeward side started in earnest, the average reduction in the water table has been about 50 feet, representing a loss of original groundwater volume of five percent, or 2.5 billion gallons.

At all of the groundwater extraction sites except Well 1 (Palawai), the water quality is excellent as expected of high level aquifers. In both the leeward and windward sectors the normal groundwater has a chloride content of less than 30 mg/l and a virtually neutral pH. Nitrate is less than 3.0 mg/l, hardness less than 50 mg/l, and total dissolved solids less than 140 mg/l. All of these concentrations are considerably below the potable limits (e.g. the limit for chloride is 250 mg/l, and for nitrate 45 mg/l). The following table summarizes chemical analyses in accessible records for water points other than Well 1.

TABLE 1

Composition of High Level Water
Concentrations in mg/l[1]

Source	Date	pH	NO_3	SiO_2	Ca	Mg	SO_4	N_a	k	Cl	HCO_3	H	TDS
Windward													
Shaft 2	11/14/63	6.8	3.8	33.3	12.3	11.5	9.5	21	0.5	34	98		
Shaft 2	4/12/49	7.2								31		32	113
Lower Tunnel	9/11/36	7.3		36						22	94	56	144
Combined Tunnels	4/17/80		2.7										
Leeward													
Well 2	4/12/49	7.7								21		32	87
Well 2	4/17/80		2.2										
Well 3	4/17/80		3.0										
Well 4	4/17/80		2.6										

(1) pH = acidity; NO_3 = nitrate; SiO_2 = silica; Ca = calcium; Mg - magnesium; SO_4 = sulfate; N_a = sodium; k = potassium; Cl = chloride; HCO_3 = bicarbonate; H = hardness; TDS = total dissolved solids

Well 1 on the northern margin of Palawai Basin has yielded anomalously high chloride water since first tested in 1948. The concentration has fallen from an initial value of about 800 mg/l to stabilize at about 330 mg/l. Obviously a source of salinity external to normal recharge affects the well. A summary of available analyses for the well is given below.

TABLE 2

Composition of Water from Well 1 (Palawai)

Concentrations in mg/l(1)

Date	pH	NO_3	Cl	SO_4	H	TDS
1948	7.5 to 7.7		517 to 816		291 to 534	993 to 14
1949	7.3 to 7.9		444 to 558	51 to 76	312 to 365	1007 to 16
1975			328			
1977			340			
1978			310			
1980		19.5				
1983			332		546	

(1) See Table 1 for footnote explanation.

The salinity of the Palawai water could be attributable to one of the following causes:

1. Residual sea water (suggested by Stearns)
2. Modern sea water intrusion (also suggested by Stearns)
3. Concentration of salts in rainfall
4. Dissolved fertilizers
5. Geothermal convection of deep saline water

Stearns identified ancient sea levels as high as about 1100 feet above the present datum, and speculated that pockets of residual sea water might contribute salt to modern recharge. This is unlikely because any ancient water would have been cleared by subsurface infiltration by now. The intrusion of modern sea water is a possibility because Well 1 reaches to below sea level, but in no other instance in Hawaii has high level water at an elevation of more than 800 feet been known to have been affected by sea water contamination.

Because the Palawai Basin has no drainage outlet, all soluble salts accompanying rain water must percolate to the zone of saturation, but this is an effective way of increasing salinity only if the proportion of infiltration to rainfall is very small. The simple equation, $I/P = C(P)/C(I)$, in which I is infiltration, P is rainfall, C(P) is concentration in rainfall, and C(I) is concentration in the infiltrate, suggests that infiltration would have to amount to just three percent of rainfall to produce groundwater of 330 mg/l chloride, given average rainfall chloride as 10 mg/l. This rate is much lower than is likely to occur.

Dissolved fertilizer can't be the source of salinity because chloride is not used as a carrier for nutrients; sulfate in the past was the carrier for nitrogen and is still used for potassium. Some dissolved fertilizer does escape below the root zone, however, because the nitrate concentration in Well 1 is 19.5 mg/l, more than six times the background count of 3 mg/l.

The last possibility, upward convection of salt water caused by geothermal heating, is suggested by the unexpectedly high temperature of the groundwater from Well 1. Recharge from rainfall at elevations of 1000 to 1500 feet should result in groundwater temperatures averaging about 70°F; the measured temperature of discharge at Well 1 is 81°F. The difference is not extraordinary, but it offers an alternative to the other proposed mechanisms for adding an extraneous saline component to high level recharge.

On April 17, 1980, samples were collected for DBCP and EDB analyses from the Maunalei Pump House, the Maunalei Tunnels, and Wells 1, 2, 3 and 4. At detection limits of 50 ppt for DBCP and 100 ppt for EDB, neither of these compounds were detected. More recent analyses of the drinking water sources failed to show the fumigants at lower detection levels.

PRESENT GROUNDWATER DEVELOPMENT

On Lanai a water supply was never easy to locate or develop. Meager seeps at the heads of leeward gulches were exploited by Hawaiians, and in windward Maunalei the stream was perennial and utilized chiefly above an elevation of about 1000 feet only because of high level springs. An attempt early in the century to pump basal water on the northeast coast for irrigation of sugar quickly failed because of salinity. The first successful effort to establish a controlled water supply was the excavation of tunnels in upper Maunalei at the sites of the springs and seepages. Further succes was achieved lower in the valley, but not until after the second world war was exploration extended to the leeward slopes.

In 1911 a tunnel, called the Lower Maunalei Tunnel, was excavated over a length of 1000 feet at elevation 1103 feet near the floor of the gulch at the head of Maunalei. It successfully yielded a good supply of water and is still in use today. Another tunnel (Upper Maunalei Tunnel) further upstream at elevation 1500 feet was constructed soon afterward, and it also provided water, though less than the lower tunnel. The combined yield of these tunnels is diverted to a pumping station in the mid portion of the valley, then pumped over the divide to the leeward sector. Between 1926 and 1939 the lower tunnel provided an average of 260,000 gallons per day (181 gpm) and the upper tunnel 65,000 gallons per day (45 gpm) for a total of 325,000 gpd (226 gpm). In later years somewhat less water was captured, probably because after Shaft 2 and the leeward wells came on stream the system was not maintained as rigorously as earlier. Between 1948 and 1974 average production was 197,000 gpd (137 gpm). By repairing the tunnel system, the yield can be increased by about 100 gpm. This quantity may sound modest, but it is sufficient to supply the needs of 500 to 1000 people.

