DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

PREPARED IN COOPERATION WITH THE
STATE OF HAWAII, DEPARTMENT OF LAND AND NATURAL RESOURCES
DIVISION OF WATER AND LAND DEVELOPMENT

HYDROLOGIC INVESTIGATIONS
ATLAS HA-358 (SHEET 2 OF 2)

GROUND WATER

RECHARGE

The volcanic aquifer is recharged by infiltration of rainfall and surface runoff originating in the area. The alluvial and coralline aquifers are recharged by infiltration of rainfall and surface runoff and also by underflow from the volcanic aquifer. There probably is no significant recharge as underflow into the study area because of dikes, which generally parallel its boundaries.

Average annual rainfall (see rainfall map) ranges from about 20 to about 100 inches. It totals about 110,000 acre-feet, which is equivalent to about 98 mgd (million gallons per day).

Streams are perennial only in their upper reaches, where they are fed by discharging ground water. Fair-weather flow that is not diverted by pipelines infiltrates the channel bottoms and recharges the ground-water reservoir. During wet periods, the percentage of infiltration from runoff depends largely on the duration and intensity of rainfall. Runoff to sea occurs only during periods of heavy rainfall.

DISCHARGE

The volcanic aquifer is discharged by underflow to the alluvial and coralline aquifers; by spring, stream, and tunnel flow; by pumping; and by evapotranspiration. Some ground-water flows from the alluvial aquifer to the coralline aquifer, otherwise evapotranspiration is the principal discharge from both aquifers. In areas where water levels are shallow, pumping of wells in the alluvial and coralline aquifers will probably not reduce evapotranspiration unless the luxuriant growth of kiawe is eliminated. Increased pumping from the alluvial aquifer will only reduce underflow to the coralline aquifer, and pumping from the coralline aquifer will induce further sea-water intrusion.

Numerous test holes along the coast indicate that little fresh water escapes to sea as underflow. An exception is the coast along Makua Valley, where water from test holes tapping calcareous sand has a chloride content of less than 200 mg/l. The sand there, which has a saturated thickness of 28 feet, is underlain by a 47-foot thick clay bed, which separates the sand from the coral bed that is intruded by sea water. Profiles, elsewhere along the coast, showing chloride content of the water at depth from selected test holes are shown on the water-quality map (sheet 1).

STORAGE

Most ground water underlying the Waianae District is stored in volcanic rocks. The top of the volcanic reservoir extends to an altitude of at least 1,800 feet. Its bottom is undetermined but is probably limited only by the inability of the rocks to transmit water at some great depth below sea level. Storage is significantly less in alluvium, where saturated volume is less, and still less in calcareous rocks, where it is limited to a thin lens.

Water in volcanic rocks is stored between dikes and moves from areas of higher to lower heads. Stored water discharges as base flow of streams, by tunnels, and by springs, wherever the land surface intersects saturated rock. Discharge fluctuates with the level of storage in the dike reservoir, which, in turn, fluctuates with the amount of precipitation recharging the ground-water reservoir. Owing to the extensive volume of saturated rock, the net change in storage from the highest to lowest levels in the reservoir is only a fraction of the total storage.

Water-development tunnels bored deep into saturated rock—such as the Waianae City and County, Makaha, and Navy Lualualei Tunnels—have depleted storage by at least 3,200 million gallons, but this depletion is probably small in comparison with the total water still remaining in storage.

Hirashima (1963, p. 10) found that the empirical equation $Q_t = Q_o e^{bt}$ gives a good approximation of the recession curve derived from data obtained during the depletion of storage by water-development tunnels. The initial discharge Q_o at near full storage recedes to some stable discharge Q_t after the dewatering. Q_t is then the base-flow discharge (equivalent to average recharge) of the tunnel; t is the time in days for Q_o to recede to Q_t; and b is the recession constant governed by the characteristics of the storage reservoir.

