HYDROLOGIC-DATA NETWORK DESIGN CONCEPTS PERTINENT TO GROUND-WATER RESOURCES INVENTORY IN THE HAWAIIAN ISLANDS

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ABSTRACT

The purpose of this thesis is to formulate concepts of hydrologic-data network design pertinent to ground-water resources inventory which will be applicable in the Hawaiian Islands. Various principles of hydrologic-data network design for ground and surface water have been developed from earlier studies throughout the world. From these studies, the principles of network design for the Hawaiian Islands are formulated. Because of the dissimilarities in hydrology and geology between the Hawaiian Islands and those areas for which the principles of network design were originally developed, modifications of the principles of design are necessary in order to be applicable under the geologic and hydrologic conditions of the Hawaiian Islands.

Three types of hydrologic-data networks identified on the basis of functions have been well-recognized. They are: 1) water-system management networks, 2) experimental networks, and 3) hydrologic-inventory. This dissertation is concerned with the hydrologic-inventory network for ground water. The primary purpose of a ground-water hydrologic-inventory is the evaluation of the safe yield of ground water bodies.

Various methods of safe yield determination have been identified and discussed together with the parameters they essentially involve. These parameters are grouped into two broad categories: 1) Those required for the definition of the ground-water hydrologic environment, such as aquifer depths, permeabilities, and storage coefficients, and 2) Those required for the definition of the ground-water flow system, such as well water levels, recharge and natural and artificial discharges.

In the Hawaiian Islands, the determination of safe yield of ground-water bodies is complicated by the nature of the occurrence of ground water. The predominant type of ground-water occurrence is the basal water body, confined or unconfined, which floats on and displaces the denser salt water in accordance with the Ghyben-Herzberg principle. Methods of determination of safe yield which involve the evaluation of storage in the Herzberg lens have used estimates of storage changes based on variations of head relative to sea level. However, because of the dynamic nature of the Herzberg lens, a potential lag in the response of the salt-fresh water interface to changes in head exists. This lagging effect has tended to yield erroneous conclusions on the safe yield value when the storage in the lens is computed on the basis of heads above sea level.

The present hydrologic-data networks in the Hawaiian Islands, Oahu and Molokai in particular, from which data for ground-water inventory may be obtained, consist of networks for measurement of: 1) Precipitation, 2) Evapotranspiration, 3) Stream discharge, and 4) Discharge and water levels in wells.

From a ground-water inventory standpoint, it is shown that these networks are generally inadequate in meeting present and future data demands for ground-water inventory purposes.

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INTRODUCTION

The design of a hydrologic data network for any type of ground-water study pertinent to available resources and supply depends upon the answers sought and the problems involved. The general and specific knowledge concerning the natural characteristics of the area under study that is needed includes the hydrology of both surface and ground water, the surface and subsurface geology, the special structural features present, the extent and location of areas of ground-water recharge, evaporation and precipitation characteristics, and the relationships of these parameters with hydrology. In addition to these, knowledge of the occurrence, quantity, and quality of the ground water oa an area is indispensible for its successful exploitation.

Ground-water data are the fundamental basis through which ground water may be more thoroughly and successfully exploited. The lack of such data may frequently lead to delay in water development projects required by water-data using agencies. In many instances, costly water-development projects fail because of the lack of necessary data at the initial stage of development. It is imperative, therefore, that before any kind of water-resources development is to be undertaken, an inventory of the availability of necessary data be made. The inventory should include the type of data that have been collected, additional data that need to be collected, the availability and adequacy of data-collection facilities and their instrumentations, and the evaluation of existing data-collecting network with respect to their capabilities and reliabilities. Suggestions for any needed improvements of the existing data-collection network should be made. A further and important evaluation of the usefulness of the data in terms of the amount of money invested on the existing network and any planned expansion of the network should be carefully made.

Objectives of This Study

The objectives of the present study are 1) to illustrate the needs for basic hydrogeologic data in the various phases of ground-water studies and in the development of ground-water resources by evaluation of existing hydrologic-data networks, 2) to develop criteria and principles of hydrologic-data network design pertinent to inventory of ground-water resources and supply in the Hawaiian Islands, and 3) to apply the formulated principles of hydrologic-data network design to their ultimate purpose of improving the existing hydrologic-data networks in the Hawaiian Islands with particular emphasis on Oahu and Molokai.

This study is a part of a more comprehensive project of the University of Hawaii Water Resources Research Center which is concerned with developing criteria for the design of hydrologic-data networks to collect basic data for use in various water resources planning and research. The comprehensive study by the Center includes developing criteria for hydrologic-data network designs encompassing the area of 1) hydrometeorology, 2) surface water, 3) ground water, 4) water quality, 5) water utilization, 6) coastal water, and 7) soil and erosion. This thesis is concerned with the ground-water phase of the project.

The purpose of this thesis centers on the formulation of concepts of hydrologic-data networks for ground-water inventory; concepts which may be considered applicable in the design of a network that would be appropriate under the hydrologic and geologic conditions in the Hawaiian Islands. More specifically, the ultimate purpose and objective is to try and implement the concepts formulated in the design of a ground water hydrologic-data network for the ground-water inventory on the island of Molokai which has been designated by the Center for a pilot study.

Previous Work

A review of the literature on the design of ground-water data networks in the Hawaiian Islands has shown an almost complete absence of any previous work on the subject. Visher and Mink (1964) have cited in their studies of ground-water resources on southern Oahu the use of selected wells for geochemical studies in which water samples were collected on the basis of availability of existing network of wells. Perhaps because of the expense involved in establishing a geometrical pattern of network of wells based on some established principles of network design, most ground-water studies throughout the Hawaiian Islands have been carried out utilizing the existing wells and test holes drilled by the Boards of Water Supply of the various counties, the United States Geological Survey, the plantations, and private individuals.

A number of studies have been made of ground-water network design, mostly in continental areas. Stephenson (1965) did a study on the design of a ground-water data network for a small watershed in one area in Idaho. In the Union of Soviet Socialist Republic two studies were made, one by Lebedev (1965), and the other by Konoplyantsev, Kovalevsky, and Semenov (1965). Mandel (1965) and Zorzi (1965) separately carried out studies on the design and instrumentation of hydrogeological observation networks and network design for recording ground-water levels, respectively. Felius (1965), of the Netherlands, made a study of the design of a network for ground water investigations. In addition to these studies which cited principles of network design established for the specific areas mentioned, general principles of ground-water hydrologic-data network design have been developed or inferred by Williams and Lohman (1947), Langbein and Hoyt (1959), Langbein (1960), Leopold (1962), Davis (1965), and Uryvaev (1965) for continental areas. Ineson (1965) has developed principles of ground-water network design for Great Britain.

HYDROLOGIC DATA NETWORKS AND THEIR USES IN GROUND WATER INVESTIGATIONS

Introduction

Langbein (1965) has defined a data network as: "an organized system for the collection of information of a specific kind. Its component parts must be related to one another; that is, each section, point, or region of observation must fill one or more definite niches in either space or time." There is, of course, a wide variety of hydrologic data, and elements of these data may be combined in a network in a variety of different ways for different purposes. Networks may be classified in terms of the parameters or combinations of related parameters whose measurements they include, the functions they are intended to perform, or the particular water resource they are intended to inventory.

Networks for Various Hydrologic Elements

A network may involve measurements of just a single kind at a number of stations such as a raingage network or a network of wells at which water levels are regularly measured. One might recognize also networks through which several parameters all pertaining to a single element in the hydrologic cycle are recorded. A precipitation network would record not only rainfall but snowfall, hail, fog-drip, etc. A hydrometeorology network would include all these plus evaporation and evapotranspiration. A surface-water network might include stations at which stream stage is continually recorded and the stage-discharge relation determined at regular intervals, and in addition stations at which diversions in ditches are measured by standard weirs or flumes. A ground-water network might consist of sub-networks of observation wells at which water levels are measured, springs and discharge wells whose flows and pumpage are measured, and wells at which various water-quality parameters are measured.

A review of the literature shows that networks that are designed for the collection of such data as stream discharges have been relatively well recognized. This type of network design has been studied by Kohler (1958), Langbein (1954), and Linsley (1958) among others. The same situation may be said of network designs for studies of rainfall, snowfall, and evaporation. Except for the papers presented in a symposium in Quebec by the International Association of Scientific Hydrology (1965, Design of Hydrological Networks), studies dealing with the design of ground water hydrologic inventory networks are essentially lacking.

Networks for Various Functions

Linsley (1965) has distinguished three types of hydrologic networks on the basis of function, and hence design, although each type might serve to collect the same type of information on the other.

WATER-SYSTEM MANAGEMENT NETWORKS. According to Linsley (1965) water management networks are those utilized in the operation of water-control works. Examples are reservoir inflow and outflow stations, gaging stations on canals, soil-moisture stations for purpose of scheduling irrigation, stations that monitor water pollution, and stations required in forecasting of hydrological events. To be more precise, these networks should perhaps be called water-system management networks by nature of their functions. The location of water-system management stations is determined by the specific need. In general, their locations are not rarely subject to network design of the same sort as in the case of other networks although for some observations such as soil moisture for irrigation purposes, the location of the observation site is determined on a network basis. Principles of network design for water system management stations are different from the other types of network which will be discussed later.

EXPERIMENTAL NETWORKS. Experimental networks generally are established to fill needs for specific types of research. This type of network usually covers a small area, and in general it has a much greater density of observation stations than other networks. A study made by Stephenson (1965) on network design for ground water studies in small watersheds and studies by Huff and Niell (1957), Linsley and Kohler (1951), and Spreen (1947) on rainfall patterns are some of the examples of network design for experimental purposes.

HYDROLOGIC-INVENTORY NETWORKS. What Linsley (1965) calls the data-acquisition network collects data that may be needed sometime in the future for planning, exploitation, or management of water resources. Such a network will here be described as a hydrologic-inventory network to clearly differentiate it from other networks.

It is this type of network that is the primary subject of this dissertation.

It is often impossible at times to know in advance the purposes for which the data are being collected except that the data is needed. Lead time requirements for some type of water resources planning may often be long and, owing to the usually undeterminable uses of the data, it is often difficult to design a hydrologic-inventory network. In some cases accessibility to locations of observation points may be difficult and this condition will often make the hydrologic-inventory network a relatively costly operation.

Networks for Inventory of Various Water Resources

Among the networks intended for hydrologic-inventory purposes may be distinguished types based upon the particular resource being inventoried. The complexity of the data to be collected depends to a considerable extent on the particular resource of interest. An inventory of precipitation, for example, might involve no more than a network of precipitation gages. In a surface-water inventory, however, it is common that an adequate number of stream-gaging stations cannot be provided, and that the stream-gaging sub-networks must be supplemented by a sub-network of precipitation gages. Generally, a network for the inventory of ground water, such as is of interest in this dissertation, must involve not only sub-networks by which ground-water parameters are directly measured, but other sub-networks by which surface-water, precipitation, and evapotranspiration parameters may be measured from which various ground-water parameters, not directly measurable, may be estimated.

Types of Data Pertinent to Ground Water Inventory

The United States Geological Survey (Davis, 1965) has classified the ground-water and other hydrologic and geologic data to be obtained in its national ground-water network program in two main categories depending upon the use to which they will be put: 1) those data required for the definition of the ground-water hydrologic environment, and 2) those data required for the definition of the ground-water flow system. Ground-water data needs and requirements for each specific type of ground-water investigation have been discussed by Davis (1965). 1) The data that are required for the definition of the hydrologic environment include relatively unchanging parameters such as a) geometry of the aquifer system, b) storage properties such as porosity, specific yield, specific retention, and storage coefficient, c) transmission properties such as hydraulic conductivity and transmissibility, and d) thermal and geochemical properties. 2) The data that are required for the definition of the ground-water flow system include such changeable parameters as a) hydraulic characteristics of the external and internal boundaries of the aquifer system, b) the response of the aquifer to some external forces, c) the changes of the aquifer in its physical and chemical properties with time, d) the head distribution, and e) recharge to and discharge from the aquifer.

Quantitative data necessary to further define the ground-water flow system may include data collected from a geohydrologic system simulated by analog model or other means. This may enable the evaluation of the response of the system to natural or artificial stimulations which may be monitored with reasonable accuracy for any projected period of time and under different sets of conditions. Lau and Mink (1967) demonstrated the usefulness of such a study in their work on the maximization of well yields of the Kalauao area near Pearl Harbor, Oahu, which was based on an analog-model study of the ground-water area.

From another viewpoint, data requirements for the estimation of ground-water supply of a given area may be fulfilled by 1) data derived in the field from direct observations of natural events. These data may include a) water levels in wells, b) records of natural discharge from ground-water bodies at springs and seeps, c) precipitation, d) evapotranspiration, e) stream discharge, and f) properties of the aquifer as observed in well logs and drill cuttings, and 2) derivative data that are the result of a) laboratory analysis of samples of water-bearing materials, and b) pumping tests and other field evidences of hydraulic behaviors such as hydraulic conductivity, transmissibility, specific yield, and storage coefficient.

To some extent, the uses to which the ground water is expected to be put determine the data needed. Davis (1965) discussed prospective uses of ground water in relation to data needs with regard to quantitative and qualitative aspects as follows: 1) In relation to water supply for domestic, municipal, industrial, irrigation, and stock uses, both the quantity and quality of water are required. 2) In relation to land drainage for agriculture and construction, the principle requirement is quantitative, although the quality of the water may be important locally. 3) In relation to losses from or gains to streams and reservoirs, the required information deals with both quantity and quality. 4) In relation to the use of the water as a heating or cooling medium, the quantity and temperature of the water are important.

Portrayal of Data

Portrayal of the data in the form of maps may be useful in the study of ground-water resources and supply. Da Costa (1960) referred to such maps as hydrologic maps, and in the United States, these maps are grouped as 1) maps showing general hydrologic features and water availability, 2) maps showing basic hydrologic data, 3) maps relating hydrologic features and geologic features, and 4) maps showing chemical-hydrologic features and their relationships.

Time-series plots showing variation of the hydrologic parameters with time, as for example, the variation of water level in the well with duration of pumping or duration of natural discharge such as from springs are ordinarily very useful. Other useful types of plots of the hydrologic data may show interrelationships among hydrologic parameters, for example a plot of head measurements against the salinity of the ground water, or a plot of a salinity or dissolved solids variation with depth in a well. Frequency plots of various parameters may also be useful in the study of ground-water resources and supply.

Changing Needs for Detail in Relation to Development of Ground Water Resources

The following discussion of the changing needs for detail of hydrologic data in relation to development of ground water resources is based on Davis (1965).

When ground-water investigation is a reconnaisance-type survey, the objectives are: 1) preliminary appraisal of the region and the condition of the ground water, and 2) identification of problems related to ground water and geology.

Definition of the hydrologic environment requires: a) a general description of geologic features, b) description of the main wells and springs, c) an estimate of the occurrence of water in the aquifer, and d) an appraisal of the quality of the ground-water.

Quantitative information that may be needed to define the ground water flow system include a) estimates of recharge and discharge of the ground-water supply utilizing climatological and runoff data when available, and b) estimates of yields of typical wells within the ground-water region.

For a general ground water investigation in an area with moderate ground-water development which has no unusual local water problems, the main objective of the investigation is generally to obtain the ground-water data necessary for planning for urban, industrial, and irrigation developments.

Definition of the hydrologic environment in a general study may include a) geologic mapping of the surface and subsurface, b) test drilling and geophysical investigations when feasible, c) systematic inventory of wells and water-level measurements, d) construction of maps which show water-level contours, depths to water, saturated thickness of the aquifer, transmissibility, storage capacity of the aquifer, and maps showing quality of the water or variations in quality.

Quantitative data derived from measurements may include a) probable quantity and quality of water in the aquifer, b) direction of ground-water flow, c) estimates of areas and rates of discharge and recharge, and d) water storage in relation to water levels in wells.

For an intensive investigation of ground water such as is often carried out in areas where there is existing or potential intensive development for municipal, industrial, or agricultural uses, the objective is the collection of precise quantitative hydrologic data for planning supplemental water supplies and to alleviate management problems such as a) rapid decline of water level, b) intrusion of poor quality water which may be from the underlying or adjacent sea water or from irrigation soil enrichment practices, c) pollution from various sources on the surface, and d) soil salinization that may be related to agricultural practices.

Appraisals to define the environment in an intensive study may include collection of data to study in detail the a) lithology, b) porosity, c) hydraulic conductivity, d) transmissibility, and

e) storage coefficient or specific yield.

For a detailed appraisal of the quality and quantity of the ground water, maps should be prepared which would show a) water-level contours, b) depths to water, c) saturated thickness of the aquifer, or thickness of the fresh water lens, d) heads in dike compartments, e) transmissibility, f) storage capacity, and g) quality of water.

For a continuing surveillance of the ground-water conditions, the main objective is to provide current answers to questions regarding the status of water resources and to assist in solving problems of planning, development, and management as they arise.

Data necessary to define the hydrologic environment may include: a) current information on ground-water developments, and b) new data on the geology, hydrology, and on ground-water problems.

As a part of the quantitative information necessary for continuing surveillance of the ground water, the quantitative interpretations of estimation of recharge, discharge, and changes of ground-water storage should be brought up to date.

Objectives and Methods of Ground-Water Inventory

INTRODUCTION. The process by which items in the hydrologic equation are evaluated and balanced may be described as a hydrologic inventory (Tolman, 1937). When the equation pertains to the evaluation and balancing of items of input and output of a ground-water aquifer, rather than to all water resources, then the equation is called a ground-water inventory equation or a ground-water storage equation. The inventory itself is commonly referred to as the ground-water inventory. In its more generalized form, the ground-water inventory equation may be given by the equation below:

$$I_s + I_1 + I_p + I_a = 0_s + 0_1 + 0_{et} + 0_d + \Delta S$$

where I_s is the natural inflow from surface water bodies, I_1 is the subsurface inflow from adjacent aquifers, I_p is the inflow from precipitation, I_a is the inflow from artificial recharge, 0_s is the outflow into surface water bodies, 0_1 is the subsurface outflow, 0_{et} is the loss from evapotranspiration, 0_d is outflow by artificial discharge, and ΔS is the change in ground-water storage. Where the net change in ground-water storage is considered to be essentially zero, it is eliminated from the inventory equation.

In general, in most attempts to evaluate and balance the equation of the ground-water inventory, it is found that after what appear to be the best independent estimates of the individual items are inserted in the equation, the equation is out of balance, and therefore it is necessary to make an adjustment. Such adjustment involves primarily those values in the equation that are believed to be inherently subject to large probable error. The accuracy of the data determines the extent of the imbalance and the amount of adjustment required. In general, long-term mean values are the most useful values to effect the balancing of the equation.

In practice, a base period is usually selected for which the parameters in question are to be determined. The base period must be chosen in such a way that it will: a) allow direct determination of most of the items in the equation, b) be long enough so that the mean values of the data collected are, in general, statistically accurate, and c) permit some values in the equation to be eliminated because they may equal zero over the period. In general, zero values of some items is used because the safe yield to be determined by the equation is defined in terms of a long period.

DEFINITION AND IDENTIFICATION OF AQUIFERS. Many authors (Wisler and Brater, 1947, Todd, 1959, Davis and DeWiest, 1966) have attempted to define an aquifer in relation to its occurrence and relative position in the earth's crust with other types of water present in the crust.

The terms vadose, pellicular, or suspended water are applied to water occurring in the zone of aeration where most of the interstices are filled with gases. Below this zone is the zone of saturation and the water occurring in it is called ground water or phreatic water. This is the zone of the crust that hydrologists usually refer as the regimen of ground-water and in which the term "aquifer" is defined. In general, the zone of saturation usually consists of materials of varying permeabilities so that an aquifer is also defined in terms of the ability of the water-bearing materials to transmit water. The quantity of water obtainable in the formation of permeable material also influence the definition of an aquifer as the term "quantity" is relative. Where ground water is obtained with great difficulty, for example, even a very poorly productive material is often classed as an aquifer. Further, the definition of an aquifer is limited by the quantity of water that a permeable material can yield for different requirements. For example, a water-bearing material that yields only enough water to supply a household may be considered an aquifer by the user, but may not be considered as an aquifer if it is to be exploited on a larger basis.

In general, an aquifer has been defined as that part of the phreatic zone "that yields sufficiently large amounts to be important economically" (Davis and DeWiest, 1966). In order to distinguish the term "aquifer" from other terms used by hydrologists, the following definitions of terms are given. Where a geologic unit may store or transmit water, but of an amount considered insignificant, the term "aquitard" is used. The term "aquiclude" is used to define a porous but impermeable material and may be distinguish from an aquitard by their relative permeabilities. The distinctions between the terms "aquifer", "aquitard", and "aquiclude" are, in general, arbitrary, and depend on the factors discussed earlier.

Aquifers may be found occurring in nature as a single hydrogeologic unit. They may also be found to comprise several hydrogeologic units, differentiable but hydraulically interconnected. The interconnection between the aquifers may be so good that any change within the aquifers, such as discharge or recharge, may influence the entire aquifer system. In other cases where the interconnections may not be as good, the influences of recharge and discharge may not have significant effect on the parts of the aquifer system farther away from these sources.

Todd (1959) refers to the collection of hydraulically interconnected aquifers as a "ground-water basin." In the evaluation of potential water supplies, the yields obtainable from a basin is often the most useful criterion of potential supply rather than the yields of individual aquifers. The yields of individual aquifers are useful when considered in conjunction with each other and also in conjunction with potential surface water occurring above them. Especially important in this regard is the collection of hydrologic data for ground water evaluation by a network which is done by evaluating the data collected over the individual aquifers and then integrating the results to estimate the yield of the entire basin. Witherspoon and Freeze (1966, 1967, 1968) have suggested a regional flow concept to the evaluation of ground water.

