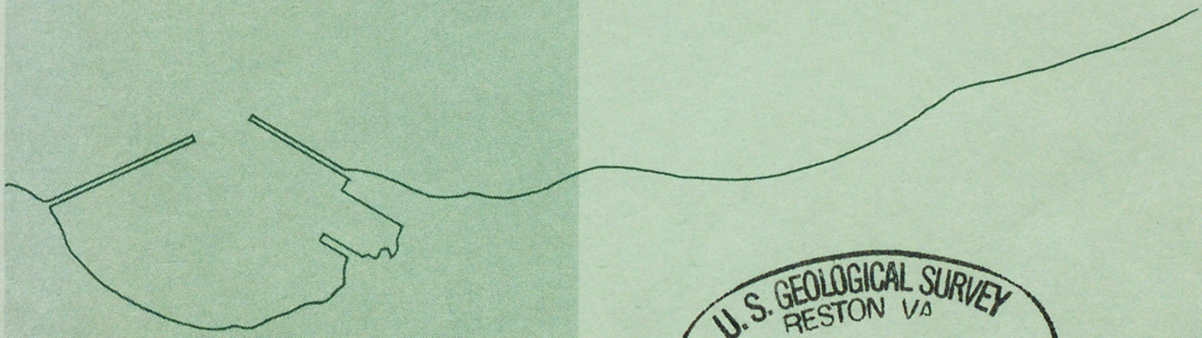
UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

DISTRIBUTION OF INJECTED WASTEWATER IN THE SALINE LAVA AQUIFER, WAILUKU-KAHULUI WASTEWATER TREATMENT FACILITY, KAHULUI, MAUI, HAWAII

Open-File Report No. 77-469



Prepared in cooperation with
COUNTY OF MAUI
DEPARTMENT OF PUBLIC WORKS

Honolulu, Hawaii
June 1977

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By W. L. Burnham, Steven P. Larson and Hilton H. Cooper, Jr.

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FACTORS FOR CONVERTING ENGLISH UNITS TO INTERNATIONAL SYSTEM (SI) UNITS

Multiply English units	By	To obtain SI units
acres	4.047×10^{-3}	square kilometers (km^2)
acre-feet (acre-ft)	1.233×10^{3}	cubic meters (m^3)
acre-feet (acre-ft)	1.233×10^{-3}	cubic hectometer (hm^3)
cubic feet per second (ft^3/s)	2.832×10^{-2}	cubic meters per second (m^3/s)
feet (ft)	3.048×10^{-1}	meters (m)
gallons (gal)	3.785×10^{-3}	cubic meters (m^3)
gallons per day (gal/d)	4.38×10^{-8}	cubic meters per second (m^3/s)
gallons per minute (gal/min)	6.308×10^{-5}	cubic meters per second (m^3/s)
inches (in)	25.4	millimeters (mm)
miles (mi)	1.609	kilometers (km)
square miles (mi^2)	2.590	square kilometers (km^2)
million gallons per day (Mgal/d)	4.38×10^{-2}	cubic meters per second (m^3/s)
million gallons per year (Mgal/yr)	1.2×10^{-4}	cubic meters per second (m^3/s)

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ABSTRACT

Field studies and digital modeling of a lava rock aquifer system near Kahului, Maui, Hawaii, were employed to define and describe the distribution of planned injected wastewater from a secondary treatment facility. The lava rock aquifer contains water that is almost as saline as seawater. The saline water is below a seaward-discharging freshwater lens, and separated from it by a transition zone of varying salinity. Injection of wastewater at an average rate of 6.2 cubic feet per second is planned through wells open only to the aquifer deep within the saline water zone. The lava rock aquifer is overlain by a sequence of residual soil, clay, coral reef deposits, and marine sand that form a low-permeability caprock which semiconfines the lava rock aquifer.

A two-dimensional finite-difference model was used to describe initial conditions within the freshwater part of the aquifer, and to indicate response of the freshwater part of the system to injection of wastewater. Steady-state distribution of the wastewater within the saline and the freshwater parts of the lava rock aquifer was simulated by use of a three-dimensional finite-difference model. This model, using vertical-to-horizontal ratios of hydraulic conductivity of 1:10 and 1:100, shows that wastewater with a lesser density than that of either the saline or freshwater aquifer, will form a roughly cylindrical column around the injection well base and rise through the transition zones into the freshwater lens flow system. The column diameter varies with the ratio, and the column, or plume, widens progressively through the transition zone, then maintains virtually constant size through the freshwater part of the lava rock aquifer. Seaward flow within the freshwater lens tends to distort the plume seaward.

Under conditions measured and assumed for the study, it is evident that wastewater injected at the planned rate will move upward, then seaward without significant change. After reaching a new steady state, the wastewater will discharge into and through the caprock sequence within an area measuring approximately 1,000 feet inland, 1,000 feet laterally on either side of the injection site, and about 2,000 feet seaward. Little, if any, of the injected wastewater may be expected to reach the upper part of the caprock flow system landward of the treatment plant facility.

INTRODUCTION

The Wailuku-Kahului wastewater treatment plant near Kahului, County of Maui, Hawaii, is scheduled to dispose of the treated (secondary treatment) effluent by injection through wells into the saltwater saturated basaltic lava aquifer beneath the plant site. At the request of the U.S. Environmental Protection Agency and the County of Maui, the U.S. Geological Survey made hydraulic tests and hydrologic studies to further evaluate the distribution of the injected wastewater within the lava aquifer. The interpretations and conclusions drawn from those studies are reported herein to provide information on which to base decisions concerning injection-well location, construction, and operation.

Statement of Problem

The Wailuku-Kahului wastewater treatment plant site is on the coastal dune ridge between the Kanaha Pond Waterfowl Refuge and Kahului Bay at the northeast edge of Kahului, Maui (fig. 1). The plant is designed to provide secondary treatment to the domestic sewage of the Wailuku-Kahului area, and to produce an average of approximately 4 Mgal/d (million gallons per day) of effluent which is scheduled for disposal by injection through wells. Peak period flows may reach as much as 12 Mgal/d. As designed, four injection wells will be used, each 200 ft from its neighbor and on an alinement approximately parallel with the beach. The wells will be 100 to 200 ft from the beach, and approximately 600 feet from the refuge boundary. Each well will be cased and cemented to a depth of about 170 ft below mean sea level (msl). Thus, approximately 200 ft of basaltic lava rock will be exposed to the borehole. Saline water of nearly seawater composition is thought to occupy the interstices within the lava throughout the exposed borehole depths, and to be overlain by a lens of fresh or brackish water. In the vicinity of the injection wells, the lava is overlain by coral and sedimentary material about 40 to 80 ft thick, with Kanaha Pond occupying a shallow depression at the land surface.

Previous analyses of the hydraulic effects of injection, and of the distribution of the effluent in the subsurface geologic-hydrologic system, have been based on meager data. The studies did not meet agreement among all parties concerned with the potential impact of the effluent on the ecological balance of Kanaha Pond, should a significant quantity find its way into the ground water supplying part of the inflow to the pond. Existing data were not sufficient to describe the subsurface hydrologic system in enough detail to satisfy the needs.

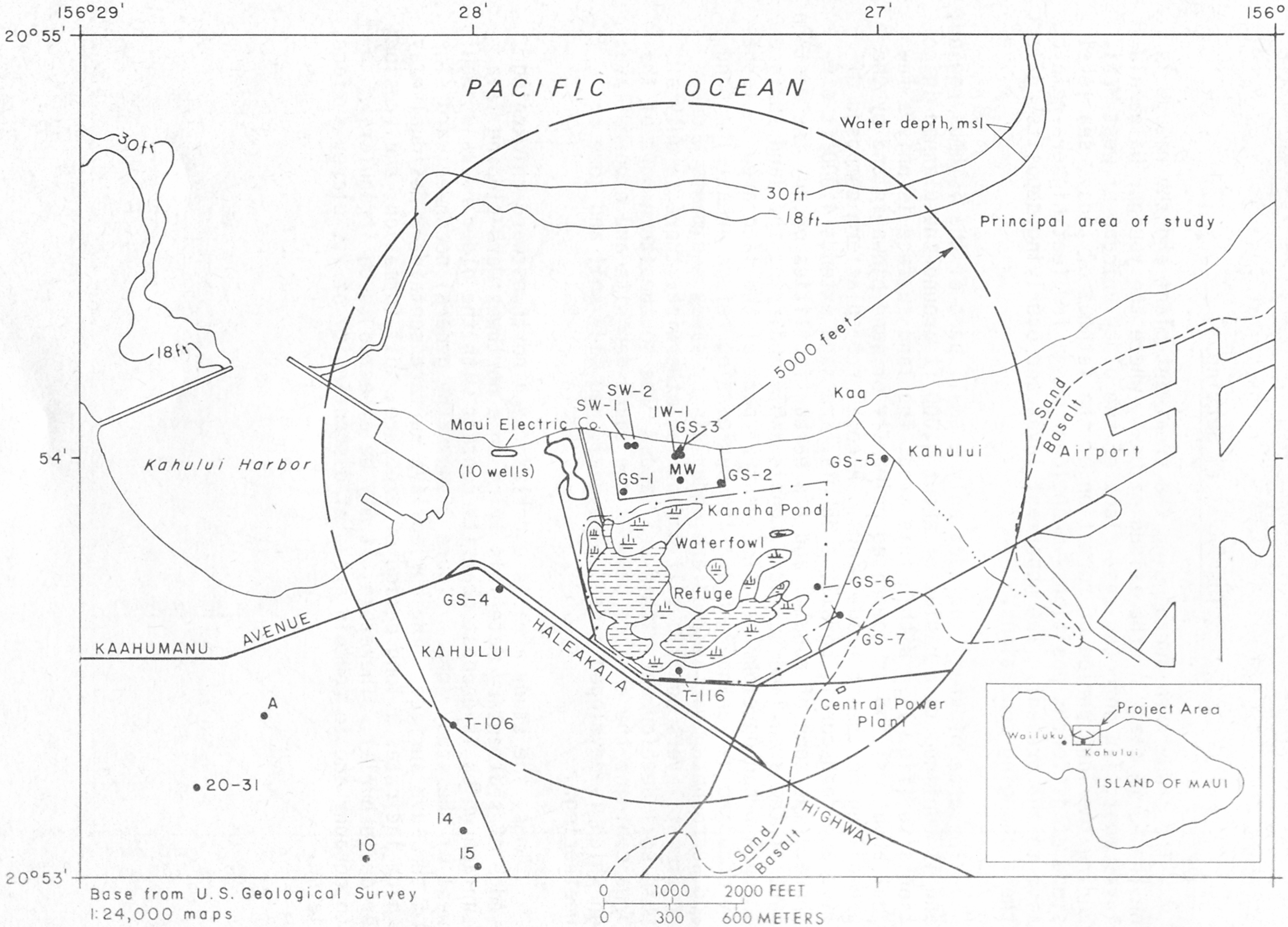

Figure 1. Map of the Kahului area showing area of study, well locations, and cultural features.

The Physical Setting

The study area surrounding the treatment plant and the refuge is on the north coast of the island of Maui, where the younger Haleakala lavas meet, lap onto the east flank of the older volcano of west Maui. During the long period of formation of the isthmus of today, sea level stood at different positions--much lower and a few feet higher--relative to the present. The uppermost lavas and overlying deposits reflect these changing conditions.

The area of study includes only a small part of the isthmus region, and is confined to a radius of about 5,000 ft around the planned injection site (fig. 1). Within this area, the land surface is only a few feet about msl and is comprised primarily of sand blown inland by the prevailing northeast trade winds. A coral reef platform composed of live and dead coral, coralline debris, and sand extends 4,000 ft offshore. The town of Kahului and its harbor facilities occupy the western part of the area land surface, considerably modifying the land surface through urban development. The central part of the land area is largely occupied by Kanaha Pond and its surrounding refuge area. The pond and surrounding marshy area are underlain by sandy sediments whose uppermost layers contain silt and humus; otherwise, there is only a thin soil development within the sands. The southeastern part of the area contains the contact between the sandy deposits and exposed lava, on which is developed a deep, residual, red clay soil and zone of weathering.

Thus, the study area is underlain by a northwestward-thickening wedge of sedimentary materials lying on a northwestward-sloping lava surface which is deepest near its contact with the older rocks of Maui west of the study area. Figure 2 shows the general northwestward slope of the lava surface. The buried lava surface contains a residual clay which indicates a long period of exposure, soil formation, and erosion prior to burial. Therefore, it may be expected to be irregular in topography and to contain areas of discontinuity of its clayey surface layer.

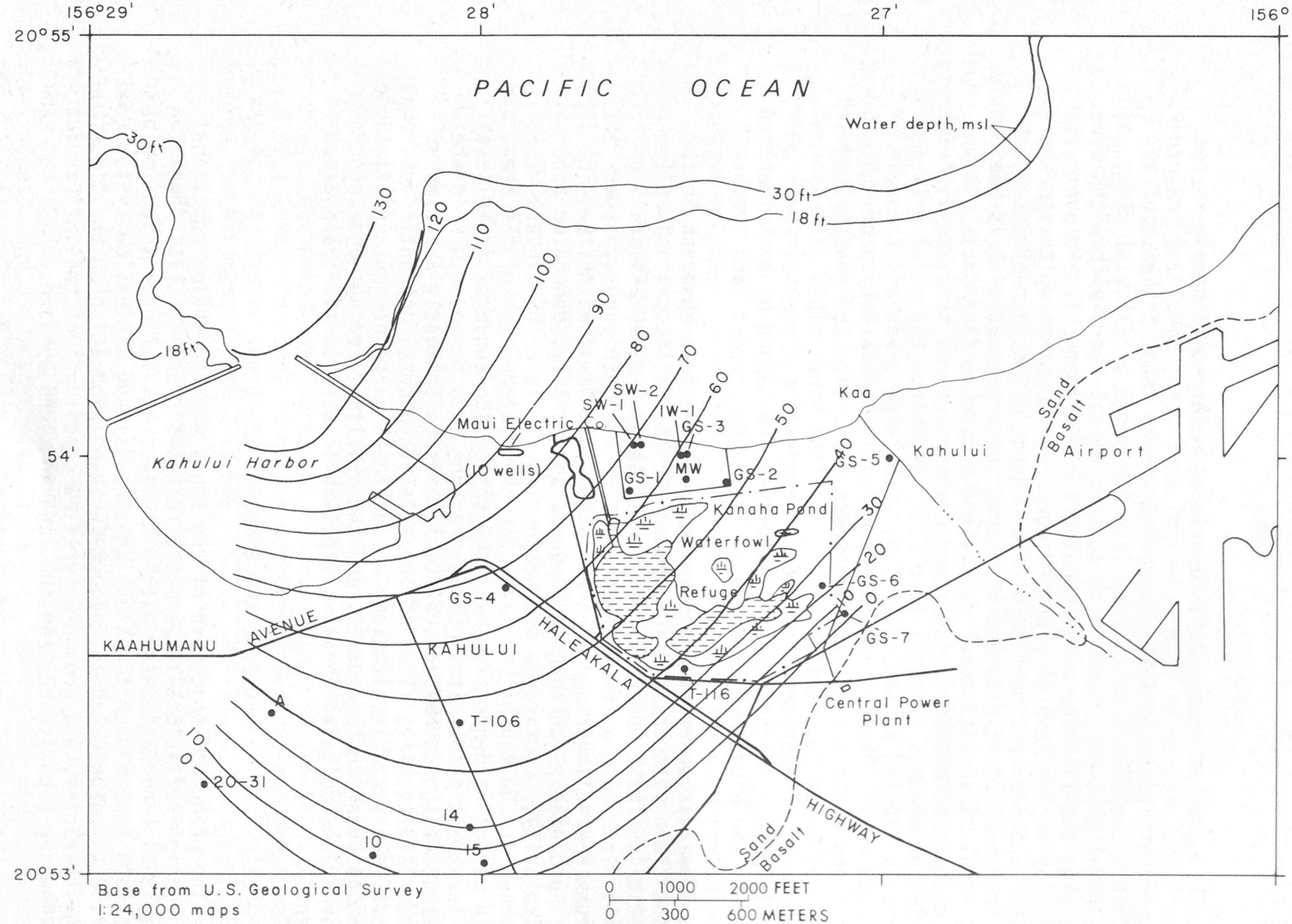

Figure 2. Map of the Kahului area showing depth below mean sea level of the top of the lava rock aquifer. Contour interval 10 ft.

