GROUNDWATER POLLUTION FROM SANITARY LANDFILL LEACHATE, OAHU, HAWAII

by

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ABSTRACT

A two-year study was conducted to determine the chemical characteristics of leachate derived from domestic refuse typical of that found for Honolulu, Hawaii, and to determine the removal characteristics of select Oahu soils with respect to the substances found in these leachates. Based on these findings, guidelines for sanitary landfill site selection, in relation to the prevention of groundwater pollution, were developed.

Four Oxisol soils (Molokai, Wahiawa, Helemano, and Lahaina), one Mollisol soil (Mamala), and one Marsh soil, were subjected to both saturated and unsaturated flow conditions, using as the percolating liquid, leachate produced by saturating (domestic refuse) with water. The domestic refuse had a composition typical for that of Honolulu, Hawaii. Leachate and percolate samples were analyzed for various chemical constituents including pH, hardness, alkalinity, nutrients, chemical oxygen demand, particulates, and a number of metallic cations and heavy metals.

Ion exchange was responsible for altering the concentration of inorganic substances in the percolating liquid, while microbial degradation appeared to be the primary mechanism for removing organic substances. Under the test conditions, and using the leachate produced from typical Honolulu refuse, the soils examined were found to have relatively low exchange capacities, while at the same time, organic removals were not significant. Thus, migration of inorganic and organic substances to the groundwater table is possible, and these results suggest that a cautious approach to landfill site selection should be taken, although soil depth to water table and dilution characteristics of the underlying groundwater must also be considered.

A procedure for evaluating the feasibility of landfill operations in relation to possible groundwater contamination has been suggested. This procedure utilizes the removal characteristics for the various soils as observed in this study.

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INTRODUCTION

The magnitude of the solid waste problem in Hawaii has shown rapid growth in recent years and, following the national trend, should continue to do so in the near future. Furthermore, although much interest and considerable activity have been demonstrated in recycling a part of this waste, it is unlikely that there will be a significant decrease in the total amount of solid waste that must be disposed of annually.

To the layman there are many methods of disposal available to a municipality, including incineration, baling, shredding, grinding, composting, and sanitary landfill. However, all but the last are, in fact, volume reduction processes, and ultimately, the products of these processes are returned to the land utilizing the technique of sanitary landfill.

Unfortunately, the chemical and physical nature of refuse is such that bacteriological decomposition, in addition to chemical action, will release organic and inorganic product salts. If sufficient water is allowed to percolate through a fill, and this is difficult to prevent, a liquid normally referred to as leachate is formed which may have an extremely high potential for causing water pollution. This means that in areas where the receiving water is a potable groundwater supply, extreme caution must be exercised so that public health protection is maintained.

On the island of Oahu, Hawaii, the existence of an extensive basal groundwater resource has caused agency officials to exercise this very cautious approach mentioned previously. With one exception, all approved sanitary landfill sites are located in coastal areas where the basal groundwater is not threatened, due to coastal geologic features (Fig. 1). In regions overlying the unconfined basal groundwater, unfavorable consideration is given to proposed land fill operations.

Although it is generally accepted that potential groundwater pollution from leachate does exist, it should be pointed out that this pollution potential is usually defined on the basis of the character of the leachate itself, and little consideration is given to the changes in leachate character as it passes through the underlying soil formations prior to entering the groundwater table, if it does at all. In order to more realistically define this pollution potential, the renovating capacity of the underlying soil must be taken into account, and it is this information that has not been available for Oahu. Thus, planning decisions for solid waste management systems on

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FIGURE 1. LOCATION OF EXISTING LANDFILL FACILITIES, ISLAND OF OAHU, HAWAII



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Oahu have been made in part, on the basis of a "worst-possible condition," and not on the basis of a clearly defined pollution potential represented by leachate-soil interactions. For this reason, data describing these leachate-soil interactions are highly desirable, and the rpesent study was initiated for the purpose of accumulating such data. Evaluation of this data would then provide a basis upon which rational design criteria and guidelines could be developed for site selection, construction, and operation of sanitary landfills on Oahu.

The present investigation was carried out in a series of laboratory experiments in which artificially produced leachate was passed through columns containing select Oahu soils under both saturated and unsaturated conditions. Applied leachate and percolates from each column were then analyzed to assess the renovating capacity of each soil type examined. The saturated flow experiment was conducted preliminary to the unsaturated flow experiment, and based on experimental results and operational experience, a number of procedural changes were implemented prior to initiating the unsaturated flow experiment. These procedural changes were duly considered during subsequent data analysis and evaluation for both experiments.

LITERATURE REVIEW

Pollution of Groundwater

In a critical review of the literature by Zanoni (1972), only a few reported incidents of serious or even troublesome contamination of groundwater directly attributable to leachate from refuse sanitary landfills were found. However, there no doubt have been cases that have gone undetected as well as unreported.

Carpenter and Setter in 1940 analyzed leachate taken from the bottom of a refuse landfill in New York and concluded that the area groundwater was being contaminated by the leachate, inasmuch as chemical and bacterial levels were observed to be high.

Studies (California State Water Pollution Control Board 1952, 1954) conducted in California during the 1950's on incinerator ash dumps and on a typical sanitary landfill at Riverside concluded that refuse landfills located in intermittent or continuous contact with groundwater will cause the water to become grossly polluted and unfit for domestic or irrigational use. A biochemical oxygen demand approaching 20,000 mg/ ℓ and an ammonia nitrogen content as much as 10,000 times that of unpolluted groundwater was measured, along with high concentrations of sodium, potassium, calcium, chloride, sulfate, and bicarbonate.

Andersen and Dornbush (1967) studied the Brookings County, South Dakota, refuse landfill located in an abandoned gravel mine characterized by gravel pits penetrating a high water table. The study indicated that the groundwater leaving the 5-year old, 64.75 ha (160 acres) disposal site was not seriously impaired, however, well samples downstream of the fill showed definite evidence of refuse fill leachate dispersion into the groundwater.

Walker (1969) reported in Aurora, Illinois, a case where residents of twelve private dwellings in the vicinity of a garbage disposal site complained to state public health officials of an inky black substance polluting their water supply wells. It was found in an ensuing investigation that all of the wells involved were bacterially and chemically contaminated by effluent from the nearby garbage dump that was located in an abandoned sand and gravel strip mine excavation.

It has been found that leaching pollution may appear almost immediately or require a substantial passage of time before appearing. In 1932, Calvert reported that garbage waste liquor from an impounding pit placed into operation only 8 months prior had increased the hardness and organic content in a groundwater supply some 152.4 m (500 ft) away making it unfit for boiler and condenser purposes. In 1940, Lang and Burns reported a case of an ash and garbage dump located in an old sand pit reaching below groundwater level. Although the pit had not been used as a dumping ground for 15 years and had since been transformed into a park, contaminants were found in wells 609.6 m (2000 ft) away. Well samples showed increases in hardness, iron, and manganese, and perceptible taste.

Leachate Quality

Noting the possibility that refuse landfill leachate poses a potential hazard to ground supplies, numerous investigations of leachate quality have been undertaken. The reported leachate quality from those investigations are summarized in Table 1.

The Riverside, California study (California State Water Pollution Control Board 1954) furnished results from various locations within the fill area (Well Point 4) and 1066.8 m (3500 ft) downstream from the landfill (Well Point 7). These field investigations were augmented by a percolation study using wood bins containing 10.9 m³ (384 cu ft) of refuse. Water was artificially applied to

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	CARPENTER		COOK AND	STEINER FT AL	QUASIN	1 AND BURC (1970)**	HINAL	SCHOLL CANYON (CSWPCB	RIVERSI (CSW	DE, CALII PCB 1954	FORNIA)
CONSTITUENT	(1940)	(1971)*	(1974)	(1971)		11		1954)	WELL 4	WELL 7	BIN 1
ALKALINITY, mg/& as CaCO ₃	2863	502	3280	1999 - 1999 - 1999 - 1999 - 1999 - 1999 - 1999 - 1999 - 1999 - 1999 - 1999 - 1999 - 1999 - 1999 - 1999 - 1999 - 19	10,630	16,200	20,850	1 1	1070	395	55 23
COD, mg/l			15,800	100-50,000				5750			
TOTAL PHOSPHORUS, mg/l			13								
TOTAL KJELDAHL NITROGEN, mg/l			280	20-500	761	1420	2522		3.13	3.9	732
рH	6.9	6.49	5.4		6.3	6.43	5.88	7.4	6.86	7.29	6.31
TOTAL SOLIDS, mg/8				1000-45,000	21,140	49,800	59,200				
DISSOLVED SOLIDS, mg/l		51 (1) 61 10 12						2058			
CALCIUM, mg/l	8	186	1200		3030	4080	2790	382	250	125	1358
IRON, mg/L		578	240	200-1700	175	540	860		6.0	6.0	136
MAGNESIUM, mg/l		37	170					148	100	32	205
SODIUM, mg/L		39		100-3800	584	1428	1439	90	505	165	1080
POTASSIUM, mg/l		51			1050	2535	3770	7.2	35	12	1027
ZINC, mg/l				1-135		ла "					

TABLE 1 LEACHATE QUALITY CHARACTERISTICS REPORTED IN THE LITERATURE

* Single analysis. ** Maximum value measured.