SAFE YIELD: DEFINITION OF CONCEPT AND LIMITATIONS. In utilitarian terms, the usual goal of a hydrologic inventory is to estimate the safe yield of an aquifer or system of aquifers.

In a general ground-water usage, Meinzer (1923) defined safe yield as "the rate at which water can be withdrawn from the aquifer for human use without depleting the supply to such an extent that withdrawal at the rate is no longer economically feasible." Cox (1969, per. comm.) suggests that the safe yield of an aquifer is a function of the natural inflow, the rate at which this inflow is modified by drawdown, natural outflow and the rate at which natural outflow is modified by drawdown, the relation of the quality of water withdrawn to the draft and spatial and temporal patterns of draft, the level of technology, and economics and social considerations. The latter factors may be related to safe yield in relation to cost of construction of facilities for ground-water developments, maintenance cost, cost for artificial recharge to the ground-water, and the value of water in relation to desirability and uses as measured by its quality. Legal and political constraints may sometimes become important determinants in the definition of safe yield. Safe yield, therefore, may be more precisely defined as a resource parameter that incorporates not only the restrictions of the hydrologic conditions existing in the aquifer, but a number of other factors that pertain to socio-economic and technological aspects. For example, in some areas in the Hawaiian Islands, when only steam-pumped drilled wells were available for development of water inland, the maximum safe yield of the thin Herzberg lens was found to be very small because of the vulnerability of such wells to salt water coning. However, with the introduction of the Maui-type well, the safe yield was greatly increased. In addition, following the development of deep-wells and submersible pumps, the safe yield was increased by allowing practicable drilling of wells far inland where the depth to the lens was several hundred feet. This permits the advantageous spreading of the draft over a much larger area overlying the thicker and fresher portion of the Ghyben-Herzberg lens (Cox, 1969, per. comm.).

The maximum safe yield of an aquifer may involve drafts of two different qualities of water with different intent of utilization. In some islands, for example, a water from the fresh part of the Ghyben-Herzberg lens having a higher quality may be withdrawn wholly for domestic use. From the same lens, water with lower quality, usually more brackish, may be withdrawn for irrigation and cattle watering.

Cox (1969, per. comm.) suggested that it may be useful to separate out from the safe yield concept the "hydrologic equivalent" of the safe yield. The yield of water of satisfactory quality which could be continued indefinitely may be defined strictly by the hydrologic parameters under assumed unchanging socio-techno-economic conditions. This concept may be useful in some ways since the definition is not restricted to present availability of data to evaluate the hydrologic equation in order to determine safe yield, but can be projected taking into account the changing factors of the data and the socio-economic-technological aspects.

Wentworth (1951) defined safe yield locally by saying that safe yield or safe usage is the "rate of draft which under present conditions of use and exploitation is judged by competent opinion to be neither destructive to any contemporary exploitation by presently reasonable method nor trending irrevocably toward conditions which would deny to a future generation a like choice of reasonable method and level of exploitation and use." The techno-socio-economic factors mentioned earlier as affecting the safe yield are easily seen to be implicit in the definition.

Examples of Methods of Safe Yield Determination

The following methods of safe yield determination are summarized from discussions by Todd (1959). The methods are applicable to the extent that geologic and hydrologic conditions and the factors that govern safe yield are reasonably well-defined. The methods are formulated on the basis of and predicated upon the general hydrologic equilibrium equation that defines a given ground-water basin or aquifer.

HILL METHOD. The safe yield method developed by Hill is based on the relationships between the annual change in the elevation of the ground-water level and the annual draft from a given basin. The hydrologic data collected for use in the estimation of safe yield must cover several years. From the data collected, the annual change in elevation of the ground-water level is plotted against annual draft values over the basin for a given period. A straight line is fitted through the plotted points and the annual draft that corresponds to a zero change in ground-water level is taken as the safe yield of the basin. An example of this method is illustrated in Figure 1

HARDING METHOD. For the determination of safe yield by the Harding method, two types of basic hydrologic data are needed: (a) annual values of retained inflow into the basin, and (b) annual changes in ground-water table elevation. Retained inflow is defined as the total inflow minus the total outflow of the ground-water basin. The assumption that both inflow and outflow parameters can be completely delineated implies a more or less closed basin. Retained inflow values are plotted against changes in ground-water elevation and a straight line is fitted through the plotted points. A point on the mean line corresponding to a zero change in water table elevation is taken to be the safe yield of the basin. The method requires

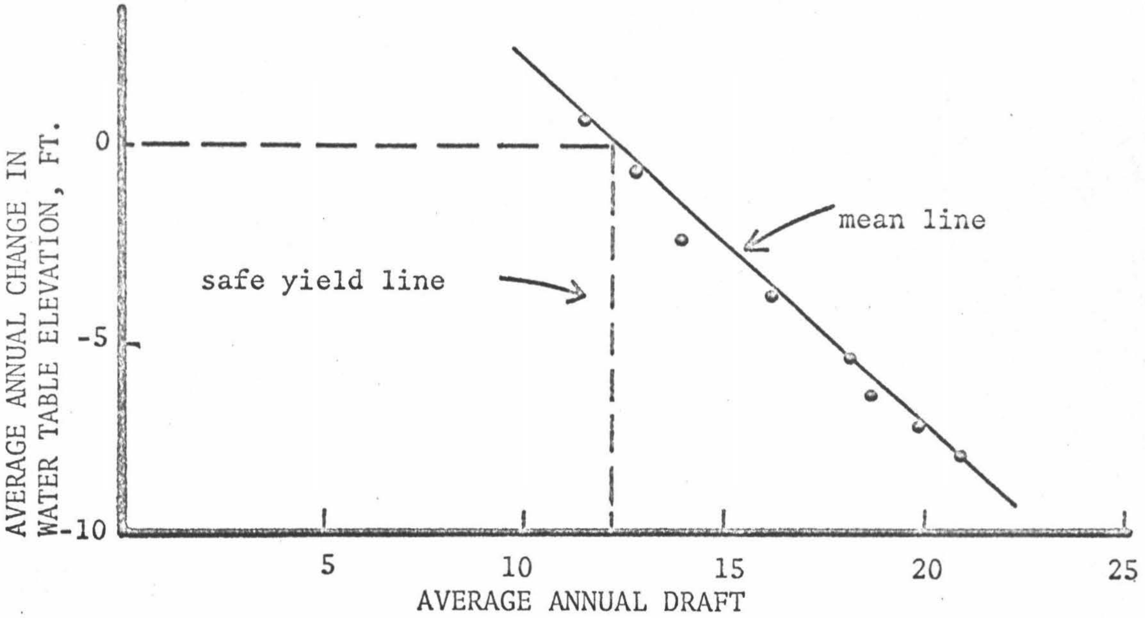

FIGURE 1. SAFE YIELD DETERMINATION BY HILL METHOD (REDRAWN FROM TODD, 1959)

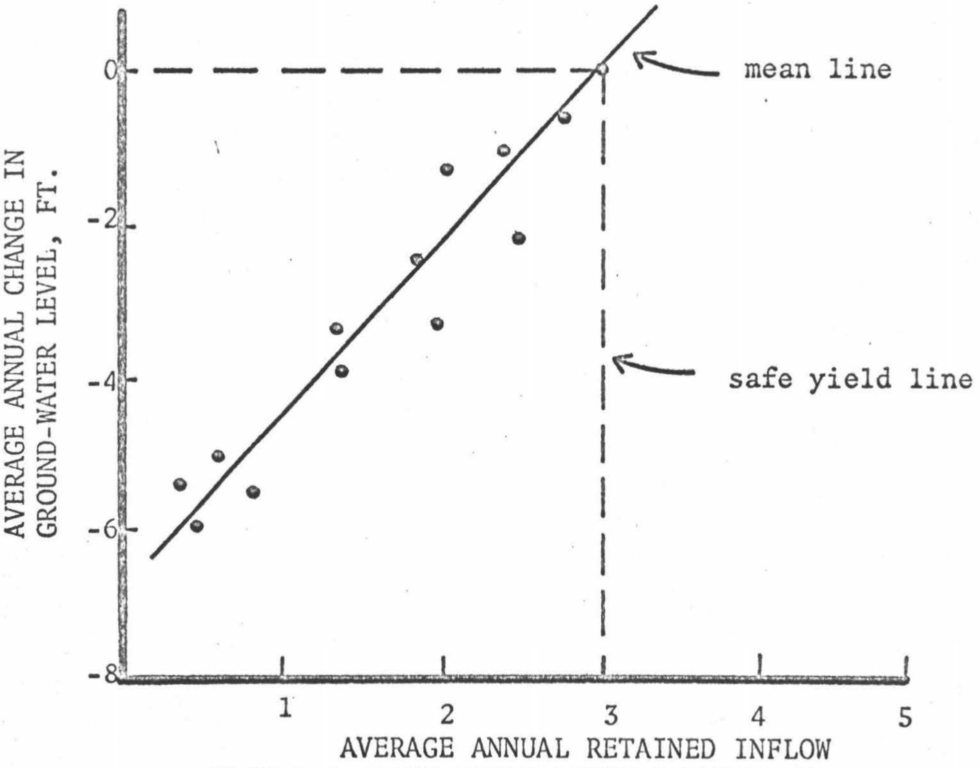

FIGURE 2. SAFE YIELD DETERMINATION BY HARDING METHOD (REDRAWN FROM TODD, 1959)

constancy of the draft over the basin, thus suggesting a condition of no significant change in the consumptive use of the ground water, and unconfined ground-water conditions in which there is a direct connection between surface and ground water. An example of this method is illustrated in Figure 2.

SIMPSON METHOD. This method was developed by T. R. Simpson and was first applied over a confined aquifer bordering a coastal area. Data requirements include (a) drafts over the basin, and (b) accurate information on direction of slope of the piezometric surface. In Simpson's investigation, sea-water intrusion was noted when the piezometric levels fall below sea level. The safe yield of the basin is maintained for as long as the piezometric surface slopes away from the pumping area. When an overdraft condition occurs, a pumping trough is created causing a reversal of the sloping direction of the piezometric surface toward the pumping area. In coastal areas, this reversal of slope will eventually promote the intrusion of sea water as a result of the reversal of direction of movement of the fresh water. The safe yield under the above condition is determined to be the basin draft just before the appearance of the trough which brings about the reversal of the piezometric surface or the basin draft established immediately after the pumping trough has disappeared.

ZERO NET GROUND-WATER FLUCTUATION. A method based on zero net ground-water level fluctuation requires data of annual net draft and ground-water elevations. The average annual draft on the ground-water basin is taken as a measure of safe yield when, over a long period, the elevation of the ground-water level at the beginning of a base period and at the end of a base period is essentially constant. After corrections of the net annual draft for such values as percolation, precipitation, and storage, the safe yield is obtained. Figure 3 illustrates an example of safe yield determination by this method.

DARCY'S LAW. Data requirement for the determination of safe yield based on Darcy's Law include the hydraulic gradient of the water table, the permeability of the aquifer, and the cross-sectional area of the aquifer. Additional data are the inflow into the basin observed over a long period and the direction of the ground water movement. The average long-term inflow computed by Darcy's Law on the basis of collected data is assumed to be the safe yield of the aquifer. The application of this method may be limited to aquifers having an unidirectional ground water flow.

SPECIFIC YIELD AND AVERAGE ANNUAL RISE IN WATER TABLE. A method based on specific yield of the aquifer and the average annual rise in water table is applicable in unconfined aquifers. The annual recharge computed by finding the product of specific yield, annual rise in water table, and area of the aquifer is taken to be the safe yield of the aquifer.

Determination of the Relationships of Parameters in the Ground-Water Inventory Equation

SUBSURFACE INFLOW AND OUTFLOW INTO PHREATIC ZONE FROM ADJACENT AQUIFERS. One of the major difficulties that may be encountered in the

EXAMPLE OF SAFE YIELD DETERMINATION
BY METHOD BELOW

	Volume Unit
Average annual net draft during period	41,600
Difference between average period and mean percolation	1,000
Difference between average period and mean precipitation	-2,400
Average period change in groundwater storage	- 900
Safe yield =	39,300

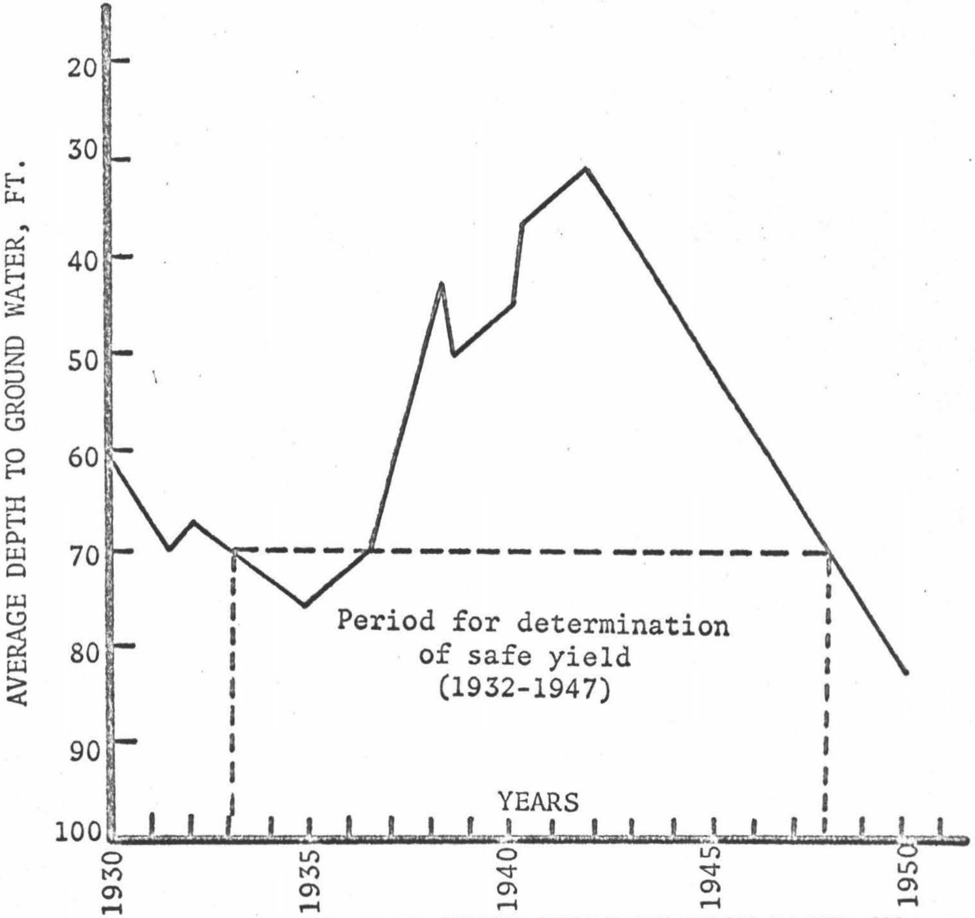

FIGURE 3. SAFE YIELD DETERMINATION BASED ON
ZERO NET GROUND WATER FLUCTUATION
(REDRAWN FROM TODD, 1959)

balancing of the inventory equation is the determination of subsurface inflow and outflow into the phreatic zone from adjacent aquifers. Where geologic and hydrologic investigations show a strong possibility that both of these parameters are negligible, the problem of balancing the equation may be greatly simplified. Great difficulty, however, may arise in a situation in which there may be flows from or to adjacent aquifers, as is generally the condition found in nature. The rates of such flows depend on the head differential between the aquifers exchanging the flows which may vary from time to time.

The underground inflows and outflows of an aquifer may, in some cases, be estimated, given a sufficient amount of geologic data to determine cross-section, by estimating the velocity of flow. With sufficient information on the hydraulic gradient, cross-sectional area, and hydraulic conductivity, Darcy's Law may be applied to determine the discharge. Electrolytic or dye methods may be useful in making direct velocity measurements. In order to determine the quantity of flow using the dye method, the velocities of flow obtained must be converted to gross-area or Darcy equation velocities.

INFLOW TO GROUND-WATER BODY FROM SURFACE-WATER BODIES. This item in the hydrologic equation may be determined by making stream-discharge measurements at selected cross-sections of the stream channels. From this, it may be possible to obtain continuous records of discharge data and this may be correlated with data during base-flow periods to determine the recharge from the surface-water bodies. Because, in general, the amount of influent seepage per foot of channel is usually small in comparison to the total discharge, in practice, it is necessary to measure the stream discharge with great precision and repetition.

OUTFLOW FROM GROUND WATER BODIES INTO SURFACE WATER BODIES. The discharge from ground-water bodies to surface water bodies, in general, represents the base-flow of most streams and may be measured at the discharge points with standard hydrographic and hydraulic methods as used in the measurements of the previously mentioned inflow item.

The determinations of inflow from surface-water bodies and outflow from ground-water bodies into surface-water bodies are generally easier and the data are more satisfactory than that of other parameters. In some cases, sufficient data have been collected for other purposes to satisfy the ground-water inventory needs.

INFLOW TO GROUND-WATER BODIES FROM PRECIPITATION. The estimation of water from precipitation entering the ground-water body is generally made by analysis of the fluctuations of the ground-water level on a long-term basis. The water-level hydrographs from wells are correlated with precipitation records to determine the effect of precipitation on the rise of the water level. Throughout the period of precipitation recharge, there is a continuous discharge from the aquifer, so that in correlating the water-level hydrographs with precipitation, the actual recorded rise in water-level represents a net difference between recharge and discharge.

A second method of estimation is to measure total precipitation and deducting from it values of total evapotranspiration and surface runoff.

OUTFLOW FROM GROUND WATER BODIES AND LOSSES FROM PRECIPITATION BY EVAPOTRANSPIRATION. The effect of evapotranspiration on the ground water bodies is important only in areas where roots of phreatophytes and other vegetation extend downward into the phreatic zone. The significance of evapotranspiration values in the inventory equation is on its effect on water losses from precipitation. Evapotranspiration and consumptive use are sometimes used interchangeably, the latter representing water loss through transpiration by plants plus evaporation of soil moisture, snow, or intercepted precipitation. The water loss by these processes is one of the most difficult to determine because of the large number of variables to measure and the difficulties in their measurement. The combination of these losses are, in general, taken as the consumptive use or evapotranspiration, and their sum is subtracted from precipitation in the inventory equation. The data for these losses are obtained by measurements using various methods such as evaporimeters for measurement of evaporation and lysimeters for measurement of consumptive use. In practice, to determine this loss, it is first necessary to make land-use or cultural surveys which will show areas and typical rates of water consumptive use. From this, a unit value of consumptive use is determined from the values of transpiration and evaporation. The total consumptive use is determined by multiplying the unit value of consumptive use by the corresponding area of the aquifer or basin.

INFLOW TO GROUND-WATER BODIES FROM ARTIFICIAL RECHARGE. Artificial recharge of ground-water bodies may be accomplished by either 1) water spreading, using the diffusion method, basin method, or the ditch or furrow method, and 2) by diffusion wells. The quantity of recharge to ground-water bodies may be determined by the inventory of pumping records in the case of the diffusion wells method, and by surface water measurements in the case of water spreading.

OUTFLOW FROM GROUND-WATER BODIES BY ARTIFICIAL DISCHARGE. Water withdrawn from the aquifer may be estimated by making a comprehensive survey of all well owners to determine the rates of pumping and the extent to which these rates fluctuate daily, weekly, monthly, or annually. By using data from a pumpage inventory, a map of an aquifer area or basin may be drawn showing the distribution of draft during the period of the ground-water inventory. If a water-level contour map is also drawn, an areal correlation between pumpage and water levels may be made from the two maps. This, in general, will show that regions of large withdrawal will correspond to low water-level and regions of little or no pumping will correspond to areas of high water-level, assuming the absence of zones of natural recharge or geologic boundaries. Construction of graphs showing pumpage versus time may be useful in determining the relation between the seasonal and long-term trends of withdrawal with the water level hydrographs from the wells. From the above information, it may be possible to derive values of outflow from the ground-water bodies which may be useful in the evaluation of the inventory equation.

HEAD. Head is not listed nor indicated implicitly in the ground-water inventory equation, but as is already apparent and will be further pointed out later, it is one of the most important component in the determinations of most of the items in the equation.

The water level in unconfined aquifers and the piezometric level in confined aquifers fluctuate under the influence, in general, of the variation of the rates of recharge and discharge. These variations are, in turn, governed by the patterns of precipitation, stream discharge, consumptive use, etc., patterns involving annual cycles and also shorter period and longer period changes. In general, artificial draft from the aquifer usually promotes or increases the inherent variability of recharge and discharge rates. The effects of this variability on the ground-water aquifer are manifold. For example, a lowering of the water level in an unconfined aquifer indicates the reduction of volume of water in storage. The lowering of the head, however, may also result in the increase of opportunity for recharge from influent streams and from subsurface inflow from adjacent aquifer or aquifers. It may also bring about a decrease in subsurface outflow, discharge to effluent streams and springs, and possibly a reduction in evapotranspiration. The effect of the reduction in head will, in general, then might make more water available for draft for beneficial purposes. The effects, on the other hand, of increase or rise in head will always tend to have the opposite effects listed above.

When the piezometric level is lowered by draft from a confined aquifer, the following things may tend to take place and are often observable: 1) an increase in the hydraulic gradients between the areas of recharge or adjacent aquifers and the area of draft promoting the flow from the recharge area and from adjacent aquifers, 2) a reduction in the rate of discharge from natural outlets of the aquifer, 3) a compaction of the aquifer and confining structure, which in turn, reduce porosity and hydraulic conductivity and may cause subsidence of overlying lands, and 4) reduction of the yield of water from storage.