The yield of the tunnels was insufficient for plantation needs, and in the summer of 1936 an infiltration gallery (Shaft 1) was driven in the lower portion of Maunalei from an elevation of 294 feet. Basal water was encountered, but pumping had to be restricted to less than 300 gpm to insure salinity of 350 to 400 mg/l chloride. The unacceptable quality of the water for domestic purposes and the low permissible production rate prompted Hawaiian Pineapple Co. to seek high level water further up the gulch. In December of the same year a shaft was driven from elevation 851 feet and struck water at elevation 735 feet. A well 261 feet deep was drilled below the chamber at the bottom of the shaft to exploit the resource. This station, Shaft 2, has been producing high quality water for transfer to the leeward side ever since.

From 1948 until 1967, when Shaft 2 ceased operating for a number of years, its average draft was 139,300 gpd (97 gpm). It lay idle between November, 1967, and September, 1978. Additionally, from March, 1974, until August, 1978, the free flowing Maunalei tunnels were abandoned so that over a four year period, during which rainfall was below normal, no windward water was pumped to the plantation side. In 1979 both the tunnels and Shaft 2 were on line again, the shaft producing about 127 gpm but the tunnels less than ten gpm. Only a fraction of the potential yield of these resources is being taken. Production of windward high level water, in particular that in Maunalei, can be expanded significantly.

The initial water table at Shaft 2 was 735 feet above sea level and the maximum recorded has been 747 feet. A minimum of 716 feet has been reported. The volume of water stored in the aquifer is the same today (water table elevation 738 feet) as it was in 1936. The station is capable of appreciably greater yield. Water production and maximum heads by months and years, starting with 1947, are tabulated in Anderson (1983).

In the leeward sector the first producer, Well 1, was drilled in 1945, and four others - Wells 2, 3, 4 and 5 - were completed by the end of 1950. Locations of the wells are shown on Figure 1. All were successful. Each was preceded by an exploratory boring, but a sixth test hole (T-6) in Kaiholena was not followed up with a well even though the water table lay 1067 feet above sea level. The greatest depth of drilling, 1270 feet, was at Well 1; the shallowest, 903 feet, in Well 2. The bottoms of Wells 4 and 5 are at the highest elevations (1149 and 1174 feet, respectively) and these wells penetrate below the water table. Basic specifications of the wells are given in Appendix C. Also included in the appendix is a diagram relating elevation, depth and location of each well, along with available information on casing and pump settings.

Well 1 penetrates 825 feet below the original water table and Well 2 about 660 feet. In the others, penetration of the saturated zone ranges from 389 feet at Well 5 to 473 feet at Well 3. The shallow depth of penetration, except at Well 1, coupled with the high elevations of the pump settings (see Appendix C) are restrictions on manipulating groundwater storage to provide maximum aquifer yields.

Shaft 3 was constructed in 1954 at the site of Well 2. An inclined shaft was dug from ground elevation 1815 feet to a chamber at 1515 feet, then a horizontal tunnel was driven into a dike compartment having a water table about 40 feet above the invert. A bulkhead across the key dike was emplaced to control the escape of stored water. Pressure recovered to a high of 32 psi (74 feet) after bulkheading, but since June, 1976, it has never reached ten psi (23.1 feet) again. The current difference in heads between Well 2 and Shaft 3 is approximately 60 feet even though the bulkhead and the vertical boring are within 200 feet of each other. Nevertheless, on a regional scale the behavior of individual aquifer units is subsumed in changes affecting all of the high level resource.

Production from leeward wells and Shaft 3 as the major water supply for plantation operations started in earnest in 1950. From 1949 through 1958 leeward production averaged 0.962 mgd, then jumped to 1.63 mgd in the period 1959 - 1962. It fell to 0.674 mgd from 1963 through 1968 because of good rainfall, but in the interval 1969 - 1978 increased sharply to 1.83 mgd as rainfall averaged less than normal. Since 1979 production has averaged 1.41 mgd. Monthly and annual production from each source is tabulated in Anderson (1983).

Two lengthy periods during which relatively uniform average annual pumpage prevailed illustrate the decay and recoverability of the water table level as a function of draft. In 1963-1968 the lowest average draft over five or more consecutive years was experienced. At a total yield of 0.676 mgd the water table in each well recovered to its original level or even higher. In the following decade (1969-1978) the greatest average pumping of record was experienced. At average total output of 1.83 mgd, the water table dropped up to 74 feet from maximum highs. The rate of descent appeared to be decreasing toward the end of the decade, which suggests that at some lower elevation an equilibrium water level would become established. An equilibrium model of head as a function of draft and recharge is discussed in a later section.

Table 3 lists average annual draft (calculated to a daily basis) at each station for the low and high production periods, as well as for the entire lenght of record (1947-1982) and for the most recent four years (1979 - 1982). Only those years with reported production were included in the averages. The unusually high average rainfall for 1963 - 1968 accounts for the small pumpage in that period. The low rainfall of 1969 - 1978 combined with loss of production from Shaft 2 in Maunalei, and later in the interval from the Maunalei tunnels, explains the high average draft required.

TABLE 3

Average Rainfall and Average Draft, Leeward Sector

Selected Periods

(Rainfall in inches; draft in mgd)

Source	Period 1947-82	1963-68	1969-78	1979-82
Rainfall (Lanai City)	38.1	55.3	31.4	42.4
Well 1	.091	.020	.137	.144
Well 2	.328	.242	.415	.286
Shaft 3	.436	.270	.433	.368
Well 3	.215	.059	.297	.270
Well 4	.195	.052	.312	.178
Well 5	.157	.033	.236	.163
Total Draft	1.26	.676	1.83	1.41

Table 4 summarizes maximum head data for the same periods given in Table 3. Maximum annual head is used as an index of change because it is presumed to be a static head that has recovered from pumping. From 1950 to the end of 1982 head losses averaged about 40 feet, less than five percent of the thickness of the saturated zone above sea level. Head loss inevitably takes place when an aquifer is exploited, but for each average draft - so long as draft is less than infiltration rate - an equilibrium head will be attained.

The ability of the leeward sources to produce water at acceptable head losses was tested only once, in the 1969 - 1978 decade. The average draft of 1.83 mgd was half the infiltration rate assigned to the principal recharge zone of the leeward sector. When draft decreased in 1979, heads had not yet reached an equilibrium level and were still falling, but an equilibrium would have set in because the high rate of draft was less than long term average infiltration.