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the bins and the leachate collected and analyzed. Also reported in the study were leachates from wells immediately downstream of the municipal refuse fill at the Scholl Canyon in Glendale, California.

Apgar and Langmuir (1971) studied the character and movement of landfill leachate through unsaturated soil at the State College refuse sanitary landfill in Pennsylvania. Cook and Foree (1974) collected and characterized leachate from the Environmental Protection Agency experimental sanitary landfill site near Walton, Kentucky. Steiner et al. (1971) conducted laboratory simulations of a sanitary landfill at Drexel University and presented concentration ranges for typical leachate values. Quasim and Burchinal (1970) published results of pollution load leached from simulated landfill columns of three different heights operating under similar conditions of inflow and leachings.

As shown in Table 1, values of various leachate constitutents varied over a wide range. Chemical oxygen demand (COD), for example, ranged from 100 to 51,000 mg/1. Average pH ranged from 5.4 to 7.4. Also, several cations were measured at high concentrations: calcium, 4080 mg/1; iron, 1700 mg/1; potassium, 3770 mg/1; and sodium, 3800 mg/1.

Leachate Prevention and Control

The ultimate objective of most landfill studies to date have been to establish guidelines and criteria to prevent and control leaching from refuse landfills. In his review of the literature, Zanoni (1972) reported on the landfill operation practices conducted in twenty-one states, and also included a set of recommendations to government agencies responsible for regulating and licensing sanitary landfill operations within the respective states. Additional recommendations have been made by Salvato et al. (1971)., Landon (1969), Legrand (1964 α , 1964b), Remson, Fungaroli, and Lawrence (1968), Brunner and Keller (1972), Sorg and Hickman (1970), and Morgan, Skrinde, and Small (1973).

Leachate Treatment

To date, only a few investigations dealing with treatment of leachate have been reported. Conventional waste water treatment processes have been studied, as well as recirculation of leachate through the landfill.

Boyle and Ham (1974) investigated both biological and chemical treat-

ment of landfill leachate. The results of their study indicated that anaerobic biological treatment of leachate is efficient in removing a substantial portion of the organic pollutants, while chemical treatment, using lime and sodium sulfide precipitators, chlorine and potassium permanganate oxidants, and alum and ferric chloride coagulants, was less efficient. However, chemical treatment was effective in removing color and multivalent cations. Although aerobic biological treatment appeared promising, liquid-solid separation problems occurred.

Cook and Foree (1974) reported aerobic biological treatment to be effective in stabilizing leachate. Under optimum operating conditions of 10-day detention time with no recycling, over 97% of the COD was removed.

Pohland and Mao (1973) investigated landfill stabilization using leachate recirculation, neutralization, and sludge seeding. Among the important conclusions reported were: (1) leachate recirculation more rapidly establishes an active anaerobic biological population in the fill which was further enhanced with pH neutralization, and (2) leachate recirculation increases the rate of biological stabilization of the organic fraction of refuse.

Leachate Renovation by Soil Percolation

Only a few studies on leachate renovation by soil percolation have been reported in the literature. Of these, Apgar and Langmuir's (1971) in-situ study is perhaps the most significant. The investigators reported decreases in: (1) chlorides caused by dilution and dispersion, (2) phosphates resulting chiefly from precipitation as insoluble ferric and aluminum phosphates, (3) BOD and ferrous ion resulting from oxidation, and (4) ammonia resulting from cation exchange and bacterial assimilation. Furthermore, sulfates and certain metallic cations were removed as a result of cation exchange on soil colloids. Finally, physical filtration by the soil removed bacteria, ferric oxyhydroxide, and other suspended substances from the leachate.

Emrich and Landon (1969) also investigated the travel of leachate through soil in a landfill in Pennsylvania. The investigators reported that as leachate moved through the unsaturated soil, partial renovation was accomplished, as evidenced by reductions in BOD and iron. They further reported that the various constituents of leachate do not move through the soil at the same rate, with iron lagging BOD by several months.

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Soil Ion Exchange

The ability of a soil to remove contaminants from a percolating liquid is dependent on the nature of the soil and the substance being applied. The most predominant processes involved are adsorption and cation exchange, with both being influenced by the laws of mass action. As leachate is percolated through the soil, the amounts of ions adsorbed will depend on the cation exchange capacity of the soil which is a function of the clay content. The removal of the ions will decrease until an equilibrium between the leachate and the soil is attained. The relative concentrations of the ions in the leachate will determine to a great extent which ions will be retained in the soil and which will be leached out (Buckman and Brady 1966; Wentik and Etzel 1972).

The direct inference of the soil information from the temperate climate of the continental United States to the subtropical climate of Hawaii must be made with caution, especially when describing ion exchange behavior. Uehara, Swindale, and Jones (1973) stated that there is a general concensus among agricultural scientists who work in the tropics that the quantity of transferable information lies somewhere between wholesale acceptance to total rejection.

Uehara, Swindale and Jones (1973) noted that minerals which are frequently found in quantity in tropical soils, but which rarely occur in abundance in temperate regions, are the hydrous oxides and oxides of iron and aluminum and, in some cases, the manganese and titanium soils of the Oxisol order. The temperate climate experience may be extrapolated to that of the tropics when a tropical soil consists mainly of phyllosilicates. However, temperate climate experience fails when applied to soils which are predominantly hydrous oxides and oxides of iron and aluminum mineralogy.

In general, soils in the temperate regions are characterized by surfaces bearing a constant surface charge. In layered silicates, surface charge arises from defects in the lattice interior, and the charge is relatively independent of the conditions in the soil solution. The cation exchange capacity of these soils cannot be changed by soil management (Uehara, Swindale, and Jones 1973; Tsuji, Keng, and Uehara 1973).

Soils commonly found in Hawaii, particularly those of the Oxisol order, are characterized by surfaces with constant surface potential. In oxide systems, the electrical charge arises from adsorption of ions on the particle surfaces. These ions are called potential-determining ions and include hydrogen and hydroxyl ions as well as the metal ions which make up the lattice structure. These ions are not exchangeable as are those in temperate soils, but are potential-determining ions which cause tropical soils to behave as variable charge colloids.

Soils which contain minerals whose surface charges vary with pH are referred to as soils with pH-dependent charges. An increase in pH caused by anion adsorption increases the cation exchange capacity. A decrease in pH caused by cation adsorption decreases cation exchange capacity.

METHODS AND PROCEDURES

One of the major problems often encountered in laboratory studies is simulating, as much as possible, field conditions on a bench-scale model, and the present study is no exception. Attempts were made to provide a leachate that was not only typical of that produced in the field, but also a leachate that was of rather uniform quality so that experimental variables could be minimized while performing the series of experimental trials. Inasmuch as adequate quantities of leachate were difficult to produce at one time and in one container, it was necessary to generate the leachate over a period of time and in several containers.

In order to simulate a typical refuse landfill on Oahu, several studies of the quantity and character of Oahu's solid waste were considered (Metcalf and Eddy Engineers 1971; Burbank, Yamashita, and Koizumi 1964; Ryckman and Yamashita 1963). Since the Metcalf and Eddy study was most recent (1971), the refuse composition reported in that study was used in this experiment (Table 2). In order to facilitate leachate production, wood shavings were used in place of larger pieces of wood, and the paper trimming, and food components were ground to a nominal size of 0.635 cm (1/4-in.) with a Reitz RP-6 Disintegrator. The remainder of the components were shredded by hand or cut with scissors.

The leachate applied to the soil columns was artificially produced by saturating refuse, placed in plastic lined containers, with distilled water. To each of the leachate containers about 9 kg (20 lb) of sample refuse was placed, along with from 68 to 75.7 & (18-20 gal) of distilled water, so that a nearly uniform ratio of total refuse weight to total water volume was

maintained.

In preparing the leachate for the saturated flow experiment, the refusedistilled water mixture was allowed to stand for 30 days, after which the leachate was collected, placed into a common container, and homogenized. The homogenized leachate was then placed in $4-\ell$ (about 1-gal) containers and frozen until needed.