When the decrease in the piezometric level in a confined aquifer extends to the areas of recharge or areas of natural discharge, the effects listed under (1) and (2) may take place. Assuming that the effects under (3) are not significant, the effect of the drop on the piezometric level will spread in each direction until the points of outlet and inlet are reached and the total inflow, under this condition, could equal the total outflow. In the area of draft, head also controls pumping lifts, the flow of the artesian wells, and the position of the salt-fresh water interface if one is present.

It is seen from the above discussion that all the components of storage are functions of the head, and although head is not implicitly included in the ground-water inventory equation, it is in fact, one of the most important parameters to be determined.

WATER QUALITY. In general, the significance of water quality in ground-water is measured in terms of the dissolved constituents, of inorganic origin, present in it. In some cases, the presence of organic materials, suspended sediments, and microorganisms, may be important. The origin of inorganic dissolved solids in ground water may be from many different sources such as: 1) the atmosphere, 2) weathering processes, 3) sea-water intrusion, 4) connate water, 5) metamorphic and magmatic processes, 6) agricultural soil enrichment practices, and 7) from waste disposal of domestic and industrial nature.

The modes of entrance of these constituents into the ground water also vary. The atmosphere or meteoric constituents are introduced by rainfall to the land surface and subsequently are leached downward to the ground-water body. The constituents formed through solution or exchange during the weathering processes may be introduced into the ground-water bodies by leaching. These constituents may also originate in situ when the weathered material is in direct contact with the ground water. Constituents of marine origin are usually introduced into the ground water through encroachment of sea water into the fresh water zone by a mixing process. Their influence on the quality of water in the aquifer may depend in part on their original concentration outside the zone of mixture, the rate of mixing with the fresh water, the rate of flushing of these constituents by the overlying fresh water, and the rates of base exchange and solution within the aquifer. Connate constituents may be introduced into the fresh water by mixing process if these constituents were present in the aquifer before the introduction of fresh water.

Constituents from metamorphic and magmatic processes, although they are not usually significant, are introduced into the ground water by the mixing of the thermal water which is released by these processes with the ground water. Constituents from domestic and industrial wastes, and from agricultural practices are, in general, introduced into the ground water by percolation from the ground-water bodies where these constituents are disposed, through leaching of these constituents from areas of disposal in the case of domestic and industrial wastes, and through leaching of these constituents from areas of use, above or below land surface, as in the case of agricultural constituents.

The quality of the ground water is important when the purpose of the monitoring points of the network is for the investigation of water available for development. In addition to this, from the monitoring points, it may be possible to use water-quality data to determine 1) ground-water flow patterns 2) the length of time that the water stays in the ground-water body, 3) water quality at various depths of the ground-water body, 4) changes in the position of the interfaces of fresh and salt water and hence, changes in storage, and 5) changes in the thickness of mixing zones. Water-quality data may also be useful in delineating areas where dissolved constituents may have been introduced at the land surface. Additionally, the purpose of monitoring may include the determination of the distribution of domestic and industrial wastes and their influence on the ground-water quality. Temperature monitoring may be useful for some purposes such as air-conditioning and heat exchange processes. A monitoring of the tritium content of ground water may be useful in the age determination and sources of recharge to ground water, and pH monitoring may be useful in determining the necessity of controlling corrosion in pipes.

Changes in Ground-Water Storage

In the solution of the ground-water inventory equation, changes in storage are, in general, limited to those changes occurring in the zone of saturation. In many attempts to balance the equation for the determination of safe yield, the effect of the changes in storage on the equation is eliminated by assuming the changes are equal zero over the period of evaluation. This is done, in general, because of the difficulty in measuring such changes with reasonable accuracy, and because of the complexity it might present in the overall analysis of the equation.

When the effect of the changes in storage is to be considered in the evaluation of the ground-water inventory equation, a common method given by Todd (1959) and Wisler and Brater (1947) in which short-term changes in storage may be determined is based on periodic observations of the changes in the water level for a selected network of observation wells. In addition to the water-level data collected in the network, additional information on the geology, aquifer boundaries, pumpage data, pumping test data, specific yield or storage coefficient, and data on the dimensions of the aquifer are collected. From the water-level measurements, contour maps of water table of piezometric level are constructed. The changes in storage are then computed as the product of the average change in water level times specific yield or storage coefficient times the area of the aquifer. It is obvious that this method may be strictly applicable to aquifers with lower confining structure in which the extent of their saturated thickness may be delineated, and would be essentially inapplicable in a condition in which there is hydraulic interconnection with sea water as the case in the Hawaiian Islands.

Parameters to be Measured by the Ground-Water Data Network Monitoring

The various parameters to be measured by the network have been listed in previous sections. These parameters include those that are fixed and those that vary. A more detailed breakdown of the parameters have been given by Cox (1969, unpublished report, Tables 1 and 2) and will be presented in the following section.

Time Relationships with Parameters of the Ground-Water Inventory Equation

TIME AND STORAGE. In general, changes in storage may be said to be dependent on the amount of inflow or recharge, amount of discharge, the rate and duration of drawdown and draft on the aquifer. In general, storage decreases with increasing duration and rate of draft and consequent drawdown, other things being equal, so that under these conditions, water in storage will eventually be depleted over an indefinite period. Where there is continuous inflow into the aquifer, under the above conditions, after the amount of inflow is

TABLE I. PARAMETERS TO BE DETERMINED FOR VARIOUS GROUND-WATER NETWORK MONITORING PURPOSES

PURPOSES AND QUANTITY NEEDED

Potential yield--conduit method

- Aquifer dimensions
- Hydraulic conductivity
- Transmissibility
- Hydraulic gradient

Potential yield--reservoir method

- Aquifer dimensions
- Location and extent of recharge
- Location and extent of discharge areas
- Percolation
- Influent seepage
- Interaquifer inflow and interbasin inflow
    - Dimensions
    - Transmissibility
    - Hydraulic gradient
- Artificial recharge
- Evapotranspiration
- Effluent seepage
- Interaquifer and interbasin outflow
    - The same as for interaquifer and interbasin inflow
- Draft
- Top storage
    - Head
    - Specific yield or coefficient of storage
- Compression storage
    - Head
    - Storativity
- Bottom storage
    - Head differential
    - Porosity
    - Salinity gradient
    - Dispersivity
- Quality
    - Concentration and concentration gradients
    - Discharge
    - Dispersivity

TABLE II. PARAMETERS NEEDED FOR GROUND-WATER EVALUATION

PARAMETER (FIXED OR ESSENTIALLY FIXED)

Dimensions of Aquifer

- Length
- Width
- Thickness
- Slope
- Location and area of recharge areas
- Location and area of discharge areas

Characteristics of Aquifers

- Hydraulic conductivity
- Transmissibility
- Storativity
- Porosity
- Specific yield or coefficient of storage
- Dispersivity

PARAMETERS (VARIABLE)

In the Aquifer

- Head
- Draft
- Influent rates
- Effluent rates
- Quality
  - Salinity
  - Other dissolved solids
  - Temperature
  - pH

Meteorological Parameters

- Rainfall rate
- Evapotranspiration rate

Surface water parameter

- Surface water discharge

exceeded by draft, the water left to be withdrawn will ultimately be derived from storage.

The influence of time on the net change in storage is usually considered over a long period in the evaluation of the ground-water inventory equation so that, as previously pointed out, it is often assumed to be zero.

TIME AND HEAD. In general, under condition of continuing drawdown on the aquifer, and hence, continuing draft, the head is correspondingly reduced, the magnitude of such reduction being a function of both the duration of the draft and drawdown. A long draft period would, in effect, promote a significant reduction in head and vice versa.

In most attempts to evaluate the ground-water inventory equation for the determination of safe yield, the net change in head is commonly assumed to be constant over the inventory period, so that the safe-yield value is often correlated to a zero change in head over the period of evaluation.

TIME AND WATER QUALITY. The changes of water quality with time may be related to the amount of water stored in the aquifer and the consequent reduction of the head over the period of draft. In many cases, a reduction in storage due to overdraft conditions would result in the yield eventually of lower quality water, especially in areas where the equilibrium of the fresh water and other types of water of lower qualities is critical. In areas where the fresh water is hydraulically interconnected and in equilibrium with sea water, the effect of time on water quality as influenced by draft and drawdown may be very important.

Because of the importance of water quality in the determination of safe yield, its variation due to the influence of draft and drawdown should be closely monitored and appropriately evaluated in conjunction with the other items in the ground-water inventory equation.

GEOLOGY OF THE HAWAIIAN ISLANDS

General Statements

The Hawaiian Archipelago is made up of the exposed peaks of mid-oceanic volcanoes of the central Pacific. The length of the archipelago covers a distance of about 1,600 miles from the island of Hawaii to Kure Island, and trends in a general northwestward direction. The major islands (Figure 4), consisting of Niihau at the northwestern part of the chain of islands, Kauai, Oahu, Molokai, Lanai, Maui, Kahoolawe, and Hawaii toward the southeast, extend over a distance of about 380 miles.

The islands are constituted by shield-shaped volcanoes, each being made up of one to five of these shields. The shields are composed of many lava flows typified by the present-day occasional outpouring of Mauna Loa and Kilauea volcanoes. Because of the presence of such features as cracks, gas cavities, lava tubes, and clinkers, the basaltic lava flows are usually highly porous and pervious. As a result, the lavas are generally excellent transmitters of water.

The volcanic eruptions of the Hawaiian Islands are characteristically fissure type eruptions (Stearns, 1946). The fissures or rifts represent the main feeding system through which lavas from great depth find their way to the surface. These openings generally follow axial or tri-axial zones of weakness extending through the centers of the volcanoes. The fissures may be a few inches to many tens of feet wide, and in general average about two feet wide.

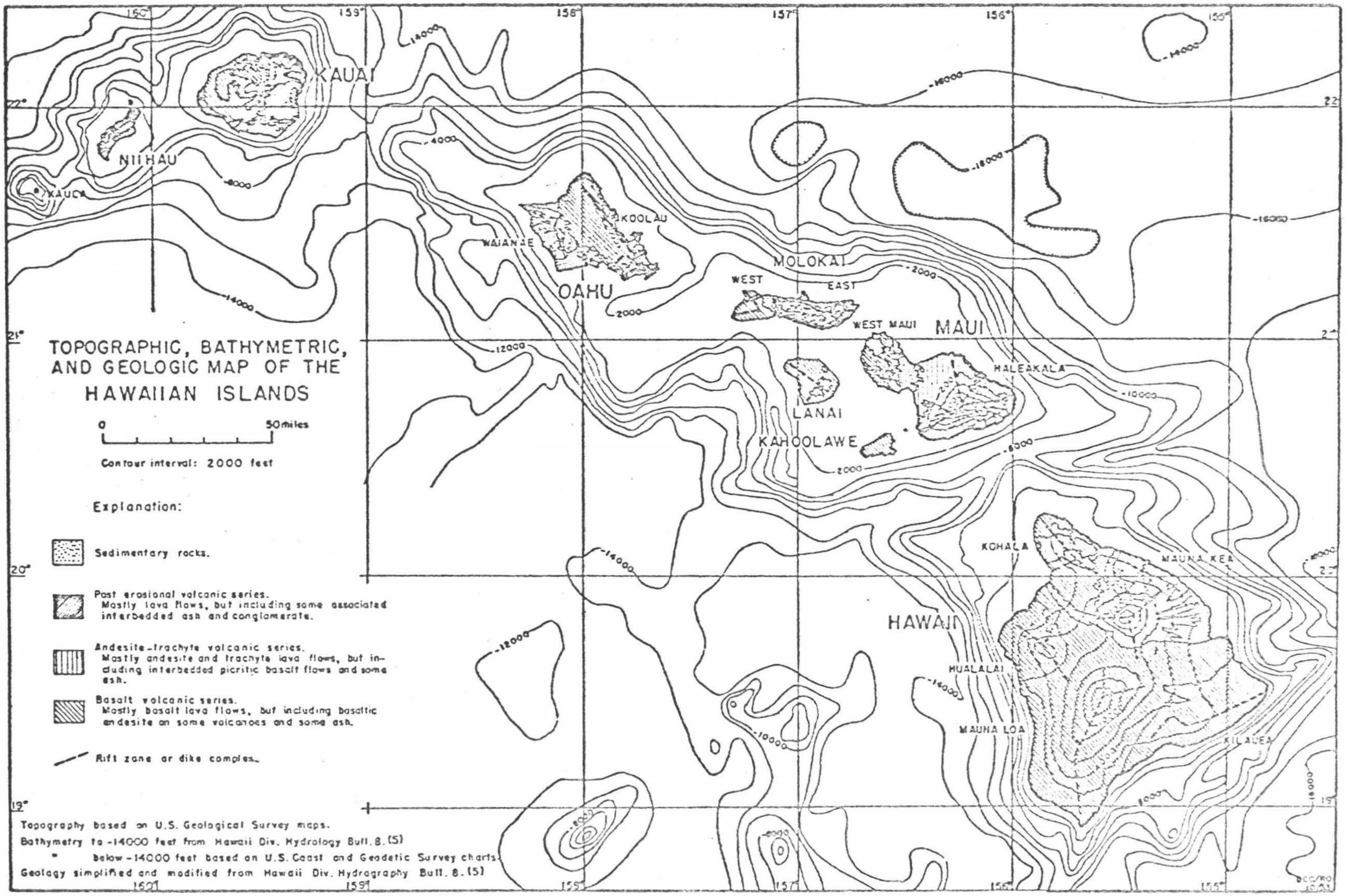

FIGURE 4. TOPOGRAPHIC, BATHYMETRIC, AND GEOLOGIC MAP OF THE HAWAIIAN ISLANDS (FROM COX, 1954a).

At the end of each volcanic eruption, lava that entered the rift plugs the rift resulting in the formation of a near-vertical sheet-like intrusive called a dike. The dikes are composed of denser rock, more compact than the layered lava flows through which they cut. Stearns and Macdonald (1942) refer to the zones intruded by many dikes as dike complexes.

In places within a dike complex, the dikes may be very closely spaced and appear to have completely displaced the layered lava flows. In places where the dikes are more or less widely spaced, they form compartments by enclosing the less dense and less compact country rocks. Closed compartments of the country rocks are commonly formed when the dikes intersect vertically and along the predominant strike. Where the compartments are open upward, water percolating downward may be impounded in them.

A collapse depression or caldera is a typical feature in the central portion of the Hawaiian volcanoes. In general, a cycle of lava filling and then collapse of the caldera typifies the volcanic activity. The lava flows ponded in the caldera are generally thicker and more compact than the lava flows that have been erupted on the flanks of the volcano (Cox, 1954a).

The eruptions are commonly associated with cinder cones whose formation is due to gas-induced fountaining (Stearns and Macdonald, 1942). Although the cinder cones represent only a very small part of the main volcanic shields in either volume or area, the fine ash materials from them may be widely scattered. The ash accumulations after series of eruptions may form extensive sheets of the ash material that are considerably less pervious than the flows that eventually buried them.

The primitive olivine basalts that make up the major parts of the shields have been covered on some shields by flows of andesite composition, more siliceous than the basalt. The andesitic flows are sometimes found interbedded with picritic basalt flows. Because of the relatively more viscous nature of the andesitic lavas in comparison to the basalt, the flows are thicker and more massive. The andesitic flows thus form a less pervious mantle over the more pervious basaltic flows. A still more viscous and siliceous lava than the andesite, trachyte, has been erupted at vents in some islands resulting in the formation of very thick "bulbous domes," (Cox, 1954a). The volcanoes of Mauna Kea, Kohala, Hualalai, Niihau, Kauai, Waianae, East Molokai, Kahoolawe, West Maui, and Haleakala, have all reached or passed through an andesitic or trachyte stage.

The eruptions during the basaltic stage are very frequent, and due to the short intervals between the eruptions, the process of weathering does not proceed far. Thus few soils are produced during the basalt stage except on ash beds, which are less resistant to weathering than the flows. During the andesitic stage the frequency of eruptions is reduced appreciably, enabling the formation of thicker soil layers and some valleys due to the longer periods for weathering and erosion.

After or close to the end of the andesite or trachyte stage, a long period of weathering and erosion permits the carving of great valleys with depths commonly greater than those of the present valleys. Deep soils also form during this long period of quiescence.

A period of volcanism, commonly referred to as post-erosional eruptions, may follow the period of extensive erosion. Present-day examples of the products of this period include the well-known Diamond Head cone on Oahu and the Kilohana cone on Kauai. Basalts and rocks that are more deficient in silica characterize the post-erosional eruptions. Lava flows produced by the post-erosional eruptions are less porous and less permeable than the older basalt flows because they are commonly ponded in valleys.

A complicated series of emergences and submergences has followed due to shifts of sea level relative to the islands, resulting from isostatic adjustments and glacial shifts of sea level. The submergences that took place as a result of isostatic adjustments are directly related to the development of the volcanoes during the early stages of island building. However, the series of submergences and emergences of the islands brought about by glaciation during the middle and late Pleistocene are not related to the volcano development of the past era.

The erosion of deep valleys by streams on the older volcanoes began, in general, before isostatic submergence. Hence the valleys or these volcanoes have been submerged as much as 1,200 feet below present sea level. The submergence was gradual and thus allowed the aggradation of the valley floors and the coastal plains by terrestrial and marine sediments. The valleys were filled essentially with stream derived sediments, and the coastal plains were aggraded mostly of reef limestone and marine sediments of non-calcareous variety intercalated with sediments (Stearns and Macdonald, 1942).

The erosion and sedimentation of the islands during middle and late Pleistocene accompanied by glaciation followed an oscillatory pattern of emergence and submergence. This oscillation in sea level was believed to be contemporaneous with the well-known advance and withdrawals of the polar ice caps during these periods. In between these periods, and during the time when the islands were above sea level, valleys were cut and there was extensive soil formation. Evidences of these processes and those that took place during the emergence phase of the islands include the present soil formations and valleys, and the deposits of reefs materials during the various stands of the sea well above the present sea level.

With additional submergence and continuation of erosion and weathering, the Hawaiian Islands will ultimately be reduced to shoals and coral atolls like those of the leeward islands of the Hawaiian Archipelago (Cox, 1954a).

GROUND WATER HYDROLOGY OF THE HAWAIIAN ISLANDS

Ground water occurs in the Hawaiian Islands in a wide variety of conditions, most of which, however, may be considered as representing four major types (Figure 5).

1. Basal ground water floating on sea water in the lava aquifers, a part of which may occur under artesian conditions, but most of which occurs under water-table conditions;
2. Dike-impounded ground water;
3. Ground water perched in lava aquifers on interbedded ash or tuff, soil, or alluvial layers; and
4. Ground water in permeable sediments of coastal plains and valley fills.

The major fresh ground-water bodies of the Hawaiian Islands have heads of a few feet or tens of feet above sea level and exist essentially in hydrostatic equilibrium with sea water. To distinguish the water in these bodies from ground water at high level perched on ash and other perching members, or impounded by dikes, Meinzer (1930) applied to these bodies the term basal ground water, a term which has been used very commonly by hydrologists since. The bulk of the lava flows making up the Hawaiian Islands is porous and permeable far below sea level and, hence, saturated throughout with sea water except where the sea water is displaced by fresh water. The two European enunciators of the principle of hydrostatic balance of fresh water and sea water, now commonly referred to as the Ghyben-Herzberg principle, were Badon Ghyben who in 1887 utilized this knowledge in the prediction

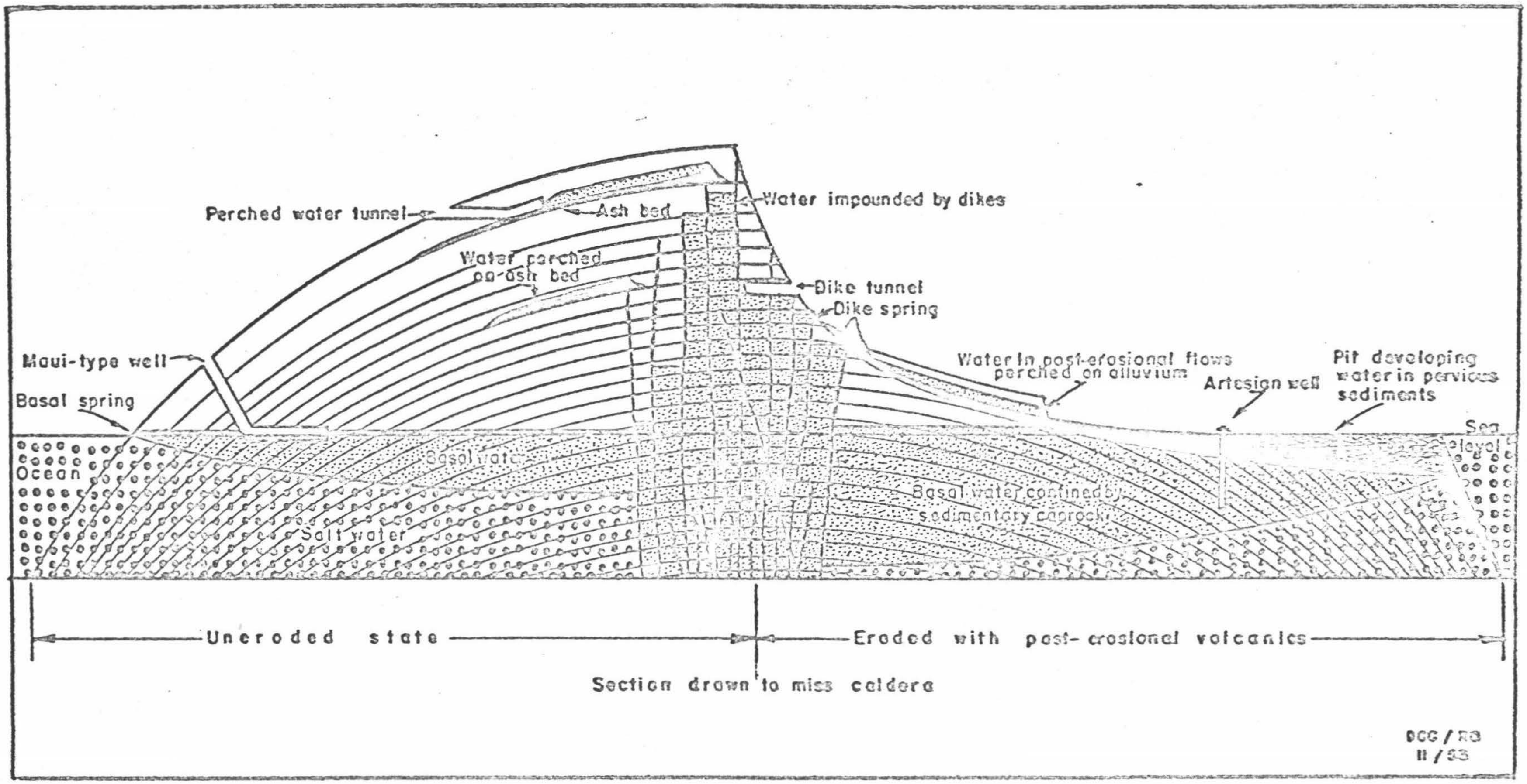

FIGURE 5. DIAGRAMMATIC CROSS-SECTION OF AN IDEALIZED HAWAIIAN VOLCANIC DOME SHOWING OCCURRENCE AND DEVELOPMENT OF GROUND WATER (FROM COX, 1954a)

of the results of drilling for water in the Netherlands, and Herzberg who in 1901 independently developed the principle and presented a better exposition of the idea based on the studies on the island of Norderney (Wentworth, 1939, Palmer, 1957). Andrews (1909) recognized independently, without advanced knowledge of the work done in Europe in ground-water studies, the principle of hydrostatic equilibrium in conjunction with his research on the structure of the southeastern portion of the island of Oahu. He was the first Hawaiian worker to work out mathematically the ratio of the depth to salt water to the height of the water table, treating the ratio as a function of the relative densities of the sea water and fresh water. In his Masters thesis, Andrews wrote:

> "The water-bearing lava rock is covered with a layer of clay, the product of decomposition of lava, which in turn, is covered with a stratum of coral rock, formed as a fringing reef, above which strata of coral and volcanic material alternate. The depth below sea level to which the retaining clay stratum would need to extend in order that fresh water in wells should be raised forty-two feet above sea level by the hydrostatic pressure of sea water of density 1.026, is 1614 feet, which is but a little deeper than the depths at which clay was found in the deeper wells."