Total discharge for the period t is equal to:

$$\frac{Q_o - Q_t}{b};$$

water released or depleted from storage is then equal to:

$$\frac{Q_o - Q_t}{b} - Q_t t.$$

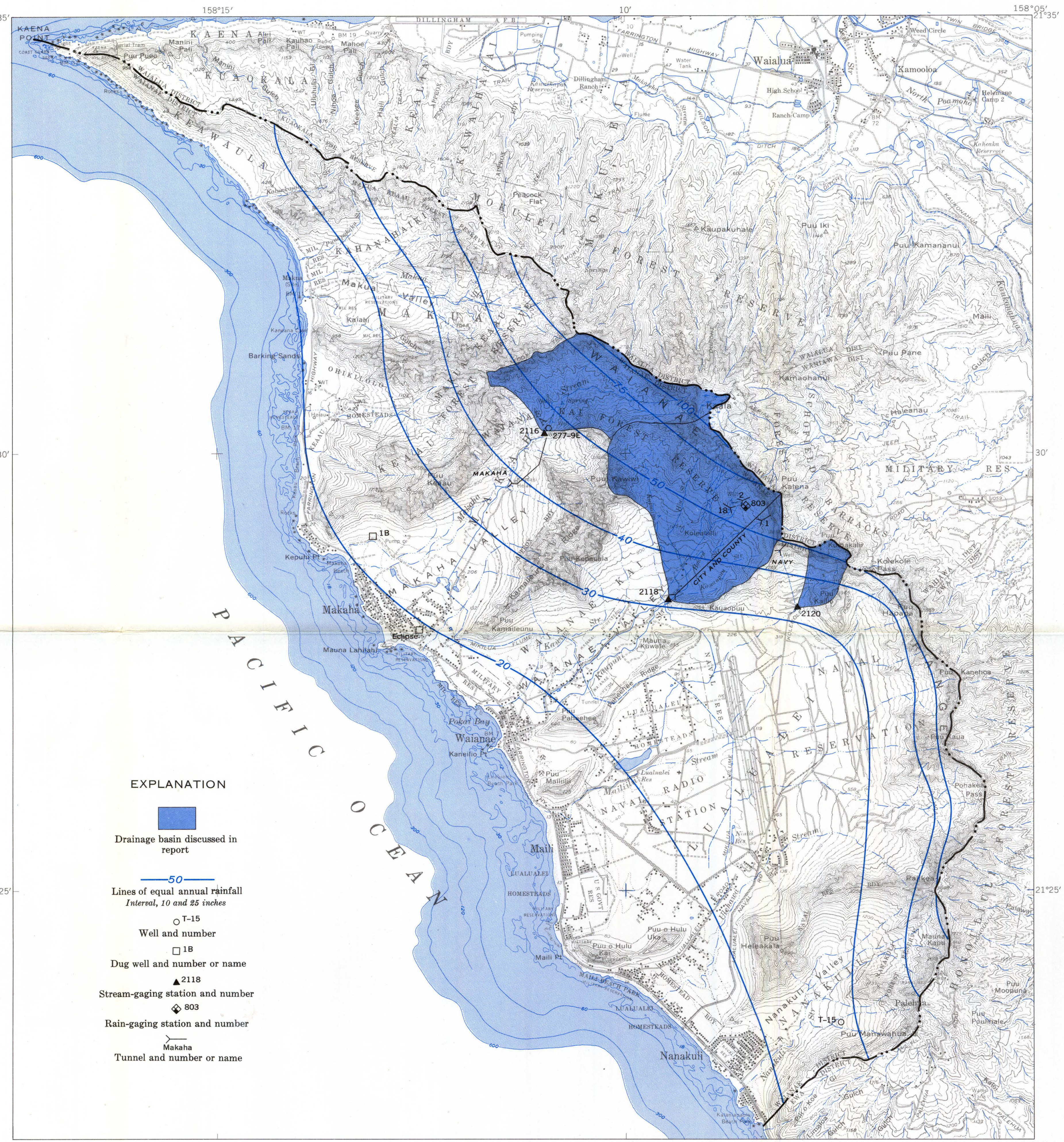
Calculations showing quantity of storage depleted from the Waianae City and County and Makaha Tunnels are given in their respective hydrographs.

Effects of tunneling in Waianae and Makaha Valleys can be summarized thus:

Valley	Estimated base flow before tunneling (mgd)	Tunnel	Tunnel length (feet)	Water released from storage (millions of gallons)	Estimated base flow after water released from storage (mgd)
Waianae	2	City and County	10,300	1,514	3
Makaha	0.6	Makaha	4,207	1,660	0.8

Recharge and, therefore, base-flow discharge, likely was increased because dewatering increased available reservoir space. Storm water that formerly might have been rejected by a full reservoir now may become recharge because of the increased space.