COMPONENTS	METCALF & EDDY % BY WEIGHT	WEIGHTS USED IN EXPERIMENT KILOGRAMS
PAPER	28	2.54
TRIMMINGS	16	1.45
RAGS	1	0.09
WOOD	22	1.99
FOOD	2	0.18
PLASTICS	1	0.09
METALS	6	0.54
GLASS	3	0.27
DEMOLITION ε CONSTRUCTION*	21	1.90
TOTAL	100	9.05

TABLE 2. REFUSE COMPOSITION USED IN LEACHAIE PRODUCT	FUSE COMPOSITION USED IN LEACHATE PROD	N LEACHATE	IN	USED	TION	COMPOS	REFUSE	2.	TABLE
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NOTE: Distilled water 68-76%. * Dirt, rock.

Upon completion of the preliminary saturated flow experiments, it was decided to alter the leachate production method for the unsaturated flow experiments. In preparing the leachate for the unsaturated flow experiment, the refuse-distilled water mixture was allowed to stand for 72 days, and the leachate was drawn as needed. Large debris were removed by filtering through fiberglass wool.

Soil Selection

The soils utilized in this study were selected primarily because they are the predominant soils types in the areas of existing and planned refuse landfills on Oahu. The extent of occurrence of the soil, based on Soil Conservation Service maps (Foote et al. 1972), was another criterion for selection.

Three soils were selected for use in the preliminary saturated flow experiment. These included soils of the Wahiawa, Lahaina, and Helemano soil series. After the saturated flow experiments, it was decided to expand the list of soils to be examined to include soils from the Lualualei, Mamala, Marsh, and Molokai soil series, and to delete the Lahaina soil. Figure 2 shows the location of each soil and Table 3 provides additional soils information

Soil Collection and Column Preparation

Slightly different soil collection and column preparation procedures were followed during the saturated and unsaturated flow experiments.

In preparing for the saturated flow experiment, soil was collected as disturbed samples in 0.076-m (3-in.) layers beginning at the surface down to a depth of .61 m (24 in.). Each .076-m soil segment was then passed through a 2.0-mm sieve and the soil passing through the sieve was weighed, prior to its placement into .089-m (3.5-in.) ID plexiglass cylinders (Fig. 3). Although .61 m (24 in.) of soil was collected, a soil column depth of only .305 m (12 in.) was prepared. This .305-m soil column was prepared using the soil specimens collected between the .152-m (6-in.) and .457-m (18-in.) depth. The soils were placed into the column in the same order as they were collected in the field, beginning with the .381- to .457-m (15- to 18-in.) specimens and ending with the .152- to .229-m (6 to 9 in.) specimens. The columns were partially filled with water prior to soil placement to ensure complete saturation, to remove small bits of roots remaining after sieving, and to provide compaction.

To ensure that the percolate collected for analysis represented leachate that had passed through the soil and not along the soil-cylinder interface, the bottom of the cylinder was equipped with a short length of a smaller diameter .064-m or 2.5-in. plexiglass cylinder to which a collecting drain tube was attached, as shown in Figure 3.

The soil columns were conditioned over a 6-day period by percolating three pore volumes of tap water through each.

In preparing for the unsaturated flow experiment, soils were collected as disturbed samples from two depths, 0 tc .152 m (6 in.) and .152 to .305 m (6 in. to 12 in.). Soil specimens were placed into an .089-m (3.5-in.) ID plexiglass cylinder using vibration techniques to minimize layering and maximize homogeneous particle size distribution (Jackson, Reginato, and Reeves 1962). Although soil specimens were collected throughout a depth of .305 m, a soil column of only .152 m was prepared.



FIGURE 2. LOCATION OF SOIL SELECTION SITES

SOIL SERIES	ORDER	GREAT SOIL GROUP	LOCATION
MARSH		LOW HUMIC LATOSOL*	VICINITY OF CITY & COUNTY KAWAILOA LANDFILL
MOLOKAI	OXISOL	LOW HUMIC LATOSOL	PACIFIC CONCRETE AND ROCK CO. QUARRY AND LANDFILL, MAKAKILO
HELEMANO	OXISOL	LOW HUMIC LATOSOL	VICINITY OF CITY & COUNTY WAHIAWA LANDFILL ¹ KIPAPA GULCH ²
WAHIAWA	OXISOL	LOW HUMIC LATOSOL	SUGARCANE FIELD IN WAHIAWA ¹ PINEAPPLE FIELD IN WAHIAWA ²
MAMALA	MOLLISOL	LOW HUMIC LATOSOL	VICINITY OF ABANDONED QUARRY NORTHEAST OF NANAKULI
LUALUALEI	VERTISOL	DARK MAGNESIUM	VICINITY OF ABANDONED QUARRY NORTHEAST OF NANAKULI
LAHAINA	OXISOL	LOW HUMIC LATOSOL	VICINITY OF ABANDONED PINEAPPLE FIELD ADJACENT TO MILILANI TOWN

TABLE 3. CLASSIFICATION OF SOILS

* CES Circ. 476 (McCall 1973, p. 22).
 ¹ Location of soil used in unsaturated flow experiment.
 ² Location of soil used in saturated flow experiment.



FIGURE 3. ILLUSTRATION OF PERCOLATION COLUMN AND LEACHATE APPLICATION AND COLLECTION PROCEDURE, SATURATED FLOW EXPERIMENT

During the unsaturated flow experiment, leachate was applied from the bottom of the column, therefore the soil specimens were placed in reverse order from which they were collected in the field. Thus, the first .076 m (3 in.) of the .152-m soil column was emplaced by first adding soil collected from the 0 to .152-m depth, and then adding soil collected from the .152- to .305-m depth.

The percolation column used for the unsaturated flow experiment differed slightly from that used in the saturated flow experiment (Fig. 4) due to the percolation technique used.

Percolation and Collection Procedures

The percolation and collection procedure used in the saturated flow experiment is illustrated in Figure 3. The leachate was added to the top of the soil column while maintaining a head of about .102 m (4 in.).

Each of the three soil types examined was subjected to percolation with 4800 ml of leachate. Since the columns were initially saturated with tap water, the first 400 ml of percolate was discarded.

The percolation and collection procedure used in the unsaturated flow experiment is shown in Figure 4. In an effort to minimize short-circuiting, reverse or countercurrent flow was utilized.

Leachate was slowly applied to an unsaturated soil column. After the soil reached field capacity, the head was slowly increased in .025-m increments until percolate began to flow into the collection container. Once established, the head was maintained by periodically adding leachate to the reservoir. The head was determined by trial and error because leachate infiltrated the different soils at different rates. After approximately 650 ml of percolate was collected, the applied leachate was withdrawn from the soil column. The soil was allowed to drain for 24 hr, and then the application phase started again. The cycle of applying, collecting, and draining was repeated for ten trials.

Leachate and Percolate Analysis

All water samples were preserved and analyzed in accordance with *Standard Methods* (APHA, AWWA, and WPCF 1971).

A Perkin-Elmer Model 303 atomic absorption spectrophotometer was used in the measurement of cadmium, calcium, chromium, copper, iron, magnesium,



FIGURE 4. ILLUSTRATION OF PERCOLATION COLUMN AND LEACHATE APPLICATION AND COLLECTION PROCEDURE, UNSATURATED FLOW EXPERIMENT manganese, nickel, and zinc.

A Coleman Model 21 flame photometer was used in the measurement of potassium and sodium.

Alkalinity was measured by the potentiometric titration method. Standard 0.02 N sulfuric acid titrant was used with a Corning Model 10 pH meter.

Chemical oxygen demand (COD) was measured with 0.01 N ferrous ammonium sulfate which was standardized daily.

Total Kjeldahl nitrogen was measured with standard 0.02 N sulfuric acid titrant. A 100-ml volume sample was digested and distilled for each test.

pH was measured with a Photovolt Model 126-A pH meter.

Total phosphorus was measured by the ascorbic acid method following persulfate digestion. A Bausch and Lomb Spectronic 20 Spectrophotometer was used as the colorimetric equipment.

Solids measurements, which included total, total volatile, total suspended, and total volatile suspended solids, were performed using 50 mL samples processed through Whatman GF/C glass fiber filter disks.

Soil Analysis

Soil physical properties were not measured during the saturated flow experiment. However, during the unsaturated flow experiment, the soil physical properties and pH analyses were accomplished in accordance with *Methods* of Soil Analysis (Black 1965a, 1965b).

Particle density measurements were made using 10 g of air-dried soil samples.

Bulk density was measured by the clod method (Black 1965a, 1965b).

Soil pH was measured in water with a Corning Model 10 pH meter.

Cation exchange determinations were also made for the soils examined during the unsaturated flow experiment and were accomplished in accordance with the University of Hawaii, Agriculture 268 Soil Chemistry course handout. A one N ammonium acetate (pH 7.0) solution was used to saturate soil samples. After shaking the soil solution for an hour and allowing it to stand for 24 hr, the soils were filtered and washed on a Buchner funnel with a No. 53 Whatman filter. The filtrate plus washings were analyzed for cations.

The calcium, magnesium, manganese, potassium, and sodium cations were measured in accordance with accepted water quality methods, except that one N ammonium acetate was used in place of distilled deionized water for blanks and dilutions.

