HYDROGEOLOGY OF THE WAIPAHU LANDFILL AREA

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We certify that we have read this thesis and that in our opinion it is satisfactory in scope and quality as a thesis for the degree of Master of Science in Geology and Geophysics.

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INTRODUCTION

Background

The Waipahu landfill site was the refuse disposal facility of the City and County of Honolulu until December 1972 when it was closed to the disposal of domestic refuse. It is thought that the water passing through the landfill may carry biological and chemical contaminants into the water of the West Loch of Pearl Harbor. If this is the case, the degradation of the West Loch water could seriously affect the oyster beds and other aquatic life as well as discourage the use of the water for recreational purposes. In order to determine the possible pollutional effects of the landfill water, knowledge of the occurrence and movement of water through the landfill as well as the quality of the water must be known.

A preliminary study of the pollution potential of leachate from the Waipahu refuse landfill was done by Lee, Bolduc, and Mitter during the Fall of 1971. However, the findings proved insufficient for drawing any definite conclusion about the possible pollutional effects of the landfill water on the West Loch water. As a result of the findings of this initial study, and the objections raised to the landfill operation by the Environmental Protection Agency (EPA), the City and County of Honolulu contracted the Water Resources Research Center of the University of Hawaii to conduct a study to determine whether the Waipahu landfill is a potential source of pollution of West Loch, Pearl Harbor.

Objective

The objective of this study was to determine the hydrogeologic conditions prevailing in the Waipahu landfill area. It was planned to determine:

a) the geologic and hydrologic characteristics of the landfill material,

b) the occurrence and movement of water within the landfill, and

c) the tidal influence on the water regime,

in order to estimate the quantity and rate of movement of the water through the landfill.

Location and Extent of Area

The Waipahu landfill area, shown in Figure 1, is located on the eastern side of West Loch, Pearl Harbor. This sixty acre area is bounded by Kapakahi stream, Waipahu sugarcane fields, and West Loch.

Previous Investigations

Research concerning the ground water pollution potential of sanitary landfills and dump grounds has been conducted particularly in the State of Illinois, California

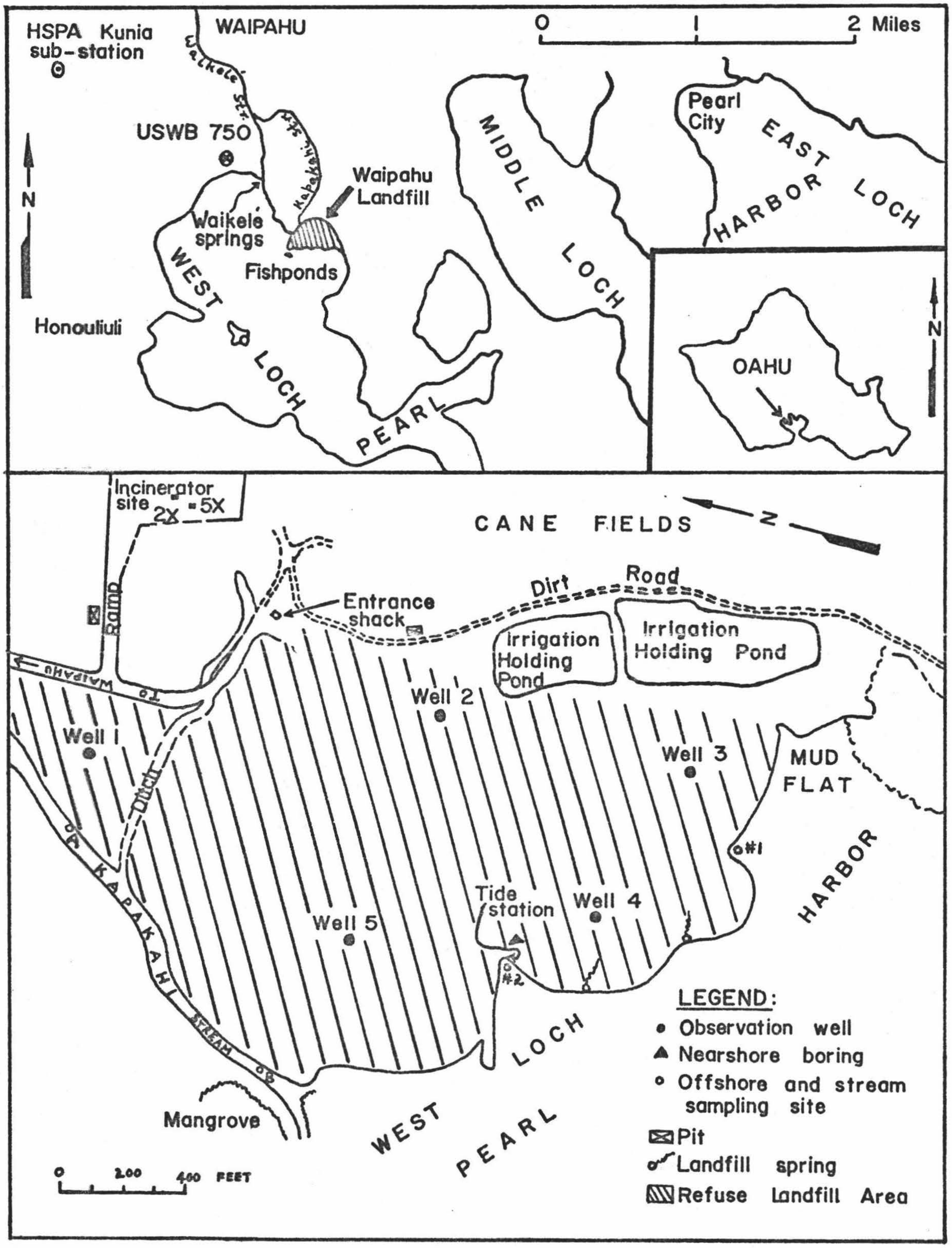


FIGURE 1. LOCATION MAP OF WAIPAHU LANDFILL AREA

and South Dakota (Zanoni, 1972). The landfills studied are under an unsaturated condition as may be gathered from reports by Landon (1969); Remson, Fungaroli and Lawrence (1968); Apgar and Langmuir (1971); and Cartwright and McComas (1968). Unlike the landfills mentioned above, the Waipahu refuse landfill is under a saturated condition, hence, a hydrologic study of this saturated Waipahu refuse landfill should yield different results.

In Hawaii, there has been some research done on the groundwater pollution potential of a refuse landfill. However, these research were primarily concerned with aspects of water quality.

The earliest known study of the pollution potential of a refuse landfill in Hawaii was done by Lee, Bolduc, and Mitter (1971). This study resulted in:

1) a partial characterization of the leachate of landfill water,
2) the belief that tidal flux and groundwater seepage may be the main sources of recharge, and
3) an estimate of the coefficient of permeability (100 to 10,000 gal/day/ft^2) of the landfill material near the shoreline.

More recent studies concerning refuse landfills were done by Bolduc (Fall 1971) and Yamamoto (Spring 1973).

Bolduc's study was essentially to determine how leachate derived from domestic refuse would percolate through three selected Oahu soils and also how good the soils would filter out various constituents present in the leachate.

Yamamoto's study was primarily concerned with the characterization of the Waipahu landfill leachate and its pollution potential of West Loch, Pearl Harbor.

Thus, of the three studies mentioned above only the study by Lee et al. (1971) mentioned anything about the hydrologic nature of the landfill. However, no estimate of the rate of movement of landfill water, the discharge into West Loch, and the extent of tidal fluctuations upon the landfill water regime was arrived at. Therefore, a hydrogeological study of the Waipahu landfill area is necessary.

Methods of Investigation

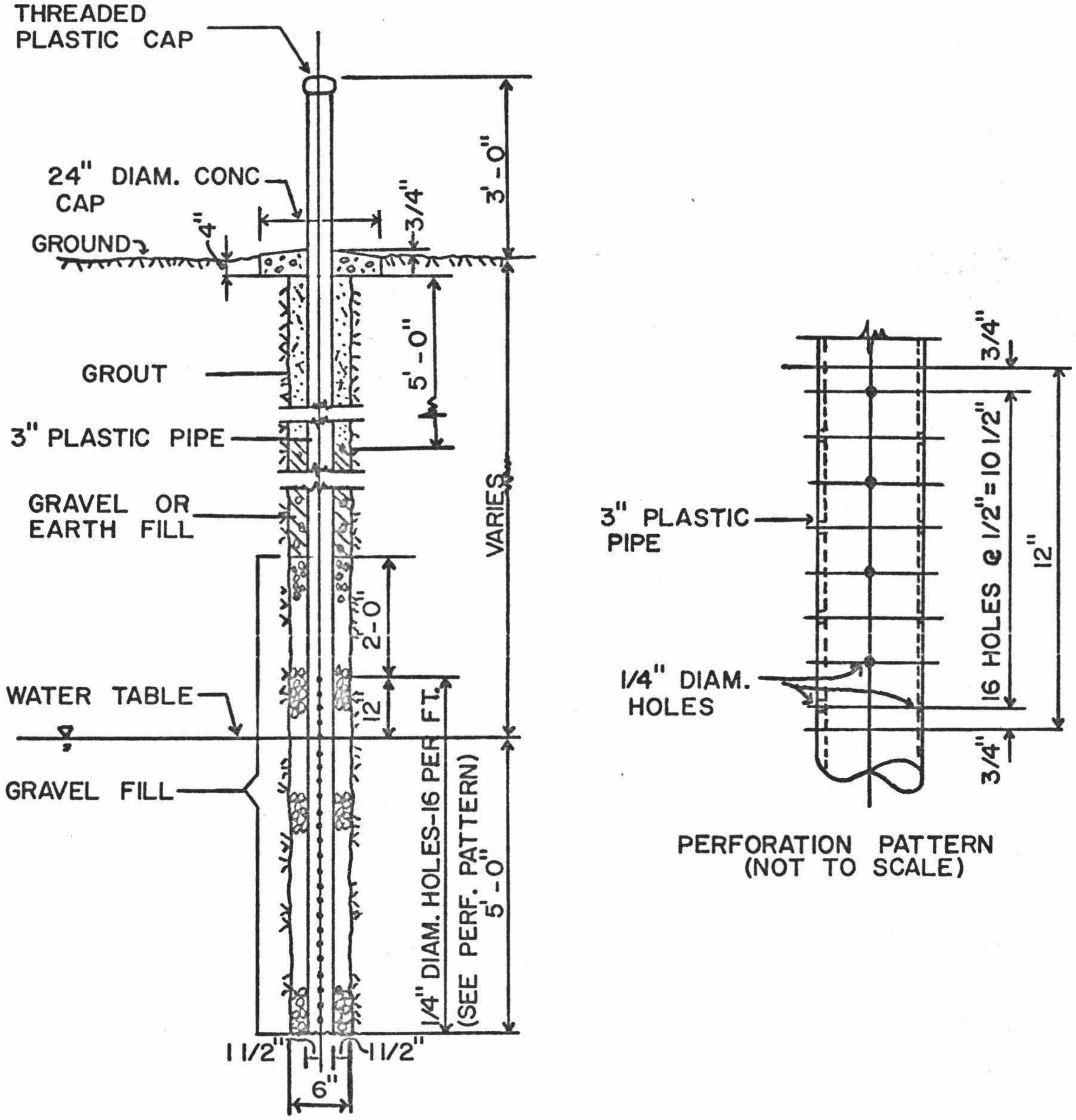
Data on the geology of the Waipahu landfill area was obtained from existing literature on the nature of the caprock region of Pearl Harbor and southern Oahu. Additional data on the caprock composition were obtained from geological observations of the surrounding area, two open pits (now closed), and logs of borings which were drilled by the Nat Whiton Drilling Co., Inc. (1967) in the vicinity of the incinerator site (Figure 1).

The nature of the landfill material was studied by observing cuttings from the five observation wells which are located about the landfill as shown in Figure 1. These observation wells were drilled during the month of June (6/14/72 - 6/19/72) by the Continental Drilling Company under contract with the U.S. Navy. The well construction was according to the plan shown as Figure 2. The wells were drilled with a truck-mounted power auger. The diameter of the auger stem was 8 inches. The wells were cased with 3 inch diameter plastic pipe, the bottom six feet of which was perforated. A gravel fill surrounds the perforated portion of the wells, and the remaining annular space was filled with soil and topped off by a 24 inch square concrete cap. The depth of each well and the distance of each well from the shoreline is given in Table 1.

The data needed for studying the hydrology of the landfill were obtained from published literature and from various field tests conducted and observations made during the present study.

The water-level in each well was monitored over a two week period with the aid of a Stevens or a Belfort automatic water-level recorder. The water-level records provided data for the development of a water-level map, the computation of the coefficient of transmissibility and the tidal efficiency of the aquifer.

Even though the observation wells were constructed primarily for gathering samples of landfill water, an attempt was made to gather pump-test data for determining the coefficient of transmissibility. Pump-tests were run



OBSERVATION WELL DETAIL
(NOT TO SCALE)

PERFORATION PATTERN
(NOT TO SCALE)

FIGURE 2. DESIGN DETAIL OF AN OBSERVATION WELL

TABLE 1

OBSERVATION WELL DEPTH AND DISTANCE FROM SHORELINE

WELL	DEPTH*, IN FEET	DISTANCE FROM SHORELINE, IN FEET
1	21.0	170**
2	14.5	1000
3	22.5	250
4	26.5	260
5	48.0	420

*Datum is ground level.

**Distance is from Kapakahi Stream bank.

on all the shallowest wells except Well 2, which was heavily silted. Pump-tests on Wells 1 and 3, using a 4 horsepower Gorman-Rupp pump, were unsatisfactory owing to maximum discharges of less than 1 gal/min. This failure is a result of insufficient suction lift (due to the considerable depth of the wells) and the small well diameter which precluded the use of a submersible pump. Despite the failure of the pump-tests, slug-injection tests of Wells 1, 3 and 4 were successful.

West Loch tidal fluctuations were monitored for a week with a Belfort water-level recorder whose location is shown in Figure 1. A comparison of the West Loch tide with that of Honolulu Harbor was made possible with this data.

The recharge to the landfill was determined by conducting a hydrologic budget study. Rainfall and pan evaporation data used in this study were taken from records collected at the Waipahu station (USWB 750) and the Hawaiian Sugar Planters Association Kunia sub-station, respectively (Figure 1). These two stations were chosen because they are the closest to the landfill area. The rainfall and pan evaporation data were used to determine the period having a water surplus. Inflow and outflow were determined from data gathered from tests already mentioned.

Chemical analyses of the well water and the sea water in terms of salinity, conductivity and temperature were performed with a portable Temperature-Conductivity-Salinity measuring device. In particular, the conductivity of the water in the wells was monitored over a tidal cycle in order to note any change in water quality. Other water quality data collected (Yamamoto, unpublished M.S. thesis) were also used to support the findings of this study.

During the low tide period, a search for springs was conducted at the toe of the landfill. Two major springs (Figure 1) were discovered in addition to a number of tiny seepages along the edge of the landfill. The discharge from the springs was measured by timing the flow into a receptacle of known volume.

All of these data collected were used to describe the hydrogeologic characteristics of the landfill.

CHAPTER II

PHYSIOGRAPHY AND CLIMATOLOGY

Surface Features and Drainage

The area containing the Waipahu refuse landfill is situated within the coastal plain Geomorphic Province of southern Oahu. This sedimentary feature is bounded by the Waianae Range, the Schofield Plateau and the Koolau Range to the north. The coastal plain is drained by streams emptying into West, Middle and East Lochs of Pearl Harbor. The Waipahu landfill area lies on the relatively flat eastern coast of West Loch (see Figure 1 for location).

Climate

The mild climate of Oahu may be attributed to its location as the island is a little south of the Tropic of Cancer. This places it in the influence of the northeast tradewinds. The city of Honolulu has a mean annual temperature of 75.2^{o}F as recorded near sea level.

The distribution of rainfall on Oahu is shown in Figure 3. The Pearl Harbor area where the landfill is located lies between the 20 and 30 inch isohyetal lines. The nearest rainfall gauging station to the landfill is at Waipahu (USWB 750) which is 60 feet above sea level and less than half a mile from the shore of Pearl Harbor (Figure 1). Rainfall records collected at this station

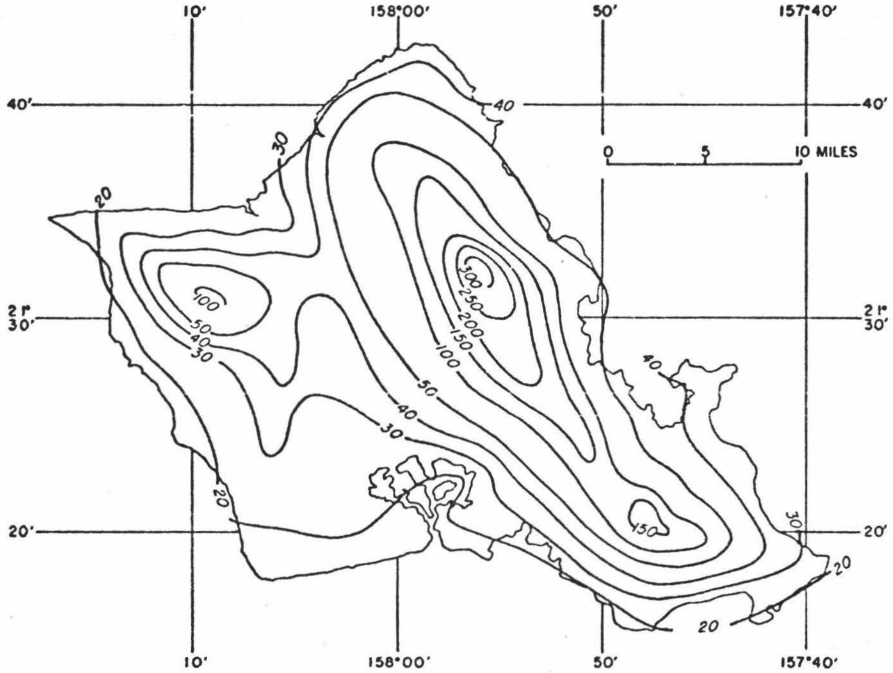


FIGURE 3. RAINFALL DISTRIBUTION MAP OF OAHU

Isohyetal lines, showing precipitation in inches, by U.S. Weather Bureau. (Taken from F. N. Visher and J. F. Mink, 1964) show very low monthly precipitation. The summer months are the driest and the winter months are the wettest as can be seen on the graph of Figure 4. The average annual rainfall at the Waipahu station (USWB 750) is about 28.81 inches (determined from USWB records for 1951-1971 gathered at Waipahu).