The wedge of sedimentary materials, referred to herein as the caprock, is made up of four principal units, one overlying the other. Westward of about the western edge of Kanaha Pond, the base of the sediments contains a westward-thickening wedge of alluvial clay, sand, and gravel that may reach 30 to 50 feet in thickness within the area. Overlying the alluvium and extending farther southeastward over residual clay on the lava is a buried coral reef complex which appears to be the landward continuation of the present offshore reef. Beneath the treatment plant site and westward, this reef material is dominantly soft coral mixed with coral debris and medium to fine sand. To the south and east it becomes more sandy and contains coarse sand, coral fragments, and lesser amounts of coral in place. Offshore, the coral unit is generally exposed at the sea floor, with large areas and channels of sand and coral rubble. The reef complex is overlain by sand that is coarse and clean beneath the treatment plant site and grades landward into a somewhat less uniform medium to fine sand. This unit is continuous with the present "backreef" deposits and reaches 20 to 30 ft in thickness. The sedimentary materials are capped beneath the land areas by the windblown sand and soils of the present land surface.

The lavas underlying the study area have been observed in the southeastern outcrops and in cores or drill cuttings at only a few locations. These observations show it to be made up primarily of basalt flow units a few feet to about 50 ft in thickness, separated by rubble or clinker zones a few inches to a few feet thick. The flow units are highly variable in hardness and density, depending upon vesicularity, fracturing, and weathering. A layer of cinders was observed at the top of the lava near the eastern edge of the area, and again beneath a dense flow near the top of the sequence in wells at the treatment plant site. Elsewhere, the lava sequence within the upper 400 ft beneath land surface appears to be mostly a series of normal basaltic lava flows of irregular thickness, discontinuous areal extent, and variable lithology. Individual units are not identifiable from one location to another, and the drilling, coring, and logging information indicates great variability in both vertical and areal extent.

Purpose and Scope of the Study

The principal objective of the study was to develop additional information sufficient to permit a reanalysis and description of the distribution of wastewater within the lava aquifer once injection had continued long enough to establish a new steady-state flow system. An additional purpose was to collect further information on the distribution, character, and ground-water-flow conditions of the intervening sedimentary deposits between the lava and land surface.

The study scope was guided by several constraints and conditions:

1. Injection shall be at a continuous rate of 4 Mgal/d or greater.

2. Injection will be by gravity flow, and the injection head shall not exceed about 8 ft above msl. (Information received after the study indicates the injection head may reach about 12 ft.)

3. The injected wastewater will have a salinity of about 600 mg/L (milligrams per liter), or slightly greater. The wastewater temperature will be at least as warm as the water in the receiving aquifer.

4. The injection wells will be cased and cemented to at least 155 ft below msl, and all injection shall take place below that depth.

5. The receiving lava aquifer contains water of essentially the same salinity as seawater, or about 36,000 mg/L.

Based on these conditions, the scope of study included review of the existing information about the lava aquifer hydrologic system, formulation and testing of a conceptual model of the system to determine additional data needs, conducting field tests and test drilling to gain new information, simulation and computer analysis of the three-dimensional flow system prior to and following injection, and the making of interpretations and conclusions relative to wastewater distribution following injection.

Acknowledgments

The material assistance of many individuals and organizations in field data collection and the assembly and interpretation of information is gratefully acknowledged. Principal among these is Mr. George Leupold of Maui Electric Co. for facilities and assistance with aquifer tests at company wells; Mr. Al Souza and staff of the county of Maui for materials, equipment, and direct assistance with test drilling; the staff of the Maui Subdistrict of the Geological Survey; and personnel of the Pacific Arctic Branch of the Geologic Division, U.S. Geological Survey, for assistance with offshore data collection.

Special assistance with pumping tests and interpretations was furnished by Mr. Robert Scott, then of the U.S. Environmental Protection Agency (EPA); Mr. Robert Dale, USGS; and Mr. Richard Torres of Maui County. Mrs. Jackie Davis of Maui County furnished chemical analyses and laboratory assistance. Mr. John Wall, Resident Engineer for Maui County and the J. M. Montgomery Consulting Engineers, Inc., furnished data, access, and assistance with field work, as did representatives of the E. E. Black Co. and their contractors.

PLAN OF STUDY

The study was made in three phases. Initially, the problem was formulated, existing data were collected and evaluated, a conceptual model of the geohydrologic system was developed and tested, and additional field data needs were identified. The second phase included aquifer testing, test drilling, and record collecting to gain necessary additional data. The third phase was done concurrently with the second, using the existing and acquired data to develop a three-dimensional computer model to simulate and test the interpretations, and to develop predictive interpretations of the wastewater distribution.

Previous Work

Work on the geology and hydrology of the lava aquifer within the study area prior to the current study was oriented to specific problem solution, and furnished meager data on the ground-water system within the lava. Even less information is available about the occurrence and behavior of ground water within the overlying sedimentary caprock sequence.

Although studies have been made and descriptions given of the general geology of the Haleakala volcanic rocks, probably the most complete and useful for this study is that by Stearns and Macdonald (1942). From that report, and further descriptions of the occurrence and distribution of the Haleakala eruptive sequence by Macdonald and Abbott (1970) and Takasaki (1972), the volcanic rocks which will receive the injected wastewater are probably basalts, basaltic lava tending toward andesite, clinker, and some cinder of the Upper Tertiary (?), Kula Volcanics. Further details of the character and hydrologic properties of these rocks are provided for specific sites west of the study area in reports by Hargis and Peterson (1970), and Peterson and Hargis (1971), and in an unpublished report by S. P. Bowles in work done on drain wells in the southwestern area of Kahului in 1970. Also, logs of wells, shafts, and borings at sites in and near the study area furnish insight to the character and distribution of the subsurface units.

An early study by D. C. Cox for the Hawaiian Sugar Planters' Association on a deep test well (well 30) northeast of Kahului Airport furnishes the earliest specific information on the position and character of the interface and zone of mixing between the freshwater lens and saltwater. This unpublished study, made in 1954 on a well equipped with multiple piezometers showed that the transition zone from fresh to saltwater at the location is about 50 ft thick, with its center at about 80 ft below msl.

The State of Hawaii, Department of Land and Natural Resources, had a well (T-116) drilled at the south edge of Kanaha Pond in 1962. Data from the drilling and testing, and from further testing in 1971, furnish information about the upper 40 ft of the lava aquifer, the overlying caprock sequence, and the head relation with Kanaha Pond. A recorder record for a period in early 1975, as compared with a similar record of water-table fluctuations in a Maui well at the old Central Power Plant about 2,200 ft southeast, shows that the water level in the upper part of the lava aquifer at this location is representative of the upper part of the lens in the lava aquifer.

The most detailed information about the lava aquifer within the study area is found in the report by Takasaki (1972) and in the log and testing data of the J. M. Montgomery Consulting Engineers, Inc., for a pilot injection well (IW-1) at the treatment plant site. This latter information, obtained in 1970, gives the most detailed description of the injection of water into the lava sequence, and presents results of tests to determine aquifer hydraulic characteristics and acceptance rates for the injected fluid.

Phase I Conceptual Model

Following review of previous work, and also of the considerable amount of analyses, interpretation, and data development reported in correspondence and reports associated with preparation of the Environmental Impact Statement for the treatment plant, a preliminary concept was developed for the hydraulic effects of the proposed injection. This procedure quickly identified the deficiencies of data and pointed out the need for additional field measurements. Data were deficient for all the critical factors required to describe the wastewater distribution. The hydraulic conductivity of the lava aquifer was known only from specific-capacity data of wells such as the pilot injection well (IW-1), which indicated a very large value. No reliable head measurements were available for the various parts of the aquifer, and salinity measurements at various depths were available at only a few locations. A uniform datum to which all measurements could be referenced had not been established, and the interrelation of tide and well response was not documented. The flow gradient, direction, and velocity within the freshwater part of the aquifer was unknown, as was the position and thickness of the transition zone at the base of the freshwater lens at the planned injection site.

To assist in identifying which of the deficient data elements was most critical to the problem solution, assumed values were assigned to all elements and a preliminary digital computer model was constructed to describe the assumed steady-state aquifer system. The model results were then used to plan and establish the field studies needed to acquire additional data.

Field Data Collection

A field program was designed and carried out during the period of February-April 1976, based on the information from the phase 1 evaluation. Nearly all the field work was done by the Geological Survey with assistance from Maui County and contractor personnel.

Tide and Datum Measurements

A tide gage was established and operated on Pier 2 of Kahului Harbor from February 21 to April 7, 1976. The gage was placed beside the official gage of the National Ocean Survey, whose record was not available within the timing required, and was used to interrelate the ocean tide and tidal response in wells. A segment of the tide record is given in figure 3.

To establish a common datum to which all field measurements could be related, the U.S. Coast and Geodetic Survey (NOAA) bench mark R-6 in Kahului was used as the common msl bench mark from which most local surveys were made. Level lines were surveyed and temporary bench marks established from bench mark R-6 to all points of measurement made during the field studies. These surveys reestablished and checked the reference elevations for Kanaha Pond, the tidal records, and the datum used for construction at the treatment plant. The reference elevation for water-level records at the Central Power Plant well (shaft 20) was leveled from bench mark Q-6, which has long been recognized as a stable bench mark in the local surveying network and to be accurately related to bench mark R-6.

Hydrologic Character of the Lava Aquifer

As earlier described, the lava aquifer consists of a sequence of flows of variable lithology and areal extent, separated by rubbly interflow material, clinkers, and occasional beds of cinder. The flows vary from dense, fractured, hard basalt trending in some locations toward andesite and varying in thickness from a few feet to as much as 50 ft, to relatively soft, scoriaceous or vesicular basalt a few feet or tens of feet thick. Wherever observed, the flows contain numerous cross-flow cracks or fractures with weathered surfaces.

The hydrologic character of these lava rocks is expressed by their ability to transmit or conduct water in both the lateral and vertical directions. This ability may be expressed quantitatively in terms of hydraulic conductivity and transmissivity.

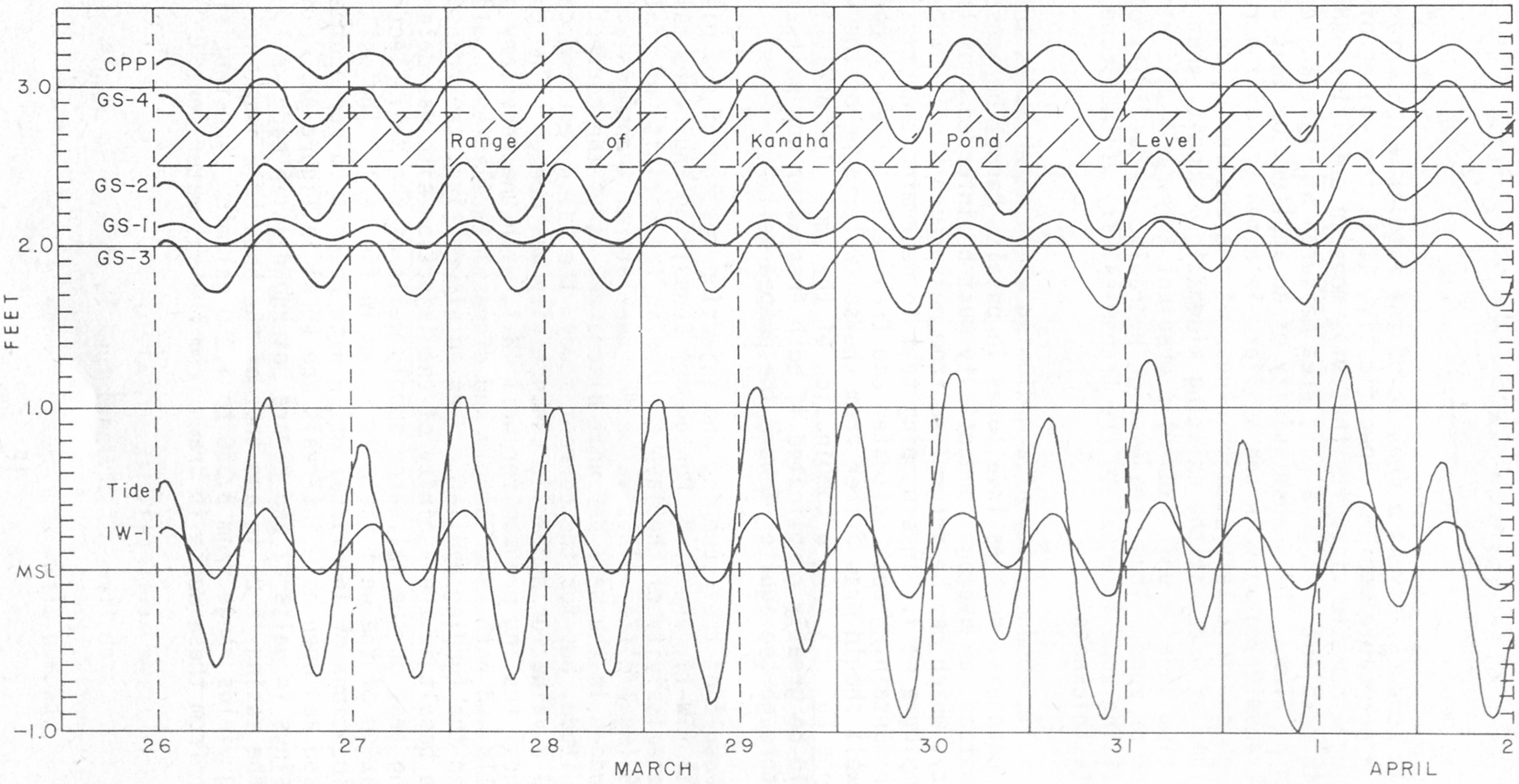

Figure 3. Graph of tide, water-level fluctuations in wells, and range of water level in Kanaha Pond, 1976.

Hydraulic conductivity is a measure of the rate at which water will flow through a permeable medium. Specifically, it is the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow. The transmissivity of an aquifer, or that of a given water-transmitting zone in the aquifer, is a measure of the rate of flow through the full saturated thickness of the aquifer or the zone. It is the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit width of the aquifer or zone. Thus, the average hydraulic conductivity of a water-transmitting zone is equal to the transmissivity of that zone divided by its thickness.

The hydraulic conductivity of a medium in which water moves through sizable open channels, such as lava tubes in basalt, cannot be measured directly. Instead, an average conductivity must be inferred from the transmissivity, which can be determined from measurements of drawdown caused by pumping a well. In a pumping test to determine transmissivity of an aquifer containing both saltwater and freshwater bodies in contact, the pumping well should draw either from the saltwater zone or the freshwater zone but not from a combination of the two. The analysis of the test would be greatly complicated if both freshwater and saltwater were moving through the aquifer toward the pumped well.

As one result of their pumping and injection testing of the pilot injection well (IW-1), the J. M. Montgomery Consulting Engineers calculated the transmissivity of the lava aquifer in the vicinity of that well to be about 5 (Mgal/d)/ft. This value for the lateral transmissivity, based on drawdown in the well per unit discharge, is of the correct order of magnitude, but for the current study, the value required confirmation and a value for hydraulic conductivity was needed. The cost of an additional testing program for well IW-1, with the necessary observation wells and both water supply and disposal facilities, would greatly exceed the funding available. As an alternative, the transmissivity of the basalt in the vicinity of the injection site was determined from a pumping test on the saltwater supply wells of the Maui Electric Co. The location of the well field is shown in figure 1. The well numbers and locations of individual wells with respect to one another and their cased and open-hole intervals are shown in figure 4A. (The depths of casings in wells 21 and 22 are not known.) In each well, the diameter of the casing is 26 in and that of the open hole is 20 in. Their pumping yields range from 3,350 to 4,350 gal/min. Substantially all the water from these wells is drawn from the saltwater zone.

