REPORT DOCUMENTATION FORM
WATER RESOURCES RESEARCH CENTER
University of Hawaii at Manoa

[1]Report Number Technical Report No. 131	[2]FCST Category V-B, V-D
[3]Title *Leachate Quality from Lysimeters Treating Domestic Sewage*	[4]Report Date April 1980
	[5]No. of Pages viii + 86
	[6]No. of Tables 26 / [7]No. of Figures 13
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	[10]Grant or Contract No. 14-34-0001-7025, 8013 (A-069-HI)

[11]Keywords *Descriptors:* *Sewage disposal, *Sewage treatment, *Lysimeter, *Waste water treatment, *Domestic wastes, Soil treatment, Cesspools, Hawaii. *Identifiers:* *Oxisol, *Inceptisols, *Entisols, Wahiawa series, Lahaina series, Tantalus series, Jaucas series, Oahu.

[12]Abstract (Purpose, method, results, conclusions)

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LEACHATE QUALITY FROM LYSIMETERS
TREATING DOMESTIC SEWAGE

by

Gary T. Tasato
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Technical Report No. 131

April 1980

Final Technical Completion Report
for
Quality of Cesspool Leachates Under In Situ and
Designed Soil Complex Conditions, Phases I, II

OWRT Project No. A-069-HI
Grant Agreement Nos. 14-34-0001-7025, 8013
Principal Investigator: Gordon L. Dugan
Project Period: 1 July 1976 to 30 June 1979

The work upon which this publication is based was supported in part by funds provided by the Office of Water Research and Technology, U. S. Department of the Interior, Washington, D. C., as authorized by the Water Research and Development Act of 1978.

DISCLAIMER

ABSTRACT

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INTRODUCTION

The disposal of human body waste onto and/or into the land is an ancient and ecologically compatible method. The nutrient value of "night soil" for soil fertilization has been recognized for centuries in the Far and Middle East and is still routinely used in countries such as Taiwan and Korea (Julius 1977).

The expansion of urban areas and the need for more sanitary and aesthetic methods of handling human waste led to the development of water-carriage sanitation facilities, rather than the "dry" methods used previously, e.g., privies. The water-carried wastes were discharged on or into the land, or more commonly, into receiving waters, such as streams, lakes, and the ocean.

For household and relatively small discharges without access to community sewer lines, the cesspool, septic tank, and numerous mechanically aerated systems were developed with discharge, in nearly all cases, into the soil system (a necessity for cesspools). The cultivation of crops using sewage effluent and/or direct discharge onto the land has been used on a limited scale throughout the southwestern United States and other parts of the world. This practice has also been encouraged by a recent U.S. Environmental Protection Agency policy which will consider waiving the long-standing and rigid requirements of secondary sewage treatment (EPA 1977). On O'ahu secondary sewage has been used for the irrigation of sugarcane for several years (Lau et al. 1975, 1977, 1978).

The use of cesspools (pervious sides and bottom) declined in the continental United States until their use by the start of the 1950s was nearly nonexistent. This decline was largely the result of the inability of most mainland soils to continuously percolate cesspool effluent without plugging. Because many soils in Hawai'i have a high drainability, cesspools are still used in many areas of the state. However, there are several areas in Hawai'i where cesspools do not function properly due to "plugging" conditions; there are other areas where their use has caused receiving-water pollution and aesthetic problems.

The requirements for installing cesspools are specified in the Hawaii State Department of Health's (DOH) *Public Health Regulations* (1979, chap. 38), Private Wastewater Treatment Works and Individual Wastewater Systems. Basically, Chapter 38 (DOH 1979) precludes the "disposal of wastewater in areas where such disposal methods may contaminate an existing or potential potable water source." However, the specific regulation appears to be more of a hydraulic concern inasmuch as the depth regulations for cesspools are relaxed if a "stratum of gravel or equally pervious material of at least four (4) feet thickness is found, or a lava tube is encountered which provides adequate drainage" (DOH 1979). Besides Chapter 38, the Honolulu Board of Water Supply has stringent regulations for situations where discharged waste water could potentially percolate to groundwater supplies.

Data on cesspool usage for the individual counties of the state have been compiled in Table 1. Values for private treatment plants and municipal sewerage have also been included for comparison. Most of the values were taken from water quality management plans for the individual counties (DOH 1978*b*, *c*, *d*). Prior to the Department of Health publications, an independent survey of cesspool usage was conducted as part of this investigation. In most instances, both surveys produced numbers which were fairly consistent.

Besides having the largest population of all the islands, the City and County of Honolulu (O'ahu County) also has the most municipal sewerage, with cesspool users accounting for 9% of O'ahu's population (Table 1). This value translates to a total of nearly 21,000 cesspools, a figure which leads each of the other counties.

The other island counties are less populated but cesspool use is much more widespread. Maui County has over 7000 cesspools serving 34% of the population.

The counties of Hawai'i and Kaua'i each have between 14,000 and 16,000 cesspools serving respectively 65 and 73% of their population. Municipal sewerage has been somewhat limited on the outer islands and only recently have plans been implemented for the expansion of municipal service (DOH 1978*b*, *c*, *d*). For the entire state, 18% or approximately one-fifth of the total population utilizes cesspools as a form of waste water disposal. (Maps showing the distribution of cesspools for the individual counties are provided in App. A.)

Although there is a possibility that contamination from the cesspools may reach the basal water lens, Hawai'i has been fortunate enough to maintain its high quality groundwater supply. Groundwater is pumped directly to the user without treatment or chlorination, although facilities are on-line

TABLE 1. COMPARATIVE USE OF WASTE WATER DISPOSAL MODES FOR THE INDIVIDUAL COUNTIES, STATE OF HAWAI'I

COUNTY	CESSPOOLS			PRIVATE STP			MUNICIPAL STP		
	No.	Population Served	% County Population	No.	Population Served	% County Population	No.	Population Served*	% County Population
City and County of Honolulu[1]	20,638	70,170	9	22	31,730	4	18	664,200	87
Hawai'i[2]	15,900	54,060	65	24	5,730	7	4	23,010	28
Maui[3]	7,244	22,800	34	60	25,870	38	7	18,930	28
Maui	(6,107)	(15,900)	(27)						
Moloka'i	(512)	(4,900)	(84)						
Lāna'i	(625)	(2,000)	(99)						
Kaua'i[4]	14,275	28,550	73	18	9,890	25	4	860	2
TOTAL (State)	58,057	175,580	18	124	73,220	8	33	707,000	74

*Based on remainder of total population (Department of Planning and Economic Development 1977) not served by cesspools or private STPs.

[1]DOH (1978*a*).

[2]From cesspool data on file with State Department of Health in Hilo (July 1977).

[3]DOH (1978*d*).

[4]DOH (1978*c*).

for the latter. Hawai'i has yet to experience a reported health incident attributed directly to contaminated drinking water from basal sources.*

Of concern is the fact that O'ahu's developable groundwater supply may be fully committed by the year 2000 (SWC 1979). As Hawai'i's population and corresponding water demands increase and, in light of legislation such as PL 92-500[1], continued research on the treatability of the indigenous soils is vital for safeguarding the groundwater supply and for the wise overall management of Hawai'i's water resources.

PURPOSE AND SCOPE

As part of the research on the safeguarding of Hawai'i's groundwaters, this investigation was undertaken to determine the treatability of raw domestic wastes using soil lysimeters, particularly for incorporation into an individual household treatment unit.

A pilot waste water treatment unit was constructed, its design incorporating a central collection reservoir which could disseminate raw sewage to four adjacent outer lysimeters. Each lysimeter enabled the testing of four Hawaiian soil series as the primary treatment medium. Graded rock and gravel were used in three of the four waste water treatment lysimeters. The soils consisted of two Oxisol silty clays of the Wahiawa and Lahaina series, an Inceptisols silty loam of the Tantalus series, and an Entisols beach sand of the Jaucas series. The pilot unit was located near two residential cottages which served as the domestic waste water source.

Treatment efficiencies were obtained by characterizing both the raw sewage or influent and the leachate collected from each soil lysimeter. In the waste water analyses, temperature and pH, and the following parameters were measured:

Organics — Biochemical oxygen demand, chemical oxygen demand, and total organic carbon

Nutrients — Total phosphorus and total nitrogen (ammonia, organic, and nitrite and nitrate nitrogen)

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*T. Arizumi: personal communication (1978).

[1]Public Law 92-500, also known as the Federal Water Pollution Control Act Amendments of 1972, sets forth provisions to achieve its objective to restore and maintain the chemical, physical, and biological integrity of the Nation's waters.

Bacteria	Fecal streptococcus, and fecal and total coliform
Residue	Total solids or residue, suspended solids (nonfiltrable residue), dissolved solids (filtrable residue), volatile suspended solids, and fixed suspended solids.

LITERATURE REVIEW

The subsurface disposal of waste waters by methods such as cesspools, leachate fields, and seepage pits has been traditionally used strictly as a means of disposal. However, if these disposal systems are prudently engineered, other benefits such as irrigation, the addition of nutrients for crops, and the recharge of the groundwater table could be also realized.

Treatment Mechanisms in the Soil

As waste water is applied to a soil, it is subjected to various processes or treatment mechanisms. The principal mechanisms include physical filtering, biological activity, adsorption and precipitation reactions, and uptake by vegetation.

PHYSICAL FILTERING. Filtration of suspended solids is probably one of the most apparent processes in which the soil material can be utilized in a waste water treatment scheme. It is also the vital mechanism which retains microorganisms and facilitates the biological treatment of dissolved and suspended organic matter.

Many factors affect the filtering capabilities of a soil, not the least of which are the basic properties of the soil itself. McGauhey and Winneberger (1965) define some of these properties as follows:

> Infiltrative capacity. The rate at which liquid will pass through the soil-water interface and a measure of the ability of a soil to accept water
>
> Percolative capacity. The rate at which water moves through the soil after it has passed the interface and a measure of the ability of a soil to transport water
>
> Porosity. The percentage of the volume that is comprised of void space and a measure of the volumetric capacity of a soil to hold water
>
> Perviousness. The size and continuity of the voids, a factor which governs the rate at which water will pass through the system
>
> Permeability. A measure of the rate of passage of a liquid through a soil system; for practical purposes it is measured in saturated soils under standard conditions.

The filtration process may also be affected by the size of the suspended particles in the waste water. McGauhey and Krone (1967) presented a discussion on four possibilities regarding the relative sizes of suspended particles and pore openings. For the first three cases, the particles are considered noncohesive and rigid.