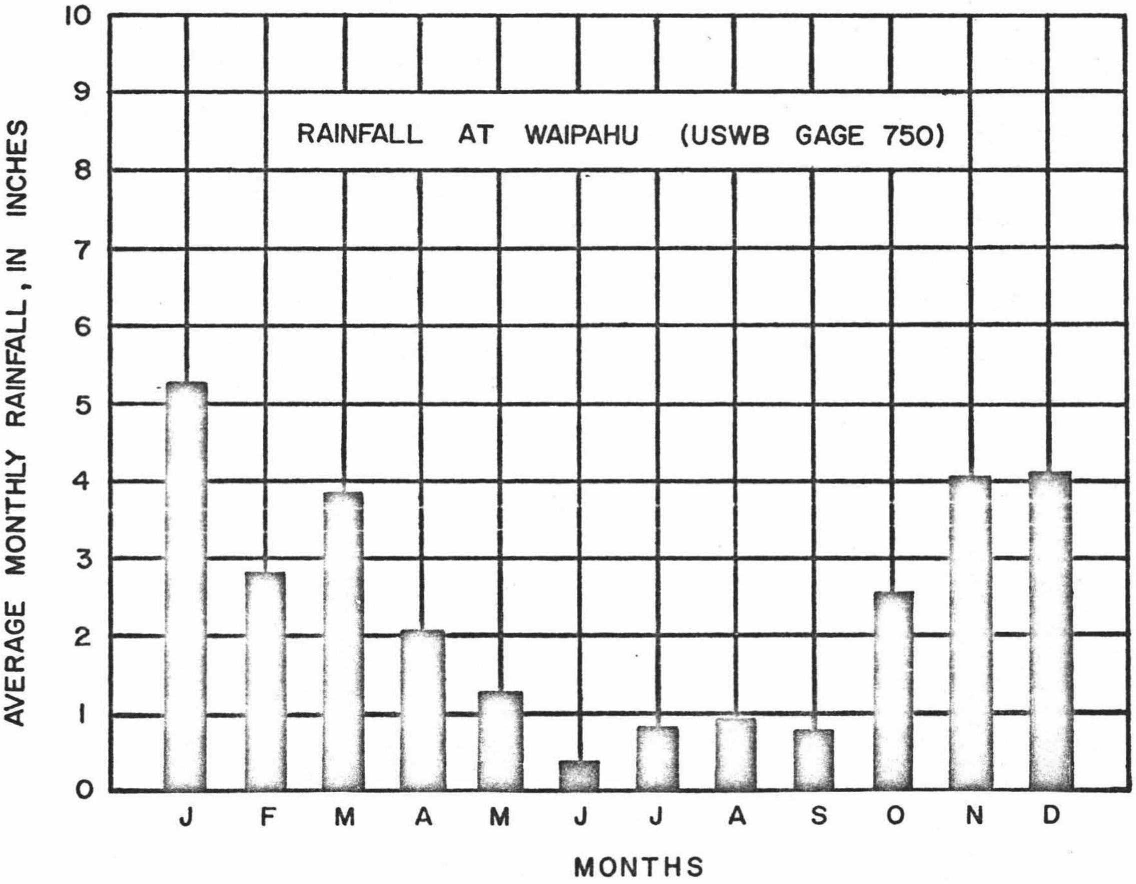


FIGURE 4. GRAPHICAL REPRESENTATION OF RAINFALL AT WAIPAHU (USWB 750), FOR 1951-1971

CHAPTER III

GEOLOGY OF THE AREA

Geologic History

The island of Oahu began in early Tertiary time as two separate volcanoes which eventually formed the Waianae and Koolau shield volcanoes (Stearns and Vaksvik, 1935). After activity ceased in the Waianae volcano, the Koolau volcano continued to pour out lava which welled up against the Waianae dome and eventually built the relatively flat Schofield plateau. Streams sculptured deep valleys into the domes and after periods of deposition and submergence and re-emergence of the land owing to eustatic adjustments, the coastal plain was formed.

The Origin of Pearl Harbor

The Pearl Harbor re-entrant is essentially a drowned river system comparable to other coastal areas such as San Francisco Bay (Stearns, 1966). Streams having their headwaters in the Koolau Range were forced southward by the slope of the ground surface. Deep canyons carved by the streams were later submerged and sediments were deposited within them. The origin of Pearl Harbor and hence West, Middle, and East Lochs may have been in stages according to Stearns (1966) as shown in Figure 5. The ending of the Pleistocene about 11,000 years ago resulted in the flooding

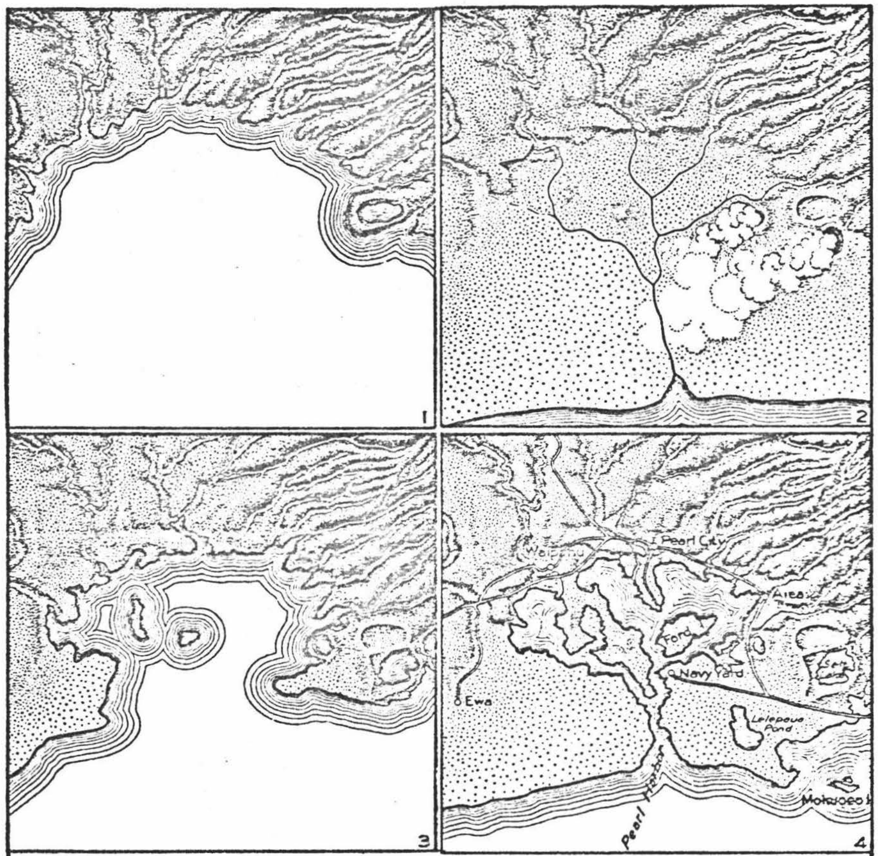


Figure V.3—Diagram showing the geologic history of Pearl Harbor lochs. *1.* When the sea stood 95 feet higher. *2.* When the sea stood about 60 feet lower. *3.* When the sea stood 25 feet higher. *4.* Present sea level.

FIGURE 5. DIAGRAM SHOWING THE HISTORICAL STAGES OF PEARL HARBOR LOCHS (Taken from H. T. Stearns, 1966)

of the river valleys to form the Lochs of Pearl Harbor.

The Caprock Formation

The caprock formation is a triangular wedge of sedimentary deposits extending below sea level. In general, these sedimentary deposits consist of unconsolidated and consolidated terrestrial alluvium, unconsolidated and consolidated marine sediments and volcanics of the Honolulu volcanic series. From a study of well logs in the Pearl Harbor area, Wentworth (1951) pointed out the variation in caprock composition. Coral and clay was found to be dominant about the western side of the Pearl Harbor entrance, whereas a great volume of clay and gravel and only scattered bodies of coral was noticed farther inland. The relationship of the caprock formation to the basaltic rock is shown in the schematic diagram of Figure 6.

The nature of the caprock below the landfill is revealed from observations of well borings and pits. The well borings (Figure 7) in the vicinity of the incinerator site (Figure 1) show a predominance of reddish silty clay and soft dark silty clay. The pit by the ramp (Figure 1) reveals a reddish brown clay with thin layers of poorly sorted pebbles, whereas the pit by the dirt road (Figure 1) exposed a mixture of white-gray calcareous clay deposits and coral reef fragments. The thickness of the caprock below the landfill is between 100 and 200 feet as shown in Figure 8.

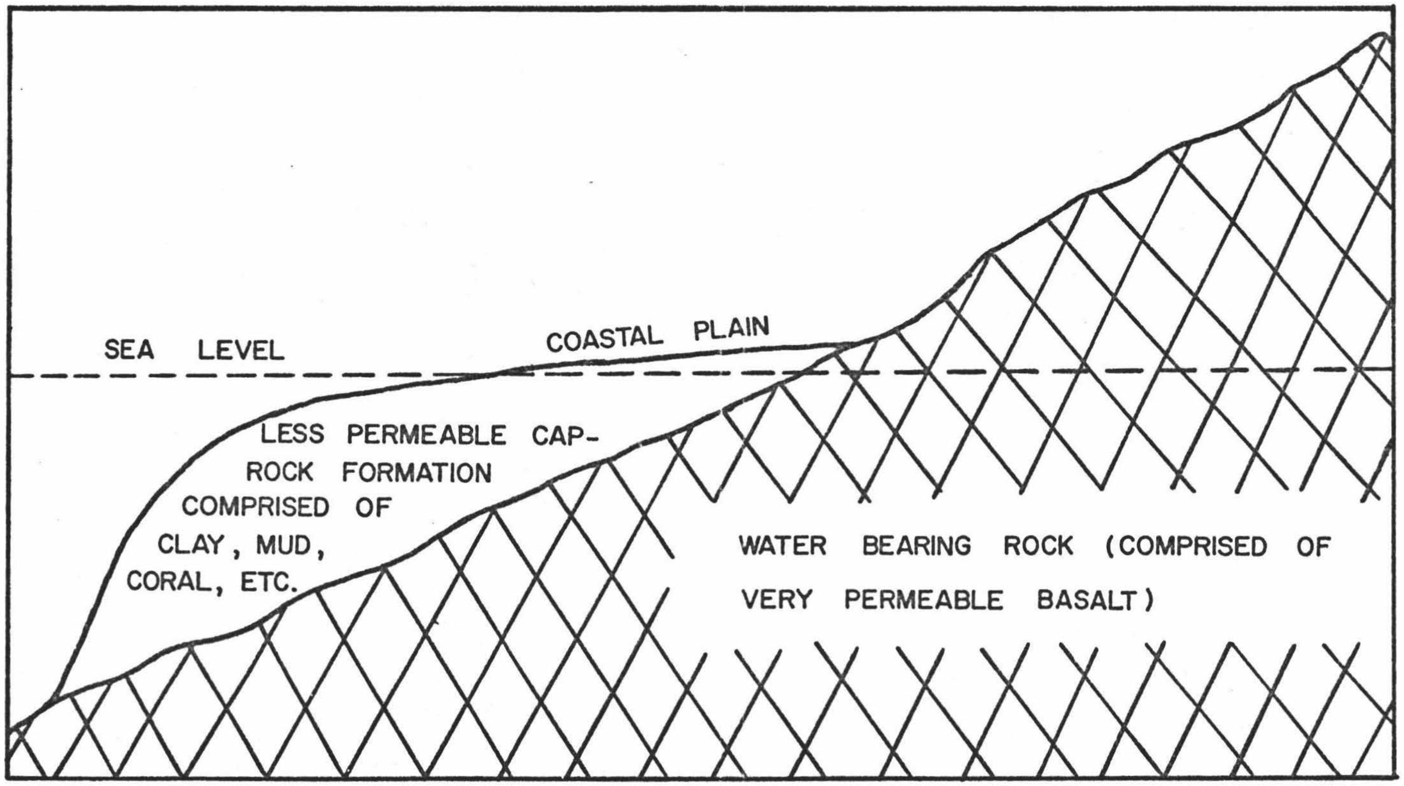


FIGURE 6. SCHEMATIC DIAGRAM OF THE CAPROCK FORMATION AND UNDERLYING BASALT

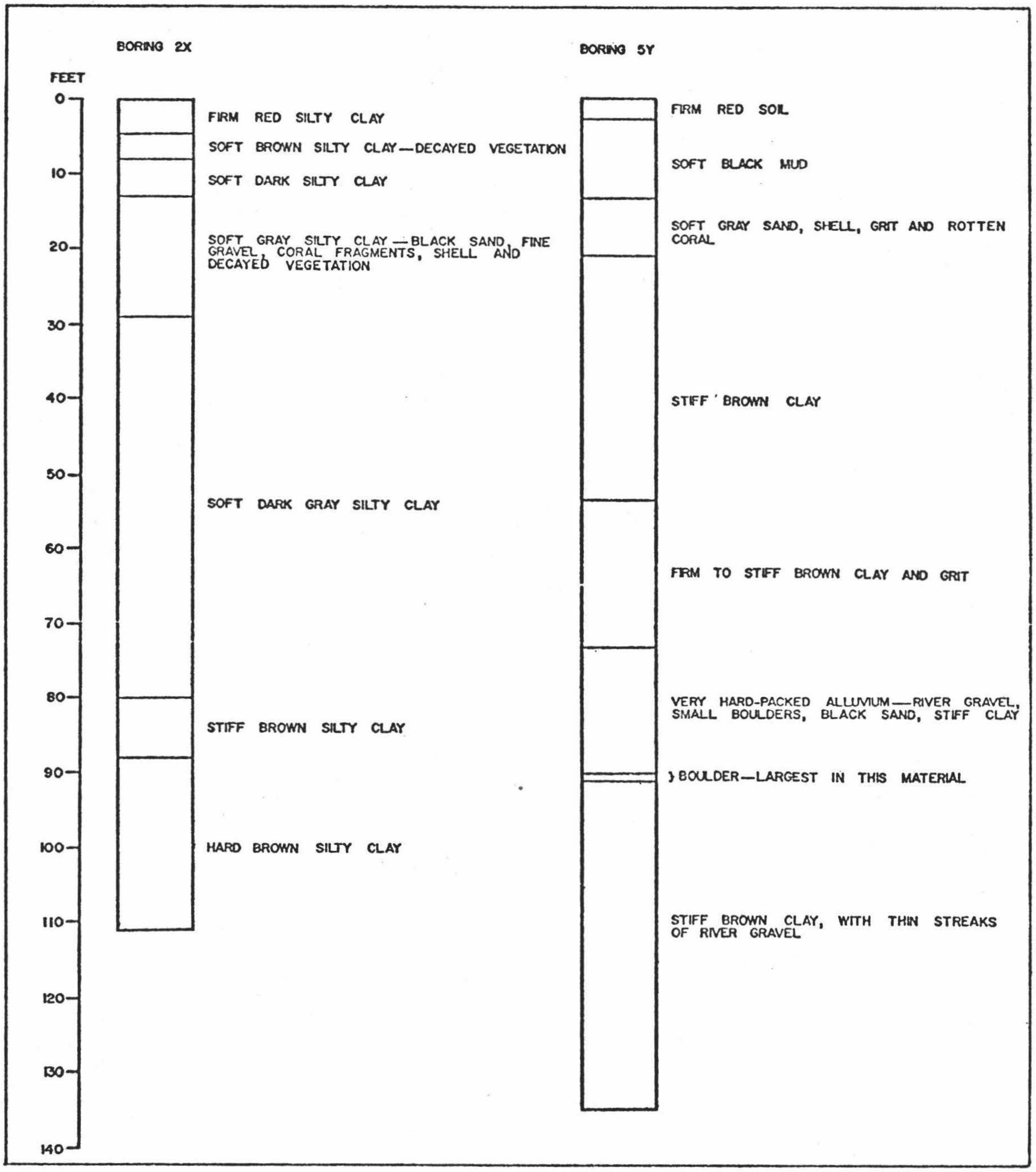


FIGURE 7. LOGS OF BORINGS ABOUT THE INCINERATOR SITE
(Taken from Nat. Whiton Drilling Co., Inc., Report, 1967)

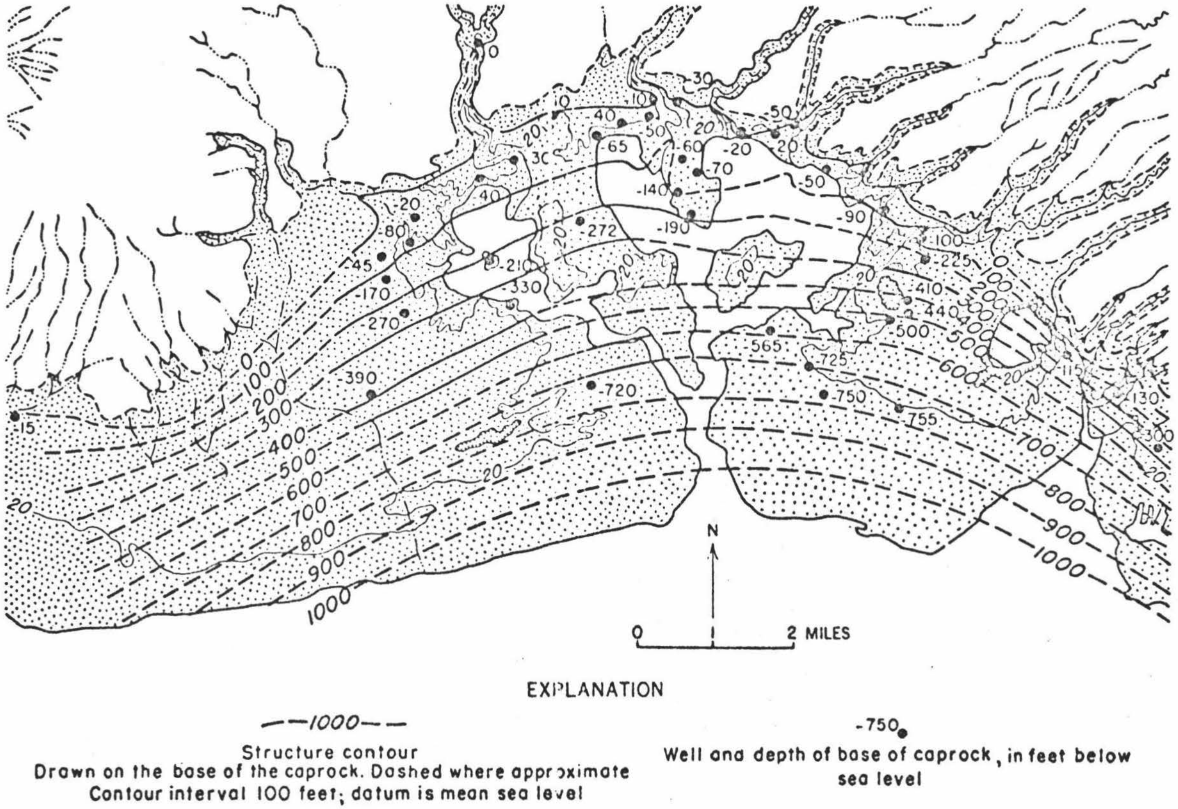


FIGURE 8. STRUCTURE CONTOURS OF CAPROCK ABOUT PEARL HARBOR
(Taken from F. N. Visher and J. F. Mink, 1964)

Water-Bearing Character of Caprock

The caprock, when compared with fresh basalts, may be about 1/10,000 as permeable (Wentworth, 1951). This low permeability makes the caprock an effective water barrier. Even though the caprock has a low permeability overall, great differences in porosity and permeability are observed locally. Sand and gravel materials have porosities ranging from 15 to 35 percent, volcanic ash of angular fragments can have porosities up to 60 percent, and mud and clay porosities may range from 20 to 55 percent. While coral may be very permeable due to solution cavities and natural openings, coral mud is highly impermeable. Permeability tests conducted on the caprock by Wentworth (1951) resulted in values ranging from 0.14 to 2.8 gal/day/ft^2.

CHAPTER IV

LANDFILL CHARACTER

The Waipahu refuse landfill occupies an old fish pond on the West Loch shoreline (Figure 1). The landfill surface is generally flat throughout with occasional rises and shallow depressions with its surface elevation averaging about 20 feet above sea level.

Description of Fill Material

The fill consists of a mixture of soil, rock, gravel, mud, clay and a variety of refuse materials. Borings into the landfill (Figure 1) encountered solid waste materials similar to those classified by the American Public Works Association in its manual on Municipal Refuse Disposal (1970). The most common types of solid waste materials fall into the category of garbage, rubbish, ashes and cans from incineration, industrial wastes, demolition wastes, construction wastes, and street refuse.

Structure of Landfill

The structure and composition of the landfill was determined from observation of cuttings from the observation wells which were drilled about the landfill (Figure 1). Each observation well was drilled with an auger bit which disturbed the original setting of the fill materials, but despite this a reconstruction of the types of materials occurring at various depths was possible. The well logs in Figure 9 show the composition and the structural zones of the landfill.