TABLE 4

Maximum Annual Water Levels, Leeward Sector

(Draft in mgd; head in feet above sea level)

	1947 - 62			1963 - 68			1969 - 78			1979 - 82		
Source	Av. Draft	Initial Head	1962 Head	Av. Draft	1963 Head	1968 Head	Av. Draft	1969 Head	1978 Head	Av. Draft	1979 Head	1982 Head
Well 1	.091	818	782	.020	828	846	.137	846 (e)	772	.144	777	782
Well 2	.328	1502	1456	.242	1480	1495	.415	1495	1456	.286	1456	1456
Shaft 3	.436	1553	1515	.270	1555	1577	.433	1589	1515	.368	1521	1515
Well 3	.215	1124	1045 (e)	.059	1034	1114 (e)	.297	1114 (e)	1051	.270	1080 (e)	1045 (e)
Well 4	.195	1580	1565	.052	1566	1589	.312	1593	1551	.178	1555	1565
Well 5	.157	1563	1514	.033	1545	1586	.236	1588	1516	.163	1518	1514

Footnote:
(e) = estimated

POTENTIAL HIGH LEVEL GROUNDWATER DEVELOPMENT

As shown in Figure 1, the high level groundwater resource lies on either side of the mountain crest and its exploitation takes place in both sectors, but development is more practical in the leeward portion where the plantation and population are located. Now, and probably over the usual planning horizons, development of the resource on the windward side will be restricted to Maunalei Gulch, although additional opportunities exist in Hauola and other valleys. In the leeward sector at least one new start is worth considering, and reconstruction of the present wells to increase yield may be feasible.

The sustainable yield of the aquifers may be examined from two perspectives, one concerned with the production system as it now exists and the other with the potential yield of the resource as a whole. The evaluations of Anderson and of Bowles were directed chiefly to the system currently in place. This report deals with the present system as well as the entire resource, and has its main focus on the leeward sector because of the greater feasibility of expanding sustainable yield there.

Sustainable yield refers to the permissible average production that could go on indefinitely for selected water table elevations. A steady high water table is accompanied by a smaller sustainable yield than a lower water table. Any draft will depress the water table, though at low rates the change may be obscured by natural perturbations.

The system configuration of the leeward sector is shown in Appendix C. The immediate constraint determining attainable sustainable yield is the pump setting, below which the water table must not descend. Because a pump can be reset to a lower level if it lies above the well bottom, the ultimate constraint is the depth of the well. A well may be deepened to accommodate a lower pump setting, thereby increasing potential sustainable yield.

The sustainable yield of the present leeward system given by Anderson in his 1983 review is 2.07 mgd, somewhat greater than the 1.85 mgd proposed in his 1961 report. Combined with the Maunalei contribution, he lists the total operating sustainable yield as 2.56 mgd. Bowles (1973) proposed a sustainable yield for the existing leeward system as 2.19 mgd and for Maunalei as 1.22 mgd, a total of 3.41 mgd. Anderson's 1983 estimate represents 43 percent of the total leeward - windward recharge (4.85 mgd) he computed in a water balance, while Bowles' estimate amounts to 53 percent of the total recharge (6.5 mgd) he assumed.

In this study a modeling approach has been taken in evaluating sustainable yield. A model aimed at assigning a value for sustainable yield must take into consideration recharge (infiltration) and natural leakage. The change in the system as expressed by the movement of the water table (head) during adjustment toward the equilibrium state is affected by the initial volume of water in the aquifers in addition to recharge and leakage. This is called the transient interval because the head moves downward, or upward, toward its equilibrium position. When the head stabilizes the system is in equilibrium, which is called the steady state condition.

Modeling the leeward sector as a regional aquifer requires values for average infiltration and initial head in order to determine any steady state position of the water table and its accompanying sustainable yield. The transient state is considerably more difficult to model because variable draft, initial volume in storage and time are also included in the equations. The transient model shows how and over what period of time adjustment to equilibrium occurs, whereas the steady state model is concerned only with the condition that will prevail once the adjustments are made. The transient model is not critical to assessing permissible sustainable yield, and for this reason and because system changes have not varied over a sufficient range for practical transient simulation, emphasis has been placed on the steady state approach.

Steady state can be achieved only if draft is less than infiltration. Equilibrium is impossible if draft is greater than recharge or if it equals recharge. It is plain why a steady head will not be established when draft exceeds recharge (all of the storage eventually is used), but not as evident when draft is equal to infiltration. But in this case all of the storage also is eventually dissipated; what ever isn't taken in draft is lost by leakage. Consequently, allowable draft should never be equal to recharge.

Before settling on the steady state model, an attempt was made to simulate decay in head for the decade of highest average draft (1969 - 1978) using the transient equations. Declining head as a function of time was best simulated employing leeward sector infiltration values of 3.0 to 4.0 mgd and an initial volume of 100 to 200 billion gallons. The simulation was not accurate enough to justify further exploration of the transient approach.

The steady state equation for average sustainable yield and infiltration is expressed as follows:

$$h_e = h_o \left[1 - \frac{D}{I}\right]^{1/2}$$

in which h_o is initial head, I is infiltration, and h_e is the equilibrium head for given sustainable yield, D. It is convenient to consider sustainable yield as a fraction of infiltration when plotting the steady state relationship. Figure 2 is a graph of equilibrium head at each of the wells as a function of the ratio of sustainable yield to infiltration. Included in the plot are the elevation positions of the pump settings and bottoms of the wells. It is clear from the graph that sustainable yield of the present system is constrained by these parameters. For instance, the present pump settings restrict potential sustainable yield to less than one half the average infiltration.

By inserting in the sustainable yield equation known values of initial head and computed values of infiltration (Appendix A) a sustainable yield can be assigned to any selected equilibrium head. For the leeward sector the average infiltration rate in the principal recharge zone is 3.8 mgd and in the subsidiary recharge zone, 1.2 mgd, for a total of 5.0 mgd. Rather than employing 5.0 mgd for infiltration, the mean of 5.0 and 3.8, or 4.4 mgd, is used as the average in calculating sustainable yields for scenarios of potential water production. This is consistent with the Anderson and Bowles estimates and also the transient simulation.

Scenarios of potential production for the high level water resource, varying from the current in-place system configuration to full optimal development, are given below in Table 5. Full development is arbitrarily defined as stabilizing the water table at half its original height. Production from the windward sector is limited to Maunalei except in the full development scenario. The first four scenarios assume that all production will be derived from stations now in existence; scenarios five and six incorporate an additional leeward well; and scenarios seven and eight refer to full development and, therefore, system re-configuration. In every scenario the available depth of fresh water is assumed to be the saturated zone standing above sea level.