Case 1. Suspended Particles Larger Than Pore Openings. Under this condition, straining occurs as the particles accumulate on the soil surface as the water passes through the soil. These particles themselves may become a filter capable of removing even finer particles. While such action produces effective and nearly complete separation of the fine suspended material, it also restricts the flow and as the fines accumulate, the permeability of the system is continually lowered.

Case 2. Suspended Particles Smaller Than Pore Openings. When these particles are slightly smaller than the pore openings, they penetrate the surface until they reach a pore opening or passageway constriction that stops individually or bridges their passage. The bridging process depends on the relation between the largest particle size and the smallest constriction along a passageway. Bridging has been found to occur when the filter medium's grain diameters are less than five times the particle diameters. When the grains are about 15 times the particle size, the particles usually pass through the medium. When bridging does occur, the fines accumulate in the voids within the medium rather than on the medium surface. This increases the resistance to flow and here, permeability may be reduced two or three times that experienced by surface straining.

Case 3. Suspended Particles Both Larger and Smaller Than Pore Openings. This represents a combination of the first two cases and also includes a sedimentation phenomenon. Sedimentation of the suspended particles may occur as the water flows through enlarged portions of the passageways.

Case 4. Cohesive Particles. When the suspended particles are cohesive, they may form aggregates whose size and shape can change in response to local hydraulics and particle concentrations. The filtration of cohesive particles is the more usual situation as clay and organic particles, bacteria, hydrous oxides, and many other hydrated compounds are at least weakly cohesive under common conditions. The filtering mechanisms of the previous three cases all apply in this situation. In addition, the suspended particles may be removed by their adhesion onto the grains of the filter material.

BIOLOGICAL ACTIVITY. When waste water is applied to a soil, the degradation of organics is accomplished chiefly through biological activity. The organic material serves as a food source for the microorganisms (primarily bacteria) present in both the waste water and the soil itself. Through their respiratory processes, the organic matter is synthesized into new protoplasm and cell material (McKinney 1962). The ultimate end products are mineralized compounds which escape the soil system through either the percolating water, plant root uptake, or as evolved gases (McGauhey and Krone 1967). The biodegradation usually occurs in a soil system which is aerobic as the organics are stablized through the process of oxidation. Under anaerobic conditions, degradation also occurs but other oxidants besides oxygen gas must be utilized and a sensitive balance of selected bacterial populations is required (McKinney 1962). Quantitative relationships between the amounts of organic matter that can be stabilized and the required oxidants have been presented by Sawyer and McCarty (1967). The metabolic products from the microbial degradation of organic matter in soil are described by Miller (1974) in the following generalized formulas:

Aerobic Condition

$$(CHO)_n\,NS \xrightarrow{O_2} \underset{(60\%)}{CO_2} + H_2O + \underset{(40\%)}{\text{Microbial Cells and Storage Products}} + \underset{\underset{NO_3^-}{\downarrow}}{NH_4^+} + \underset{\underset{SO_4^=}{\downarrow}}{H_2S} + \text{Energy}$$

Anaerobic Condition

$$(CHO)_n\,NS \longrightarrow \underset{(20\%)}{CO_2} + \underset{(5\%)}{\text{Microbial Cells and Storage Products}} + \underset{(70\%)}{\text{Organic Intermediates}}$$

$$+ \underset{(5\%)}{CH_4} + H_2 + NH_4 + H_2S + \text{Energy}$$

The values in percent are estimates of the distribution of carbon from the original organic compounds after metabolism by the microbial population. It can be seen that the main products under aerobic respiration are CO_2, H_2O, and cell material, while under anaerobic conditions, intermediate substances such as organic acids, alcohols, amines, and mercaptans accumulate. Since the energy yield during anaerobic fermentation is relatively small compared to the same quantity for aerobic processes, there are fewer microbial cells which accumulate per unit of degraded organic carbon (Miller 1974). In addition, the end products of organic nitrogen and sulfur compounds are nitrate and sulfate under aerobic conditions, whereas hydrogen sulfide and

and ammonia are formed in the absence of oxygen.

Land treatment in the form of cesspools and septic tanks utilize anaerobic digestion to stabilize waste material. The cesspool is essentially a covered pit dug into the ground into which sewage, primarily from individual households, is deposited. In the cesspool, the major action is hydrolysis of the organic material which can then be carried out into the soil where further stabilization can occur (McKinney 1962). Septic tanks operate biologically in a similar fashion except that the solids are allowed to settle in the tank and the effluent is dispersed into the soil through leaching fields.

ADSORPTION AND PRECIPITATION REACTIONS. In a discussion by Ellis (1974), adsorption is defined as the adhesion, in an extremely thin layer, of gas molecules, dissolved substances, or liquids to the surface of solids with which they are in contact. McGauhey and Krone (1967) state that this affinity of dissolved or suspended matter for particles in the soil results from the attractions of opposing electrostatic charges (ion exchanges), van der Waals attractions (all matter at close proximity), and valence bonds. The ion exchange process is one of the more significant factors associated with the adsorption phenomenon. Ellis (1974) has defined ion exchange as the reversible process by which cations and anions are exchanged between solid and liquid (or other solid) phases if in close contact with each other. Various forms of chemical bonding may occur between ions and the solid phases of the soil medium.

Precipitation reactions are similar to adsorption processes and are described as chemical reactions which produce crystallization products which are only slightly soluble in the medium in which they are formed. Adsorption differs from this description in that one of the components of the chemical reaction is already a solid (Ellis 1974). Precipitation reactions also account for ion species in waste water by combining with other soil ions to form insoluble products which may be quite stable. The adsorption and precipitation phenomena in soil media are important because they provide removal mechanisms for both suspended and dissolved matter and also retain this material for biological stabilization.

UPTAKE BY VEGETATION. When soil and land treatment incorporates the use of vegetation in forms such as salable crops or grasses, another removal process is utilized. The primary constituents considered here are the nutrients found in domestic waste water. The major nutrients are nitrogen and phosphorus but may also include potassium, lime (calcium), trace elements, and humus (Pound and Crites 1973*b*). Removal is effected by nutrient uptake by the vegetation through the root zone. This means of treatment may be taken a step further if the plant material is physically removed from the soil system. To a limited extent, these processes also enable the removal of some heavy metals and other toxic elements from the applied waste water (Pound and Crites 1973*a*).

Removal of Common Waste Water Pollutants

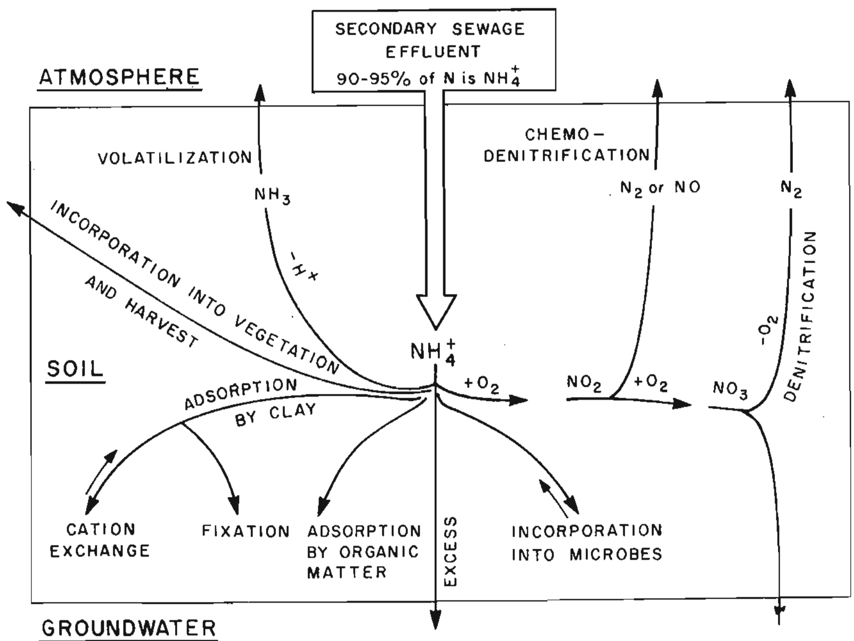
SOLIDS. Suspended and settleable solids and floatables are the usual constituents which can be physically removed in the filtering process. Dissolved solids are removed mainly through adsorption and precipitation reactions although the remaining treatment mechanisms also contribute to dissolved solids removal.

ORGANICS. As discussed previously, the removal of organics in waste water is accomplished chiefly through the respiratory processes of the microorganisms present in the soil-water system. All of the other removal mechanisms are essential in that they retain the organic matter for biological degradation. Organics which are readily degraded (as measured by BOD_5 values) can be almost totally removed by the soil matrix, especially in Hawaiian soils (Lau et al. 1974, 1975, 1977, 1978).

Many refractory organics are a source of concern because they are considered recalcitrant in their biodegradability. Detergent residues are among this group including the alkylbenzene sulfonates (ABS) which have, since 1967, been eliminated from household detergents, and phosphates which gained a reputation as being biostimulants in aquatic systems. Pesticides, especially the chlorinated hydrocarbon insecticides and the polychloroaromatic herbicides, have received considerable publicity as being not only extremely persistent in nature but also as being potential carcinogenic or teratogenic agents (Miller 1974; Shuval 1977).

NITROGEN. The nitrogen in waste water may exist in any of four forms—organic, ammonia (primarily ammonium ion), nitrite, or nitrate. Organic and ammonia nitrogen constitute the predominant forms found in domestic waste water. The removal of nitrogen from waste water may be effected through several chemical and biological processes available through a soil treatment system. In a discussion by Lance (1972), such removal mechanisms included biological denitrification, chemodenitrification, adsorption of ammonium ion, fixation of ammonium ion by clays, volatilization of ammonia, fixation of ammonia by the organic soil fractions, incorporation of nitrogen into microbial cell tissue, and uptake by vegetation and subsequent removal of vegetation (harvesting or cutting). A diagram of these processes is shown in Figure 1. Biological denitrification is perhaps the most desirable removal mechanism as the reduction of nitrate to nitrogen gas and its subsequent escape to the atmosphere reduces the threat of groundwater contamination or eutrophication. The physical removal of plant tissue is the only other significant method of completely removing nitrogen from the soil-water system.

The adsorption and fixation mechanisms can remove significant amounts of ammonium ions. However, this nitrogen retention is not necessarily stable as biological nitrification may transform the ammonium into nitrate which passes quite readily through soil systems (Lance 1972; Pound and Crites 1973*a*). Studies by Ardakani, Shulz, and McLaren (1974) indicated that ammonium ion removal from percolating waters is primarily due to oxidation and adsorption in the soil. In their tests, approximately half the



SOURCE: Lance (1972).

Figure 1. Nitrogen transformations during land disposal of waste water

ammonium was biologically oxidized to nitrate in the top 0.03 m (1.2 in.) of soil while the rest was gradually adsorbed.

