GEOLOGY OF THE HONOLULU GROUND WATER SUPPLY

PALMER

R. S. Kuykendall

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Honolulu Ground Water Supply

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BOARD OF WATER SUPPLY
CITY AND COUNTY OF HONOLULU
HONOLULU, HAWAII
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FOREWORD

This report is a revision of an earlier one on the Geology of the Honolulu Artesian System, published in 1927. In it Dr. Palmer offers a non-technical description of the geologic nature and hydraulic working of the main ground water system of the Honolulu area. For many years it has been the policy of the Board of Water Supply to attempt to supply water to Honolulu from the ground water of the Honolulu district. Accordingly this report is chiefly confined to discussion of that ground water body.

Recently, water from the adjacent Pearl Harbor area has been made available to the city through the Halawa underground pumping station. While this additional source has been of great assistance in meeting the augmented war-time demand of Honolulu, the lowering of ground water heads in both the Pearl Harbor and Honolulu areas indicates progressive depletion of stored water and withdrawal at a rate greater than that of addition by rainfall.

Delivery of water from a distance will always remain expensive and the development of sources within the Honolulu area should be carried to their ultimate capacity. Modification of operating methods and particularly decrease in the number of deep wells may permit some gain through regulated head lowering. Because of financial, legal and mechanical impediments, such gain will come very slowly and its value must be weighed against the corresponding loss of storage. Responsibility of this board for the maintaining of the city water supply enjoins great deliberation in determining its future course. Gains through water development, over long periods, are often far short of the apparent initial additions. Experience does not support the view that water anywhere on Oahu can be considered as permanently plentiful.

Accordingly, Dr. Palmer's paper is presented as a primer on the Honolulu ground water system, in an effort to emphasize in simple terms its advantages and limitations. It offers an important beginning in the discussion of the broader problem of the Honolulu water supply, a problem for the solution of which data are being gathered, but on which no conclusive statement has yet been attempted.

FREDERICK OHRT

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I. INTRODUCTION

Pure water, one of the greatest blessings that a community can have, is not an inexhaustible commodity. On the contrary, its amount is absolutely dependent on the rainfall and on the characteristics of the rocks underlying the region. Man cannot modify either of these controlling factors. Man cannot alter the rocks beneath him and he cannot cause or prevent the fall of water from the sky. He must adjust himself to the rocks that have been made in past ages by varied geologic processes and to the varying amounts of rain, snow, etc., that the winds bring from year to year. Consequently it is necessary that he understand so far as possible the behavior of the water that moves through the pores and cracks of the rocks if he is to make the fullest possible continuing use of this water.

Four types of sources exist and have been used for public water supply in Honolulu. These may be classified as (1) surface water, (2) high-level ground water, (3) artesian ground water and (4) free water of the main ground water body.

Surface water has the advantage that it can be collected in reservoirs at high levels and distributed by gravity without expense for pumping, but it has the disadvantage that it is easily contaminated, is often turbid and discolored, and that droughts may empty the reservoirs. The conformation of the long, narrow valleys and their steep gradients limit markedly the amount of water that can be impounded by a dam of reasonable size. Furthermore, the great variations of rainfall from year to year and the relatively high rate of leakage into the permeable basalt bedrock are serious handicaps to large scale utilization of surface waters.

High-level ground waters, derived from springs or from tunnels driven into the mountains, are sanitary, clear and sightly and can also be distributed by gravity without pumping expense, but are unfortunately inadequate in amount. The painstaking researches of Dr. Chester K. Wentworth, for the Board of Water Supply, show that it is improbable that any major supply of ground water can be developed by tunnels at high levels in the Honolulu district.

The main dependence of Honolulu for nearly half a century has been on the artesian part of the main ground water body, which yields water that is of excellent quality but which requires steady expense for pumping. In the last decade considerable water has been obtained by means of shafts and tunnels which reach the free or unconfined part of the same main ground water body as that tapped by artesian wells. The water from the shafts, like that from artesian wells, involves pumping expense. Nevertheless, the high quality and the supposition that the supply was inexhaustible have made the community willing to bear the expense of pumping. Unfortunately, the supply is not unlimited and the penalty will inevitably be paid if we withdraw water, whether by artesian wells or by shafts, from the main ground water body in the rock beneath Honolulu faster than it is replenished.

Persons who have observed the gushing of large amounts of water into excavations in the downtown district of Honolulu have suggested the possibility of using this water. These waters are being used for some purposes for which high quality is not essential. In one excavation a system of underdrains was installed which lead to a fire hydrant at the curb, to be used as an emergency source of water for fire fighting should the regular water mains fail. A number of other wells have been sunk to obtain water for use in air conditioning equipment. But the quality of the water makes it unfit for public supply. For one thing these waters contain from a thousand to sixteen thousand parts of chloride to a million parts of water, whereas the U. S. Public Health Service (1)[1] considers 250 parts the limit for potable water. Moreover, though the writer has been unable to find relevant data, these waters are probably too hard as they come from limestones. And since this water presumably originates in part by the seepage of rain into the ground in the densely populated parts of Honolulu, there is too much chance for bacterial infection, so that the waters would be very unsafe from the sanitary point of view. It would, of course, be possible in great emergencies, such as destruction of other facilities by warfare, earthquake, or conflagration, to make this water potable by boiling, chemical treatment, or otherwise, but the water would not be of desirable quality.

The present paper is a revision of the writer's "The Geology of the Honolulu Artesian System," which was published in 1927 as a supplement to the Report of the Honolulu Sewer and Water Commission to the Legislature. In making the revision some parts of the earlier paper have been used without change, but most of it has been rewritten, amplified, and brought up to date.

Much of the matter used has been gotten over a period of years from many sources, and for which it is impossible to give specific credit. The various reports of the Honolulu Board of Water Supply and of the Territorial Division of Hydrography have been invaluable.

Appreciative thanks are hereby tendered to Dr. Chester K. Wentworth, Mr. Walter H. Samson, and Mr. Clarence K. Lum, of the Board of Water Supply and to Mr. Sam Wong of the Division of Hydrography for supplying data. And also to Mr. K. H. Lee, Mr. Bunji Higaki and Mr. Rijo Hori of the Board of Water Supply for making finished drawings of the author's rough drafts of the various illustrations.

Valuable changes have resulted from suggestions made after critical reading of the first typescript by Mr. L. H. Herschler, Mr. S. T. Hoyt, Mr. Goichi Nakamoto, Mr. Walter H. Samson, and Dr. C. K. Wentworth. These have materially improved the paper.

[1] The numbers in parentheses refer to the list of references cited at the end of the paper.

II. ORIGIN OF GROUND WATER

The assertion was made in the first paragraph of this paper that the amount of ground water is dependent on the rainfall. This proposition is so important that it deserves supporting evidence. The term "rainfall," in a loose sense, includes all forms in which water gets from the air down onto the surface of the earth, but rain is the only form abundant enough here to be effective. The term "ground water" means water that fills voids or interstices in rock or soil, but it does not include the thin films of water adhering to grains of soil that is damp but not saturated. In general if we dig down we pass first through soil containing more or less moisture but not enough so that water will drain out of it; then we pass through soil or rock that is drier and finally into a zone where the voids (chinks, interstices, cracks, fissures, holes, pores, etc.) are filled with water some of which is able to drain from the voids into our excavation. Ground water, then, is water that can be recovered by means of wells or that discharges naturally through springs.

A. THE SPACE ARGUMENT

In New England the rainfall is far more uniform than in Hawaii and ranges from 40 to 55 inches a year. Springs and spring-fed lakes are abundant in New England and it is possible to make successful domestic wells at very many points by digging fifteen feet. In Nevada the rainfall ranges from 3 to 15 inches a year. Springs and spring-fed lakes are scarce in Nevada. Wells are successful at rather few points and require much deeper digging than in the more humid New England region. Similar comparisons between other rainy and dry regions show that rainy regions have much more ground water than dry regions. It is said that there are no springs and no permanent streams on the island of Kahoolawe, which has very little rainfall. The Koolau Mountains of the island of Oahu are much rainier than is Kahoolawe, and springs and spring-fed streams are present in moderate abundance. It would be easy to give many more examples of the proposition that humid regions have more abundant ground water than do arid regions. One seeming exception should be mentioned. If a humid region is underlain by highly permeable rocks there may be few springs and it may be necessary to dig wells to great depths because of the lack of impervious rock layers that would hold up the water or bring it to the surface. There would, however, be an abundance of ground water, though it would be found only at considerable depth.

B. THE TIME ARGUMENT

1. Observations in Pomperaug Valley, Connecticut

In Pomperaug Valley, Connecticut, according to Meinzer and Stearns (2) the level at which water stands in the wells depends in large part on the amount of rainfall, although rock type, topographic situation, temperature, and other factors modify this relationship. Figure 1 shows the average amounts of rainfall by months at four gages in or near Pomperaug Valley, and also the average depth to the water surface in twenty-two wells. The depth is expressed in terms of the depth below the highest level found during the period of weekly observations, which was from October, 1913, through December, 1916. Inspection of figure 1 shows that the water level, in general, rose during and shortly after times of large rainfall, and that it fell during times of small rainfall. There is also an annual swing of the water level since there is less loss of water by evaporation during the cold of winter. Hawaii's small temperature range will not affect water levels greatly.

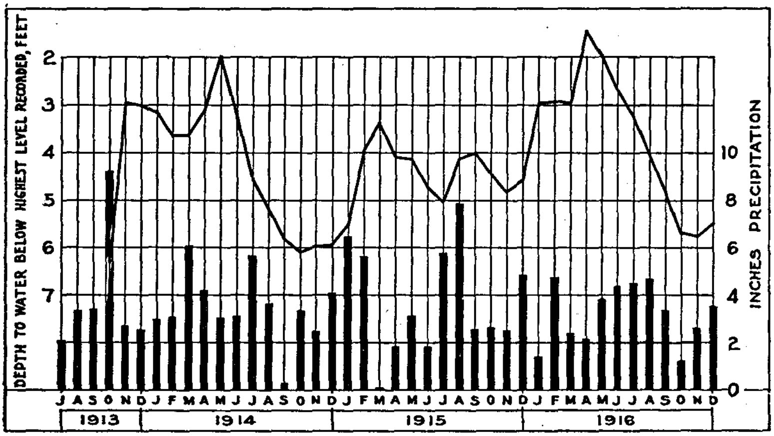

Figure 1. Rainfall and Water Levels in Pomperaug Valley, July, 1913, through Dec., 1916.

Many other examples might be cited to show how the water level rises and ground water becomes more abundant in seasons of greater rainfall. One record, namely that of the well at Punahou School, Honolulu, with a continuation at the Thomas Square well, will be given.

2. Fluctuations in the Punahou and Thomas Square Wells, Honolulu

The fluctuations of the artesian level in the Punahou and Thomas Square wells are instructive. These wells draw on the same artesian part of the main ground water body and their fluctuations are closely parallel. Data on the levels in these two wells are given by Stearns and Vaksvik (3) through 1934, and subsequent data were furnished by the Board of Water Supply. In figure 2 the height, as of the 15th of each month, was plotted, giving the wavy curve. The monthly rainfall at the lower Luakaha rain gage is plotted as a bar graph in the lower part of the figure. The average annual rainfall at this station, over a period of 53 years, is 139.74 inches. One twelfth

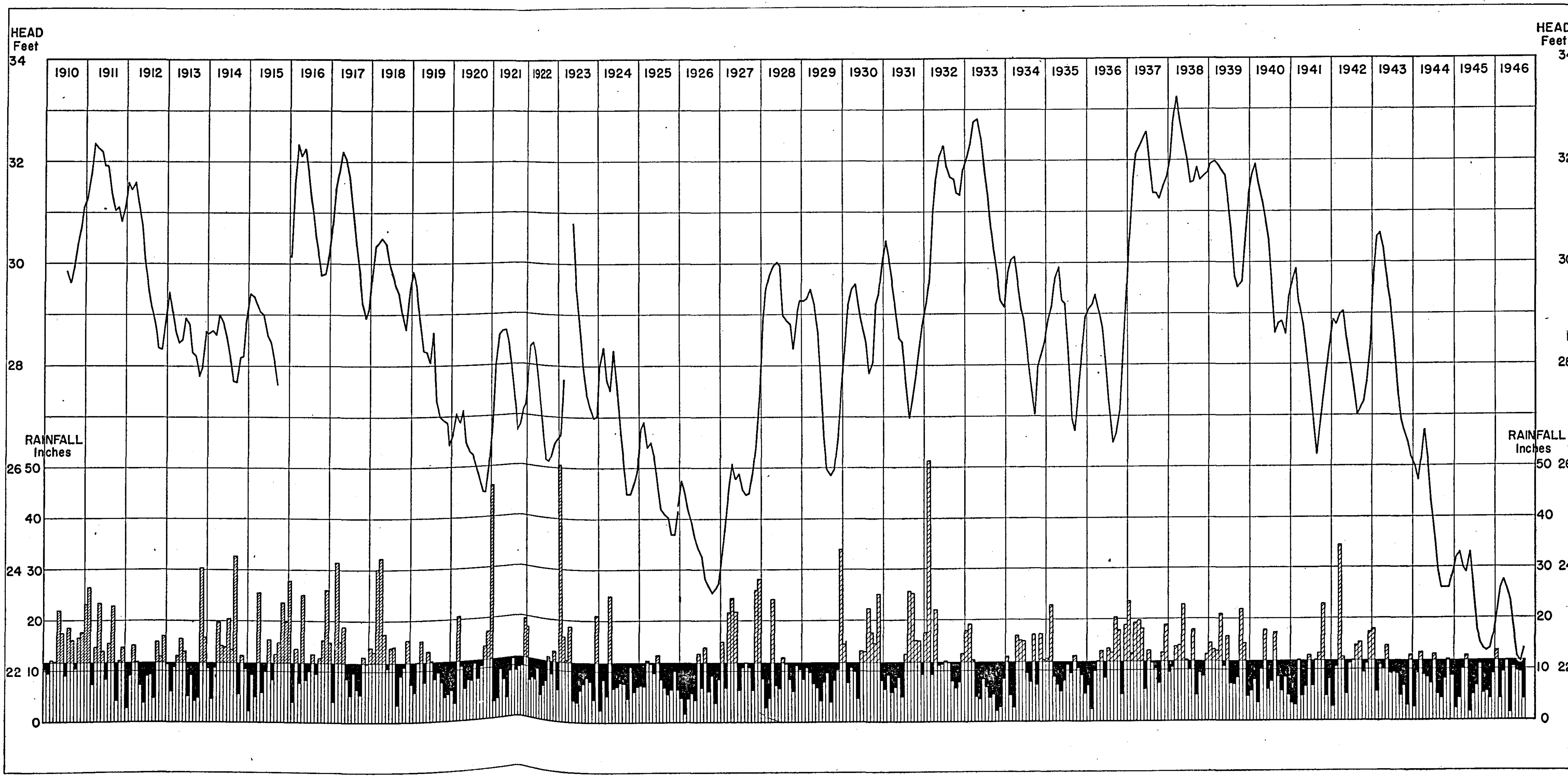

Figure 2. Rainfall and Artesian Levels in the Honolulu Area.

of this is 11.64 inches, which is the average for all months, regardless of seasons. (The different months of the year have different averages, of course, and range from 9.53 inches, for June, to 13.72 inches, for December.) A horizontal line is drawn at the height representing 11.64 inches rainfall. For months with less than average rainfall, the space between the top of the bar and this average line is filled in with black, so that black areas in the graph represent times of deficient rainfall. For example, in December, 1931, the rainfall was 9.31 inches. The bar for this month is blank up to the 9.31 inch height, and is black from there up to the 11.64 inch height, representing a deficiency of 2.33 inches. For months with more than average rainfall, the part of the bar above the average level is ruled diagonally. December, 1923, with 21.03 inches, or an excess of 9.39 inches, illustrates this convention.

From figure 2 we can see that there have been several contrasting epochs of rising and falling artesian level.