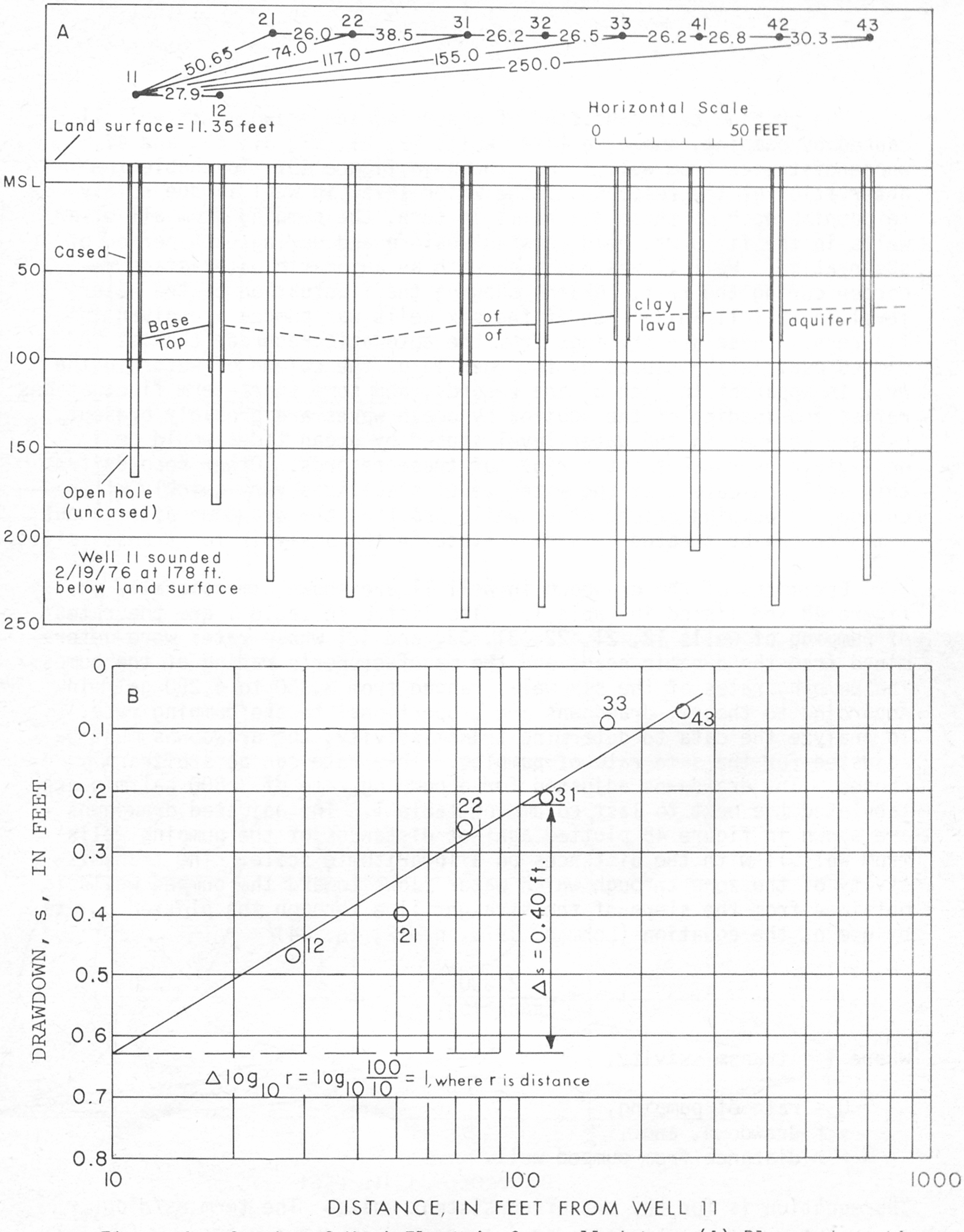

Figure 4. Graphs of Maui Electric Co. well data. (A) Plan and section views of well locations and construction. (B) Drawdown in well 11 versus distance to wells pumped.

The pumping test consisted of observing the drawdown in well 11 caused by pumping, one at a time, wells 12, 21, 22, 31, 33, and 43, whose distances from well 11 are shown in figure 4B. To enable the observation of the response of the water level in well 11 due solely to pumping each of these six wells in turn, the pumping from all other wells in the field was held constant before and during each period of observation. Well 11 was equipped with an automatic water-stage recorder during the test. Graphs showing the fluctuation of the water level in well 11 while each of the six wells was pumped are given in figure 5. These are tracings from the automatic recorder charts. A damped oscillation caused by the inertia of the column of water in the well is apparent in each of the records, and some short-term fluctuations reflecting loading of the aquifer by ocean waves are probably present, but any changes in the water level caused by ocean tides would be negligible over the short periods of these records. Other records from this well indicate that the water level stabilizes very quickly after changes in pumping of the other wells, so that the drawdown after about 1 minute can be treated as steady state in the analysis for transmissivity.

Estimates of the drawdown in well 11 are shown dimensionally in figure 4B and listed in table 1. Also listed in table 1 are the rates of pumping of wells 12, 21, 22, 31, 33, and 43, whose rates were determined from the dynamic heads and the manufacturer's rating of the pumps. The pumping rates of the six wells ranged from 3,350 to 4,200 gal/min. According to theory, drawdowns are proportional to the pumping rate. To analyze the data to determine transmissivity, the drawdowns must be adjusted for the same rate of pumping. This rate can be arbitrarily chosen. The drawdowns adjusted for a pumping rate of 3,800 gal/min are tabulated the next to last column of table 1. The adjusted drawdowns are shown in figure 4B plotted against distances of the pumping wells from well 11 with the distances on a logarithmic scale. The transmissivity of the zone through which water flows toward the pumped wells is obtained from the slope of the straight line through the plotted points by use of the equation (Lohman, 1972, p. 12, eq. 34)

$$T = - \frac{2.30Q}{2\pi \Delta s / \Delta \log_{10} r} ,$$

where T = transmissivity,

Q = rate of pumping,
s = drawdown, and
r = distance from pumped well.

The equation is for any set of consistent units. The term $\Delta s/\Delta \log_{10} r$ is the slope of the straight line in figure 4B. The difference Δs over one logarithmic cycle is 0.40 ft, hence, the slope is 0.40. Using Δs = 0.40 ft and Q = 3,800 gal/min, we find

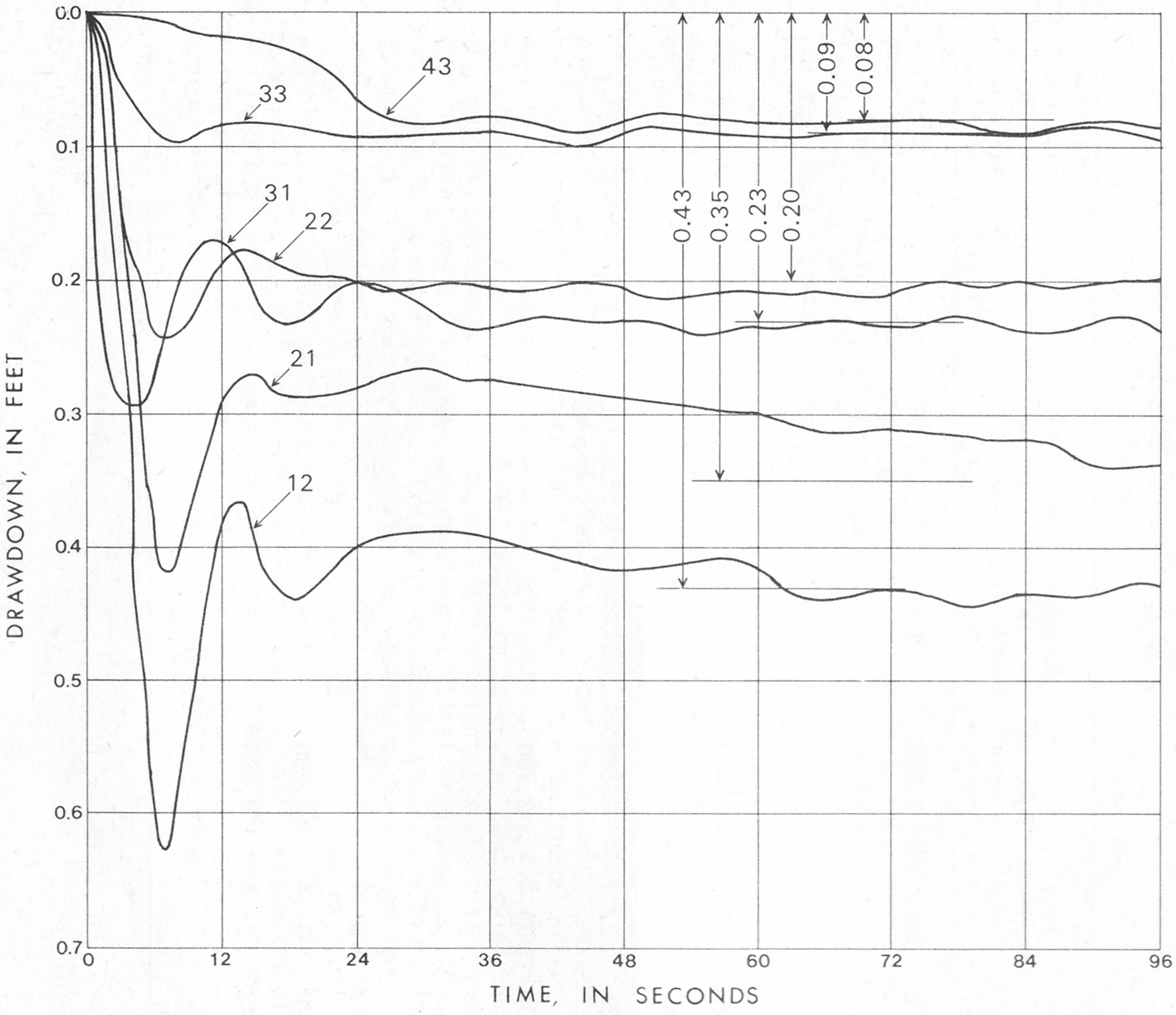

Figure 5. Hydrographs showing drawdowns in well 11 caused by pumping, one at a time, wells 12, 21, 22, 31, 33, and 43.

Table 1. Data used in analysis of effects of pumping tests on observation well 11

Well no.	Total dynamic head (ft)	Pumping rate (gal/min)	Drawdown in well 11 (ft)	Other wells pumping during tests	Distance (ft)	Drawdown adjusted to 3,800 gal/min (ft)
12	36.6	3,500	0.43	21, 22, 32, 33, 41, 42, 43	27.9	0.47
21	38.0	3,350	.35	12, 32, 33, 41, 42, 43	50.6	.40
22	37.3	3,400	.23	12, 21, 32, 33, 41, 42, 43	74	.26
31	37.9	3,600	.20	12, 32, 33, 41, 42, 43	117	.21
32	34.4	3,800				
33	34.0	3,850	.09	21, 22, 31, 32, 41, 42, 43	155	.09
41	35.9	4,350				
42	37.4	4,200				
43	37.4	4,200	.08	12, 21, 22, 32, 33, 41, 42	250	.07

$$T = \frac{2.30 \times 3{,}800}{2\pi(0.40)} = 3{,}500\ \text{(gal/min)/ft}$$

$$= 5{,}000{,}000\ \text{(gal/d)/ft}$$

$$= 7.75\ \text{ft}^2/\text{s}.$$

To determine the average hydraulic conductivity, we must decide, from an inspection of figure 4A, on the thickness by which the transmissivity is to be divided. In actuality, the flow toward a discharging well occurs throughout the aquifer. We can reasonably expect, however, that within a distance of no more than 250 ft from the discharging well, practically all the flow will be through the open-hole interval of the pumped well, especially when we consider that the hydraulic conductivity in the vertical direction is much less than that in the horizontal. The open-hole intervals shown in figure 4A are no more than about 150 ft. A conservative estimate of the horizontal hydraulic conductivity probably can be obtained, therefore, by dividing the transmissivity by 200 ft. Thus, dividing 7.75 ft^2/s by 200, we obtain a hydraulic conductivity of 0.04 ft/s, which is the figure used in modeling the effects of injection.

The hydraulic conductivity in the vertical direction cannot be determined from available information, but one can assume with reasonable certainty that it is much less than that in the horizontal, probably by at least one or two orders of magnitude. Even so, the vertical conductivity is sufficient to permit water to be transmitted rapidly in the vertical direction wherever appropriate gradients exist. Data from test drilling and coring show numerous near-vertical fractures capable of transmitting water readily. For purposes of the study, the hydraulic conductivity in the vertical direction was assumed to be between one-tenth and one one-hundredth that of the horizontal direction, and most probably nearer the one-tenth. There is some suggestion from regional hydrologic conditions that the ratio may be even closer to 1:5. In the modeling analysis, both 1:10 and 1:100 were used to obtain estimates of the probable range of values. The results of the modeling show, however, that the lateral distribution of the effluent immediately below the caprock is not greatly affected by the vertical conductivity.

The Freshwater Lens

Test holes were drilled at locations GS-1 through 7 as shown on figure 1, and piezometers were constructed at locations GS-1 through 4. The holes were drilled with a truck-mounted hollow-stem auger and wire-line core drill, which allowed coring at any depth and sampling of water by airlift wherever desired. The drill logs and data on well construction are given in table 2, and piezometer records and head relations are given in figures 3, 6, and 7. Salinity was determined by measuring electrical conductivity in µmho/cm (micromhos per centimeter) at 25°C (Celsius). The conductivity measurements were checked by laboratory analysis of total salinity on selected samples.

The test drilling showed that a continuous lens of fresh-to-brackish water exists within the caprock and the upper part of the underlying lava aquifer. The water level in shaft 20 at the old Central Power Plant represents the water table within the lens in the area free of the confining residual clay, which occurs elsewhere beneath the study area. Continuous records of water levels from piezometers at sites GS-2, 3, and 4, and from well T-116 show that the freshwater lens in the upper part of the lava aquifer is slightly confined, with heads a few tenths of a foot higher than in the overlying caprock.

The base of the lens is a transition zone, or zone of mixing with the underlying saline water. The early work by Cox on well 30 near the airport, by Bowles in 1970 at well 20-31 for the Kahului Development Co. near the Maui Pineapple Co. plant, and by Heizer and Stearns on a test hole (T-106) at the Kahului Fairgrounds in 1936 show the general position and thickness of the transition zone (fig. 7). Although these measurements were made at widely spaced times, there is no evidence--nor reason to expect--that the general configuration of the lens has changed markedly.

Transition zone at the injection site

Test well GS-3 was drilled about 60 ft northeast of well IW-1 to determine the position and thickness of the transition zone in the vicinity of the planned injection from the treatment plant. As drilling and coring progressed, electrical conductivity was measured at intervals of each few feet beneath the clay at the top of the lava by airlifting samples through the core barrel. This process yielded samples representative of specific depth intervals.

Table 2. Well logs and construction details for test holes and piezometers

Log, test hole GS-1

Description: Augered to consolidated rock, then diamond drilled with NX wireline equipment to full depth. Cored throughout.

Location: In southwest corner of treatment plant site, about 25 ft N and 15 ft E of SW corner of fenced enclosure.

Land surface datum: 4.4 ft above msl.

0 - 1	Sand, dune sand from modern beach.
1 - 17	Sand, coarse shell and coral sand with few inches of soil at top. Loose and caving below water table. Water table at about 2.5 ft. Some coral fragments to 4 in. Generally bluish-gray.
17 - 18.5	Sand, coarse coral and shell sand. Blue-gray to dark gray. Some large coral fragments.
18.5 - 20	Coral, soft coral mixed with fine, running sand. Some coral fragments to 3/4 in.
20 - 32	Coral, very soft. Drills and cores as though a "honey-comb' structure intermixed with soft, fine, running sand.
32 - 37	Coral, slightly harder, more compact. Core still yields only a limey slush like a fine sand plaster with coral fragments.
37 - 38.5	Coral, harder than above and yields larger fragments. Appears to be essentially pure, crumbly coral.
38.5 - 54	Coral, mixed with fine sand. Color changed to darker gray, with much basalt sand mixed in near the bottom.
54 - 56	Clay, red-brown. Relatively dry and crumbly, earthy. Contains glassy grains to 1/2 mm that are soft and easily crushed. No grit in the sample.
56 - 59.5	Clay, red. Appears to be residual basalt clay, but no relict structure of the basalt is evident.

Table 2. Well logs and construction details for test holes and piezometers (continued)

Log, test hole GS-1 (continued)

59.5- 61	Clay, dense, red-orange near base. Contains a 4-in streak of gritty clay just above 61 ft. Gritty zone mostly basaltic grains that appear to be sand.
61 - 62.5	Clay, hard, red. Few streaks of gritty to sandy material.
62.5 - 64	Clay, same as above but gray to gray-green. Very hard and dry near bottom.
64 - 67	Clay, brown-black, lumpy, with fragments of deeply weathered basalt toward base. A few fragments of "fresh" basalt at 67 ft.
67 - 68	Clay and weathered basalt.
68 - 74	Basalt, deeply weathered and decomposed at top, becoming progressively fresher.
74 - 79	Fresh basalt, with some fractures. Few vesicles.