PHOSPHORUS. Phosphorus occurs in both natural waters and waste water almost entirely in the form of phosphates. These are commonly classified as either orthophosphates, condensed phosphates (pyro-, meta-, and polyphosphates) and organically bound phosphates. The phosphates in domestic waste water are comprised primarily of orthophosphates.

The soil system provides extremely effective processes for removing phosphate compounds from waste water and includes the mechanisms of adsorption and precipitation reactions, incorporation into microbial cell tissue, and uptake by vegetation (Pound and Crites 1973*a*). The immobility of phosphorus in the soil lattice was noted by Taylor (1967) when phosphorus applied as a fertilizer was found to be converted to water-insoluble forms in a few hours. In other studies, over 95% of the phosphorus applied as fertilizer remained in the top 0.18 or 0.20 m (7 or 8 in.) of various soils, 11 to 26 years after application (Scarseth and Chandler 1938; Morgan and Jacobson 1942). The immobilization of the phosphorus was attributed to strong adsorption by finely divided mineral soil particles. Coleman (1944) has studied the fixation of phosphate in kaolinitic and montmorillonitic clays. It was noted that most of the phosphate fixed by the soil was held in the clay fractions. However, it was discovered that phosphate adsorption was more dependent on the presence of free iron and aluminum oxides rather than on the particular type of clay minerals. In studies involving the application of secondary sewage to Hawaiian soils (Oxisol) over 95% of the applied phosphorus was not recovered in the effluent (Lau et al. 1974, 1975). Phosphates may also be removed from waste water through precipitation reactions, particularly with calcium ions. Uptake by vegetation followed by harvesting or cutting also contributes to significant phosphorous removal.

PATHOGENS. Pathogenic organisms in untreated waste water may be found in great numbers, both in variety and populations. These organisms are principally derived from the waste material of infected human and animal hosts which have found either direct or indirect routes to the sewer system. It is difficult to evaluate exactly what the general pathogenic character of a particular waste water will be because the relative densities of the pathogens present in waste water depend on a number of complex factors. Some of these factors include the sources contributing to the waste water, the wide variety of pathogens which may be present. The various environmental conditions affecting the waste water and the survival times of the pathogens out-side their hosts.

Foster and Engelbrecht (1974) have described how the populations of most pathogens are greatly reduced through conventional waste water treatment which includes chlorine disinfection. The numbers which survive disinfection are still significant, however, particularly if the waste water is to be applied to a soil-plant treatment system. The viruses are more resistant to chlorine disinfection than the bacterial pathogens. The enteroviruses in particular have been found to be quite resistant to conventional chlorination practices (Foster and Engelbrecht 1974; Shuval 1977).

When waste water treatment incorporates application to soil systems, the removal of bacteria and larger pathogenic organisms is effected through a combination of straining, entrapment, sedimentation, adsorption, natural die-off, and predation. Viruses can also be removed almost as effectively as bacteria but primarily through adsorption reactions (McGauhey and Krone 1967; Krone 1968; Lance 1972). The straining and adsorption mechanisms retain most of the pathogens near the soil surface, thus reducing their travel distance and subjecting them to wide variations in temperature and moisture conditions which enhance die-off (Krone 1968). Despite the persistance of numerous pathogens, the hazards from treated waste water application to the soil are relatively remote. The hazards do exist, but the epidemiological evidence suggests that few disease incidences have been related to this practice (Miller 1974).

Clogging of Soils

The clogging of a soil during waste water application is one of the primary problems associated with soil treatment. When soil clogging occurs, treatment application rates are severely restricted due to flooding and ponding situations which become undesirable for both health and aesthetic reasons.

The nature of soil clogging is quite varied, but it is essentially a physical phenomenon. It can be described as a change in friction or viscosity coefficients, or a reduction in the size and volume of pore spaces which results in increased physical resistance to flow (McGauhey and Krone 1967). These changes in the soil system may stem from the biochemistry of aerobic and anaerobic systems, chemical reactions, organic loading, hydraulic loading, system geometry, and numerous constructional or operational procedures. The principal causes of soil clogging can thus be classified as either physical, chemical, or biological in nature. It is rather obvious that most of the removal mechanisms in the soil are also the prime factors associated with clogging. These factors have been discussed by McGauhey and Winneberger (1965) and McGauhey and Krone (1967) and may be described as follows.

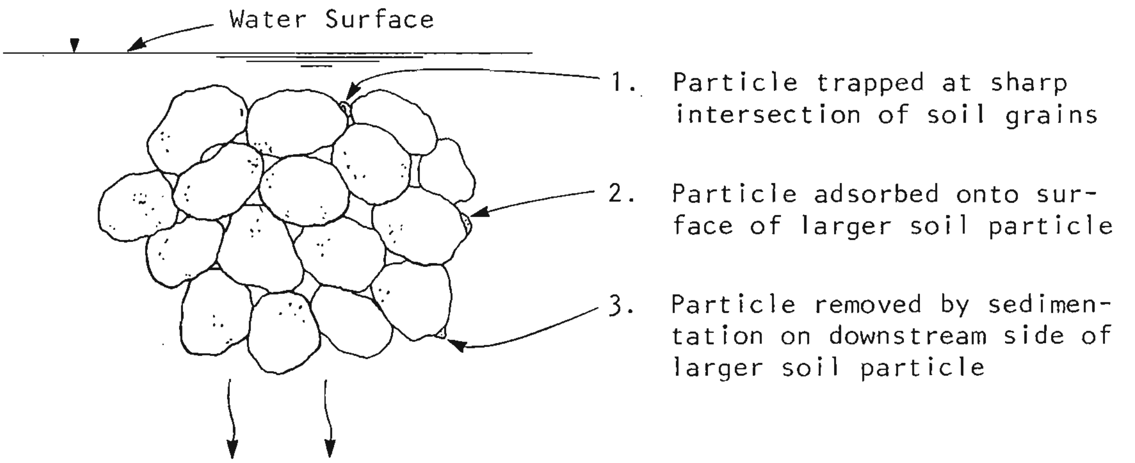
PHYSICAL FACTORS. The physical factors in clogging are primarily the same mechanisms by which the filtering and straining processes are effected, as previously described. Some of the factors are illustrated in Figure 2.

Other factors may also include:

1. Compaction of soil by superimposed loads such as ponded water or heavy equipment
2. Smearing of soil surface by excavating equipment
3. Migration of fines by vibration of soil during preparation of the site area
4. Migration of fines due to rainfall beating against soil surface
5. Washdown of fines perched on larger particles.

CHEMICAL FACTORS. The most significant of the strictly "chemical" factors in clogging is ion exchange which can change the physical nature of a soil. The most common example is the deflocculation of soils, particularly clays, which occurs when sodium represents a high percentage of the cationic content of the applied water. The predominance of sodium ions on clay particles has the effect of dispersing the soil particles and thus decreasing the soil permeability (Pound and Crites 1973*a*).

Chemical reactions which result in the formation of insoluble precipi-



SOURCE: McGauhey and Winneberger (1965).

Figure 2. Removal of particles from water through a soil system

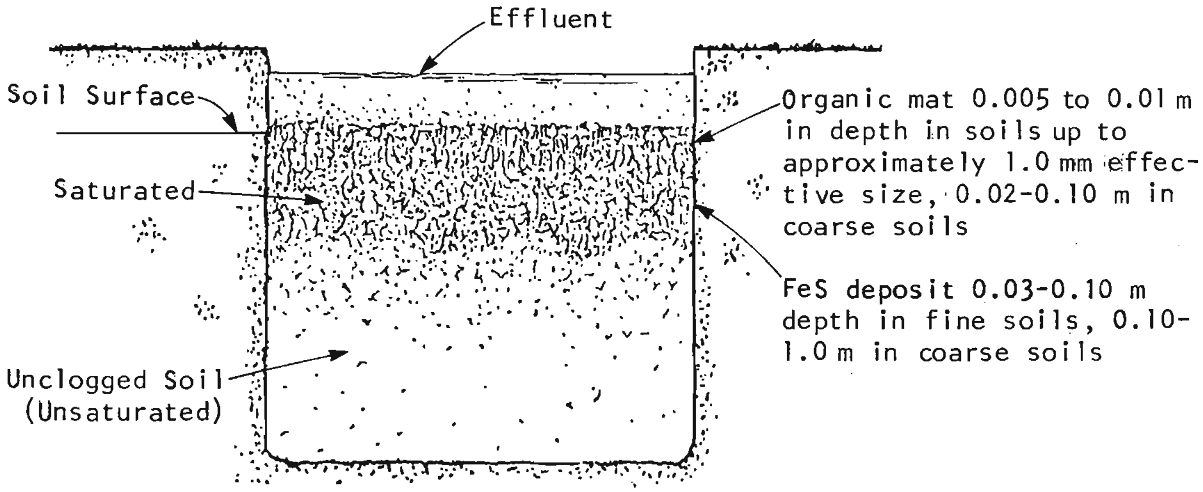
tates may also be a source of clogging. Calcium, barium, strontium, magnesium, and other earth metals may produce relatively insoluble carbonates, sulfates, orthophosphates, fluorides, and hydroxides. These anions may also form insoluble compounds with metals such as iron, aluminum, cadmium, zinc, manganese, and chromium.

BIOLOGICAL FACTORS. Biological agents and their activities are considered to be the prime causes of a soil's loss of infiltration capacity. Although microorganisms can help to keep open pore spaces in the soil system through decomposition of entrapped organics, their subsequent growth can also lead to extensive clogging effects. In most cases the clogging is a result of the formation of an organic mat on the surface of the soil.

This mat is comprised of the trapped organic solids plus an overgrowth of bacteria which feed on particulate and dissolved organic matter. The mat itself becomes a filtering medium which continually screens out finer particles and thus becomes the controlling element for the system's infiltration capabilities.

This mat may range from 0.005 to 0.203 m (0.2-8 in.) in depth depending on the particle sizes of the particular soil. Under predominately anaerobic conditions, this organic mat takes the form of black biological slimes. Underlying the biological slime is a characteristic zone of blackened soil. The black color is the result of ferrous sulfide which has precipitated from the anaerobic degradation of sulfates. Typically, the organic mat is only about 0.005 to 0.010 m (0.2-0.4 in.) thick while the ferrous sulfide layer penetrates roughly 0.051 to 0.102 m (2-4 in.) below the mat (McGauhey and Winneberger 1965). These elements of the clogging zone are shown in Figure 3. The accumulation of sulfides can reduce the infiltration capacity of a soil but in many cases it is merely an indicator rather than the primary cause of clogging (Rice 1974).