GROUND-WATER CIRCULATION



Base from U.S. Geological Survey, 1960

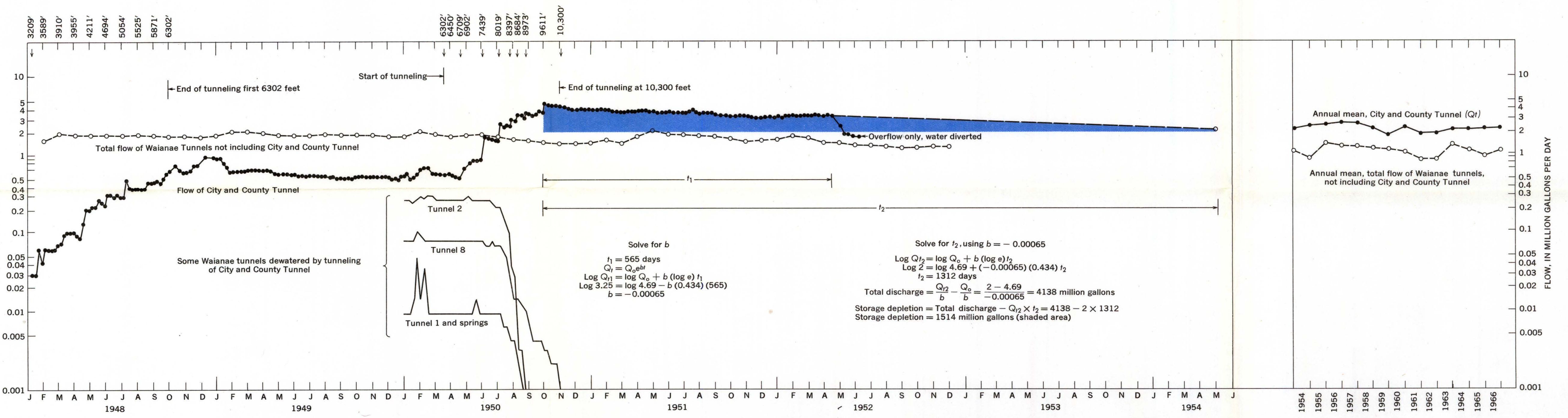
TRUE NORTH
MAGNETIC NORTH
11°
APPROXIMATE MEAN DECLINATION, 1971

SCALE 1:62 500
1 ½ 0 1 2 3 MILES
1 .5 0 1 2 3 KILOMETERS

CONTOUR INTERVAL 80 FEET
DOTTED LINES REPRESENT 20-FOOT CONTOURS
DATUM IS MEAN SEA LEVEL
DEPTH CURVES IN FEET—DATUM IS MEAN LOWER LOW WATER
SHORELINE SHOWN REPRESENTS THE APPROXIMATE LINE OF MEAN HIGH WATER
THE MEAN RANGE OF TIDE IS APPROXIMATELY 2 FEET

Data from geologic map of Oahu, Stearns (1939) and geologic map of the Waianae Range, Oahu, Macdonald (1940)