Hole cased to 33.5 ft below land surface with 4-in PVC, and left with open bottom. No perforations. Converted to an observation well for the coral section of the caprock sequence.

Note: Three additional test holes were augered and drilled near this site in an attempt to construct a cased piezometer for the upper part of the basalt aquifer. All holes had essentially the same log.

Table 2. Well logs and construction details for test holes and piezometers (continued)

Log, test hole GS-2

Description:	Augered to consolidated rock, then diamond drilled with NX wireline equipment to full depth. Cored throughout.
Location:	In extreme southeast corner of treatment plant site, about 15 ft N and 20 ft W of SE property corner.
Land surface datum:	6.0 ft above msl.

0 - 22	Sand, modern dune sand near surface, grading into coarser, less uniform coral and shell sand. Buff to blue-gray color.
22 - 27	Sand, coral and shell sand, coarse.
27 - 42	Coral, soft, running, coral and fine sand mix. Appears as a thick plaster with a few coral fragments.
42 - 49	Coral, slightly harder, but still largely mixed with fine sand. Soft and "greasy" drilling at 49 ft.
49 - 53	Coral and light gray fine sand.
53 - 59	Clay, red to red-orange. Pure, nongritty residual basalt clay.
59 - 60.5	Basalt, deeply weathered, clayey.
60.5 - 62	Basalt, hard and essentially fresh. A thin clinker or cinder layer at surface.
62 - 67.5	Basalt, hard, dense, blue with about 3 in of vesicular basalt at top and fractures 6-8 in apart. A few vesicles scattered throughout. Fractures are oxidized on surfaces.

Well cased with 2-in PVC to 65 ft, with bottom 5 ft perforated. Cemented opposite clay at 53-59 ft. Top of hole cased with 10-ft length of 4-in PVC, overlapping the 2-in and cemented between 2 in and 4 in. Water level thus represents only the top of basalt beneath the clay.

Table 2. Well logs and construction details for test holes and piezometers (continued)

Log, test hole GS-3

Description: Augered to consolidated rock, then diamond drilled with NX wireline equipment to full depth. Cored in clay and basalt.

Location: About 60 ft northeast of existing injection well (IW-1) on a line toward planned injection well no.3.

Land surface datum: 9.6 ft above msl.

0	- 17	Sand, modern dune sand from present strand.
17	- 32	Sand, coarse, blue-gray coral and shell sand.
32	- 43	Coral with fine sand. Soft, loose, and running.
43	- 57	Coral, soft, fine sand and coral with some harder streaks.
57	- 62	Coral and sand, very soft.
62	- 64	Clay, red-brown residual clay grading into weathered basalt.
64	- 68	Basalt, weathered and vesicular. Drills up into cobbles and pebbles of weathered basalt.
68	- 72	Basalt, dense, with weathering at top, very dense at 70 ft, then vesicular again toward 72 ft.
72	- 76	Basalt, vesicular, and highly fractured. Some very dense rock, takes large quantity of drill water. No return circulation.
76	- 85	Basalt, dense, with clusters of vesicles at 78 ft and at 81.5 ft. Fractured.
85	-117	Basalt, dense, hard drilling. Numerous, nearly vertical fractures, many with slight oxidation bands and zones associated near the fractures. From about 102 ft, fractures are more nearly horizontal.

Cased with 2-in PVC to 70 ft with 10 ft of perforations and open pipe end. Packer set at 62 ft and cemented. Twelve ft of 4-in PVC set at surface, with 10 in of cement seal between 2-in and 4-in pipe.

Table 2. Well logs and construction details for test holes and piezometers (continued)

Log, test hole GS-4

Description: Augered to consolidated rock, then diamond drilled with NX wireline equipment to full depth. Cored throughout.

Location: In southeast corner of yard surrounding the Kahului Sewage Pump Station along Hana Highway, about 35 ft W and 10 ft N of SE corner of property.

Land surface datum: 5.0 ft above msl.

0 - 9	Fill, with thin soil and medium sand.
9 - 10.5	Sand, fine beach sand with coral fragments.
10.5 - 37	Coral, soft, fine sand. Very soft and running.
37 - 45	Coral, soft, with fine sand. Somewhat more compact and contains coral fragments.
45 - 52	Clay, dark brown, earthy. Relatively dry and crumbly. Appears as a decomposed clayey soil zone. Hard drilling.
52 - 53.5	Clay, with rounded pebbles. Dark brown, pebbles are stream- or beach-rounded. Clay is earthy.
53.5 - 59.5	Clay, drills smooth and relatively soft. No sample.
59.5 - 69.5	Clay, red, greasy. Appears as a residual basalt clay. No grit. Color grades to red-orange.
69.5 - 71	Basalt, cinders or clinkers, deeply weathered, easy drilling.
71 - 79.5	Basalt, very vesicular with a deep weathered zone at top. Solid, vesicular core from 78 ft.
79.5 - 87	Basalt, highly vesicular with weathered, red-brown fractures.

Cased with 2-in PVC to 87 ft with bottom 16 ft perforated and packer set at 70-71 ft. Cemented opposite lower clay. Ten ft of 4-in PVC set at surface and cemented between 2 in and 4 in. Water level reflects upper part of basalt.

Table 2. Well logs and construction details for test holes and piezometers (continued)

Log, test hole GS-5

Description: Augered to consolidated rock, backfilled and abandoned.

Location: On south side of gravel road on old RR alinement about 30 ft S and 50 ft E of BM-7 and 100 ft W of bridge over Kalialinui Stream.

Land surface datum: Approximately 6.0 ft.

0 - 10	Sand, soft. Dune sand from present strand.
10 - 12	Sand, very soft with coral fragments.
12 - 18	Coral with fine sand. Very soft. Auger falls through with no pressure.
18 - 22	Coral, coarser and harder, with fine sand.
22 - 49	Coral, with fine sand. Soft.
49 - 53	Coral to clayey fine sand, harder drilling.
53 - 56	Clay, red-brown. In two 6-in streaks separated by cindery or ashy gravels.
56 - 60	Lava clinker or cinder. Appears as weathered scoria or ash. Uniform, granular, ashy material about 1/4 to 1/2 in.
60 - 70	Lava, weathered scoriaceous cinder or clinker getting progressively harder. Hard, fresh basalt at 70 ft.

Table 2. Well logs and construction details for test holes and piezometers (continued)

Log, test hole GS-6

Description:	Augered to consolidated rock, backfilled and abandoned.
Location:	Along dirt road on east side of Kanaha Pond Waterfowl Refuge opposite first concrete bunker about 400 ft NW of concrete-lined ditch.
Land surface datum:	Approximately 3.0 ft above msl.

0 - 2	Soil and buff-to-brown medium sand.
2 - 27	Sand, uniform, medium, with occasional coral or basalt fragment.
27 - 28	Basalt, weathered, fractured. Hard, fresh basalt at 28 ft.

Log, test hole GS-7

Description:	Augered to consolidated rock, backfilled and abandoned.
Location:	Along dirt road on east side of Kanaha Pond Waterfowl Refuge at concrete-lined ditch. About 400 ft NW of highway to airport.
Land surface datum:	Approximately 11 ft above msl.

0 - 1	Soil and sand.
1 - 15	Sand, medium, uniform.
15 - 16	Basalt rubble. Hard, fresh basalt at 16 ft.

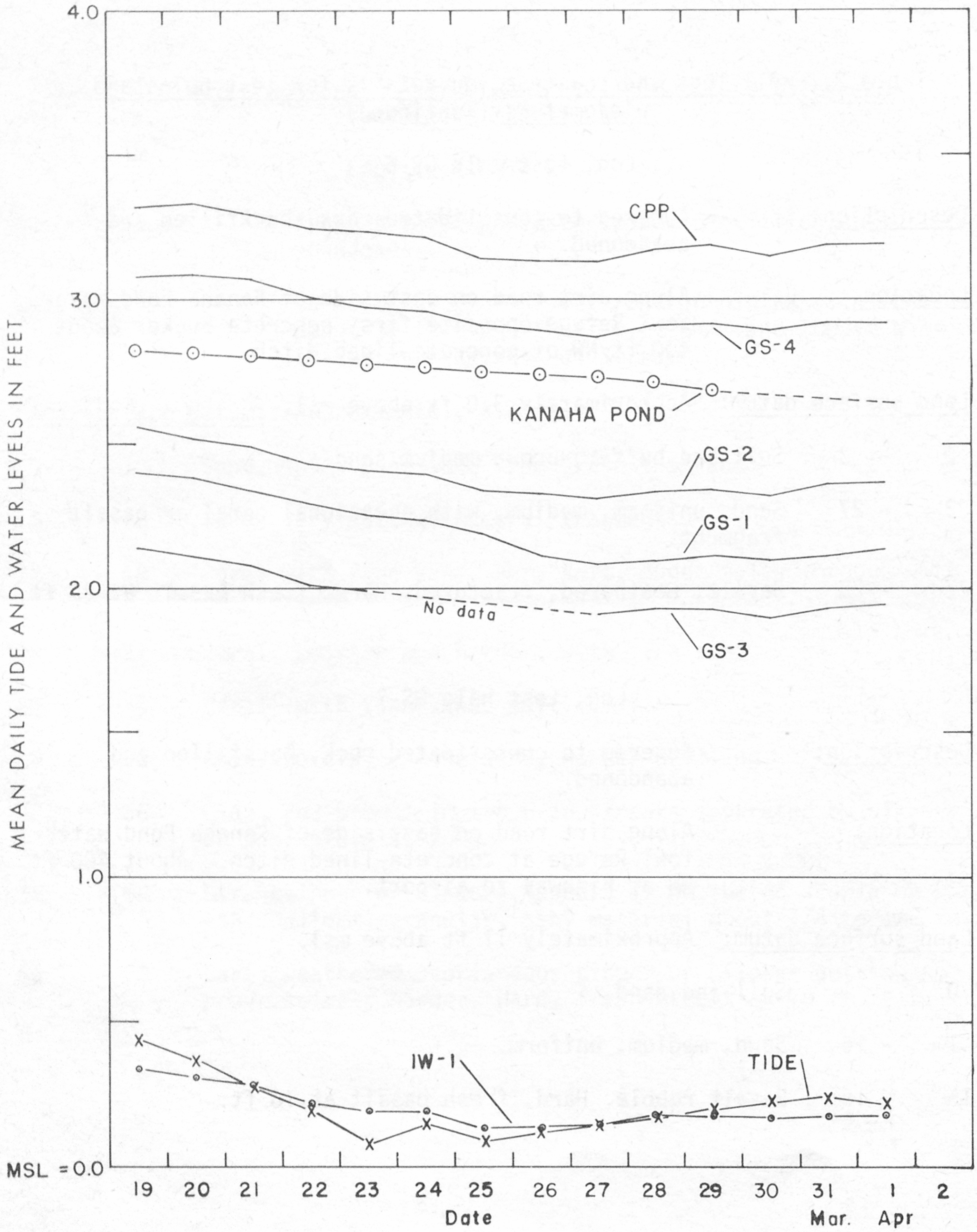

Figure 6. Graph of mean daily tide and water levels in wells, March 19 to April 2, 1976.

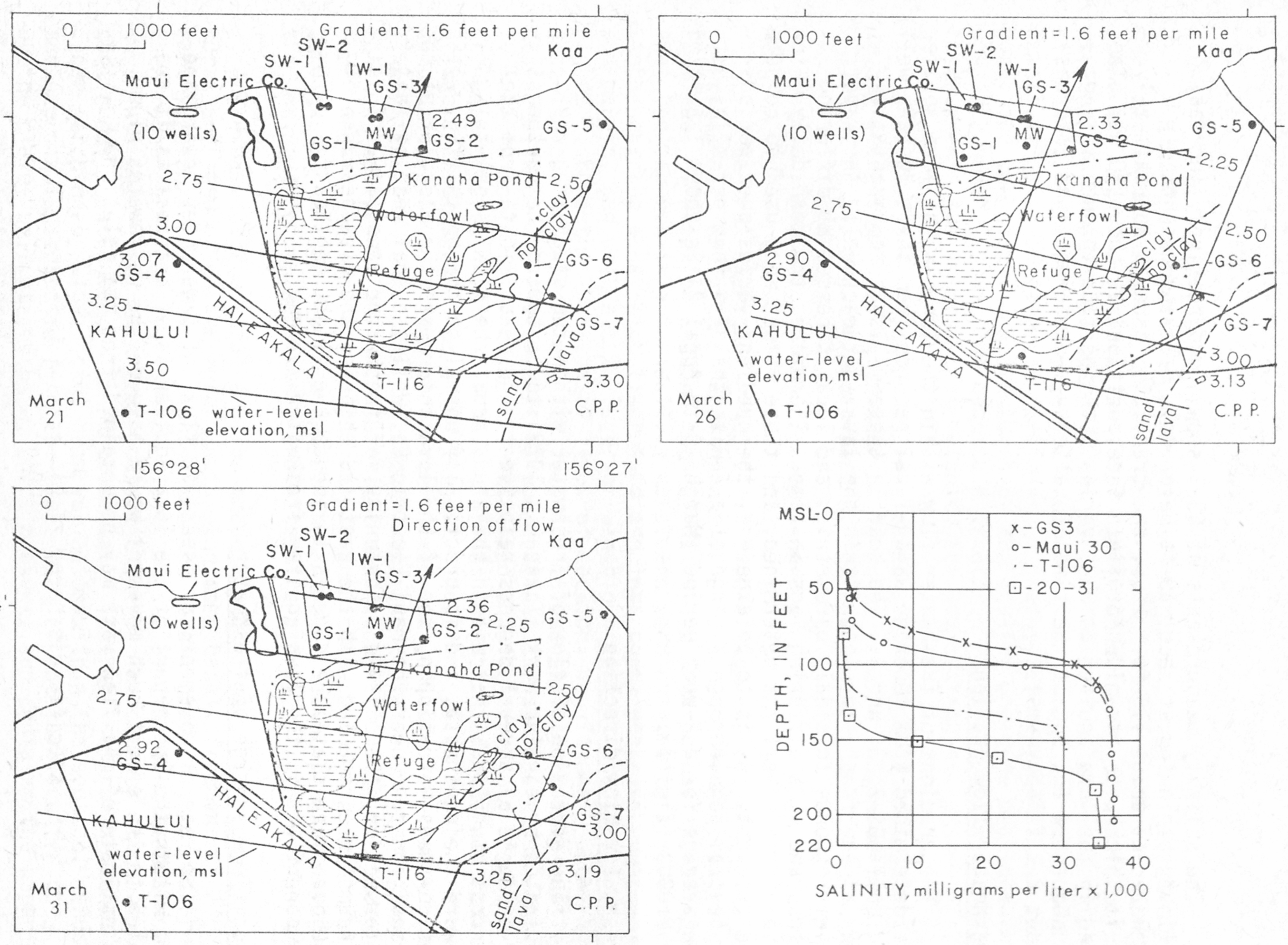

Figure 7. Maps showing water-level gradients of the freshwater lens in the lava aquifer, March 21, 26, and 31, 1976; and the salinity gradient at four locations.

The salinity measurements at GS-3 show a progressively increasing salinity beginning at about 65 ft below msl, becoming essentially seawater at about 115 ft. Thus, the transition zone is approximately 50 ft thick with its midpoint (interface position) at about 90 ft. The head in the lava aquifer at GS-3 varies with the tide through a range of about 0.4 ft, but at the time of salinity measurement, the head was about 2.2 ft above msl.

Freshwater flow gradient

The gradient of freshwater flow within the lens in the lava aquifer was determined from recorder water-level records from shaft 20 (CPP well) and wells GS-2, 3, and 4. The head in these wells is representative only of the freshwater lens within the lava. At each well, the water level responds to tidal, barometric, and local stresses at differing rates, and with differing lags in time. Therefore, the mean daily water level in each well was determined, and those values were used to compute the gradient. As is to be expected, the gradient varies over periods of several days through a range of a few tenths of a foot per mile, but the average for a 2-week period (March 19 to April 2) is about 1.6 ft/mi, or 0.0003 (fig. 7).