RESULTS AND DISCUSSION

Table 4 summarizes the average quality of leachate applied to the soil columns during both the saturated and unsaturated flow experiments. It is noted that not all parameters were measured for both leachates. For those constituents that were measured for both, the pH and COD were significant. In the leachate applied during the saturated flow experiments, the pH was 5.0 and the COD concentration was 4670 mg/l. The respective values for the leachate applied during the unsaturated flow experiment were 6.9 and 2246 mg/l. The differences in these two parameters are an indication of the relative ages of the leachate; in the former case the leachate was collected after 30 days of refuse-liquid contact and in the latter case, the leachate was collected after 72 days. Within the first 30 days of leachate production, anaerobic activity could account for the high COD and low pH as a result of volatile organic acid production. Given enough time, these organic acids are utilized by methane bacteria resulting in an overall decrease in COD and an increase in pH after 72 days. Although volatile acid content was not specifically determined and gas analysis not performed, it is not unreasonable to assume the foregoing interpretation to be correct.

With respect to the remaining constituents that are reported for both leachates, the concentrations measured appear comparable, insofar as they are for the most part in the same order of magnitude.

Although the higher zinc concentration measured in the leachate used in the saturated flow experiment can be attributed to lower pH, the expected higher total iron concentrations in this leachate did not follow. Instead, total iron concentrations were higher in the leachate used in the unsaturated flow experiment, which showed a higher pH. However, considering the difficulty in securing identical refuse samples, this may not be significant.

Comparison of the leachate characterization reported in Table 4 with those given in Table 1 suggests that the leachate used in this study was somewhat weaker than that reported by other investigators. However, most of the constituents measured here were in the reported range of values shown in Table 1, and since these ranges in reported constituent concentration vary greatly, the leachate used in this investigation cannot be considered

PARAMETER	SATURATED	UNSATURATED
рН	5.0	6.9
ALKALINITY, mg/L as CaCO3		1280
TOTAL HARDNESS, mg/ ℓ as CaCO $_3$	1080	1410 ^a
SPECIFIC CONDUCTANCE, µmhos/cm	960	
TOTAL SOLIDS, mg/l	10 Å.	2760
TOTAL VOLATILE SOLIDS, mg/&	2	1270
SUSPENDED SOLIDS, mg/L		127
VOLATILE SUSPENDED SOLIDS, mg/l		95
TOTAL DISSOLVED SOLIDS, mg/L	2720	2630 ^b
CHLORIDES, mg/l	82	
CALCIUM, mg/l	291	496
MAGNESIUM, mg/l	67	40
TOTAL IRON, mg/l	31	39
MANGANESE, mg/l	8.4	3.5
ZINC, mg/l	3.1	0.7
POTASSIUM, mg/l		94
SODIUM, mg/l		38
CHEMICAL OXYGEN DEMAND, mg/&	4670	2250
TOTAL KJELDAHL NITROGEN, mg/l		16.5
TOTAL PHOSPHORUS, mg/&		5.3

TABLE 4. QUALITY OF LEACHATE APPLIED, SATURATED AND UNSATURATED FLOW EXPERIMENT

^a Calculated from Ca⁺⁺ and Mg⁺⁺ Concentrations.
^b Calculated as difference between total solids and suspended solids.

atypical.

From Tables 1 and 4, it is clear that leachate derived from municipal refuse does have important environmental implications. Significant concentrations of organic and inorganic substances can be generated in and transported by this leachate.

During the initial planning stages of this study, the determination of leachate production rates was included as a study objective. However, the length of time involved in simulating field production rates precluded further investigation into this area. This judgment also considered that more important than the production rate of leachate was the quality of this leachate once generated and the alteration of this quality during passage through soils.

Soil Analysis

During the saturated flow experiment, only soil pH was measured for the three soil types studied. All three soil types were acidic, with the Wahiawa and Lahaina soils both having a pH of 6.1, while the Helemano soil had a soil pH of 4.9. This is not unexpected inasmuch as agricultural soils in humic regions commonly have acidic characteristics (Buckman and Brady 1966).

During the unsaturated flow experiment more extensive soil analysis was performed. Results for the Lualualei soil were not included because leachate did not filter through the column and percolate could not be collected. Lualualei is an expanding clay which expands when wetted, thus preventing percolation.

Table 5 includes the results of the analyses performed on the Marsh, Molokai, Wahiawa, Helemano, and Mamala soils used during the unsaturated flow experiment. Particle density ranged from 2.74 grams per cubic centimeter (g/cm³) for the Marsh soil to 3.13 g/cm^3 for the Helemano soil at the .15- to .30-m (6- to 12-in.) depth. The bulk density varied over a wider range, 1.16 g/cm^3 for the Mamala soil at the .15- to .30-m depth to 1.68 g/cm³ for the Molokai soil of the same depth. Bulk density measurements were not accomplished for the Marsh soil because the friable sandy texture did not form clods.

The densities of the mechanically packed soil columns were all within the same range. The Molokai soil column had the highest density at 1.38

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SOIL	DEPTH (m)	PARTICLE DENSITY	BULK DENSITY (g/cm ³) —	COLUMN DENSITY	IN-SITU POROSITY (%)	COLUMN POROSITY (%)	PORE VOLUME (cm ³)
MARSH	0.015 .1530	2.74 2.74	 	1.18		57 57	618.14
MOLOKAI	.1530	2.80 3.00	1.46 1.68	1.38	48 45	51 54	499.27
WAHIAWA	.1530	2.82 2.76	1.61 1.40	1.28	43 49	55 52	587.38
HELEMANO	.1530	3.13 3.06	1.27 1.25	1,13	59 59	64 63	689.89
MAMALA	.1530	2.89 2.89	1.16 1.27	1.30	58 56	55 55	598.63

TABLE 5. PHYSICAL SOIL ANALYSIS, UNSATURATED FLOW EXPERIMENT

 g/cm^3 and Helemano soil the lowest at 1.13 g/cm^3 .

The Molokai soil column had the lowest column porosity at 51% and 54%, respectively, for the 0- to .15-m and .15- to .30-m depth, while Helemano soil had the highest at 63% and 64% for the same depths. As would be expected, Helemano soil filtered the least number of percolate pore volumes, 9.54 and Molokai the most, 13.32. The other three soils produced results between the two soil extremes.

The soil pore volumes were calculated as the difference between column volumes and volumes occupied by the soil. Helemano soil had the highest pore volume at 689.89 cm^3 and Molokai soil the lowest at 499.27 cm^3 .

It is recognized that the physical soil properties reported herein are related to the specific manner in which the soil columns were prepared. However, the inclusion of the data does provide a description of the relative differences between soil types, at least in terms of physical properties, that may be expected under other soil column preparation procedures.

The pH and exchangeable cation capacities for the Marsh, Molokai, Wahiawa, Helemano, and Mamala soils were also examined during the unsaturated flow experiment and are shown in Table 6.

The pH for these soils ranged from acidic to slightly alkaline, and for most soils, pH varied with depth. As observed during the preliminary

	SOIL ANALYSIS BEFORE PERCOLATION								
SOIL	DEPTH (m)	рН	EXCHAN Ca	GEABLE K	CATIONS Mg	(me/100 g) Mn	Na		
MARSH	0.015 .1530	7.40 7.30	27.81 24.38	1.42 0.48	8.23 12.69	0.027* 0.016*	4.07 10.70		
MOLOKAI	.1530	6.10 6.10	11.88 7.19	1.74 1.53	7.55 7.76	0.007* 0.031*	0.27 0.28		
WAHIAWA	.1530	5.46 5.62	3.85 3.44	0.64 0.15	2.69 2.26	0.007* 0.004*	0.15 0.12		
HELEMANO	.1530	4.60 4.75	0.44 0.30	0.44 0.10	0.25 0.24	0.009 0.004	0.23 0.56		
MAMALA	.1530	7.70 7.55	12.81	0.18 0.13	1.35 1.19	BDL BDL	0.27 0.40		

TABLE 6. CHEMICAL SOIL ANALYSIS BEFORE AND AFTER PERCOLATION

SOIL ANALYSIS AFTER PERCOLATION

SOIL	COLUMN LOCATION	рН	EXCHA Ca	NGEABLE K	CATIONS Mg	(me/100 g) Mn	Na
MARSH	ENTER	7.50	35.00	2.52	3.92	0.017*	0.53
	MID	7.33	39.38	3.00	8.02	0.007*	0.67
	EXIT	7.33	39.38	3.00	5.52	0.007*	0.65
MOLOKAI	ENTER	6.40	16.67	3.21	4.10	0.378*	0.46
	MID	6.70	14.58	2.24	5.24	0.172*	0.34
	EXIT	6.70	15.00	1.86	6.50	0.19*	0.35
WAHIAWA	ENTER	7.00	13.13	2.24	2.19	4.111*	0.36
	MID	7.05	8.75	1.87	2.19	1.099*	0.25
	EXIT	6.90	7.50	1.60	2.76	0.007*	0.25
HELEMANO	ENTER	6.75	5.38	1.76	0.71	BDL	0.27
	MID	6.40	1.90	2.24	0.36	BDL	0.41
	EXIT	6.10	1.50	1.65	0.32	BDL	0.25
MAMALA	ENTER	6.75	18.75	2.85	2.14	0.052	0.32
	MID	6.90	14.84	1.92	2.32	0.047	0.28
	EXIT	7.00	17.03	0.81	2.19	0.013	0.35

* Soil Conservation Service field test indicated manganese present in soil.

but decreased in the Marsh and Helemano soils. The sodium ion content increased for the Molokai and Wahiawa soils but decreased for the Marsh soil category. Helemano and Mamala soils both increased and decreased in sodium ion content at different depths within the columns.