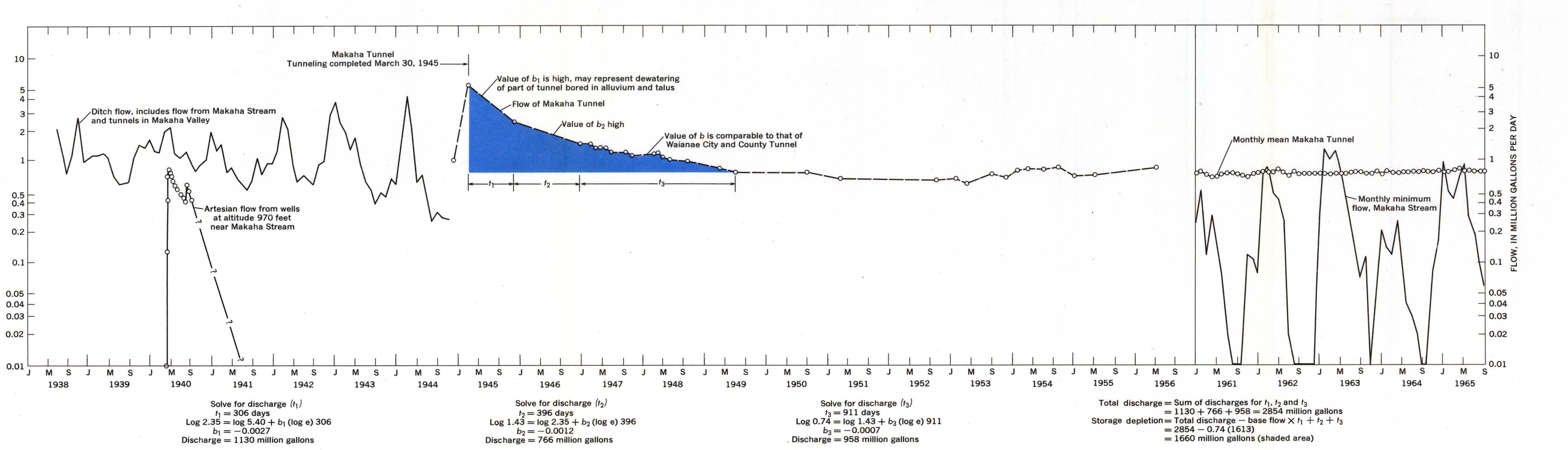
RAINFALL MAP SHOWING LOCATIONS OF SELECTED HYDROLOGIC DATA SITES AND AREAS



Solve for b
$t_1 = 565$ days
$Q_t = Q_o e^{bt}$
$\text{Log } Q_{t1} = \log Q_o + b (\log e)\, t_1$
$\text{Log } 3.25 = \log 4.69 - b\,(0.434)\,(565)$
$b = -0.00065$

Solve for t_2, using $b = -0.00065$
$\text{Log } Q_{t2} = \log Q_o + b (\log e)\, t_2$
$\text{Log } 2 = \log 4.69 + (-0.00065)\,(0.434)\, t_2$
$t_2 = 1312$ days
$\text{Total discharge} = \frac{Q_{t2}}{b} - \frac{Q_o}{b} = \frac{2 - 4.69}{-0.00065} = 4138$ million gallons
$\text{Storage depletion} = \text{Total discharge} - Q_{t2} \times t_2 = 4138 - 2 \times 1312$
Storage depletion = 1514 million gallons (shaded area)

HYDROGRAPH SHOWING DISCHARGE AND PROGRESS OF TUNNELING, CITY AND COUNTY WAIANAE TUNNEL



Solve for discharge (t_1)
$t_1 = 306$ days
$\text{Log } 2.35 = \log 5.40 + b_1 (\log e)\, 306$
$b_1 = -0.0027$
Discharge = 1130 million gallons

Solve for discharge (t_2)
$t_2 = 396$ days
$\text{Log } 1.43 = \log 2.35 + b_2 (\log e)\, 396$
$b_2 = -0.0012$
Discharge = 766 million gallons

Solve for discharge (t_3)
$t_3 = 911$ days
$\text{Log } 0.74 = \log 1.43 + b_3 (\log e)\, 911$
$b_3 = -0.0007$
Discharge = 958 million gallons

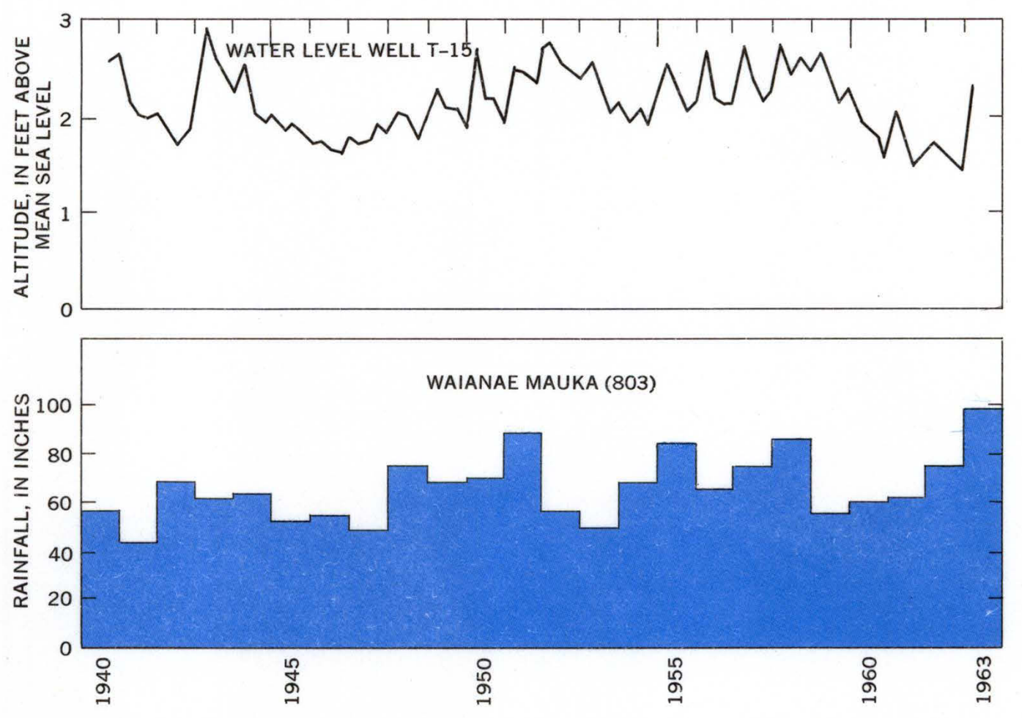
Total discharge = Sum of discharges for t_1, t_2 and t_3
$= 1130 + 766 + 958 = 2854$ million gallons
Storage depletion = Total discharge − base flow $\times\, t_1 + t_2 + t_3$
$= 2854 - 0.74\,(1613)$
= 1660 million gallons (shaded area)