Freshwater flow direction

The direction of flow of freshwater within the study area was indicated by earlier work (Takasaki, 1972) to be toward the northeast at an angle of several degrees relative to the beach. Data from the current study show that within the study area, the flow is only slightly toward the northeast, and is practically normal to the beach (fig. 7). The northwestward-sloping top of the lava intersects the midpoint of the transition zone near the Maui Electric Co. wells so that west of that intersection, there is no opportunity for freshwater lens flow. This circumstance, coupled with the eastward thinning and disappearance of the overlying clay zone appears to induce the slight northeast flow component within the lava aquifer freshwater system.

Specific discharge of freshwater

The rate of movement, or "specific flux" of freshwater toward the sea within the upper part of the lava aquifer is of interest as it relates to the effect such movement would have on the wastewater plume. An estimate of the flow rate may be obtained from the relation

$$\text{specific discharge} = \frac{kI}{A},$$

where k = hydraulic conductivity of the lava aquifer,
I = hydraulic gradient within the freshwater lens in the lava aquifer, and
A = unit cross-sectional area of the aquifer.

Assuming the hydraulic conductivity within the freshwater zone is the same as that for horizontal flow throughout the lava aquifer, and using the measured gradient of 1.6 ft/mi (0.0003), a specific discharge of about 1.0 ft/d is obtained. This is the "bulk," or "Darcian" velocity as it pertains to the general seaward flux through the zone. The actual velocity of discrete particles of freshwater moving through the pores and the cracks and fractures of the aquifer would be much greater--possibly several orders of magnitude greater. Porosity data with which to calculate the interstitial velocity are not available.

The value of 1 ft/d may be considered a maximum rate of movement of the general mass of freshwater as it moves seaward. Such movement will tend to distort the upper part of the wastewater plume downgradient.

The Caprock Sequence

The general character and distribution of the caprock sequence is described earlier in this report under the section on physical setting. From that description and the logs of wells and test holes, it is clear that the caprock is principally a coral and sand unit, with clayey sections near the base, with finer sand and less coral near its southeastern margin, and with a thin layer of windblown sand at the surface. Figure 8 shows the location of lines of section, and figure 9 shows the distribution of caprock and its relation to the underlying lava aquifer. At the site of GS-1, 1 or 2 ft of poor soil at the surface grades quickly into 16 to 18 ft of uniform coarse sand consisting mainly of shell and coral debris. This unit also contains fragments of well-abraded "finger" coral up to 2 or 3 in, longest dimension. With depth, the sand passes abruptly into coral reef mixed with uniform fine to medium-fine calcareous sand. The calcareous reef structure is very soft and the sand appears to be in a slurrylike condition within the reef structure, whose openings contain the poorly compacted sand. The drill fell through the section from its own weight, or with slight pressure, and the coring tube contained only a plasterlike slurry.

The base of the coral section grades into firmer, more compact coral and sand of darker color containing some basalt fragments. An earthy, brownish, sandy clay underlies the coral, grading into red-brown, then red-orange, greasy, compact clay. This clay, in turn, grades downward into weathered, then fresh basaltic lava. The caprock sequence is continuously saturated, with no evidence of internal separating zones to cause perching or significant head variation within the section. Thus, the caprock is separated from the upper part of the lava aquifer only by the clayey unit at its base, where present, and contains the upper part of the freshwater lens.

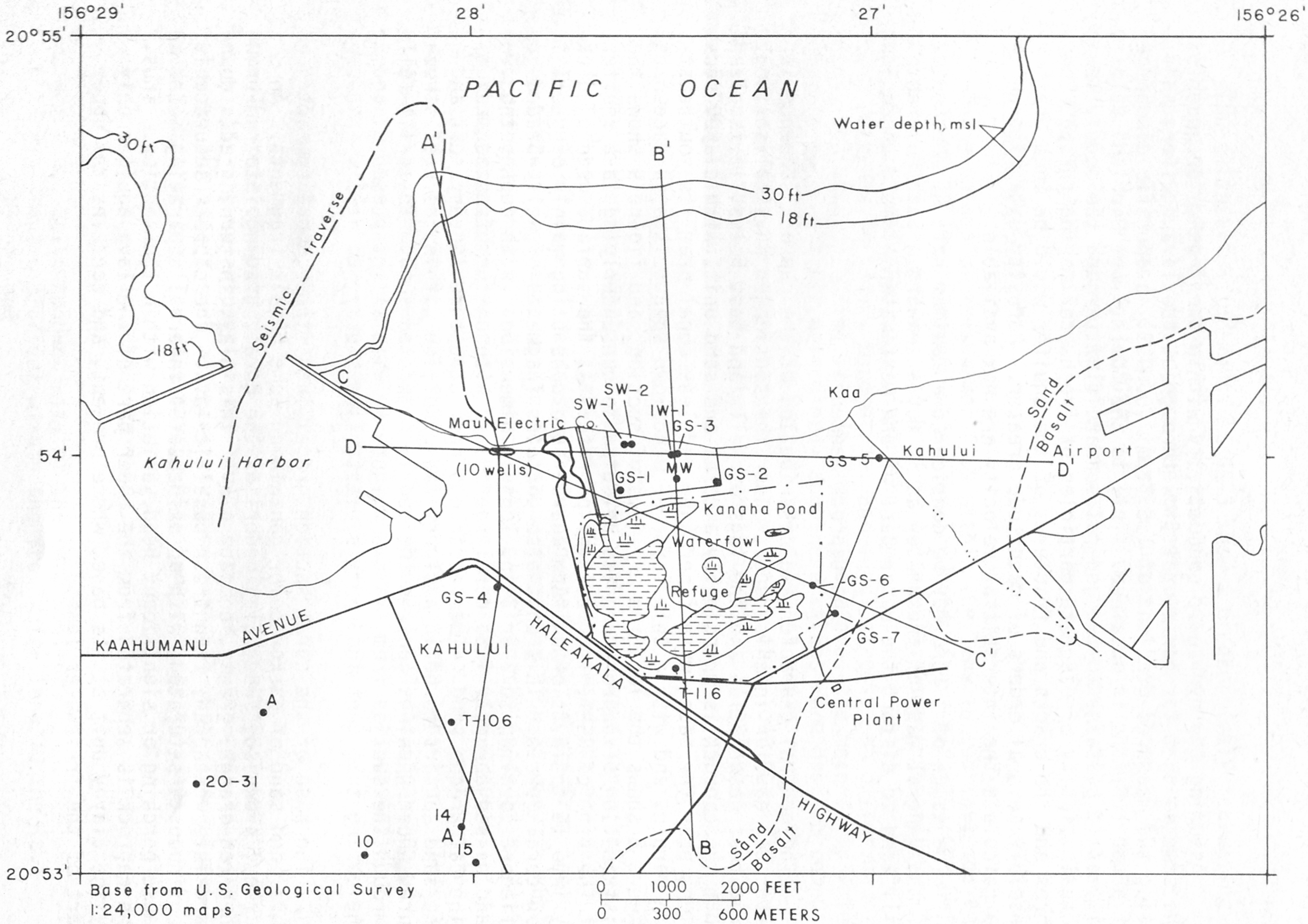

Figure 8. Lines of section A-A', B-B', C-C', and D-D', and the trace of offshore seismic traverse.

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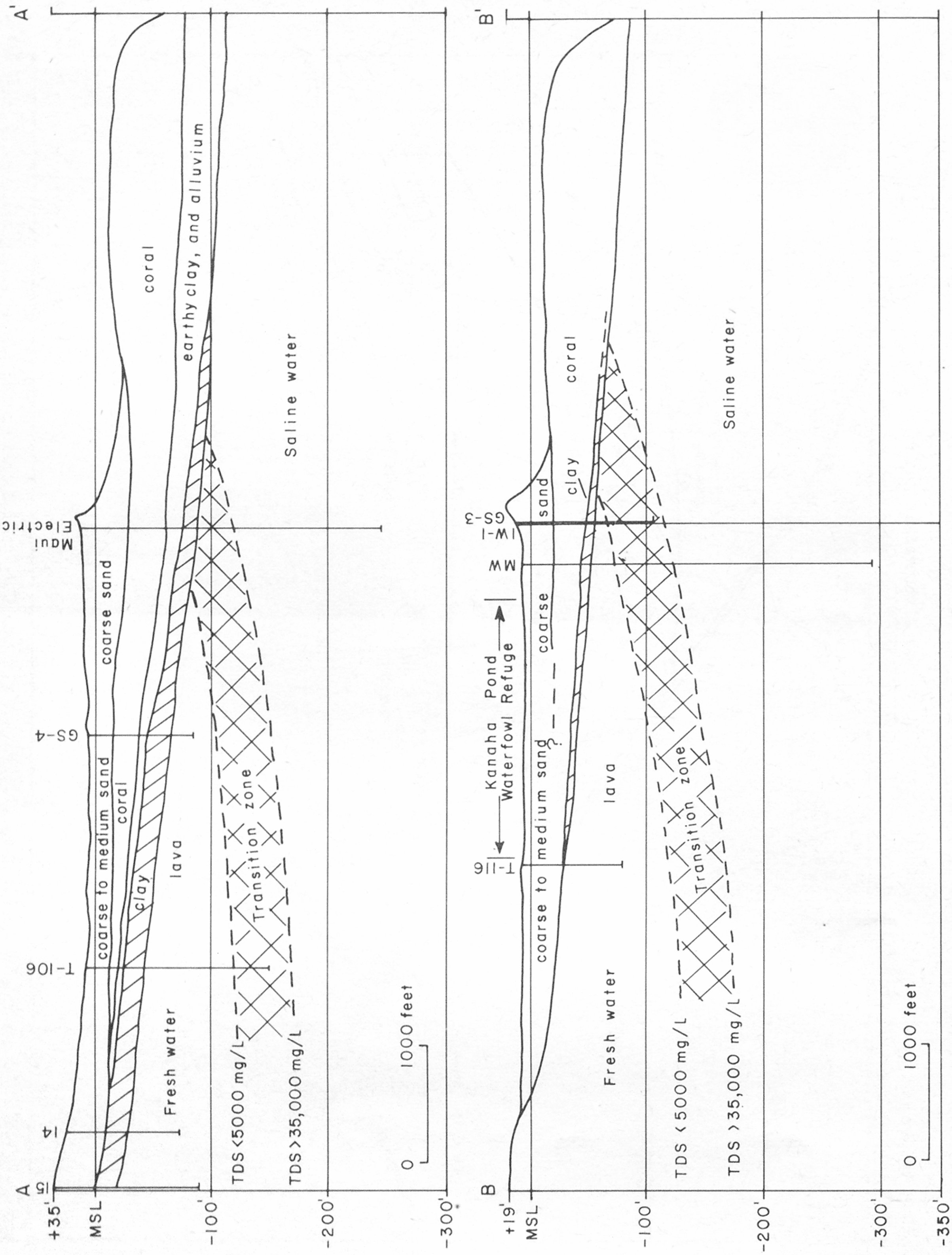
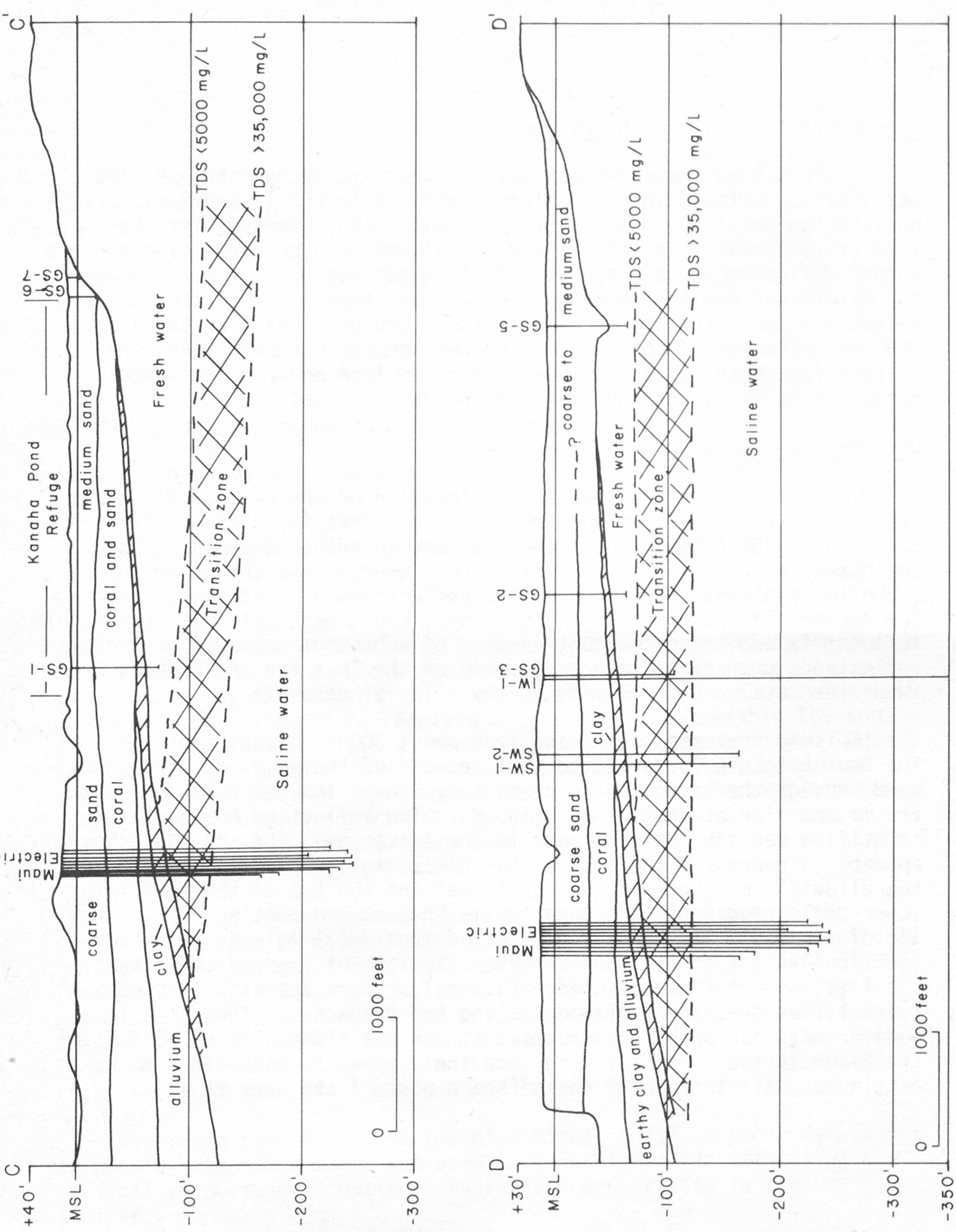


Figure 9. Cross sections showing relation of lava aquifer to caprock sequence and



the position of the transition zone.

Freshwater lens within the caprock

That part of the lens within the caprock is unconfined, and the water-table surface fluctuates from about 1.9 to 2.3 ft above msl beneath the treatment plant site. The water table varies with the tide (fig. 3) and responds rapidly to rainfall and recharge from surface runoff following storms. The gradient of the water-table surface was not determined during the study, but may be inferred to be the same or slightly steeper than the gradient within the upper part of the lava aquifer. The record for site GS-1 shows the caprock water-table head to be a few tenths of a foot lower than the lava aquifer freshwater head, yet to the south and east, the heads are equal.

Offshore continuation of the caprock

To gain data on the seaward continuation of the caprock sequence, profiles of the sea floor and the subbottom rocks immediately offshore for about 5,000 ft were made using seismic sounding equipment. The equipment introduces high-intensity sonic energy into the water and subbottom sediments, and records the reflections of that energy from the various layers of differing density. From these data, it is possible to identify and trace the continuation of subbottom units of contrasting reflectance character, such as the top of the lava and the contact between the coral and underlying earthy alluvial deposits.

Seismic traverses were made from about 300 ft directly offshore of the Maui Electric Co. plant to just seaward of the reef, then southwestward through the harbor entrance to buoy 8 near the beach at the southern inland side of the harbor (fig. 8). Two reflecting horizons were identified beneath the sea floor in the traverses. The shallower horizon appears to represent the base of the coral reef complex, or the top of the alluvial unit between the coral reef and the top of the lava. The lower reflecting horizon apparently is the seaward continuation of the top of the lava, as shown by projection from drill-hole data on land (section A-A', fig. 9). One important feature of these data is that the lava is seen to be covered with coral or sand deposits to depths of several feet everywhere offshore along the traverses. Thus, the lava aquifer does not appear to crop out at the sea floor within 5,000 ft of the beach in the area traversed, and the caprock is considered to be a continuous unit throughout the offshore part of the area of study.