TABLE 5

Scenarios of Potential High Level Groundwater Development

Steady State Sustainable Yields (SY)
(values in mgd)

Scenario	Description	Leeward SY	Windward SY	Total SY
1	Present leeward wells, as existing. Improved windward.(1)	1.4	0.5	1.9
2	Present leeward wells, pumps set on bottom. Improved windward	2.4	0.5	2.9
3	Present leeward wells, as existing. Enhanced windward.(2)	1.4	0.7	2.1
4	Present leeward wells, pumps set on bottom. Enhanced windward.	2.4	0.7	3.1
5	Present leeward wells, as existing. Add 1 leeward well. Improved windward.	1.8	0.5	2.3
6	Present leeward wells, pumps set on bottom. Add 1 leeward well. Enhanced windward.	2.8	0.7	3.5
7	Full development leeward. Enhanced windward.	3.3	0.7	4.0
8	Full development leeward. Full development windward.	3.3	2.7	6.0

(1) Upgrading of windward system to achieve production attained 1936 - 39.

(2) Enhancing windward yield by putting larger pump in Shaft 2 in addition to upgrade.

Sustainable yield at each scenario requires a reduction in head from its initial position. This is natural and inevitable. Given the present configuration, for instance, a sustainable yield of 1.4 mgd will eventually stabilize head at about 1500 feet elevation in Wells 2, 4 and 5, about 900 feet in Well 3, and about 700 feet in Well 1. Adjustment will take a very long time and will be accelerated or delayed by dry and wet years. Full development is based on allowing the head to be reduced to one half its original value. Further reduction would yield a greater sustainable yield.

Anderson (1985) states that plantation irrigation demand will average 1.5 mgd following readjustment of pineapple acreage and conversion to drip irrigation, and that the Lanai City plantation demand will be 0.4 mgd, resulting in a total plantation demand of 1.9 mgd. Current production from all sources is 1.6 mgd (average 1979 - 1983). Assuming plantation demands will have first priority on supply, increases in consumption associated with non-plantation ventures will have to be satisfied from surpluses generated in the scenarios listed above. A summary of the surpluses is given in Table 6. For comparison, surpluses are computed for the prevailing average draft of 1.6 mgd and Anderson's projected total plantation demand of 1.9 mgd.

TABLE 6

Surplus Sustainable Yields Over Plantation Demand

Scenarios From Table 5

(values in mgd)

Scenario	TOTAL SY	Plantation Demand 1.6 mgd	Plantation Demand 1.9 mgd
1	1.9	0.3	0
2	2.9	1.3	1.0
3	2.1	0.5	0.2
4	3.1	1.5	1.2
5	2.3	0.7	0.4
6	3.5	1.9	1.6
7	4.0	2.4	2.1
8	6.0	4.4	4.1

Plans are under consideration to develop residential lots at a rate of about 50 units per year over the next 20 years and to construct two hotels, each with 100 to 150 rooms. Assigning four people to a lot and equating one hotel room to a lot, the equivalent new resident population will total about 5000 people at the end of 20 years. The average water demand at 150 gallons per person per day will total 0.75 mgd. Allowing a contingency of 0.25 mgd, twenty years from now, say about the year 2000, another 1.0 mgd of potable water will be required for non-plantation ventures.

The water production system as it now exists and is operated will yield little or no surplus water above the anticipated plantation requirement of 1.9 mgd. Improvement of the system will be necessary if the 20 year expectation of new residential demand is to be met. Because the new ventures will gradually evolve, however, improvements will not have to be completed at the same time nor, for that matter, initiated immediately. Several of the scenarios can be accomplished with modest effort and cost. For instance, scenario 3 would require minimum investment yet provide one fourth to one half of the new demand.