HYDROGRAPH SHOWING DISCHARGE IN THE MAKAHA TUNNEL

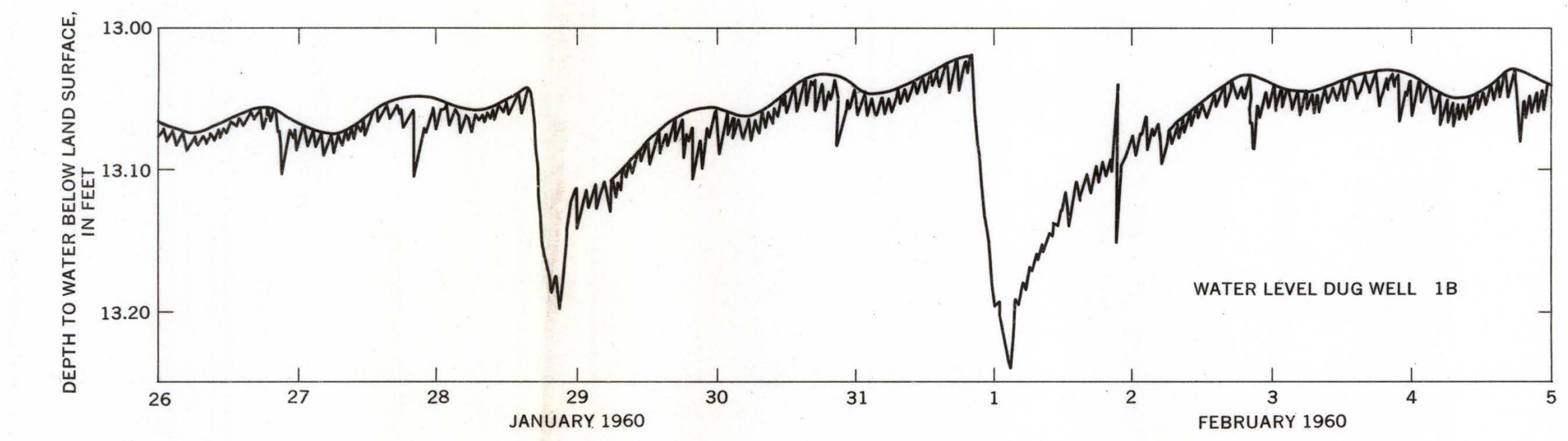
WATER-LEVEL FLUCTUATIONS

Water levels fluctuate in response to changes in natural recharge, draft, barometric pressure, tides, and transpiration as shown by the hydrographs. Long-term water-level records are not available for wells in the rainy mountainous areas. In these areas, changes in water levels are inferred from changes in base flow of tunnels. (See hydrographs of Waianae City and County and Makaha Tunnels.)