Simulation Analysis

The complexity of aquifer geometry, aquifer characteristics, and boundary conditions within the study area limited the utility of analytical methods. Consequently, numerical techniques were employed to simulate injection of the wastewater into the combined freshwater-saltwater aquifer system. Several important, or potentially important factors that were considered in the simulations included:

1. Location and extent of the transition zone between fresh and saline water in the aquifer.

2. Anisotropy and nonhomogeneity of the aquifer.

3. Relative hydraulic conductivity of materials overlying the lava aquifer.

4. Relative densities among the freshwater, saline water, and injected fluid.

Preliminary tests, using a three-dimensional finite-difference model of ground-water flow, mass transport, and energy transport, showed that the model could simulate the effects of the above factors. However, the scale of the field problem caused numerical and hydrological problems that could not be resolved with such a model within the constraints of available field evidence and computing capability. These problems were related primarily to attempts to simulate a dispersed transition zone between fresh and saline water and could probably have been resolved through additional research and development. However, the time required would have been several months--a period much longer than was available for the study.

A modified approach, undertaken to obtain an estimate of the system's behavior in response to injection, included a two-dimensional ground-water-flow model to simulate flow in the freshwater part of the lava aquifer system and an analytical method to simulate the effects of saline water withdrawal. For this approach, a sharp interface was assumed to exist between fresh and saline water and an iterative technique was devised to compute simultaneous equilibrium (steady-state) response to stresses in the fresh and saline parts of the aquifer.

Utilizing results of the two-dimensional model, a three-dimensional ground-water-flow model was used to investigate the effects of the vertical to horizontal ratio of hydraulic conductivity in the basalt aquifer.

Two-Dimensional Flow

A two-dimensional finite-difference aquifer model developed by Trescott, Pinder, and Larson (1976) was adapted to simulate flow in the freshwater part of the lava aquifer. The partial differential equation of two-dimensional ground-water flow can be written as (Pinder and Bredehoeft, 1968)

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_{yy}\frac{\partial h}{\partial y}\right) = W\ (x,y,t) \qquad (1)$$

where T_{xx}, T_{yy} are the principal components of the transmissivity tensor (L^2T^{-1}),
h is hydraulic head (L), and
$W\ (x,y,t)$ is the volumetric flux of recharge or withdrawal per unit surface area of the aquifer (LT^{-1}).

Equation 1 assumes that the Cartesian coordinate axes x and y are alined with the principal components of the transmissivity tensor, T_{xx} and T_{yy}. To simulate the freshwater part of the aquifer system, transmissivity is dependent upon the position of the interface between fresh and saline water. Assuming that the coordinate axes are also colinear with the principal components of the hydraulic conductivity tensor, equation 1 for equilibrium conditions (derivatives with respect to time and zero) may be expressed as

$$\frac{\partial}{\partial x}\left(K_{xx}b\ \frac{\partial h_f}{x}\right)+ \frac{\partial}{\partial y}\left(K_{yy}b\ \frac{\partial h_f}{\partial y}\right) = W(x,y) + \frac{k'}{m'}\left(h_f-h_c\right) \qquad (2)$$

where K_{xx}, K_{yy} are the principal components of the hydraulic conductivity tensor (LT^{-1}),
b is the thickness of the freshwater part of the aquifer (L),
$\frac{k'}{m'}$ is the leakage of an overlying confining layer (T^{-1}), and
h_c is the head above an overlying confining layer (L).

The subscript, f, of the hydraulic head denotes freshwater zone.

An approximate solution to equation 2 can be determined by finite-difference methods once an equation for b is established. The approach is to subdivide the region of interest into rectangular blocks in which the aquifer characteristics are assumed to be uniform, and to replace the continuous derivatives in equation 1 or 2 with finite-difference approximations for the derivatives at a point (the node at the center of the block). The result is N equations in N unknowns (head values at each node) where N is the number of blocks representing the region of interest. The equations can be solved simultaneously to obtain an approximate solution to the partial differential equation. The reader is referred to Trescott, Pinder, and Larson (1976) for detailed development of the finite-difference equations and solution algorithmns.

The thickness of freshwater in the aquifer, b (assuming a sharp interface), depends upon the freshwater head above sea level at the interface location. If water in the saline part of the aquifer is static, the depth below sea level to a point on the interface would be (Hubbert, 1940, p. 872),

$$z = \frac{\rho_f}{\rho_s - \rho_f} h_f \qquad (3)$$

where ρ_f is the density of the freshwater (ML^{-3}),
ρ_s is the density of the saline water (ML^{-3}), and
h_f is the head of freshwater above sea level at the point on the interface (L).

Because of large withdrawals of saline water at the Maui Electric Co. well field, the saline water in the basalt aquifer is not static. Although knowledge of the effective thickness of the saline water zone is limited, an approximation can be made to simulate the effect of saline water withdrawal on the interface position. Assuming that the ocean creates an effective constant head boundary condition near the well field, response to saline water withdrawal can be approximated analytically and predicted drawdowns can be used to modify the interface position described by equation 3.

Using the method of images (Ferris and others, 1962), the analytical solution for drawdown at any point resulting from a well pumping in a system bounded by a line source at constant head can be expressed as

$$s_s = \frac{Q_s}{2\pi T_s} \ln \frac{r_i}{r_w} \qquad (4)$$

where Q_s is the discharge rate from the saline water zone (L^3T^{-1}),
T_s is the transmissivity of the saline water zone (L^2T^{-1}),
r_i is the distance from the observation point to the image well (L), and
r_w is the distance from the observation point to the real well (L).

Equation 4 simulates the effect of a line source at constant head normal to the line between the real well and the image well, intersecting the line at its midpoint.

Equation 3 (static conditions) assumes that the pressure on the saline water side of the interface is equal to $z\rho_s$. If the flow in the freshwater zone is nearly horizontal and a drawdown, s_s, occurs in the saline water zone at the interface, the pressure on the saline side would be $(z-s_s)\rho_s$. The pressure on the freshwater side would be $(h_f + z)\rho_f$. Assuming a sharp interface, these pressures must be equal and an expression for z in terms of freshwater head, h_f, and saline water drawdown, s_s, can be written,

$$z = r_f h_f + r_s s_s \qquad (5)$$

where r_f is the ratio $\rho_f/(\rho_s-\rho_f)$ (dimensionless), and
r_s is the ratio $\rho_s/(\rho_s-\rho_f)$ (dimensionless).

Given an interface position described by equation 5, the thickness of the freshwater zone, b, within the basalt aquifer can be expressed as,

$$\begin{aligned} b &= z - d; \quad d < z \\ b &= 0; \quad d \geq z \end{aligned} \qquad (6)$$

in which d is the depth below sea level of the top of the basalt aquifer. If d is greater than z, a freshwater zone does not occur at that location in the aquifer system.

Field evidence indicates that at the Maui Electric Co. well field, a small amount of freshwater (or relatively freshwater) must be withdrawn to maintain an interface position near the top of the open intervals in the wells. Discharge from the wells has seawater salinity (specific conductance about 36,000 μmho/cm). Thus, the quantity of freshwater withdrawal is so small compared to that of saltwater that its diluting effect cannot be detected by measuring specific conductance.

To simulate the effect of freshwater withdrawal, the rate was assumed to be proportional to the length of screened interval exposed to the freshwater zone. Therefore,

$$Q_f = \frac{(z - d_c)}{(d_w - d_c)} Q \qquad (7)$$

where Q_f is the rate of freshwater withdrawal (L^3T^{-1}),
d_c is the depth of the bottom of the well casing below sea level (L),
d_w is the total well depth below sea level (L), and
Q is the total withdrawal from the well (L^3T^{-1}).

The total withdrawal from the well is the sum of the fresh and saline water withdrawals. Thus,

$$Q = Q_f + Q_s \qquad (8)$$

If the total withdrawal, Q, and the freshwater head, h_f, are known, equations 4, 5, 7, and 8 can be solved simultaneously for Q_f, Q_s, s_s, and z. It is assumed in equation 4 that the transmissivity T_s of the saline water zone is not affected by changes in the thickness of the freshwater zone. Equations 4, 5, and 6 can then be used to determined the thickness of the freshwater zone at any location in the system. Substituting into equation 2 and solving numerically yields h_f, which can be used to compute Q_f, Q_s, s_s, and z. Thus, an iterative scheme is established that can be repeated until a solution is reached. Computer code for the solution of equation 2 developed by Trescott, Pinder, and Larson (1976) was modified to allow thickness of the freshwater zone, b, to be defined by equations 4-8. The strongly implicit procedure (Stone, 1968) was selected to solve the simultaneous equations for h_f (equation 2), and Q_f, Q_s, s_s, and z were recomputed after each iteration of the algorithmn. Approximately 30 to 40 iterations are required to reach a solution.

Aquifer system parameters

A 34 by 36 variably spaced grid was selected to simulate groundwater movement in the freshwater zone (fig. 10). Grid block sizes ranged from 200 ft in the vicinity of the injection site and the Maui Electric Co. wells to about 2,800 ft at the extremities of the modeled area. A constant-head condition was imposed along the southern boundary of the modeled area and no-flow conditions were imposed along the remaining boundaries. The eastern and western boundaries closely approximate streamlines and are thus valid no-flow boundaries, provided that effects of freshwater withdrawal or injection do not significantly change the streamlines at these locations. Along the northern boundary, discharge from the freshwater zone through a clay unit into overlying zones is assumed to occur. The area of discharge (or the seaward distance over which it occurs) is a function of the seaward rate of freshwater dissipation in the freshwater zone. As the freshwater head decreases in a seaward direction, the freshwater-saline water interface will be higher, eventually intersecting the top of the basalt aquifer. From this point seaward, a freshwater zone will not exist and the model area is terminated by a no-flow boundary. The grid system selected provided sufficient seaward extent to enable the intersection of the interface and the aquifer top to be determined as part of the solution without being constrained in the seaward direction.

Hydraulic conductivity of the basalt aquifer was assumed to be uniformly 0.04 ft/s, and the thickness of the freshwater zone is defined by equation 6. The depth below sea level of the aquifer top is shown in figure 2, and in places where it is above sea level, and effective top was assumed at sea level. This ignores the small increment of thickness of the freshwater zone associated with the freshwater head above sea level in those parts of the aquifer under water-table conditions. The maximum increment was less than about 4 ft and was considered negligible.

The objective of the analysis was to simulate equilibrium (steady-state conditions); therefore, knowledge of aquifer storage coefficients was unnecessary.

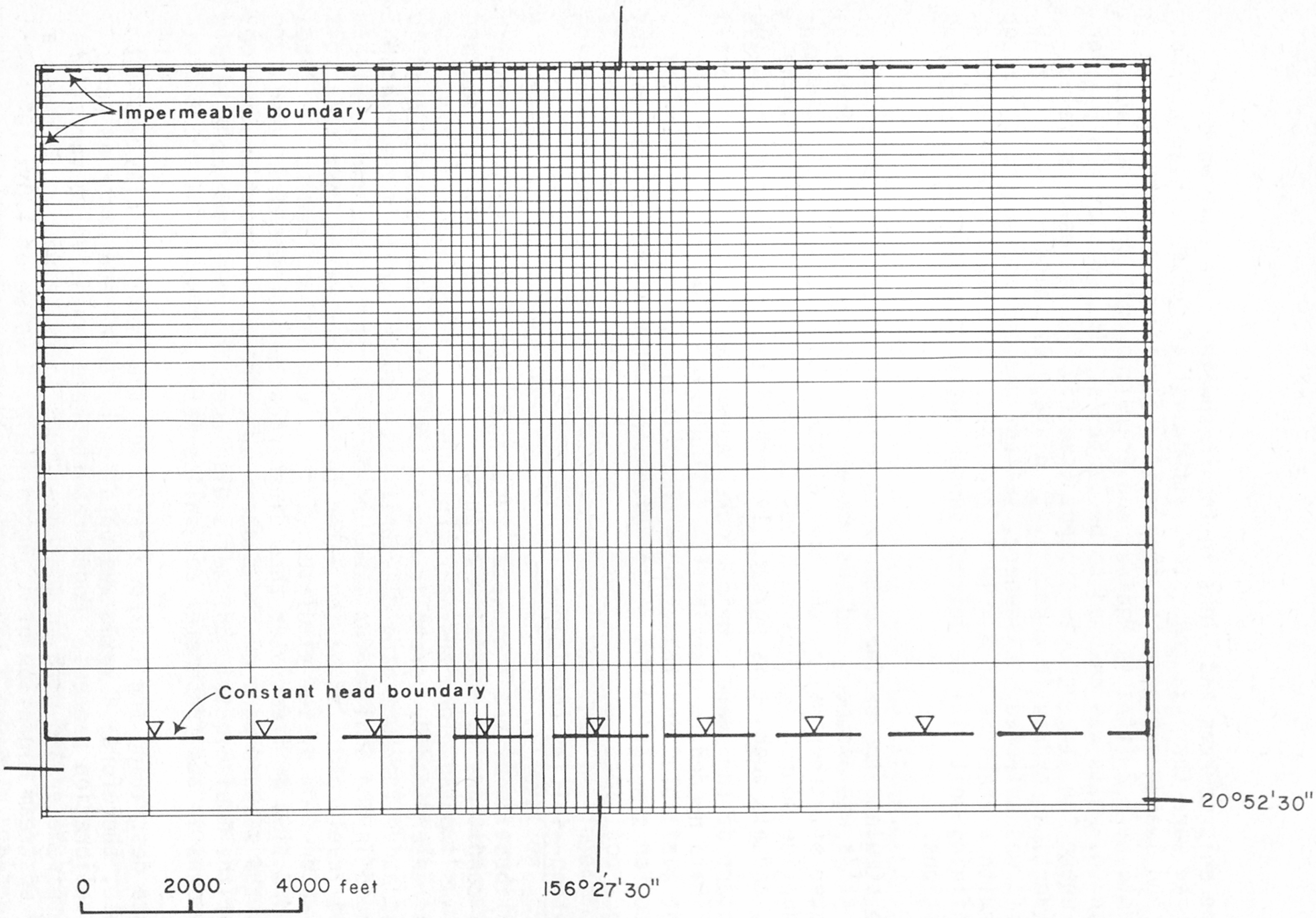


Figure 10. Grid configuration and boundary conditions for two-dimensional simulation.

The only sources and sinks in the freshwater zone that were considered were the injected water, withdrawal at the Maui Electric Co. wells, and leakage through the clay unit. The injection rate was assumed to be 6.2 ft^3/s (4 Mgal/d) and the withdrawal from the Maui Electric Co. wells was assumed to be 68 ft^3/s. In parts of the aquifer system where the clay unit is present (see fig. 7), a leakance value k'/m' (vertical hydraulic conductivity divided by thickness), of 1×10^{-6} (ft/s)/ft was selected. Elsewhere, leakage was assumed to occur through basalt with a leakance of 4×10^{-4} (ft/s)/ft. The head imposed above the confining unit will be defined subsequently in discussion of model calibrations.

To simulate the saline water zone (equation 4), a transmissivity of 8.5 ft^2/s was assumed, and the image well was located 219 ft from the center of withdrawal at the Maui Electric Co. wells. This assumes that the line source is located about 110 ft from the center of withdrawal, and although it is physically unrealistic, drawdowns at $r_w = 100$ ft (centers of the nearest grid blocks) agree favorably with field evidence. Data needed to describe the saline water zone more accurately were not available, and this simple model (equation 4) was considered adequate for simulating the effect of saline water withdrawal on the interface position.

Calibration--initial conditions

Calibration of the freshwater zone model was conducted to establish initial conditions for the simulation of injection. A constant head of 4.1 ft was imposed along the southern boundary of the modeled area. This was determined by parabolic extrapolation of field measurements. The head above the confining clay unit was assumed equal to the freshwater head in the aquifer for landward parts of the system and equal to a sea-level column of saline water for seaward parts. Thus, the ground-water-flow system simulated (initial conditions) can be described as seaward flow of freshwater that discharges through the overlying clay in the seaward part of the system. Withdrawal of fresh and saline water at the Maui Electric Co. wells displaces the interface as a result of drawdowns in the freshwater and saline water zones.