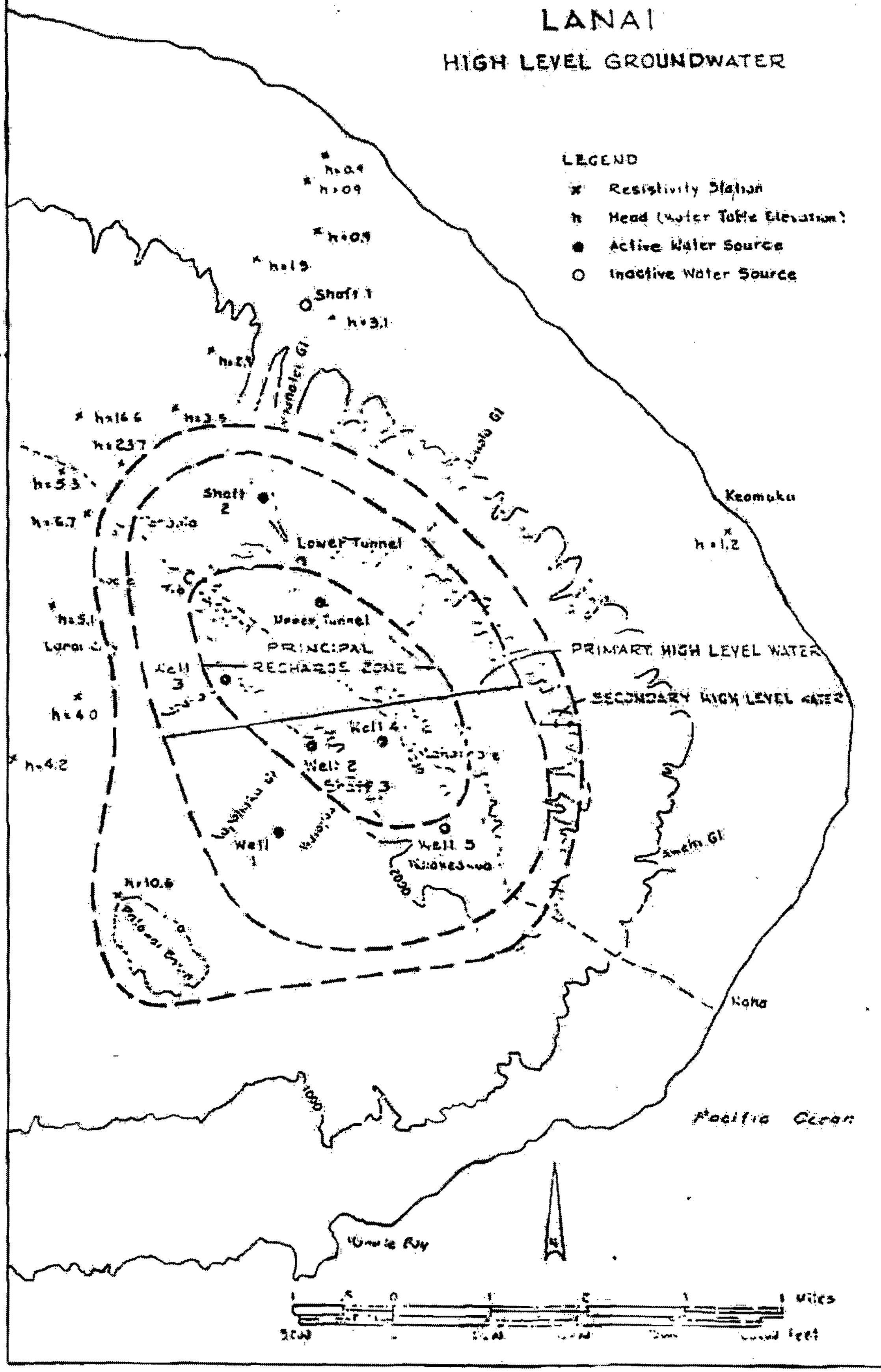
Comments on Basal Groundwater

All of the analyses given above and the conclusions concerning sustainable yields refer to high level groundwater, all of it potable except for the output of Well 1. In all directions beyond the high level region the island is underlain by a thin lens of basal groundwater. Recharge to the basal lens originates from infrequent rain storms and from leakage out of the high level resource. Total recharge is small, amounting to less than 20 mgd over 127 square miles. At this trivial rate of recharge the opportunity for creation of a fresh water lens is virtually non-existent.

Fresh water may accumulate in the basal system at the boundary where the seepages from the high level aquifers are concentrated. The volume would be small and its quality would be easily affected by pumping. Elsewhere the basal water is brackish, although the level of salinity may be low enough to permit the water's use in irrigating tolerant plants.

Basal groundwater is developable, but none of it is likely to be acceptable for drinking purposes.

FIG. 1



LANAI
HIGH LEVEL GROUNDWATER
LEGEND
Resistivity Station
Head (Water Table Elevation)
Active Water Source
Inactive Water Source
Shaft 1
Shaft 2
Lower Tunnel
Upper Tunnel
PRINCIPAL
RECHARGE ZONE
Well 3
Well 4
Well 2
Shaft 3
Well 1
Well 5
PRIMARY HIGH LEVEL WATER
SECONDARY HIGH LEVEL WATER
Keomuku
h=1.2
h=0.9
h=1.5
h=3.1
h=3.5
h=16.6
h=23.7
h=5.3
h=6.7
h=5.1
h=4.0
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h=10.6
Naha
Pacific Ocean
2000
1000
Miles
Feet

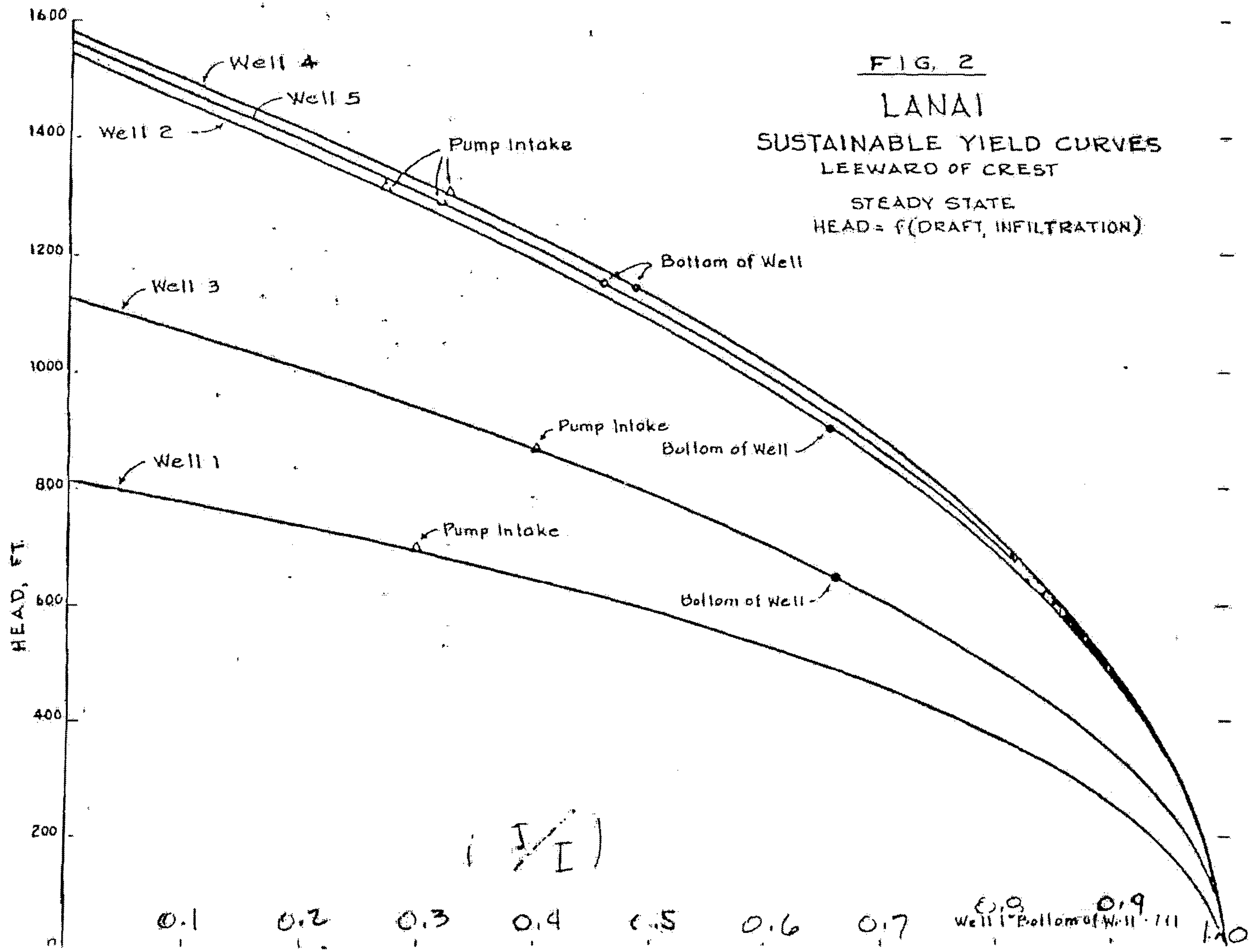

FIG. 2
LANAI
SUSTAINABLE YIELD CURVES
LEEWARD OF CREST
STEADY STATE
HEAD = f(DRAFT, INFILTRATION)
Well 4
Well 5
Well 2
Well 3
Well 1
Pump Intake
Bottom of Well
HEAD, FT.
1600
1400
1200
1000
800
600
400
200
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