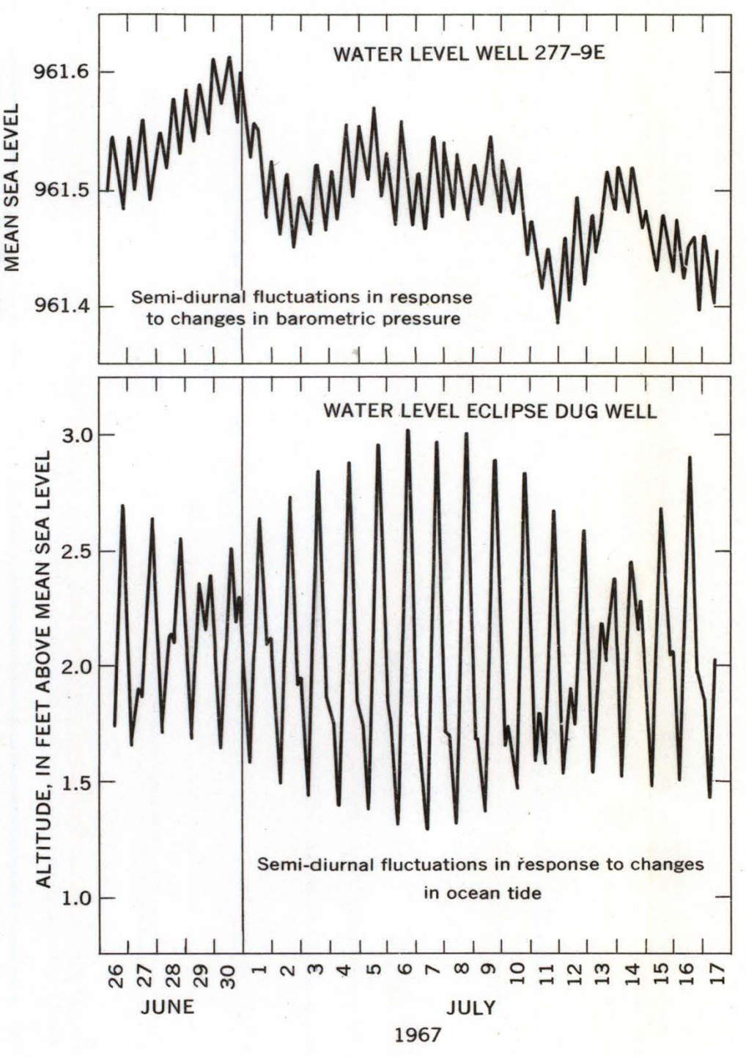
Fluctuations are semidiurnal (barometric pressure and ocean tides), diurnal (transpiration), cyclic (natural recharge), and induced (draft).



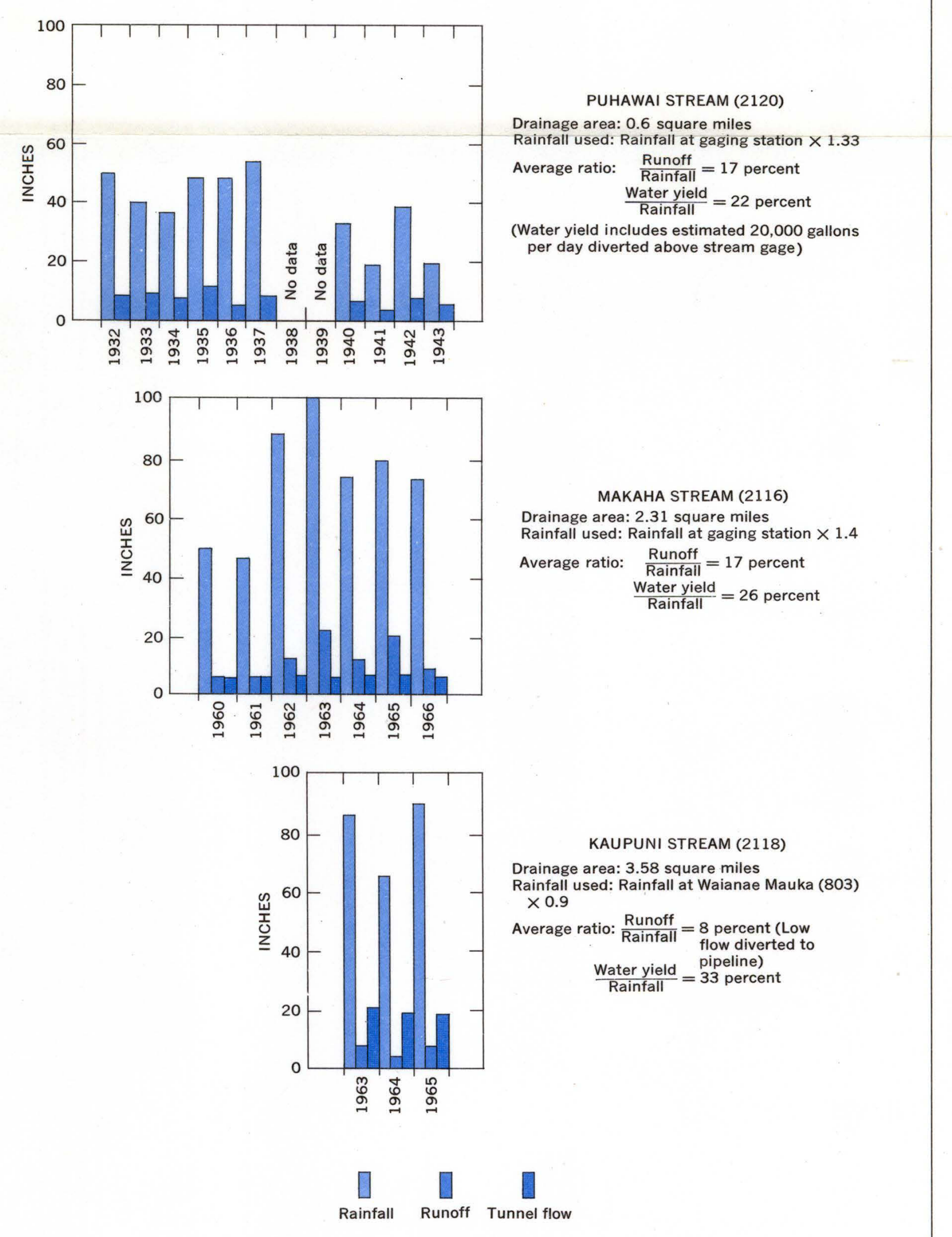
HYDROGRAPHS SHOWING WATER-LEVEL FLUCTUATIONS IN RESPONSE TO CHANGES IN NATURAL RECHARGE