The restoration of biologically clogged soil systems can be accomplished by providing a period of drainage and rest from water application. This introduces oxygen into the soil and permits aerobic decomposition of the slime material and the oxidation of the ferrous sulfide to soluble sulfates. In addition, cracks and fractures may accompany the drying process which can increase the infiltrative capacity of the soil.



SOURCE: McGauhey and Winneberger (1965).

Figure 3. Elements of clogging zone in organically loaded soil

Nature of Hawaiian Soils

The soils and subsoils of the Hawaiian Islands originate primarily from volcanic lavas, cinders, and ash. To a limited extent, some soil material is also derived from coral reefs and other beach material. The parent materials of the soils are predominately basaltic or andesitic igneous rocks or their pyroclastic equivalents (Foote et al. 1972).

Hawai'i's soil groups are quite diverse throughout the entire state. Localized variations in climate, weathering exposure, parent material, plant and animal life, and other factors of soil formation account for the wide variety of existing soil types.

Table 2 lists the soils utilized in this study and their present classifications. Their previous classifications are also given because the old classification descriptors are used in much of the available literature. The first three soils, like most other Hawaiian soils, are considered clays based on mechanical analysis. Their permeabilities range generally from moderate for the Lahaina series to moderately rapid for the Wahiawa and Tantalus series. The soils are also characterized by relatively high amounts of the oxides of silica, iron, aluminum, and titanium (Kanehiro and Chang 1956; Foote et al. 1972).

TABLE 2. CLASSIFICATION FOR THE LAHAINA, WAHIAWA, TANTALUS, AND JAUCAS SERIES, O'AHU, HAWAI'I

	SERIES			
	Lahaina	Wahiawa	Tantalus	Jaucas
Family	Clayey, kaolinitic isohyperthermic	Clayey, kaolinitic isohyperthermic	Medial over cindery, isothermic	Carbonitic, isohyperthermic
Subgroup	Tropeptic Haplustox	Tropeptic Eutrustox	Typic Dystrandepts	Typic Ustipsamments
Great Group	Haplustox	Eutrustox	Dystrandepts	Ustipsamments
Suborder	Ustox	Ustox	Andepts	Psamments
Order	Oxisol	Oxisol	Inceptisols	Entisols
Great Soil Group of 1938 System	Low Humic Latosols	Low Humic Latosols	Humic Latosols	Regosols

SOURCE: McCall (1975).

Selected Treatment Studies Utilizing Hawaiian Soils

There have been numerous investigations on the various treatability aspects of Hawaiian soils, particularly with the predominant soils of O'ahu. Koizumi, Burbank, and Lau (1966) studied the infiltration and percolation of domestic and synthetic sewage in simulated cesspool lysimeters. The tests utilized soils of the Lolekaa (Humic Latosols) and Wahiawa (Low Humic Latosols) series. Overall reductions in chemical oxygen demand (COD) ranged from 62 to 92%. Appreciable reduction in organic nitrogen were reported but significant increases in ammonia nitrogen were also observed due to the anaerobic nature of portions of the lysimeters. In sections of the lysimeters where aerobic conditions are maintained, nitrate formation ranged between 13 and 53 mg/ℓ.

Kumagai (1967) also used simulated cesspool lysimeters with Lolekaa soil in tests with domestic sewage. In the same study, soil columns of Low Humic Latosol soils and quartz sand were dosed with anaerobic sewage. The lysimeters yielded protein and carbohydrate reductions of 90 and 50%, respectively. COD removal efficiencies were relatively high, averaging about 90%. The high COD removals were attributed to the aerobic conditions maintained in significant portions of the lysimeters. The tests with the soil columns indicated poor removal of sewage organics for both the soil and sand media. COD, biochemical oxygen demand (BOD), and total organic carbon (TOC) data for the sewage and the percolates frequently revealed increases in organic material. Other tests indicated the soil column to be more effective than the sand in removing sulfides. However, sulfide precipitates on the soil surface also caused relatively early clogging in the column.

Ishizaki, Burbank, and Lau (1967) studied the effects of soluble organics in sewage on flow through thin cracks of basaltic lavas. Clogging in the thin cracks was the primary phenomenon observed and was attributed to microbial cells and their biochemically synthesized products. Data on BOD_5, organic carbon, ammonium, and other parameters showed little or no treatment capabilities on the flow through the cracks.

Young, Lau, and Burbank (1967) studied the travel of ABS (alkyl benzene sulfonate) and ammonia nitrogen through saturated soils. The soils tested were Lolekaa (Humic Latosols), Lahaina and Wahiawa (Low Humic Latosols)—all silty clays; and Manana (Humic Ferruginous Latosols)—a silty clay loam. The results of the tests showed all four soils to be effective in removing ammonia and ABS from percolating waters at the applied respective concentrations of approximately 7.5 mg/ℓ and 5.5 mg/ℓ. Due to the nature of the test, the removal processes were primarily caused by adsorption phenomena with little or no biodegradation. The Manana soil had the highest exchange capacity for ammonia and ABS, Wahiawa and Lahaina soils the next highest, and Lolekaa the lowest.

Nitrogen removals in Lahaina soil have also been detailed by Dugan, Ekern, and Tsutsui (1976), where secondary effluent was passed through a laboratory soil column. Under continuous loading, total Kjeldahl nitrogen was adsorbed, and under anaerobic conditions denitrification occurred, as evidenced by a steady decrease in nitrate values. Intermittent loading also produced effective removals of total Kjeldahl nitrogen while maintaining aerobic conditions in the column. Nitrification was very active with high nitrate formation.

The fixation of phosphate in typical Hawaiian soils was studied by Chu and Sherman (1952). The acid soils, particularly the Humic, Low Humic, and Hydrol Humic Latosols, were shown to fix as much as 90% of added soluble phosphate. These soils are characterized by a relatively high content of hydrated free oxides—particularly iron and aluminum—and kaolinitic clay, both of which make the soils conducive to fixation by ionic exchange.

Chun et al. (1975) investigated the renovation of sanitary landfill leachate using numerous Low Humic Latosols in unsaturated soil columns. COD reduction efficiencies ranged from 40 to 50% while total Kjeldahl nitrogen removals averaged 60%. Phosphorus was consistently removed with reductions near 80% from the applied leachate.

Fischer, Green, and Burbank (1977) studied refractory organic compounds in treated effluent and their removal by Lahaina and Ewa soils (Low Humic Latosols) under field and laboratory conditions. Electron capture gas chromatography indicated that organic compounds were effectively removed by percolation through Lahaina soil in field irrigation tests. Other detection methods showed the soil to be less effective in removing high-molecular-weight organics such as paraffins and steroids. Organic removals under laboratory conditions for Lahaina and Ewa soils were less than those observed in the field tests.

Studies of virus transmissions through Lahaina and Wahiawa soils via percolating water were conducted by Tanimoto et al. (1968) and Hori et al. (1970). Bacteriophage T_4 (a vegetative virus) was found to be completely adsorbed on soil thicknesses greater than 0.06 m (2.5 in.) at the applied concentration of 2.5×10^6 pfu/mℓ. In tests with poliovirus type 2, 0.15-m (6-in.) soil columns retained 99.3% of the applied virus at a 1.5×10^5 pfu/mℓ dosage.

Intensive investigations on the recycling of sewage effluent by irrigation have been undertaken by Lau et al. (1972, 1974, 1975, 1977). The field studies entailed the application of secondary effluent to plots of sugarcane and grass cultivated in Lahaina soil. The treatability of the soil-plant systems was monitored with point samplers and hydraulic lysimeters. Analysis of the percolate waters indicated effective removals of BOD, TOC, suspended solids, nitrogen, phosphorus, potassium, and boron. In viral assays, human enteric viruses isolated in the applied effluent were not detected in either the sugarcane or grass percolates at a 1.5-m (5-ft) depth. In addition, cane production remained at satisfactory levels under effluent irrigation.

Chang (1976) studied the use of a highly treated secondary effluent for golf-course irrigation. The two major soils in the test area were a silty clay loam of the Ewa series (Low Humic Latosols) and a Jaucas sand (Regosols). Percolate samples were obtained through sampling wells extending 1.8 to 2.7 m (6-9 ft) below the ground surface. Nitrogen removals of approximately 98 and 86% were respectively observed for the Ewa and Jaucas series. Phosphorous removals exceeded 98% for both series. Complete removal of fecal coliform through the soil systems was indicated.

MATERIALS AND METHODS

Project Site

The project site was located on the grounds of the Harold L. Lyon Arboretum, an organized research unit of the University of Hawaii. The arboretum is situated in the upper reaches of Mānoa Valley on O'ahu and is located about 402 m (0.25 mile) beyond the urbanized portion of the valley. The facility encompasses an area of 5.02×10^5 m^2 (124 acres) and includes several greenhouses and a tract of cottages used for residential and office purposes. Waste water disposal for all of the cottages is provided by individual cesspools. Two of these cottages, D and E, served as the domestic waste water source for this study. The D cottage was one of several administrative offices at the Lyon Arboretum facility and was occupied by an average of one to three staff members. The E cottage was used as a residential unit with one permanent occupant.

Waste water flow from the two cottages was intercepted and diverted to the test unit through a concrete distribution box and approximately 27.4 m (90 ft) of 0.102 m (4 in.) polyvinyl chloride (PVC) piping installed in the area behind the D cottage (Fig. 4). The PVC pipeline in the garden area was buried 0.15 to 0.76 m (6-30 in.) deep, depending on the ground topography, to protect both the pipe and anyone working in the general area. The distribution box allowed the combined flows from the two cottages to be diverted either to the test unit or to the existing waste line from D cottage. When flow to the unit was desired, the PVC line was left open and the waste line to the cesspool was sealed off using either wooden or plastic slats. This process was simply reversed whenever it became necessary to stop the flow to the unit. A removable plywood cover provided access into the distribution box to make the required adjustments.