The Ghyben-Herzberg principle under the assumptions of static conditions may be expressed in the form of the equation given below:

$$h_s = \frac{h_f}{p_s - p_f} p_f$$

In this equation, h_s is the distance to which the fresh water extends below sea level, h_f the height of the water table above sea level, p_f and p_s are the specific gravity of fresh and sea water respectively.

Hubbert (1940) indicated that the form may be applied validly and correctly only in the case of static conditions in the two bodies of water in contact. Hubbert recognized that the conditions in nature are dynamic and from this knowledge, he modified the static equilibrium theory of the Ghyben-Herzberg principle. From his modification, the actual depth to the sea water-fresh water interface (Figures 6,7) is found to be greater than that given by the Ghyben-Herzberg equation. The difference in depths to interface calculated by the Ghyben-Herzberg equation and by Hubbert's modification is small for flat gradients, but for steep gradients the difference may be large. Locally, steep ground-water gradients are encountered in the vicinities of basal springs and discharging wells.

Wentworth (1939), commenting on the non-applicability of the hydrostatic equilibrium equation on Oahu, presented the following evaluation:

> This equation (hydrostatic equilibrium equation) is a complete statement only if there is no movement of the water, which is not true at Honolulu. The lens-shape of the body of fresh ground water, where it is non-artesian, involves a slope seaward of the water table. This slope causes a seaward motion of the fresh water which would eventually level off the whole top of the lens, and thus eventually drain of all the fresh water, including the sub-sea level part of the lens, if no more rain water were added to its top. Static equilibrium does not prevail, because the slope of the water table cuases a constant spreading movement in a seaward direction, and because of irregularity of rainfall addition and loss by the incessant lateral movement. Hence the water table can never have the perfect adjustment to the exsiting pressure of sea water which is implied by the static equation. In short, as in many other complex natural systems, dynamic and static characteristics are combined.

Some of the more important governing factors determining the thickness of the fresh water lens include a) the densities of both the

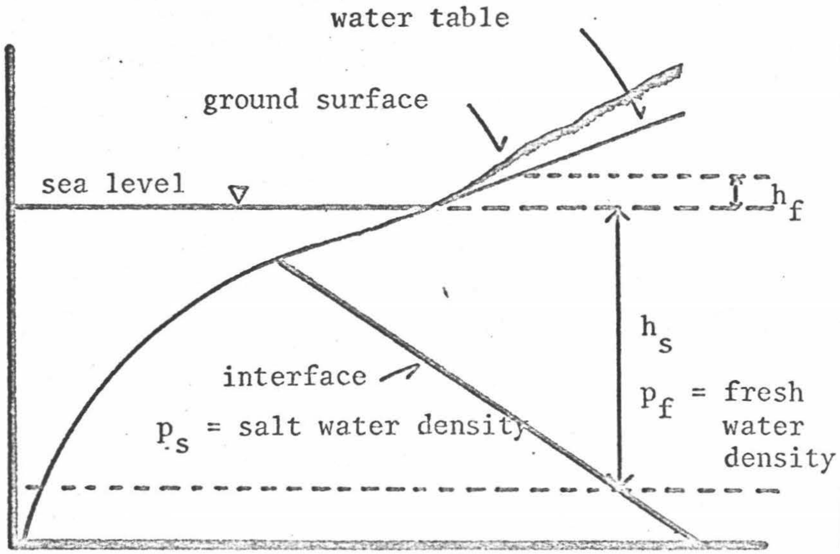

FIGURE 6. DEPTH TO SALT-FRESH WATER AT STATIC CONDITION (FROM TODD, 1959)

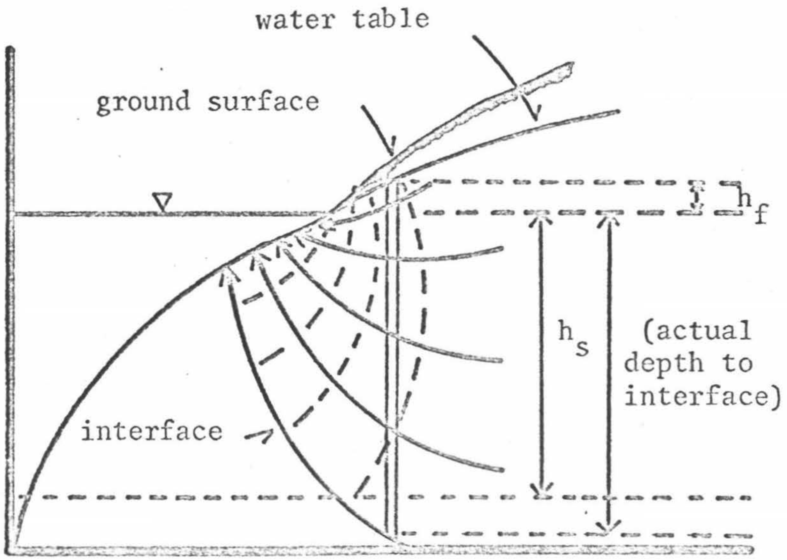

FIGURE 7. DEPTH TO SALT-FRESH WATER INTER- AT DYNAMIC CONDITION (FROM HUBBERT, 1940)

sea water and fresh water which in turn are affected by b) salt content of both waters as well as the c) temperatures of the two waters. The ratio of the difference between the two fluid densities, therefore, is not constant, due to the different factors and their variations with time and locations. Wentworth (1939), in an attempt to establish the practical application of the static equation on the Hawaiian Islands, based on density or specific gravity considerations of the fluids alone and without flow (in static conditions) found through studies of sea water samples around the islands that there was more variation in the density of the sea water from time to time than from place to place. He indicated that a more valid average of density value may be determined more accurately by sampling over a long period of time at a few carefully selected places, instead of sampling once or twice at many different places.

A density ratio of fresh water to sea water of 1/1.025 has been widely used in the islands in the estimation of the depth of the zone of transition and the thickness of the fresh water lens. The use of this ratio is perhaps largely due to its facility in computation of the hydrostatic equilibrium equation. When the ratio of 1/1.025 is used in the equation, the value of hs becomes $40h_f$, or for every foot of fresh water above sea level, the fresh water lens extends 40 times its height above sea level.

Unconfined Basal Ground Water

Free basal ground water or unconfined basal ground water, to distinguish it from confined or artesian basal ground water is that water that occurs on parts of the islands under a hydrogeologic environment where there is no restriction of ground-water movement in either horizontal or vertical direction and in which permeable rocks extend both above and below sea level (Figure 5, left portion). The water table gradient of the unconfined basal water on most of the islands is determined by the rate of recharge and permeability of the aquifer. Stearns and Vaksvik (1935) found that in some locations on Oahu, the hydraulic gradient is less than 0.5 feet to the mile. On parts of Maui Isthmus, at a distance of a quarter mile from the coast, the head is about one foot (Cox, 1969, per. comm.), and at a distance of 3 miles inland from the coast in a mountainward direction the head is about 5 feet (Cox, 1954a). On the Big Island, in the vicinity of Hilo and Hamakua, at a distance of one half mile from the coast, Cox (1969, per. comm.) gave a figure of 2-3 feet of head. In some places on Oahu, the hydraulic gradient of the unconfined basal water may even approach 3 feet to the mile (Stearns and Vaksvik, 1935).

It is evident from the above examples that there is no single value to characterize the hydraulic gradient of the unconfined water bodies. In general, however, in the areas where the pervious lava flows containing the basal water extends to the coast without the caprock directly above it, the fresh-water head increases on the order of one foot to the mile from the coast (Cox, 1954a).

Although, in general, the rate of recharge of ground water in the Hawaiian Islands is great, the water table is nearly flat or attains a low dome shape (Meinzer, 1930, Wentworth, 1951) because of the exceedingly permeable water bearing rocks. The thickness of the lens is a function of the height of the water table above sea level and the specific gravities of the fresh and sea water as explicitly pointed out by the hydrostatic equilibrium equation. Therefore, the fresh water lens thickens inland as the water table increases in height.

In general, dike complexes are commonly found on most of the islands, and the basal water underlying an island does not penetrate the dikes, but rather terminates against them (Figure 5). The height of the unconfined basal ground-water table near a dike complex may be only a few feet higher than along the shore (Stearns, Vaksvik, 1935).

Confined Basal Ground Water or Artesian Water

To distinguish the confined or artesian basal water from the unconfined basal water, its occurrence on the Hawaiian Islands has been attributed (Stearns and Macdonald, 1942; Wentworth, 1951; Cox, 1954; and Visher and Mink, 1964) to the presence of a caprock, a poorly permeable layer that is found along the coast which exercises a retarding effect on the free escape of the fresh water into the sea (Figure 5, right portion). The restriction by the caprock causes the head under and immediately behind the caprock to build up to several tens of feet, and in some cases higher than the surface of the ground resulting in the development of artesian conditions. A lower confining layer, an essential part of the usual continental type of artesian system has not been observed on any of the Hawaiian Islands.

The caprock in general is composed of marine and alluvial sediments. The first general description of the character of the caprock of the Honolulu artesian basin was probably given by Judge McCully in 1882 (Thrums Annual, 1908, p. 46) from well borings. Subsequent investigations by Andrews (1908), McCombs (1927), Stearns and Macdonald (1942), and Wentworth (1951), and more recently investigations by the Hawaii Institute of Geophysics for stratigraphic studies (Stearns and Chamberlain, 1967), paleontologic studies by Resig (1969), and electric well logging by Cox and Lao (1967) have greatly enlarged the knowledge of the nature and composition of the caprock in the Hawaiian Islands, Oahu in particular.

In greater detail, the caprock is commonly described as consisting of intercalations of clay, coral materials, mud, sand, gravel, volcanic ash, soil, sandstone, shales, and conglomerates (Stearns and Macdonald, 1942). As a result of compression of the finer grained units of the caprock materials by overlying rocks, the effect is one of low bulk permeability or relative imperviousness in comparison to the basaltic aquifer that underlie or may overlie the caprock.

Because of the effect of retardation by the caprock, the ground water of the confined basal water is impounded and, hence, results in the build up of head. This impoundment will cause an increase in pressure on the caprock and will eventually force the flow of ground water through openings such as springs over the edge of the caprock, and through deep submarine springs under the caprock "or the water will further back up higher and deeper in the bedrock until the pressure on leaks through the cap is sufficiently high to make the leakage balance the inflow," (Cox, 1954a). In the Honolulu region, Wentworth (1951) observed that the damming of the outflow by the caprock originally caused the basal water to pile up in one area to 42 feet above sea level. As a result, the fresh water lens was theoretically more than 1600 feet in thickness.

Where tongues of caprock sediments extend some distance inland into drowned valleys, so as to extend below sea level and below the unconfined water table, the tongues act as submerged weirs (Wentworth, 1951) on flow parallel to the coast as observed in the Honolulu-Pearl Harbor area. This effect causes the basal water levels on the two sides of the tongue to be effectively and persistently different, with a differential of between 1 and 10 feet or more at times.

Dike-impounded Ground Water

Although in much of the island areas the infiltrating water percolates directly to the basal ground-water bodies, there are some areas where geologic structures prevent this direct movement resulting in the formation of high-level ground-water bodies.

Among the high-level ground-water bodies, dike-impounded ground-water bodies are generally the most important because of the greater discharge available from such bodies at particular localities. The confinement of the water between dikes may be attributed to two important factors: 1) the imperviousness of the dikes themselves, and 2) their intersections with each other in the horizontal and vertical directions. Although parallel dikes would not fully impound the water, sub-parallel dikes would and do. The Hawaiian dikes are actually sub-parallel and they impound water in such a fashion. In the vertical, the effect is due both to sub-parallelism and to increase in number of dikes with depth (Cox, 1969, per. comm.).

The water percolating downward from the ground surface is accumulated between the dikes and may eventually overflow the dike compartments or issue from leaks through the dikes. The level of the water table in the dike compartment is determined by the amount of recharge, either from direct rainfall percolation or indirectly from issuing springs above it, and by the rate of discharge through leaks from the dike compartment. When the recharge is equal to the discharge from the dike compartment, the water table level is essentially constant.

Except for very short stream courses fed by basal springs near sea level, the most stable streams in the islands are those which are supplied by dikes (Cox, 1954a). Streams cutting through the dike complex generally have much more reliable flows than streams whose discharges are dependent mostly on surface runoffs. In general, springs issuing from dike compartments are more reliable than perched water springs because of the greater storage capacity of the dike compartments (Cox, 1954a, 1954b).

Ground Water Perched in Lavas

Ground water may also occur at high levels where it is perched on ash, tuff, soil, and alluvium interbedded with lava flows. The perching materials are, in general, relatively impervious in comparison with the lava flows. Such ground water bodies may be revealed by springs issuing from the outcrops of the impervious materials, most commonly where they are exposed by erosion.

The prevalence of perching members varies in a single volcanic formation and from one volcanic formation to another. There are also variations in thickness of these materials within a single formation and from one formation to another.

Weathered ash beds are the most common perching members. The accelerated rate of weathering of the ash beds probably accounts for the great frequency with which soil derived from ash serve as perching members than soils formed by the weathering of lavas. In terms of effectiveness as perching members, however, there is no significant difference between the two kinds of soil.

Younger alluvial deposits are, in general, of minor importance as aquifers owing to their limited areal distribution. In valley fills, the gravels in the younger alluvium may be water-bearing locally such as has been found in Hanapepe Valley in Kauai, and in the Iao Valley in West Maui (Cox, 1969, per. comm.).

In some areas, where a section of a lava flow is massive, water may be perched on this massive portion of the lava flow and may be important locally. Offshoots of dikes called sills which follow the bedding of the lava flows may also perch water (Cox, 1954a).

Another type of ground water perched in lavas and whose occurrence on Oahu has been described by Wentworth (1951) is the water that is perched by alluvium in the intra-valley lava flows. Wentworth referred to this water as a portion of the caprock water. However, because of its occurrence in the lava flows and its relatively distant location from the main caprock area, it should probably be more properly grouped under the water perched in lava flows. He found this particular ground water to be perched above the main basal water on alluvium and detritus. In some valleys, such as Nuuanu, he found that the later valley fills, consisting of late volcanic formations of lava flows, ash, and cinders constitutes the aquifer above the perching alluvium. He indicated further that in few places where there is a tight impervious layer above the water table, a slight artesian pressure may develop. In Kalihi Valley, he observed that the maximum head of this water exceeded 60 feet above ground surface. The valley-fill water is observed to respond very promptly with increased rainfall (Wentworth, 1951).

Ground Water in the Coastal Plains

The water in the coastal plains is described by Wentworth (1951) as caprock water. Although this water maintains a rather poor hydraulic communication with the basaltic bedrock aquifer, it may derive its water in part from the leakage from the bedrock aquifer. It may also derive part of its water from stream effluent, return irrigation water, water from the post-erosional volcanics as in

Honolulu, and from the percolation of rainfall, the latter perhaps being the least important source of recharge. It is believed that in areas close to the shore where the caprock water occurs, that the occurrence of the caprock water is found in the porous and permeable coral materials of the caprock. The water in the coral materials is believed to exist in a dynamic balance with the sea water and may extend downward in accordance with the Ghyben-Herzberg principle (Wentworth, 1951). However, further inland into the valleys, it is believed that no Herzberg relation between this water and sea water exists. The dynamic balance of the caprock water with sea water near the coast is believed to be restricted to that part of the caprock water occurring in the coral materials and not including water that may occur within the muds, silts, marls, and other impermeable materials of the caprock (Cox, 1969, per. comm.). In general, the water in the caprock near the shore is probably somewhat brackish and not potable. This condition is believed to be strongly influenced by the thin lens in the coral materials. The caprock further inland, however, may be comparatively less saline.

Ground-Water Resources in the Islands

The ground water resources in the islands are briefly summarized below from detailed investigations of ground water resources on the islands by Stearns (1939, 1940), Stearns and Vaksvik (1935), Stearns and Macdonald (1942, 1947), Wentworth (1951), Palmer (1946), Cox (1954a, 1954b), Macdonald, Davis, and Cox (1960) and others.

KAUAI. Basal water occurs on Kauai in both pre-erosional and post-erosional lavas. The latter are of greater extent on Kauai than on the other islands. Compared with the major basaltic aquifers found elsewhere in the other islands, the lavas of the post-erosional volcanics are low in permeability and the total basal ground-water development on Kauai is restricted in comparison, with that, for example, on Oahu. A part of the basal ground water is artesian. Water perched in the post-erosional volcanics is also known to occur and has been developed to some extent in Kauai. Water from dike compartments supplying many streams has also been slightly developed.

NIIHAU. Ground-water knowledge on Niihau is limited. The ground-water conditions in the dike complex are unknown, and because of the generally low rainfall on Niihau, it is doubtful that any significant quantity of dike water is available for development. The basal water body is generally thin and generally yields brackish water.

OAHU. On Oahu, the basal water occurrence is of essentially two major forms; as unconfined and as confined or artesian. Confined basal water occurs on the coastal plains in which the confining structure is the caprock. The water is artesian in the makai areas and non-artesian or unconfined toward the mauka areas. Dike water occurs on both the Koolau and Waianae volcanoes, but predominantly on the Koolaus where rainfall is more abundant. Perched water, mainly found on post-erosional deposits, is also a common ground-water occurrence, and is significantly developed locally. Other ground-water occurrences which are generally of minor importance include water perched in impervious materials interbedded in the lava flows, and water in the coral material of the coastal plains.

MAUI. On Maui, ground-water occurrences may be considered in terms of the three major physiographic areas; West Maui, East Maui, and the Isthmus.

On West Maui, extensive water impounded by dikes is known to occur. Water for domestic use is developed by tunnels. There is extensive basal water, mostly unconfined. Confined basal water is found only on limited areas of West Maui, as elsewhere there is no appreciable caprock.

On East Maui, the dikes are deeply buried and therefore very little knowledge of the dike-impounded water is available. Perched water occurs extensively on the northern slopes of Haleakala, and locally, perched artesian water is encountered.

Unconfined basal water occurs extensively at the coast and in the Isthmus proper. The lens, however, are generally thin, and the water is too saline for domestic needs. However, the water is extensively developed for irrigation uses.

LANAI. On Lanai, dike water is the major domestic water source. The basal water on Lanai is brackish because of the thin lens. Other water occurrences are known such as water perched on soils and water in the sediments but they are of minor importance.

MOLOKAI. Molokai's ground-water resources generally include three types. These are the basal, perched, and the dike-impounded ground water. Most of the occurrence of ground water on Molokai is on East Molokai where the hydrologic and geologic conditions are the more favorable. Ground-water developments, which include tunnels driven through dike complexes, tunnels driven in andesite of the upper member of the East Molokai volcanic series developing water perched by ash beds, and basal water development by wells, have been limited, in general, to East Molokai. Basal springs are found along the southern coast of East Molokai and further inland in sediments of the coastal plains, in addition to springs issuing from the ground water of the dike complex and ground water perched by the following perching members: dense lava beds, decomposed aa clinker, soil, and palagonitized ash. The latter perching member is the most common and most widely distributed in East Molokai. Basal springs have been observed on the southern shore of West Molokai, but the water is very brackish. Also, the dike complex of West Molokai, in general, appears to be much less developed in comparison to the dike complex of East Molokai. Where dike water is known to occur, it is generally brackish also.