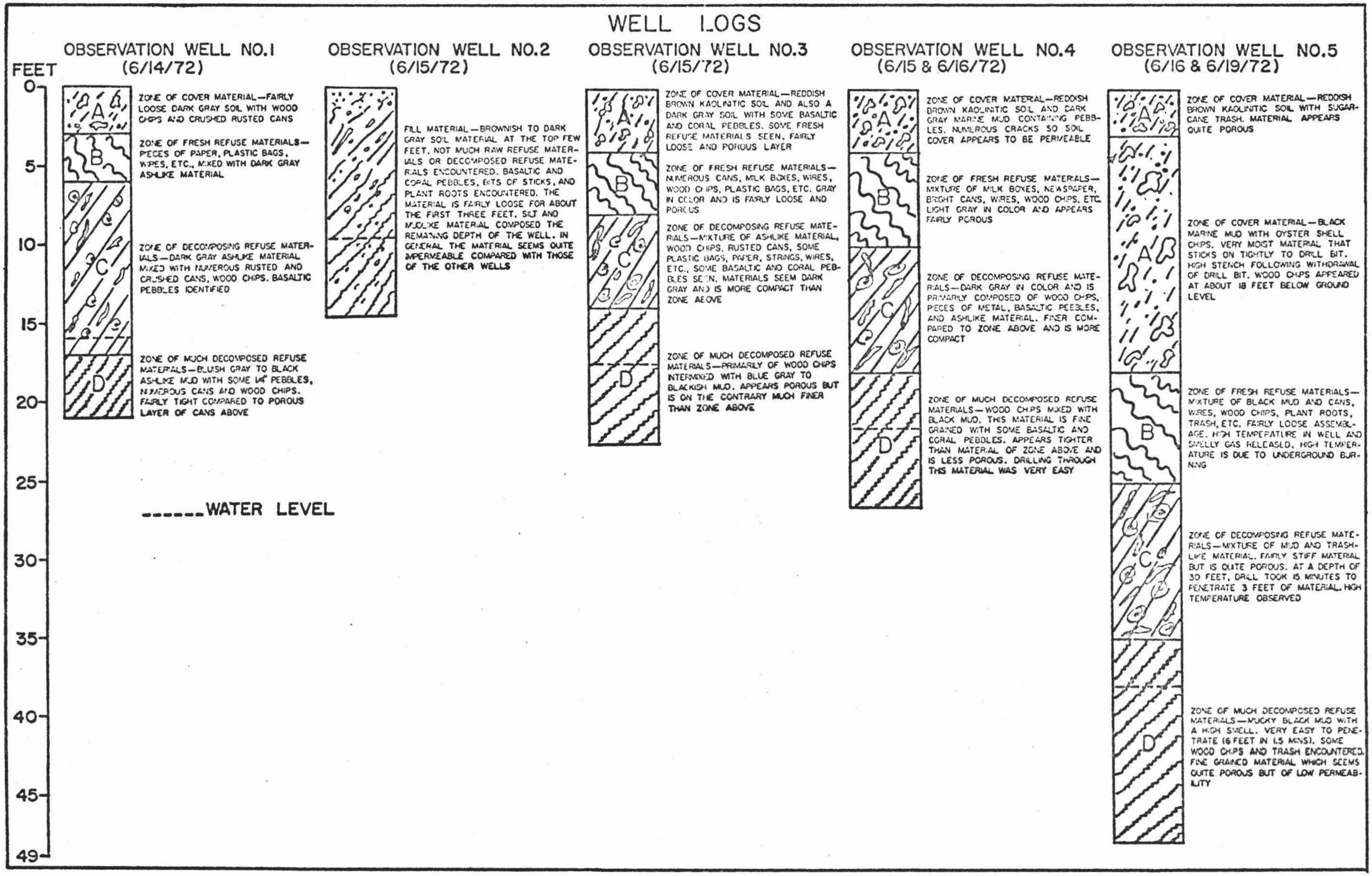
All of the observation wells except Well 2 show four structural zones. The first zone (A) is the zone of cover material composed of dark gray soil, reddish-brown kaolinitic soil or grayish-black marine mud. The second zone (B) is the zone of fresh refuse materials. The third zone (C) is the zone of decomposing refuse materials. Finally, the fourth zone (D) is the zone of much decomposed refuse materials and black mud. This black mud or claylike material observed at the bottom of the observation wells probably is the bottom sediment of the old fish pond into which refuse materials were dumped.

The deepest penetration of 10 feet into the black mud was at Well 5. This indicates that the black mud is at least 10 feet thick.

The material comprising Well 2 is fill material of brownish and dark gray soil in the upper portion with mud and silt near the bottom of the well. Coral pebbles, plant roots and traces of refuse materials were encountered.

Porosity of Landfill Materials

The porosity of the landfill materials was estimated from observations of the well cuttings. Cover material



OBSERVATION WELL NO.1 (6/14/72)

ZONE OF COVER MATERIAL—FAIRLY LOOSE DARK GRAY SOIL WITH WOOD CHIPS AND CRUSHED RUSTED CANS

ZONE OF FRESH REFUSE MATERIALS—PIECES OF PAPER, PLASTIC BAGS, WIPES, ETC., MIXED WITH DARK GRAY ASHLIKE MATERIAL

ZONE OF DECOMPOSING REFUSE MATERIALS—DARK GRAY ASHLIKE MATERIAL MIXED WITH NUMEROUS RUSTED AND CRUSHED CANS, WOOD CHIPS. BASALTIC PEBBLES IDENTIFIED

ZONE OF MUCH DECOMPOSED REFUSE MATERIALS—BLUISH GRAY TO BLACK ASHLIKE MUD WITH SOME 1/4" PEBBLES, NUMEROUS CANS AND WOOD CHIPS. FAIRLY TIGHT COMPARED TO POROUS LAYER OF CANS ABOVE

OBSERVATION WELL NO.2 (6/15/72)

FILL MATERIAL—BROWNISH TO DARK GRAY SOIL MATERIAL AT THE TOP FEW FEET. NOT MUCH RAW REFUSE MATERIALS OR DECOMPOSED REFUSE MATERIALS ENCOUNTERED. BASALTIC AND CORAL PEBBLES, BITS OF STICKS, AND PLANT ROOTS ENCOUNTERED. THE MATERIAL IS FAIRLY LOOSE FOR ABOUT THE FIRST THREE FEET. SILT AND MUDLIKE MATERIAL COMPOSED THE REMAINING DEPTH OF THE WELL. IN GENERAL THE MATERIAL SEEMS QUITE IMPERMEABLE COMPARED WITH THOSE OF THE OTHER WELLS

OBSERVATION WELL NO.3 (6/15/72)

ZONE OF COVER MATERIAL—REDDISH BROWN KAOLINITIC SOIL AND ALSO A DARK GRAY SOIL WITH SOME BASALTIC AND CORAL PEBBLES. SOME FRESH REFUSE MATERIALS SEEN. FAIRLY LOOSE AND POROUS LAYER

ZONE OF FRESH REFUSE MATERIALS—NUMEROUS CANS, MILK BOXES, WIRES, WOOD CHIPS, PLASTIC BAGS, ETC. GRAY IN COLOR AND IS FAIRLY LOOSE AND POROUS

ZONE OF DECOMPOSING REFUSE MATERIALS—MIXTURE OF ASHLIKE MATERIAL, WOOD CHIPS, RUSTED CANS, SOME PLASTIC BAGS, PAPER, STRINGS, WIRES, ETC., SOME BASALTIC AND CORAL PEBBLES SEEN. MATERIALS SEEM DARK GRAY AND IS MORE COMPACT THAN ZONE ABOVE

ZONE OF MUCH DECOMPOSED REFUSE MATERIALS—PRIMARILY OF WOOD CHIPS INTERMIXED WITH BLUE GRAY TO BLACKISH MUD. APPEARS POROUS BUT IS ON THE CONTRARY MUCH FINER THAN ZONE ABOVE

OBSERVATION WELL NO.4 (6/15 & 6/16/72)

ZONE OF COVER MATERIAL—REDDISH BROWN KAOLINITIC SOIL AND DARK GRAY MARINE MUD CONTAINING PEBBLES. NUMEROUS CRACKS SO SOIL COVER APPEARS TO BE PERMEABLE

ZONE OF FRESH REFUSE MATERIALS—MIXTURE OF MILK BOXES, NEWSPAPER, BRIGHT CANS, WIRES, WOOD CHIPS, ETC. LIGHT GRAY IN COLOR AND APPEARS FAIRLY POROUS

ZONE OF DECOMPOSING REFUSE MATERIALS—DARK GRAY IN COLOR AND IS PRIMARILY COMPOSED OF WOOD CHIPS, PIECES OF METAL, BASALTIC PEBBLES, AND ASHLIKE MATERIAL. FINER COMPARED TO ZONE ABOVE AND IS MORE COMPACT

ZONE OF MUCH DECOMPOSED REFUSE MATERIALS—WOOD CHIPS MIXED WITH BLACK MUD. THIS MATERIAL IS FINE GRAINED WITH SOME BASALTIC AND CORAL PEBBLES. APPEARS TIGHTER THAN MATERIAL OF ZONE ABOVE AND IS LESS POROUS. DRILLING THROUGH THIS MATERIAL WAS VERY EASY

OBSERVATION WELL NO.5 (6/16 & 6/19/72)

ZONE OF COVER MATERIAL—REDDISH BROWN KAOLINITIC SOIL WITH SUGARCANE TRASH. MATERIAL APPEARS QUITE POROUS

ZONE OF COVER MATERIAL—BLACK MARINE MUD WITH OYSTER SHELL CHIPS. VERY MOIST MATERIAL THAT STICKS ON TIGHTLY TO DRILL BIT. HIGH STENCH FOLLOWING WITHDRAWAL OF DRILL BIT. WOOD CHIPS APPEARED AT ABOUT 18 FEET BELOW GROUND LEVEL

ZONE OF FRESH REFUSE MATERIALS—MIXTURE OF BLACK MUD AND CANS, WIRES, WOOD CHIPS, PLANT ROOTS, TRASH, ETC. FAIRLY LOOSE ASSEMBLAGE. HIGH TEMPERATURE IN WELL AND SMELLY GAS RELEASED. HIGH TEMPERATURE IS DUE TO UNDERGROUND BURNING

ZONE OF DECOMPOSING REFUSE MATERIALS—MIXTURE OF MUD AND TRASHLIKE MATERIAL. FAIRLY STIFF MATERIAL BUT IS QUITE POROUS. AT A DEPTH OF 30 FEET, DRILL TOOK 15 MINUTES TO PENETRATE 3 FEET OF MATERIAL. HIGH TEMPERATURE OBSERVED

ZONE OF MUCH DECOMPOSED REFUSE MATERIALS—MUCKY BLACK MUD WITH A HIGH SMELL. VERY EASY TO PENETRATE (6 FEET IN 1.5 MINS). SOME WOOD CHIPS AND TRASH ENCOUNTERED. FINE GRAINED MATERIAL WHICH SEEMS QUITE POROUS BUT OF LOW PERMEABILITY

FIGURE 9. LOGS OF OBSERVATION WELLS AT WAIPAHU LANDFILL

consisting of reddish-brown kaolinitic soil is quite porous and permeable as it is loose and contains numerous cracks. Cover material consisting of gray-black marine mud is quite porous but relatively impermeable. The uncompacted assemblage of tin cans, papers, wires, lumber, trees, etc., makes the zone of fresh refuse materials (B) porous. The zone of decomposing refuse materials (C) is less porous than the zone of fresh refuse materials (B) because the materials of zone (C) are undergoing chemical breakdown and compaction due to the frequent passes by bulldozers about the area. The zone of much decomposed refuse materials (D) is compact and includes mud and silt which makes it porous but fairly impermeable. However, where there are pockets of concrete pilings, lumber, tree trunks, car frames, bottles, cans, etc., this zone (D) could be quite permeable.

CHAPTER V

WEST LOCH TIDAL INFLUENCE

A Comparison of Honolulu Harbor and West Loch Tides

A comparison of the Honolulu Harbor and West Loch tidal fluctuations was made in order to establish whether tide tables for Honolulu Harbor could be used also for indicating the tidal condition at West Loch, Pearl Harbor.

Tidal data for Honolulu Harbor were taken from the U.S. Department of Commerce (1972) tide tables. Tidal observations made by means of a Belfort Tide Gauge conveniently placed at West Loch shoreline (Figure 1) were compared with those for Honolulu Harbor. The one week (August 6-13, 1972) tidal observations at West Loch and the tidal data for this same period at Honolulu Harbor are tabulated in Table 2.

A comparison of the tidal fluctuations at Honolulu Harbor and at West Loch can best be made by plotting graphs with the data. Figure 10 shows that a linear relationship exists between the arrival-time data of Honolulu Harbor and West Loch tides. Similarly, Figure 11 indicates that the tidal elevation data of Honolulu Harbor and West Loch follow a linear pattern.

The coefficient of correlation is a quantitative measure of the correlation of the two sets of data. A correlation coefficient of 1 signifies a perfect correlation

TABLE 2

HONOLULU HARBOR AND WEST LOCH TIDE DATA

		HONOLULU TIDE (TABLES)		WEST LOCH TIDE (OBSERVED)	
DATE	TIDE	TIME	ELEVATION, FT	TIME	ELEVATION, FT
8-06-72	HIGH	2:43 PM	2.5	2:52 PM	2.5
8-06-72	LOW	10:02 PM	0.2	10:04 PM	0.3
8-07-72	HIGH	2:40 AM	0.8	3:16 AM	0.8
8-07-72	LOW	8:00 AM	-	8:00 AM	-
8-07-72	HIGH	3:25 PM	2.4	3:02 PM	2.4
8-07-72	LOW	10:33 PM	0.2	10:33 PM	0.2
8-08-72	HIGH	3:27 AM	0.9	3:50 AM	0.9
8-08-72	LOW	8:49 AM	0.0	8:40 AM	0.0
8-08-72	HIGH	4:01 PM	2.4	3:40 PM	2.4
8-08-72	LOW	10:59 PM	0.2	10:52 PM	0.2
8-09-72	HIGH	4:10 AM	1.0	3:48 AM	1.1
8-09-72	LOW	9:36 AM	0.1	9:16 AM	0.1
8-09-72	HIGH	4:36 PM	2.2	4:02 PM	2.3
8-09-72	LOW	11:26 PM	0.2	11:15 PM	0.2
8-10-72	HIGH	4:53 AM	1.1	5:40 AM	1.2
8-10-72	LOW	10:18 AM	0.2	10:56 AM	0.2
8-10-72	HIGH	5:05 PM	2.0	4:41 PM	2.0
8-10-72	LOW	11:49 PM	0.2	11:50 PM	0.2
8-11-72	HIGH	5:33 AM	1.2	5:48 AM	1.2
8-11-72	LOW	11:00 AM	0.3	11:02 AM	0.3
8-11-72	HIGH	5:33 PM	1.8	5:23 PM	1.9
8-12-72	LOW	12:11 AM	0.2	12:32 AM	0.1
8-12-72	HIGH	6:16 AM	1.3	6:18 AM	1.5
8-12-72	LOW	11:51 AM	0.5	11:51 AM	0.5
8-12-72	HIGH	5:57 PM	1.6	6:28 PM	1.6
8-13-72	LOW	12:35 AM	0.2	12:52 AM	0.1
8-13-72	HIGH	7:05 AM	1.4	6:40 AM	1.3

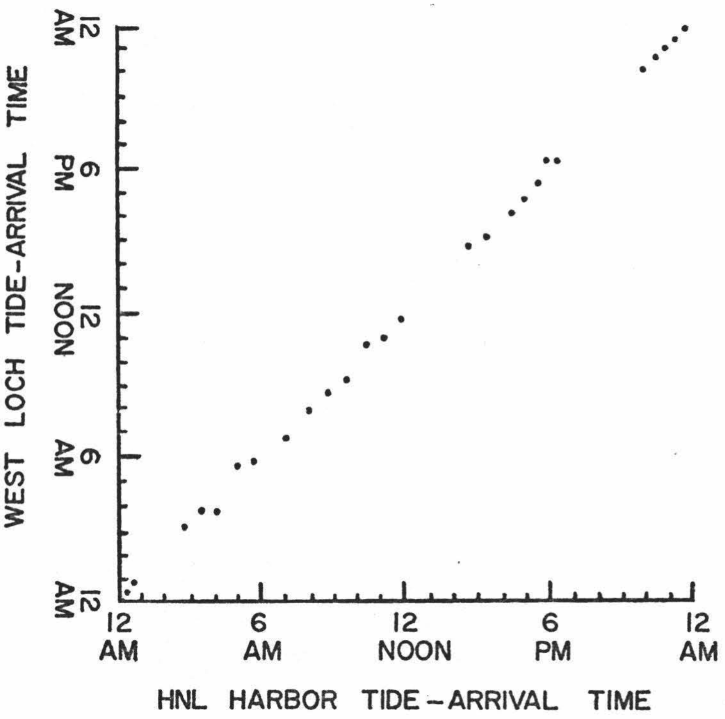


FIGURE 10. GRAPH SHOWING TIME RELATIONSHIP OF HONOLULU HARBOR AND WEST LOCH TIDES

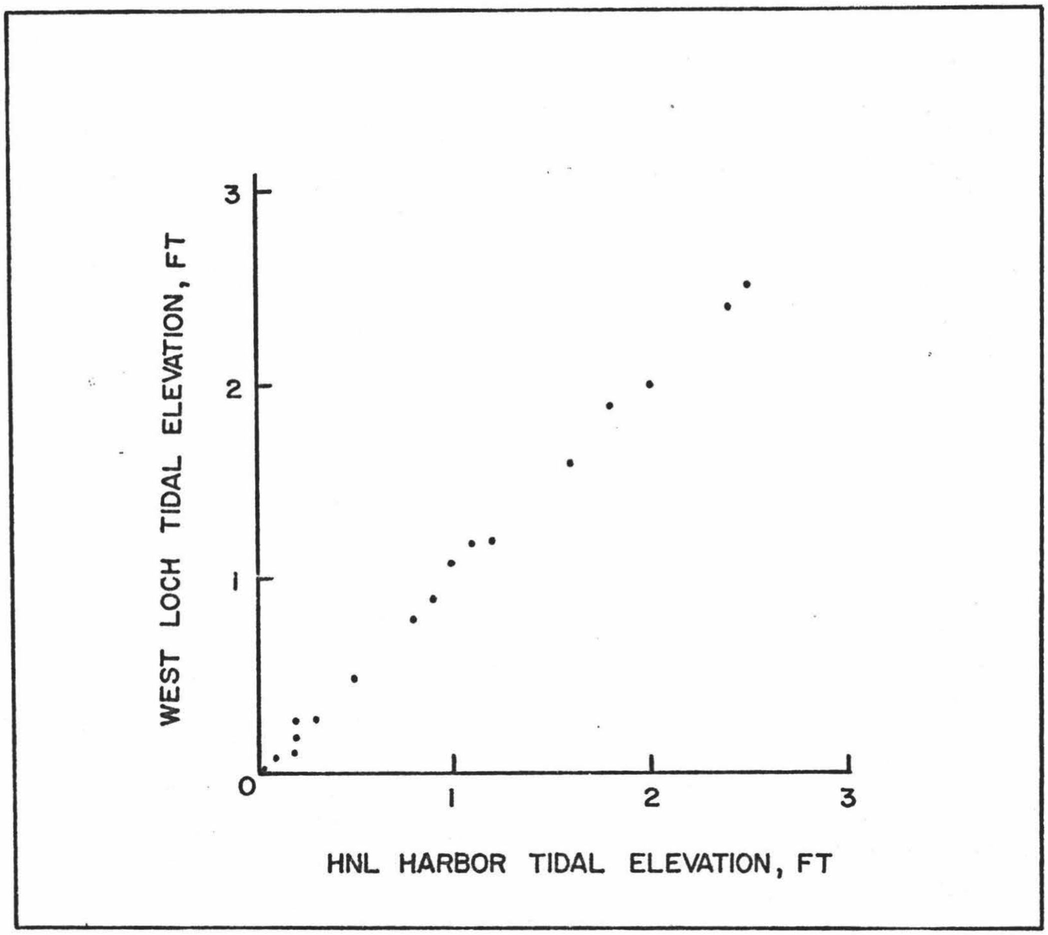


FIGURE 11. GRAPH SHOWING STAGE RELATIONSHIP OF HONOLULU HARBOR AND WEST LOCH TIDES

of the data whereas a correlation coefficient of 0 indicates no correlation. The coefficient of correlation for the arrival-time data was computed as 0.991 and the coefficient of correlation for the tidal-elevation data was computed as 0.996. These high coefficients of correlation of the arrival-time data and the tidal-elevation data suggest a strong correlation of the tide data for Honolulu Harbor and West Loch. On this basis, the tidal conditions at Honolulu Harbor and West Loch, Pearl Harbor are similar, hence, the tidal fluctuations in West Loch over the duration of the landfill study period can be taken from Honolulu Harbor tide tables.