Data describing the leakance factor of the overlying clay was not available; therefore, a value was obtained by trial and error as part of the calibration process. Model results were sensitive to variations in this parameter and with an awareness that lower values would cause a greater upstream migration of injected fluid, a value of 1.0×10^{-6} s^{-1} was selected. Although a larger value would produce a smaller maximum difference with observed freshwater heads at five observation points, the selected value did not produce unreasonable results (maximum difference, +0.25 ft).

Freshwater withdrawal at the Maui Electric Co. wells was computed to be approximately 2 percent of the total withdrawal. Although specific-conductance measurements of the mixed withdrawal (fresh and saline) did not indicate the presence of freshwater, the computed freshwater withdrawal (2 percent) was considered to be within measurement error. Thus, the assumptions made in developing equations 4-7 produce results that are in agreement with field evidence.

Response to injection

Although wastewater is to be injected into the saline water zone, its density (less than the saline water; in fact, slightly less than the freshwater) will cause vertical migration due to buoyancy. It is assumed that the injected water will move vertically upward and eventually intercept the seaward flow of freshwater. Therefore, when the system is at steady-state, injection into the saline water zone represents an injection into the freshwater zone in terms of simulating the net effect.

The water level increase caused by injection will create a stagnation point in the seaward flowing freshwater that represents the maximum upstream migration of injected fluid. Streamlines emanating from this point represent the extent of the injected fluid from the injection site.

Based on the initial conditions determined by calibration, the steady-state (equilibrium) response to injection was simulated. The heads above the clay zone in landward parts of the system were assumed to remain at their initial levels after injection. An injection rate of 6.2 ft^3/s results in an injected fluid plume as shown in figure 11. The streamlines outlining the plume were constructed subjectively. The maximum upstream extent of the plume is about 1,200 ft from the injection site, and the contact between the interface and the top of the aquifer is displaced seaward a maximum of about 500 ft from its initial position. Although all the injected fluid is discharged from the system via upward leakage through the clay, only about 2 percent is discharged within the area beneath Kanaha Pond. The disposition of the injected fluid after leaving the lava aquifer system was not determined in this study.

Steady-State Three-Dimensional Model

A three-dimensional finite-difference aquifer model developed by Trescott (1975) was used to estimate the effects of vertical to horizontal anisotropy of hydraulic conductivity in the basalt aquifer. The theory and use of this simulator is outlined clearly in the documentation (Trescott, 1975) and will not be discussed here except to clarify its application to this problem.

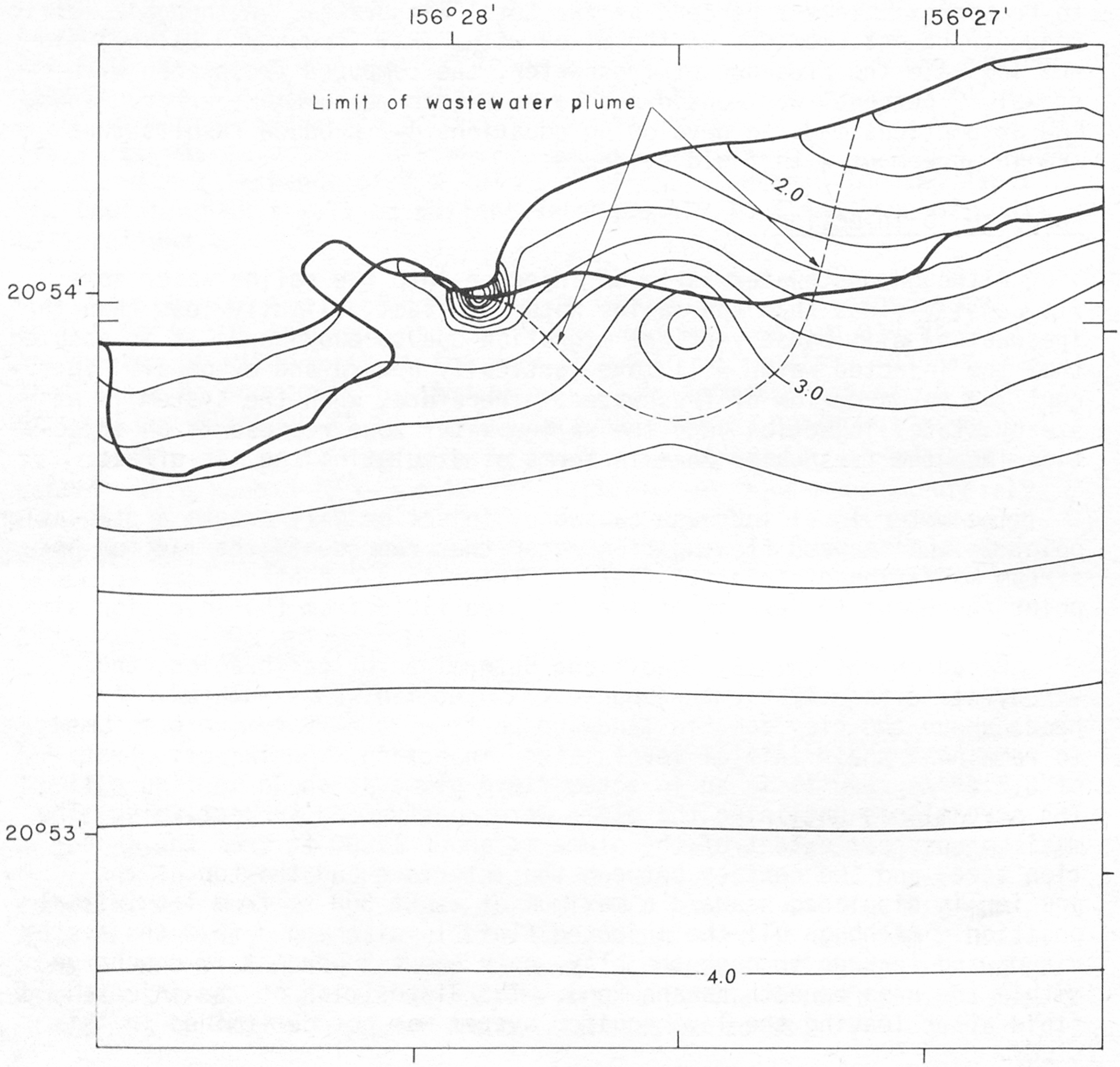


Figure 11. Head distribution and extent of wastewater plume as shown by two-dimensional simulation.

The model is used to obtain an approximate solution to the partial differential equation shown below (Trescott, 1975).

$$\frac{\partial}{\partial x} \left(T_{xx} \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y} \left(T_{yy} \frac{\partial h}{\partial y}\right) + b \frac{\partial}{\partial z} \left(K_{zz} \frac{\partial h}{\partial z}\right) = bW\,(x,y,z,t) \qquad (9)$$

where h is hydraulic head (L),
T_{xx}, T_{yy} are the principal components of the transmissivity tensor (L^2T^{-1}),
K_{zz} is the vertical hydraulic conductivity (LT^{-1}),
b is the thickness of a hydraulic unit (L), and
$W\,(x,y,z,t)$ is a volumetric flux per unit volume (T^{-1}).

Equation 9 assumes that the system has been divided into a series of hydraulic units of various thicknesses (b). The first two terms of equation 9 describe areal flow within a unit, and the third term describes vertical flow among the various units.

The basic approach for this application was to simulate an equivalent freshwater zone as that defined by the two-dimensional injection analysis and manually adjust its thickness (interface position) in accordance with head changes in this zone caused by the anisotropy. The adjustment was continually repeated until further adjustments did not significantly change the results. Because of the time constraint on this study, the process was not automated on the computer and adjustments were confined to the vicinity of the injection site. The adjustments in other parts of the system were almost always less than 5 ft and were considered insignificant.

The effects of saline water withdrawal as defined by equation 4 are implicitly included in the initial thickness of the freshwater zone as defined by the two-dimensional analysis. Variation of Q_f and Q_s caused by changes in the interface position at the Maui Electric Co. wells was considered to be insignificant and therefore no adjustments to interface position were made with respect to Q_s.

Aquifer system parameters

A part of the two-dimensional model area was selected for three-dimensional analysis. The grid block sizes used in the two-dimensional analysis were repeated in the reduced area resulting in a 30 by 32 variably spaced grid (see fig. 12). The vertical dimension was divided into nine hydraulic units, eight in the basalt aquifer and one to simulate leakage through the overlying clay zone. The units in the basalt aquifer represented the following thicknesses, beginning at the top of the aquifer; 5, 8, 13, 21, 33, 52, 59, and 59 ft. The transmissivity (T_{xx} or T_{yy}, equation 9) of the unit in which the interface was located was decreased to simulate the proper freshwater thickness within the unit. A uniform hydraulic conductivity of 0.04 ft/s was used to determine T_{xx} and T_{yy} for each unit. Also, it was assumed that $T_{xx} = T_{yy}$. Units below the interface (at a given areal location) are in the saline water zone and were not considered in this simulation of the freshwater zone.

The uppermost unit (layer 9) was used to represent the head above the clay zone overlying the aquifer. Values of freshwater head were assigned equal to the results of the two-dimensional initial condition analysis and were not changed. Vertical hydraulic conductivity (k_{zz}) and thickness (leakance factor) between this unit and the aquifer was also the same as the two-dimensional analysis. The vertical hydraulic conductivity between units within the basalt zone was the parameter of interest and simulations were made for values of 0.004 ft/s (0.1 k_{xx}) and 0.0004 ft/s (0.01 k_{xx}). The injection rate of 6.2 ft^3/s was distributed uniformly over the two lowermost units in the basalt zone, from approximately 190 to 310 ft below msl. Freshwater withdrawal at the Maui Electric Co. wells was made equal to 1.5 ft^3/s, the rate determined from the two-dimensional injection analysis. This rate was not adjusted.

As in the two-dimensional analysis, a constant-head boundary condition of 4.1 ft of freshwater head was imposed along the southern boundary for all saturated or partially saturated units (saturated in terms of freshwater). Along the eastern and western boundaries, no-flow conditions were imposed. The locus of the contact between the interface and the aquifer top was fixed at the location predicted by the two-dimensional injection analysis and was not adjusted. This line represents the northern boundary of the freshwater zone and was simulated by an impermeable (no-flow) boundary.

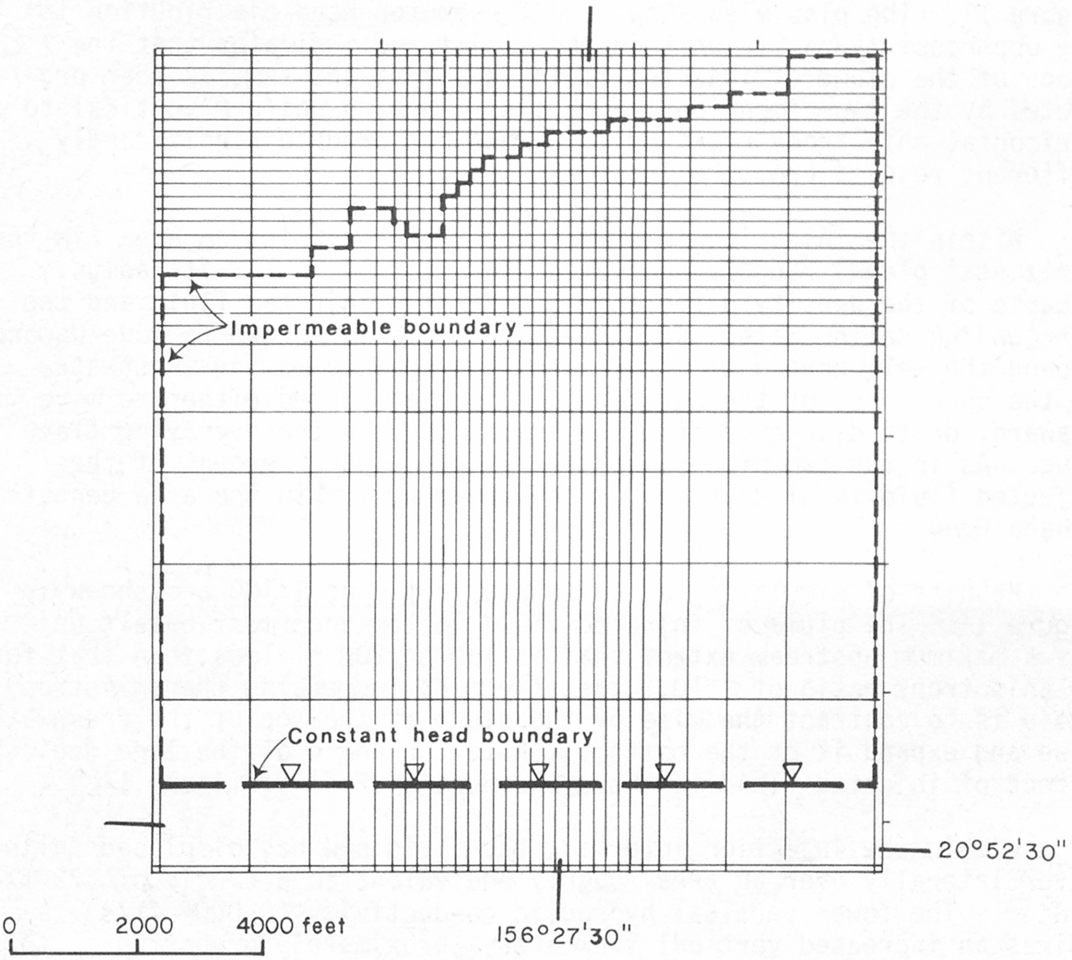


Figure 12. Grid configuration and boundary conditions for three-dimensional simulation.

Simulation results

Results of simulating an anisotropy ratio of 1:10 are shown in figure 13. The plan view shows the freshwater head distribution in the uppermost hydraulic unit in the basalt and indicates that the shape of the plume of injected fluid is almost the same as that predicted by the two-dimensional analysis. Thus, a uniform vertical to horizontal anisotropy ratio of 1:10 does not produce significantly different results from the isotropic case.

Within the injection interval, the fluid occupies an area (in the horizontal plane) roughly equivalent to a circle of 113-ft radius. Because of the density difference between the injected fluid and the surrounding saline water, the injected fluid is forced to move upward around the well bore until it reaches the seaward-moving freshwater in the upper part of the aquifer. It is then forced either to move seaward, or to discharge from the system through the overlying clay zone. As in the two-dimensional analysis, about 2 percent of the injected fluid is discharged through the clay within the area beneath Kanaha Pond.

Results of simulating an anisotropy ratio of 1:100 are shown in figure 14. The plume of injected fluid in the uppermost basalt unit has a maximum upstream extent that is 150 to 200 ft less than that for an anisotropy ratio of 1:10. The effect of increasing the anisotropy ratio is to contract the size of the plume at the top of the freshwater zone and expand it at the bottom. (Note the angle of the line depicting extent of injected fluid in the cross section F-F' of figure 14.)

Within the injection interval, the fluid now has displaced saline water laterally over an area roughly equivalent to a circle of 422-ft radius. The lower vertical hydraulic conductivity (0.0004 ft/s) requires an increased vertical flow area approximately proportional to the decrease in hydraulic conductivity (10 times). Thus, the radial extent of injected fluid around the well bore is increased by a factor approximately equal to the square root of the decrease in vertical hydraulic conductivity $\sqrt{10}$. However, the values presented here may not correspond exactly to this relation because in the simulation, areas of flow must be incremented in steps equal to the area of a grid block. The smallest grid block represented an area 200 by 200 ft, thus, the smallest increment in vertical flow area that could be simulated was $4 \times 10^4 ft^2$.