Early in 1923 there was a marked rise from 26.6 feet to 30.75 feet, as a result of good rains in the winter of 1922-23. From May, 1923 to October, 1926 the level fell to 23.51 feet, but with two upward swings following generous rains in December, 1923, and in April, 1924. Two other upward swings in this epoch may be partly due to nearly normal rainfall and partly due to decreased pumping during the cooler and moister winter months.

In 1927 the rainfall for the year was 190.60 inches, or about 36% more than normal, and it was distributed so that six of the twelve months were each above normal. By April, 1928, the level had risen to about 30 feet. August, 1928 was the first of 17 successive months with less than normal rainfall, and the artesian level dropped a little below 26 feet by October, 1929.

Of the 40 months from December, 1929 through March, 1933, 21 were above normal in rainfall, and three more were only a little below normal; and the artesian level rose to 32.8 feet by April, 1933. This pronounced rise is believed to have been due partly to abundant rainfall and partly due to decreased withdrawals of water as a result of the sealing of leaky wells, metering of services, and reduction of other wastes as a consequence of the conservation program of the Board of Water Supply.

Of the 41 months from April, 1933, through August, 1936, only 13 had more than normal rainfall, and only one was much over normal. With this protracted dry period, the artesian level fell to 26.46 feet.

This dry period was followed by a 16-month period with 11 months over average, and the level rose to 33.23 feet by March, 1938.

Next came an 18-month period, with 11 months over average, but none much over average rainfall, and with a moderate drop of the artesian level. Deficient rainfall in July, August, and September, 1939, caused a drop of about two and a half feet, but good rains in October and November, 1939 led to a rise to 31.92 in February, 1940.

The 57-month period from December, 1939, through August, 1944, had only 17 months with more than normal rainfall. Of these 17 months, eight were only a little above normal, and only two were markedly above normal. The general trend was downward for these 57 months, so that by the middle of August, 1944, the artesian level was a little below 24 feet. Increasing withdrawals of water under wartime conditions had, of course, also done much to lower the artesian level.

In summary, we may say that figure 2 shows that for this locality the abundance of ground water, of which the artesian level is a measure, varies from time to time with the rainfall. In general, peaks of the artesian level curve are preceded a little by abundance of rainfall. Some of the months of abundant rainfall are not followed by peaks of the artesian level, but they are followed by more rapid rise or slower fall than would otherwise have occurred. Conversely, every trough of the artesian level curve is preceded by several months of deficient rainfall and every period of several months of deficient rainfall is followed by a trough of the artesian level curve.

C. ARGUMENT FROM THE QUALITY OF GROUND WATERS

Rain as it falls from the clouds is almost chemically pure water, and contains mainly dust washed out of the air and gases dissolved from it. The quality of water is altered during its passage underground by the addition of substances dissolved from the rocks with which it comes in contact. I once camped by a spring which emerged from gypsum-bearing strata. The water was so "hard," due to dissolved gypsum, that it had a strong bitter taste and was unfit for drinking or washing. It is proverbial that the waters of limestone regions are "hard" due to the lime dissolved from the rocks. Our Hawaiian waters are "soft" because the rocks through or over which they have moved yield but little hardening matter. The fact that the composition of waters reflects the character of the rocks with which they have been in contact could be shown for many regions. It implies that the waters are originally almost chemically pure and the only conceivable source of such pure water is in rainfall.

D. HONOLULU GROUND WATERS ARE NOT DERIVED FROM THE OCEAN

The hypothesis is sometimes suggested that the ground water supply of the Honolulu region is derived from the ocean by percolating underground, the salts being removed by a filtering action of the ground. This false hypothesis seems to be suggested by the vastness of the total volume of water recovered in this region. It seems to the advocates of this hypothesis that the ocean is the only source large enough to yield so much water. Nevertheless, the rainfall on the higher land back of Honolulu is sufficient in amount. Careful studies by Chester K. Wentworth of the Board of Water Supply indicate that about 25.60 square miles have rocks that can absorb water, and that the average rainfall on this area is 106 inches a year (4). The corresponding volume of water is 2,713.6 mile inches or 47 billion gallons. If this were uniformly distributed throughout the year, it would amount to about 129 million gallons a day. Even allowing for the inevitable loss of water through streams and by evaporation, this seems an adequate source for our main ground water body.

Two additional facts disprove the supposition that the artesian water is derived from sea water. In the first place, although filters can remove suspended matter, such as clay or silt, from water, simple filters cannot, by mechanical action remove matter that is in true solution like the salts of sea water. The second argument against the sea water hypothesis is that there is no known mechanism by which the sea water could develop pressure and raise itself above sea level in wells. At many places in beaches, sea water percolates through sand and can be gotten by digging wells, but it never rises above sea level.

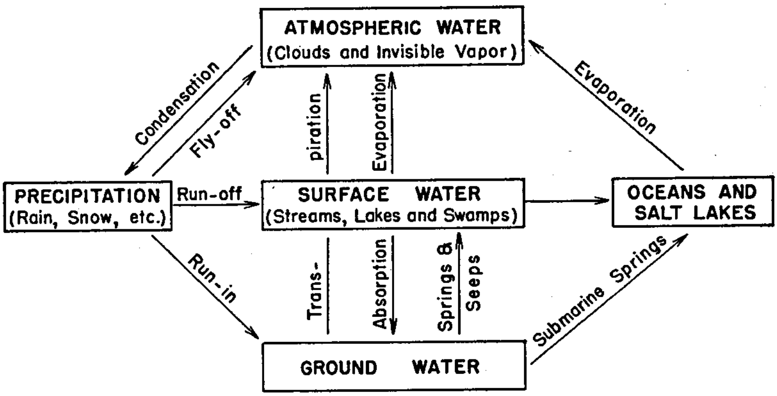

Figure 3. The Cycle of Water.

III. BEHAVIOR OF GROUND WATER

Three possible fates await the water that reaches the ground as rain or melted snow or ice. It may collect and flow off as streams, it may go back to the air as vapor, or it may sink into the ground and become ground water. Although a little may become locked up in the ground in chemical combination with rock matter, most of the water of the ground and of the streams will eventually reach the ocean or salt lakes and be evaporated and form clouds to fall again as rain or snow. Thus water goes through a sort of circulation which may be diagrammed as in figure 3. The part of the rainfall that goes back to the atmosphere is sometimes called the "fly-off" and includes not only water evaporated from moist ground and from streams and lakes but also the water raised from underground by the roots of plants and breathed out by the leaves. The part that collects and flows off as streams is called the "run-off" and the part that sinks into the ground is called the "run-in." Much of the run-off reaches the ocean, but part joins the fly-off directly, and where the stream bed is not watertight some may join the run-in and increase the ground water supply. Conversely ground water may become surface water where springs, seeps, or drainage ditches bring it to daylight. Some ground water along sea coasts joins the ocean water through shoreline springs and through submarine springs.

When water is absorbed it moves downward under the influence of gravity through the interstices between grains of soil or through openings of various kinds in firm rocks. The path is downward and as nearly vertical as the winding passages permit until some obstacle is reached. The obstacle may be an impermeable bed of rock, and then the water will move obliquely downward in the direction of the steepest slope of the impermeable bed. In this case there will be a zone overlying the impermeable bed in which the voids are all filled with water which is moving down the slope. Or it may be that the descending water will come to a zone in which there are abundant voids but where the voids are already full and can take up no more water. Such a zone is called a "saturated zone," because the voids are saturated with water in contrast with an "aerated zone" in which air is the chief matter in the voids. Usually the transition from the aerated zone to the saturated zone is not sharp because the capillary or wick-like action of the voids raises some water into the aerated zone forming a "capillary fringe." The boundary between the two zones is the "water table."

The saturated zone extends downward to a depth which depends on how far down there are voids in the rock which might contain water. In deep quarries and mines the rocks become tight with depth and contain little water. There are some regions in which there is no saturated zone because impermeable rocks crop out at the surface.

The depth below the ground surface to the water table, or upper surface of the saturated zone, varies from place to place and from time to time, as shown on pages 3 to 8. In general, the water table is at less depth during and after rains, beneath valleys, and in rocks of low permeability, and it is at a greater depth during droughts, beneath uplands, and in highly permeable rocks. When a hole is dug or bored into the saturated zone, water will percolate out of the saturated rock or soil into the hole or well. As soon as the water level in the well is lowered by pumping, more water will percolate out of the adjacent saturated material into the well. If pumping is kept up the water table nearby will be lowered, making a "cone of depression" in the water table. If there are a number of wells close together the cone of depression, made by pumping from one well, will be manifested by a lowering of the water level in the other wells. The water will be lowered more in the nearer wells than in the more distant wells. This condition is known as "interference between wells," because the lowering in the affected wells will decrease or interfere with the amount of water that may be gotten from them.

The preceding paragraph has referred to ground water in a saturated zone which is directly under an aerated zone. Such ground water is known as "free" or "unconfined" ground water, and also as "common" or as "phreatic" ground water.

Free ground water has one important feature that distinguishes it from artesian water. Artesian water, also called "confined" water, is under hydrostatic pressure and will rise in wells to a level above that of the water-bearing rocks. Free ground water, on the other hand, will not rise above the level to which the water-bearing rocks are saturated. (Obviously this does not preclude the raising of water by pumping, but refers only to the natural rise of the water.)

Every artesian ground water body is continuous with a free ground water body, as is true of the artesian system of Honolulu, which, on its inland side, is continuous with ground water that is not under artesian pressure. Or, put it another way, the main ground water body at Honolulu has two parts: the seaward part is artesian ground water or water so confined as to have artesian pressure, whereas the inland part is free, or unconfined, or common ground water.

IV. BEHAVIOR OF ARTESIAN WATER

The term "artesian," derived from the name of the French district of Artois, where wells of this sort first became known to Europeans, has been used in various ways, and it is desirable that we adopt a single definition for the present discussion. Some restrict the term to wells which discharge water at the ground surface without pumping and do not include wells in which the water comes only part way to the surface. This limitation is illogical since the altitude of the mouth of the well is an important factor in determining whether water will flow or have to be pumped. These two types of artesian wells are contrasted in the present discussion as "flowing" artesian wells and "pumping" artesian wells.

The similarity between flowing and pumping artesian wells is the feature on which the definition of "artesian" should be based, namely that their water is under such pressure that it is forced up the well to a level above the top of the water-bearing rock. This may be termed artesian pressure, and we may define as artesian those wells which yield water under artesian pressure. A corollary is that artesian water is water under artesian pressure. Having defined artesian wells in this roundabout way, we may turn to the causes of artesian pressure. Every body of artesian or confined water extends to and is continuous with a body of free or common ground water that is not under artesian pressure. If we could trace the course of the water we would find that it passed from a region where there was no impermeable barrier to its horizontal movement and came to a place where there was some sort of inclined barrier below which it was forced to go. Being driven horizontally by the addition of water absorbed from rain in the region of free ground water, it goes beneath the inclined barrier and comes to have greater and greater pressure as it goes downward. If the inclined barrier is pierced by a drill hole the water will rise through it and may flow out at the surface, if the ground is low; or it may come only part way up to the surface, if the ground is high.

It is obvious that there must be rather unusual structures or geometrical arrangements of bodies of suitably permeable and impermeable rocks in order to provide the necessary water-bearing rock and the necessary inclined barrier. Before coming to the rather unusual artesian structure at Honolulu, we may consider three other topics: the usual types of artesian structures, the usual behavior of ground water in oceanic islands, and the geologic history of the Honolulu region.

A. USUAL ARTESIAN STRUCTURES

The term "artesian basin" is reserved by geologists for conditions like those illustrated in figure 4, where an extensive bed of sedimentary rock has been warped downward into a basin-like shape. (For

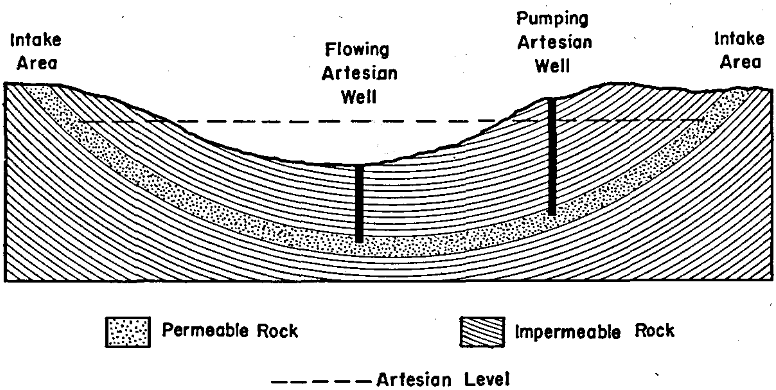

Figure 4. Diagram of an Artesian Basin.

years the term has been used in Hawaii to refer either to the whole artesian system or to its parts, and has, unfortunately for clear thinking, become established in Territorial law.)

A body of rock that can carry water is called an "aquifer." Its permeability may be due to a vast number of tiny chinks between sand or silt grains, to cracks made by mechanical stresses, or to other voids. The aquifer of figure 4 has been warped in such a way that its edges crop out at higher altitudes as "intake areas" on two or more sides of the tract in which the aquifer has been downwarped to a considerable depth. The aquifer absorbs water that in some way reaches the high intake areas. This water may be rain, or melted snow or ice, that has fallen on the intake areas, or it may be water that seeps down from streams that cross the intake areas.

The aquifer is overlain and underlain by impermeable beds. The impermeable rock may be of so fine grain that water is prevented from passing through its voids by molecular attraction of the walls of the voids for the water. The impermeable beds restrain the escape of water from the aquifer, and thus cause the artesian head or hydrostatic pressure. The condition is analogous to the imaginary water works of figure 5, in which there are two reservoirs connected by a

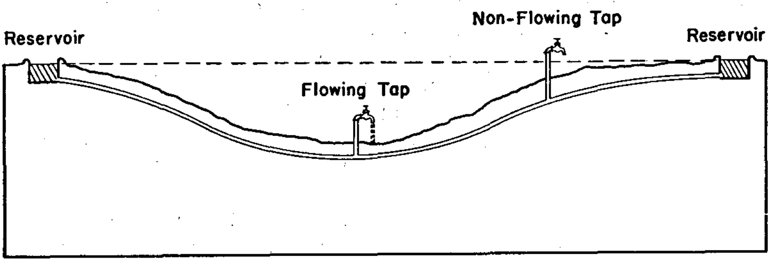

Figure 5. Diagram of a Water Works Analogous to an Artesian Basin.

main pipe. The two reservoirs are analogous to the two intake areas of figure 4; the bore of the pipe is analogous to the aquifer; and the walls of the pipe are analogous to the impermeable beds. If the aquifer of figure 4 were perfectly permeable and the restraining beds were perfectly impermeable, water would rise through wells drilled into the aquifer to the same height as the intake areas, just as water in the service pipes will rise above the main pipe of the imaginary water works. In nature, however, the aquifer presents considerable frictional resistance to the movement of water through it and the impermeable beds are not perfectly impermeable and therefore dissipate some of the head by letting water escape. Therefore, water

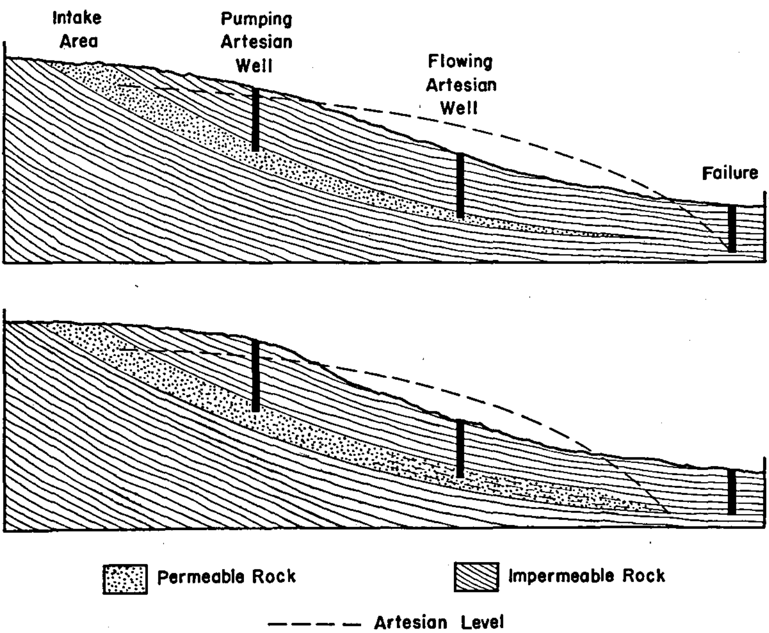

Figure 6. Diagrams of Artesian Slopes.

will not rise in wells to the same height as the intake areas. It rises only to the height of a surface known as the "artesian level." Whether an artesian well will flow or will have to be pumped depends on whether the artesian level is higher or lower than the ground surface at the point where the well is sunk. Wells illustrating the two conditions are shown in figures 4, 6 and 12. The nonflowing or pumping wells are analogous to faucets in the upper stories of high buildings or on high ground which because of their high altitude fail to function at times.