West Loch Tidal Effect

The effect of West Loch tides upon the water-level in the landfill aquifer was determined by monitoring the water-level changes in each well continuously over a two-week period with either a Stevens or a Belfort automatic water-level recorder. The water-level changes in the wells were compared with tidal fluctuations at West Loch as shown in Figures 12, 13, 14, 15 and 16. These comparisons show that the water-level in some of the wells fluctuates in response to the tidal changes at West Loch. The two wells (No. 3 and No. 4) nearest the sea are found to be directly influenced by tidal fluctuations at West Loch.

Changes in the water-level in Well 1 are in response to

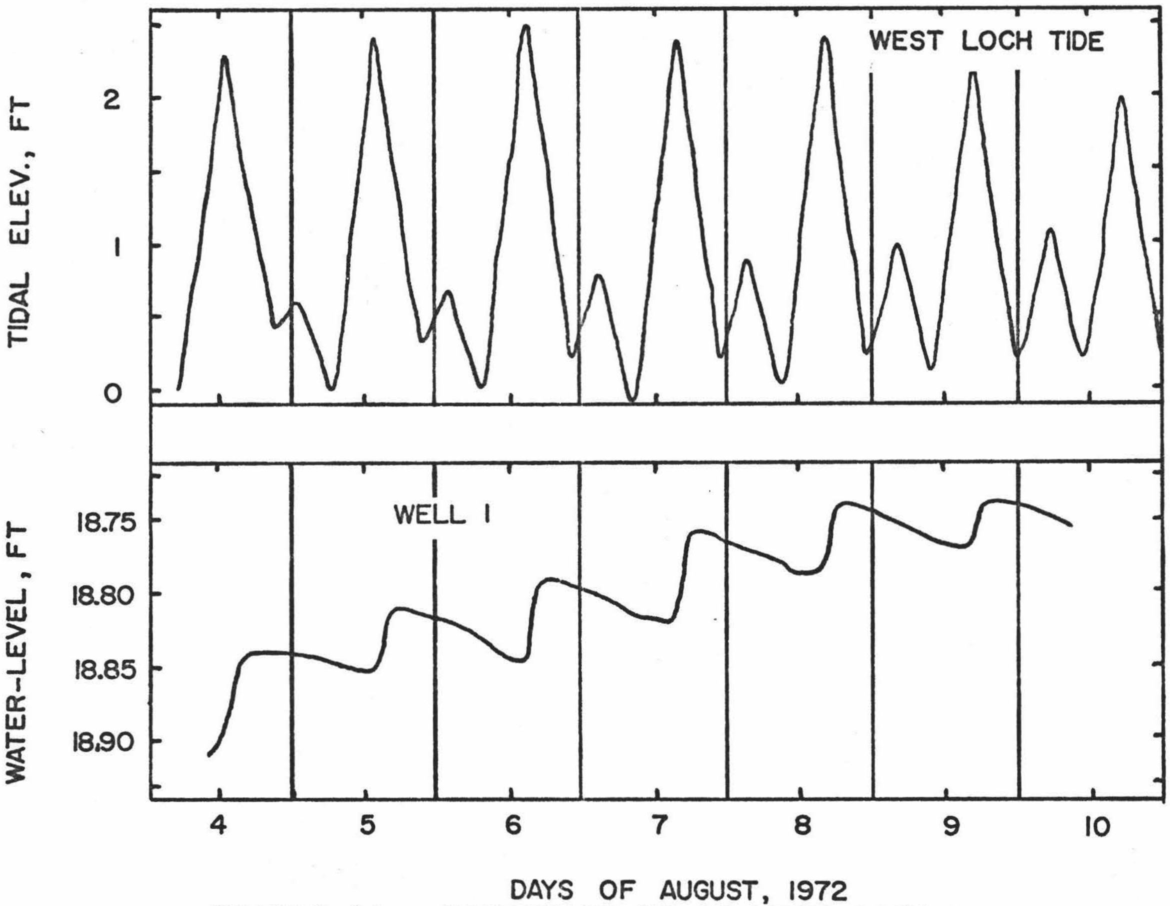


FIGURE 12. FLUCTUATIONS OF WEST LOCH TIDE AND WATER-LEVEL IN WELL 1

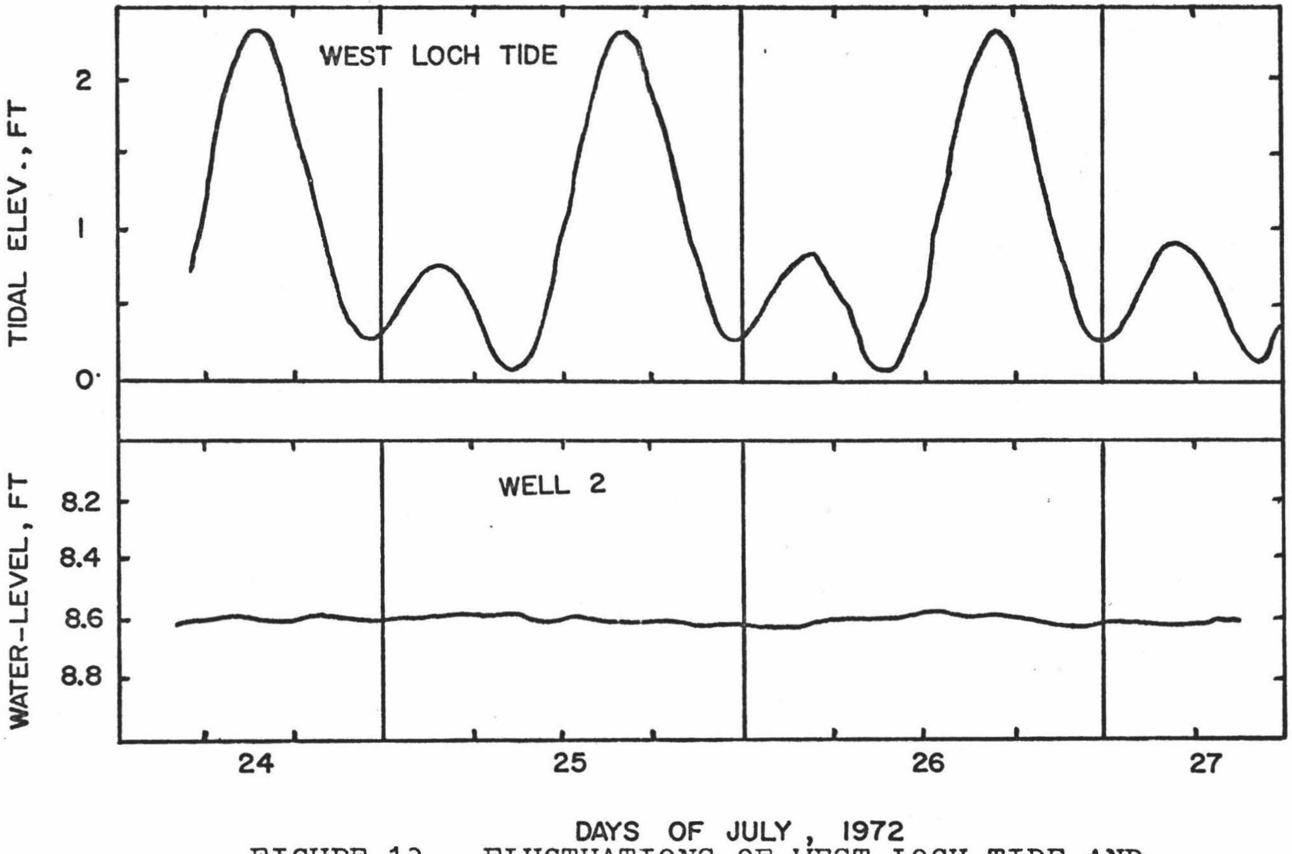


FIGURE 13. FLUCTUATIONS OF WEST LOCH TIDE AND WATER-LEVEL IN WELL 2

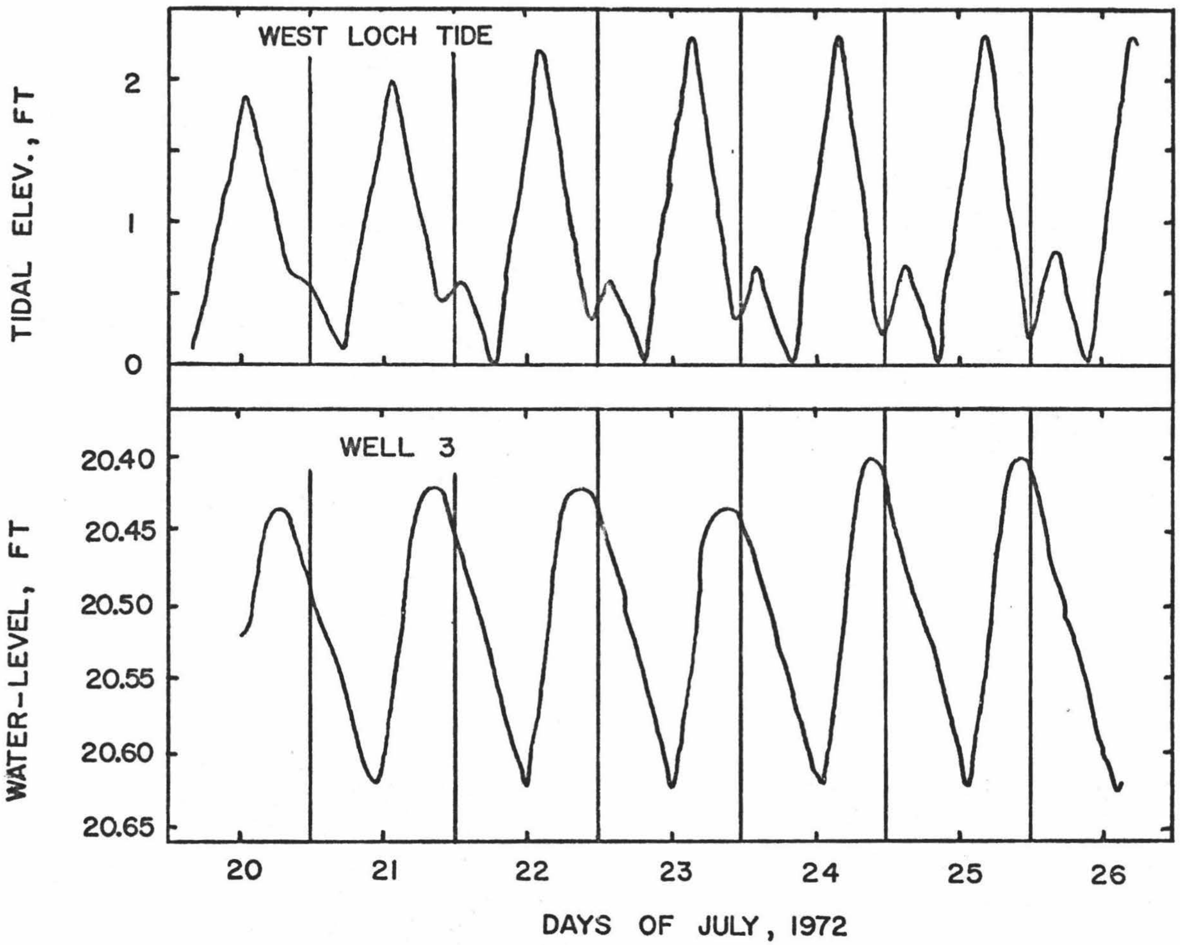


FIGURE 14. FLUCTUATIONS OF WEST LOCH TIDE AND WATER-LEVEL IN WELL 3

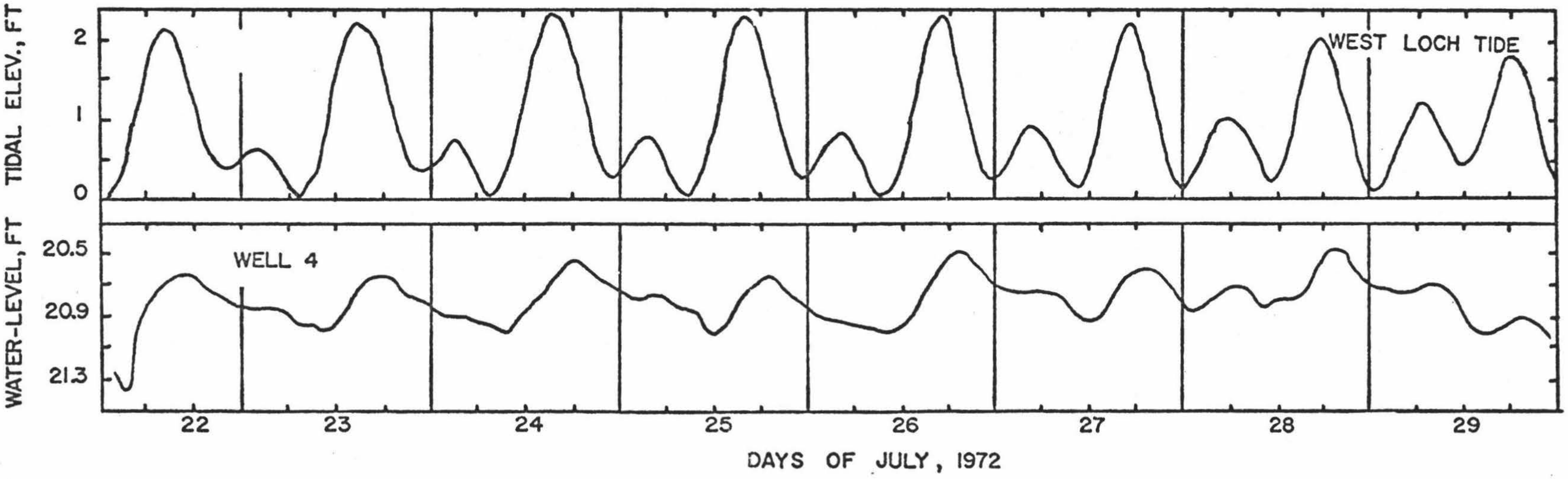


FIGURE 15. FLUCTUATIONS OF WEST LOCH TIDE AND WATER-LEVEL IN WELL 4

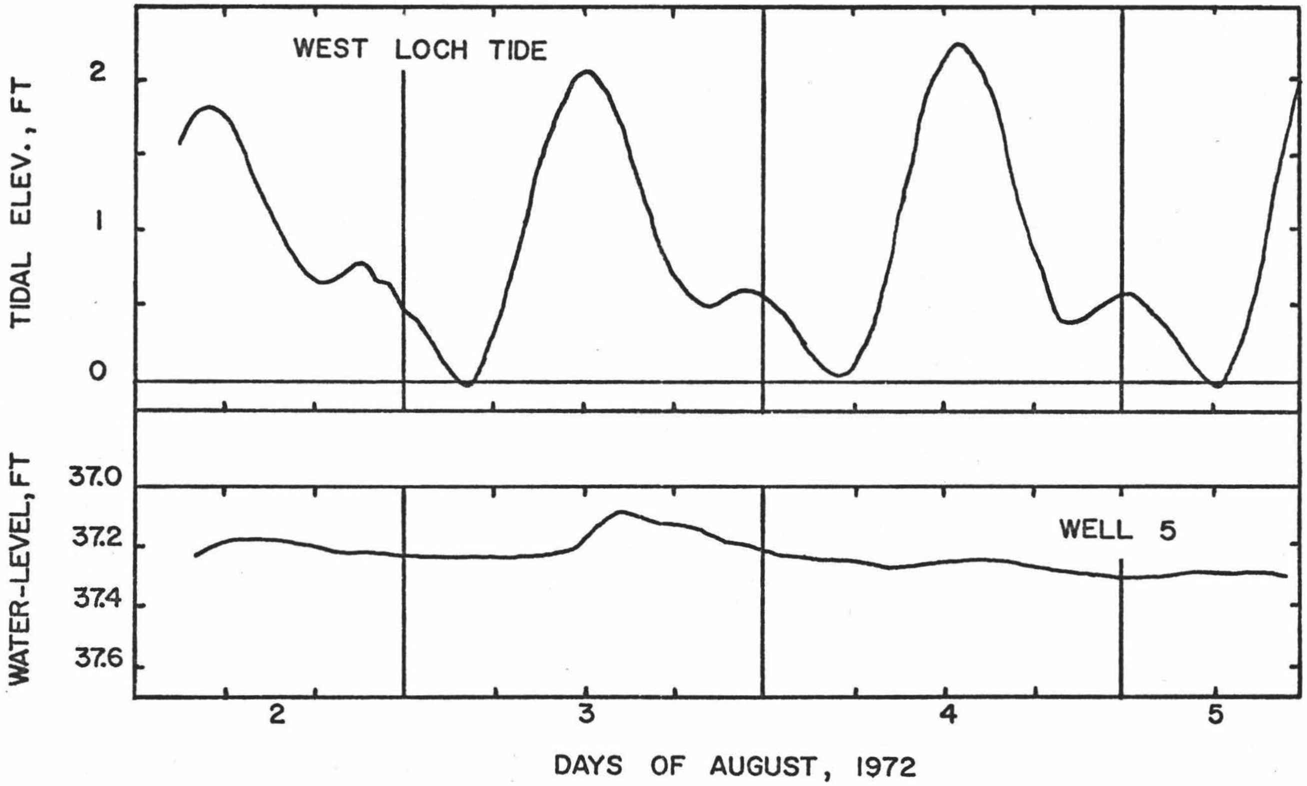


FIGURE 16. FLUCTUATIONS OF WEST LOCH TIDE AND WATER-LEVEL IN WELL 5

the changing stage of Kapakahi stream nearby. This stream is an intertidal stream which flows into West Loch, Pearl Harbor. The water-level changes in Well 5 show a slight response to the changing tides of West Loch, whereas the water-level changes in Well 2 are unaffected by the tides. The poor response in Wells 2 and 5 to the West Loch tide is because of their location farther inland.

The amplitude of the West Loch tide (Figures 14 and 16) is reduced considerably as it transgresses the landfill. For example, the tidal amplitude at Well 4 is only 0.5 feet as compared to the tidal amplitude in West Loch of 2.2 feet. This means that the tidal amplitude in West Loch is about $4\frac{1}{2}$ times that in Well 4.

A time-lag or time elapsing between the arrival of high or low tide and the arrival of high or low water in Wells 3 and 4 is apparent from the tidal and water-level fluctuation records in Figures 14 and 16. The average time-lag recorded at Well 3 is 5.5 hours, and the average time-lag recorded at Well 4 is 2.5 hours. These time-lags indicate that a water-table condition prevails at least in the vicinity of Wells 3 and 4. For a confined aquifer situation or a pressure condition, the response of the water-level in the wells to tide changes should have been virtually instantaneous. Thus upon this basis as well as the nature of the landfill materials observed in the borings, the landfill aquifer appears to be under a water-table condition.