HAWAII. On the island of Hawaii, three types of ground water generally occur; unconfined basal water, dike-impounded water, and perched water.

All of the basal water occurrence on Hawaii is unconfined. The hydraulic gradients are generally low. On the windward side, basal water is plentiful and generally fresh. On the leeward side, however, the lens is thin, and the water is consequently brackish.

Dike complexes in Mauna Kea, Hualalai, Mauna Loa, and Kilauea are believed to be saturated with water but the dikes are very deeply buried and this limits practical and economical water development. In Kohala, however, where the dikes are closer to the surface, water has been developed for domestic uses. The water in the Pahala area is also probably confined by dikes.

Perched water is an important source of ground water on the windward side of Mauna Kea, on the northeast and southeast sides of Mauna Loa, and on the windward side of Kohala.

SAFE YIELD ESTIMATION IN HAWAII

Kunesh

Although the safe yields of various ground-water aquifers in Hawaii were undoubtedly estimated implicitly in many earlier studies, the first explicit estimates may have been those made for the Honolulu aquifers by Kunesh in 1929. Kunesh estimated the safe yield by two methods. In the first, the method of zero net ground-water fluctuation (Todd, 1959), Kunesh considered the storage in the aquifers equal at times when their heads were equal. The total draft for periods between such times, he considered, must then equal the total recharge (neglecting underground discharge) for the same periods (Kunesh, 1929, plate 13). Kunesh's second method was simply a straight-forward solution of the hydrologic equation, considering it on a mean annual basis. The recharge was to be determined as:

Recharge = Precipitation - Evapotranspiration - Surface runoff

Kunesh obtained estimates of 41 mgd for the Honolulu aquifer by the first method, and 42 mgd by the second method, a check he considered indicated considerable reliability, although he was careful to indicate that his conclusions were preliminary and merely indicated "possibilities of definite conclusions".

Hoyt

In 1934, Hoyt proposed a method for the estimation of recharge of the Honolulu aquifers which has subsequently been identified as the method of zero net ground-water fluctuation (Todd, 1959) identical to the first method used by Kunesh in 1924.

Hoyt based his approach to the estimation of recharge on the Honolulu aquifers on the ground-water hydrologic equation, and expressed this idea when he said that "the concept that the Ghyben-Herzberg lens sector in each artesian area is a container whose content of water at any given time is indicated by the artesian head and whose capacity to supply to wells is the difference between intake from rainfall and loss by leakage to the ocean, modified by gains from, or losses to, adjacent areas and by gains, or losses, in its own storage status" (Wentworth, 1951). The estimation of safe yield was modified by the recognition that additional inflow might be obtained by the 1) increase of the hydraulic gradient toward Honolulu aquifer, as suggested by Kunesh (1935), or 2) reduction of the hydraulic gradient toward the sea, as suggested by Stearns (1935). Wentworth later (1951) further expanded the concept by his recognition that "the lowering of head would tend to decrease flow to any areas of lower head, such as the ocean or adjacent ground-water areas, and would tend to increase flow to the Honolulu area from any areas of higher head, such as adjacent parts of Oahu." He further indicated that adjacent areas should include the artesian structure below sea level, and that any net head lowering would result in a net gain in storage through increase in inflow from adjacent aquifers and other inflow or through decrease of natural outflow from aquifer or aquifers, or a combination of both effects.

The general ground-water hydrologic inventory equation for the estimation of the recharge to the aquifers in the Honolulu isopiestic areas as conceived by Hoyt is:

$$R = D + C_o h^a + C_1(h - h_1)^b + C_2 (h - h_2)^b + (A + C_3 h) \Delta h$$

where R = recharge to the aquifer,

D = draft on the aquifer,

h = head in the artesian area in question,

h_1, h_2 = heads in the artesian areas adjacent to the artesian area in question,

A = area of cross-section of flow

Δh = change in head during period of observation,

C_o, C_1, C_2 = constants to be determined by simultaneous solution of equations from several periods of observation,

C_3 = constant of proportionality related to change in head in the estimation of storage change,

$a = \frac{n + 1}{n}$, $b = 1/n$, where n is determined from the drawdown in the well equation, $H = CQ^n$, where H = drawdown, Q = draft, C = constant determined by well size, and n = constant related to flow in the well, equalling 1 when the flow is laminar and greater than 1 when flow is turbulent.

With the assumption of no net change in the head ($\Delta h = 0$), and hence, constant-storage, during the base period selected, the equation reduces to:

$$R = D + C_o h^a + C_1(h - h_1)^b + C_2 (h - h_2)^b$$

It was found upon inserting the values of the items in the equation that the results obtained were unsatisfactory, the error being due to inconsistent values of the supposed constants.

Wentworth (1951) attributed the failure of this attempt to determine the recharge of the aquifer in the isopiestic zones partly to the disregard of the effect of rainfall percolation during the time of the test on the overall recharge equation. Rainfall recharge was hypothetically eliminated in the above method by making the tests during periods of fairly constant rainfall. It was assumed that during the test period, no net change in head would take place. Wentworth (1951) however, believed that variations in rainfall from 5 to 6 months previous to the test period, might significantly affect the head during the period of the test.

A second factor which Wentworth believed to have contributed to the erroneous results of the calculation of recharge by Hoyt was confusion between the essentially turbulent flow regime in wells and the essentially laminar flow regime in the aquifer. Apparently distrusting the applicability of the Darcy law to Hawaiian aquifers, Hoyt proposed to allow for either a linear or non linear relationship between flow and differential head in the aquifer, and by introducing the coefficient n which could be either equal to one (laminar) or greater than one (turbulent), but then proposed to use well test data, as indicated above, to determine the coefficient.

Since the well test data available involved drawdowns measured at the tops of the casings rather than in the aquifer, they combined the effects of turbulent flow in the casings with laminar flow in the aquifer, indicating values of n greater than one, to which were then erroneously applied to the flows through the aquifer as a whole.

The most important source of error, Wentworth contended, was due to "non-completed hydraulic flow". He considered that the transfer of water from bottom storage could not be expected to take place at the same time that the head changed as postulated in the test, but that there must be a considerable lag in achieving equilibrium in the ground-water body. Wentworth showed that equilibrium of the ground-water body can be reached only after a certain period of time following the drop in head, and that changes in the "position of the bottom of the Ghyben-Herzberg lens, because of the large amounts of water, must lag greatly behind the causal changes at the top", and that "similar lags must affect the movement of water from or to an adjacent area of different head". Although a change in head in a given area may indicate roughly a change in the quantity of water above sea level, Wentworth (1951) indicated that it should not be taken as a true measure of the amount of water in the lens because, there is no basis in the assumption that equilibrium in the ground-water has been reached.

Analysis of the Hydrologic Equation by Statistical Methods: Wentworth

Two fundamentally important innovations that Wentworth (1951) made from the original postulate given by Hoyt in the evaluation of recharge of the Honolulu aquifers were 1) consideration of the lags in the response of head due to rainfall, and 2) consideration of the lags in the response of the bottom storage to changes in head. These changes were based on Wentworth's belief that following the rainfall season, the artesian and basal heads responded by increasing, and conversely, following the dry season, the head falls. One of the main objectives of the evaluation, then, was to find the amount of rise or fall in head corresponding to any rainfall increase or decrease. A further change proposed was the recognition that an increase in draft during steady rainfall season would reduce the head below its former level and would then remain steady under increased draft. Wentworth retained the original idea of Hoyt (1934), Kunesh (1935), and Stearns (1935) that, at a lower head, less leakage is permitted to the ocean and to adjacent areas of lower head, and more inflow from adjacent areas of higher heads, and that the net gain in amount of water due to the above conditions was that amount contributing to the increase in draft.

Recognizing the inadequacies of absolute estimates of recharge from measurements of precipitation less evapotranspiration and runoff, Wentworth adopted a scheme of analysis involving the correlation of head changes with relative changes in rainfall, or rather a function of past rainfall, using statistical tests to determine the exact functional relation providing the best fit.

The form of the multiple correlation equation used by Wentworth is given below:

$$1) \qquad Q = C_1 + C_2\, f(R) - C_3\, H$$

where Q is the total measured draft, H is the head, and f(R) is a function of past rainfall serving as an "index of infiltration". The term, C_3H, represents loss through leakage, which is proportional to the first power of the head. The infiltration function used by Wentworth took the form:

$$f(R)_m = (1 - i)\ f(R)_{m-1} + I_m$$

$$= (1 - i)I_m + (1 - i)^2 I_{m-1} + (1 - i)^3 I_{(m-2)} + \ldots (1 - i)^{n+1} I_{(m-n)}$$

where $f(R)_m$ = infiltration function for month m,

$f(R)_{m-1}$ = infiltration function for month (m - 1),

I_m = $100\ (P_m/\bar{p})^s - 100$ = a month's rainfall index,

P_m = monthly precipitation on the recharge area,

$\bar{p}$ = mean monthly precipitation on the recharge area

s = a power to be determined

For a period of mean precipitation, $\bar{p} = P_m$ and $I_m = 0$. If this continued indefinitely, f(R) would also equal zero. In this case

2) $$D = C_1 - C_3 H$$

from which it may be seen that C_1 represents recharge associated with mean precipitation.

It is evident that by use of the function of infiltration with an inherent allowance for lags, Wentworth hoped to allow for changes in storage resulting from, but lagging behind, changes in the rate of recharge. He did not allow similarly, however, for lagging changes in storage resulting from changes in draft. Using values for the three constants derived from least squares analysis, he found that the "presumptive draft" indicated by his inventory equation over some extensive periods was greater than the actual draft, and over other periods the "presumptive draft" was less than the actual draft. He attributed the differences as probably due to changes in storage.

Caskey's Analysis of the Mass Balance Equations

In a study on the recharge of the Waikapu aquifer on the slope of West Maui (Caskey, 1968, Master's Thesis) computed the retained inflow into the Waikapu aquifer from all possible sources of water by the equation of the hydrologic mass balance equations applied over the high level aquifers and the basal aquifer of the slope of West Maui.

In his computation of the recharge, Caskey separately evaluated the two mass balance equations for the two types of ground-water occurrences and then combined the computed inflows to obtain the net recharge of the basal aquifer. His study differed from the studies of Hoyt and Wentworth in that the complex influence of the Ghyben-Herzberg lens and its associated problems (lowering of head, changes in bottom storage, rainfall influence over the period of analysis, etc.) did not enter into his calculations.

By making the assumption that, over a long period of time, the net-change in storage for each of the ground-water aquifer is zero, Caskey utilized the general equations below to compute the net recharge. The hydrologic mass balance equation for the assumption made above is:

1) Inflow - Outflow = Zero

For the high level aquifers, the hydrologic mass balance equations are:

2) $I_h = P_h - E_h - S_{oh}$ and

3) $O_h = S_{sh} + D_h + G_h$

where I_h is the inflow into the high level aquifers, P_h is the precipitation over the high level aquifers, E_h is evapotranspiration over the high level aquifers, S_{oh} is overland flow from high level aquifers, O_h is the outflow from the high level aquifers, S_{sh} is the spring discharges from the dike compartments, D_h is the draft on the high level aquifers, and G_h is the ground-water discharge from the high level aquifers. The draft (D_h) on the high level aquifers on the slope of West Maui was zero for the period of his analysis so that the equation could be transposed to provide its net recharge to the basal aquifer from the high level aquifers as:

4) $$G_h = P_h - E_h - S_{oh} - S_{sh}$$

Using the same procedure as above for the evaluation of equations for the basal aquifer, Caskey derived the equations below as representing the inflow and outflow parameters:

5) $$I_b = G_h + P_b + Ir_b - E_b \quad \text{and}$$

6) $$O_b = G_b + D_b$$

The items in the above equations are as defined previously except for differences in their subscripts plus the addition of irrigation return water (Ir_b) and ground-water discharge from the basal aquifer (G_b). Equating these (equations 5 and 6), and by substituting the value of the ground-water discharge, G_h from equation (4), Caskey obtained the value for the natural ground-water discharge from the basal aquifer by the equation below:

7) $$G_b = P_{h+b} - E_{h+b} - S_{oh + sh} + Ir_b - D_b$$

From measurements or estimates of the precipitation over the whole area (P_{h+b}), the evapotranspiration over the whole area (E_{h+b}), the total stream discharge (S_{oh+sh}), the irrigation return water (Ir_b), and the basal ground-water draft (D_b), an estimate of the basal ground-water discharge could be obtained from equation (7) without knowing precisely the location of the boundary between the high level and basal ground-water bodies.

Safe Yield Estimation by Visher and Mink

In their study of the ground-water resources of southern Oahu, Visher and Mink (1964) investigated the relationships between rainfall, pumpage, head, and salinity particularly in the Pearl Harbor ground-water body. Although they demonstrated that progressive increases in salinity were related to the development of draft, and particularly intermittent draft, they concluded that the overall rate of draft, which had remained essentially constant over 40 years did not exceed the "sustained yield" by which they appeared to have meant, at least approximately, the safe yield under the explicit assumption of no change in average recharge from tributary ground-water bodies. Implicitly, they assumed also that there would be no change in recharge from recharge from irrigation return or possible artificial recharge.

They pointed out that during this period, when the average draft somewhat exceeded 160 mgd, the average coastal spring discharge was about 70 mgd, and concluded that further development could be made equal to the minimum flow of the springs. The total, amounting to something in excess of 200 mgd, could then be regarded as safe yield, although they did not use this terminology.

It is apparent that this estimate was based, in addition to the assumption concerning recharge already noted, on the assumption that there were no significant concealed and unmeasurable spring discharges, that there was progressive change in storage over the 40-year period, that any fluctuation in recharge could be compensated by reversible changes in storage, and that no progressive increases in salinity would occur if the natural spring discharge were reduced to the difference between the recent past average and the recent past minimum. In essence, their analysis was based entirely on measurements of discharge, without requiring estimation of recharge or the details of short-term storage changes.

DATA NETWORKS FOR GROUND-WATER INVENTORY ON OAHU AND MOLOKAI

The networks for ground-water inventory on the islands of Oahu and Molokai will now be described and analyzed in relation to the principles of ground-water network design and the needs for ground-water data for safe yield investigation in Hawaii.

The major reasons for choosing Oahu as one of the examples are: 1) The extensiveness of Oahu's hydrologic data network, although it is by no means necessarily adequate, 2) the complexity of Oahu's hydrology, especially its basal ground-water hydrology, and 3) the extensive development of its water resources, especially ground-water.

The choice of Molokai to characterize a contrasting pattern is based on: 1) The relative scarcity of documented hydrologic data, although this scarcity may not necessarily exist in comparison to needs, 2) the relative simplicity of Molokai's basal ground-water hydrology, and 3) the limited development of its water resources.

Precipitation Networks

ON OAHU. The distribution of recording and non-recording rain gages on the island of Oahu is shown by figures 8 and 9. Of the total of 276 rain gages on Oahu, 49 are recording gages, 55 are non-recording gages read daily, and 172 are gages read less frequently. Of the 172, 84 are read after each rainfall, 28 are read weekly, 54 are read monthly, and 6 are read at irregular intervals. A total of 214 additional former rain gage stations has been discontinued altogether.

On its 602 square mile area, Oahu has an average active rain gage density of 46 gages per 100 square miles, a figure that appears to be

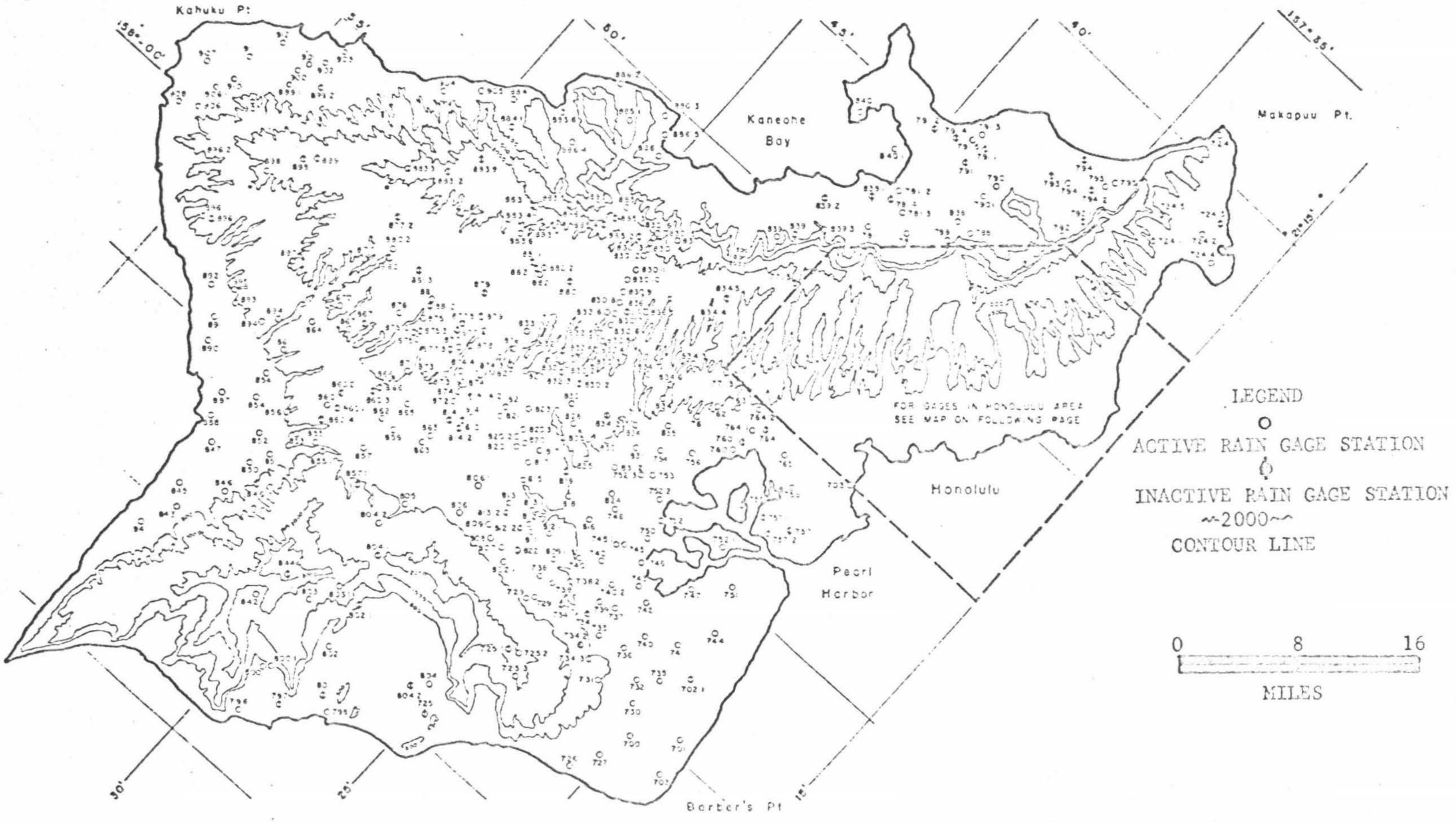

FIGURE 8. PRECIPITATION NETWORK ON OAHU
(FROM HAWAII WATER AUTHORITY, 1959a)

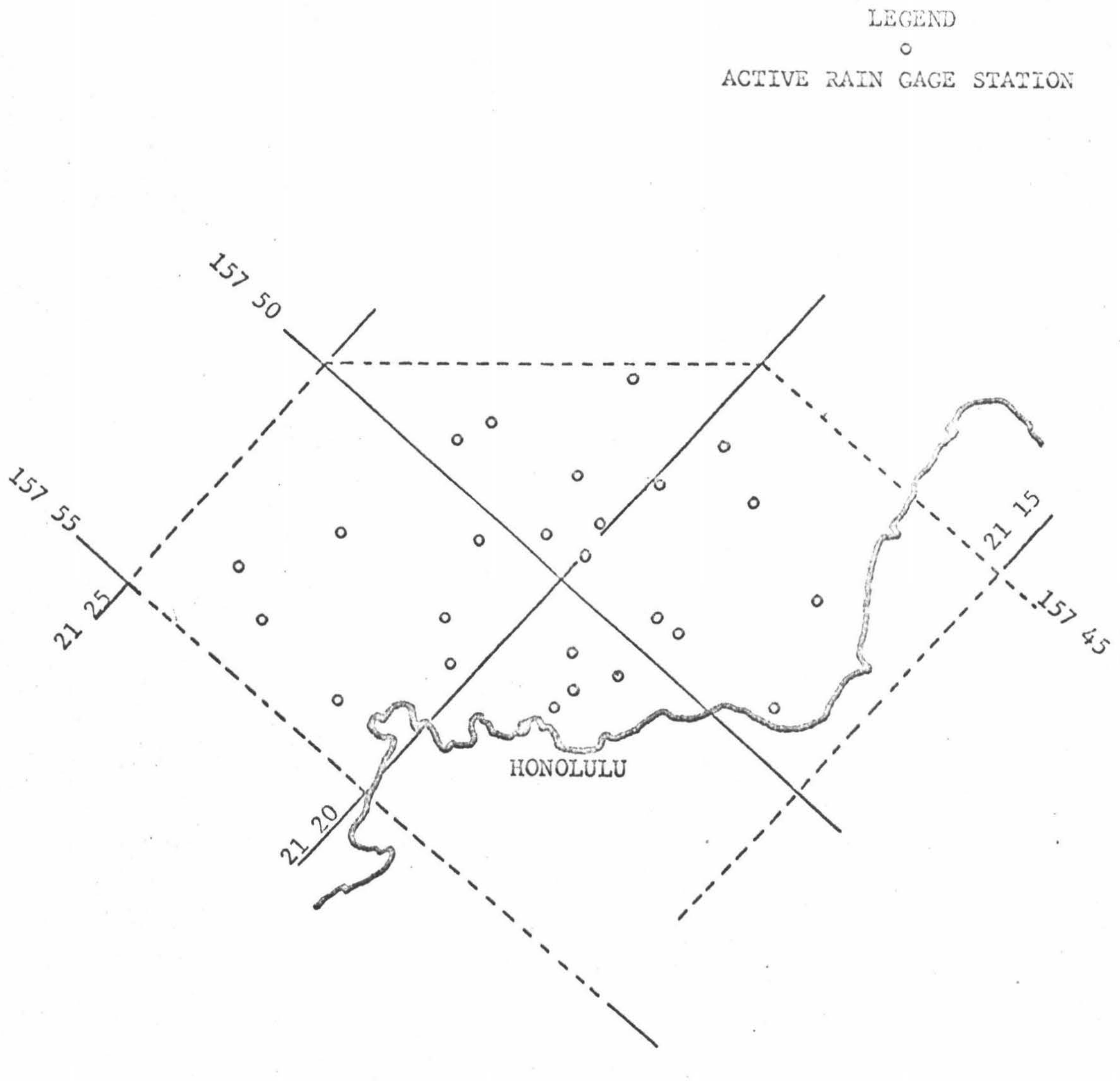

FIGURE 9. RAIN GAGE STATIONS IN HONOLULU AREA, OAHU (OPERATING IN 1966) (FROM WU, 1967).

extremely high in comparison to the United States mainland average of 0.4 gage per 100 square miles.