A more common condition of rock structure than the artesian basin is the "artesian slope" in which the aquifer is inclined in only one direction. This is analogous to a simple sort of water works where the distributing mains lead from a single reservoir. If the main of such a system were open at the far end the water would escape and little or none would be discharged at the various connections. Similarly the far end of the aquifer of an artesian slope must be closed in order to prevent escape. Figure 6 illustrates two of many ways in which this closing may be accomplished. In the upper diagram the aquifer thins toward its distal end so that the overlying and the underlying impermeable rocks come in contact. In other artesian slopes the texture of the aquifer changes and becomes impermeable, as indicated in the lower diagram. Wells will be failures if drilled at places more remote from the intake area than the point of thinning out or of change to impermeability, as shown at the extreme right in these diagrams.

The artesian basin, from the geometric point of view, may be considered as two artesian slopes whose pressures oppose one another and prevent the escape of water.

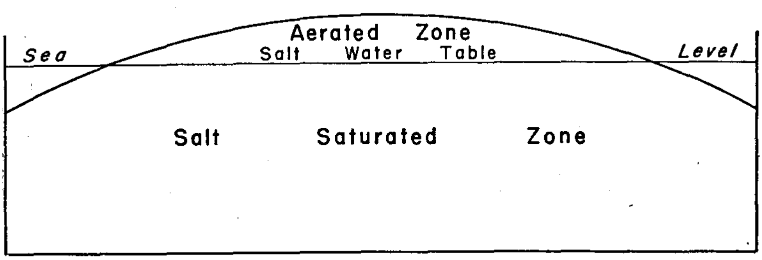

Figure 7. Diagram of an Ideal, Rainless, Oceanic Island.

V. GROUND WATER IN IDEAL ISLANDS

Before considering the causes of artesian pressure at Honolulu it will be well to see how water would be distributed in homogeneously permeable oceanic islands. Figure 7 is a vertical cross section of an imaginary island which consists of rocks of uniform and high permeability. It is further supposed that this island has no precipitation. It is clear that in the course of time sea water would work its way in from the shores and that all the voids that lie below sea level would be filled with sea water. The voids above sea level would contain air, except for a narrow zone a little above sea level into which some water would be raised by capillary action. The continuation of sea level under the island would then be a salt water table, separating the overlying aerated zone and the underlying salt saturated zone. The child playing at the sea shore, who digs down through the sand far enough, passes through the aerated zone and the salt water table into the salt water saturated zone. Many attempts to sink wells on small sand islands have gotten only salt water, or perhaps brackish water if there is fair rainfall.

Let us modify the preceding conditions by supposing there is a good deal of rain. Some of the rain will flow off in streams and some will be evaporated, but some will soak into the ground, since the rocks are permeable. The water that soaks into the ground will move vertically downward in obedience to gravity until it meets some obstacle. In our homogeneously pervious island the obstacle will be the zone in which the voids are filled with sea water. The fresh water will react in two ways. It cannot displace the salt water completely, because the salt water is heavier and tends to be held in place by pressure transmitted from the open water along the shores. Therefore, the fresh water will in part move shorewards over the surface of the salt water. This movement will be resisted by interstitial friction and the fresh water will therefore be backed up more or less. Being backed up will cause it to rest on the salt water thus producing a downward pressure that will partly counteract the pressure applied to the salt water from the shores. Thus the fresh water will press the salt water downward and to some extent outward. The amount to which the salt water will be depressed depends on how much pressure the overlying fresh water exerts, and this in turn depends on the distance from the shore. The greater the distance from the shore, the greater will be the total interstitial friction against which the fresh water must move. The greater the frictional resistance, the higher the fresh water will be backed up and the greater the pressure it will apply to the salt water. The greater this pressure, the greater the depression of the boundary between fresh and salt water. Thus there will be under our homogeneously pervious, rainy island the following zones, as shown in figure 8:

1. A zone in which the voids are filled with air. (Note: This zone may contain a little water that is in transit from the surface downward, having been absorbed only recently.)

2. A zone, shaped like a bi-convex lens, in which the voids are filled with fresh water. The curvature of the lower side of this lens will be much greater than the curvature of the upper side.

3. A zone, extending downward as far as voids exist, in which the voids are filled with sea water.

The boundary surface between the upper and middle zones is a water table. Between the middle and lower zones there is not a mere surface but rather a transition zone with a more or less gradual change from fresh water to salt water.

Since the middle zone contains fresh water it is of importance as a source of ground water supply. It is shaped like a lens, and is often known as the "Ghyben-Herzberg lens" from the names of the Netherlands and German geologists who first developed its theory (5). The thickness of the lens of fresh water depends in part on the permeability of the rock, and is greater in less permeable rocks. The thickness also depends on the rate of water supply by rain.

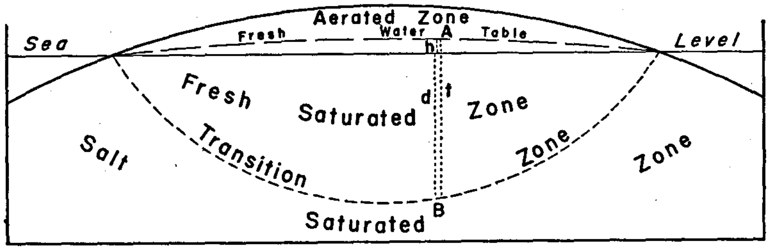

Figure 8. Diagram of an Ideal Oceanic Island with Rain.

In figure 8, let h = the height to which the lens of fresh water rises above sea level at some point, as at A. Let d = the depth to which fresh water extends below sea level, and let t = the thickness of the lens. Obviously the thickness is equal to the sum of the height above and the depth below sea level, or

$$t = d + h \tag{1}$$

In a condition of equilibrium, the downward pressure of fresh water at B will be equal to the upward pressure of salt water. Let P = this pressure, which can be expressed in two ways, in terms of feet of head of fresh water, and in terms of feet of head of salt water. The head due to fresh water will be equal to the depth or, in this case, its thickness, times the specific gravity of fresh water, but since the specific gravity of water is unity, we can write,

$$P = t \tag{2}$$

The head due to salt water will be equal to its depth, d, times its specific gravity, which is about 1.025 or $\frac{41}{40}$. Therefore,

$$P = \frac{41}{40} d \tag{3}$$

Since the two pressures are equal, we can write

$$P = t = \frac{41}{40} d \tag{4}$$

But in equation (1), t = d + h, so we can transpose and write

$$\frac{41}{40} d = d + h \tag{5}$$

And, solving for d, multiply through by 40 to clear of fractions,

$$41 d. = 40 (d + h) = 40 d + 40 h,$$

And, $$d = 40 h \tag{6}$$

The last equation means that the transition zone between fresh and salt water is about 40 times as far below sea level as the water table is above sea level. Wentworth (6) has shown that for the Honolulu region the factor, 38.3, is more accurate than the factor 40, but for simplicity in arithmetic the round number 40 will be used in this paper. The principle is not altered.

The upward bulge of the lens-shaped zone of fresh water is due to the fact that the fresh water is lighter than the sea water, and therefore floats upon it. Brown (7) gives a summary of laboratory experiments and of field observations on the coasts of the Netherlands and Germany, which show the validity of this theory.

In attacking the problem of the occurrence of water in oceanic islands we first considered an island composed of uniformly permeable rocks, with no rainfall. We then modified this by supposing the island to have an appreciable amount of rain. Let us next modify this rainy island still more by supposing that there is a capping of impermeable rock extending somewhat above and below sea level, as indicated at the left side of figure 9. Such a cap would oppose the movement of fresh water seaward, with the result that the body of fresh water would have an unusually great thickness beneath the

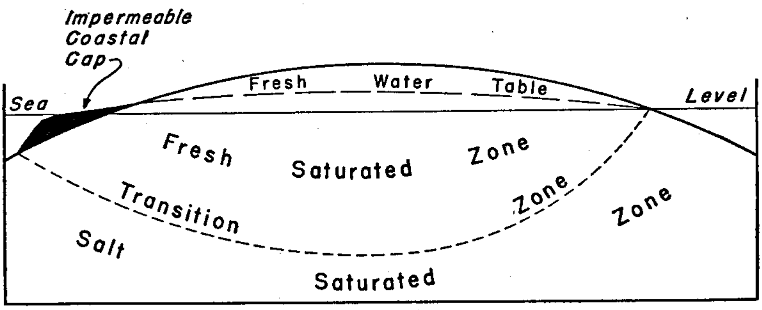

Figure 9. Diagram of an Ideal Oceanic Island with Rain and with an Impervious Coastal Cap.

cap and landward from it. It would also prevent, or at least retard, the escape of fresh water to the sea in a zone extending both above and below sea level.

If the impermeable cap extended only a little way above sea level but far below sea level, the fresh water might be backed up enough so that it would overflow and form springs at the upper edge of the cap. The springs along the shores of Pearl Harbor are thought to be of this sort, although the actual point at which water reaches the surface of the ground may be other than at the exact edge of the cap rock, if the easiest outlet is through the upper part of the cap rock or through lava rock.

If the cap rock extended only a little way below sea level, it would cause only a little raising of the fresh water table, and fresh water would escape under the edge of the cap rock.

We may summarize the effect of such a cap by saying that it may hold fresh water up to a height above sea level equal to one fortieth of the depth of the lower edge of the cap below sea level, provided of course that the cap extends this far above sea level.

VI. GEOLOGY OF THE HONOLULU DISTRICT

In the following discussion of the geology of Honolulu and Oahu the processes which have been at work will be described briefly first, then the geologic history will be summarized, without going into the evidence, and finally the resulting structure will be described.

A. GEOLOGIC PROCESSES ON OAHU

The geologic processes, which have operated to make Oahu what it is today, may be divided into three classes, the contrasting constructive and destructive processes and the diastrophic processes.

1. Constructive Geologic Processes

Volcanic mountains are composed of many thousands of batches of lava discharged successively and heaped on one another. The Hawaiian volcanoes usually erupt by quietly pouring out molten matter to form lava flows, but at rare intervals they have explosive eruptions. On being discharged the lava will flow down the steepest slope until it cools, freezes, and stops. The first flow from a vent will flow in one direction and make an obstacle around which the second flow takes a more or less different direction. The third flow will take a third direction, and successive flows will take still different directions radiating outward from the eruptive vent. Later flows will fill depressions in or between older flows making the volcanic pile smoother. Flows will be most closely jammed together and heaped highest near the vent and will be spread out wider and thinner away from the vent. The accumulation of many thousands of such flows results in a smoothly curving dome like Mauna Loa. Nearly all the rocks of both the Waianae and Koolau Mountains of Oahu are of this type. A very small proportion of the rocks of these mountains were injected while still liquid into vertical cracks or between older flows making "dikes" and "sills" which are rather dense and impermeable.

At times, especially late in their individual histories, the Hawaiian volcanoes have erupted violently because the proportion of gas in the lava was unusually high. When the proportion of gas to molten rock is large the gas tends to break the molten matter into small clots, just as the blast of air in a fly-spray "gun" breaks the liquid into small drops. The clots of lava are thrown high into the air and freeze solid before reaching the ground. The resulting material is "volcanic ash" and forms the so-called "black sand" that underlies much of Honolulu. In time, the ash may be cemented to form a moderately strong rock, called "tuff," such as that composing most of Diamond Head. Since the falling ash is angular it heaps up as steep-sided cones, such as Round Top, instead of forming gently sloping lava domes.

Living organisms, winds, and waves have made small amounts of rock on Oahu. The constructive geologic work of living organisms is represented by the reefs that fringe parts of the shore. In many places, such as the Ewa plain, there are ledges of such rocks which have been exposed by rising of the land or by falling of the sea. In places waves gnaw away at the shore and wash the cobbles, pebbles and sand, which they have loosened, to quieter spots thus forming wave-made gravels or sands. Elsewhere, especially on the windward side of the island, the wind has picked sand from the beach and blown it inland to form sand dunes. If the wind-made sand dunes or the wave-made sands or gravels are composed of carbonate of lime, water percolating through them may dissolve the lime in one place and precipitate it in another forming a cement which will change the sand to sandstone and the gravel to a conglomerate. So far as can be ascertained rocks made by wind or wave are of little importance in the Honolulu artesian structure, but the reef-rock is of considerable importance.

Streams are the most effective destructive geologic agents on Oahu, but they have also done some constructive work. Their destructive work consists of dissolving, loosening and carrying away rock matter, which is eventually deposited somewhere to form the constructive product of stream work. The size of particles that running water can move increases greatly with increasing velocity of the water, as does also the total amount of material, both fine and coarse, that a stream can carry. In sluggish streams only small amounts and only fine grained materials are carried. In perfectly quiet water all the sediment will eventually settle out. It is obvious that the upper parts of our streams have the steepest grades and the swiftest water and can therefore carry much more sediment than can the more sluggish down-stream parts. As a consequence much of the sediment settles out to form flats like those in the valleys east of Diamond Head. Sea water has the property of making finely divided soil particles settle out very quickly where the fresh water flows into and mixes with the salt water. Thus the finest material, that is carried past the mouth of a stream, soon settles to the bottom and forms a mantle over the upper part of the submarine slopes of the island.

2. Destructive Geologic Processes

Winds, especially in regions of scant vegetation, may pick up grains of dust and fine sand and by blowing them against objects perform a small amount of erosion. This process is active in but few places on Oahu, such as the regions of Koko Head and Ulupau Head.

Waves perform erosive work by their direct impact on the land and by the cobbles and sand that they hurl against the shore. If the rocks along the shore are fissured the surging of waves produces alternating compression and suction, which may loosen large blocks of rock. One peculiarity of wave work is that it is restricted vertically to a narrow zone that extends only a few feet or yards above and below sea level. Waves therefore tend to cut a terrace or bench whose surface is a little below sea level, and to develop a cliff, or even an overhanging cliff, at the back of the terrace. If there is a reef offshore the effectiveness of wave erosion is greatly lessened. We can see the results of wave work in the steep lower slopes of Diamond Head. Excellent examples of ancient wave erosion, at a time when the sea stood higher than at present, may be seen in the bench and cliffs that skirt Hanauma Bay.

Waves and wind have done little destructive work on Oahu compared to that done by streams of running water. Water running over bare soil or soil with sparse vegetation will pick up sand and soil grains. Water that flows somewhat more rapidly in well developed stream beds will pick up pebbles and cobbles, and the swiftest streams may pick up very large boulders. Soil grains, sand, pebbles, cobbles and boulders are all tools with which a stream cuts away its bed.

During the time that a volcanic dome is being built, running water will be at work on the growing surface, but its rate of work will be far less than the rate of volcanic building. Eventually volcanic activity slows down and the streams get ahead. Let us consider how streams would sculpture a volcanic dome. The streams at first will follow whatever depressions exist in, around, and between the lava flows. These channels will be parallel to the flows and will radiate from the center of the volcanic heap. The map would suggest a wheel: the rim representing the shore line, the hub representing the crater, and the spokes representing the stream courses.