Percolate Analysis

SATURATED FLOW EXPERIMENT. The results obtained during the saturated flow experiment are presented in terms of percolate quality with respect to through-put volume expressed both as ml of percolate and pore volume. For further clarity, these results were reduced to determine the applied-removal characteristics, on a cumulative basis.

pH. The percolates from all three soil columns, Wahiawa, Lahaina, and Helemano, ranged from acidic to slightly acidic. Initially, the percolate from the Wahiawa and Lahaina soil columns had a pH of 6.9 and 6.2, respectively, and as the volume of applied leachate increased, both the pH decreased to 5.3. Figure 5 shows this decrease in pH, as well as the pH change in the percolate from the Helemano soil column. The pH of the Helemano percolate decreased from an initial 4.4 to 3.8 after 2.3 pore volumes of percolate was collected, and then increased slightly to about pH 4.1 thereafter.

It is noted that the pH of the applied leachate was 5.0, and the pH of the Wahiawa and Lahaina percolates were greater throughout the experiment, or in other words, the hydrogen ion concentration in the percolates were less than that in the leachate. This suggests that free hydrogen ions were being removed, possibly by soil adsorption or perhaps by chemical reaction. As the volume of collected percolate increased, however, the capacity of these two soils to remove the free hydrogen ions decreased. These removals are shown in Figure 6.

In the Helemano percolate, the pH was consistently lower than that of the applied leachate, suggesting a release of free hydrogen ions from the soil. This is not unexpected inasmuch as this soil is acidic, having a measured pH of 4.9. However, the percolate pH would be expected to eventually increase and approach the pH of the applied leachate as the amount of leachable hydrogen ions decreased. Note in Figure 6 that the Helemano removal data is plotted above the line of complete removal. On a log-log scale this indicates a release of ions, and as plotted in this case, the magnitude of the release is indicated.



Percolate Volume, ml/Pore Volume

FIGURE 5. pH RESPONSE CURVE, SATURATED FLOW EXPERIMENT

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FIGURE 6. CUMULATIVE REMOVAL OF HYDROGEN IONS APPLIED, SATURATED FLOW EXPERIMENT
Calcium. The calcium concentration in the initial percolate samples from all three soil columns were all less than 25 mg/ ℓ , as compared to the 291 mg/ ℓ in the applied leachate (Fig. 7). However, as the volume of applied leachate was increased, the calcium concentration in the Lahaina and Wahiawa percolates increased, surpassing that in the applied leachate before two pore volumes of percolate had been collected and eventually reaching a nearly constant level after about 2.5 pore volumes had been collected. The calcium concentration in the Lahaina percolate was approximately 450 mg/ ℓ from this point until the end of the experiment, while in the Wahiawa percolate the concentration was approximately 340 mg/ ℓ . The calcium concentration in the Helemano percolate remained below 100 mg/ ℓ for the duration of the experiment.

Cumulative calcium removal for all three soils is shown in Figure 8. After 4 pore volumes of leachate had been passed through the Helemano soil column, calcium removal had decreased to approximately 0.93 mg/g applied, although additional removal capacity was still indicated. If removal capacity of the soil is defined arbitrarily as being equivalent to the cumulative applied load at the point when removal of this cumulative applied load falls below 90%, then the capacity of Helemano soil to remove calcium under the present test conditions is about 59 mg/100 g of soil. It is probable that the calcium ions were displacing hydrogen ions, which is substantiated by the release of hydrogen ions from the soil to the percolate as shown in Figure 6. This is characteristic of acid, well-drained soils such as Helemano (Wentink and Etzel 1972; Chinn 1936).

Although Figure 8 shows initial removals by Wahiawa and Lahaina soil up to a cumulative loading of approximately 26 mg/100 g of soil, it cannot be concluded that these soils do in fact remove calcium, since the removal curves assumed a negative slope after that point which indicates the release of calcium ions from the soil into the percolate. It is possible that these ions were being displaced by hydrogen ions which were being removed from the applied leachate as shown in Figure 6. This is characteristic of humid soil types such as Wahiawa and Lahaina (Kanehiro and Chang 1956; Sherman and Alexander 1959; Kimura 1966).

Magnesium. As expected, the Helemano, Wahiawa, and Lahaina soils showed magnesium removal characteristics similar to that for calcium removal (Fig. 9), although the removal capacity of Helemano soil was somewhat lower for magnesium than calcium. Figure 10 shows the magnesium removal by Helemano





FIGURE 7. CALCIUM RESPONSE CURVE, SATURATED FLOW EXPERIMENT



FIGURE 8. CUMULATIVE REMOVAL OF CALCIUM APPLIED, SATURATED FLOW EXPERIMENT







FIGURE 10. CUMULATIVE REMOVAL OF MAGNESIUM APPLIED, SATURATED FLOW EXPERIMENT

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soil to decrease to approximately 0.9 g/g applied after about 2.5 pore volumes had passed, which represents a removal capacity of about 8 mg/100 g of soil. As with calcium, this cannot be considered the ultimate removal capacity of Helemano soil, since the trend of the curve still assumed a positive slope at this point.

Manganese. Relatively low concentrations of manganese were measured in the percolate from all three soil columns, as shown in Figure 11. Unlike calcium and magnesium, however, manganese appeared to be removed from the leachate by all three soils during the entire course of the experiment. After about 2.5 pore volumes had been passed, manganese removals by the Wahiawa and Helemano soils had decreased to about 90% and was rapidly approaching the applied leachate concentration as shown in Figure 11. On the other hand, the Lahaina soil was continuing to remove manganese at a rate of about 0.94 g/g applied after 4 pore volumes had been passed. The removal capacities, under the test conditions, were 1.4, 1.7, and 1.85 mg/g of the Wahiawa, Helemano, and Lahaina soils, respectively.

Iron. Although the total iron concentration in the applied leachate was significant, about 31 mg/l, no iron was detected in the percolate from all three soil columns. It is unlikely that precipitation due to oxidation was causing this removal inasmuch as the pH of the leachate and percolate ranged from slightly acidic to acidic, and anaerobic reducing conditions within the soil column were no doubt present. On the other hand, iron in the ferric state at pH greater than 3.0 is insoluble and may have been removed mechanically. Finally, microbial utilization of ferrous iron under anaerobic conditions could account for this removal.

Hardness. Total hardness in both leachate and percolate was determined by calculation, assuming the contributing divalent metal ions to be calcium, magnesium, manganese and iron. The removal behavior demonstrated by the three soils are influenced greatly by calcium and magnesium, as shown in Figures 13 and 14.

From Figure 13, it is seen that both the Wahiawa and Lahaina soils lack the capability of renovating leachate with respect to hardness, whereas Helemano soil appears to readily remove the ions contributing to this water quality characteristic. Furthermore, after about 3 pore volumes of leachate had been passed, hardness removal by Helemano soil had only decreased to about 90%, while Wahiawa and Lahaina soils were releasing the hardness-causing cations. At this point, Helemano soil had removed 180 mg of hardness (as



FIGURE 11. MANGANESE RESPONSE CURVES, SATURATED FLOW EXPERIMENT













 $CaCO_3$) per 100 g of soil, which as mentioned previously is taken as the removal capacity of the soil.

Zinc. The concentrations of zinc in the percolate from all three soil columns remained well below that found in the leachate, as shown in Figure 15. Furthermore, as shown in Figure 16, almost complete removal of zinc is provided by all three soil types studied, approximately 0.98 g/g applied after about 4 pore volumes of leachate had been passed, or greater than 0.7 mg/100 g of soil. The high zinc removals for all three soils were expected due to the rather low concentrations observed in the applied leachate.