HYDROGRAPH SHOWING DIURNAL FLUCTUATIONS IN RESPONSE TO TRANSPIRATION. MINOR FLUCTUATIONS ARE CAUSED BY PUMPING NEARBY WELLS AND LARGE FLUCTUATIONS ARE CAUSED BY PUMPING AT THE DUG WELL. THE SMOOTH CURVE SUPERIMPOSED ON THE HYDROGRAPH INDICATES GENERAL TREND OF THE WATER LEVEL (ZONES, 1963)



HYDROGRAPHS SHOWING SEMI-DIURNAL FLUCTUATIONS IN RESPONSE TO CHANGES IN BAROMETRIC PRESSURE AND TO CHANGES IN OCEAN TIDE



PUHAWAI STREAM (2120)
Drainage area: 0.6 square miles
Rainfall used: Rainfall at gaging station × 1.33
Average ratio: $\frac{\text{Runoff}}{\text{Rainfall}} = 17$ percent
$\frac{\text{Water yield}}{\text{Rainfall}} = 22$ percent
(Water yield includes estimated 20,000 gallons per day diverted above stream gage)

MAKAHA STREAM (2116)
Drainage area: 2.31 square miles
Rainfall used: Rainfall at gaging station × 1.4
Average ratio: $\frac{\text{Runoff}}{\text{Rainfall}} = 17$ percent
$\frac{\text{Water yield}}{\text{Rainfall}} = 26$ percent

KAUPUNI STREAM (2118)
Drainage area: 3.58 square miles
Rainfall used: Rainfall at Waianae Mauka (803) × 0.9
Average ratio: $\frac{\text{Runoff}}{\text{Rainfall}} = 8$ percent (Low flow diverted to pipeline)
$\frac{\text{Water yield}}{\text{Rainfall}} = 33$ percent

GRAPHS SHOWING RELATIONS OF WATER YIELD TO RAINFALL IN SELECTED DRAINAGE BASINS

STREAMFLOW

All streams are intermittent at low altitudes. Under natural conditions, streamflow was probably perennial above an altitude of about 600 feet in Makaha Valley, Waianae Valley, and the northern part of Lualualei Valley. Ground water discharging from dike compartments constituted this flow. Development of the water by extensive tunneling and diversions to pipelines since the early 1900's in Waianae Valley, 1935 in Lualualei Valley, and 1945 in Makaha Valley, has reduced the flow to the extent that streams are now perennial only above an altitude of about 1,000 feet.

Continuous streamflow records are available for gaging stations on Makaha (2116) and Kaupuni (2118) Streams since July 1959 and May 1960, respectively. The only other continuous record is one for Puhawai Stream (2120) for the period 1931–45. Base-flow diversions affect streamflow at all these stations. The combined drainage areas above these three stations represent about 10 percent of the total study area (shaded areas on the rainfall map).

From records of gaged streams, average surface runoff to the sea is estimated to be not more than 15 percent of average rainfall.