At the start, the streams will have their steepest courses and their greatest velocities, and will therefore spend most of their energy in cutting their beds downward, tending to make narrow, steep-sided valleys. After the beds have been cut down, the courses will be less steep, and the streams will cut downward less rapidly. With the lapse of time, the rocks of the valley sides will decompose and the products of decomposition will move down to the stream, at times rather catastrophically as landslides, but mostly as slow "soil creep." Thus, the narrow valley will widen, and its steep sides will become increasingly flaring. The sides of neighboring valleys will approach one another and will finally meet, the streams having gnawed away all of the intervening original smooth slope of the lava dome. As time goes on the intervening ridges become lower and lower and the valleys wider and wider. If the island were to remain stationary long enough, it would eventually be worn almost completely away. Uplift or depression of the island relative to sea level may modify the process. Or renewed volcanic eruptions may fill in the valleys and more or less bury the ridges. Waves will, of course, modify the shore lines all the time that streams are doing their sculpturing. When the island has become very low its rainfall will decrease, and waves may eventually bevel it off so that the island becomes a shoal, which may be surmounted by coral reefs and low sand islets, as has the shoal at Midway Island.

3. Diastrophic Processes

Diastrophic processes produce movements of one or more parts of the earth with respect to others, and are often manifested as changes in the relative heights of land and sea. The term "emergence" implies that part of the ocean floor has become dry land but does not imply whether the sea receded or the land rose. Similarly "submergence" does not imply whether the sea rose over the land or the land sank beneath the sea.

Where emergence has occurred we find submarine features exposed on dry land. These may be erosional features like the wave-cut bench and cliffs at Hanauma Bay or they may be constructional features such as the reef rock of the Ewa plain. Emergence, obviously, increases the altitude of the headwaters of streams and, by thus increasing their gradient, increases their swiftness and eroding power, and results in a modification of the normal cycle of stream erosion described in the preceding section. Sometimes the mouths of streams are raised above sea level by emergence so that the streams enter the sea by falls or rapids, though this condition may also be produced where waves cut sea cliffs more rapidly than the streams can lower their beds, as on the Hamakua coast of Hawaii.

Where submergence has occurred, shore features may be detected if numerous soundings are made, but the chief evidence is in the "drowning" of valleys. When this takes place the shoreline, which formerly ran rather straight past the mouths of the valleys, bends a greater or less distance into each valley making it into a bay. Sediment carried into such a bay tends to fill it. The valleys between Kaimuki and Koko Head have had such histories, and their filling has made the level land on which forage crops are grown.

We have now considered the manner of operation of the geologic processes most important in Hawaii, and may turn to a summary of the history of Oahu.

B. GEOLOGIC HISTORY

Twelve principal stages in the geologic history of Oahu may be recognized, and are stated briefly in the following paragraphs:

(1) At an unknown date in the past, in what is now the western part of Oahu, a volcano built a dome reaching five or six thousand feet above sea level. This may be called the "Waianae Dome," and was the body of rock out of which erosion has carved the present Waianae Mountains.

(2) The weight of this dome was so great that the underlying support failed and, step by step, the southwest part of the dome sank below sea level, leaving a mountain mass with a fairly straight, cliff-like southwest boundary.

(3) A long period elapsed, during which streams cut deep valleys into the Waianae Dome, and brought it to a condition much like the present.

(4) A northwest-southeast trending rift, or line of volcanic vents, east of the eroded Waianae Dome came into action and built another volcanic dome, which had a pear-shaped ground plan, with the broad end at the southeast. This pear-shaped "Koolau Dome" extended far enough to leeward so that it overlapped the eroded flank of the older Waianae Dome.

(5) The load imposed by the weight of the Koolau Dome was also excessive so that the underlying support failed, and the northeast part of the broad, southeast end sank step by step, beneath the sea.

(6) Erosion by running water dissected the Koolau Dome about to its present condition, and wave work pushed back the shoreline, especially on the windward side. During this time further erosion was done in the Waianae Mountains, but because of their leeward and therefore drier position it was far less in amount than that done during the same interval in the Koolau Mountains. This erosion was accomplished at a time when the ocean was at a level at least a thousand feet lower, relative to the island, than at present.

The evidence for the lower level of the ocean is derived from the depths at which the artesian wells pass from sedimentary rock into volcanic rock, and is discussed on pages 25 to 29. Since corals grow well only in shallow water, some persons have cited the finding of coral at depths of a thousand feet in well bores as proof of a great submergence. This is disputable evidence for it may be that the drill has penetrated a bed composed of fragments that were broken from a reef and fell or rolled to great depths and accumulated to make a rock very much like true reef rock, and indistinguishable to the driller.

(7) The island of Oahu became submerged at least a thousand feet deeper than it had previously been. This submergence appears to have been due to a sinking of the island as a whole. The reporting of a layer of coral with its base about 200 feet below sea level in 29 out of the 43 well logs available in 1926 suggests that there was a halt after 800 feet of submergence had occurred, but as indicated above this is not provable. This submergence, when completed, brought the shoreline somewhat higher on Oahu than it is now. The later history of the position of the shoreline is complicated by several oscillations, which have been studied by Stearns (8). The last seems to have been a recession of the sea by about twenty-five feet.

(8) Streams still continued to bring mud, silt and sand and some coarser material down from the mountains, which accumulated in favorable places along the shore. The submerged parts of the valleys were to a large extent filled with such sediments. The inward curving shore between Diamond Head and Pearl Harbor appears to have been especially adapted to retain these sediments and to prevent their being swept away by ocean currents. Diamond Head acted as a barrier to divert the west-flowing current and make a quiet lee. Along with the mechanical sediments from the mountains there was also accumulated much reef-rock made by corals and associated plants and animals. In addition to fringing the shore and filling the bays, tongues of the mechanical sediments extend inland up the valleys a few miles.

(9) The eruption of younger volcanic rocks, largely ash and tuff, building such forms as Koko Crater, Diamond Head, Tantalus, Round Top, and Salt Lake Crater, occurred toward the end of the preceding stage. Stream deposited sediments, reef-rock, and ash and tuff built up a coastal plain with its surface near sea level. They

constitute the prism-shaped cap-rock of the artesian system. Parts of the younger volcanic matter belong with the prism just described, but other parts, such as Diamond Head, rise above the upper surface of the prism.

Some of the younger volcanic vents, at times, discharged liquid lavas instead of ash and other fragmental products. These lavas made flows within the valleys, such as the one which has been quarried for years at Moiliili.

(10) There followed an interval of erosion during which both streams and waves were active. The work accomplished by streams during this interval cannot be separated from that accomplished both earlier and later. Waves cut a rather definite terrace backed by a cliff.

(11) Wave erosion was interrupted, and shifted to a different level, by the recession of the sea to its present level. This former higher stand of the sea is indicated by the existence of typical reef-rock above sea level at many places on Oahu. This emergence exposed the wave-cut cliff and terrace and they have survived to the present in a number of places.

(12) The latest stage in the geologic history includes the present. It is characterized by continued stream erosion, by wave erosion at the new sea level, and by the accumulation of more sediments on the coastal plain, in valley plains, and off the shores of the island.

C. GEOLOGIC STRUCTURE

It now becomes appropriate to consider the results accomplished by the various processes discussed in the preceding section; that is, the kinds of rocks in the Honolulu region and their positions or attitudes.

1. The Water-Bearing Lavas

Forming by far the greater part of the bulk of Oahu are two series of lava flows, corresponding to the Waianae and the Koolau domes. The flows of each dome were poured out in rapid succession so that little or nothing was eroded from one flow before the next flow covered it. Therefore they lie as nearly parallel to one another as is possible for lava flows, and are said to be "conformable" on one another. Since the vents from which the Koolau lavas of the Honolulu district came, lay to the northeast, the flows are now found to slope downward in a southwesterly direction at an angle of 4° to 8° from the horizontal.

The lavas contain a great many voids, which include the following types:

1. **Intercrystal Spaces.** While the lava is cooling and crystallizing minute voids may develop between the mineral grains of which the rock is composed. These voids are far too small to be of importance in ground water supply.

2. **Shrinkage Cracks.** In cooling after solidification a lava flow must shrink. This causes internal tension which results in cracking.

The tension cracks are in general roughly vertical, that is at right angles to the surface of the flow where most of the heat is lost. Many of these cracks are very narrow, but some are fairly wide. The wider ones are effective water carriers because they extend for fairly long distances.

3. **Gas Pores.** Live lava is a complex solution of molten rock matter and gases. As the gases come out of solution they make bubbles or gas pores. In extreme examples the lava rock may resemble a frozen froth or foam. The lavas at Honolulu vary greatly in the abundance of gas vesicles. Where the vesicles are of fairly good size, are abundant, and connect with one another they may transmit a great deal of water.

4. **Clinker Voids.** When an "aa" lava flow is in motion the chilled and brittle crust is dragged along by the viscous lava beneath. The crust is broken by this drag into extremely rough and irregular pieces. Since these pieces or "clinkers" do not fit together, there are large voids between them, which are very effective in carrying ground water. Less abundant and less effective are the voids made similarly by "pahoehoe" flows.

5. **Bedding Voids.** When a later flow is poured out over the irregular surface of an earlier flow, it is impossible for the two to come into perfect contact. The younger flow would have to be very fluid to fit itself to the irregularities of the older flow. But many a flow advances over a sort of pavement that it has laid down for itself consisting of its own solidified and shattered crust. Such voids may be made between the successive batches of lava that are discharged in a single short spasm of activity as well as between flows made a long time apart. Bedding voids are very effective carriers of ground water in the Hawaiian lavas, for they are not only very abundant, but are also very open so that they present little frictional resistance to the movement of water. Moreover, bedding voids may form pervious zones that extend great distances, and are formed both by aa and pahoehoe.

6. **Subsequent Cracks.** Should the lavas, after coming into place and solidifying, be subjected to mechanical stress they may be cracked. Such stress might be due to jarring by earthquake waves, to faulting, or to settling. Subsequent cracks are fairly extensive and many are open enough to carry water.

7. **Lava Tubes.** Some lava flows develop strong crusts by the cooling and solidification of the upper surface. Later the supply of lava will stop and the liquid lava may drain out, leaving a long tubular opening under the crust. Lava tubes formed in this way would be as good as artificial pipes for carrying water, but they are far from common.

8. **Tree Molds.** Where a lava flow invades a forest it may kill but not burn up some of the trees. The lava hardens around the charred tree, and forms a tubular mold when the tree finally rots away. These are not of importance in the matter of ground water supply.

From the preceding inventory of the voids in lava rocks it is clear that these rocks are highly permeable and constitute a splendid aquifer or water-bearing rock body. The extremely high permeability is illustrated by the conditions at the well of the Oahu Railway and Land Co. at 250 feet altitude on the line between Waipahu and Schofield Barracks. The water level in this well, which is about 3½ miles inland, was about 22 feet above sea level on August 16, 1926. On July 14, 1926 the water level in the well three miles nearer the sea, used by the Territorial Division of Hydrography as a standard for Waipahu, was about 15½ feet above sea level. Thus the water level rises only about 6½ feet in 3 miles. This implies that the impermeability or resistance to flow through the lava is so slight that it is overcome by a slope as low as 6½ feet in three miles, or about 26 inches to the mile.

A little attention may be given here to the erroneous but recurrent idea that the water-bearing rock is only a relatively thin layer. A fair number of wells extend more than 200 feet into the aquifer. The Hawaiian Electric Company's well in the rear of the Seamen's Institute is 1,150 feet deep, and extends 340 feet into the aquifer. It does not appear that any one has ever drilled through the aquifer into a lower, water-free rock. The various shafts that have been sunk in and near Honolulu have permitted direct observation of the aquifer, which was impossible in the days when our only source of information was in the cuttings brought up during drilling operations. These direct observations show that the aquifer is rather a series of more or less permeable lava flows. Furthermore, it is not conceivable that a single discharge of lava could have mantled all the slopes to form an impermeable base under the water-bearing rocks. The normal method of growth of a lava dome implies that it should be rather uniformly permeable and that Herzberg's law (see page 15) should apply. The mistaken idea of a thin water-bearing layer seems to have carried over from the diagrams of artesian basins and artesian slopes in stratified rocks elsewhere in the world, and to have been applied erroneously to the Honolulu artesian system which is neither an artesian basin nor an artesian slope.

The aquifer, or water-bearing rock member of the Honolulu ground water body is the great aggregate of many lava flows, heaped up on one another to make a broad dome, but now trenched by valleys in its upper part and buried under coastal plain sediments in its lower part. If appropriate pressures could in some unimaginable way be applied to the water in the mass of lava flows in the Honolulu artesian system, the water could be made to move through it in any direction. The only pressure actually applied is that due to gravity, but it is opposed by the overlying cap of coastal plain sediments and by the back pressure of sea water. The great number of voids of the several kinds constitute channels by means of which the water can readily move through the lava rocks.

2. The Unconformable Relationship Between the Cap-Rock and the Water-Bearing Rock

The main mass of the Koolau Mountains was built up by a series of lava flows which followed one another so quickly that only negligible erosion occurred between. When the eruptive action died down erosion became dominant. At this time the Honolulu region stood at least a thousand feet higher with respect to sea level than it does now. The evidence in support of this statement is that the subterranean contour lines representing the upper surface of the water-bearing lava rocks make V-shaped re-entrants that extend up the valleys instead of sweeping as smooth curves past the valleys.

The artesian map of the Honolulu District, figure 10, was prepared in the following way. The positions of all known wells were transferred to a sheet of tracing cloth from a street map on which the Board of Water Supply had plotted them. The serial numbers assigned them by the U. S. Geological Survey were entered in slanting numbers by the well symbols. Three "lost" wells were similarly plotted in their approximate positions. By each well symbol there was also entered the depth in feet below sea level at which the well passed from the impermeable cap-rock into the water-bearing lava rock. The degree of certainty varies, and is greatest for wells for which logs are available. The best-known depths were entered in larger, erect figures. Next most reliable are wells for which the depth of the original casing is known. It was arbitrarily assumed that ten feet of casing are in lava rock. These depths were entered in smaller, erect figures. More doubtful depths were entered in the same smaller, erect figures, but followed by one or two interrogation points.

There were also plotted the locations of four diamond-drill holes in Palolo Valley, with the height above sea level or the depth below sea level at which they passed from valley-fill sediments into lava rock.

The tracing, with only the well symbols, well numbers, drill holes, drill-hole numbers, and altitudes of the top of the lava rock, was removed from the street map, and the subterranean contours were drawn to indicate as well as possible the shape of the irregular surface between the overlying cap-rock and the underlying water-bearing lava rock. These contour lines are drawn as lines of short, heavy dashes.

The tracing was next laid over another map from which the present surface contour lines, at intervals of 500 feet, were drawn as continuous light lines. Next there were drawn, with long, light dashes, other contour lines that are tangent to the seaward parts of the present contour lines, just described. These long-dash contour lines indicate approximately the original form of this part of the Koolau volcano, when eruption had ceased and it was a rather smooth and uneroded lava dome. These may be spoken of as the "primitive contour lines," in contrast to the present day contour lines. For the purpose of orienting the reader there were finally added the shore line, the reef edges, and a few streets.