CHAPTER VI

HYDRAULIC CHARACTERISTICS

Coefficient of Transmissibility

An attempt was made to gather pumping-test data at the observation wells for computing the coefficient of transmissibility for the saturated landfill material. However, this attempt was unsuccessful because the small well diameter prohibited the use of a submersible pump. Furthermore the depth to water rendered useless any of the available turbine pumps as their maximum discharge was only one gallon per minute under the existing lift conditions. Despite these shortcomings, the coefficient of transmissibility was able to be determined by the slug-injection test method and also by considering cyclic water-level fluctuations.

Transmissibility from Slug-Injection Test

The slug-injection test for estimating the coefficient of transmissibility of an aquifer, as described by Ferris and Knowles (1963), is based on the consideration that a well is an instantaneous line source or sink if a very small quantity or slug of water is instantaneously injected into or withdrawn from a well. Since only a small quantity of water is involved in a slug-injection test, the result is an estimate of the transmissibility about the immediate vicinity of the well. Despite the simplicity of the test, it is quite useful for fully developed wells of a confined aquifer with small or moderate transmissibilities (less than 50,000 gal/day/ft).

The equation for residual head in an instantaneous vertical line sink is given as:

$$s^1 = \frac{q\, e^{-\frac{r^2 S}{4 Tt}}}{4 \pi Tt} \qquad (1)$$

where,

s^1 = the residual head following the injection of a known volume of water,

r = the distance between the injection well and an observation well,

t = the time elapsed after the slug injection,

q = the volume of the slug of water,

T = the coefficient of transmissibility, and

S = the coefficient of storage.

The effect from the slug of water is around the immediate vicinity of the injection well, and is not usually measured in the observation well. Therefore, only the water-level in the injection well is monitored; the distance, r, is then the radius, r_w, of the well. For values of r as small as r_w, especially where S is small (as for confined aquifers), the exponent of e in equation 1 approaches zero as t becomes large and the value of the exponential term approaches unity. Thus equation 1 becomes:

$$T = \frac{114.6\ g\ (^1/t_m)}{s^1} \qquad (2)\ .$$

if q is expressed in gallons, T in gal/day/ft, t in minutes, and s^1 in feet, with:

t_m = the time in minutes measured from the average of the times at the beginning and ending of the injection.

Equation 2 was developed for the case of a confined aquifer with fully penetrating wells. However, if the assumption is made that the water-table gradient is small and the head in a vertical section is uniform (Dupuit assumptions, Todd, D. K., p. 79), then the equation can be used for estimating the coefficient of transmissibility of the unconfined aquifers.

As was previously discussed, the maximum depth penetrated below the water-table at the landfill (Well 5, Figure 1) is 10 feet. The black mud or silt penetrated is likely to have a low permeability, thus the wells at the landfill will be assumed to be fully penetrating. Therefore, it was now assumed that equation 2 is applicable for the unconfined landfill aquifer, and the following procedure was used to determine the coefficient of transmissibility.

First, the water-level in the well was measured by means of an electric resistivity device, then a known volume or slug of water was injected instantaneously into the well.

The apparatus used for performing the slug-injection test is shown in Figure 17. It consists of a container to hold the slug of water to be injected into the well. A nipple was attached to an opening in the bottom of the container by using a flange connection. A rubber plug with wire attached was used to block the outlet to the well. The time at which injection first began and the time at the end of the injection was recorded. After injection, the apparatus was quickly removed and the water-level decay as a function of elapsed time was carefully observed. With these data, the residual head and the time elapsed since injection were tabulated and used to obtain the straight-line plot necessary for the transmissibility computations (Appendix A).

Values of transmissibility for Wells 1, 3 and 4 were found to be 18,800 gal/day/ft, 1,200 gal/day/ft, and 1,500 gal/day/ft respectively. An examination of the well logs (Figure 9) shows the extreme variability in the landfill composition, thus these values of transmissibility are reasonable. The smaller values are representative of the finer materials whereas the largest value most likely represents permeable pockets of incinerator cans, and concrete pilings, discarded lumber, tree trunks, auto frames, boulders, etc.

Transmissibility from Cyclic Water-Level Fluctuations

In areas near the ocean or any other fluctuating bodies of water, wells close to the fluctuating bodies frequently

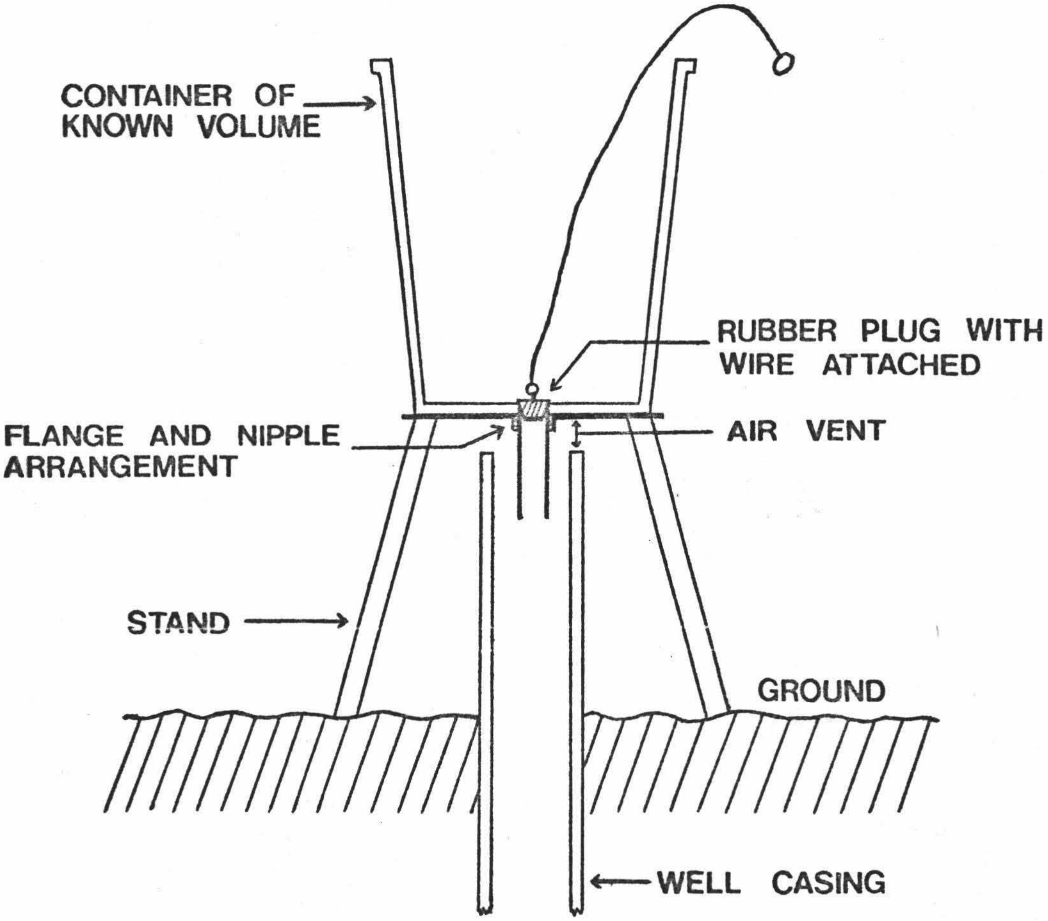


FIGURE 17. SLUG-INJECTION TEST APPARATUS

exhibit sinusoidal fluctuations in response to periodic changes of the tide. As the tide stage rises, the recharge from the ocean to the aquifer increases and the discharge to the ocean decreases, thus causing a rise in water-level in the well. The opposite is true for low tide conditions. The extent of the water-level change in the wells and the magnitude of the time-lag is dependent upon the transmissibility of the aquifer material. Using these data, the coefficient of transmissibility of the aquifer can be determined by either the stage-ratio method or the time-lag method.

Stage-ratio method. Ferris (1963) provides a detailed account of the derivation of an equation for the determination of the coefficient of transmissibility using cyclic water-level fluctuations. Before deriving the equation, the following assumptions must be made:

1) The aquifer is homogeneous and is of uniform thickness and is of great lateral extent.
2) The decline of pressure is followed by the immediate release of water from the aquifer at a rate proportional to decline.
3) The flow is uni-dimensional and that the full thickness of the aquifer abuts the ocean or other fluctuating water bodies.

Since the landfill aquifer is under water-table condition, the following two additional assumptions must be made in order that the analysis will be satisfactory: 1) the observation well must be far enough from the subaqueous outcrop so that it is unaffected by vertical components of flow, and 2) the range of the cyclic fluctuation in the observation well is only a small fraction of the saturated thickness of the formation.

The conditions mentioned above are assumed to be adequately met in the landfill aquifer, hence, an estimate of the coefficient of transmissibility using cyclic water-level fluctuations can be made.

The differential equation governing the linear flow of water in an aquifer near fluctuating water bodies such as the ocean is:

$$\frac{D^2 s}{D\,x^2} = \frac{S}{T}\,\frac{Ds}{Dt} \qquad (3)$$

where,

s = the net rise or fall of well water-level with reference to the mean well water-level over an observed period,

x = the distance from the ocean's edge to observation well,

t = the time elapsed from convenient reference point within any cycle,

S = the coefficient of storage of aquifer, and

T = the coefficient of transmissibility of aquifer.

The water-level in the well will show sinusoidal fluctuations in response to corresponding tidal fluctuations. If the ocean tide stage fluctuates as a simple harmonic motion, a train of sinusoidal waves is propagated shoreward through the aquifer. With increasing distance from the ocean, the amplitude of the transmitted wave decreases, and the time-lag of a given maximum or minimum increases.

For the boundary condition, $s = s_o \text{ Sin } Wt$ at $x = o$, where s_o is the amplitude or half-range of tidal fluctuations, and W is the angular frequency, the solution of the differential equation 3 in its final form is:

$$s = s_o \, e^{-x\sqrt{WS/2T}} \text{ Sin } (Wt - x\sqrt{\frac{WS}{2T}}) \qquad (4)$$

Expressing W in radians per time unit as $2\pi/t_o$, in which t_o is the period of the tide, equation 4 becomes:

$$s = s_o \, e^{-x\sqrt{\pi S/t_oT}} \text{ Sin } (\frac{2\pi t}{t_o} - x\sqrt{\frac{\pi S}{t_oT}}) \qquad (5)$$

which defines a wave motion whose amplitude rapidly decreases with distance x as given by the factor $s_o \, e^{-x\sqrt{\pi S/t_oT}}$. From equation 5, the range of water-level fluctuations at an observation well, s_r, a distance x from the ocean's edge is:

$$s_r = 2s_o \, e^{-x\sqrt{\pi S/t_oT}} \qquad (6)$$

Equation 6 may be rewritten in the gallon-day-foot system of units as:

$$\frac{s_r}{2s_o} = e^{-4.8\ x\sqrt{S/t_oT}} \tag{7}$$

A further simplification of equation 7 as expressed in terms of T becomes:

$$T = \frac{4.4\left[-\log\ (s_r/2s_o)\right]^2\ S}{t_o} \tag{8}$$

where t_o is the tide period, in days; T is the coefficient of transmissibility, in gal/day/ft; S is the storage coefficient; and the logarithmic quantity $s_r/2s_o$ is, in effect, the ratio of the range of water-level fluctuation to the range of tidal fluctuation.

In solving equation 8, a semi-logarithmic plot of the logarithm of the ratio $(s_r/2s_o)$ against the distance x from observation well simplifies the solution. If the change in the logarithm of the ratio of the two ranges is selected over one log cycle the numerator of the expression for the slope reduces to unity. Thus equation 8 becomes:

$$T = \frac{4.4\ (\Delta x)^2\ S}{t_o} \tag{9}$$

Using the tide and water-level data for Wells 3 and 4, and substituting values for the coefficient of storage or specific yield, S, appropriate for a water-table condition, the coefficient of transmissibility was computed as shown in Appendix B. Examples of the coefficient of transmissibility was computed as shown in Appendix B. Examples of the coefficient of transmissibility (Well 3) are 29,700 gal/day/ft (for a specific yield of 0.05), and 59,500 gal/day/ft (for a specific yield of 0.10).

Time-lag method. The time-lag method for determining the coefficient of transmissibility from cyclic water-level fluctuation data also depends on the assumptions already discussed in the section on the stage-ratio method. The equation relating the time-lag and the coefficient of transmissibility as developed by Ferris (1963) is presented below.

The lag in time of occurrence of a given maximum or minimum water-level stage, t_1, is:

$$t_1 = x\sqrt{\frac{t_o S}{4\pi T}} \qquad (10)$$

Equation 10 may be rewritten in the gallon-day-foot system of units in terms of T as:

$$T = \frac{0.60\ x^2\ St_o}{t_1^2} \qquad (11)$$

in which t_1 is the time-lag in occurrence of a given maximum or minimum water-level stage following the occurrence of a similar tidal change, in days; t_o is the period of the tide, in days; and x is the distance from edge of ocean to well, in feet.

The computation of the coefficient of transmissibility using equation 11 is given in Appendix B. Examples of the values of the coefficient of transmissibility (Well 3) are 16,700 gal/day/ft (for a specific yield of 0.05), and 33,400 gal/day/ft (for a specific yield of 0.10).

Table 3 gives a summary of the coefficients of transmissibility determined by the stage-ratio, time-lag, and slug-injection test methods.

Ferris (1963) showed that the stage-ratio and time-lag methods can give a good estimate of the coefficient of transmissibility of an aquifer near a fluctuating body of water despite the assumptions made and the need to assume values of the coefficient of storage or specific yield which can be estimated from knowledge of the aquifer material. For the case of the landfill aquifer, a specific yield of 5 percent was chosen on the basis of the aquifer material being a fine-grained mixture of predominantly mud. The values of the coefficient of transmissibility determined by the time-lag method should be similar to those determined by the stage-ratio method. However, there is a big difference between the values.

In order to account for the difference between the values, Ferris (1963) noted that the time of occurrence of maximum and minimum water-levels cannot be determined as

TABLE 3

SUMMARY OF THE COEFFICIENTS OF TRANSMISSIBILITY

WELL	COEFFICIENT OF STORAGE, S	COEFFICIENT OF TRANSMISSIBILITY, T (GPD/FT)		
		METHOD		AVERAGE
		STAGE - RATIO	TIME - LAG	
3	0.05	29,700	16,700	23,200
	0.07	41,600	23,400	32,500
	0.10	59,500	33,400	46,450
4	0.05	40,900	87,800	64,400
	0.07	57,300	122,900	90,100
	0.10	81,900	175,600	123,800
		SLUG - INJECTION TEST		
1		18,800		
3		1,200		
4		1,500		

precisely as the ranges in stage if the time scale on the recorder charts is compressed to a greater degree than the gauge-height scale. Furthermore, differences in the effective screen resistance of the observation wells would tend to distort observations of the timing of maximum and minimum water levels.

For the landfill case, a Stevens water-level recorder having its time scale on the recorder charts compressed to a greater degree than the gauge-height scale was used to monitor the water-level in Well 3. Therefore, the time occurrence of maximum and minimum water-levels in Well 3 cannot be determined as precisely as the ranges in stage. On the other hand, a Belfort water-level recorder having its gauge-height scale on the recorder charts compressed to a greater degree than the time-scale was used to monitor the water-level in Well 4. Thus, the ranges in stage cannot be determined as precisely as the time occurrence of maximum and minimum water-levels.

Another possible cause for the difference in the transmissibility values could be the gravel fill surrounding the well casing plus the perforation pattern of the well casing which would tend to distort observations of the timing of maximum and minimum water-levels.

As for the slug-injection test, the smaller values may be a result of the compaction of the material about the immediate vicinity of the well during the drilling.

Thus an average of the values of transmissibility as determined by the stage-ratio and time-lag methods gives an overall value of the coefficient of transmissibility of the landfill aquifer as 43,800 gal/day/ft.

Water Movement

The direction of flow of the landfill water was found by constructing a general water-level contour map. An attempt to use a suitable tracer for indicating the water flow direction was unsuccessful because of the absorptive nature and the low permeability of the landfill material.

Water-level data for each well during low tide was selected for making the water-level contour map. A low tide period was chosen because a seaward flow direction is dominant during this period. Data for the construction of the water-level map is given in Table 4. Figure 18 shows the general water-level contour map of the landfill area. The placement of arrows perpendicular to the contour lines indicates the direction of flow to be generally toward the ocean. This is supported by the occurrence of springs and seepage areas about the toe of the landfill. The accuracy of the water-level contour map may be enhanced if more drill holes were available, nevertheless, the present data is sufficient to provide an adequate picture of the flow direction.

An estimate of the rate of movement of the landfill water was made by using the Darcy flow equation (Todd, 1959):

TABLE 4

WATER-LEVEL CONTOUR MAP DATA

WELL	DEPTH TO SEA LEVEL, IN FEET	WATER LEVEL, IN FEET	HEAD, IN FEET
1	18.75	16.04	2.71
2	11.35	8.62	2.73
3	18.17	16.73	1.34
4	22.21	20.98	1.23
5	39.66	37.29	2.37

*Single measurement of water-levels taken during a low tide period.

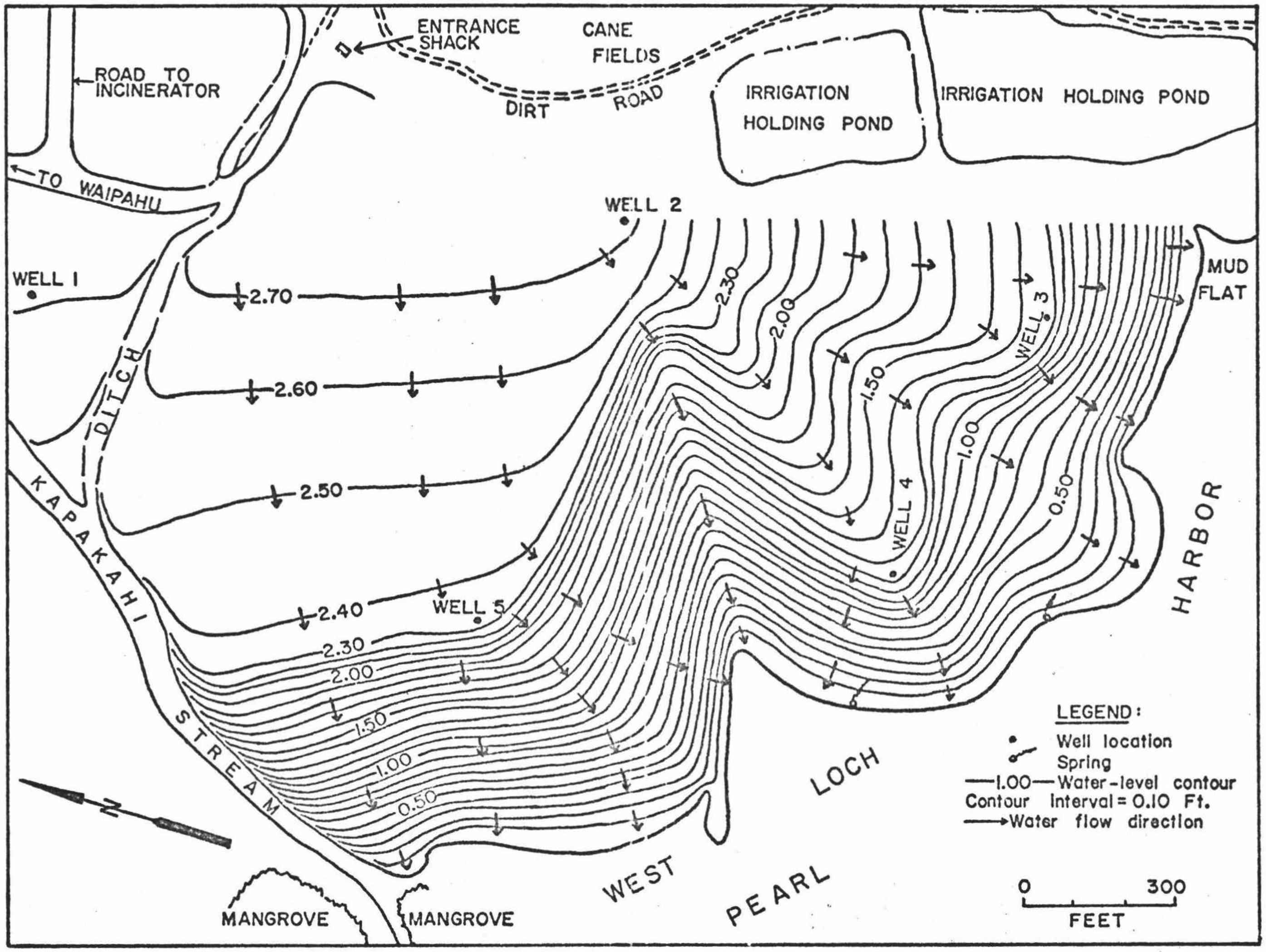


FIGURE 18. WATER-LEVEL CONTOUR MAP OF WAIPAHU LANDFILL

$$Q = -KA \frac{dh}{dl} \qquad (12)$$

or $$Vap = \frac{Q}{A} = -K \frac{dh}{dl}$$

where,

Vap = the apparent flow velocity,

Q = the discharge,

A = the cross-sectional area over which flow occurs,

K = the coefficient of permeability ($K = T/b$), and

$\frac{dh}{dl}$ = the flow gradient.