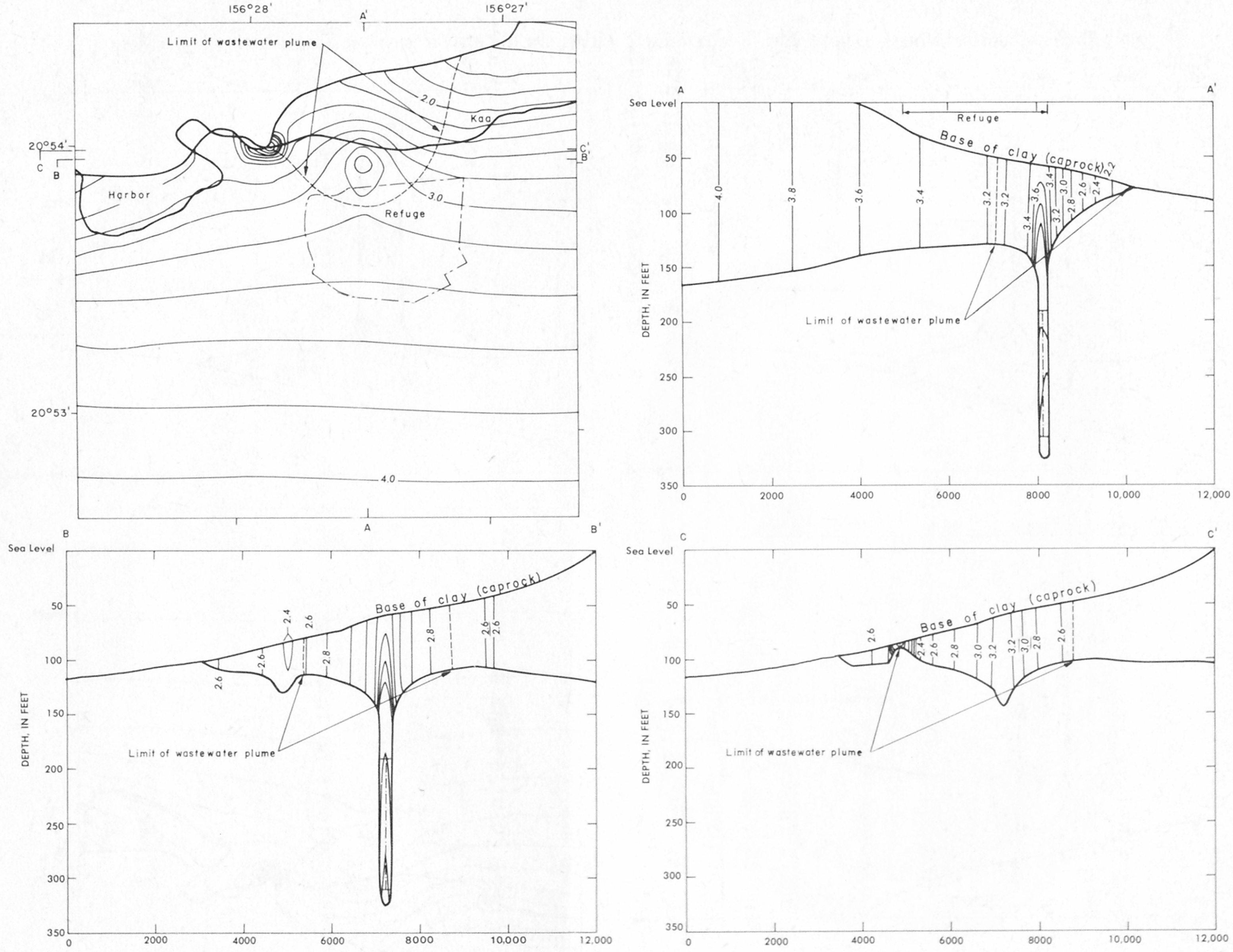


FIGURE 13. PLAN AND SECTION VIEWS OF HEAD AND WASTEWATER DISTRIBUTION IN LAVA AQUIFER WITH ANISOTROPY RATIO OF 1:10.

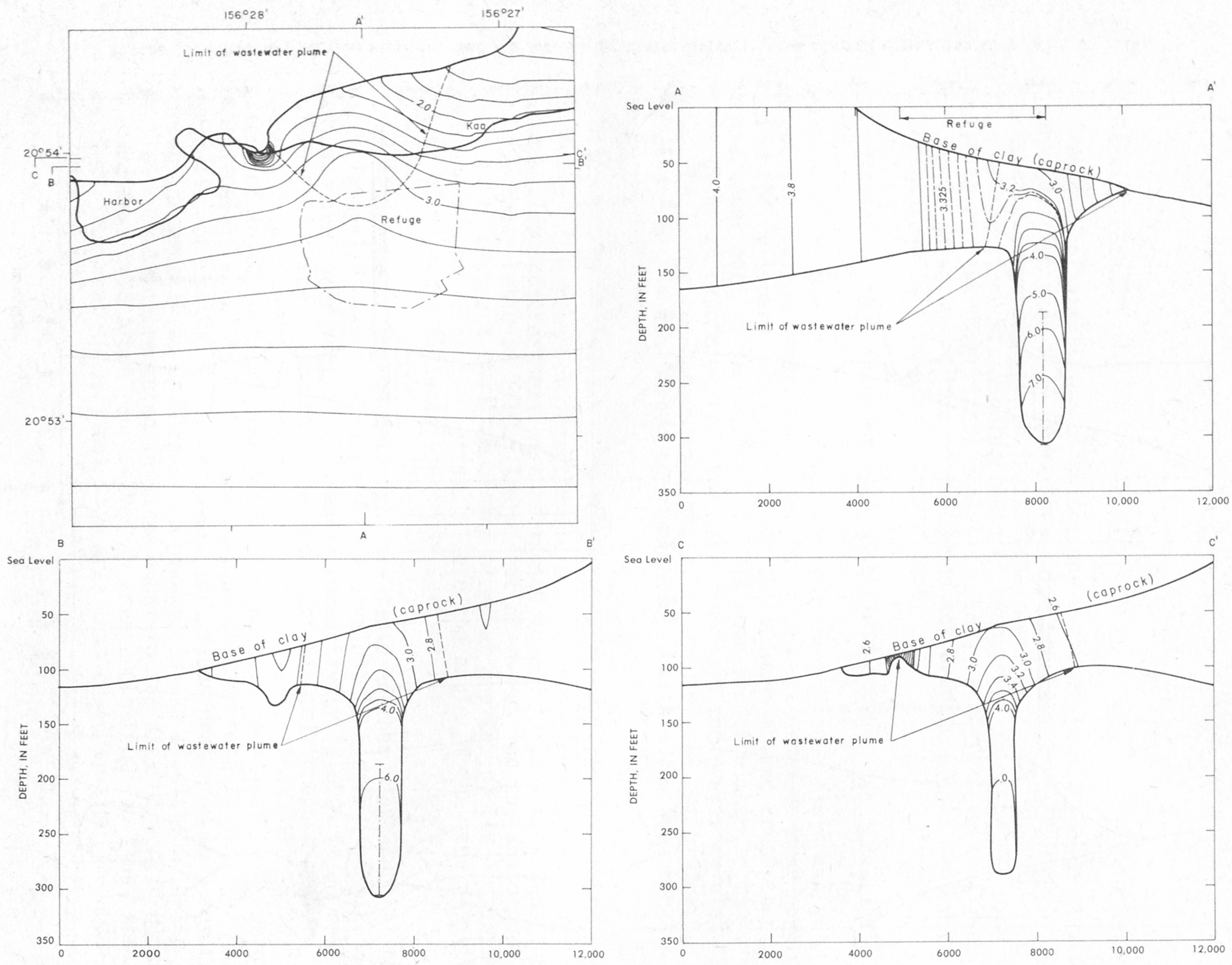


Figure 14. Plan and section views of head and wastewater distribution in lava aquifer with anisotropy ratio of 1:100.

The radial extent of injected fluid around the well bore (not the extent of the plume at the top of the aquifer) can also be approximated analytically if the following assumptions are made:

1. The injection rate Q_i is uniformly distributed over the screened interval, ℓ.

2. Because of the high horizontal hydraulic conductivities, K_{xx} and K_{yy}, and horizontal (radial) gradient around the well is small; therefore, the vertical gradient is approximately equal over any horizontal plane.

The radial extent $r\ (z_\ell)$ of the injected water at any horizontal plane situated at an elevation z_ℓ above the bottom of the screen, depends on the amount of flow $Q\ (z_\ell)$ crossing the plane, the vertical hydraulic gradient I_z, and the vertical hydraulic conductivity K_{zz}. From assumption (1), the flow crossing the plane is:

$$Q\ (z_\ell) = Q_i \frac{z_\ell}{\ell}$$

The vertical gradient along the interface depends on the ratio of the fresh to saline water density, and is:

$$I_z = \frac{\rho_s}{\rho_f} - 1$$

From assumption (2), the vertical gradient at any point on a horizontal plane is equal to I_z. Hence, applying Darcy's law:

$$Q\ (z_\ell) = Q_i \frac{z_\ell}{\ell} = K_{zz}\ \pi r^2 (z_\ell)\ (\frac{\rho_s}{\rho_f} - 1)$$

Solving for $r(z_\ell)$

$$r(z_\ell) = \left[\frac{Q_i z_\ell}{\pi \ell K_{zz} (\frac{\rho_s}{\rho_f} - 1)} \right]^{\frac{1}{2}}$$

Thus, the radial extent ranges from zero at the bottom of the screen to a maximum

$$r_{max} = \left[\frac{Q_i}{\pi K_{zz} \left(\frac{\rho_s}{\rho_f} - 1\right)} \right]^{1/2}$$

at the top of the screen.

The average extent $\bar{r}$ over the screen interval is obtained by integrating over z_ℓ from 0 to ℓ and dividing by ℓ.

$$\bar{r} = \frac{2}{3} \left[\frac{Q_i}{K_{zz} \left(\frac{\rho_s}{\rho_f} - 1\right)} \right]^{1/2}$$

For K_{zz} = 0.004ft/s, $\bar{r}$ = 94 ft, and r_{max} = 140 ft.

For K_{zz} = 0.0004 ft/s, $\bar{r}$ = 296 ft, and r_{max} = 444 ft.

In the numerical simulation, the area of vertical flow is represented by a group of blocks and is constant with depth. Thus, intuitively, the area of flow should have an equivalent radius between $\bar{r}$ and r_{max}. Thus, these analytical results compare favorably with the values of 113 ft and 442 ft predicted by the numerical simulation.

CONCLUSIONS

The study reported herein yields the following conclusions relative to the lava aquifer and its physical setting within the study area, and the distribution of injected wastewater.

The Lava Aquifer

The lava aquifer is primarily basaltic lava flows of the Kula Volcanics, and possibly the underlying upper Tertiary (?) Honomanu Volcanics of Haleakala; made up of variably distributed flows, interflow rubble and scoria, clinker, and cinder.

The lava aquifer is uniform in its lithologic variability throughout the area of study, contains areas of dense flows of limited extent and zones of extremely permeable materials, and has a generally northwest slope to its flow bedding of about 70 ft/mi (1 ft in 80), as reflected by the upper surface of the lava.

The aquifer has a measured transmissivity of 5 to 5.55 (Mgal/d)/ft in the horizontal direction, or a hydraulic conductivity of 3,300 to 3,700 ft/d. The hydraulic conductivity in the vertical (cross-flow) direction is estimated to average about one-tenth the horizontal, although it may vary considerably from that figure. In the study analysis, the value was considered to range from about one-tenth to as little as one one-hundredth the horizontal.

The designed depth of injection is within a part of the lava aquifer completely occupied with water of seawater salinity.

Near the injection site, the aquifer contains a salinity transition zone about 50 ft thick separating the deep saline water from a fresh-to-brackish lens within the upper 30 to 40 ft of the aquifer.

The aquifer is overlain by a caprock sequence everywhere except in the southeastern part of the area. The caprock thickens northwestward and contains the upper part of the fresh-to-brackish water lens.

The top of the lava contains a residual clayey soil horizon found in all drill holes except in the eastern and southeastern parts of the study area. The clayey zone thickens westward and acts as a confining member sufficient to create a head difference of several tenths of a foot between the freshwater body in the aquifer and that in the caprock.

Existing Hydrologic Conditions

The water level in the saline part of the aquifer, as recorded at well IW-1, is virtually that of msl. These data document the theoretical condition of virtually zero head and gradient in the saltwater part of the aquifer; therefore, essentially no flow. Flow within the saltwater aquifer--other than the oscillatory motion induced by tidal stress--is that slight landward flow necessary to satisfy saline water diffusion upward through the transition zone into the seaward-flowing base of the freshwater lens. Thus, there is no seaward flow within the saltwater zone of planned injection which could entrain or transport injected fluids seaward.

Mean daily water level in wells open only to the freshwater part of the lava aquifer shows a seaward gradient of approximately 1.5 ft/mi and a slightly northeast flow direction. The freshwater head in the upper part of the aquifer at the injection site ranges from about 1.9 to 2.3 ft above msl, and averages about 2.0.

Because of the large hydraulic conductivity, the average of about 35 to 45 Mgal/d pumped from the saltwater part of the lava aquifer by Maui Electric Co. does not create a measurable drawdown at the planned injection site.

The head distribution and character of fluctuation within the upper part of the lava are attained by a uniform upward seepage rate into the base of the overlying caprock. Therefore, the natural discharge from the lava aquifer part of the freshwater lens is indicated by this analysis to be by way of leakance into the caprock and thence seaward and upward to discharge through the reef complex. The model analysis shows this discharge to occur within 2,000 to 3,000 ft of the beach.

Post-Injection Hydrologic Conditions

Given a uniformly variable lava aquifer with vertical hydraulic conductivity one-tenth that of the horizontal, the planned wastewater injection would displace the existing aquifer fluids and form a new, steady-state, plumelike flow system around the injection site. The plume would have a columnar base within the saltwater about 230 ft in diameter, or less; would expand upward through the area of the pre-injection transition zone; would move farther upward through the freshwater lens; and would spread at the top of the lava aquifer to about 1,000 ft landward; 1,800 ft laterally each side of the injection site, normal to the freshwater flow direction; and about 2,000 ft seaward.

Increasing the degree of anisotropy to a horizontal hydraulic conductivity 100 times that of the vertical would result in a plume at steady state with about an 850-ft diameter basal column but with a slightly smaller plume area at the top of the aquifer.

Under post-injection steady-state conditions, the wastewater within the plume would be virtually unchanged in quality from that at injection, and thus would have a lesser density than any of the native water within the aquifer. There would be, therefore, some buoyancy effect within the plume beneath the caprock at the top of the lava aquifer.

The top of the plume would be displaced seaward in response to the seaward gradient of the freshwater lens at the top of the aquifer.

The injected wastewater would discharge from the lava aquifer by upward seepage into the base of the caprock over the area of the plume, but principally seaward of the injection site.

The part of the plume which extends landward under the geographic area of Kanaha Pond would contain about 2 percent (or less) of the volume of the injected wastewater. Upward leakage from this part of the plume would be displaced seaward by the gradient within the overlying caprock flow system.

The injected wastewater plume would remain approximately 2,000 ft seaward of the state well (T-116) at the south side of Kanaha Pond, and there appears to be no possibility that pumped water from this well would be affected by wastewater injection.

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RECORDS AND DATA AVAILABILITY

The data, records, and general information on which the interpretations of this report are based are to be found in the cited publications, and in the files of the Hawaii district office of the U.S. Geological Survey, Honolulu. These records and data consist of the following:

Geologic Data

Drilling logs of seven test holes drilled as a part of the study, with information on well construction.

Geophysical Data

Seismic profile tracing and descriptive material for subbottom profiling off Maui Electric Co. generating plant and in Kahului Harbor.

Borehole geophysical and measurement logs for selected wells and test holes:

Injection well IW-1

Caliper
Temperature (before, during, and after pumping)
Nuclear--gamma gamma
Nuclear--natural gamma
Nuclear--Neutron
Conductivity

Saltwater supply well 1

Caliper
Nuclear--gamma gamma
Nuclear--neutron

Saltwater supply well 2

Caliper
Nuclear--gamma gamma
Nuclear--natural gamma
Nuclear--neutron
Temperature

Test well GS-1

Nuclear--gamma gamma
Nuclear--natural gamma
Nuclear--neutron

Test well GS-2

Nuclear--gamma gamma
Nuclear--neutron

Hydrologic Data

Pump discharge, drawdown, and aquifer-test data for the 10 salt-water supply wells at Maui Electric Co. generating plant in Kahului:

Recording gage record of tide in Kahului Harbor, February 21-April 7, 1976.
Recording gage record of water level in old Central Power Plant well (shaft 20), January 30-April 2, 1976.
Recording gage records of water level in wells:

Injection well IW-1--February 13-April 7, 1976
GS-1 (caprock well)--March 14-April 7, 1976
GS-2 --March 14-April 7, 1976
GS-3 --March 15-24, March 26-April 7, 1976
GS-4 --March 12-April 7, 1976.

Chloride content and (or) electrical conductivity measurements at various locations, including:

Maui Electric Co. wells 11, 31, 32, 33, 41, 42, and 43
Test holes GS-1, GS-2, GS-3, and GS-4
Caprock water table
Seawater.