Chlorides. The behavior of chlorides in the Helemano percolate indicated possible washout of chloride ion from the soil, with the concentration increasing until it exceeded that found in the leachate and then approaching the leachate value. Chloride concentrations in the percolates from the Wahiawa and Lahaina soils, on the other hand, reached constant values which were less than that found in the leachate, as shown in Figure 17. This occurred by the time 2 pore volumes of percolate had been collected. Figure 18 shows the "apparent" removal characteristics of the Wahiawa and Lahaina soils with respect to chlorides. This figure suggests, as expected, that chlorides are conservative and pass through the soil relatively unchanged. Any discrepancy between percolate and leachate values after equilibrium has been established is felt to be due to analytical technique in measuring chlorides, and perhaps also to a dilution effect from pore water.

Total Dissolved Solids. Figure 19 describes the behavior of total dissolved solids in the percolate from the three soil columns. Again, the Wahiawa and Lahaina soils had similar patterns, with concentrations approaching that found in the leachate and attaining near constant levels after about 2.5 pore volumes had been passed. The removal capacities of the Wahiawa and Lahaina soils were 220 and 180 mg/100 g, respectively, as shown in Figure 20.

Helemano soil was slightly more effective in removing total dissolved solids, with about 90% of the applied load being removed after about 3 pore volumes had been passed, representing a removal capacity of 300 mg/100 g of soil.

Chemical Oxygen Demand. The behavior of all 3 soils with respect to organic removal (as measured by COD) was strikingly similar, as seen in Figure 21. The percolate COD concentration increased rapidly to about 3400 mg/lafter approximately 3.5 pore volumes had been passed. After 4 pore volumes had been passed, the Wahiawa percolate COD concentration had increased to



FIGURE 15. ZINC RESPONSE CURVES, SATURATED FLOW EXPERIMENT



FIGURE 16. CUMULATIVE REMOVAL OF ZINC APPLIED, SATURATED FLOW EXPERIMENT



CHLORIDE RESPONSE CURVES, SATURATED FLOW EXPERIMENT FIGURE 17.





FIGURE 19. TOTAL DISSOLVED SOLIDS RESPONSE CURVES, SATURATED FLOW EXPERIMENT



FIGURE 20. CUMULATIVE REMOVAL OF TOTAL DISSOLVED SOLIDS, SATURATED FLOW EXPERIMENT



FIGURE 21. COD RESPONSE CURVES, SATURATED FLOW EXPERIMENT

about 4000 mg/ ℓ , while the Lahaina and Helemano percolate CODs were being maintained at approximately 3500 mg/ ℓ . Figure 22 shows the removal characteristics for all three soils, with Lahaina and Helemano soils showing removal capacities of 360 and 360 mg/100 g of soil, respectively, and Wahiawa 420 mg/100 g of soil.

UNSATURATED FLOW EXPERIMENT. The results obtained during the unsaturated flow experiment are presented in terms of percolate quality with respect to throughput volume expressed as pore volume. These results were then evaluated to determine removal characteristics on a cumulative basis.

Alkalinity. Although alkalinity has little sanitary significance, its presence in water supplies is of some interest due to its effect on pH and precipitation reactions in distribution systems and industrial applications. In the unsaturated flow experiments, decreases in leachate alkalinity were measured in Wahiawa, Helemano, and Mamala soils, with little change seen in the percolates from the Marsh and Molokai soils as seen in Figure 23. Change in leachate alkalinity appeared to be a function of soil pH, with the highly acidic Helemano soil showing the greatest capacity to decrease leachate alkalinity, as shown in Figure 24. On the other hand, the Marsh and Molokai soils which were nearly neutral to slightly acidic had relatively little capacity to alter the leachate alkalinity.

pH. Hydrogen ion concentration in percolate samples, as measured by pH, are shown in Figure 25, along with the average leachate pH value. The behavior of Helemano percolate was similar to that experienced in the saturated flow experiments in that the percolate pH was less than that of the leachate; however, after about 4 pore volumes had been passed, percolate pH began to increase rapidly, until it eventually exceeded that of the leachate after about 9.5 pore volumes. These results indicate that although hydrogen ions were being released from the soil, the release was decreasing with passage of more leachate. Soil pH analysis substantiated this release of soil hydrogen, as shown in Table 6, where the pH of Helemano soil increased from an initial of 4.6 to a pH of 6.4 after about 9.5 pore volumes had been passed.

Wahiawa soil, on the other hand, did not behave as it did in the saturated flow study. During the initial applications of leachate, the soil appeared to be releasing hydrogen ions as evidenced by a lower pH in the percolate. As more leachate was applied, the amount of hydrogen ions released decreased



FIGURE 22. CUMULATIVE REMOVAL OF CHEMICAL OXYGEN DEMAND, SATURATED FLOW EXPERIMENT





FIGURE 24. CUMULATIVE REMOVAL OF ALKALINITY (CaCO3), UNSATURATED FLOW EXPERIMENT



FIGURE 25. pH RESPONSE CURVES, UNSATURATED FLOW EXPERIMENT

until eventually there appeared to be a removal of hydrogen ions from the leachate after about 4 pore volumes had been passed.

One possible explanation for this apparent inconsistency in behavior may be the difference in concentration gradient existing between leachate and soil hydrogen ions during the saturated and unsaturated flow experiments. In the saturated flow study, the applied leachate had a pH of 5.0, while the soil pH was 6.1; this "concentration" gradient would cause a shift in hydrogen ions from leachate to soil, resulting in higher percolate pH values, as was observed. As more leachate is applied, this exchange should decrease with the percolate pH approaching that of leachate, as was also observed. In the unsaturated flow study, leachate pH was 6.9, whereas soil pH was 5.5; this "concentration" gradient would cause a shift in hydrogen ions from soil to leachate resulting in lesser pH in the percolate than in the leachate, as was observed in both Wahiawa and Helemano percolates. As more leachate is applied, this concentration gradient would decrease resulting in a decreasing release of hydrogen ions from the soil to the percolate, thus causing an increase in percolate pH. In the absence of any other exchangeable ions, an equilibrium condition might be expected to be established where the percolate pH would eventually approach that of the leachate. However, in the present case, the percolate pH eventually exceeded that of the leachate pH, probably due to other reactions taking place. These results show that pH response cannot be predicted on the basis of soil characteristics alone, rather the applied leachate hydrogen ion concentration must also be considered.

All the remaining soils studied, Marsh, Mamala, and Molokai, were removing hydrogen ions from the leachate during the unsaturated flow experiments.

• Calcium. Calcium concentrations in percolate samples are shown in Figure 26, along with the average concentration measured in the leachate. In every case except the initial Marsh sample, the percolate calcium concentration was lower than the average of 496 mg/L measured in the leachate. This obviously suggests removal on the basis of cation exchange by all the soils. Analyses of each soil prior to, and after completion of the percolation studies showed that exchangeable calcium ion increased, and that the predominant ion species involved in this exchange varied from soil to soil, as would be expected. For example, the exchange in Wahiawa soil appeared to involve primarily hydrogen ions, where the soil-associated species decreased greatly during the percolation studies, as compared to other exchangeable



FIGURE 26. CALCIUM RESPONSE CURVES, UNSATURATED FLOW EXPERIMENT

species. This also explains the apparent dissimilarity in calcium response between the saturated and unsaturated flow studies for Wahiawa soil. In the saturated flow experiment, hydrogen ions were being removed from the leachate and calcium released from the soil, while the opposite occurred during the unsaturated flow experiments.

Figure 27 shows the cumulative removal of calcium as a function of cumulative applied load. During this study phase, each soil type had some calcium removal capacity, however, unlike the saturated flow study, Wahiawa soil was more effective in its removal capacity than Helemano soil. The data obtained from both studies suggest that this response is dependent on the hydrogen ion balance between leachate and soil, as well as the concentration of calcium ions present in the leachate. Nevertheless, under these test conditions, none of the soils demonstrated significant capacity to remove calcium ions. For example, Wahiawa soil, which had the best overall removal characteristics, was unable to remove more than 75% of the applied load throughout the percolation studies. Furthermore, Helemano soil demonstrated an initial removal capacity (based on 90% of applied load) of about 30 mg/100 g of soil, somewhat lower than that observed in the saturated flow study of 59 mg/100 g of soil.

Magnesium. Removal of magnesium by the five soils was expected to follow a similar pattern as that for calcium, however, whereas all soils had some capacity to remove calcium, only the Helemano and Mamala soils were observed to remove magnesium, presumably by cation exchange as evidenced by an increase in exchangeable magnesium ions during the percolation studies as shown in Table 6. On the other hand, magnesium in the Marsh, Molokai, and Wahiawa soils was being displaced by other cations, primarily calcium, and released into the percolate. Analyses on these soils showed a decrease in exchangeable magnesium upon completion of the percolation tests, although the decrease observed in Wahiawa soil was slight, due probably to the establishment of conditions near the end of the percolation studies that provided for magnesium removal. The magnesium response is shown in Figure 28, while Figure 29 shows the removal characteristics for each soil type.