Inspection of the map shows that the original topography can be restored by the smoothly-sweeping, primitive contour lines, which resemble those of the present uneroded slopes of Mauna Loa. The present topography and the buried upper surface of the water-bearing lava rocks are shown by strikingly wavy contour lines whose

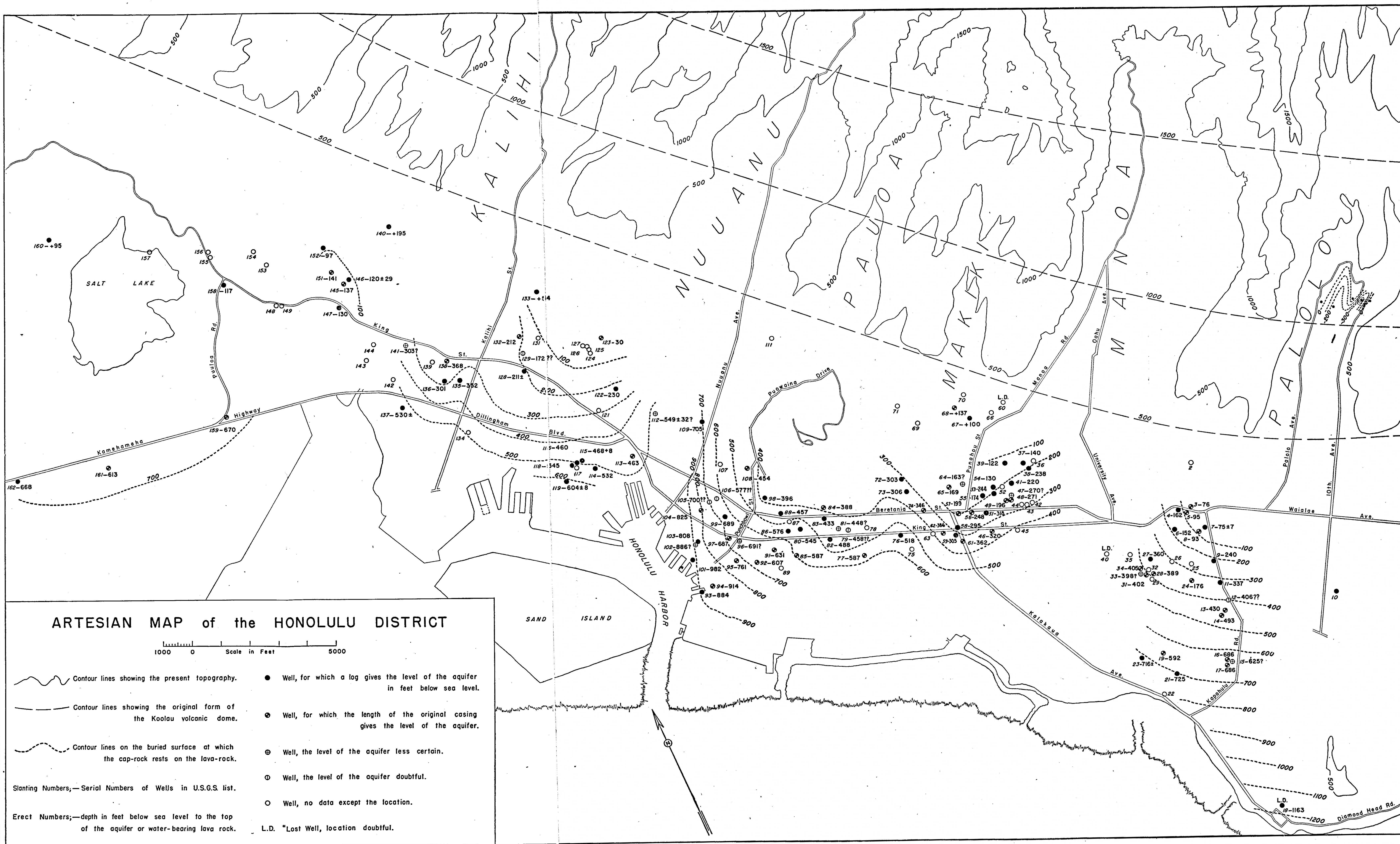

Figure 10. Artesian Map of the Honolulu District.

re-entrants represent surface valleys or buried valleys, whereas the salients represent surface ridges or buried ridges. Streams can cut valleys only above sea level. Opposite Nuuanu Valley the contour for 900 feet below sea level makes a decided re-entrant which must have been above sea level when it was cut. Data are insufficient for drawing the 1,000-foot contour, but it would also presumably make a notable re-entrant, as might also the lines down to 1,300 feet below sea level. Such a re-entrant would prove that this part of the island once stood 1,300 feet higher than it does now. The most that we can assert is that this part of the island once stood at least 1,000 feet higher than now.

Less pronounced re-entrants appear opposite Kalihi, Pauoa, and Makiki Valleys. Manoa Valley is broad and its center lacks wells, so that re-entrant contour lines cannot be drawn. However, there is suggestion on both the east and west sides that the contours swing inland as if to make a re-entrant, instead of extending boldly across Manoa Valley. (Well No. 40, whose position is doubtful, is said to have failed to reach lava rock although it extended 720 feet below sea level).

Wells are lacking opposite the mouth of Palolo Valley, but the contour lines based on the drill holes inland, show that this valley was cut to a notable depth this far from the shore.

The foregoing shows the character of the surface of contact where the body of sedimentary rocks, that form the Honolulu Coastal Plain, rests on the underlying body of lava rock. In other words, it shows the surface between the overlying, impermeable cap-rock, and the underlying, permeable water-bearing lava rock. The contact is a surface that in general slopes seaward at the rate of about one in eight. It is complicated by troughs that depress parts of it, and these troughs lie underneath the valleys and their seaward extensions beneath the coastal plain. Thus, these troughs represent ancient parts of the valleys which are now filled with sediments and buried.

If we could excavate one of these valleys and look at its sides, we would see the eroded edges of many lava beds. The view would resemble that in upper Nuuanu Valley, where beds sloping gently seaward may be seen. The beds removed from such an imaginary excavation would be approximately horizontal. In other words, their position would not conform to the inclined position of the beds of lava. The contact between the two sets is spoken of as an "unconformity."

3. The Cap-Rock

The coastal plain, on which much of Honolulu stands, varies in width from a little over a mile in its eastern part at Waikiki to about three miles in its western part at Moanalua. The eastern part is mostly dry land, but formerly included a moderate amount of wet land, now largely filled in. The western part includes only a narrow strip of dry land, seaward of which is a broad stretch of shoal water and tidal lands extending out to the reef. This coastal plain is underlain by the sedimentary and other rocks of the cap-rock, and extensions of these deposits continue inland up the valleys for greater or less distances as tongues of valley fill.

The body of sedimentary rocks underlying the coastal plain constitutes a rude, triangular prism with the coastal plain as its upper face. Shoal water or tidal land extends from the shore out to the reef, which, though under water, may be taken as the outer edge of the coastal plain. The seaward or outer face of the prism of the coastal plain is only poorly known because few soundings are available. In general, it slopes downward rather gently to a depth of about 300 feet a mile or a little more off shore. Thence it slopes more steeply down to 2,000 feet about two miles from shore.

The lower face of the prism is in unconformable contact with the water-bearing lava rock, and is therefore somewhat like a tremendously enlarged, and battered piece of corrugated sheet-steel roofing, except that the corrugations are of very uneven sizes. The corrugations correspond to the buried ridges and valleys.

In 1926 an earlier edition of this report was prepared, and included a study of the materials reported by well drillers. A number of logs of wells drilled since then are available, but have not been included as it is thought that they would not change the general conclusions. Consequently what follows is only a restatement of matter from the earlier report.

Over a hundred different terms were used by well drillers in describing the material encountered in sinking the wells of the Honolulu district. For study and comparison these were combined so as to reduce them to only six classes, namely, lava, ash and tuff, coral, clay and mud, silt and sand, and gravel. These classes may not be pure and the last four grade into one another. Thus, true reef rock may grade into a firm rock composed of hardened coral mud, which grades into soft coral mud, which in turn grades into clayey mud. Again, gravel may grade into sand, sand into silt, and silt into mud.

Making such interpretations of the drillers' reports as seemed reasonable, the per cent distances drilled through each class were tabulated. Only one well was considered from each of the groups of wells at the pumping stations. The data were treated separately for each of the four isopiestic areas of the Honolulu district, and averages for the whole district were calculated, as in the following table:

Rock Classes Encountered in 39 Wells in the Honolulu District
(Percentages, lava rock omitted)

Isopiestic Area	Ash	Coral	Clay	Sand	Gravel
1. Waikiki-Moiliili	6.5	49.8	32.4	5.5	5.8
2. Punahou to Nuuanu	3.0	44.5	45.8	3.7	3.0
3. Nuuanu to Kalihi	0.6	16.4	78.0	0.7	4.3
4. West of Kalihi	....	14.1	58.6	13.8	13.5
Average of all wells	3.3	39.6	49.3	3.7	4.1
Average of 4 areas	2.5	31.2	53.7	5.9	6.7

The mechanically formed sediments, those made by the accumulation of debris washed from the mountains, including clay, sand, and gravel, increase from about 44 per cent to about 86 per cent from the Moiliili-Waikiki area to the area west of Kalihi. The abundance of coral, the sediment formed by living organisms, decreases in the same direction from about 50 per cent to about 14 per cent. Ash (including tuff) decreases from 6.5 per cent to 0.6 per cent in Area No. 3 and is lacking in Area No. 4. Ash from Salt Lake Crater occurs in part of Area No. 4, but was not reported in the few logs available.

Clay, with which mud is included, constitutes nearly half of all the volume of the cap-rock and is therefore almost as abundant as the other four types taken together.

Graphic plots of the logs available in 1926 were made, but were not published. They were deposited with the Territorial Bureau of Hydrography, where they may be consulted. The graphic plots for wells which are so situated geographically that there might be a chance of correlating the beds shown in each of two or more wells were laid out on a large table for comparison. The following generalizations can be made:

(1) Volcanic ash or tuff, a cemented form of ash, is found near the surface in wells which are close to Punchbowl and Round Top. This ash is now believed to have been erupted by the crater of Tantalus.

(2) A bed of coral of varying thickness is found near sea level in 23 of the 43 wells for which data were available. All of the wells which lie in the seaward part of the coastal plain have penetrated this bed, but it fails to appear in a majority of the wells in the landward part. This is probably the bed which crops out at Moiliili, Iwilei, Kalihikai and other places.

(3) Of the 43 wells for which data were available, 29 penetrated a heavy coral bed whose base is about 200 feet below sea level.

(4) Of the 43 wells, 34 penetrated clay as the last material before entering the water-bearing lava rock. In two wells there was coral on the lava rock, and in seven wells there was sand or gravel or a mixture of the two. Clay, however, is the usual thing to find above the lava rock. Of the nine wells that do not have clay immediately above the aquifer there is, with one exception, only a thin layer of sand, gravel, or coral between the lava rock and the lowest clay zone. Probably some of the material called "clay" by the driller is actually thoroughly rotted and decomposed lava rock and constituted a residual soil at the time that this part of the island sank.

The types of sediments comprising the cap-rock differ considerably in permeability or ability to permit or obstruct the movement of water. Gravel, sand and ash consist of larger or smaller fragments which are packed together closely. Nevertheless they cannot be packed perfectly tightly and there are always spaces or voids between the grains. In most gravels and sands the fragments are fairly well rounded and the total pore space is from 15 to 35 per cent of the total volume. In other words, if we had a watertight box of 100 cubic feet capacity and filled it with the gravel or sand we would be able to add from 15 to 35 cubic feet of water which would find place in the chinks or voids between the pebbles or sand grains. The fragments that comprise ash are angular and cannot be packed as closely as the rounded constituents of sand or gravel. Consequently the ash has a larger porosity; which ran up to 60 per cent in one sample that was tested. In all three of these types of sediments the pores are not only numerous but are also fairly large and therefore permit water to pass through them readily.

The clay and mud also consist of small particles which are packed together and which have pore spaces between them that may equal 20 to 40 per cent of the total volume of the rock. However, clay and mud permit little water to move through them and constitute a highly impermeable material. The impermeability seems at first thought paradoxical in view of the fact that per cent pore space is high. The reason is that though the pores are numerous they are very small; so small, in fact, as to restrict greatly the movement of water through them. Attraction of the molecules of which the clay or mud is composed for the molecules of water is great if the distance is as small as it is in these minute pores. The attraction is effective across the whole width of such minute pores and prevents flow. Once water gets into such small voids it requires heat or tremendous pressure to overcome the attraction and dislodge the water. The attraction also exists in gravel, sand or ash but it is effective only a small part of the distance across the larger pores. Few rock types are more impermeable than clay or mud.

The rock made by corals and other organisms that grow on the reef varies greatly in permeability. If waves grind up the reef material a very impermeable mud may be made which may be hardened to an equally impermeable limestone. Or the spaces between the coral branches may be filled with coral sand and gravel and therefore be rather permeable. If minute channels in reef rock carry water continually, the water will dissolve some of the rock and enlarge the channels to considerable size. Such channels might develop from thin fissures in otherwise impermeable reef rock, and transmit water readily.

In summarizing the permeability of the cap-rock we may say that ash, sand, and gravel are rather high; reef rock is usually high but may be low; and clay and mud are very low in permeability. Since clay and mud constitute about half of the total bulk of the cap-rock, and since the beds composed of the various types interfinger, the clay and mud layers tend to enwrap the others. As a consequence the cap-rock taken as a whole is relatively impermeable, though parts of it may be more or less permeable.

From time to time one hears the erroneous statement that the water of the water-bearing lava rock of the Honolulu artesian system is held in by a layer or capping of clay that extends over the whole surface of the lava rock. Logs of 46 wells in the Honolulu district give the kind of rock immediately overlying the lava rock and are summarized as follows:

Character of Material Resting on Lava Rock in 46 Wells

Number of Wells	Per Cent of Total	Material
32	69.5	Clay, mud, etc.
5	10.9	Volcanic ash or black sand
5	10.9	Sand and gravel
3	6.5	Coral
1	2.2	Sand

It is obviously not true that there is a continuous capping layer of clay, for over 30 per cent of the wells lack it. In this respect the Honolulu artesian system differs from most artesian systems which do have rather continuous capping strata of clayey material. From the geologic viewpoint it is, moreover, difficult to conceive of a process which might make a single continuous layer of so weak and plastic a material as clay that would extend up and down over the buried ridges and valleys in the lava rock foundation. A thin layer of clayey matter would not stick to such steep surfaces. The thing that prevents the escape of water from the lava rock is the whole body of material underlying the coastal plain. Parts of it are indeed permeable, but it appears that the permeable parts are themselves sealed off by other parts that are impermeable. Water might thus move through the cap-rock a little distance, but would be prevented from escaping because the permeable bed along which it started thins out to nothing between impermeable beds. The distinction is not important to an understanding of the behavior of the Honolulu artesian waters as the restraining effect of a great mass of deposits that is impermeable as a whole, though permeable in parts, would be essentially the same as the restraining effect of a thin, continuous capping of clay. The massive cap is better in that it is far less liable to damage, by the disturbance involved in a severe earthquake, than the single, thin, capping layer would be. Undoubtedly the coastal prism of cap-rock is not absolutely impermeable, and an unknown amount of water is lost through it by what we may call "leakage springs." Perhaps some of the water recovered from the cap-rock by shallow wells is water that has escaped from the artesian part of the main ground water body by such leaks. We do not know of any submarine springs supplied by leakage through the cap-rock, but such may exist. The rate of leakage through the cap-rock will be greater when the artesian level is high than when it is low.

4. The Isopiestic Areas of the Honolulu Artesian System

By the term "Honolulu Artesian System" is meant the combination of (a) the body of water-bearing lava rocks, so exposed as to absorb part of the water that falls as rain and so shaped as to carry the water laterally, and (b) the body of cap-rock which causes the artesian pressure by restraining the lateral movement of the water. The whole system may also be divided into contrasting geographic areas. These areas are called "Isopiestic Areas" (Greek, "iso" meaning equal, and "piezein" meaning to press) as they are characterized by having uniform artesian pressure. Measurements of the height to which water will rise in various wells of the Honolulu district are made from time to time by the Board of Water Supply and also by the Territorial Division of Hydrography. It is found that the water rises to about the same height above sea level in all the artesian wells in the area from Moiliili to Waikiki, except in wells with leaks. The leaks allow water to escape underground thus dissipating the pressure and causing less rise of water than in nearby sound wells. This is Isopiestic Area No. 1.

A second area of uniform, but different, rise of artesian water extends from about McCully Street through the Punahou and Makiki districts, and the center of the city as far as Nuuanu Valley, and forms Isopiestic Area No. 2. The rise of water in this area was originally about seven feet more than in Isopiestic Area No. 1.

Isopiestic Area No. 3 extends from Nuuanu Valley to Kalihi Valley, and Isopiestic Area No. 4 extends westward from Kalihi Valley. The distinction between Areas No. 3 and No. 4 is not as pronounced as that between Nos. 1 and 2, or that between Nos. 2 and 3. The original rise in No. 4 was about five feet less than in No. 2. Data on the original rise in No. 3 are not available to the writer.

Isopiestic Area No. 5 lies east of Area No. 1 and has decidedly lower heads.