ADEQUACY ON OAHU. In the plantation areas of Central Oahu, it is evident from the map that the distribution of gages is relatively dense and uniform. That portion of the Oahu network may be considered adequate even for purposes of water measurements to determine needs for irrigation, and more than adequate for hydrologic inventory purposes. Southern Oahu, where the bulk of domestic water sources are exploited is comparatively densely gaged, and in general, may be considered to be adequately gaged also. However, a large portion of the higher areas in the Koolau and Waianae mountain ranges and most of the eastern and a large part of the western areas appear to be inadequately gaged.

With particular regard to hydrologic inventory needs, the following additional points may be made:

1) Precipitation gages are lacking on most of the dike-complex areas where precipitation gradients are greatest, especially on the recharge areas of the Koolaus.

2) Additional precipitation gages appear to be needed from the palis of the Koolaus toward the coast along most of the eastern portion of Oahu where precipitation gradients are also relatively high as indicated by the isohyetal map of figure 10.

3) The northern and western portions of Oahu, although the precipitation gradients are low in comparison to most of the eastern section, would also require additional gages in order to obtain better estimates of precipitation values on these relatively dry areas.

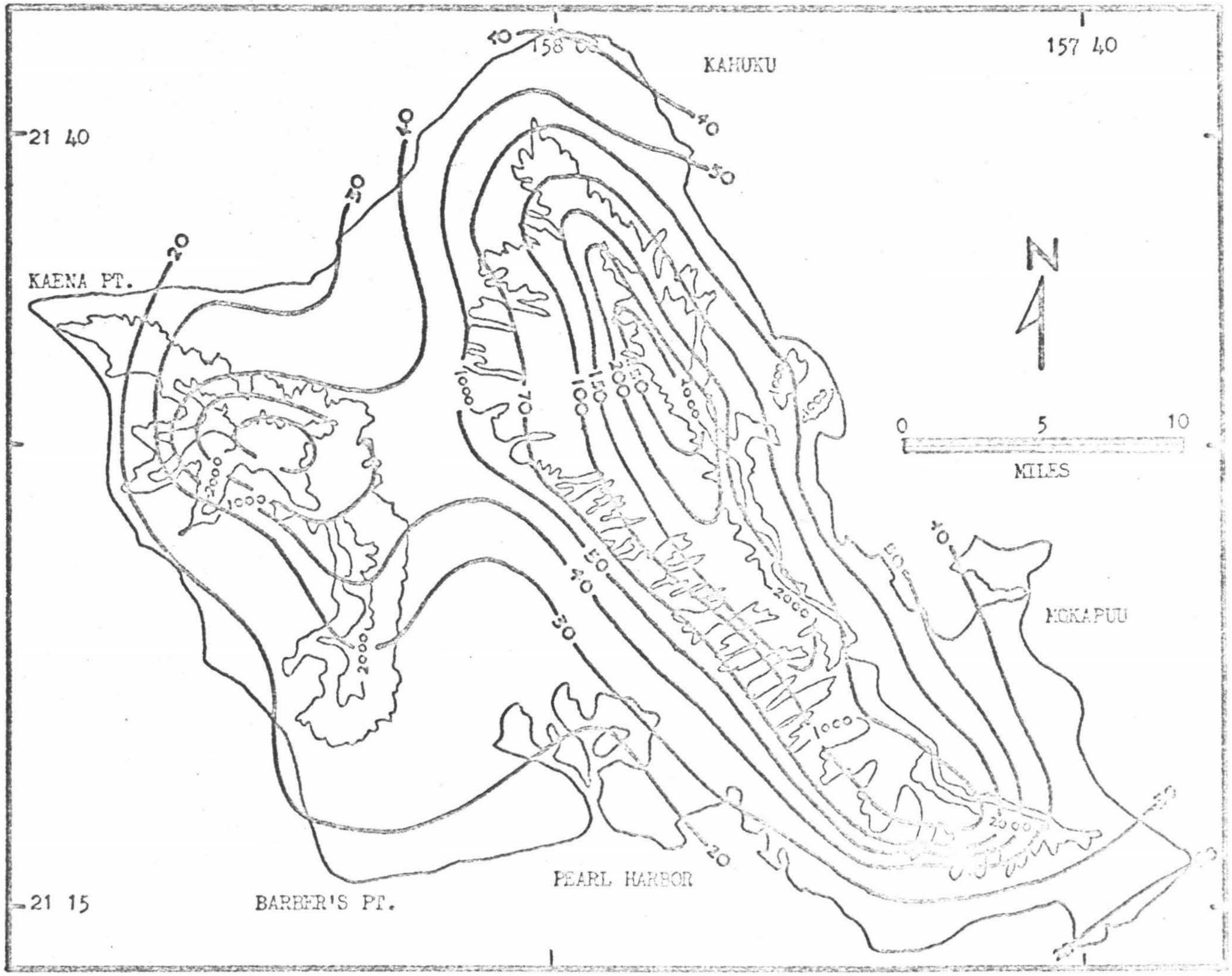

FIGURE 10. MEDIAN ANNUAL RAINFALL ON THE ISLAND OF OAHU (FROM HAWAII WATER AUTHORITY, 1959b).

4) In areas such as the palis, although cloud drop impingement, occurring at above cloud base level of approximately 2,500 feet (Ekern, 1964), has an appreciable influence on precipitation, the precipitation values indicated by conventional rain gages do not include this component of precipitation. The absence of precipitation gages in these areas is primarily due to the inability to measure such effect by rain gages, and secondly because of the difficulty of installing gages in these areas due to their inaccessibility. A further difficulty with regards to precipitation measurement by conventional rain gage on the palis may be encountered because of the upward trajectory of raindrops due to wind effects. The raindrops under the above condition will probably not be recorded by a vertically oriented rain gage so that the overall effect on measured precipitation would be less than the actual due to such effects (Caskey, 1968 Master's Thesis). Caskey observed that the non-gaged precipitation may represent a significant fraction of total precipitation in an area on West Maui similar to that on the windward slope of the Koolaus.

ON MOLOKAI. Of the active precipitation gages on Molokai, 39 are distributed fairly uniformly over Central Molokai, 25 on West Molokai and only 8 on the windward and leeward sides of East Molokai. Of the discontinued gages, 11 were on Central Molokai, and 7 are on East Molokai. The average active rain gage density over the 259 square miles of Molokai is about 27 per 100 square miles. Precipitation stations on Molokai are shown by figure 11.

ADEQUACY ON MOLOKAI. If, as mentioned earlier, Oahu is to be used as a base for comparison of the adequacy of the networks on Molokai, it

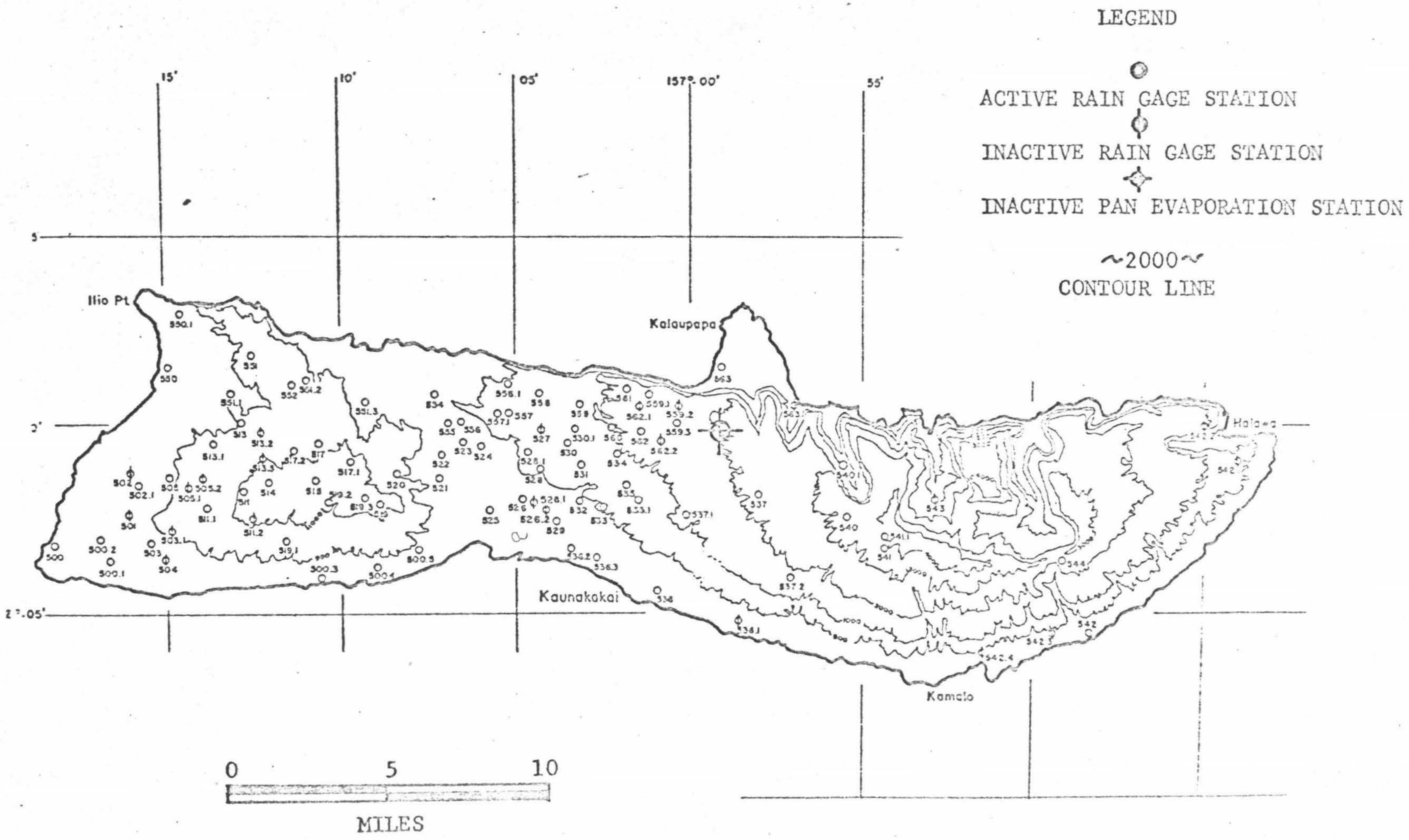

FIGURE 11. PRECIPITATION NETWORK ON MOLOKAI (FROM HAWAII WATER AUTHORITY, 1959a).

is clear from the gage densities of the two islands that the network on Molokai is just over half as dense as that on Oahu, and hence, it appears to be inadequate in this respect.

As shown by figure 11, (rain gage distribution) and 12(isohyetal map) the principal areas where there are very little coverage of precipitation on Molokai are on the areas of greatest recharge or greatest precipitation gradient. Furthermore, as evident from figure , the distribution of the gages over the high recharge areas are not uniform to actually give a good precipitation pattern without having to interpolate a great deal for additional precipitation data.

In terms of sectional distribution, based on rough calculations, it is found that in West Molokai over an approximate area of 110 square miles, the average gage density is about 30 per 100 square miles. On Central Molokai, over an area of roughly 50 square miles, the average gage density is about 50 per 100 square miles, and on East Molokai, over an area of roughly 200 square miles, the average gage density is a meager 5 per 100 square miles.

The factors that usually determine the adequacy are, of course, to be based on needs with respect to the ultimate uses of the data collected. In Central Molokai, where the ultimate use of the data is principally for determination of precipitation for irrigation needs, the existing gage density is probably adequate in providing such information. In contrast, West Molokai, where the ultimate use of the data is also largely for irrigation purposes, the existing network in that area is relatively inadequate. For purposes of ground-water inventories, it is probably reasonable to imply that the existing

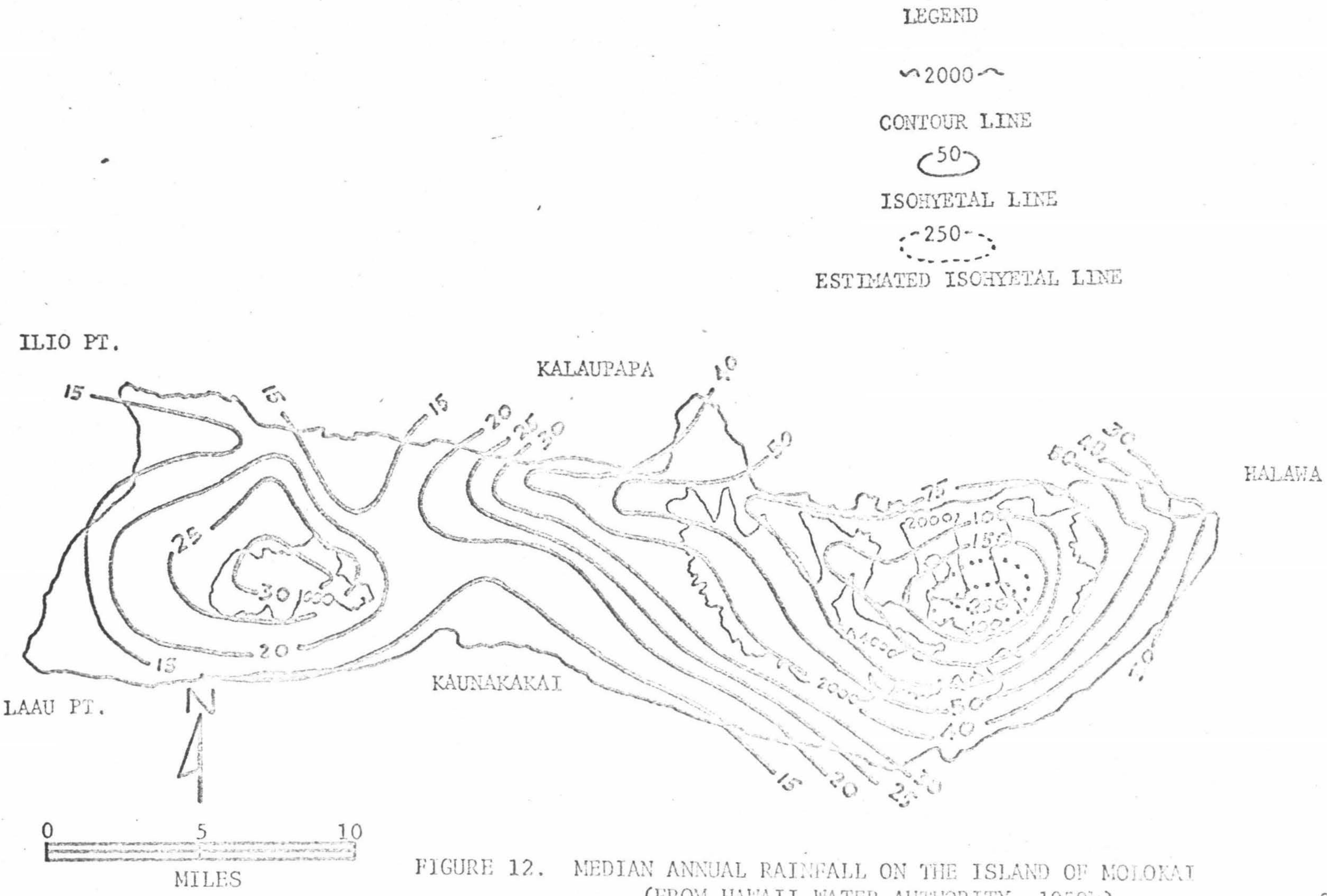

FIGURE 12. MEDIAN ANNUAL RAINFALL ON THE ISLAND OF MOLOKAI (FROM HAWAII WATER AUTHORITY, 1959b).

precipitation network on Molokai is essentially inadequate for such purposes.

Stream Gaging Networks

ON OAHU. Stream gaging in the Hawaiian Islands is the responsibility of the United States Geological Survey. The program is financed partly by the Federal government, partly by the State government, and partly by private agencies.

Currently, there are 58 stream gaging stations making up the network on Oahu. Of this total, 35 are water-stage gages, and 23 are crest-stage gages. Twenty-three of the stream gaging stations have records exceeding 12 years and most of the crest-stage gages have records less than 10 years (Wu, 1967). Since the initiation of the stream gaging program, a number of stations have been discontinued.

Streamflow discharge data are also collected by other agencies and this totals 26 locations. These are gages established for specific purpose and they report flows from ditches, tunnels, and springs. They are, in general, located at high elevations where maximum flows from the water sources are normally encountered.

Using a value of 58 as a base figure for the number of gaging stations, the stream gage density over the 602 square miles of Oahu is 9.6 per 100 square mile area. Figure 13 shows the location of the active gaging stations on Oahu.

ADEQUACY ON OAHU. Most of the gaging stations as shown by figure are located within the major recharge areas and permanent streams of southern Oahu of both the windward and leeward areas. A number of stations are scattered very widely over the central, the west and

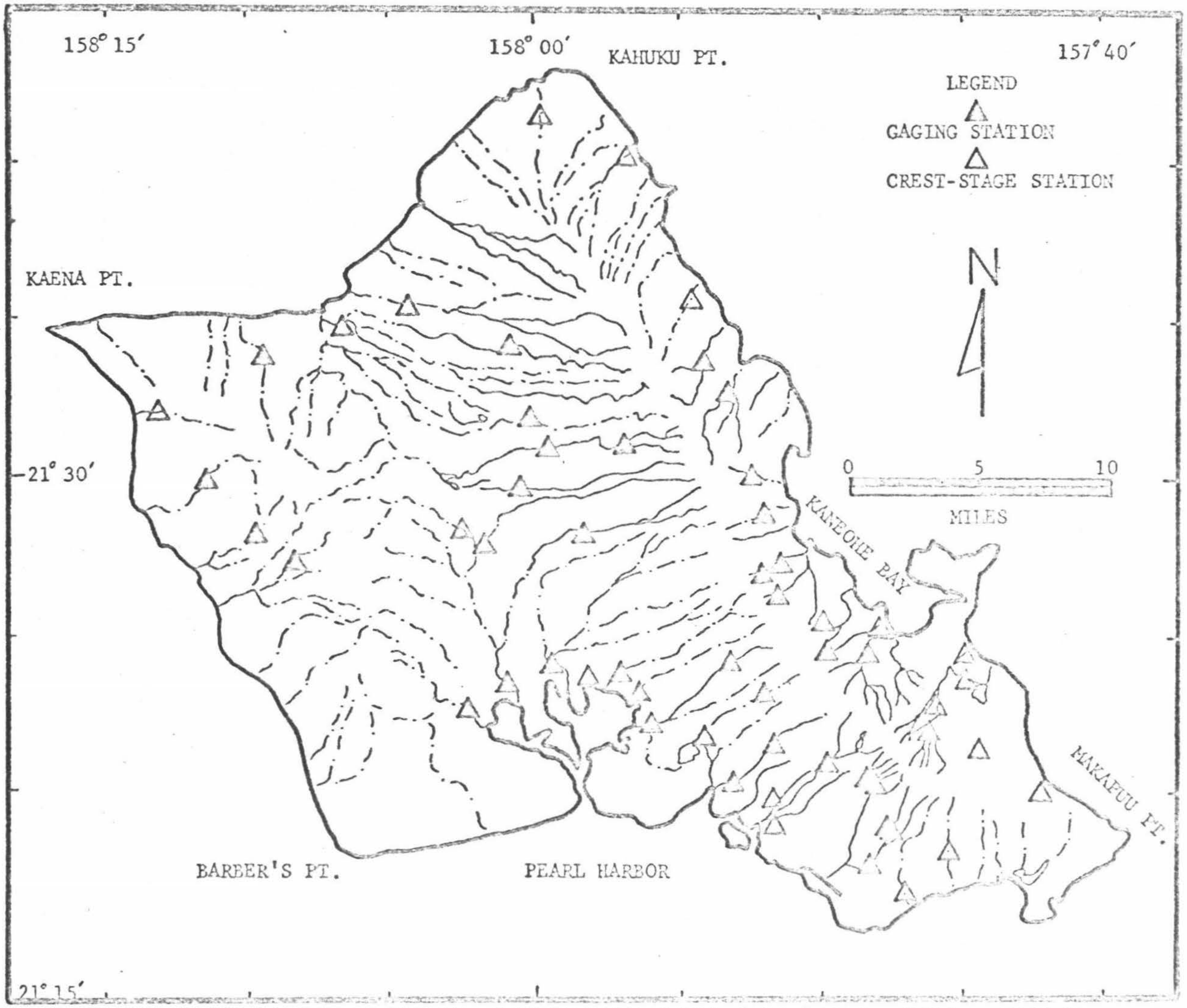

FIGURE 13. STREAM-GAGING NETWORK ON OAHU (FROM U.S. GEOL. SURVEY WATER SUPPLY PAPER 1770, 1963).

northeast parts of Oahu.