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APPENDIX A

Water Balance High Level Groundwater Region

A. Areas of high level groundwater occurrence, in square miles (see Figure 1 for boundaries).

1. Primary

a. Leeward 7.0

b. Windward 7.0

Total 14.0

2. Secondary

a. Leeward 5.0

b. Windward 5.0

Total 10.0

Grand Total 24.0

B. Recharge areas (in square miles)

1. Principal. Average annual rainfall 38 inches.

a. Leeward 2.5

b. Windward 2.0

Total 4.5

2. Subsidiary. Average annual rainfall 32 inches.

a. Leeward 4.5

b. Windward 5.0

Total 9.5

Grand Total .... 14.0 (equal to are of primary high level groundwater occurrence)

C. Balance computations: Principal Recharge Zone

1. Input variables

a. Rainfall (P): 38 inches per year

b. Fog drip (F): 22.8 inches per year (see Ekern, 1964)

Total Moisture: 61 inches per year

2. Output variables

a. Direct surface runoff (DRO) = (.15) (P) = (.15) (38) = 5.7 inches per year

b. Evapotranspiration (ET) = (.80) (Evaporation) = (.80 (25) = 20 inches per year

c. Infiltration (by difference)

I = (P+F) - ET - DRO = 61 - 22 - 6 = 33 inches per year

I (Leeward) = (2.5 sq. mi) (33) = 3.92 mgd, say 3.8 mg

I (Windward) = (2.0 sq. mi) (33) = 3.14 mgd, say 3.0 mg

Total 6.8 mg

D. Balance computation: Subsidiary Recharge Zone

P = 32 inches/yr; F = (.3)(P) = 9.6 inches/yr;

DRO = (.10)(P) = 3.2 inches/yr; ET = 33 inches

I = 41.6 - 3.2 - 33 = 5.4 inches/yr.

I (Leeward) = (4.5 sq. mi) (5.4) = 1.2 mgd

I (Windward) = (5.0 sq. mi) (5.4) = 1.3 mgd

Total 2.5 mgd

E. Summary of Infiltration

1. Leeward

a. Principal Recharge Zone = 3.8 mgd

b. Subsidiary Recharge Zone = 1.2 mgd

Total = 5.0 mgd

2. Windward

   a. Principal Recharge Zone = 3.0 mgd

   b. Subsidiary Recharge Zone = 1.5 mgd

   Total = 4.5 mgd

TOTAL RECHARGE HIGH LEVEL WATER 9.5 mgd

APPENDIX B

Pumping Tests

Graphs of Pump Test Data

Data for the pumping tests, which were conducted on the leeward wells in 1950, were located in the Files of the U.S. Geological Survey.

To obtain values of transmissivity (T), drawdown (s) as a function of time (t) at a constant pumping rate (Q) is plotted on semi-log paper. Recovery may also be plotted, but against t/t', in which t is time since pumping started and t' is time since it stopped. The semi-log plot is employed rather than the analytically unsolvable Theis equation because it gives an accurate value for T since the quantity, $u = \frac{r^2 S}{4Tt}$, is less than .01 for time greater than one minute at each well. For test hole T-2 near Well 5, u is approximately .08, which also is small enough to allow the semi-log plot to be a good approximation. The effective radius of each pumping well is taken as 1.0 feet, and specific yield (S) is assumed to be .10. The distance of T-2 from Well 5 was 40 feet.

Specific yield can't be calculated from drawdown data at a pumping well, but a good estimate is possible using the data for T-2. The computed S for the Well 5 test is .10, which is what is normally assigned to Hawaiian basalt in groundwater modeling.

Table B-1 summarizes the test data, and Table B-2 lists specific capacities of the wells as determined from instantaneous drawdown immediately following the start of pumping. These specific capacities do not include aquifer drawdown. The instantaneous specific capacity divided by the depth of penetration of the well below the water table gives the unit specific capacity.

Figures B-1, B-2 and B-3 are graphs of drawdowns and recoveries at Wells 3, 4 and 5, and Test Hole T-2.

TABLE B-I

Summary of Pumping Test Data

Data and computed aquifer parameters (1)

Well	Date of Test	(gpm)	T (2) By Drawdown (ft^2/d)	T (3) By Recovery (ft^2/d)	Head-Well Depth (ft)	k By Drawdown (ft/d)	k By Recovery (ft/d)
3	5/9 - 5/26/50	700	2978	2902	473	6.3	6.1
4	6/13 - 6/24/50	650	3143	2663	441	7.1	6.0
5	7/50 - 8/50	655	4203	6412	390	10.8	16.4
T-2 (4)	7/50 - 8/50	655	2513	4555	390	6.4	11.2

(1) Q = pumping rate; T- transmissivity; k - hydraulic conductivity

(2) Transmissivity computed from drawdown curve after instantaneous well drawdown subtracted.

(3) Transmissivity from recovery curve after instantaneous well recovery subtracted.

(4) Test Hole T-2 located 40 feet from Well 5.

TABLE B-2

Specific Capacities[1]

Well	Pump Test 1950 Q/s (gpm/ft)	Pump Test 1950 Q/s/l (gpm/ft/ft)	Pumping 1985 Q/s (gpm/ft)	Pumping 1985 Q/s/l (gpm/ft/ft)
1	16	.019	18	.022
2			29	.049
3	35	.074	25	.053
4			26	.060
5	22	.057		
Shaft 2[2]	21	.0311		

(1) Q = pumping rate; s = instantaneous drawdown; l = depth of penetration below water table

(2) Data from Stearns (1940)