Magnesium response in the unsaturated flow study was similar to that in the saturated flow study for Helemano and Wahiawa soils in that magnesium was removed by the former while being released by the latter. However, removal capacity in the Helemano soil was much lower, with little renovation of leachate observed. Under saturated flow conditions removal capacity based







FIGURE 28. MAGNESIUM RESPONSE CURVES, UNSATURATED FLOW EXPERIMENT





on 90% removal was 8 mg/100 g of Helemano soil; under unsaturated flow conditions at this loading only about 15% of the magnesium was being removed.

Manganese. The unsaturated flow studies provided unusual and unexpected manganese responses. Of the 5 soils, only Marsh, Mamala, and Helemano were able to remove manganese, presumably by cation exchange, while Molokai and Wahiawa soils were releasing manganese to the percolate. Figure 30 shows the manganese response in relation to the manganese concentration in the applied leachate.

As can be seen in Figure 30, manganese concentration in the Marsh percolate remained lower than that in the applied leachate throughout the percolation study. Figure 31 shows this removal of manganese by Marsh soil to be greater than 50% throughout the study. However, analysis of the soil prior to and after percolation yielded a decrease in exchangeable manganese, as shown in Table 6, which is not reasonable. The only explanation that can be advanced is that the very low concentrations analyzed were less than the optimum detection range for soil samples.

On the other hand, Molokai and Wahiawa soils both indicated that manganese was being released during this study, based on percolate and leachate concentrations, as shown in Figure 30. However, analysis of both soils indicated an increase in exchangeable manganese during the percolation studies. One explanation for this anomaly is that certain soils have been found to release manganese in the presence of phosphates and organic matter when the soil is waterlogged (Fujimoto 1947). It is possible that subjecting these soils to these conditions not only released manganese during percolation, but also made available more exchangeable manganese for measurement after percolation.

Helemano soil removed manganese during both saturated and unsaturated flow studies; the removal capacities were comparable, about 1.7 and 1.5 mg/100 g of soil, respectively.

Potassium. Figure 32 shows the potassium response for the unsaturated flow studies conducted. In every case, leachate potassium was being removed, although the Molokai and Marsh soils were somewhat less efficient. Cation exchange is responsible for these removals, as in every soil the exchangeable cations increased after completion of the percolation studies. The removal effectiveness for each soil is shown in Figure 33, which shows the cumulative potassium removed as a function of that applied.

Sodium. As expected, sodium was found to be very active in cation exchange properties for all soils. Concentration in the percolate, as shown



FIGURE 30. MANGANESE RESPONSE CURVES, UNSATURATED FLOW EXPERIMENT



FIGURE 31. CUMULATIVE REMOVAL OF MANGANESE, UNSATURATED FLOW EXPERIMENT



FIGURE 32. POTASSIUM RESPONSE CURVES, UNSATURATED FLOW EXPERIMENT



FIGURE 33. CUMULATIVE REMOVAL OF POTASSIUM, UNSATURATED FLOW EXPERIMENT

in Figure 34, exceeded that found in the initial application of leachate, but decreased as more leachate was applied, until the applied level was approached in the Mamala, Helemano, and Marsh percolates. In the Molokai and Wahiawa percolates, sodium concentration decreased to slightly below that found in the leachate. As seen in Table 6, the exchangeable sodium ion content in these 2 latter soils increased after percolation, while in the Marsh, Helemano, and Mamala soils, the exchangeable sodium content decreased. Although this observation appears reasonable, analysis of Figure 35 indicates that all soils except Wahiawa should have had an overall decrease in exchangeable sodium after percolation. The discrepancy in the Molokai results cannot be explained except to be due to analytical technique.

Iron. Although the leachate iron concentration was measured to be 38.8 mg/l, all of the percolate samples contained less than the detectable limit of 0.5 mg/l. This behavior was similar to that observed during the saturated flow experiment for Wahiawa and Helemano soils, and similar explanations on its removal can be advanced.

Zinc. As with iron, zinc was found at measurable concentrations in the leachate, 0.66 mg/ ℓ , and below the detectable limit of 0.1 mg/ ℓ in the percolates. These removals are not surprising, since zinc is very competitive in cation exchange (Leeper 1972).

Cadmium, chromium, copper, and nickel. All leachate and percolate samples had less than the detectable limits for cadmium, 0.05 mg/l; chromium, 0.5 mg/l; copper, 0.5 mg/l; and nickel, 0.5 mg/l.

Chemical oxygen demand. Figure 36 shows the COD level in the percolate from all 5 soils. Since the organic matter in the leachate was not stable over the entire percolation test series, analysis was performed on the leachate prior to each percolation trial, and these results are also shown in Figure 36.

As seen in Figure 37, COD removals for all soils were not overly impressive. Wahiawa soil was the most effective, however, after about 10 pore volumes had been passed, less than 50% of the applied load up to that point had been removed. Furthermore, in the saturated flow experiment 90% of the applied load was removed after 420 mg COD had been applied per 100 g of soil, and at this loading only 50% had been removed during the unsaturated flow experiment.

The probable removal mechanism in both saturated and unsaturated flow studies was microbial assimilation. If this is true, then the lower re-



FIGURE 34. SODIUM RESPONSE CURVES, UNSATURATED FLOW EXPERIMENT


FIGURE 35. CUMULATIVE REMOVAL OF SODIUM, UNSATURATED FLOW EXPERIMENT







	WAHIAWA	
0	HELEMANO	
×	MARSH	
0	MOLOKAI	
Δ	MAMALA	

FIGURE 37. CUMULATIVE REMOVAL OF CHEMICAL OXYGEN DEMAND, UNSATURATED FLOW EXPERIMENT

movals observed in the latter study do not seem unreasonable since the soil columns were subjected to periodic loading and the microbial population had to re-establish itself during each trial. In the saturated flow experiment the microbial population, once established, was allowed to proliferate without interruption.

Total Kjeldahl nitrogen. Fairly good removals of total Kjeldahl nitrogen were achieved by all soils, with concentration in the percolate consistently lower than that in the applied leachate for all trials as shown in Figure 38. Total Kjeldahl nitrogen consists of both ammonia and organic nitrogen, and removal of these forms of nitrogen can be explained by the following.

In aqueous solution, ammonia nitrogen and hydrogen ion will exist in equilibrium with ammonium ion:

$$NH_4^+ \rightleftharpoons H^+ + NH_3$$

This equilibrium can be shifted by altering the relative molar concentrations of any one of these constituents, the direction of shift being dependent on which of these constituent concentrations is altered, as well as on the magnitude of change in relative molar concentrations. The equilibrium will be shifted greatly to the left if NH_4^+ is removed, or if H^+ or NH_3 are increased. In the case of most natural exchange media such as soils, NH_4^+ is strongly adsorbed (Hem 1959), thus removing this ion from the aqueous solution. The equilibrium is shifted to the left and nitrogen removal will occur. Furthermore, in those soils where hydrogen ions are being released, the equilibrium will be further shifted to the left, thus enhancing nitrogen removal via soil adsorption.

A second removal mechanism that may be suggested is the release of gaseous NH_3 at the surface of the soil column. Many organic compounds contain nitrogen in the ammoniacal form, principally as proteinaceous nitrogen. Upon degradation of the organic compound by bacterial action, NH_3 is released which again may cause a shift in equilibrium, the direction of shift being dependent on the molar concentrations of NH_4^+ and H^+ existing at the time. However, if conditions are suitable, the NH_3 concentration in solution may be great enough such that release as gaseous NH_3 will occur when the percolate is exposed to air at the top of the soil column prior to discharge.

Figure 39 shows the total Kjeldahl nitrogen removal characteristics for each soil. The Mamala soil had the greatest capacity to remove these forms









of nitrogen, however, all of the soils except the Marsh soil maintained a removal efficiency of greater than 60% throughout the study, although there appeared to be a slight decrease in removal efficiency for Helemano soil after about 0.05 mg of total Kjeldahl nitrogen had been applied per g of soil. Marsh soil at first had less than 50% removal efficiency, however, after about 0.02 mg of total Kjeldahl nitrogen had been applied per g of soil, the removal efficiency increased to about 70%. Figure 39 also suggests that, with the exception of the Marsh soil, the capacity of the soils to remove total Kjeldahl nitrogen is in the order of 0.01 mg/g of soil with 90% removal of the cumulative applied load.

Total phosphorus. With the exception of the Marsh soil, total phosphorus was consistently removed throughout the unsaturated flow experiment as evidenced by the lower percolate concentrations shown in Figure 40. This consistent removal of total phosphorus can be attributed to the kaolinite clay content in these soils, where phosphates, the usual form of phosphorus in water (Sawyer and McCarty 1967), readily replaces hydroxyl anions on the kaolinite clay surface (Suehisa 1961).