For water resources development, such as for irrigation and domestic water needs, which historically was the original purpose for the establishment of most of the gaging stations, it has been indicated (Hawaii Water Authority, 1959) that the existing network is inadequate in providing data for such needs. In light of this, it seems reasonable to assume that the inadequacy of the network would even be greater in relation to its use for ground water inventory purposes.

An improvement over the existing network of gaging stations to provide data for estimation of recharge to the basal water from stream percolation, would be the installation of additional gaging stations in pairs along the streams to allow calculation of differences of the stream flows between the recharge area and the basal water area from which a rough approximation of the infiltrated water may be determined. This improvement would be especially significant along the boundaries of recharge zones and along the discharge zones of streams originating from the crest of the Koolau Mountain range.

A number of the crest-gaging stations have been installed for the purpose of determining peak flood flows of streams for flood control and design of hydraulic structures. These stations are indicated in figure as crest-stage stations and are, in general, located at lower reaches of the streams, usually in developed or intended development for residential areas where the information to be collected would yield more apparent usefulness. Wu (1967) has indicated that basic data from these stations and from available precipitation stations are neither sufficient nor adequate in providing or establishing a sound relationship between rainfall and runoff and design criteria for flood control purposes in Oahu.

ON MOLOKAI. Figure 14 shows the distribution of stream-gaging stations on Molokai. At present, there are 20 stream-gaging stations comprising the surface-water netowrk on Molokai. Eleven of this total are water-stage gages and the remainder are crest-stage gages. Nine of the water-stage stations are located on East Molokai where streamflows are, in general, more persistent, because of high precipitation. Of the nine crest-stage stations, however, only three are located on streams of East Molokai. Most stations have records of 10 years or more.

On the basis of the 20 stream-gaging stations on Molokai, the density of the surface-water network over the 260 square mile area of Molokai is about 7.6 gages per 100 square mile.

ADEQUACY ON MOLOKAI. Ever since the establishment of the network for water resources planning for irrigation and domestic water needs, all water-developments have been based on data collected from the network. Of the 20 stream-gaging stations, 12 are located within the area of major rainfall recharge on East Molokai and at relatively high elevations. The stations measure both storm flows and base flows of streams. Eight of the 12 stations are located below the 2000 foot contour where precipitation gradient is lower than at higher areas. Of the 12 stations three are located in the perennial Waikolu Stream at different elevations. One station is located at the other perennial stream at Halawa Valley. The rest of the eight stations are located in intermittent streams. There are no gaging stations in the additional

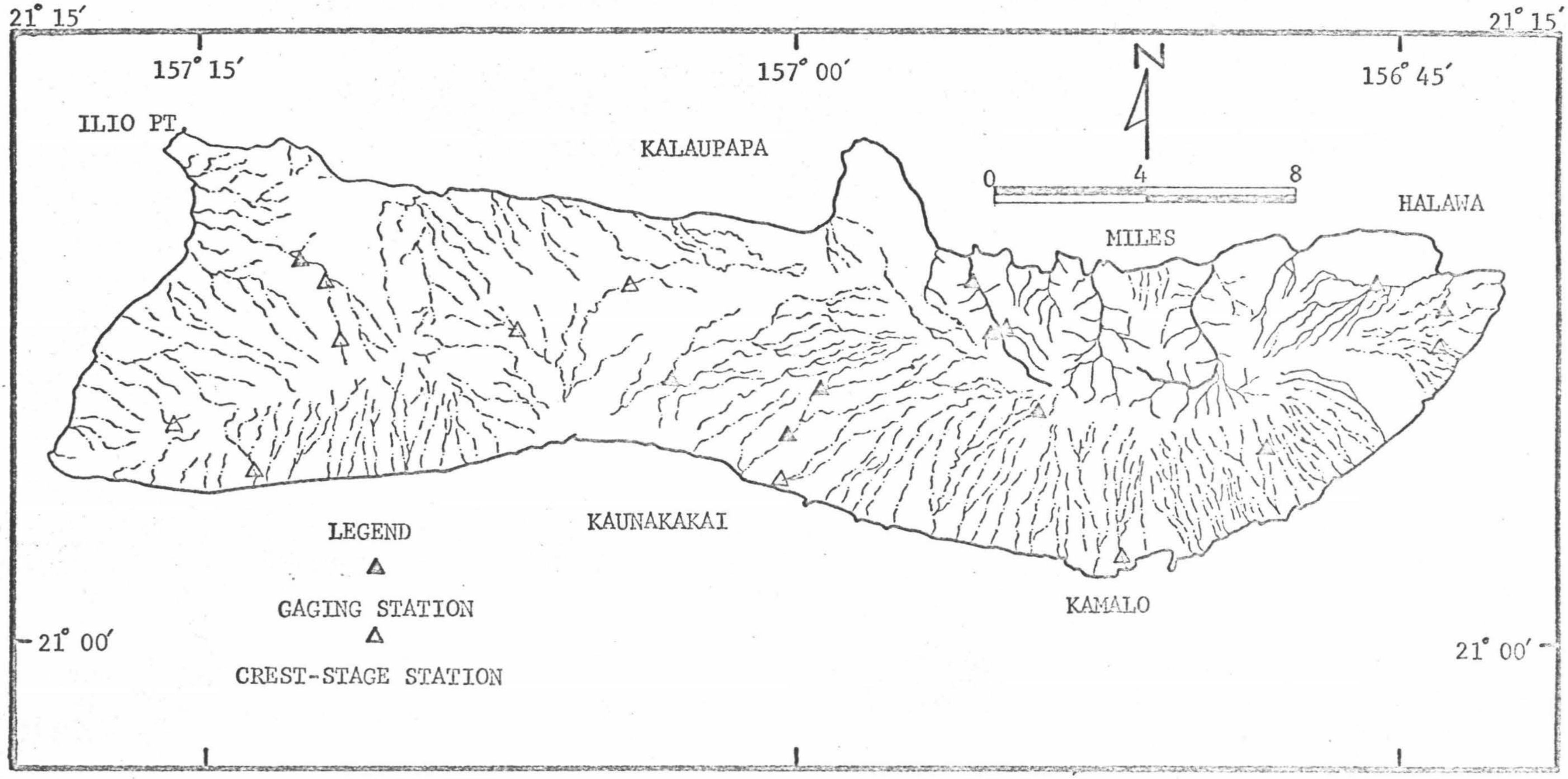

FIGURE 14. STREAM-GAGING NETWORK ON MOLOKAI
(FROM DOWALD, 1966)

five perennial streams on northern East Molokai. Two of the water-stage stations and six of the crest-stage stations are located on West Molokai all in intermittent streams.

Because all of the perennial streams on East Molokai are located on the northern section, stream-gaging stations are, in general, concentrated in those streams, although it is evident from figure 14 that most of the other major perennial streams are still ungaged. The streamflow data collected from the northern area is not particularly useful in terms of ground-water inventory needs because of the limited utilization and occurrence of the basal water in this area. However, on the southern section of East Molokai, where basal water occurrence and utilization are widespread, stream-gaging (water-stage) stations are essentially lacking except for four stations on intermittent streams. It will be in this area of Molokai that stream-gaging stations would find greater usefulness in providing data needed for ground-water inventory purposes such as for estimation of basal water recharge.

Although at present there may not be a need for gaging of streams for flood control programs, the most appropriate area to carry out this type of study would be on the southern portion of East Molokai where potential land use increases and population increases are projected for the future.

West Molokai has no known permanent streams from which surface water may be developed, and it is perhaps because of this that stream gages for any type of studies already mentioned, are non-existent. There has been, however, various speculations for large scale resort development of the western coast that the water demand may require ultimately the monitoring of surface water both for water needs and for flood protection from possible unusually high stream flows.

Evapotranspiration Networks on Oahu and Molokai

Evaporation is a term used to define the process by which precipitation reaching the earth's surface is returned to the atmosphere as vapor. The process by which water in plants is transferred to the atmosphere as water vapor is called transpiration. A hydrologist, whose main concern is often in terms of the total water losses to the atmosphere, often considers evaporation and transpiration together as evapotranspiration, total evaporation, total loss, or water losses (Linsley, Kohler, and Paulhus, 1949). The most common term used by hydrologists is evapotranspiration.

Definitions

ACTUAL EVAPOTRANSPIRATION. More specifically evapotranspiration is commonly expressed as either actual or potential. Actual evapotranspiration is very often used to include the combined effects of evaporation from water surfaces, soil, ice, and snow, and transpiration from vegetation as measured by a lysimeter. The amount of water loss by actual evapotranspiration is limited by the amount of water present in the soil and available for evaporation and transpiration.

In the measurement of actual evapotranspiration by a lysimeter, the value is taken as the difference in the amount of water applied at the surface and that draining through the porous bottom, adjusted for change in moisture content. In the evaluation of the hydrologic equation, the values of actual evapotranspiration is subtracted from precipitation to determine the contribution of precipitation to surface water and the amount of percolation into the ground water.

A synonymous term called consumptive use and widely used by irrigation engineers is often described as the total amount of water utilized by vegetation for transpiration or for use in building plant tissues plus loss by evaporation of soil moisture, intercepted precipitation, and snow.

POTENTIAL EVAPOTRANSPIRATION. Potential evapotranspiration is the amount of water loss by evaporation and transpiration from a well-watered plot or field of vegetation. It is commonly measured by evaporimeters such as pans or tanks and is sometimes considered to be equal to the amount of water lost from such measuring instruments when these instruments are located in the same environment as the actively transpiring vegetation. Potential evapotranspiration is dependent upon radiation and advected heat and may be determined in another way by the heat-balance equation. Because potential evaporation from a pan is related to atmospheric changes, meteorological data such as wind, air temperature, water-surface temperature, atmospheric humidity, and precipitation are collected where the pan is located.

Evapotranspiration Networks

ON OAHU. Figure 15 shows the distribution of active and inactive pan evaporation stations on the island of Oahu. Only 12 of the original 28 stations are presently active.

ON MOLOKAI. On figure 11 is shown the former location of a single pan evaporation station in Molokai. The station had been discontinued so

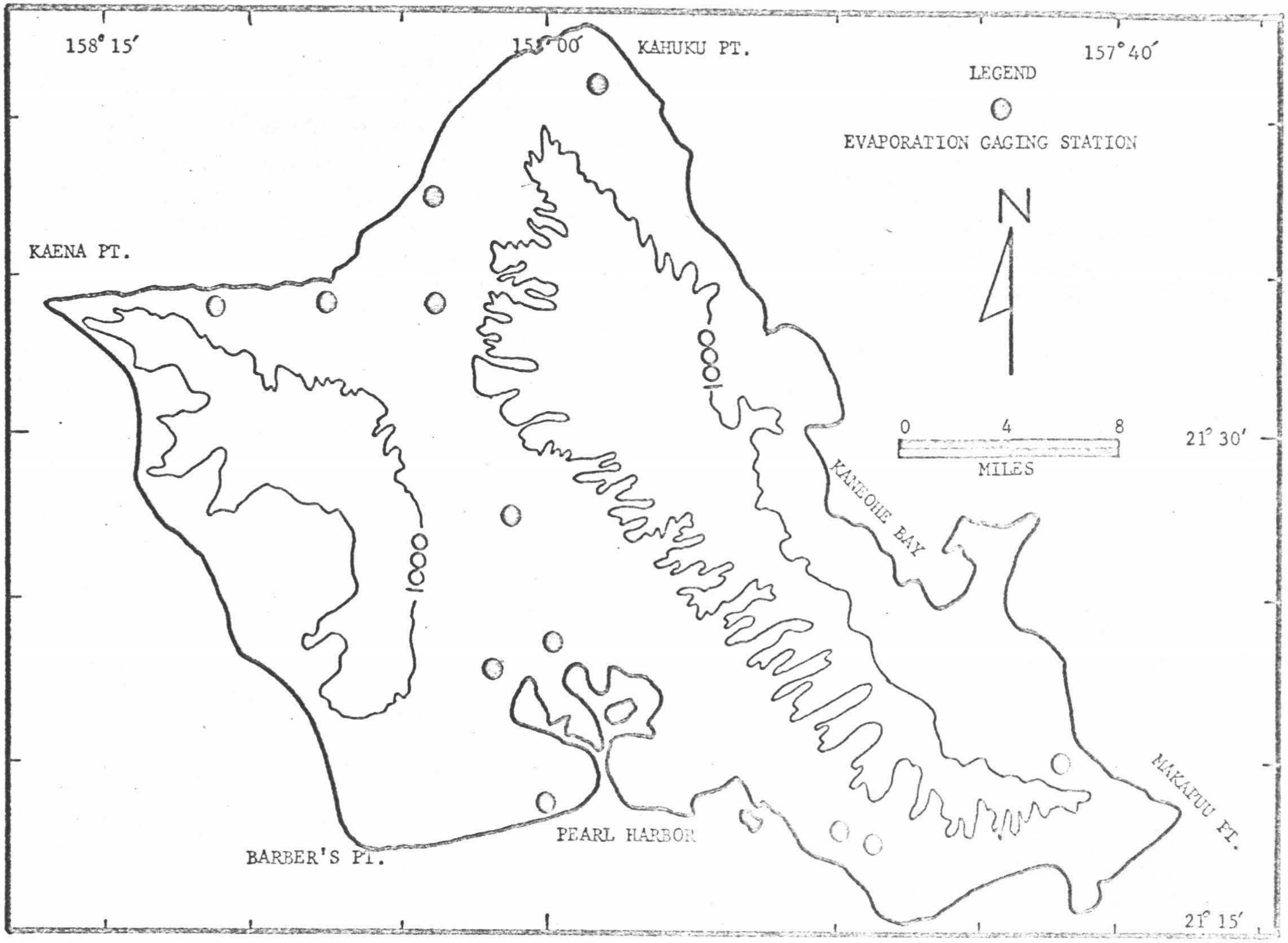

FIGURE 15. EVAPORATION NETWORK ON OAHU (FROM DOWALD, 1961).

that at present, there is no pan evaporation station in existence on Molokai.

Although various experiments have been carried out in the islands, principally Maui and Oahu (Kunesh, 1929, Stearns and Vaksvik, 1935, in Oahu, Campbell, Chang, Cox, 1960, Chuck, 1961, Wailuku Sugar Company, 1967, unpublished report, in Maui) to determine actual and potential evapotranspiration by lysimeters and pan measurements, the data collected are still very limited. This is one area in which hydrologic data is extremely lacking not only for ground water inventory needs but for other studies as well.

NETWORK OF WELLS FOR WATER LEVEL AND OTHER MEASUREMENTS

Introduction

In a well-monitoring network, three important parameters or groups of parameters may be distinguished as those whose measurements are most significant in a program of ground-water inventory and evaluation. These are 1) water levels, 2) water quality parameters, and 3) discharges.

Water levels or piestic levels in Hawaii, as elsewhere, are indicators of hydraulic gradient and hence flow. At most wells in Hawaii, whether maintained by the United States Geological Survey, the Board of Water Supply, or private firms, the water or piestic level is included as one of the standard parameters in the well-monitoring program. Because of the importance of sea level as the base level for the discharge of the major ground-water aquifer, water levels are generally expressed as heads above mean sea level, as appropriate.

In basal ground-water bodies of low head (less than 5 foot or so), Cox (per comm.) has indicated that even a moderate tidal fluctuation will constitute a relatively large variation in head. In such ground-water bodies the recording of semi-diurnal, diurnal, and seasonal tidal movements in the network of head gages may be needed to provide significant measurements of head. It may be noted that tidal fluctuations may cause a relatively large dispersion in the transition zone of basal lens of low head.

Water levels are seldom readily observable in high-level ground-water bodies, especially in dike-confined bodies which occur in areas of high topographic relief. However, in those dike-confined bodies which have been developed by tunnels equipped with bulkheads, and from which the flow is regulated by valving at the bulkhead, pressures convertible to piestic levels may be measured at the bulkheads. Where the development of high-level ground water has been by drilled wells, water levels may be measured by the usual means.

The monitoring of water quality parameters in pumping wells used for domestic supplies, industrial, and irrigation, has often been considered of importance in Hawaii only in relationship to changes in salinity resulting, in general, from the admixture of fresh water with sea water, as measured in terms of chloride content of the water. There are, however, other important water quality parameters which are not, at present, monitored at most of the wells.

Constituents which may be introduced into the ground-water bodies thorugh application of fertilizers and industrial wastes on the land surface, and whose potential in degrading the quality of the water seems obvious, have been monitored only for short-term experimental studies and not for long-term programs. Pesticide nutrients, used largely in connection with agricultural practices, may also be introduced into the ground water bodies, thereby presenting significant quality problems. This type of water quality effect has not been monitored. With the increasing use in the islands of cesspools and septic tanks for waste disposal, the possibility of organisms such as viruses and pathogenic bacteria entering the ground-water bodies exists (Hori, 1969). No monitoring program for viral contamination is being carried out at present, although most significant public domestic water sources are monitored for bacterial concentration.

In the planning of water-supply developments in the islands, water-quality probelms are seldom anticipated. Monitoring programs for measurement of water-quality parameters other than salinity are not commonly included in the planning. A recognition of the different parameters that may ultimately affect the usefulness of water may lead to a more efficient analysis of information obtained from a well-monitoring of physical, chemical, and biological changes and quality of the water source. When these water-quality parameters, which may have deleterious effects on the water quality, are not recognized and are not included in the monitoring program, they may impose considerable restrictions on future uses of ground-water sources.

The third parameter monitored by a network is discharge. Discharge values are useful in ground-water evaluation as they are an indication of water supply potential. The discharges of major pumped wells or well batteries are generally measured by meters, weirs, or rated flumes, or estimated from pump rate and pumping times on from power consumed. The discharges from a few tunnels developing high level ground water are recorded by weirs or flumes. However, the discharges from many minor pumped wells, wells with artesian flow, and most tunnels developing high-level ground water are commonly not measured. Hence the total discharge of most aquifers, as a function of time, can only be estimated.

Present Network on Oahu

There have been about 750 drilled wells in existence throughout Oahu. Many of the wells have been lost, sealed, or have become inaccessible. At the present, the Board of Water Supply maintains a total of 48 separate water supply stations. These stations include 97 individual producing units. Of the 48 water supply stations, 22 are well fields consisting of a total of 64 wells. Six stations are shafts with horizontal collection tunnels. Twelve of the stations represent the high level dike-water system which includes 19 tunnels. The remaining 8 stations are located on springs and streams. Only those wells that are presently being monitored for water level data by the U.S. Geological Survey are shown in figure 16. These wells number 40 (including Board of Water Supply wells) and are equipped with continuous water-level recorders. Data collected from these wells are regularly published in the 5-year water-level reports of the Survey. Chemical analyses results from water samples from the wells are not included in the reports. Chemical analyses from some selected wells owned or maintained by the Board of Water Supply are routinely conducted and results are recorded.