The term "artesian basin" has been applied to these areas, which is inappropriate as it should be reserved for downwarped sedimentary structures, such as are described on pages 12 to 14. (See, for example, Larrison, et al. [9]). There is no intention to doubt the existence of these contrasting areas. The intention is to stress the fact of their existence and to give them the appropriate name, "isopiestic areas," meaning areas of like artesian pressure.

It is due to the fact that inverted, underground dams exist that it is possible for the areas to differ from one another in artesian level. The lack of such dams within each area permits the artesian level to be uniform. The degree of difference varies from time to time because of differences in the amount of water supplied by rain and because of differences in the amounts of water removed by pumping and otherwise.

The boundaries between the several isopiestic areas cannot be precisely located, and never will be unless a vast number of well logs become available. Their general nature, however, is clear. The separation is due to the fact that inverted, subterranean dams project downward from the general under surface of the prism of cap-rock and constitute underground, impermeable barriers. These downward projecting dams are the fillings of old valleys. Manoa Valley is the widest and most open of the valleys in the Honolulu region and its submerged end therefore contains a broad and effective underground dam. This explains the fact that the original contrast between the two isopiestic areas that border the extension of Manoa Valley is greater than the contrast between the other pairs of isopiestic areas to the west, which are separated by narrower and less effective underground dams.

It often happens that where several branch water mains lead out from a principal main, the pressure in them may vary though they all tap the same source. This is because of differences in elevation, in corrosion and obstruction of pipes, in leaks, in draft, and so on. The four isopiestic areas at their inland edges draw on a common source, the main body of ground water in the lava rock underlying the Koolau Mountains. The difference in pressure in the isopiestic areas must be explainable by conditions analogous to those suggested for the several water mains. The water-bearing rock of the several isopiestic areas is continuous, just as the bores in the mains are continuous. The underground dams divide the water-bearing rock into branches in which different degrees of pressure develop. The fact of connection between the several isopiestic areas by way of the inland part of the body of lava rock has been shown by pumping tests. By increasing the rate of pumping in one such area to more than usual, the artesian level will be lowered not only in that area but also in adjacent isopiestic areas.

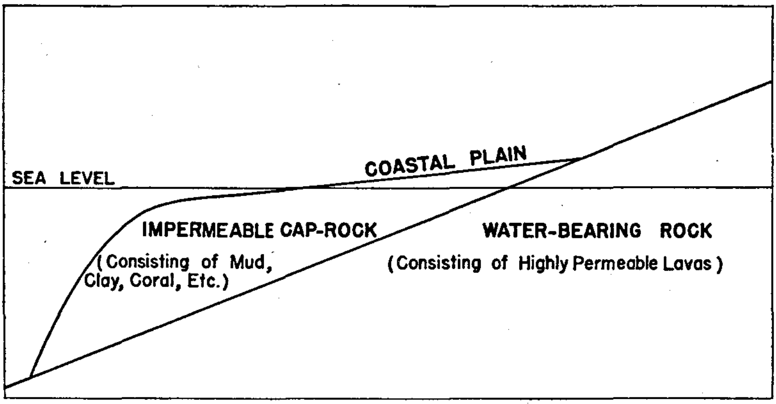

Figure 11. Diagrammatic Cross-Section, Showing the Essentials of the Geologic Structure at Honolulu.

D. GROUND WATER CONDITIONS AT HONOLULU

Figure 11 is a diagrammatic cross section across Honolulu, in the direction at right angles to the shoreline, and shows the general character of the relationship of the triangular prism of cap-rock lying on the sloping flank of the great mass of water-bearing lava rock. Figure 12 is a modification of figure 11, in which there have been added lines showing the boundaries between the various hydrologic zones. Two wells have also been added. The figure is in a way a modification of figure 9, in that it applies the general principle to the specific types of rock and attitudes of the rock bodies at Honolulu.

Rain falling in the mountain region at the right of the diagram is in part absorbed and moves downward under the influence of gravity. Rain falling on the upper surface of the prism of cap-rock does not enter the artesian system but either runs off over the surface to the sea or is absorbed to give rise to shallow ground water such as has been encountered in various excavations and wells in the central part of the city. The boundary between the regions where absorbed water joins the artesian system and where it makes only shallow ground water may be read in part from Stearns's (10) geologic map of Oahu. The boundary follows the inland edge of the cap-rock deposits (Quaternary Alluvium and Recent Alluvium on Stearns's map), where they touch the lava rock (Tertiary Koolau Basalt). Unfortunately the younger volcanic rocks have been poured out over a good deal of this boundary and conceal it, so that its full length cannot be traced. Where these younger volcanic rocks rest on alluvium they probably do not contribute to the main ground water body. Some parts that rest on the older volcanic rocks will be relatively impermeable and will therefore not contribute to the main ground water body.

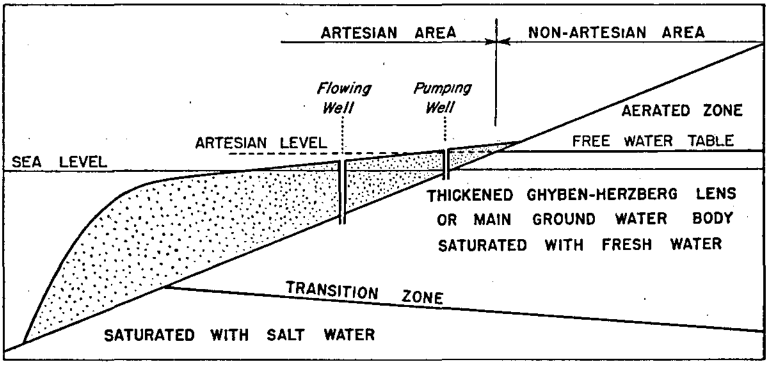

Figure 12. Diagrammatic Cross-Section, Showing the Hydrologic Conditions at Honolulu.

Returning to a consideration of figure 12, rain falling to the right of the diagram is in part absorbed and moves downward under the influence of gravity until it comes near to sea level. Then it must either move shoreward over the main ground water body already present or displace it by shoving it downward and shoreward. Thus, there results a shoreward movement of ground water, which is opposed by the prism-shaped dam or impermeable cap of clay, mud, coral, etc. The shoreward moving ground water might conceivably escape either as "leakage springs" through imperfections in the cap-rock; or over the inland edge of the prism as "overflow springs," or under the lower edge of the cap-rock as "submarine springs," as shown diagrammatically in figure 13.

Leakage springs may supply some of the water that is found in shallow wells and excavations on the coastal plain. The springs on the shores of Pearl Harbor are believed to be essentially overflow springs. Submarine springs, because of their situation are not known to exist, but prior to the drilling of the earliest artesian wells all of the water of the Honolulu district was discharged through springs of one or more kinds.

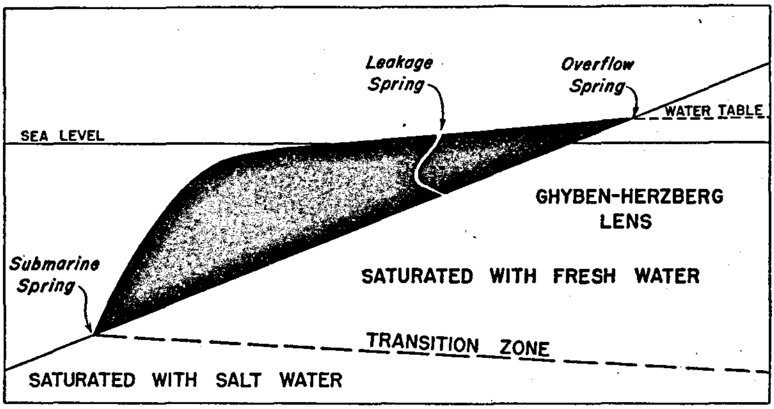

Figure 13. Diagram of Leakage, Overflow, and Submarine Springs.

Artesian wells may be looked upon as intentional, artificial leakage springs since their relation to cap-rock and water-bearing rock is the same. The first well in the Honolulu district was drilled in 1880 for Dr. Marques and his associates, close to Wilder Avenue a little west of Metcalf Street. The ground at that point is about 37 feet above sea level. After drilling to a depth of 273 feet (236 feet below sea level) water issued from the top of the well. It was found that the water would rise about five feet above the ground level or 42 feet above sea level. Other wells were soon drilled nearby and in all of them the water rose to the same height. It was soon recognized that a well would yield flowing water if the site was less than 42 feet above sea level, but that the water would not flow if the site was more than 42 feet above sea level. In figure 12 two wells are shown. The well to the left has its mouth below the artesian level and will flow, but the well to the right has its mouth above the artesian level and will yield water only by pumping. The original position of the artesian level at an altitude of 42 feet suggests that the transition zone between rock saturated with salt water and rock saturated with fresh water must have been about 40 times 42 feet or 1,680 feet below sea level. [Using the more precise value of the Ghyben-Herzberg ratio we get a little over 1,600 feet instead (38.3 x 42 = 1,608.6 feet)]. This may also have been the level of the effective lower edge of the cap-rock, but for this speculation we have no evidence. The preceding discussion refers to "Isopiestic Area No. 2," which extends from about McCully Street to Nuuanu Valley. In Isopiestic Area No. 1, including Moiliili and Waikiki, the water originally rose about 35 feet above sea level implying that the transition from fresh to salt water was about 1,400 (or 1,320) feet below sea level. In Isopiestic Area No. 4, west of Kalihi Stream, water originally rose 37 feet above sea level, implying that the transition zone was about 1,480 (or 1,417) feet below sea level (8).

There must have existed a condition of equilibrium between the amount of water brought into the artesian system by the absorption of rain and the amount of water discharged from it by springs, either on land or beneath the sea. In times of drought the water brought in by rain would have been less than in wet seasons. This presumably made some variation in the rate of discharge by springs but the variation was probably not large because of the great storage capacity provided by the abundant voids in the lava rocks.

When the first artesian wells were drilled this equilibrium was shifted a little because part of the water formerly discharged naturally by springs came to be artificially discharged by wells. As long as the wells were few the shift of equilibrium was small. Later, as the discharge through wells became great the equilibrium was markedly upset and became conspicuous as a decrease in the height to which water would rise. The following table shows the artesian heads or heights above sea level to which water would rise in the four isopiestic areas at several dates. (11).

Changes in Artesian Level in the Honolulu District
(In feet above sea level)

Isopiestic Area	Original Level	March 1911	August 1926	March 1937	October 1946
No. 1	35	25.2	18.4	27.0	23.2
No. 2	42	32.6	23.0	32.3	23.7
No. 3	....	31.4	25.0	31.5	23.5
No. 4	37	29.2	23.5	29.0	21.6

1. Analogy With a Gravity Water Works

The continued general downward trend of the artesian head in the Honolulu artesian system signifies that the withdrawal, artificial and natural, from the main ground water body has been greater than the recharge by the absorption of rain water. In the following table an analogy is developed between a gravity water works and the Honolulu artesian system. In studying the table, read the corresponding paragraphs in both of the columns before going down to the next paragraphs.

THE WATER WORKS	THE ARTESIAN SYSTEM
There is an abundant supply of water in an elevated reservoir, into which a small stream discharges limited amounts of water. The reservoir has a rather small outlet orifice, so that the amount of water going into the mains is limited.	There is an abundant supply of water from rainfall, provided enough time is allowed. During droughts the recharge is small, and even in wet seasons the rate of recharge is limited by the absorbing power of the soil.
If no faucets are open, there will be no flow and the pipes will all be under the maximum pressure or head. There may, however, be some loss of pressure through leaks.	If there are no wells there will be no artificial discharge, and the artesian level will be at the maximum, being limited by the natural discharge through springs.
If a few faucets are open they will not discharge as much water as the orifice at the reservoir is able to pass, and the pressure will be adequate.	If a few wells are in operation they will discharge less water than the recharge from rainfall. The discharge through springs will be less than before.
If many faucets are open they will be able to discharge more water than the orifice at the reservoir can pass, and the pressure will decrease. Faucets in unfavorably high situations will cease to flow and may even suck air.	If many wells are in operation they will discharge more water than the annual recharge from rain. The difference will be made up by a reversal of the flow at submarine springs under the seaward bottom edge of the caprock, or through leakage, springs, or both. Salt water will enter the region of the main ground water body. The salt water, since it is heavier, will in general stay below the fresh water, but there will be some mixing. The artesian head will fall so that wells in unfavorably high situations will cease to flow. Very deep wells will yield brackish or even salty water.

The Honolulu artesian system is now in the condition described in the last paragraph. There would be no artesian system at Honolulu were it not for the back pressure of the heavier ocean water. But, the ocean water is not an unmixed blessing, for it carries the ever-present threat of contaminating the fresh artesian water with non-potable salt water if there continues to be a draft greater than the recharge. It may be worthwhile to note that the Honolulu artesian system is in a doubly precarious situation as compared to the more usual types of artesian systems. In any artesian system, regardless of its type, overdraft inevitably results in decreased head, but in the Honolulu system overdraft carries with it the additional threat that salt contamination may result and make the water unfit for use.

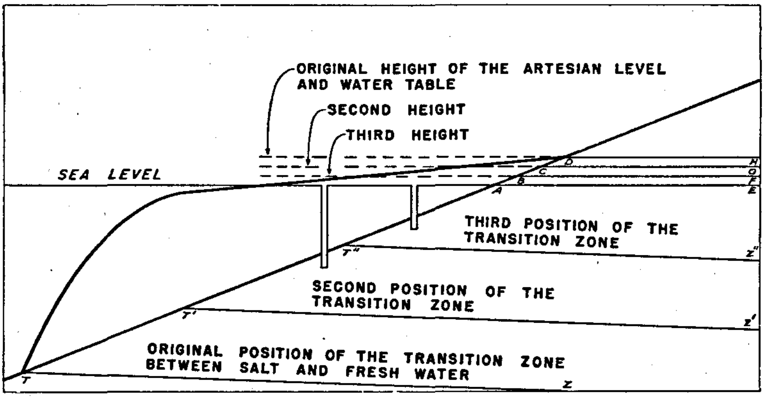

Figure 14. Diagrammatic Cross-Section to Explain Salt Contamination as a Result of Overdraft.

In figure 14, the line T-Z represents a possible original position of the transition zone between salt and fresh water, and corresponds with the line D-H representing the original position of the water table. With the withdrawal of a large amount of water year after year and in excess of the recharge from rain, the transition zone was forced upward to the position of T′-Z′, and the water table dropped to the level C-G. T″-Z″ and B-F represent the effect of still further overdraft, with the result that the left hand or seaward of the two wells reaches only salt water and has thus been made useless for most purposes. The well farther inland has also been adversely affected, for, though the well still yields fresh water, the artesian level is below its mouth and it no longer flows, but must be pumped.

2. Top Storage and Bottom Storage

It is clear that heavy rains do raise the water table and the artesian level, as is shown not only by the records of the Punahou and Thomas Square wells plotted in figure 2, but also by the records of many other wells. But it is not at all clear that a rise of the water table is accompanied by a prompt, 40-fold lowering of the transition zone. We would expect a significant time lag in view of the inertia of the tremendous amount of water that would have to be displaced downward and seaward under the submerged edge of the cap-rock.

It is clear that a large volume of rock under Honolulu has had its fresh water extracted, and that this has been displaced by salt water. The area in figure 14 between T-Z and T″-Z″ represents a cross section of a prism thus drained of fresh water; and the area between B-F and D-H represents a cross section of a prism drained of fresh water, which has been replaced by air. Bearing in mind that it was necessary to show the transition zone much less than 40 times as far below sea level as the water table is shown above sea level, in order to get the figure to fit a printed page, we can see that the part of the main ground water body below sea level has contributed about 40 times as much as the part above sea level to the total depletion of Honolulu's underground reserve as of 1880. The two contributions may be referred to as coming from "bottom storage" and from "top storage," using Wentworth's terminology. (12).

An approximate calculation may be made as to the amounts of bottom and top storage, for which purpose we may select values that will be of the right order of magnitude and which will make the arithmetic simple. Let us suppose that (a) the land area in which water can be absorbed on its way to the main ground water body, (b) the area of the freely fluctuating water table, and (c) the area of the fluctuating transition zone between fresh and salt water are all twenty-four (24) square miles. These three areas overlap each other. Let us also assume that the water-bearing lavas have a porosity of 20 per cent. A slab of rock one foot thick and 24 square miles in area has a volume of 24 mile-feet equivalent to (24 x 5,280 x 5,280 x 7.48) close to five billion gallons. If the porosity were 20 per cent, such a slab could hold one billion gallons of water.