The removal characteristics for each soil are shown in Figure 41. Again applying the 90% removal criteria, the removal capacity of the Helemano, Wahiawa, and Mamala soils is in the order of 0.015 mg/g of soil, and the average removal efficiency over the duration of the unsaturated flow experiment was about 80%. Molokai soil, although having fairly good removal characteristics after about 0.015 mg of total phosphorus had been applied per gram of soil, was less efficient. Marsh soil appeared to be leaching phosphorus from the soil until about 4 pore volumes had been passed, and then uptake of phosphorus occurred.

Suspended Solids. Figure 42 shows the suspended solids response curves developed for the unsaturated flow experiment. In every case, as expected there was removal, most probably due to filtering action by the soils. It is difficult to assess the significance of the relative removal efficiencies inasmuch as many variables will affect filtering action, such as column density, flow rate, nature of the suspended solids, etc. It is interesting to note, however, that the Helemano soil yielded the highest removal efficiency, in the order of 90% throughout the experiment, yet this soil column had the lowest column density and the highest column porosity. A possible reason is that this soil had the highest particle density, suggesting relatively large particles and, therefore, numerous openings, in comparison to the column







FIGURE 41. CUMULATIVE REMOVAL OF TOTAL PHOSPHORUS, UNSATURATED FLOW EXPERIMENT



FIGURE 42. SUSPENDED SOLIDS RESPONSE CURVES, UNSATURATED FLOW EXPERIMENT

density. According to filtration theory, these porous openings serve as tiny settling or entrapment basins for many small particles, thus enhancing overall suspended solids removal (Fig. 43).

In any event, it would seem logical that filtration of suspended solids is dependent on the manner in which the soil is compacted or to the degree of compaction attained, as well as on the physical nature or structure of the soil particles themselves.

SUMMARY

It is recognized that leachate renovation during percolation through soil is affected by chemical, biological, and mechanical factors. The results of this study suggest the important chemical factor to be ion exchange in the removal (or addition) of various inorganic cationic substances, while microbial degradation of organic substances appears to be the primary biological factor, and filtration of particulate material, both organic and inorganic, being the predominant mechanical mechanism for renovating leachate.

Ion exchange in soils was found to play a major role in altering the concentration of the various inorganic species in the percolating leachate. This observation is based primarily on the results of the unsaturated flow experiment during which the ion exchange capacity of the Helemano, Wahiawa, Mamala, Molokai, and Marsh soils was determined prior to and after percolation. Although this sorption phenomenon was found to play an active role in altering the concentrations of various ions within the percolating leachate, the degree of renovation observed indicated a rather low cation exchange capacity by the soils studied. As noted previously, the cation exchange capacity of certain soils which contain hydrous oxides and oxides of iron, and sometimes aluminum and manganese, is variable, depending on pH and soil management practices (Tsuji, Keng, and Uehara 1973). Molokai, Wahiawa, Helemano, and Lahaina soils belong to the Oxisol order, and the relatively low exchange capacities has been reported to be due to the large amount of kaolinite present (Buckman and Brady 1966; Kanehiro and Chang 1956; Sherman and Alexander 1959). Mamala soil, which belongs to the Mollisol order, may also contain free oxides of Fe and Al and behave like the Oxisol order soils, and while the Marsh soil does not belong to the Oxisol order, it may contain clays from the Oxisol order due to its alluvial origin.



FIGURE 43. CUMULATIVE REMOVAL OF SUSPENDED SOLIDS, UNSATURATED FLOW EXPERIMENT

It should be pointed out that the exchange capacity of the soils as herein reported is in relation to the applied leachate. This is important because the capacity of an exchange medium is also dependent on the nature and relative concentrations of the ions in solution. However, inasmuch as the applied leachate is considered to be typical, these low exchange capacities should also be considered typical of the soils studied and taken into account as such during site selection and design of landfill facilities on Oahu.

With respect to specific inorganic ions, the results of this study indicate that all of the soils studied readily remove iron, zinc, potassium, and the important nutrients, nitrogen and phosphorus, while more variable removal characteristics were observed for calcium, magnesium, and manganese. It must be restated that these removals in themselves were low for reasons explained previously, and practical application of these removal results must also take into account the amount of leachable material that may be released from a given quantity of refuse.

For example, under the experimental conditions, approximately 90 g of hardness, as CaCo3, were released into the leachate from 9.05 kg of refuse, or about 0.0099-g hardness (CaCo3) per g of refuse might be released over some period of time. From Figure 14, it is seen that Helemano soil had a hardness removal capacity of 180 mg/100 g of soil under saturated flow conditions, and from a combination of Figures 27 and 29, the removal capacity was about 110 mg hardness/100 g of soil under unsaturated flow conditions. These capacities are comparable in that they are of the same order of magnitude, therefore, using the greater of these values yields a (Helemano) soil requirement of about 555 x 10⁶ g of soil to remove at least 90% of the applied hardness derived from 100,000 kg of refuse. At a bulk density of 1.26 g/cm³, this represents about 440 m³ of soil. Assuming an in-place refuse density of 500 kg/m³ and one 3 m lift, the required landfill area would be about 67 m², and the depth of Helemano soil required to effectively remove the potential leachable hardness would be about 6.5 m. Since much larger quantities of refuse would be routinely handled at such a facility, the depth of soil required to prevent deterioration of a groundwater supply would likewise be much greater. In similar fashion, the depth requirements for other constituents, both inorganic and organic, can be determined.

In the foregoing example, removal capacity was based on a removal of 90%, as previously defined. In those cases where negative removals were observed, or where true removals did not approach 90%, reference to the

figures depicting cumulative applied loads vs. cumulative constituent removed will yield estimates of the possible impact on the quality of groundwater. For example, at the yield rate of 0.0032 g Ca/g refuse found in this study, 100,000 kg of refuse will yield 32 x 10^4 g of calcium. If 10 m of Wahiawa soil were available beneath the landfill and assuming identical operational procedures as previously described, then at a bulk density of about 1.4 g/cm³, approximately 9.38 x 10^8 g of soil would be available to renovate the leachate. This results in an applied load of 0.34 mg Ca/g of soil, which, from Figure 27, corresponds to a removal rate of 0.25 mg Ca/g of soil. This means that of the applied calcium load of 32 x 10^4 g, about 27% or 8.5 x 10^4 g of calcium might be expected to infiltrate beyond this depth.

Cadmium, chromium, copper, and nickel were not detected in the applied leachate, which is significant since these heavy metals could represent potential environmental and health hazards.

Organic material was removed by all soils, with removals during the saturated flow experiment being greater than those observed during the unsaturated flow experiment. For example, under saturated flow conditions, the removal capacity for Wahiawa soil was about 420 mg/100 g of soil, and under unsaturated flow conditions, about 100 mg/100 g of soil. However, the removals were not overly impressive especially when considering the potential leachable organic material present in the deposited refuse. Depending on the nature of the organic material, infiltration beyond the soil depth used in this study may occur. Several mechanisms may be responsible for this infiltration. First, nonbiodegradable material may be moving through the soil column without adsorption occurring, and second, degradation products of anaerobic decomposition may be moving through the column. In any event, depending on the flow conditions and the amount of refuse present, organic substances can be expected to percolate through the soil to significant depths.

From the results of this study, it is apparent that some caution should be exercised in selecting landfill sites with respect to potable ground water resources. In general, the Oahu soils herein studied did not demonstrate significant renovation capacities, either under saturated or unsaturated flow conditions, with respect to refuse leachate. However, landfill operations should not be universally prohibited from being located in groundwater regions on the basis of soil characteristics alone. Available soil depth and the dilution provided by regional hydrological and hydraulic characteristics should also be considered. In areas where considerable soil depth is avail-

able and dilution is great, a landfill for domestic refuse can certainly be considered despite the presence of the underlying groundwater resource.

It should be recognized that the results of this study provide a basis for evaluating the feasibility of landfill operations as related to potential impact on groundwater resources. In assessing the feasibility of landfill operation in a given area, the following is suggested:

- 1. Identify the primary area soil and determine its depth to water table, or its total depth if the soil does not penetrate the water table.
- 2. Estimate the total quantity of refuse expected.
- 3. Assume leachate is generated under saturated or "worst possible" conditions, and estimate the quantity of organics and inorganics (such as hardness and alkalinity, condition, etc.,) to be expected.
- 4. Estimate the quantity of organics and inorganics that might pass through the given depth of soil based on the herein reported removal capacities for the various soils under either saturated or unsaturated flow conditions, and also on the basic soil physical characteristics.
- 5. Determine the dilution expected on the basis of hydrologic and hydraulic considerations.
- 6. Calculate the anticipated change in groundwater quality based on these dilution considerations.

Finally, the results of this study does not preclude landfill operations from potable groundwater regions if provision is made to (1) minimize leachate generation through infiltration control, or (2) collect and remove leachate to prevent percolation through the underlying soil. Techniques to provide for infiltration control and leachate collection are available, although at increased cost.

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