Taking n = the porosity of the aquifer, the true velocity V_T is:

$$V_T = \frac{Q}{An} = -\frac{K}{n} \frac{dh}{dl}$$

With the coefficient of permeability, the gradient, and the porosity known, the actual velocity or flow rate was calculated to be about 2.1 ft/day (Appendix C).

Discharge into West Loch

The discharge or total flow of water into West Loch, Pearl Harbor may be estimated by using the equation:

$$Q_T = VapA$$

where,

Q_T = the total discharge

V_{ap} = the apparent or Darcy velocity of flow, and

A = the area through which flow occurs.

The velocity or flow rate is known from the previous section. The average width, as determined from the landfill map (Figure 1), through which flow occurs is about 1200 feet. With an aquifer thickness of 10 feet, the cross-sectional area through which flow occurs is therefore 12,000 ft^2. Thus the total discharge into West Loch is computed to be about 94,300 gal/day as shown in Appendix C.

Discharge into West Loch is evident from the presence of a few springs and many seepage areas which may be observed at the toe of the landfill during periods of low tide. The spring discharge was estimated by timing the flow from the spring into a container of known volume. Discharge from each of the two springs, Figure 1, is rated at 1 gal/min. This means that a total of about 3,000 gal/day discharge from these springs into West Loch. However, these spring discharges are but a fraction of the total discharge occurring during low tide owing to the flushing effect from the landfill aquifer. This total discharge due to flushing effect is computed to be about 66,500 gal/day as shown in Appendix C. The total discharge from the landfill into West Loch is quite small compared to the 20 MGD average flow entering from Waikele springs (Visher and Mink, 1964).

CHAPTER VII

RECHARGE

The Waipahu landfill area is located on the dry leeward side of Oahu. Rainfall and pan evaporation data were not collected directly at the landfill site. Instead data gathered at the nearest stations were used to get an idea of the amount of rainfall and evaporation to expect for this area.

The Waipahu station (USWB 750) is less than one-half mile from the West Loch shoreline (Figure 1). The average annual rainfall recorded for this station was 28.81 inches for 1951-1971 (Table 5). Class A pan evaporation data collected at the HSPA Kunia sub-station indicates an annual potential evaporation of 69.98 inches for 1963-1969 (Table 6). The evaporation potential should be high in the landfill area because of the severe dryness there. This relatively dry landfill area is characterized by a lack of vegetation which is a result of the frequent bulldozing, trucking and burning activities there. In contrast, mangrove, sugarcane and other plants flourish in the surrounding area. In spite of the high value of potential evaporation and the relatively low precipitation, a certain amount of rainfall will penetrate the aquifer during the year. Recharge of the landfill aquifer can occur anytime during the year whenever heavy rainstorms pass over the

TABLE 5

MONTHLY RAINFALL DATA FOR WAIPAHU STATION (USWB 750), (1951-1971)
(Data from National Weather Service)

MONTH	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.	ANNUAL
	5.27	2.80	3.81	2.04	1.27	0.37	0.82	0.95	0.79	2.53	4.05	4.07	28.81

TABLE 6

MONTHLY PAN EVAPORATION DATA FOR HSPA KUNIA SUB-STATION (740.4), (1963-1969)
(Data from Dept. of Land and Natural Resources)

MONTH	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.	ANNUAL
	4.15	4.45	4.92	5.67	6.58	7.65	7.67	7.87	6.65	5.55	4.67	3.94	69.98

landfill area. This was the case in September 1972 when rain falling frequently during a period of a week caused a small rise in the water-table. However, the most likely time for recharge of the landfill aquifer by rainfall would be the winter months. A comparison of the monthly rainfall data (Table 5) and the monthly evaporation data (Table 6) indicates that rainfall exceeds evaporation twice per year (during the months of December and January). The excess rainfall available for recharge during December and January could possibly be about 0.13 inch and 1.12 inch respectively. How much of this excess rainfall reaches the water-table depends upon the infiltration capacity and also the soil moisture content of the fill material. Precipitation therefore is a minor source of recharge to the groundwater body during a small portion of the year.

Another possible source of recharge is groundwater seepage beneath the landfill. The only evidence suggesting groundwater as a source of recharge is the relatively fresher water found only in Well 2. The known occurrence of major springs and tiny seepages about the Pearl Harbor area reinforces this belief. The amount of groundwater seepage would be difficult, if not impossible, to determine directly because fresher water may be seeping through openings in the caprock which underlies the landfill.

Return irrigation water may not be an important source of recharge because there are ditches or ponds to trap irrigation tailwater (see Figure 1). Besides, these ponds were noticeably dry throughout the study period.

Ocean water seems to be the major source of recharge as the influence of the tide upon the landfill aquifer was established. Sea water does not seem to extend very far inland as the saline character of the sea water is not observed in a boring located about 70 feet from the shoreline. Water issuing from the springs at the toe of the landfill during low tide is quite similar to sea water, thus tidal flushing is a significant contributor of water to the landfill aquifer. The amount of water flowing into the landfill aquifer was computed, as shown in Appendix C, to be about 66,500 gal/day, which is approximately 71 percent of the 94,300 gal/day computed as the total discharge into West Loch.

The remaining 27,800 gal/day of the total discharge may be accounted for by groundwater seepage, precipitation, and to a lesser extent, return-irrigation water. However, a detailed breakdown of the contribution of each of these sources would necessitate a complete budget study of the Waipahu landfill area which is not available.

CHAPTER VIII

CHEMICAL AND PHYSICAL CONSIDERATIONS

Measurements of chemical and physical parameters of water from the landfill wells, West Loch, landfill spring, Kapakahi stream, and a boring about 70 feet from the shoreline are summarized in Table 7.

Data from Table 7 shows that water from Well 2 varies greatly in quality compared to the other wells. For example, values of temperature, salinity, conductivity, chlorides, nitrogen, and total organic carbon (TOC) are considerably lower compared to the other wells. The very high temperature in all the wells except Well 2 can be attributed to continuous burning in places below the landfill surface. A comparison of the landfill well water and sea water indicates that the water in all the wells except Well 2 is brackish. The water in Well 2 is fresher and can therefore be considered as the standard for comparing water quality throughout the landfill.

The influence of the tide upon the landfill aquifer is evident not only from water-level fluctuations, but also from changes in the quality of the well water. The relatively high chloride, salinity and conductivity values for all the wells except Well 2 indicate the presence of sea water. The low values of the above parameters in Well 2 can be attributed to the fact that Well 2 is the farthest away

TABLE 7

DATA OF PHYSICAL AND CHEMICAL PARAMETERS

PARAMETER	WELL					WEST LOCH		KAPAKAHI STREAM		LANDFILL SPRING	BORING NEAR SHORELINE
	1	2	3	4	5	1	2	A	B		
TEMPERATURE, C	47.5	30.7	42.4	42.0	41.3	28.5	28.3	28.6	27.6	34.7	43.0
SALINITY, ‰	10.9	1.6	4.1	5.4	16.3	29.2	27.4	17.5	8.4	26.3	-
CONDUCTIVITY, μMHOS	21,460	3,000	8,185	9,400	27,000	50,000	49,500	30,000	15,770	48,100	8,000
CHLORIDES, PPM	2,830	565	1,335	2,135	7,290	16,650	15,700	8,560	4,170	15,100	6,183
ALKALINITY, PPM AS $CACO_3$	580	442	64	397	1,767	121	131	111	87	455	154
pH	6.4	7.5	7.8	7.2	7.2	7.8	7.8	7.4	7.1	7.5	7.3
OXI-RED-POT, MV	-73	-2	-1	24	-58	57	67	58	65	-164	-
DISSOLVED OXYGEN, PPM	0.45	0.58	0.41	0.38	0.43	5.65	4.34	3.86	2.15	0.3	-
NITROGEN, N , PPM	22.54	1.25	3.93	19.28	13.32	0.20	0.79	0.31	0.44	11.65	32.8
PHOSPHOROUS, P , PPM	0.13	0.37	0.13	0.30	0.11	0.15	0.12	0.23	0.26	0.32	-
TOTAL ORGANIC CARBON, PPM	1,400	32	69	79	374	14	15	24	24	27	-

from the shore and therefore could be expected to be influenced by sea water the least.

Further measurements of temperature, salinity, and conductivity at the wells during one tide cycle are listed in Table 8. These data show that the values for conductivity increased during high tide and decreased during low tide in all the wells (Well 5 was closed during this part of the study) except Well 2 (see Figure 19). Thus, this is in accordance with the above discussion.

Sea water temperature is much lower than well water temperature, therefore, a decrease in well temperatures might be expected to accompany the increase in salinity and conductivity following the movement of sea water inland. This is the case for Wells 3 and 4 (see Table 8). On the other hand, the decrease in Well 2 temperatures did not cause an increase in either salinity or conductivity, therefore, the vicinity about Well 2 is influenced by sea water the least.

The water quality in a borehole about 70 feet from the shore of West Loch is comparable to that of Wells 3 and 4. This means that the salt water wedge (Figure 20) gets thinner farther inland. Brackish water in the borehole indicates that the thickest portion of the salt water wedge invades probably no more than 70 feet inland. The fact that Well 2 is little influenced by the sea means that lateral movement of sea water through the landfill is dominant

TABLE 8

TEMPERATURE, SALINITY, AND CONDUCTIVITY DATA MONITORED OVER A TIDE CYCLE

WELL	TIME	TEMPERATURE, °C	SALINITY, ‰	CONDUCTIVITY, μ MHOS
1	8:08 am	>50	11.9	26,800
	12:10 pm	>50	11.9	27,000
	1:15 pm	>50	11.8	27,000
	2:20 pm	>50	11.5	26,500
	2:40 pm	>50	11.5	26,500
	3:50 pm	>50	11.6	26,500
	5:07 pm	>50	11.6	26,500
	5:30 pm	>50	11.7	26,500
	7:00 pm	>50	11.7	26,500
2	8:15 am	30.7	1.7	3,100
	9:40 am	30.7	1.7	3,100
	12:20 pm	30.5	1.7	3,100
	1:25 pm	30.7	1.7	3,100
	2:47 pm	31.0	1.7	3,100
	3:55 pm	31.5	1.7	3,100
	5:02 pm	31.5	1.7	3,100
	5:35 pm	31.5	1.7	3,100
	6:55 pm	31.5	1.7	3,100
3	8:26 am	43.0	4.0	8,700
	9:30 am	43.0	4.1	9,000
	12:30 pm	42.5	4.2	9,900
	1:05 pm	42.5	4.3	10,000
	1:35 pm	42.5	4.2	9,900
	2:10 pm	43.0	4.2	9,900
	3:00 pm	43.5	4.1	9,900
	3:35 pm	43.5	4.1	9,900
	4:00 pm	42.5	4.1	9,900
	4:30 pm	42.5	4.2	9,900
	4:53 pm	42.5	4.2	9,900
	5:55 pm	42.5	4.3	9,900
	6:37 pm	42.5	4.3	10,000
4	8:33 am	42.0	5.0	11,500
	9:20 am	42.5	5.0	11,500
	12:37 pm	42.0	5.0	11,400
	1:00 pm	41.2	5.0	11,400
	1:40 pm	42.0	4.9	11,000
	2:05 pm	42.0	4.9	11,000
	3:05 pm	42.0	4.9	11,000
	3:30 pm	42.5	4.8	11,100
	4:05 pm	42.5	4.8	11,100
	4:25 pm	43.0	4.8	11,100
	4:40 pm	43.0	4.8	11,100
	6:05 pm	43.0	4.8	11,100
	6:30 pm	43.0	4.8	11,100

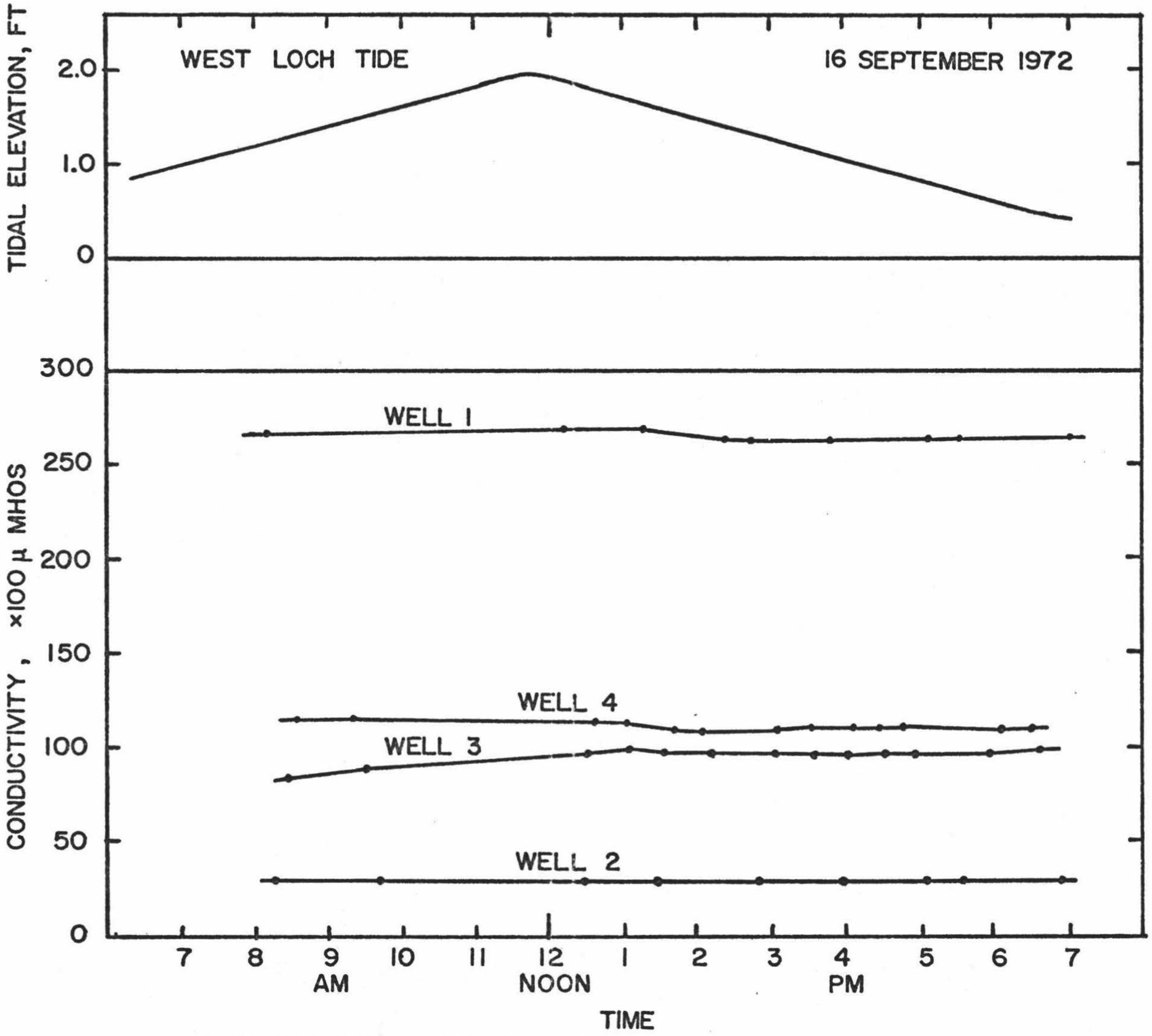


FIGURE 19. GRAPHS OF CONDUCTIVITY MEASUREMENTS TAKEN DURING A TIDE CYCLE

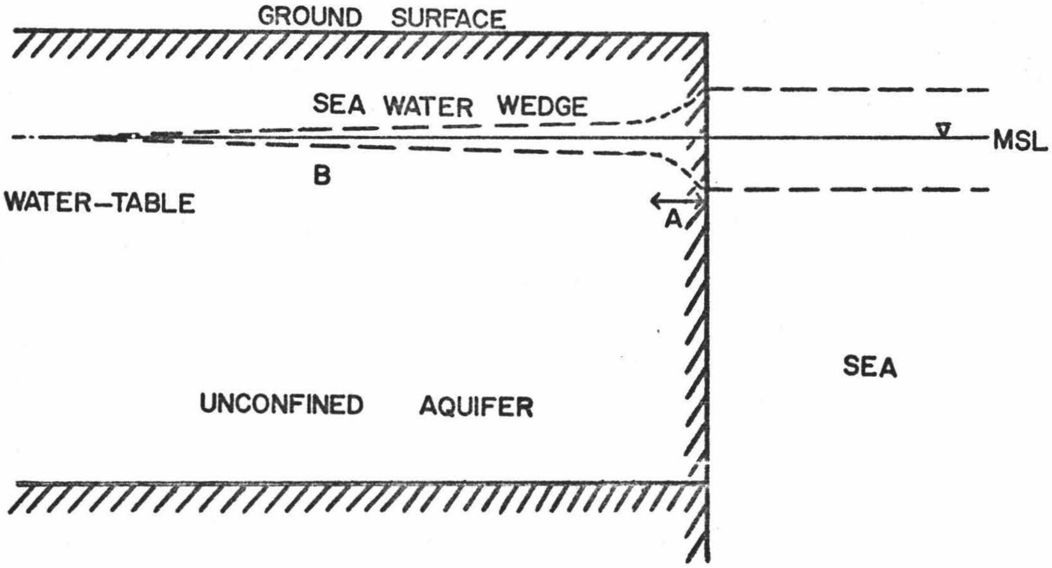


FIGURE 20. SCHEMATIC DIAGRAM SHOWING DEVELOPMENT OF A SEA WATER WEDGE IN AN UNCONFINED COASTAL AQUIFER

rather than a bobbing up of sea water beneath the landfill.

The flow of water from the landfill into West Loch is evident from the springs and tiny seepage areas observed at the toe of the landfill during low tide. This can be substantiated further by comparing the quality of the landfill water (an average of each of the parameters from Wells 1, 3, 4 and 5), West Loch water, and the landfill spring water, which are shown in Table 9. For example, the landfill spring water entering West Loch has a greater temperature (34.7°C) than sea water (28.4°C). The salinity, conductivity and chloride values of the landfill spring water are much greater than those for the landfill water but less than those for sea water. This difference between the landfill spring water and sea water is probably due to the dilution of sea water by the fresher landfill water which eventually flows back out into West Loch.