This means that one billion gallons would raise the water table one foot, and increase the top storage by one billion gallons, if it had no other effect. But, if perfect equilibrium between salt and fresh water were maintained, there would have to be added 40 times as much or 40 billion gallons as bottom storage in order to lower the transition zone by 40 feet. Let us compare this with the rainfall of an average year. The rainfall on the 24 square miles of infiltration area averages 106 inches, or two inches less than nine feet, a year. If we suppose that three feet of water, a trifle over a third of the rainfall, is absorbed, the volume comes out to about 15 billion gallons. If all of this went into storage and was divided in the 1:40 ratio between top and bottom storage the water table would be raised about 4½ inches and the transition zone would be depressed about 14½ feet. If further allowance were made for leakage and for artificial draft, the shifts would be less.

From August, 1936, to March, 1938, the artesian level in the Thomas Square well rose from 26.46 to 33.23 feet, a rise of 6.77 feet in 19 months. With perfect equilibrium this would imply that the transition zone was lowered 270.8 feet. The fresh water body of the Ghyben-Herzberg lens would be thickened by about 277.6 feet, which would require the addition of 277.6 billion gallons of water. However, no such volume of water was added. This volume of water would be gotten if one-third of a rainfall of about 833 inches had been absorbed in that period of 19 months. The calculated 833 inches is nearly eight times the normal rainfall of 106 inches (7.86 times). But the rainfall at Lower Luakaha, a station fairly typical of the infiltration area, during the 20-month period from July, 1936, through February, 1938, was only 283.55 inches or about 22 per cent above normal. If the same excess held over the whole infiltration area, the volume of water falling as rain would have been utterly inadequate to supply both the top and bottom storage implied by the rise of 6.77 feet in the artesian level, with the supposititious 270.8 feet depression of the transition zone. If the depression of the transition zone had responded promptly to the rise in artesian level, the 22 per cent excess rainfall could have moved them only about 5⅓ inches upward and 18 feet downward, respectively. But the actual rise was 6.77 feet. The conclusion that we must draw is that the excess rainfall during this period went mainly to top storage and only to a small extent to bottom storage.

If we were to assume that the average porosity of the water-bearing lava rock is only 10 per cent, which the writer believes to be too low, the amount of rise of the water level by the addition of a given volume of water would be twice as great as with the assumed 20 per cent porosity. But even this less probable value would not suffice to remove the discrepancy. The rainfall required to raise the water table 6.77 feet and lower the transition zone 270.8 feet would be about 417 inches or nearly four times normal for the 20-month period that was actually only about 22 per cent above normal. Other changes in the assumed values would not suffice to remove the discrepancies.

Thus, the final conclusion is that bottom storage is NOT replenished nearly as rapidly as top storage, but that there is considerable time lag, and that much of the water taken from the artesian system in the last few decades is water that was stored for us as bottom storage in past centuries. Times of more than normal rainfall do raise the artesian level and the free water table, and thus add to top storage, but they do not add great amounts to bottom storage. In the past much water has been taken from bottom storage. It has not been replaced, and we cannot in the future get fresh water from that deep region.

3. Nature of the Transition Zone Between the Zones of Fresh and Salty Ground Water

If we were to take a jar of a gallon or so capacity and fill it half full of sea water and then pour fresh water on top of the sea water very carefully so as to prevent mixing we would have two fairly distinct layers. The fresh water, since it is lighter, would float on the heavier sea water. After a time, however, the salt would diffuse upward so that the saltiness of all parts would be uniform. Under natural conditions there would probably be slightly unequal heating of different parts of the vessel or drafts blowing across the top which would produce gentle currents that would mix the salt and fresh layers and bring them to a uniform degree of saltiness rather quickly.

The time necessary for mixing to uniform saltiness would be greatly increased if convection and other forms of stirring could be eliminated. Keilhack (13) describes an experiment on the rate of diffusion of a salt in a liquid which was not free but which filled the pores of a fine grained sand. A vessel of sand 24 inches high, whose lower half was filled with a saturated solution of magnesium chloride and whose upper half was filled with chlorine-free water was allowed to stand for a long period. No chlorine could be detected by sensitive chemical tests in the upper part after three months and only a trace after six months.

The vessel in Keilhack's experiment is analogous to the water-bearing lavas of the Honolulu region. One difference between the two is that the voids in the lavas are much larger than the voids in the sand which would hasten the appearance of salt in the upper, fresh layer by adding the effect of mechanical mixing to the effect of molecular diffusion. A second difference is that the distance through which the processes must operate is much greater in the lava rocks, scores of feet instead of a few inches, which would greatly retard the appearance of salt. These two factors oppose one another. A third difference is that there is continual recharge of fresh water at the top of the fresh-water layer in our lava rocks, which tends to drive water seaward against the direction of salt diffusion and mixing. We would therefore expect to have preserved a more or less definite contrast between the salt and fresh ground waters.

Little is known as to whether the transition from salt to fresh water is gradual or abrupt, but we may now consider such data as are available. In figure 15, the depths of certain wells in Isopiestic Area No. 1 are plotted against the chloride content of their water in October, 1926. Since the points fall in a fairly narrow zone from the upper-left to the lower-right corner of the graph, we see that there is a general increase of salt content with depth.

The filling in of the lower part of a well near the shore of Pearl Harbor permitted a study of the transition zone. This well was originally about 600 feet deep but had filled in to a depth of 580 feet. It was cased to a depth of 400 feet. The water was originally satisfactory for irrigation but it had increased to a content of 695 parts of chloride per million parts of water. In the belief that the lower part of the well tapped saltier water than the upper part, it was decided to fill in the bottom of the well. It was first cleaned out to its original depth of 600 feet and then yielded water containing about 885 parts of chloride per million parts of water. The well was then filled in installments, samples of water being taken after each section of cement plug had had time to set. The water at all times rose to a level about six feet below the surface of the ground. Pumping tests lasting several hours were made in order to collect fair samples of water. The drawdown, or amount the pump lowered the water in the well was also noted. Presumably the rate of pumpage was about the same at all times as the same pump and engine were used but it was not measured. The chloride content of the water and the drawdown at each step are given in the following table.

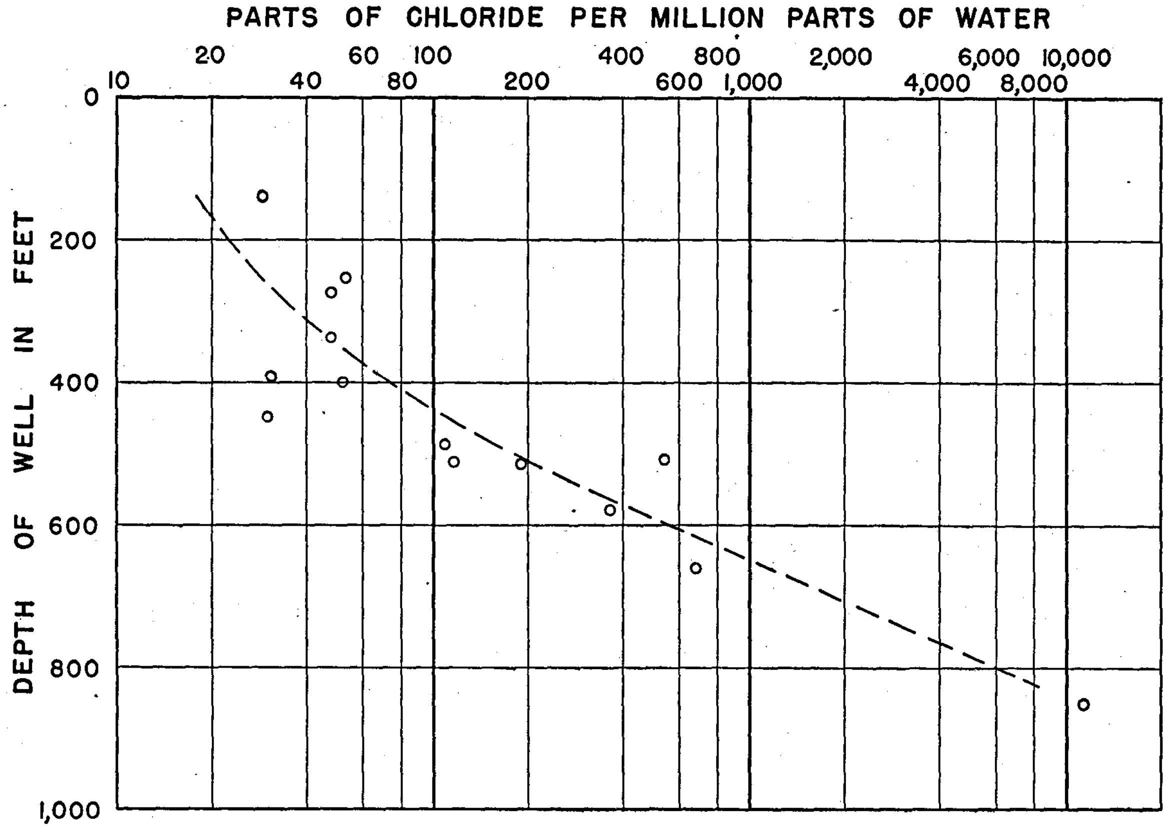

Figure 15. Depths of Wells in Isopiestic Area No. 1 and Their Chloride Content in October, 1926.

Data on Plugging of an Artesian Well Near Pearl Harbor, 1926

Date	Condition	Depth Feet	Parts of Chloride per Million Parts of Water	Draw-down Feet
May 8,	Before any changes were made	580	695	1.0
June 24,	Cleaned out 20 feet of debris	600	780	1.0
July 1,	Filled for 30 feet	570	766	1.6
July 6,	Filled for 39 feet	561	695	....
July 8,	Filled for 62 feet	538	635	2.0
July 11,	Filled for 102 feet	498	543	3.0
July 13,	Filled for 130 feet	470	505	3.2
July 17,	Filled for 138 feet	462	457	....
July 21,	Filled for 164 feet	436	408	6.2

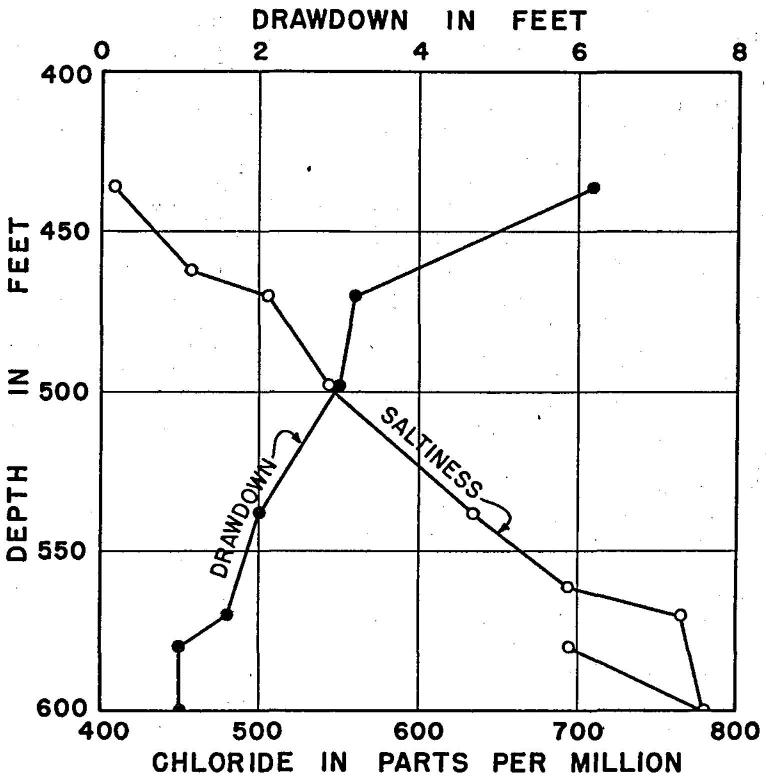

Figure 16. Graph of the Results of Filling in the Bottom of a Well on the Shore of Pearl Harbor.

These data are given graphically in figure 16. Since the well was cased to a depth of 400 feet, only that part of the well below 400 feet is capable of yielding water. As a consequence when the well had been filled to a given extent the amount of water yielding surface was decreased which means that water came into the well less readily and that a greater drawdown resulted from a like rate of pumpage. This of course means that the total capacity of the well is decreased. This loss is counteracted by the fact that the water yielded, though less in quantity, is of quality fit for irrigation. The fact that the points showing the relationship of saltiness to depth lie along a fairly straight line indicates that the transition is gradual rather than abrupt for this range of saltiness. It may be that at greater depths the change of saltiness is more abrupt, but we do not have evidence on this point.

The proposition that the quality of water yielded by a well on Oahu may be improved by plugging the lower part of the well is further supported by experience with a well on the north coast of the island. This well is about 540 feet deep and was cased to a depth of 456 feet, so that the bottom 84 feet alone yielded water. The water from this well contained about 730 parts of chloride per million. Twenty-four feet of plugging material was placed in the bottom of the well. Three days later, when the concrete had set, a pumping test showed that, though the volume yielded by the well was cut in half, the quality was so much improved that the water contained only about 125 parts of chloride per million, roughly one-sixth as much as before. The improvement from 730 to 125 parts per million, a difference of 605 parts, was made by a filling of 24 feet, which would be at the rate of 25 parts per million for each foot of filling. This is relatively abrupt as it is 14 times as rapid a change as that at the well on the shore of Pearl Harbor, where 164 feet of fill was needed to decrease the chlorine content from 695 to 408 parts per million. This is at the rate of 287 parts per million for 164 feet, or about 1¾ parts per million for each foot of fill.

The reason for the contrasting rate of change of saltiness with depth is not known, but the following hypothesis may be suggested. The artesian head varies as much as two or three feet during years with considerable rain. If the Ghyben-Herzberg ratio were strictly maintained, a variation of three feet in the artesian head would mean that, with perfect correspondence, the transition zone between salt and fresh water would vary 40 times as much, or 120 feet. However, there is probably considerable lag, both in amount and in time, in the response of the transition zone to varying artesian heads. However, be the lag great or small, there will be not only some alternate raising and lowering of the transition zone, but also the individual water particles in the fresh water zone will also rise and fall. The fluctuations of the artesian level and of the transition zone will usually be out of phase because of the time lag. At the end of a dry season, were there no time lag, the artesian head will be lowest and the transition zone will be highest. As a rainy season comes on, the artesian head will rise and the transition zone will fall, which means that fresh ground water will be forced down into a region that has recently been occupied by salt water. Some of the voids in the rock will not have free connections and will have trapped bits of salt water which will become mixed with the fresh water making it somewhat brackish. During the next dry season this somewhat brackish water will rise and will leave in the overlying rock layers a little salt, which in the next wet season will cause a very slight brackishness at a higher level than before. And so it goes on year after year. Each fluctuation of the artesian head means some fluctuation in the position of the transition zone, which in effect stirs up and mixes salt and fresh water thus bringing brackish water higher and higher.

Since heavy pumping during dry seasons must accentuate the fluctuations of the water levels, it is obvious that heavy seasonal pumping over a period of years will widen out the brackish transition zone. Since pumping is heavier in the Pearl Harbor region than along the north coast, it is reasonable to expect the more gradual transition from salt to fresh water at Pearl Harbor.

Filling of the Salvation Army well near Vineyard St. from 986 feet below sea level to 796 feet, decreased the chloride content of the water from 479 to only 53 parts of chloride per million parts of water; which is at the rate of about 2¼ parts of chloride for each foot of fill.