In the domestic water tunnels of the Honolulu Board of Water Supply, four parameters are being measured on a systematic basis. Of these, two are measured on a continuous basis, and one on a yearly basis. The parameters measured on a continuous basis are: 1) discharge, and 2) water levels in sumps in basal-water tunnels, or bulkhead pressures in the high-level tunnels. Water analysis for quality is

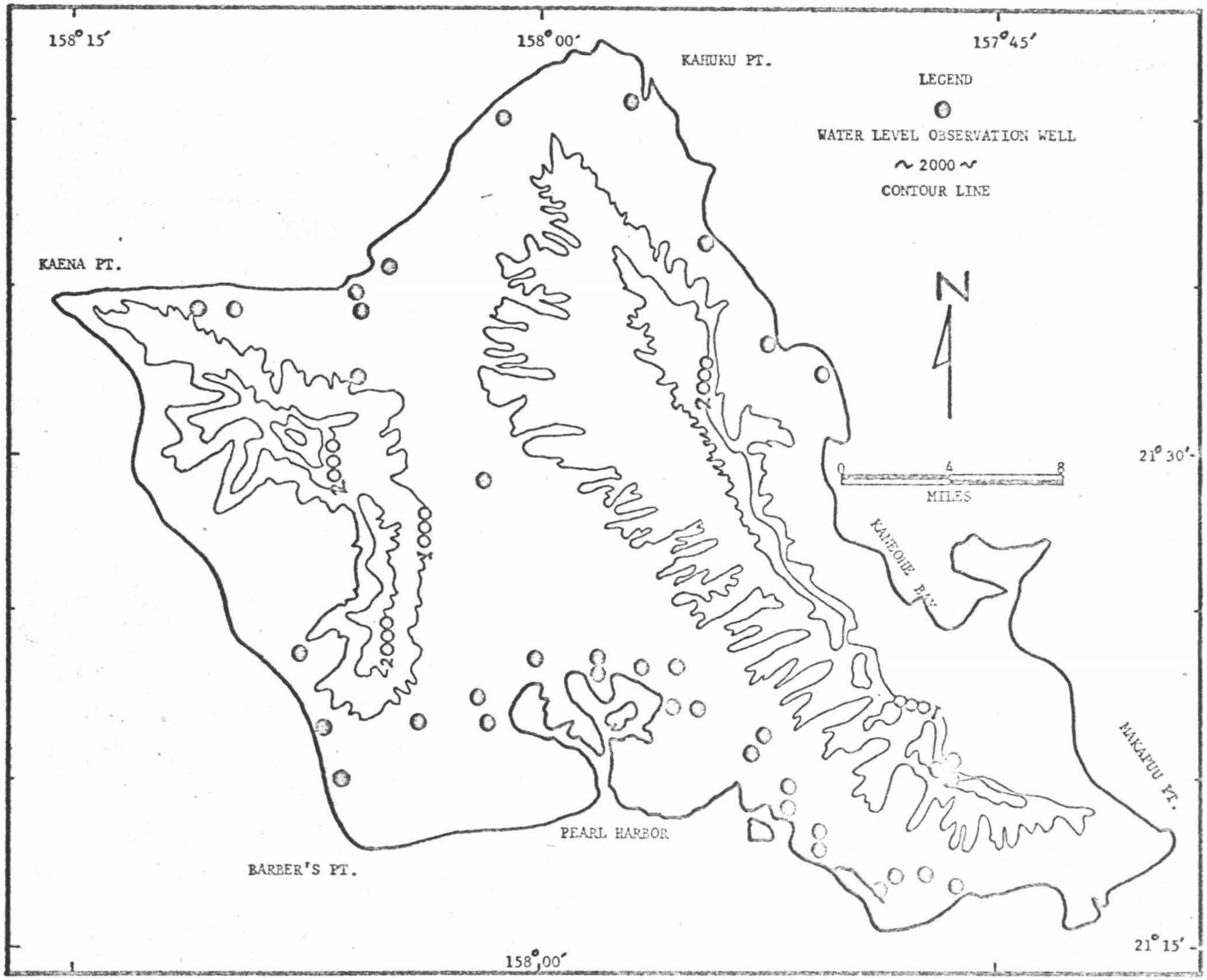

FIGURE 16. WATER-LEVEL NETWORK ON OAHU (FROM USGS WATER SUPPLY PAPER 1885, 1968).

measured on a yearly basis.

A significant portion of the high-level ground and surface water source of Oahu is utilized by Oahu Sugar Company for irrigation of its canefields in the highland areas of central and leeward Oahu. Water for this purpose is derived from the extensive Waiahole Tunnel system which transports water from dike-impounded ground water bodies and from streams of windward Oahu in the Koolau Range. Dike-impounded ground water is derived from tunnels driven into the dike-complex of the windward and leeward sides of the Range. Surface water is also collected from the windward stream channels which pass the Waiahole collection ditch. On the windward side, there are 27 tunnels and 37 intake points, one intake point at each gulch. On the leeward side there are 13 tunnels. These tunnels and intake points of windward and leeward Oahu, in addition to the main Waiahole Tunnel comprise the Waiahole System (Louis Hershler, 1969, per comm.). According to Hershler, the only continuous and systematic measurement being carried out in the Waiahole Tunnel system at present is discharge at each intake point and at the main Waiahole ditch. Measurement of the combined ground and stream discharge at each intake point is carried out to determine quantity of water taken from areas owned by various estates.

The University of Hawaii Water Resources Research Center, through its Return Irrigation Water Project, has been actively engaged for the past two years in sampling and chemical analysis of water from wells maintained by the Board of Water Supply in the Pearl-Harbor Waipahu region of southern Oahu, and in the Kahuku Plantation area of northern Oahu. The primary purpose of the Center's project is to determine the effect of return irrigation water on the basal ground water of the areas under investigation and to locate its extent of influence presently and its effect in the future. Water quality data for this short-term research project has been published.

Adequacy on Oahu

The adequacy of the network on Oahu may be evaluated in terms of utilization of the data collected from monitoring the wells.

Water-level data have been useful in studies of the areal distribution of head within the aquifers on Oahu. These data have been used to approximate the influence on the basal lens water of rainfall and other sources of recharge (Wentworth, 1951). In particular, water-level data have been used to approximate the amount of water in storage by employing the Ghyben-Herzberg relation. They have also been used to approximate changes in top and bottom storage as affected by variations of head measured in wells. In general, the water-level data seem adequate to define the head and hydraulic gradient for the major basal aquifers. For the estimation of storage however, the adequacy is limited.

Great reliance has been placed on the approximation of storage and changes in storage in terms of their relationships to the Ghyben-Herzberg principle under static ground-water condition. In a few isolated field observations (Board of Water Supply, 1969, per comm.), the 1/40 Ghyben-Herzberg relation was not obtained. This has tended to cast doubt on the reliability of this method of storage approximation. However, overall results have shown that such an approximation is still considered fairly reliable.

The measurement of salinity distribution with depth, instead of the conventional head measurement in wells, appears to offer a more adequate solution to the prediction of storage in the basal lens. It has been pointed out by Cox (1953, 1955) and by Visher and Mink (1964) that salinity distribution with depth in the basal lens when measured in terms of chloride content of the water follows a sigmoidal curve (Figure 17). A study by Cox (1955) in an area on Maui where the water table was two feet above sea level showed the sigmoidal pattern of salinity plotted against depth in the basal lens. The sharpest change in salinity occurred between a depth of 75 and 85 feet below sea level. Visher and Mink (1964) carried out a similar study on Oahu where the ground-water hydrology is more complex. In this study, where a well penetrated the transition zone down to a depth of about 1,300 feet below sea level, the sigmoidal nature of the salinity-depth curve was verified.

For purposes of ground-water storage evaluation, the method based on salinity distribution with depth would be more adequate than a method based on head measurements. Unfortunately, it is difficult to collect data for this type of analysis, because of the limited number of studies of this type being conducted, and because of the high costs involved in developing wells for such purposes. On Oahu, many relatively deep wells, drilled during the early basal-water development, were sealed when the salinity of their waters increased beyond tolerable levels to prevent leakage and possible contamination of the lens. Had the usefulness of such wells in the evaluation of ground water been recognized earlier, the wells would have been extremely valuable in the investigation of salinity distribution with depth and in providing useful

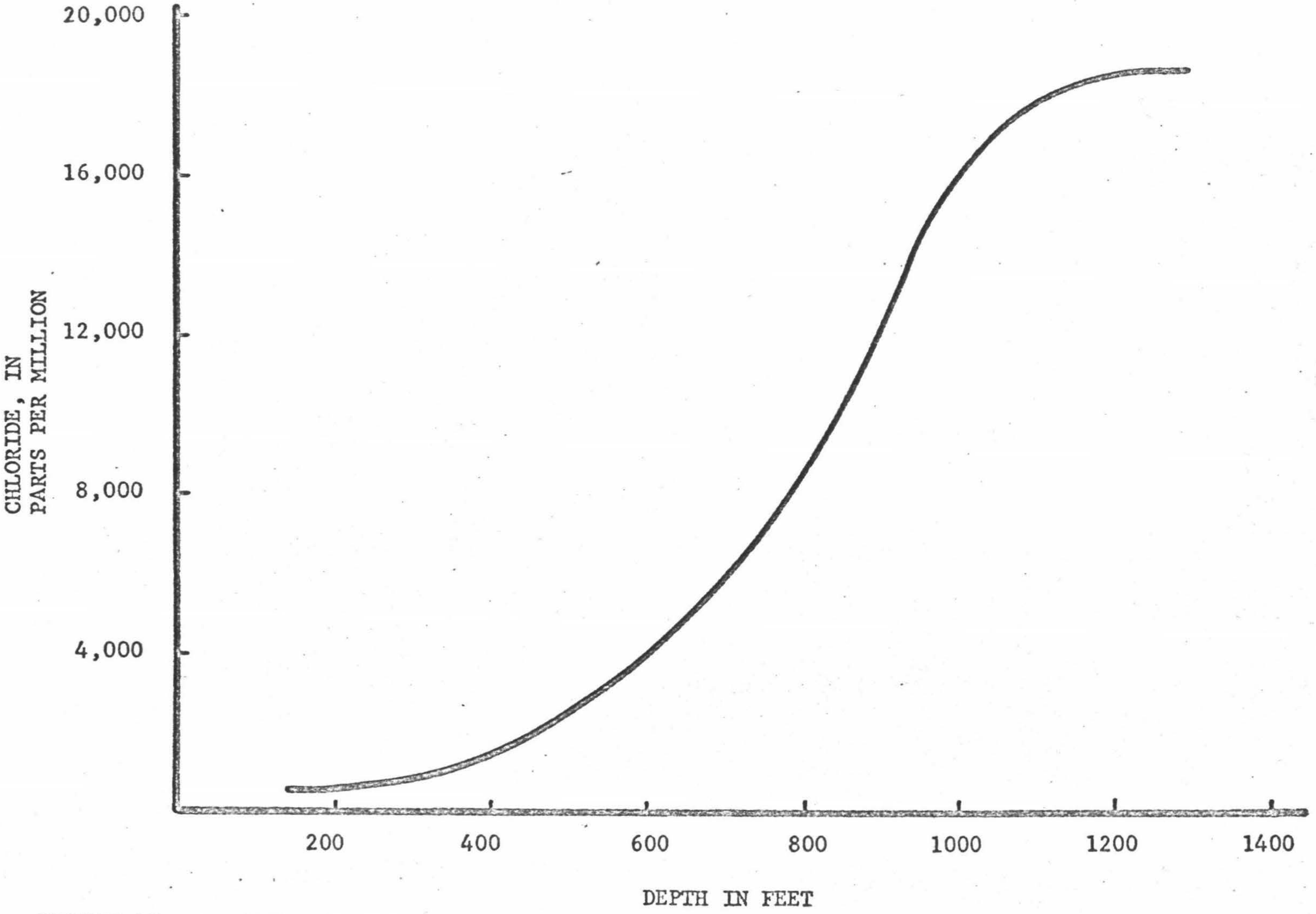

FIGURE 17. RELATION OF CHLORIDE CONCENTRATION TO DEPTH ON WELL T-67 (FROM VISHER AND MINK, 1964).

information for ground-water evaluation and inventory.

It is now generally recognized that because of the dynamic nature of the basal lens, knowledge of head distribution alone is insufficient to provide adequate or accurate information on numerous ground-water problems. Unfortunately, head is the only value presently collected and used in solutions to ground water storage problems in the Hawaiian Islands. On this basis, the existing network of wells on Oahu is considered inadequate to meet present, and more important, future demands for ground-water data for ground-water developments and for inventory purposes.

The Board of Water Supply monitoring program of hydrologic parameters in high-level ground water seems to be relatively adequate for discharge, water level, and pressure measurements. Discharge measurement, as mentioned above, is a combination of stream discharge and ground water. An improvement over the existing method of discharge measurement in tunnels would be the measurement of individual unit discharge, separating that quantity of water contributed by dike-impounded source and that contributed by surface water. Surface water quantity may then be isolated for each area or drainage basin and may be related to the stream discharge below the intake points. The actual total discharge of the stream may then be computed. This improvement is particularly needed in the Oahu Sugar Company Waiahole Tunnel system in which, for most intake points, only the total discharge (surface and ground water) is measured without separation. The usefulness of this improvement can, of course, be realized only when stream-gaging stations are located at each of the stream channels crossed by the collection ditch. There are not enough gaging stations at the present time.

An improvement on the existing water-quality monitoring system would be to increase the frequency of microbiological analyses. At present, the Board of Water Supply conducts only yearly analyses on tunnel waters. For a tunnel system in which surface and ground water are combined, and in which the water is being used or planned to be used for domestic purposes, a more frequent analysis of bacteriologiccal quality should follow established standards.

Present Network on Molokai

On the island of Molokai, there is a total of 123 active and inactive wells. Of these, 88 are dug wells, 17 drilled, 9 Maui-type shafts, and 9 test holes. In a report by the Department of Land and Natural Resources, Division of Water and Land Development (DOWALD, 1961) 76 of the 123 wells were active, and 47 were abandoned or unused. Of the 17 drilled wells only two were actively supplying water for domestic needs. Of the 9 Maui-type shafts, four remain active, and these supply most of the water for domestic needs on East Molokai. The locations of the wells on Molokai are given by figure 18.

Water-level recorders are operated by the U.S. Geological Survey in the domestic water shafts. None of the wells or shafts are being sampled for chemical analysis.

In general only discharges are measured in high-level ground water bodies on Molokai, such as dike-impounded and ash or soil-perched water bodies, and only from a few such bodies developed by tunnels. In the Molokai Tunnel, tapping dike water, the total discharge is the only

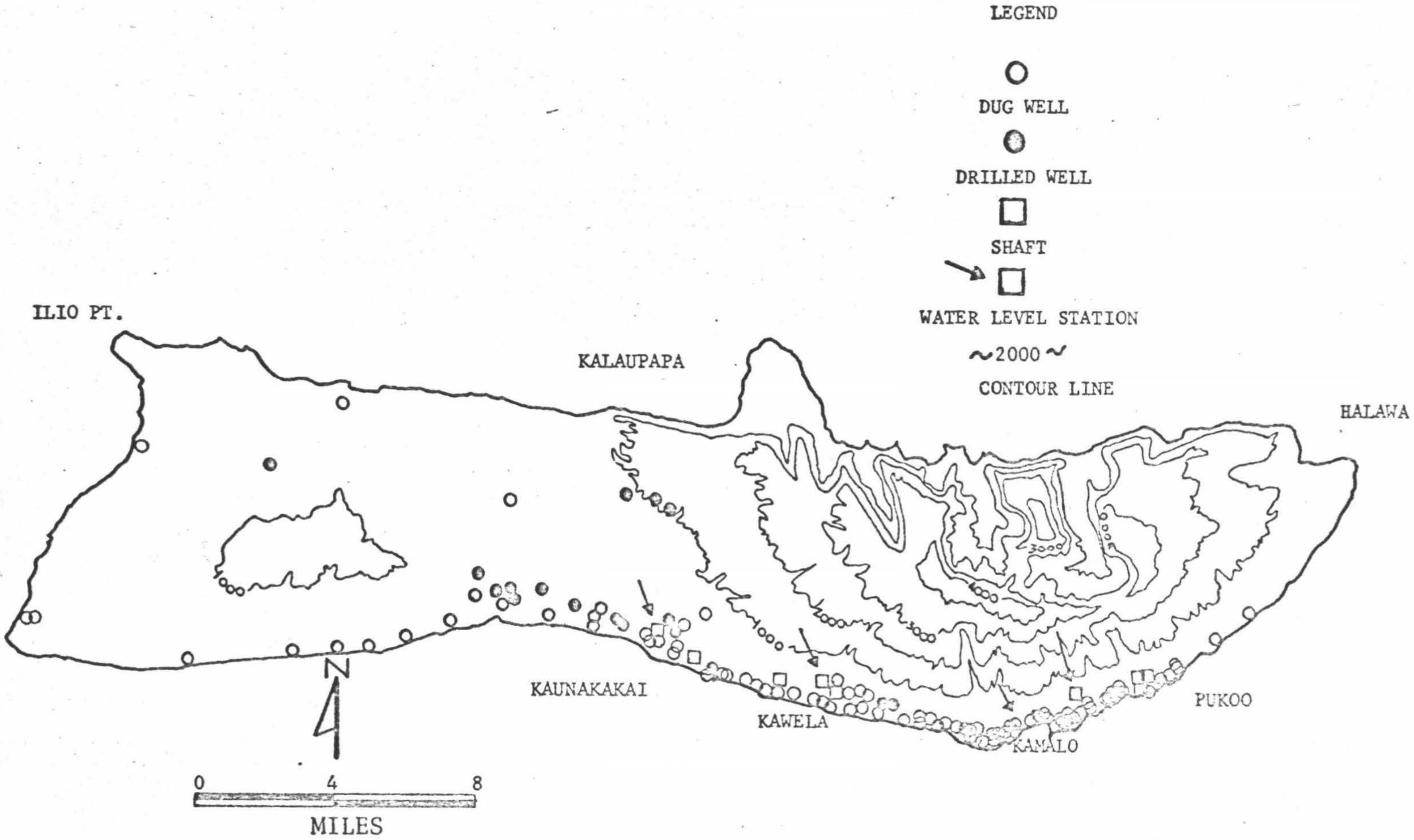

FIGURE 18. WELL LOCATIONS AND EXISTING WATER-LEVEL NETWORK ON MOLOKAI (FROM DOWALD, 1966, AND USGS WATER SUPPLY PAPER 1855, 1968).

continuous measurement made. This discharge includes water developed by the tunnel itself, water pumped from wells in the tunnel floor, and water diverted from surface water sources to the tunnel. Separate measurements of these discharges are not made at present. Water level is occasionally measured in the development wells in the Molokai Tunnel. There is no routine water quality analysis. In the Kalae area, two tunnels, Waialala and Waiakalae owned by the Meyer Estate, supply water for domestic needs. The only data collected from these tunnels is discharge.

Adequacy on Molokai

The water-level data collected from the four U. S. Geological Survey stations on Molokai are inadequate to allow even general conclusions on the areal distribution of heads and hydraulic gradients in the basal lens, and even more inadequate for providing necessary information which may be useful for ground-water planning and inventory purposes. The water-quality data are even more inadequate. Discharge measurements are almost wholly lacking.

It may be concluded that the existing ground-water network on Molokai is inadequate to meet data demands at present or in the future.

A recent Water Resources Research Center Memorandum Report (Burbank, 1969) summarizes water quality on the island of Molokai.

A catalog of information on water data (USGS, 1968) has included in the national listing of surface water quality stations, the existing stations in the Hawaiian Islands. This publication has compiled, among other types of data, the period of record of the stations, and the types of water quality data presently being monitored on the surface water networks in the Hawaiian islands.

SUMMARY

It was the intent of this study that the results obtained would be hopefully useful to agencies concerned with the collection of hydrologic data in their planning and allocation of funds for data collection, and to agencies concerned with uses of hydrologic data in their planning and operation of water resource systems.

The research techniques used in this thesis depart radically from those conventional in that they did not involve analytical laboratory or field research but primarily a comprehensive review of the literature on hydrologic data-network designs, a review of the literature on the geology and hydrology of Hawaii, and an interpretation and integration of various concepts and principles of network design from which have been selected those pertinent in the Hawaiian Islands.

Hydrologic data network designs from previous various studies were reviewed. It was found that, because hydrologic data network design, for either experimental or practical objectives, is a relatively new field in hydrology, only a few studies contribute directly to the objectives of the thesis. In Hawaii, there has never been a study of this sort. One major requirement therefore, if the concepts of data network design are to be validly used in Hawaii, is that hydrologic and geologic similarities between areas from which the concepts are originally developed for, and Hawaii, are comparable. The practical significance of this study is dependent therefore on actual application of the design criteria. The survey of available networks for hydrologic data collection on the islands of Oahu and Molokai have shown, in general, considerable degree of inadequacy. Even those networks for measurement of such parameters as precipitation and stream flow, in which the relative densities of measuring points on the islands are considerably greater than those found in the continental United States, are found to be inadequate in some areas of importance. In the case of Oahu's precipitation network, greater emphasis has been placed on the measurement of rainfall in areas where supplemental water supply is needed rather than on areas of heavy rainfall and hence areas of major water resources. The precipitation network on Molokai may be evaluated in two parts: West Molokai, probably has adequate rain gages to collect the necessary data on that dry section of the island. East Molokai, which receives the bulk of rain falling on Molokai, is very sparsely gauged, understandably because of its rugged topography. This area, however, is where more precipitation gages should be established because it is the main recharge area for most of Molokai's water resources and because it is the area where rainfall variability and rainfall of close concentration gradients are found.

Stream gaging networks on both Oahu and Molokai are considered to be essentially inadequate to meet present data demands and to provide future data for water resources development and for land development and flood control purposes.

Evapotranspiration stations are generally lacking on Oahu, and the one station on Molokai has been discontinued. Because of the significance of evapotranspiration data in the inventory of water resources, it is imperative that efforts should be initiated to expand the existing network on Oahu and to resume the program on Molokai.

The adequacy of the networks of wells used in monitoring the basal water bodies on Oahu and Molokai depends upon the monitoring functions. In general, well discharge records are adequate to permit estimations of the total discharge, with time, for the major basal aquifers on Oahu, but not on Molokai.

Water level and piestic level monitoring at wells on Oahu are adequate to indicate hydraulic gradient and changes in head in the major basal aquifers on Oahu, but totally inadequate on Molokai for any purpose. In the Herzberg lenses on both islands, head measurements are an inadequate indication of storage changes, because of the potential lags in the response of the salt-fresh water interfaces to changes in head. Measurements of salinity profiles with depth that would indicate storage changes are inadequate on Oahu and wholly lacking on Molokai.

Water-quality monitoring at wells on Oahu are inadequate to present a generalized picture of important chemical constituents and their changes in space and time. Water-quality monitoring may be generally adequate in assuring the safety of domestic supplies from the microbiological standpoints. However, viral contamination and pesticide pollution cannot be detected. Only chloride content is monitored in a few basal water wells on Molokai.

In near-shore areas of low head, the tidal fluctuations are often sufficiently large to require continuous recording and analysis before significant head values can be determined.

In the high-level ground-water bodies on Oahu, the monitoring of discharge is adequate only in the tunnels of the Board of Water Supply, bulkhead pressures can be obtained only in these tunnels, and water quality measurements are limited to these tunnels. In the high-level bodies on Oahu, practically the only measurements are those on the DOWALD tunnel and these are of limited adequacy.

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