Other water quality parameters such as alkalinity, Oxidation-Reduction-Potential (ORP), dissolved oxygen (DO), nitrogen, and Total-Organic-Carbon (TOC) show considerable change compared to sea water. For instance, more nitrogen and total organic carbon are found in the landfill spring water than in sea water. This therefore means that water is flowing from the landfill into West Loch.

The rate of flow of 2.1 ft/day seems reasonable because the change in conductivity (see Figure 19) at Wells 1, 3 and 4 over a tide cycle occurs only after several hours

TABLE 9

COMPARISON OF LANDFILL WATER, WEST LOCH WATER, AND LANDFILL SPRING WATER

PARAMETER	LANDFILL WATER	WEST LOCH	LANDFILL SPRING
TEMPERATURE, °C	43.3	28.4	34.7
SALINITY, ‰	9.2	28.3	26.3
CONDUCTIVITY, μ MHOS	16,511	49,750	48,100
CHLORIDES, PPM	3,398	16,175	15,100
ALKALINITY, PPM AS $CACO_3$	702	126	455
pH	7.1	7.8	7.5
OXI-RED-POT, MV	-108	62	-164
DISSOLVED OXYGEN, PPM	0.42	5.0	0.3
NITROGEN, N , PPM	14.77	0.49	11.65
PHOSPHOROUS, P , PPM	0.17	0.14	0.32
TOTAL ORGANIC CARBON, PPM	480	14.5	27

following the arrival of low or high tide.

The fresher water in Well 2 and the brackish water in all the other wells suggest the presence of a fresh water recharge source which cannot be monitored.

CHAPTER IX

SUMMARY AND CONCLUSION

The nature of the landfill material varies considerably in its physical properties. Values of transmissibility were found to range from 1,200 gal/day/ft to 87,800 gal/day/ft (for the selected storage coefficient or specific yield of 0.05). Observations of the character of the landfill material indicate that the low and high values for transmissibility are possible because the landfill in places is predominantly mud or silt whereas in other places it consists of concrete pilings, boulders, incinerated cans, dumped auto frames, discarded lumber, and tree trunks, etc. However, an average value of 43,800 gal/day/ft can be taken as a reasonable estimate of the overall transmissibility of the landfill aquifer. This value of the coefficient of transmissibility is very small compared to that observed for basalt in Hawaii (roughly 10^7 gal/day/ft as given by Davis, 1969).

The movement of water through the landfill is on the order of 2.1 ft/day and is directed generally towards West Loch. With this rate of flow, the total discharge from the landfill is about 94,300 gal/day. This estimate of the total discharge into West Loch is quite small when compared to the average daily discharge of 20 MG by Waikele springs.

Water-level measurements and water quality data indicate a direct influence of tidal fluctuations upon the landfill water. However, this effect is restricted to areas near the shoreline.

The bulk of the recharge to the landfill aquifer is from tidal flux and was calculated to be about 66,500 gal/day. The remaining 27,800 gal/day of the total discharge probably comes from fresher groundwater seepage beneath the landfill and surrounding areas. Other minor sources of recharge are precipitation (mainly in the winter months), and possibly return irrigation water. A further breakdown of the contribution of fresh water to the landfill aquifer by these sources cannot be determined until a more detailed water-budget study is conducted throughout the area.

Despite the assumptions made and the limitations of the equations applied, a basic knowledge of the hydraulic nature of the landfill material and a range of values of its aquifer characteristics has been established.

APPENDICES

APPENDIX A

SLUG-INJECTION TEST COMPUTATIONS

TABLE 10

DATA OF RESIDUAL HEAD AND RECIPROCAL OF TIME FOR WELL 1

WATER LEVEL FT	RESIDUAL HEAD s', FT	TIME SINCE INJECTION t, SEC	t, MIN	RECIPROCAL OF TIME $1/t_m$, MIN
18.408				
18.408	0.182	26	0.434	2.310
18.446	0.144	31	0.517	1.939
18.474	0.116	39	0.651	1.539
18.495	0.095	47	0.784	1.279
18.510	0.080	55	0.919	1.090
18.523	0.067	61	1.102	0.909
18.525	0.065	67	1.139	0.879
18.531	0.059	74	1.232	0.811
18.535	0.055	78	1.303	0.770
18.535	0.055	84	1.400	0.715
18.544	0.046	90	1.500	0.669
18.544	0.046	97	1.617	0.620
18.547	0.043	103	1.719	0.582
18.558	0.032	118	1.969	0.509
18.558	0.032	125	2.083	0.481
18.562	0.028	144	2.400	0.416
18.562	0.028	152	2.540	0.394
18.563	0.023	159	2.650	0.377
18.563	0.023	172	2.860	0.349
18.575	0.015	232	3.860	0.259
18.575	0.015	292	4.860	0.206
18.575	0.015	352	5.860	0.171

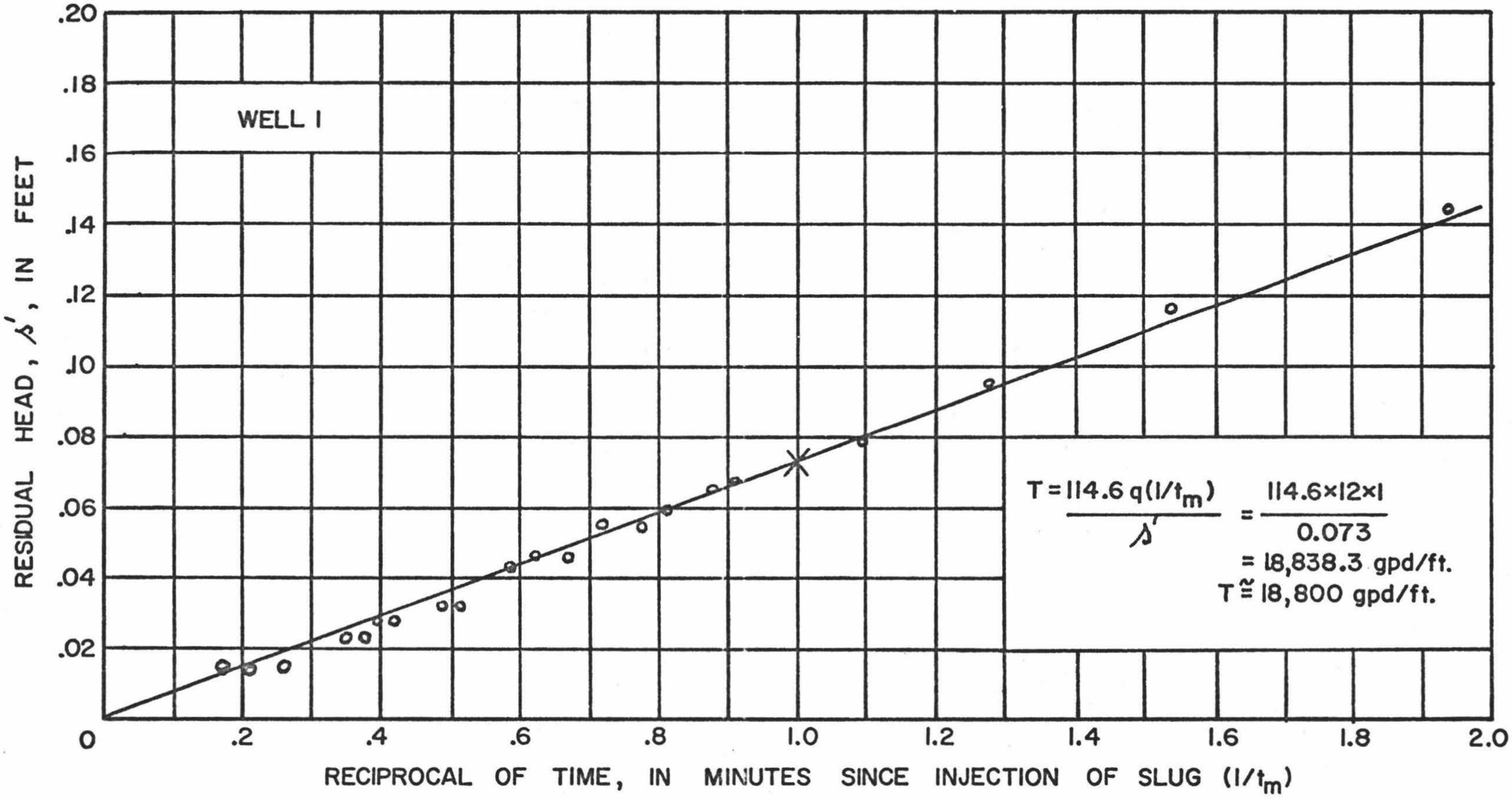


FIGURE 21. GRAPH OF RESIDUAL HEAD VERSUS RECIPROCAL OF TIME FOR WELL 1

TABLE 11

DATA OF RESIDUAL HEAD AND RECIPROCAL OF TIME FOR WELL 3

WATER LEVEL	RESIDUAL HEAD	TIME SINCE INJECTION		RECIPROCAL OF
FT	h', FT	t, SEC	t, MIN	TIME $1/t_m$, MIN
17.12				
17.12	1.13	40	0.668	0.496
17.43	0.82	55	0.919	1.088
17.58	0.67	70	1.166	0.859
17.70	0.55	85	1.415	0.705
17.79	0.46	100	1.670	0.598
17.85	0.40	115	1.920	0.520
17.91	0.34	130	2.170	0.460
17.93	0.32	145	2.42	0.414
17.95	0.30	156	2.61	0.384
17.96	0.29	166	2.76	0.363
17.99	0.26	176	2.94	0.340
18.00	0.25	186	3.10	0.323
18.02	0.23	196	3.26	0.307
18.04	0.21	206	3.44	0.291
18.05	0.20	216	3.62	0.276
18.05	0.20	236	3.94	0.254
18.08	0.17	276	4.63	0.216
18.13	0.12	336	5.60	0.178
18.14	0.11	376	6.28	0.159
18.15	0.10	416	6.94	0.144
18.16	0.09	536	8.59	0.116
18.16	0.09	556	9.25	0.108
18.16	0.09	596	9.95	0.103

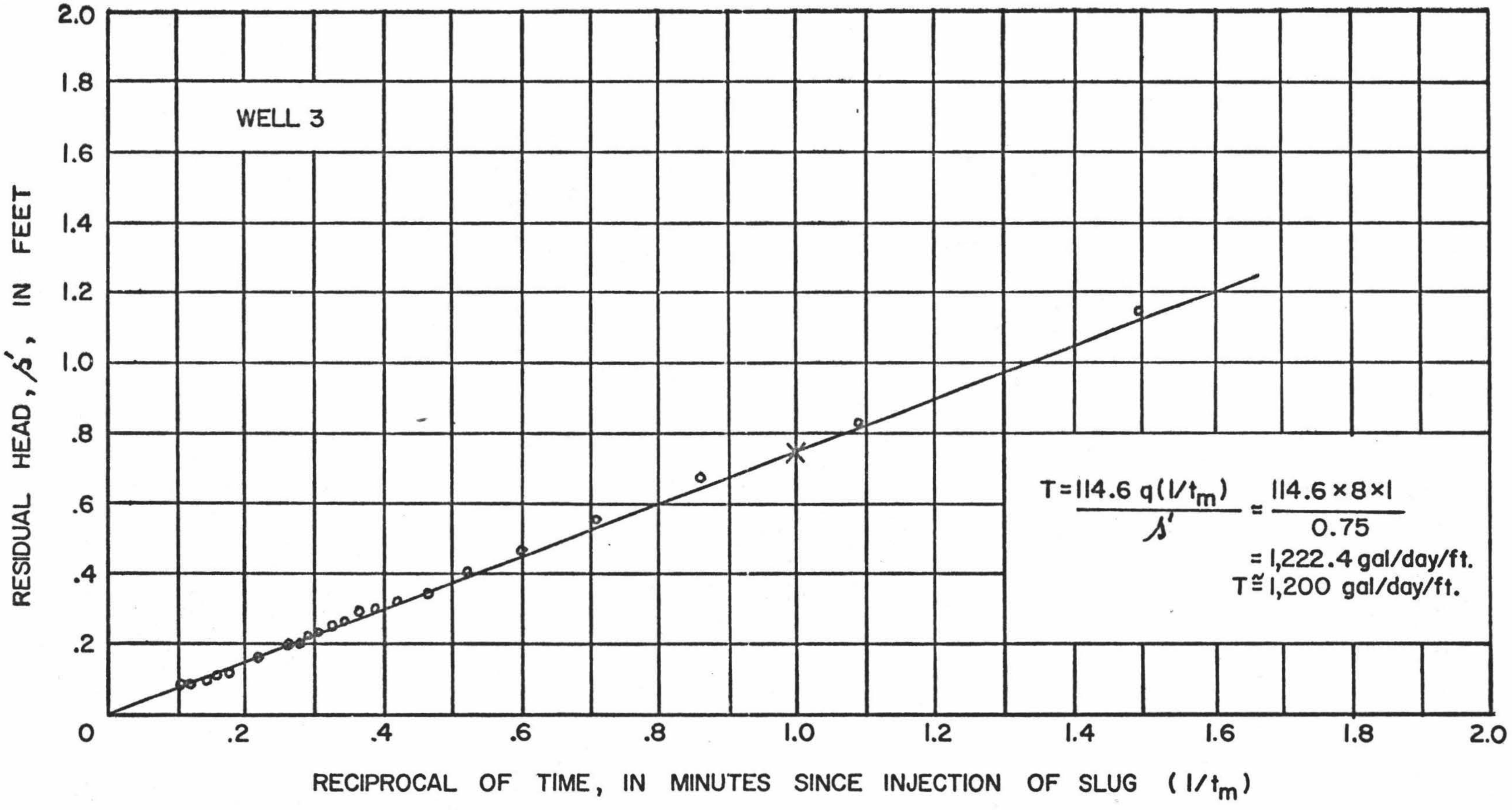


FIGURE 22. GRAPH OF RESIDUAL HEAD VERSUS RECIPROCAL OF TIME FOR WELL 3

TABLE 12

DATA OF RESIDUAL HEAD AND RECIPROCAL OF TIME FOR WELL 4

WATER LEVEL FT	RESIDUAL HEAD s', FT	TIME SINCE INJECTION t, SEC	t, MIN	RECIPROCAL OF TIME $1/t_m$, MIN
21.92				
21.92	1.45	38	0.632	1.582
22.32	1.05	50	0.844	1.184
22.49	0.88	62	1.032	0.971
22.63	0.74	74	1.234	0.812
22.74	0.63	86	1.435	0.699
22.83	0.54	96	1.602	0.623
22.88	0.49	106	1.765	0.568
22.91	0.46	116	1.939	0.519
22.94	0.43	126	2.100	0.476
22.99	0.38	136	2.270	0.441
23.01	0.36	146	2.440	0.411
23.03	0.34	156	2.61	0.384
23.07	0.30	166	2.76	0.363
23.08	0.29	176	2.94	0.340
23.08	0.29	186	3.10	0.323
23.09	0.28	196	3.26	0.307
23.12	0.25	206	3.44	0.291
23.16	0.21	236	3.94	0.254
23.18	0.19	256	4.26	0.234
23.18	0.19	266	4.44	0.226
23.18	0.19	296	4.94	0.203
23.20	0.17	336	5.60	0.178
23.22	0.15	356	5.95	0.169
23.22	0.15	376	6.28	0.159
23.26	0.11	466	7.78	0.129
23.27	0.10	516	8.59	0.116
23.27	0.10	586	9.79	0.102
23.27	0.10	606	10.10	0.099

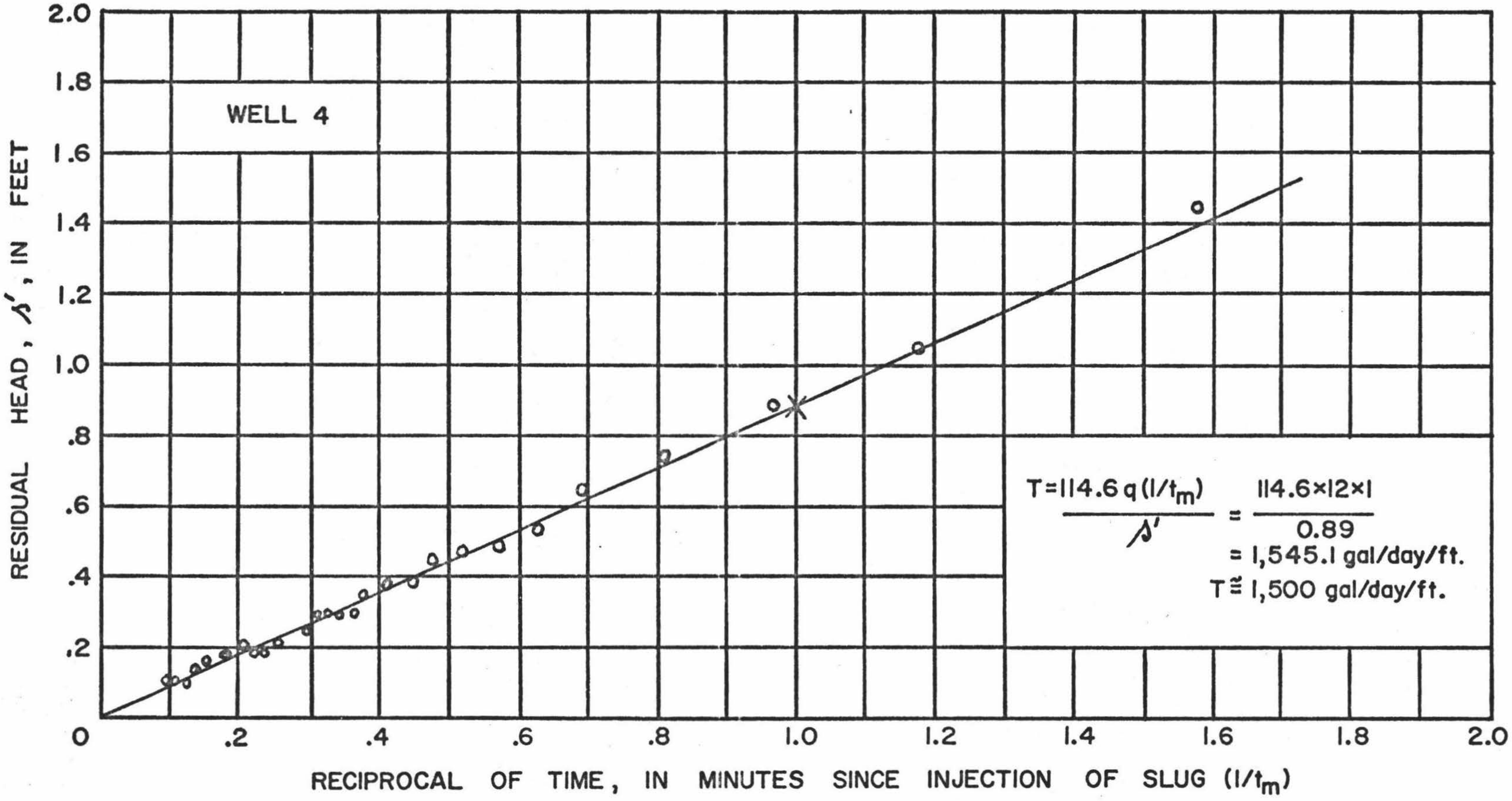


FIGURE 23. GRAPH OF RESIDUAL HEAD VERSUS RECIPROCAL OF TIME FOR WELL 4.