During the early planning stages of this study, D cottage was to have been the only influent source as it was then a residential unit with two occupants. However, when the system (distribution box, piping and test unit) was nearly completed, the occupants chose to vacate the cottage. After some

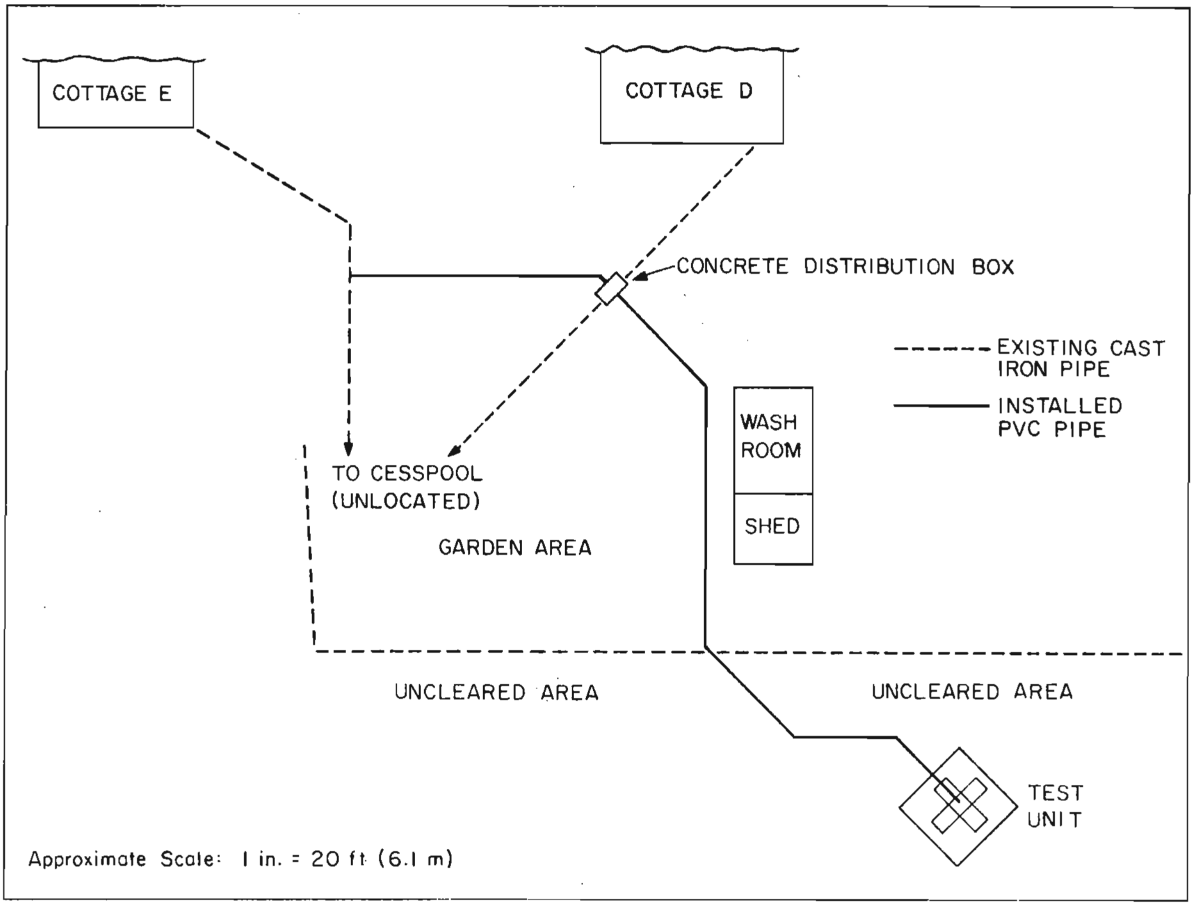


Figure 4. Physical layout of the project site

time, officials at Lyon Arboretum decided to convert the cottage into the present office. Initial analysis indicated that the collected sewage was too weak for useful application. The decision was made to intercept the flow from the adjacent E cottage. Approximately 7.3 m (24 ft) of new piping were installed connecting the E cottage waste line to the distribution box (modified to accept the new line) as shown in the present layout of Figure 5.

Test Unit

The test unit was located about 7.6 m (25 ft) beyond the edge of the garden in a heavily wooded section of the arboretum. The rather isolated area served to protect the unit and also prevented the unit from becoming an aesthetic problem—both visually and in terms of potential odors. The area was sufficiently low in elevation (about a 1.5-m [5-ft] differential

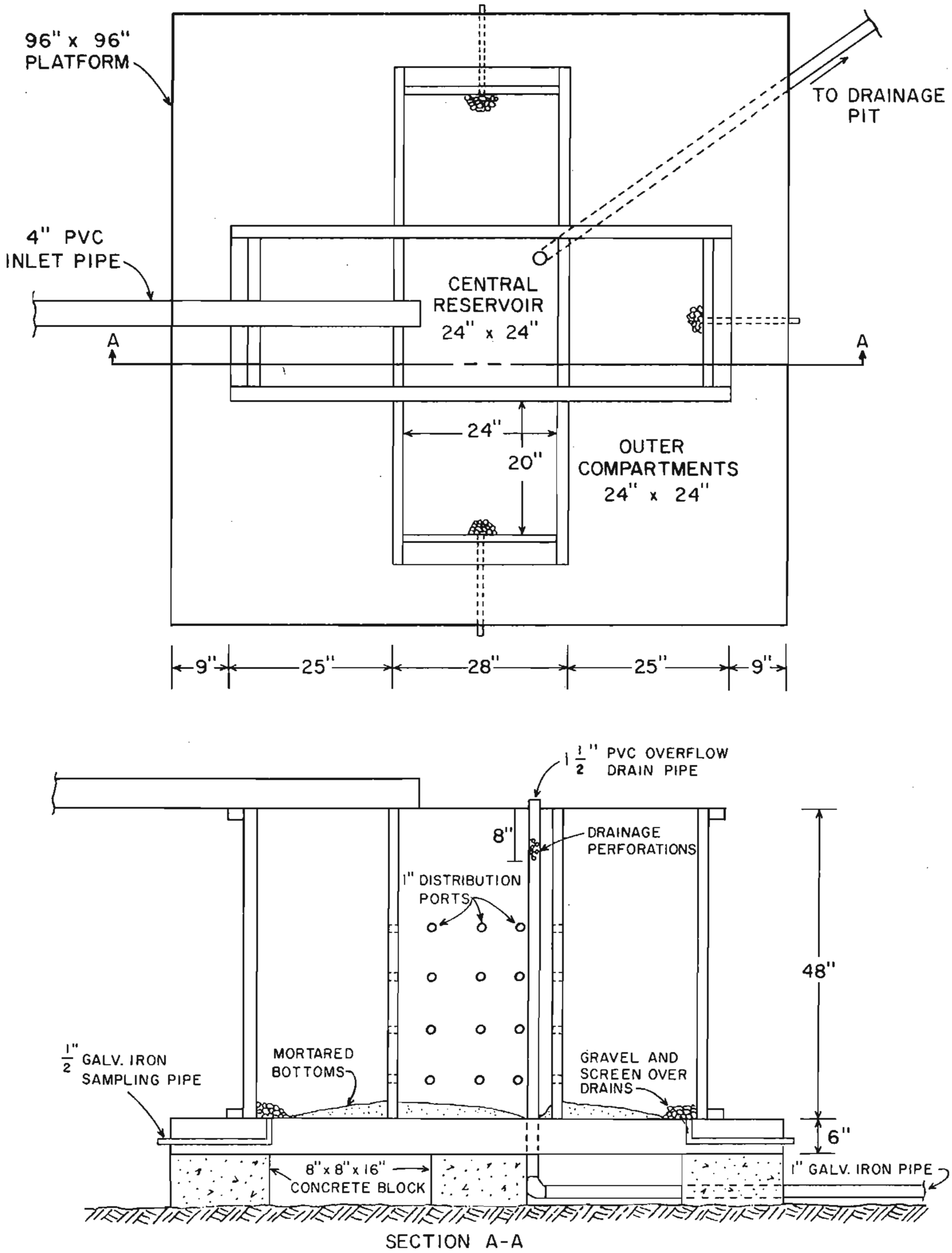


Figure 5. Test unit

from the garden edge) to permit adequate flow velocities through the pipes. A roughly 3-m^2 (10 ft^2) area was cleared of trees and vegetation and then graded level. A 2.44-×-2.44-m (8-×-8-ft) platform was constructed and supported by hollow concrete blocks about 0.2 m (8 in.) above the ground surface. The platform was constructed of 0.02-m (0.75-in.) laminated plywood (marine-grade) with 0.05-×-0.15-m (2-×-6-in.) joists for support.

The actual unit detailed in Figure 5 rested on the platform and consisted of a central collection reservoir and four adjacent outer compartments. The compartments were also constructed with the 0.02-m (0.75-in.) plywood using 0.05-×-0.10-m (2-×-4-in.) framing. The outer framing of each compartment was reinforced with two 0.13-m (0.50-in.) steel rods, each about 0.9 m (3 ft) in length. The outer compartments measured approximately 0.51 × 0.61 m (20 × 24 in.) (interior dimensions) by 1.22 m (48 in.) deep. The central chamber was the same height but measured 0.61 × 0.61 m (24 × 24 in.). The exterior of the unit was coated with a green latex stain to provide protection against weathering.

To insure a water-tight seal within the compartments, the interior was caulked with acrylic latex (at the joints) and coated with several layers of fiberglass resin. Fiberglass matting cloth provided added reinforcement at the joints.

The base of each compartment was fitted with galvanized iron piping for drain lines. The outer compartments each utilized a single drain line of 0.01-m (0.50-in.) piping for leachate collection. A 0.03-m (1-in.) line was connected to the collection reservoir and extended beneath the platform to a drainage pit 3.05 m (10 ft) away. The base of each compartment was lined with concrete mortar and sloped towards the drain. The drains in the outer compartments were covered with 0.006-m (0.25-in.) mesh screening and gravel to prevent the soil from completely clogging the drains. The drain in the central chamber was fitted with a 1.22-m (4-ft) section of 0.038-m (1.5-in.) threaded PVC pipe which served as an overflow drain. Drainage holes perforated near the top of the pipe provided a freeboard of approximately 0.20 m (8 in.).

Influent waste water entered the central reservoir through the end of the 0.10-m (4-in.) PVC line located at the top of the unit. A 0.91-m (3-ft) length of the rubber-tire tubing was connected to the pipe to dissipate some of the force of the incoming water and to minimize mixing of the settled sludge material.

Flow from the reservoir could be disseminated to the outer compartments through a grid of twelve 0.03-m (1-in.) diameter distribution ports drilled into each wall of the reservoir. The ports were arranged in four rows and three columns and were spaced about 0.20 m (8 in.) apart. The use of rubber stoppers allowed the compartments (with the designed soil lysimeters) to be run individually and also allowed for varying application schemes.

Waste Water Treatment Lysimeters

The unit allowed for the testing of four waste water treatment lysimeters. The soil chosen for the lysimeters included silty clays of the Wahiawa and Lahaina series, a silty loam of the Tantalus series, and beach sand of the Jaucas series. The sand had an effective size of 0.152 mm (0.006 in.) and a uniformity coefficient of 4.2 based on gradation analysis (Johnson Division 1975). The Wahiawa and Lahaina soils were obtained from the Mililani area of central O'ahu and the Tantalus soil from the project site at the Lyon Arboretum facility. The beach sand was purchased from a local hardward store. These soils were located and identified on the USDA Soil Survey maps (Foote et al. 1972) and also on the information provided by Paul C. Ekern.* Some of the characteristics of these soils have been compiled by Foote et al. (1972, pp. 48-49, 78-80, 121, 124-125).