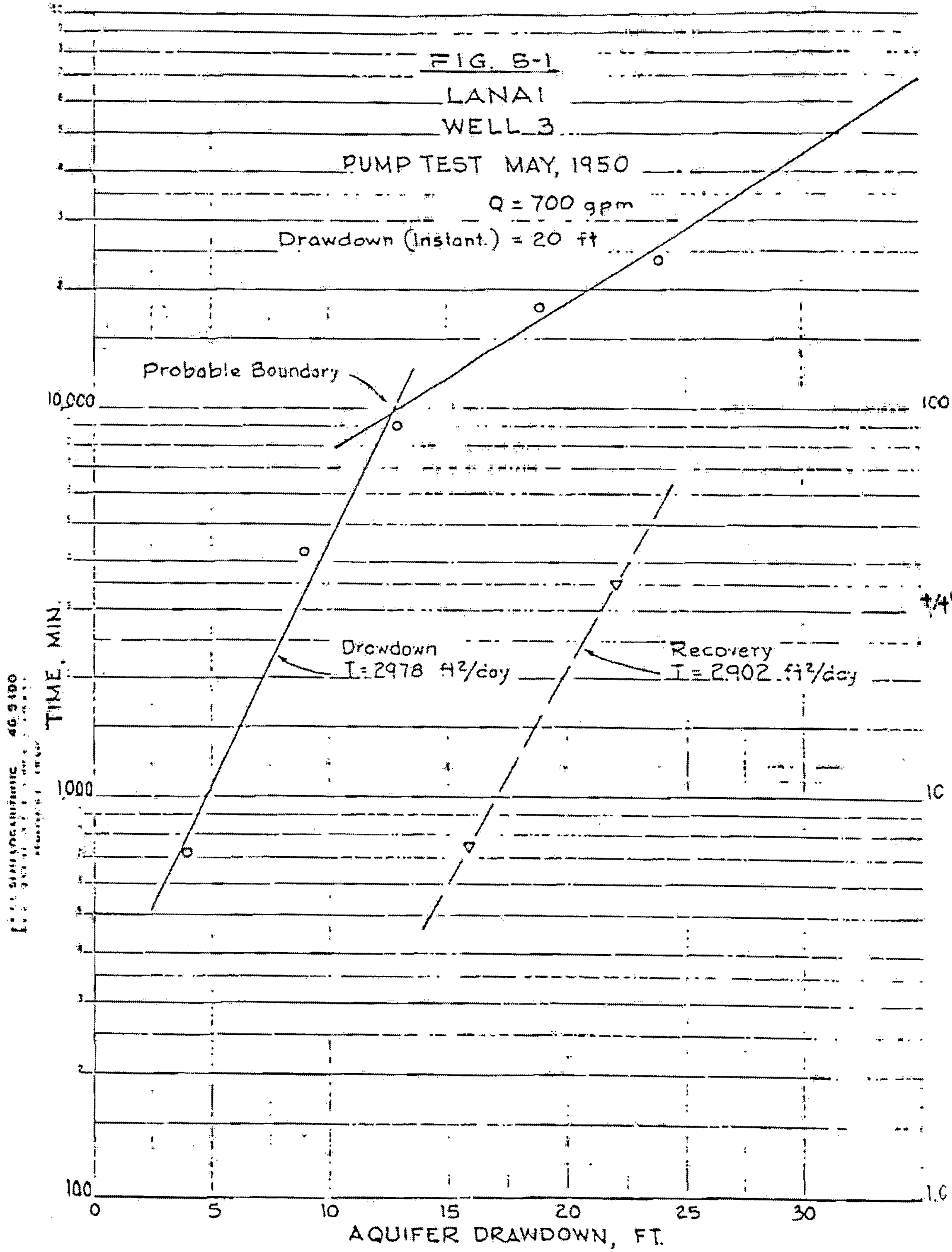

FIG. 5-1
LANAI
WELL 3
PUMP TEST MAY, 1950
Q = 700 gpm
Drawdown (Instant.) = 20 ft
Probable Boundary
Drawdown
T=2978 ft²/day
Recovery
T=2902 ft²/day
TIME, MIN.
10,000
1000
100
100
10
1.0
0
5
10
15
20
25
30
AQUIFER DRAWDOWN, FT.

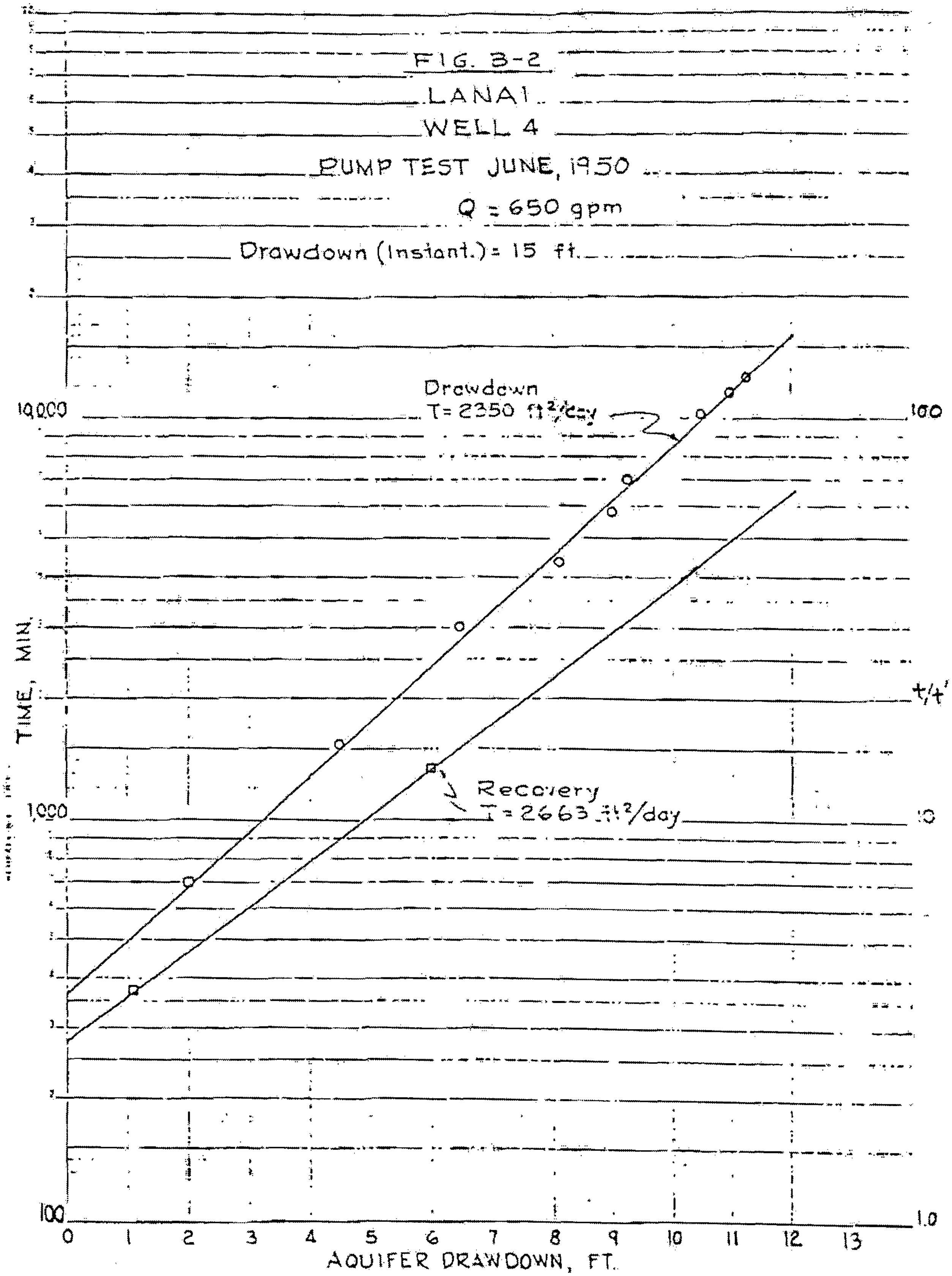
FIG. 3-2
LANAI
WELL 4
PUMP TEST JUNE, 1950
Q = 650 gpm
Drawdown (Instant.) = 15 ft.
Drawdown
T = 2350 ft²/day
Recovery
T = 2663 ft²/day
TIME, MIN.
t/t'
10,000
1,000
100
100
10
1.0
0 1 2 3 4 5 6 7 8 9 10 11 12 13
AQUIFER DRAWDOWN, FT.