RELATIONS OF WATER YIELD TO RAINFALL OF SELECTED DRAINAGE BASINS IN THE WAIANAE DISTRICT

The water yield of three drainage basins in the recharge area are shown by graphs. Water yield is defined as the sum of surface runoff and ground-water flow (underflow, tunnel flow, low-flow diversions, and pumpage). The difference between rainfall and water yield is assumed to be evapotranspiration. Underflow from these basins is assumed to be negligible owing to deep tunnels and stream channels that act as drains. The duration of records available is too short for definite conclusions but the records do indicate, generally, the dispersal of rainfall in the basin. Concurrent rainfall records were available at only one rain gage per drainage area, so these records were area-weighted by multiplying them by a factor that considers the long-term difference in rainfall at the gage site and the estimated mean rainfall in the area.

The records, however short, show an average annual water yield of about 30 percent where annual rainfall averages about 60 inches. Although similar records for the same periods elsewhere on Oahu have not been compared with these records, long-term records, 1930–60, show that average annual water yield is about 50 percent in drainage basins in the Koolau Range having comparable rainfall (Dale, 1967; Takasaki and others, 1969). Although short-term records are being compared to long-term records, the difference in average annual water yield is large enough to indicate that evapotranspiration is on the order of 40 percent greater in the Waianae Range than it is in the Koolau Range, where average annual rainfall is 60 inches.

Climatic factors such as temperature, cloud cover, solar radiation, and wind movement account for some of the difference in evapotranspiration, but most of it probably results from differences in evapotranspiration opportunity—that is, there is more opportunity for evapotranspiration in the Waianae Range because saturated rocks at or near the surface occur in drier areas than they do in the Koolau Range. Water levels are closer to the surface in the Waianae Range than they are in the Koolau Range because the Waianae rocks are generally poorly permeable and the Koolau rocks are generally highly permeable.

Because near-surface rocks are saturated in areas of low rainfall in the Waianae Range, it is advantageous, wherever possible, to dewater the rocks permanently in those areas to reduce evapotranspiration opportunity.

SUMMARY AND POTENTIAL FOR FUTURE DEVELOPMENT OF GROUND WATER

Rainfall is the source of all fresh water in the Waianae District. Aside from that part of rainfall that runs off to sea as overland flow during infrequent heavy storms, nearly all water in the District is discharged by tunnels, springs, wells, and evapotranspiration. Discharge to sea as underflow is probably negligible as ground water at shallow depths near the coast has a high chloride content. Most recharge takes place where rainfall is highest in volcanic terrane in the interior mountains, and most discharge takes place where rainfall is lowest in coralline terrane near the coast.

Surplus water from the recharge area moves as streamflow and underflow into the discharge area, except that part which quickly drains to sea during infrequent storms. Owing to the great permeability of the coastal coralline rocks all streamflow that infiltrates and all underflow probably become part of a lenslike ground-water body floating on sea water contained within the coralline rocks. This body of water, the top of which is generally near the surface, then becomes the reservoir from which kiawe and other plants discharge large quantities of water by transpiration.

If the Waianae District is assumed to be a closed basin—all water is recharged and discharged within the basin except for overland storm runoff to sea and an approximate water budget can be summarized as follows:

Recharge (mgd)	Discharge (mgd)	Source
98		Rainfall
	15	Overland storm runoff to sea
	6	Ground-water draft 4 mgd from tunnels 1 mgd from wells tapping volcanic rocks 1 mgd from wells tapping coral and alluvium
	77	Evapotranspiration

Evapotranspiration is the largest element of ground-water discharge in the Waianae District and, therefore, future ground-water development depends on decreasing evapotranspiration. Most water is evaporated and transpired in low-lying areas, where ground-water levels are shallow and kiawe grows luxuriantly. Heavy pumping would not lower water levels sufficiently to deprive the kiawe of water, and evapotranspiration would remain about the same. Low-lying areas, especially those underlain by permeable deposits of coral and coral rubble, are useless as a source of fresh ground water. The most promising areas for ground-water development are in the deeper valleys in the mountains, where water levels are shallow and where evapotranspiration is comparatively small but still significant. Any reduction in evapotranspiration in such areas, by lowering water levels, would result in additional available ground water. This is being partly accomplished by the presently free-flowing tunnels; however, the rocks penetrated by the tunnels are of such low permeability that more tunnels or wells are needed to lower water levels further.

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GROUND WATER IN THE WAIANAE DISTRICT, OAHU, HAWAII

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1971