The Wahiawa lysimeter was filled with only Wahiawa soil to a depth of about 0.61 m (24 in.) with no external compaction. The top two rows of distribution ports were left open while the remaining ports remained stoppered. This application scheme allowed influent water from the reservoir to flow over the top of the lysimeter and to percolate down through the soil mass (Fig. 6). The top surface area based on the 0.51-×-0.61-m (20-×-24-in.) dimensions was roughly 0.307 m^2 (3.3 ft^2).

The Lahaina lysimeter, which was filled with Lahaina soil was similar to the Wahiawa lysimeter except that 0.15 m (6 in.) of graded basalt rock was included as part of the design. The rock was graded in three layers of the following sizes: bottom layer, 0.02 to 0.05 m (0.75-2 in.); middle layer, 0.05 to 0.08 m (2-3 in.); and top layer, 0.08 to 0.10 m (3-4 in.). The total height of the soil and rock material was approximately 0.76 m (30 in.). All distribution ports were stoppered except the top row. Flow

*P.C. Ekern: personal communication (1977).

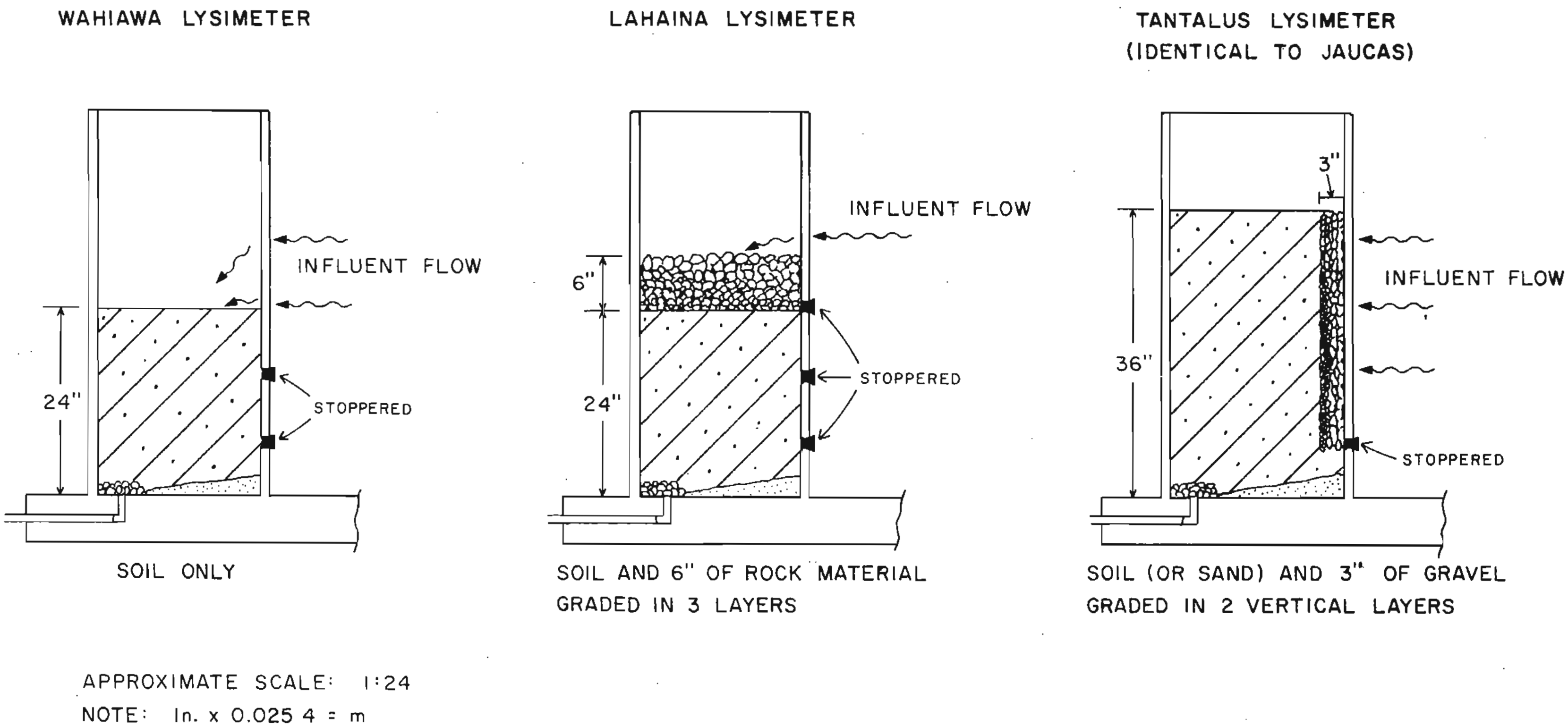


Figure 6. Wahiawa, Lahaina, and Tantalus waste water treatment lysimeters

entered through the top of the lysimeter and percolated down through the rock and soil. The rock material was used as a physical screening mechanism to prevent the large solids material and other debris from accumulating over the soil surface. It was also anticipated that the rock material might provide a medium for at least partial biodegradation of the organic material trapped on the rocks, similar to a trickling filter type of operation.

The Tantalus and Jaucas lysimeters both utilized the same basic design of a lateral flow scheme as opposed to the top surface application of the Wahiawa and Lahaina lysimeters. For these lysimeters, all distribution ports were left open except for the bottom three ports to prevent substantial quantities of sludge material from entering the soil lysimeter. About 0.08 to 0.10 m (3-4 in.) of graded rock were also utilized in the lysimeters but the rock material was set in two vertical layers behind the distribution ports (Fig. 6). The first layer (fronting the ports) consisted of rocks 0.01 to 0.03 m (0.50-1 in.) in size. The next layer (fronting the soil) contained sizes from 0.03 to 0.04 m (1-1.5 in.). The rocks were to serve as a screening media to reduce some of the physical loading on the soil mass. The soil and rock heights of both lysimeters reached approximately 0.91 m (36 in.) in the compartments. It should be noted that the rock layer did not extend all the way to the bottom of each compartment. A 0.15-m (6-in.) layer of soil material was first laid in the compartment before building up the rock material. This was to prevent the influent water from flowing down the rocks to the mortared bottom and onto the collection pipe and, thus, short-circuiting the soil material.

Operation of the Unit

The waste water treatment lysimeters in the test unit were individually tested to assess their respective treatability characteristics. The Wahiawa and Lahaina soil lysimeters were individually run but the Tantalus and Jaucas lysimeters were simultaneously run. These lysimeters were operated simultaneously because the resident in the E cottage took an extended leave-of-absence and sufficient time was not available for adequate sample collection and flow determinations for two separate operations.

The Wahiawa soil lysimeter was operated for two periods. During the first period, from 2 to 15 February 1978, the influent water (from the office) was found to be too weak for useful analysis. After modification to the collection system, sample collection resumed on 6 April 1978 and continued until 20 April 1978. During this period, sampling was performed about 4 days each week. Sampling was terminated when adequate leachate collection became impractical due to clogging in the lysimeter. After sample collection termination, the central reservoir was allowed to drain by removing the overflow drain pipe. Solids and sludge material caught in the iron drain pipe (to the drainage pit) were dislodged using a steel rod. When the chamber was drained, the distribution ports (Wahiawa soil lysimeter) were restoppered and the new ports were opened (for the next lysimeter).

The Lahaina soil lysimeter was the next lysimeter to be run and operated from 28 May to 26 June 1978. Sampling collections during this period were made approximately 5 times a week. Sampling was again terminated when clogging in the lysimeter made adequate leachate collection impractical after sampling was terminated, the central chamber was again drained and the required changes in the distribution ports (plugging the old lysimeter and opening the new one) were made.

The Tantalus soil and Jaucus sand lysimeters were both run from 16 July to 14 August 1978. During this period, samples were collected from both lysimeters on the average of 5 or 6 days/wk. The termination of sampling for these lysimeters was governed by the anticipated absence of the E cottage occupant. Leachate collection at the end of sampling was still more than adequate.

Grab samples were taken for all of the lysimeters. Influent collections were taken with a hand scoop consisting of an aluminum can attached to a length of PVC pipe. Leachates were collected by allowing the percolate to flow from the drain line of the compartment into the collection bottles.

During the operation of each lysimeter, the top of the compartment was covered with a 0.61-×-0.61-m (24-×-24-in.) piece of plywood to prevent rain water and debris (leaves and branches) from entering the compartment. This practice thus eliminated the dilution effect of rainfall. The cover was raised off the top about 0.10 m (4 in.) by using blocks to provide some aeration in the compartment. The compartments which were not in operation and the influent chamber were protected from the weather by using pieces of plywood and a 4.6-×-6.1-m (15-×-20-ft) sheet of 0.000 2-m thick (8-mil) polyethylene plastic.

Water Quality Analyses

The water quality assessment of the influents and leachates involved both field (on-site) and laboratory analyses. All laboratory analyses were conducted at the Sanitary Engineering Laboratory at the University of Hawaii. Samples were collected in liter sample bottles and transported in a chilled, styrofoam-insulted ice chest. Travel time between the project site and the laboratory averaged approximately 15 min.

The temperature measurements were performed in the field using a 0 to 100°C mercury thermometer (Scientific Products). The pH determinations were made either in the field or upon arrival at the laboratory using a Photovolt pH meter (Model 126A). Tests indicated no detectable change in the pH of the samples during the relatively short travel time.

The laboratory analyses consisted of the following determinations:

Organics	Five-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), and total organic carbon (TOC)
Nutrients	Total phosphorus and total nitrogen (ammonia, organic, and nitrite and nitrate nitrogen)
Bacteria	Fecal streptococcus, fecal coliform, and total coliform
Residue	Total solids or residue, suspended solids (nonfiltrable residue), dissolved solids (filtrable residue), volatile suspended solids, and fixed suspended solids.

The analytical procedures followed were in accordance with those outlined in *Standard Methods* (APHA, AWWA, and WPCF 1976). Certain modifications were in effect for several constituents and are noted as follows.

NITRITE AND NITRATE NITROGEN AND TOTAL PHOSPHORUS. Both analyses were performed using an automated analyzer (Technicon Autoanalyzer II) with strip chart recorder in accordance with *Methods for Chemical Analysis of Water and Wastes* (Environmental Protection Agency 1974). Nitrite and nitrate determinations required a cadmium reduction column. Samples for total phosphorus were digested as described in *Standard Methods* (APHA, AWWA, and WPCF 1976, Part 425 C, III—Persulfate Digestion).