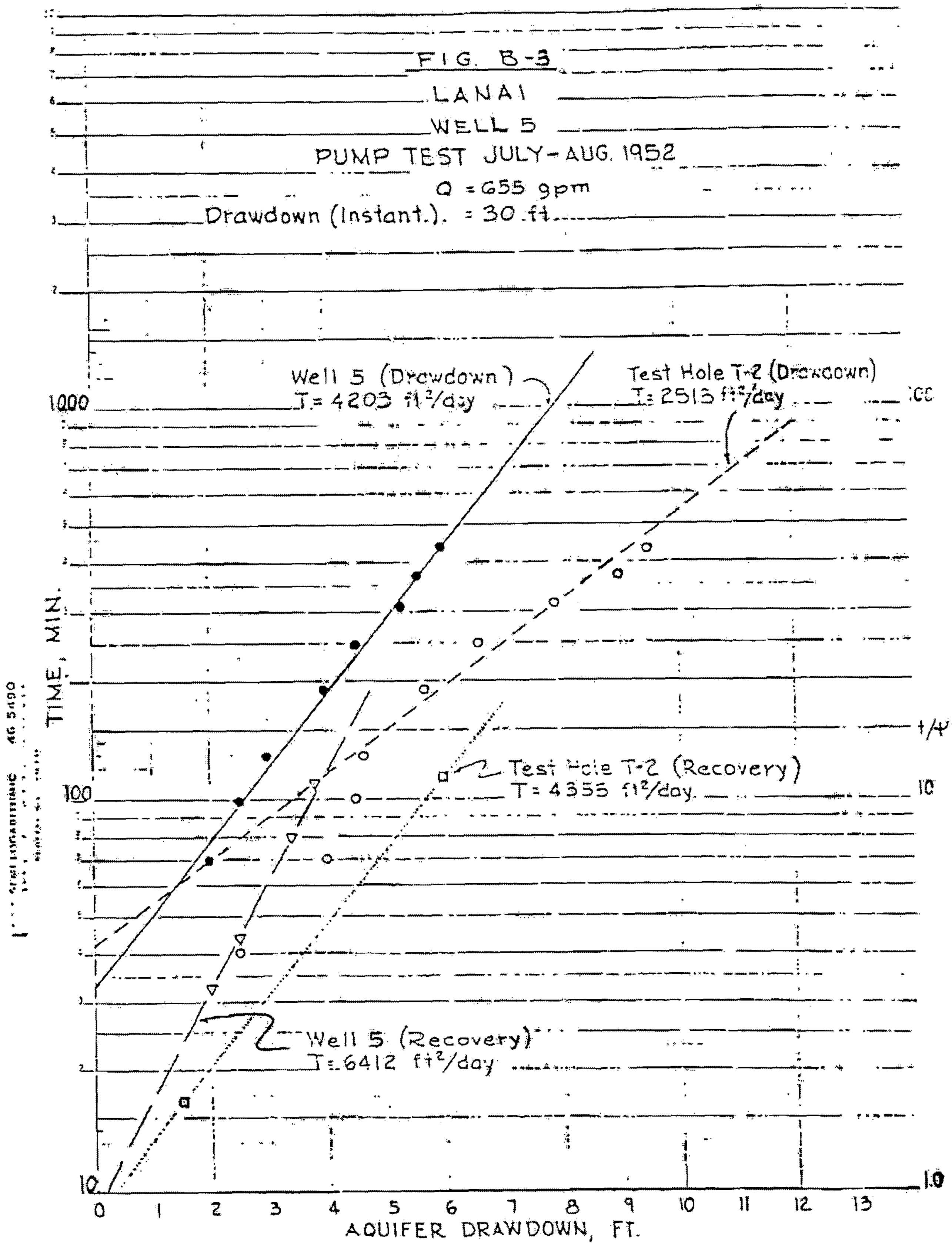

FIG. B-3
LANAI
WELL 5
PUMP TEST JULY-AUG. 1952
Q = 655 gpm
Drawdown (Instant.). = 30 ft.
Well 5 (Drawdown)
T = 4203 ft²/day
Test Hole T-2 (Drawdown)
T = 2513 ft²/day
Test Hole T-2 (Recovery)
T = 4355 ft²/day
Well 5 (Recovery)
T = 6412 ft²/day
TIME, MIN.
AQUIFER DRAWDOWN, FT.
10
100
1000
0
1
2
3
4
5
6
7
8
9
10
11
12
13

APPENDIX C

Table C-1

Well Specifications

Well	Date Drill	Well: Ground El. (ft.)	Well: Bottom El. (ft.)	Dia. (in.)	Casing: Blank Bottom El. (ft.)	Casing: Perf. Bottom El. (ft.)	Pump: Pump.[1] Intake El. (ft.)	Pump: Cap.[1] (gpm)	Head: Initial[1] Head El. (ft.)	Head: Initial[2] Head El. (ft.)	Max[3] Head Head (ft.)	Max[3] 1982 El. (ft.)	Min. Head El.
1	1915	1263	(-3)	12.5			693	600-660	818	818	830	782	772
2	1946	1815	905	18.5			1320	1000	1502	1544	1502	1456	1456
Sh 3	1954	1515	1515				1515		1553		1589	1534	1515
3	1950	1851	651	17.5	1104	662	864	800	1124	1126	1129	1045	1045
4	1950	2327	1149	17.5	1807	1144	1309	600	1580	1589	1593	1565	1551
5	1950	2296	1174	17.5	1806	1173	1290	520	1563	1570	1588	1514	1514
Sh 2	1938	851	479	20			695	420	738		747	738	716

(1) From Anderson & Kelley, 1983 Report to Dole Corp.
(2) From J. T. Munro Memo, Dated 7/12/50.
(3) From Records except for following:
a. Data for Well 3 inconsistent since 1979 (too high by approx. 100 ft.) corrected value listed.
b. Data for Well 1 inconsistent for period 1972 through 1976. This data not used.

FIG. C-1

LANAI WATER DEVELOPMENT

LEEWARD OF CREST