4. Variation in Salt Content from Time to Time

The chemical determination of the amount of chloride in a water sample is fairly simple, quick, and accurate. Table salt, which constitutes about three-fourths of all the solids dissolved in sea water, is a compound of two elements, sodium and chlorine, as sodium chloride. Sea water varies somewhat but contains about 19,000 parts of chloride in every million parts of water. We do not know just how the sodium and chlorine are related to one another and to other dissolved substances, so that it is more truthful to report saltiness in terms of chloride than in terms of some hypothetical compound. In the present report the saltiness of water is expressed in terms of chloride. The amount is expressed in terms of "parts of chloride per million parts of water," which is better adapted to decimal calculation than is "grains per gallon." One grain of salt (sodium chloride) per gallon of water is equivalent to 10.395 parts of chloride per million parts of water.

Stearns and Vaksvik (3) collected and tabulated all the chloride determinations that were available through 1934. More recent data have been obtained from the files of the Board of Water Supply and of the Territorial Division of Hydrography. For many wells only a few determinations are available, and for others there are rather long series, though most of the series are broken. For most of the series there has been no distinct change in saltiness. A few fairly clear changes are discussed below.

Several wells in the Moiliili district have shown some increase in salt content. One well shows the following ranges in chloride content:

Period	Number of Determinations	Parts of Chloride per Million Parts of Water	
		Highest	Lowest
1912-1914	25	56	41
1924-1928	5	82	55
1929-1932	49	79	65
1933-1936	6	77	70
1937-1940	7	67	58
1941-1944	24	110	64

Another well nearby was reported in 1917 as having 83 p.p.m. of chloride, but 141 determinations from 1925 through 1937 ranged from 188 to 372 p.p.m.; and 22 determinations in 1938 ranged from 145 to 598. About this time use of this well ceased, and the 41 determinations since then range from as little as 26 up to 150 p.p.m. It seems probable that if the draft on this well were renewed the chloride would again increase.

Wells in the central part of Honolulu show little change in saltiness if situated inland, but some of the deep wells near the shore have become very salty. The well at the Old Naval Station used to yield potable water, but has been abandoned because it got to yielding very salty water.

Some wells west of the city, for a time, showed a decrease in chloride content. The chloride content of the Damon well in Moanalua was 86 parts per million in the sample collected in 1910, and 83 p.p.m. in the 1911 sample. Eight samples in 1916 ranged from 77 to 81. The 33 samples of 1930 ranged from 60 to 66 p.p.m.; and the 11 samples of 1942 ranged from 52 to 57 p.p.m. Intermediate years show a general decrease in the salt content, which is perhaps due to the decrease some years back of draft for irrigating rice. Recent increase in draft in this general region has raised the chloride content, so that the 10 samples from this well from January through October, 1944, ranged from 53 to 61 p.p.m.

The McCandless well at Waimalu has a rather similar history. The single 1910 sample had 102 parts of chloride per million parts of water. Eight samples in 1916 ranged from 95 to 108 p.p.m.; and 10 samples in 1932 ranged from 77 to 93 p.p.m., which seems to have been the lowest year for saltiness. Since then there has been an increase so that the 11 samples of 1942 ranged from 109 to 136 p.p.m., and the 10 samples from January through October, 1944, ranged from 143 to 173 p.p.m.

Here we find one of the few encouraging features about the Honolulu water situation. It shows that by reducing the draft on the main ground water body the original conditions can be approached to at least a slight degree, although it is improbable that they can ever be restored.

Examination of the tables of chloride data, which are on file at the Department of Geology of the University of Hawaii, reveals very little as to seasonal fluctuation in saltiness. We might think that after heavy rains when the artesian head is raised and when the contact zone between salt and fresh ground waters is lowered, that there would be a measurable improvement in the quality of the water yielded by the wells. Our inability to find such effects is probably due to the fact that they are masked by other conditions of which irregularly varying draft is probably one.

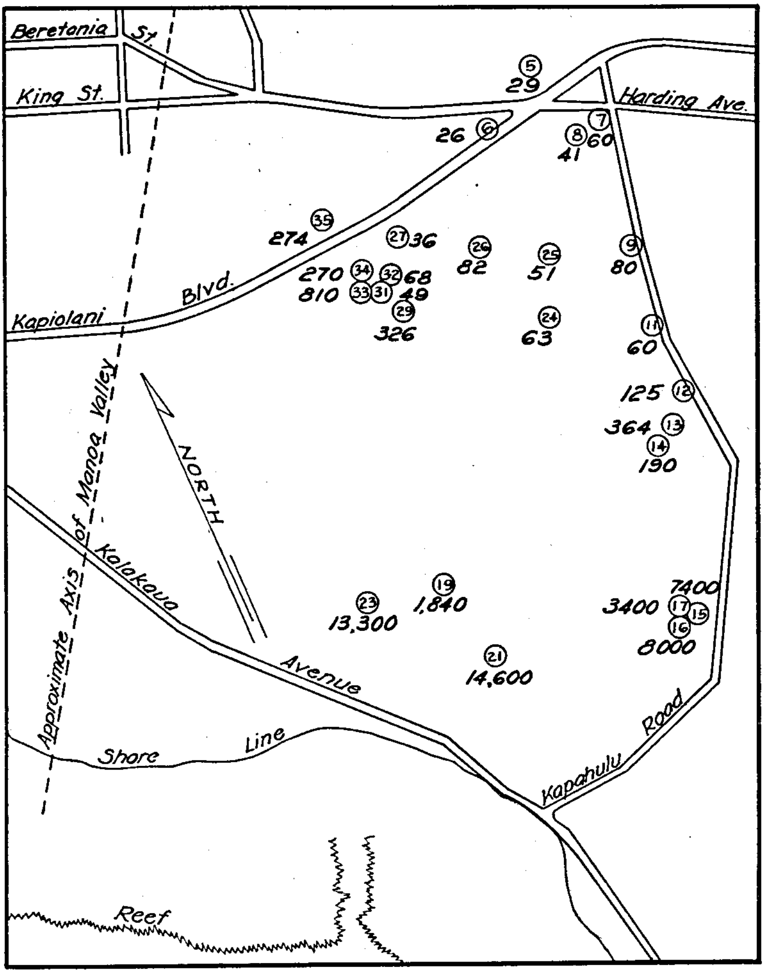

Figure 17. Chloride Map of Isopiestic Area No. 1.

5. Variation in Salt Content From Place to Place

It would be desirable to collect a water sample from every well in the Honolulu district as nearly simultaneously as possible and to determine the chloride content of these samples in order to learn the geographic distribution of salt in the main ground water body. This, however, is impracticable at present. The best thing seems to be to plot on a map the highest chloride content reported for each well in the period from 1920 through 1934. This has been done for the present report, and the Moiliili-Waikiki part (Isopiestic Area No. 1) is reproduced herewith as figure 17. This region is chosen for illustration because of the closeness and large number of wells for which information is available. The western wells in this area are nearer the axis of the valley and are deeper than the eastern wells, and those nearer the shore are deeper than those inland. This is reflected in the fact that the higher chloride contents are found in the western and seaward parts, and the lower chloride contents in the eastern and inland parts. Distance from the sea seems more effective in keeping the chloride content low than is distance from the extended axis of Manoa Valley. The Iwilei-Kapalama region (Isopiestic Area No. 3) shows the same condition almost as well. The central part of the city (Isopiestic Area No. 2) also shows it, but less well.

VII. HEEDLESS EXPLOITATION OF THE GROUND WATER SUPPLY AND ITS PENALTY

The continued fall of the artesian head and the increase in chloride content show that Honolulu and the rest of southeastern Oahu are exploiting their main ground water body in a way that cannot be kept up indefinitely with safety.

Reasoning by analogy is always dangerous because analogies are not identities. If carried too far, every analogy is bound to fail. Yet because of their vividness, the writer will offer one trusting that the reader will not insist on driving it too far.

A. ANALOGY TO A BANK ACCOUNT

The main ground water body is somewhat like a bank account. The bank balance, or the capital, is represented by the fresh water stored in the voids of the water-bearing lava rocks. The bank deposits are represented by the recharge when water is absorbed during rainy seasons. The bank withdrawals for buying goods and services are represented by the discharge from wells, springs, and shafts. There is another type of withdrawals, namely those to pay taxes which do not directly benefit the holder of the account. Please think of a special tax which is proportional to the bank balance. Such withdrawals are analogous to the losses of water by leakage, which are proportional to the artesian head or to the total amount of water stored in the main ground water body.

Honolulu is now drawing on its capital, and will have to pay a penalty like that paid by a spendthrift unless a conservative policy with regard to the ground water supply is adopted by all parties.

If a bank account is so arranged that several persons can draw on it, there must be cooperation and understanding, in order that one of the persons jointly interested will not overdraw the account, with bad effects not only on the others but also on himself. Similarly with the Honolulu main ground water body: withdrawals of water in amounts beyond the recharge will eventually injure not only other parties, but also the party making the excessive withdrawals.

We cannot, unfortunately, telegraph father for more funds. New York could go beyond the old Croton supply to the Catskills for the large Ashokan water supply, and more recently to Delaware River. San Francisco could go to the Hetch Hetchy, and the Los Angeles Metropolitan District could go to Colorado River. New York, San Francisco, and Los Angeles had the analogue of a fond father who could supply more funds. But Oahu's oceanic situation makes Oahu like a fatherless orphan—there is no place outside Oahu from which water can be brought by a long aqueduct. Oahu must keep within its income.

Some adjustments can be made and some water can be brought to Honolulu from outlying areas. However, very recent studies by Dr. Wentworth as to the behavior of the water table in the Pearl Harbor area do not indicate that large amounts of unexploited water are available there. Earlier studies show conclusively that little or no additional water can be gotten east of the city. Reduction of leakage losses seems to offer an opportunity to recover a larger proportion of the rainfall, but the amount that could be so recovered is unknown.

Our hypothetical bank account has another analogy to the main ground water body in that the deposits are supposed to be very variable and uncertain, just as the rainfall on the intake area is variable and uncertain. The following table gives the averages, for five 10-year periods, of the rainfall at Lower Luakaha, a rainfall station in Nuuanu Valley which is rather typical of the intake area of Honolulu's main ground water body.

Rainfall at Lower Luakaha for Five Periods of Ten Years Each and the Ratios to the Fifty-Year Average

Period	Average for the 10 Years (Inches)	Per Cent of 50-Year Average (Per Cent)
1894-1903	133.84	96.8
1904-1913	146.81	105.2
1914-1923	149.15	107.0
1924-1933	130.13	93.4
1934-1943	136.22	97.6

From the preceding table one sees that for a series of years the rainfall will never total much more than the average. Such excesses are analogous to times of profitable business. But no business is always more than average profitable. Times of small profits, or of deficits, come to all businesses. Times of deficient rainfall have occurred in the past and must be expected to come again in the future. In fact, planning should be conservative in estimates of future rainfall.

B. SOME EXAMPLES

The town of Versec in Hungary is underlain by sandy beds which are enclosed by clayey beds and which carry water under artesian pressure. In general the water-bearing beds can be reached by drilling only a hundred feet or so. In 1860 the first well was bored, which was soon followed by others nearby. As a result of the shallow depth and low cost of sinking wells, the desire for running water in each yard became general, and in 1893 there were 83 wells. The inhabitants of Versec did not suspect that the supply was exhaustible and the wells were allowed to flow freely night and day. To make a long story short, the splendor of artesian flow is gone and if a well owner in Versec wishes water he must pump it. Versec is more fortunate than Honolulu as it is inland and there is no danger of contamination by salt water.

In the artesian area of Roswell, New Mexico, the artesian level, according to Fiedler (14), was about 3,586 feet above sea level in 1904. By 1925 the head had dropped to 3,563 near the intake area, but farther away it had dropped to 3,379 feet above sea level. In the process the area in which wells would flow without pumping decreased from about 670 square miles to about 430 square miles. Thus about 240 square miles were changed from a condition of natural discharge of water to a condition requiring expense for pumping.

A very extensive artesian aquifer, known as the "Dakota Sandstone," underlies a great area in South Dakota and adjacent states. According to Robinson (15) the artesian level at Chamberlain dropped from 1,828 feet above sea level in 1891 to 1,684 feet in 1900, and to about 1,600, or a little less, in 1915. At Pierre the head was about 1,920 feet above sea level in 1895 or 1896, but had dropped to about 1,620 feet in 1930. Near the intake area of the Dakota Sandstone aquifer, on the eastern slopes of the Black Hills, the artesian level has fallen less rapidly, but there is a considerable area where wells that formerly flowed must now be pumped. The fall in head and the decrease in area of artesian flow are to be ascribed to the large number of wells that have been drilled and to the fact that for years many of them were allowed to discharge night and day, with no use being made of the water much of the time.

Western Long Island has rather uniform geologic conditions, and has very permeable surface deposits which can yield much shallow ground water. According to Thompson, Wells, and Blank (16) very great quantities of water have been pumped from the surface deposits of the two westernmost counties, Kings and Queens. These counties include populous Brooklyn, and the nearness has invited large pumpage. As a result the water table dropped about 40 feet between 1903 and 1936; and it fell in places to as much as 25 feet below sea level. In Nassau County, the next one to the east, the population is less and the distance to Brooklyn is greater, so that there has been decidedly less pumpage, and the water table instead of dropping progressively has oscillated. Since the geologic conditions in the two areas are very similar the difference in fall of the water table must be ascribed mostly to the contrasting effects of excessive pumpage and moderate pumpage. More water cannot be taken from an aquifer than nature supplies without deleterious effects.

A similar history holds for the artesian wells at Atlantic City, New Jersey, according to Thompson (17). These wells draw water from the so-called "800-foot sand," a layer of permeable sand about 80 feet thick, which is found at an average depth of 800 feet. It is overlain by several hundred feet of impermeable clay and is underlain by a thinner impermeable clay. The water in the 800-foot sand is under artesian pressure. In 1896 the artesian level was about six feet above the surface of the ground, but by 1927 it had fallen till it was about 90 feet below the surface. There is no continuous record available, but reports from time to time show that the drop was progressive. This is another example of what happens when more water is withdrawn from an aquifer than is replenished by rainfall.

C. THE PARTICULARLY BAD SITUATION OF HONOLULU

Withdrawal of water in greater volume than the recharge by nature has led to loss of artesian flow in many places and to marked lowering of the free water table in other places. The stories of Versec, of Roswell, of Long Island, and of Atlantic City, if modified as to dates, numbers of wells, and so on, would be the story of many other ground water bodies. The story of Versec is in fact the story of many parts of Honolulu above 25 feet altitude that had flowing wells only a few decades ago. It will be the story of lower parts of Honolulu unless our main ground water body is drawn on less heedlessly and more conservatively.

The possible situation at Honolulu is made much worse than the situation of the foregoing examples, because of the ever-present danger of contamination by salt water, as evidenced by the salting up of the well at the Old Naval Station and of other wells. The experience of the projected sugar plantation on the Island of Molokai is a familiar story locally. Pumps of large capacity were installed, and in a short time exhausted the very small amount of water in that part of the limited main ground water body of Molokai. Then the pumps delivered very salty water, and the plantation project had to be abandoned. Honolulu has a tremendously larger main ground water body, but even it has a limit. Returning to the analogy to a bank account, Molokai had only a very small capital or bank balance. Honolulu's far larger balance, too, can be overdrawn. It will not be a case of a check returned with "No Funds" written across it, but a case of turning on the faucet and getting undrinkable water.

By means of shafts and tunnels that skim the freshest water off of the top of the main ground water body it will be possible to reduce the amount of water lost by leakage, and to recover that amount of water for beneficial uses. This will not only lower the water table but will also eventually bring salt water higher up. Thus the total volume of the Ghyben-Herzberg lens, that is, the total volume of stored water, will be reduced, making a smaller reserve to draw on in the inevitable series of years of less than normal rainfall. The rising of salt water will cause the deeper artesian wells to yield salty water, but presumably legal adjustments can be made in justice to the owners of such wells, in return for the benefits to the general public. But this leads to questions of law, of economics, and of engineering which do not come in the scope of the present paper. It appears, however, that present knowledge is insufficient to indicate how far down we can safely lower the water table or how rapidly the replacement of deep wells by water table tunnels should be made. Until we have knowledge based on reasonably adequate data, it behooves us to draw no more water, whether by artesian wells or water table tunnels, than our present best estimates indicate is added by nature to the main ground water body.

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