TOTAL ORGANIC CARBON. Analysis was performed on a total organic carbon analyzer (Dorhman, Model DC-50) with direct digital readout.

Flow Determinations

The flow determinations for each lysimeter were conducted in the periods following the termination of sampling. A section of PVC piping was connected to the influent inlet pipe and flow was diverted into two 208-ℓ (55-gal) drums. The water levels in the drums (measured with a calibrated dipstick) were used to compute the flow volumes. The drums were checked twice a day, once in the morning and again in the afternoon to insure that the waste water would not overflow the drums. The flow measurements were conducted for periods of about a week or longer.

RESULTS AND DISCUSSION

Wahiawa Soil Lysimeter

Data collection on the Wahiawa soil lysimeter was originally initiated on 2 February and continued until 15 February 1978. During this period, the office in the D cottage provided the only influent source to the unit. Analysis of the influent showed the sewage to be extremely weak in comparison to typical domestic waste water as characterized in the literature. Approximate values for BOD_5 and COD averaged respectively 50 and 75 mg/ℓ. Total Kjeldahl nitrogen ranged from 2.0 to 20.0 mg/ℓ while total phosphorus remained below 4.0 mg/ℓ. Bacterial analysis of the influent also yielded relatively low values (App. Tables C.1-C.4).

The unit remained in operation until the end of February as officials at Lyon Arboretum anticipated more staff members to occupy the office. However, no significant changes were detected in the strength of the influent during this period. It was felt that assessment of the treatment system would be more meaningful if a true residential source could be obtained. Thus, the influent was supplemented with sewage flow from the E cottage in the manner described previously.

Under this scheme, sampling was resumed on 6 April and continued until 20 April 1978. Influent flow to the unit was estimated to be about 3.2×10^{-6} m^3/s (72 gpd) during this period. The actual average flow may be slightly lower than this value as the resident was not in the cottage for at least 3 days during the early part of the sampling period. The weekly averages of the measured constituents for the influent and leachate have been compiled in Table 3.

TEMPERATURE AND pH. The temperature of both the influent and leachate showed little variation throughout the sampling period with mean respective values of 22.9 and 22.8°C. These values would not be unexpected as ambient

TABLE 3. WEEKLY FLOW AVERAGES FOR INFLUENT AND LEACHATE, WAHIAWA SERIES, 6-20 APRIL 1978, O'AHU, HAWAI'I

		Week 1	Week 2	Mean*
Temperature (°C)	Infl.	22.8	22.9	22.9
	Leach.	22.8	22.8	22.8
pH (units)	Infl.	7.2	8.0	7.6
	Leach.	7.2	7.6	7.4
COD	Infl.	174	233	198
	Leach.	74 (57)	139 (38)	107 (46)
BOD_5	Infl.	138	175	160
	Leach.	60 (57)	100 (43)	84 (48)
TOC	Infl.	70	112	91
	Leach.	38 (46)	51 (54)	45 (51)
Ammonia Nitrogen	Infl.	11.3	39.9	25.6
	Leach.	7.5 (34)	30.9 (23)	19.2 (25)
Organic Nitrogen	Infl.	12.0	8.0	10.0
	Leach.	3.2 (73)	2.9 (64)	3.1 (69)
Total Kjeldahl Nitrogen	Infl.	23.3	47.9	35.6
	Leach.	10.8 (64)	33.9 (29)	22.3 (37)
Nitrite + Nitrate Nitrogen†	Infl.	<0.04-0.06	<0.04	<0.04-0.06
	Leach.	<0.04-0.12	<0.04	<0.04-0.12
Total Nitrogen	Infl.	23.3	47.9	35.6
	Leach.	10.8 (54)	33.9 (29)	22.3 (37)
Total Phosphorus	Infl.	3.2	5.7	4.5
	Leach.	0.2 (94)	0.4 (93)	0.3 (93)
Fecal Streptococcus ($\times 10^4$/100 mℓ)	Infl.	1.5	1.0	1.3
	Leach.	0.44 (71)	0.35 (65)	0.4 (69)
Fecal Coliform ($\times 10^6$/100 mℓ)	Infl.	34	25	29
	Leach.	4.1 (88)	5.2 (79)	4.6 (84)
Total Coliform ($\times 10^6$/100 mℓ)	Infl.	43	37	40
	Leach.	4.7 (89)	3.9 (89)	4.3 (39)

NOTE: All values in mg/ℓ unless indicated otherwise.
NOTE: Values in parentheses represent removal efficiencies in percent.
NOTE: Infl. = Influent, Leach. = Leachate.
*Mean of entire sampling duration for month of April.
†Represents range of values for each week.

air temperature was about 22 to 23°C during the periods of sampling. In addition, the surrounding trees and vegetation shielded the unit against direct heating from the sun.

The pH average indicated only a slight change between the influent and leachate (7.6 and 7.4, respectively). However, a noticeable rise in the influent pH during the second week was detected, with a slight rise in the leachate pH. The weekly averages for the second week were respectively 8.0 and 7.6 for influent and leachate. A possible cause for the rise in the pH may have been the use of household cleaners or other chemicals which may be highly alkaline in nature. The data indicated a general lowering of the pH as the influent passed through the soil lysimeter. This might be expected as the Wahiawa soil is characterized by medium to strong acidity.

ORGANICS. The COD, BOD_5, and TOC data indicated little variation in the organic loading for most of the first week. This may have been due to the resident's absence during the early part of the week; however, the data also indicated a general increase in organic loading during the second week of operation. While the TOC results show a slight increase in removal efficiency during the second week, BOD_5 and COD values indicate a decrease in removals during this time (from 57-43% for BOD_5 and 57-38% for COD). Based on the COD and BOD_5 results, increased loadings appear to have contributed to the reduction in removal efficiencies. Overall, the organic removal attained by the soil lysimeter was moderate, with all three parameters averaging only about 50% for the entire period. These results are well below the removals reported in the various field tests involving land treatment schemes. However, the results are comparable to the findings obtained by Kumagai (1967) utilizing soil columns (Low Humic Latosols) dosed with anaerobic sewage. COD, BOD_5, and TOC data all indicated minimal reduction of organic material and in several instances percolate organics exceeded the applied loadings. Koizumi (1966) reported high COD removals in lysimeter studies but sustained high residual BOD_5 values were observed in the percolate from anaerobic portions of the lysimeter.

NITROGEN. Both the influent and leachate data show the primary nitrogen constituents to be ammonia and organic nitrogen. Together, they comprise total Kjeldahl nitrogen (TKN) which is usually the principal form of nitrogen found in fresh domestic waste water. The tabulated data show the ammonia fraction to be the major component of the total nitrogen which is also typical of domestic sewage. Only one of the influent samples had an organic nitrogen level which exceeded the ammonia fraction. The nitrite and nitrate nitrogen values indicate that only a minute fraction of the total nitrogen constituents are in the inorganic forms. TKN values averaged in the 20 to 40 mg/ℓ range while nitrite and nitrate nitrogen values only ranged from less than 0.04 to 0.12 mg/ℓ. The levels of inorganic nitrogen were so low that many of the samples fell below the minimum detectable limit of the Autoanalyzer II unit (0.04 mg/ℓ) which made computation of true mean values quite difficult. Consequently, nitrite and nitrate nitrogen data are presented as range values in Table 3. Thus, the TKN values are essentially equivalent to the total nitrogen values.

Total nitrogen removal efficiency averaged about 37% for the whole period. Ammonia nitrogen removal was only about 25% while organic nitrogen was more effectively removed with a 69% efficiency. The weekly data reflected a substantial decrease in removal efficiency for total nitrogen during the second week (from 54-29%); however, a distinct rise in nitrogen loading also occurred during the same time period. The initial nitrogen loadings were relatively low and may have been the result of the resident's absence from the cottage.

The nitrite and nitrate nitrogen values, although extremely low, seem to indicate some degree of nitrification during the first week (maximum values of 0.06 and 0.12 mg/ℓ for influent and leachate, respectively). During the second week the nitrite and nitrate nitrogen values remained unchanged from influent to leachate. Dissolved oxygen determinations were not included as part of the regular analysis due to the anaerobic nature of the system. However, the oxygen levels were monitored on a few occasions and the results indicated an almost complete absence of dissolved oxygen in both the influent and leachate. These findings would tend to support the low nitrite and nitrate nitrogen values which were obtained.

The TKN removal results are somewhat below the levels usually reported in the field tests employing land treatment. Total nitrogen removals may be comparable to the results of the Flushing Meadows project (Bouwer, Lance, and Riggs 1974) and other studies where the total net nitrogen removals averaged about 30%. However, the low removals reflected in those studies were the result of high conversion rates to nitrate nitrogen forms which were not experienced in this study. The relatively higher organic nitrogen removal as compared to ammonia removal is consistent with the findings of

Koizumi, Burbank, and Lau (1966), where organic nitrogen was being converted to ammonia. In addition, organic nitrogen loadings are considerably lower than the ammonia loadings.

TOTAL PHOSPHORUS. The values for total phosphorus ranged from 2.1 to 7.0 mg/ℓ for the influent and from 0.2 to 0.6 mg/ℓ for the leachate. The data reflect high phosphorous removal efficiencies averaging 93% for the Wahiawa soil lysimeter. There was an increase in loading for the latter half of the sampling duration. However, no appreciable decrease in phosphorous removals was observed for the entire period. These results are consistent with the high level of phosphorous fixation experienced with Hawaiian soils in general (Chu and Sherman 1952). The data compares well with the phosphorous removals reported by Chang (1976) and Lau et al. (1974, 1975, 1977) in studies with land treatment involving Hawaiian soils.

BACTERIA. The fecal streptococcus, fecal coliform, and total coliform determinations indicate influent bacterial counts which fall within the ranges typical for domestic sewage. Removal efficiencies for fecal streptococcus, fecal coliform, and total coliform averaged respectively 69, 84, and 89%. These removals are based on percentage figures and are not truly indicative of leachate quality as the reductions are on the order of only 1 log for all 3 parameters. For the leachate, fecal streptococcus values are on the order of 10^3 per 100 mℓ while both fecal and total coliform values are on the order of 10^6 per 100 mℓ.

A decrease in influent bacterial counts during the latter half of the second week was noted. A possible cause for the observed decreases may have been the use of disinfectant cleaners or other chemicals which had a toxic effect on the bacterial populations. Another possibility would be a reduction in the influent flow from the cottages. A one- or two-day absence of the resident in E cottage near the end of the sampling period might account for the reduced bacterial counts. The data for most of the other constituents seem to show a decreasing trend for the influent near the end of the sampling period. This could be indicative of a reduced flow to the unit. A third possibility may be attributed to natural fluctuation in the bacterial populations which is a common occurrence in domestic waste water.