APPENDIX B

COMPUTATIONS OF TRANSMISSIBILITY FROM CYCLIC WATER-LEVEL FLUCTUATION DATA

OBSERVATION WELL 3

Stage-Ratio Method

The stage-ratio formula for transmissibility is:

$$T = \frac{4.4\ (\Delta X)^2\ S}{t_o}$$

For ΔX = 260 feet (see Figure 24); t_o = 12 hrs or 0.5 days.

$$T = \frac{4.4 X\ 260 X 260\ X S}{0.5}$$

$$= 594{,}880\ S\ \text{gal/day/ft}$$

Assuming appropriate values of S for a water-table condition,

when, S = 0.05, T = 29,700 gal/day/ft

S = 0.07, T = 41,600 gal/day/ft

S = 0.10, T = 59,500 gal/day/ft

Time-Lag Method

The time-lag equation for transmissibility is:

$$T = \frac{0.60\ x^2\ S\ t_o}{t_1^2}$$

For X = 145 ft (see Figure 25); t_o = 0.5 days; t_1 = 3.3 hrs.

$$T = \frac{0.60\ x\ 145 x 145 x\ S x\ 0.5\ x\ 24 x 24}{3.3\ x\ 3.3}$$

$$= 333{,}620\ S\ \text{gal/day/ft}$$

Assuming appropriate values of S for a water-table condition, when, $S = 0.05$, $T = 16{,}700$ gal/day/ft

$S = 0.07$, $T = 23{,}400$ gal/day/ft

$S = 0.10$, $T = 33{,}400$ gal/day/ft

OBSERVATION WELL 4

Stage-Ratio Method

The stage-ratio formula for transmissibility is:

$$T = \frac{4.4\ (\Delta X)^2\ S}{t_o}$$

For $\Delta X = 305$ feet (see Figure 24); $t_o = 0.5$ days.

$$T = \frac{44 X\ 305 X 305\ X S}{0.5}$$

$$= 818{,}620\ S \text{ gal/day/ft}$$

Assuming appropriate values of S for a water-table condition,

when, $S = 0.05$, $T = 40{,}900$ gal/day/ft

$S = 0.07$, $T = 57{,}300$ gal/day/ft

$S = 0.10$, $T = 81{,}900$ gal/day/ft

Time-Lag Method

The time-lag equation for transmissibility is:

$$T = \frac{0.60\ x^2\ St_o}{t_1^2}$$

For $X = 260$ feet (see Figure 25); $t_o = 0.5$ days; $t_1 = 2.58$ hrs.

$$T = \frac{0.60 \times 260\text{x}260 \times S \times 0.5\text{x}24\text{x}24}{2.58 \times 2.58}$$

$$= 1{,}756{,}571\ S \text{ gal/day/ft}$$

Assuming appropriate values of S for a water-table condition,

when, $S = 0.05$, $T = 87{,}800$ gal/day/ft

$S = 0.07$, $T = 122{,}900$ gal/day/ft

$S = 0.10$, $T = 175{,}600$ gal/day/ft

TABLE 13

TIDAL AND WATER-LEVEL FLUCTUATIONS FOR WELL 3

DATE	TIDE	TIDAL TIME	TIDAL ELEV.	TIDAL RANGE	WELL TIME	WATER LEVEL	WATER LEVEL RANGE	TIME LAG HRS	STAGE RATIO
7-20-72	HIGH	1:08 PM	1.9		6:55 PM	20.42		5.78	
7-21-72	LOW	5:47 AM	0.1	1.8	11:30 AM	20.64	0.22	5.71	0.12
7-21-72	HIGH	1:45 PM	2.0	1.9	7:30 PM	20.42	0.22	5.75	0.11
7-22-72	LOW	6:36 AM	0.0	2.0	12:10 AM	20.64	0.22	5.56	0.11
7-22-72	HIGH	2:26 PM	2.2	2.2	8:30 PM	20.41	0.23	6.06	0.11
7-23-72	LOW	7:19 AM	0.0	2.2	12:20 PM	20.65	0.24	5.02	0.11
7-23-72	HIGH	3:01 PM	2.3	2.3	9:20 PM	20.42	0.23	6.31	0.10
7-24-72	LOW	8:00 AM	0.0	2.3	1:30 PM	20.65	0.23	5.50	0.10
7-24-72	HIGH	3:34 PM	2.3	2.3	9:55 PM	20.40	0.25	6.35	0.11
7-25-72	LOW	8:41 AM	0.0	2.3	1:48 PM	20.65	0.25	5.11	0.11
7-25-72	HIGH	4:07 PM	2.3	2.3	10:30 PM	20.40	0.25	6.38	0.11
7-26-72	LOW	9:24 AM	0.0	2.3	2:30 PM	20.66	0.26	5.10	0.11
AVERAGE								5.71	0.11

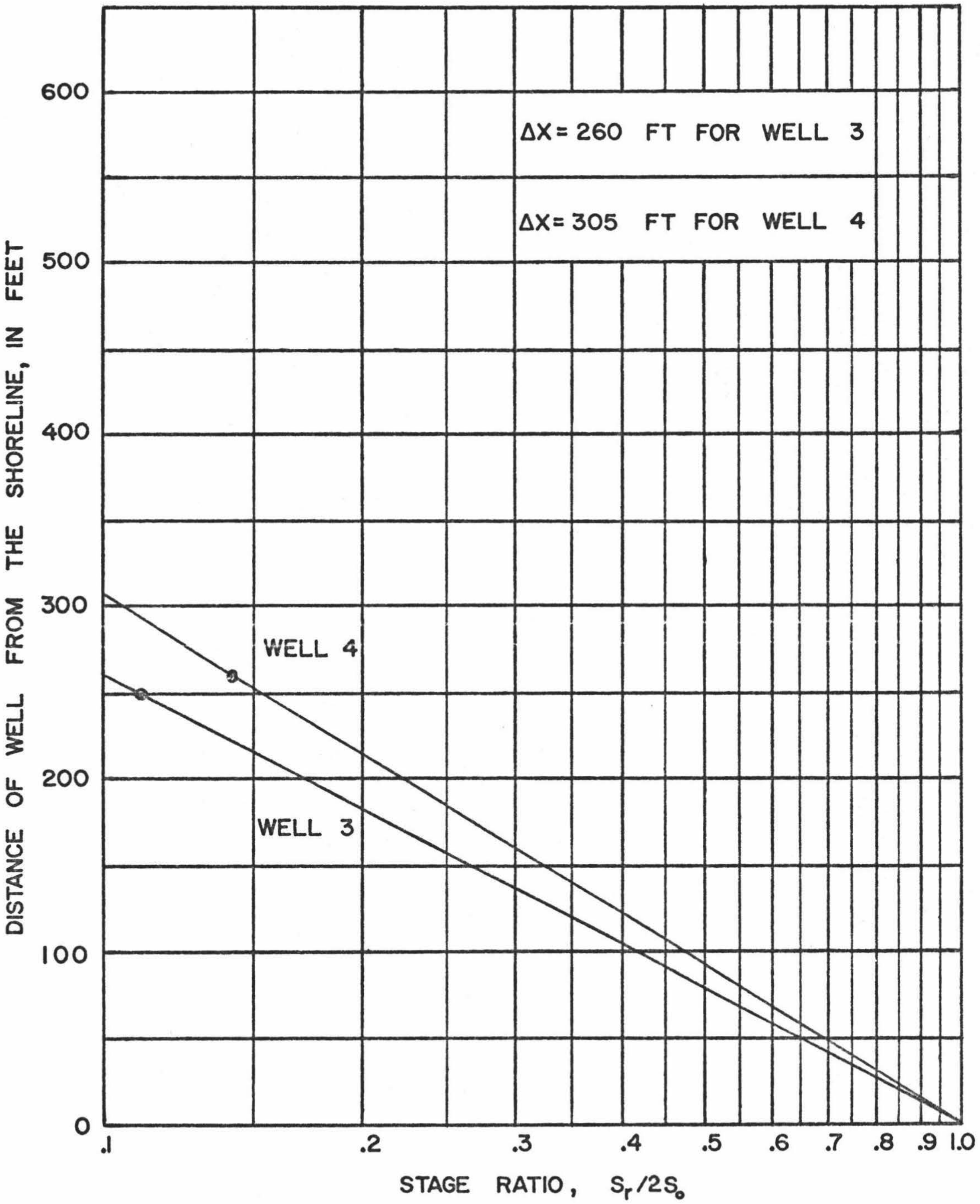


FIGURE 24. GRAPH SHOWING STAGE-RATIO VERSUS DISTANCE FROM SHORELINE FOR WELLS 3 AND 4

TABLE 14

TIDAL AND WATER-LEVEL FLUCTUATIONS FOR WELL 4

DATE	TIDE	TIDAL TIME	TIDAL ELEV.	TIDAL RANGE	WELL TIME	WATER LEVEL	WATER LEVEL RANGE	TIME LAG HRS	STAGE RATIO
7-22-72	HIGH	2:26 PM	2.2		5:00 PM	20.63		2.56	
7-22-72	LOW	10:00 PM	0.4	1.8	12:45 AM	20.85	0.22	2.75	0.12
7-23-72	HIGH	1:55 AM	0.6	0.2	4:15 AM	20.83	0.02	2.33	0.10
7-23-72	LOW	7:19 AM	0.0	0.6	10:15 AM	21.00	0.17	2.93	0.28
7-23-72	HIGH	3:01 PM	2.3	2.3	5:50 PM	20.64	0.36	2.81	0.16
7-23-72	LOW	10:27 PM	0.3	2.0	1:00 AM	20.91	0.27	2.55	0.13
7-24-72	HIGH	2:43 AM	0.7	0.4	5:05 AM	20.88	0.03	2.36	0.07
7-24-72	LOW	8:00 AM	0.0	0.7	10:00 AM	21.01	0.13	2.00	0.19
7-24-72	HIGH	3:34 PM	2.3	2.3	6:00 PM	20.54	0.47	2.43	0.20
7-24-72	LOW	10:52 PM	0.2	2.1	2:30 AM	20.73	0.19	3.63	0.09
7-25-72	HIGH	3:25 AM	0.7	0.5	5:30 AM	20.77	0.09	2.08	0.08
7-25-72	LOW	8:41 AM	0.0	0.7	11:25 AM	21.00	0.23	2.73	0.33
7-25-72	HIGH	4:07 PM	2.3	2.3	6:30 PM	20.65	0.35	2.38	0.15
7-25-72	LOW	11:17 PM	0.2	2.1	1:58 AM	20.90	0.25	2.68	0.12
7-26-72	HIGH	4:04 AM	0.8	0.6	7:15 AM	20.95	0.05	3.18	0.08
7-26-72	LOW	9:24 AM	0.0	0.8	11:30 AM	21.01	0.06	2.10	0.07
7-26-72	HIGH	4:38 PM	2.3	2.3	7:08 PM	20.49	0.52	2.50	0.22
7-26-72	LOW	11:40 PM	0.2	2.1	2:50 PM	20.75	0.26	3.16	0.12
7-27-72	HIGH	4:46 AM	0.9	0.7	7:20 AM	20.73	0.02	2.56	0.03
7-27-72	LOW	10:06 AM	0.1	0.8	1:00 PM	20.92	0.19	2.90	0.24
7-27-72	HIGH	5:07 PM	2.2	2.1	8:05 PM	20.59	0.33	2.96	0.16
7-28-72	LOW	12:03 AM	0.1	2.1	2:10 AM	20.86	0.27	2.11	0.13
7-28-72	HIGH	5:35 AM	1.1	1.0	7:58 AM	20.71	0.15	2.38	0.15
7-28-72	LOW	10:54 AM	0.2	0.9	1:30 PM	20.79	0.08	2.60	0.09
7-28-72	HIGH	5:42 PM	2.0	1.8	7:52 PM	20.48	0.31	2.16	0.17
7-29-72	LOW	12:32 AM	0.1	1.9	3:35 AM	20.75	0.27	3.05	0.14
7-29-72	HIGH	6:29 AM	1.2	1.1	8:30 AM	20.70	0.05	2.02	0.05
AVERAGE								2.58	0.141

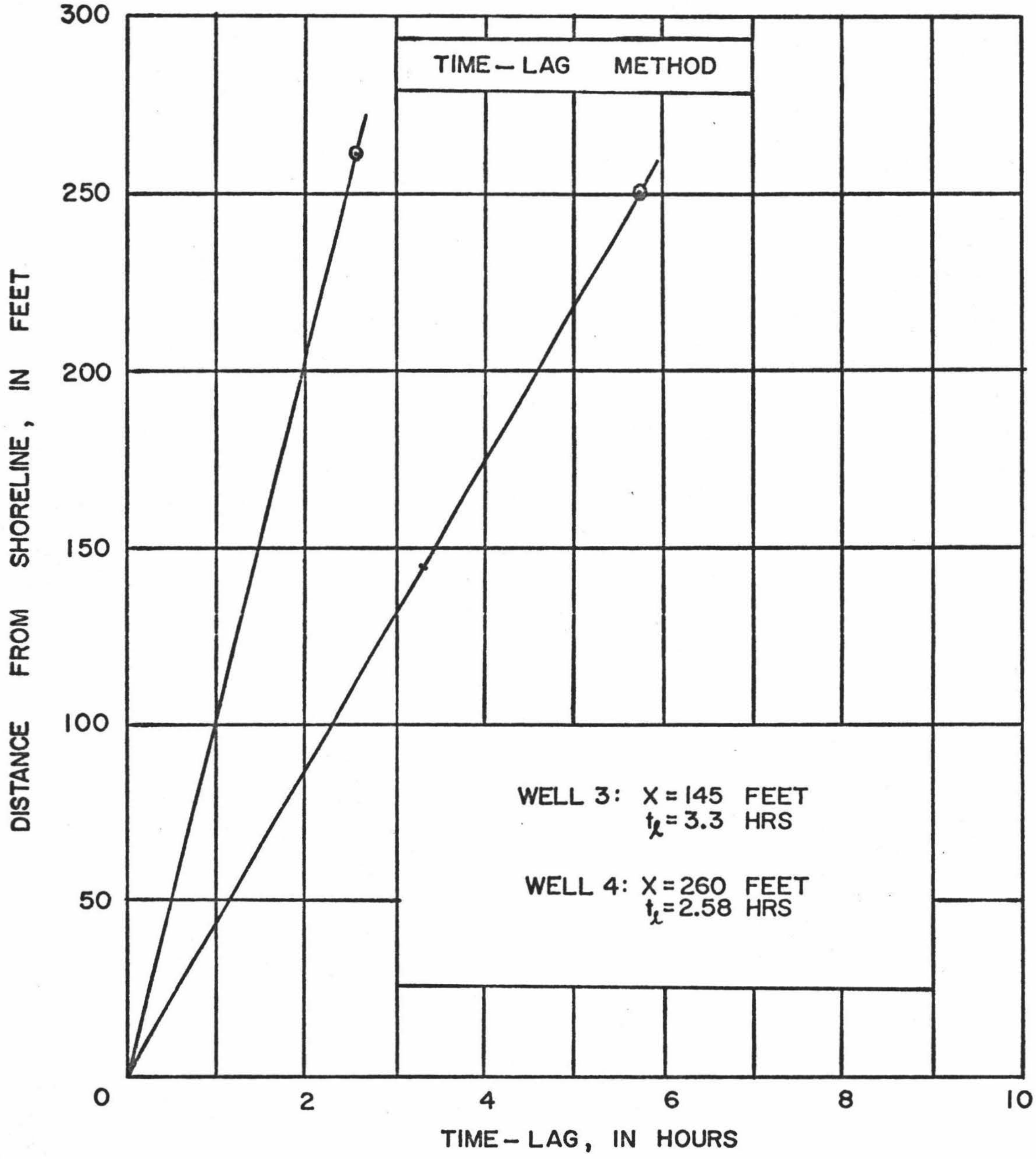


FIGURE 25. GRAPH SHOWING TIME-LAG VERSUS DISTANCE FROM SHORELINE FOR WELLS 3 AND 4

APPENDIX C

COMPUTATION OF FLOW RATE AND DISCHARGE INTO WEST LOCH

COMPUTATION OF RATE OF MOVEMENT OF LANDFILL WATER

The apparent flow velocity or Darcy velocity is:

$$V_A = \frac{Q}{A} = -K\frac{dh}{dl}$$

The true velocity is

$$V_T = \frac{Q}{An} = -K\frac{dh}{dln}$$

where, n = porosity of aquifer material.

Taking:

1) the coefficient of transmissibility, T = 43,800 gal/day/ft.

2) aquifer thickness = 10 feet.

3) porosity = 50%

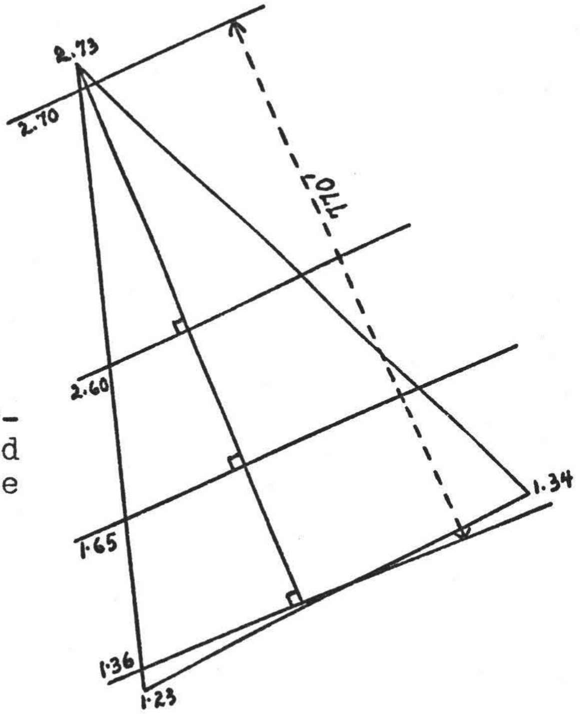
then 4) K, the coefficient of permeability, $K = \frac{43,800}{10} =$ 4,380 gal/day/ft^2

5) the water-table gradient, $\frac{dh}{dl} = \frac{1.40}{770} = 0.0018$

then $V_A = \frac{Q}{A} = -K\frac{dh}{dl} = \frac{4,380 \times 0.0018}{7.481}$ ft/day

$$= 1.05 \text{ ft/day}$$

true velocity, $V_T = \frac{1.05}{0.50} = 2.1$ ft/day.



$$*\frac{dh}{dl} = \frac{1.40}{770} = 0.0018$$

*Method for computing water-table gradient is described by Kazimierz, D., 1965 (see Bibliography).

COMPUTATION OF DISCHARGE INTO WEST LOCH

Let the total discharge into West Loch be Q_T, then,

$$Q_T = V_{ap}A$$

where, V_{ap} = apparent velocity or flow rate = 1.05 ft/day.

Average length over which flow occurs = 1,200 feet

Aquifer thickness = 10 feet

Cross-sectional area = 1200 x 10 = 12,000 ft^2

Q_T = 12,000 x 1.05 ft/day

= 12,600 x 7.481 gal/day

= 94,300 gal/day

AMOUNT OF FLOW CONTRIBUTED BY TIDE TO AQUIFER

Let Q be the quantity of flow per half cycle, then,

$$Q = TIL$$ (Ferris, J. D., 1963)

where,

L = cross-sectional length of aquifer through which flow occurs

I = hydraulic gradient of the prezometric surface

With the substitution for I in the equation above, Ferris (1963) arrived at the equation

$$Q = L S_o \sqrt{\frac{2t_oST}{\pi}}$$

where, S_o = tidal amplitude

t_o = tide period

S = coefficient of storage

T = coefficient of transmissibility

For L = 1,200 feet, S_o = 2.1 feet, t = 0.5 days; T = 43,800 gal/day/ft, and S = 0.05.

$$Q = 1200 \times 2.1 \sqrt{\frac{2 \times 0.5 \times 0.05 \times 43{,}800}{3.142}} =$$

$$2520 \times 26.4 = 66{,}530 \text{ gal/day}$$

Total amount of water supplied by the tide

≅ 66,500 gal/day

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