RESIDUE. Residue determinations were not performed for the Wahiawa soil treatment scheme since they were not included in the original scope of this study. It was thought that the migration of soil fines or larger particles into the collected leachate would prevent accurate determinations of solids removal. Subsequent evaluations, however, indicated that reasonable data on the leachate could still be obtained. Thus, residue determinations were performed for the remaining designed lysimeters.

SOIL CLOGGING. Clogging in the soil lysimeter became evident by the end of the first week of operation. Sustained ponding of the influent waste water had occurred and this was not observed during the earlier part of the week. Whenever the ponding subsided, large solids material and other debris characteristic of raw, unscreened, influent waste water were observed on the soil surface. In addition, a dark-gray slime layer was also present over the soil surface. This slime layer was similar to the anaerobic bacterial slimes and ferrous sulfide deposits described by McGauhey and Krone (1967) and Kumagai (1967). Towards the end of the second week, ponding was continuous with the influent water at the level of the overflow drain. Low leachate outflow was another indicator of clogging in the soil lysimeter. When sampling was first initiated, the outflow rate was approximately 1.67×10^{-5} m^3/s (0.264 gpm). By the end of the second week, over an hour was required to obtain a 0.003-m^3 (0.8-gal) sample. At this time, the decision was made to terminate sample collection.

The leachate outflow rates cannot be considered quantitative measurements of the flow through the soil column because soil saturation and head levels (during ponding) were not constant factors throughout the sampling duration. However, the values can be used as a qualitative assessment on the flow reduction through the soil lysimeter.

Lahaina Soil Lysimeter

The Lahaina soil lysimeter had the same basic design as the Wahiawa lysimeter except for the placement of graded rock on the soil surface. Sample collection lasted about 4 wk, beginning on 28 May 1978 and continuing until 26 June 1978. The estimated flow to the unit during this time was approximately 5.04×10^{-6} m^3/s (115 gpd). The influent flow was noticeably higher as the resident in the E cottage had 1 or 2 house guests who were present in the cottage from about the end of the first week of operation. The cottage housed at least 2 occupants for the duration of the sampling period. The occupants were still present in the cottage while the influent flow measurements were being conducted, thus providing a fairly representative estimation of the actual flows during the sampling period. The water quality data in the form of weekly averages are presented in Table 4.

TABLE 4. WEEKLY FLOW AVERAGES FOR INFLUENT AND LEACHATE, LAHAINA SERIES, 28 MAY-26 JUNE 1978, O'AHU, HAWAI'I

		Week 1	Week 2	Week 3	Week 4	Mean*
Temperature (°C)	Infl.	23.4	23.1	22.0	22.4	22.8
	Leach.	23.4	22.8	22.1	22.1	22.6
pH (units)	Infl.	8.3	8.1	8.6	8.4	8.4
	Leach.	6.8	7.4	7.7	7.7	7.4
Total Solids	Infl.	262	428	560	592	464
	Leach.	126 (52)	246 (43)	380 (32)	467 (21)	316 (32)
Dissolved Solids	Infl.	219	334	459	472	372
	Leach.	120 (45)	229 (31)	362 (21)	445 (6)	299 (20)
Suspended Solids	Infl.	43	94	101	120	92
	Leach.	6 (86)	17 (82)	18 (82)	22 (82)	16 (83)
Volatile Suspended Solids	Infl.	42	85	94	119	88
	Leach.	6 (86)	13 (85)	16 (83)	18 (85)	14 (84)
Fixed Suspended Solids	Infl.	1	9	7	1	4
	Leach.	0 (100)	4 (56)	2 (71)	4 (-300)	3 (25)
COD	Infl.	223	326	403	506	370
	Leach.	55 (75)	155 (52)	221 (45)	285 (44)	182 (51)
BOD_5	Infl.	142	212	206	241	199
	Leach.	52 (63)	77 (64)	108 (48)	163 (32)	102 (49)
TOC	Infl.	56	83	111	136	99
	Leach.	31 (45)	55 (34)	65 (41)	78 (43)	59 (40)
Ammonia Nitrogen	Infl.	33.8	56.5	92.2	88.5	61.9
	Leach.	6.4 (81)	45.7 (19)	69.1 (25)	108.0 (-22)	51.9 (16)
Organic Nitrogen	Infl.	8.9	14.5	13.7	13.3	12.5
	Leach.	3.8 (57)	3.4 (77)	4.3 (69)	3.1 (77)	3.8 (70)
Total Kjeldahl Nitrogen	Infl.	42.7	71.1	103.8	102.7	78.8
	Leach.	10.3 (76)	49.7 (30)	72.3 (30)	102.9 (-0.2)	59.7 (24)
Nitrite + Nitrate Nitrogen†	Infl.	<0.04-0.10	<0.04-0.07	<0.04	<0.04	<0.04-0.10
	Leach.	<0.04-0.22	<0.04-0.06	<0.04	<0.04	<0.04-0.22
Total Nitrogen	Infl.	42.7	71.1	103.8	102.7	78.8
	Leach.	10.3 (76)	49.7 (30)	72.3 (30)	102.9 (-0.2)	59.2 (25)
Total Phosphorus	Infl.	7.6	8.6	14.8	23.8	14.2
	Leach.	0.7 (91)	0.7 (92)	0.4 (97)	0.3 (99)	0.5 (96)
Fecal Streptococcus ($\times 10^4$/100 mℓ)	Infl.	28	17	60	45	37
	Leach.	12 (56)	7.1 (58)	9.5 (84)	4.0 (91)	8.3 (78)
Fecal Coliform ($\times 10^6$/100 mℓ)	Infl.	13	33	153	130	81
	Leach.	2.8 (78)	5.5 (83)	22 (86)	9.1 (93)	9.4 (88)
Total Coliform ($\times 10^6$/100 mℓ)	Infl.	92	278	268	226	210
	Leach.	36 (61)	89 (68)	23 (91)	16 (93)	39 (81)

NOTE: All values in mg/ℓ unless indicated otherwise.
NOTE: Values in parentheses represent removal efficiencies in percent.
*Mean of entire sampling duration.
†Represents range of values for each week.

TEMPERATURE AND pH. The mean values for the influent and leachate temperatures were respectively 22.8 and 22.6°C. Both the influent and leachate showed only minor temperature changes throughout the sampling period. The results are to be expected as the conditions of the weather and the surrounding environment remained fairly constant.

The pH for the influent was slightly high with an average value of 8.4. Sustained use of alkaline-based cleaning agents or other chemicals may be responsible for the relatively high pH. It is also possible that the addition of more occupants to the cottage may have somehow imparted this characteristic to the influent. The leachate pH was consistently lower, with an average value of 7.4. This result was expected since both the Lahaina and the Wahiawa series are acidic. There is a general rise in the leachate pH with time. This result is similar to the findings of Chun et al. (1975) in studies of soil columns dosed with sanitary landfill leachate. When the waste water was applied to an acid soil, the percolate pH was acidic but gradually approached the higher pH of the applied water.

RESIDUE. The influent values for total, dissolved, and suspended solids averaged respectively 464, 372, and 92 mg/ℓ. The data shows that the influent is typical of domestic sewage in that the dissolved solids constituted the major portion of the total solids. The overall suspended solids average is somewhat low but the averages for the last 2 wk are closer to the suspended solids range for domestic waste waters of Hawai'i (Young and Chan 1970; Chun, Young, and Anderson 1972). The relatively low values obtained may be due to some settling of the solids material in the influent reservoir. During the actual sampling of the influent, there was usually no incoming flow to the reservoir and the water (at least 0.76 m [30 in.] in depth) was generally in a state of quiescence. Volatile suspended and fixed suspended solids for the influent averaged respectively 88 and 4 mg/ℓ, which indicated that the suspended solids are primarily organic in nature.

Removal values for suspended solids were quite high, averaging 83%, while dissolved solids removal was moderate at 20%. An increase in the influent suspended solids with time was noted during this phase. With the exception of the fixed suspended solids, all of the other residue parameters in Table 4 showed an increase in loading. Removals for these parameters, particularly total and dissolved solids, also showed a decrease in removal efficiency. The fixed suspended solids data had removal efficiencies ranging from -300 to 100%. These figures might be expected as the values on which these efficiencies are based are rather low (0-9 mg/ℓ). These low values could be greatly affected by the migration of fines from the soil compartment, gravel debris over the sampling port, or other possible sources of error (including analytical).

ORGANICS. The influent concentrations of COD, BOD_5, and TOC averaged respectively 370, 199, and 99 mg/ℓ for the entire period. However, the weekly data indicates that the organic loadings averaged much higher during the last 2 wk of sampling. A general increase in the concentrations of the organics can be observed. All three parameters show a distinct jump near the end of the first week which coincides with the arrival of the house-guests in the E cottage. The weekly removal efficiencies all seem to exhibit a decreasing trend which accompanies the increased loadings. The average removal efficiencies for the entire period were 51% for COD, 49% for BOD_5, and 40% for TOC. These values are again below the reported efficiencies achieved in the land treatment field tests. However, as noted with the Wahiawa series, similar results have been reported by Koizumi, Burbank, and Lau (1966), and Kumagai (1967).

NITROGEN. The general results parallel the findings obtained from the Wahiawa soil lysimeter. Total Kjeldahl nitrogen (TKN) comprises almost the entire nitrogen content of both influent and leachate. The ammonia fraction was the primary constituent in both the influent and leachate. The nitrite and nitrate data also indicate the inorganic forms to be extremely low in concentration. Due to the low levels, the results are again reported as range values. The influent range was from less than 0.04 to 0.10 mg/ℓ and the leachate range was from less than 0.04 to 0.22 mg/ℓ. The ammonia nitrogen values for the influent were noticeable in that they reached high values, averaging about 62 mg/ℓ for the entire period. The weekly data show that the ammonia level attained a maximum value in excess of 90 mg/ℓ. Because of high ammonia values, the corresponding TKN results were also extremely high. The influent organic nitrogen also averaged slightly higher than the average for the Wahiawa influent (12.5 mg/ℓ vs. 10.0 mg/ℓ).

One of the factors responsible for the high nitrogen levels was probably the additional occupants in the E cottage. With the resulting higher flow rates, the previously observed pattern of increased loadings could have been accelerated. Another factor may have been the introduction of an external nitrogen source into the water collection system. At about the middle of the sampling period, it was noticed that approximately 30 or 40 red clay flowerpots had been rinsed and soaked in a wash basin beneath the office in the D cottage. Soil and granules of what appeared to be fertilizer material were still visible in the flowerpots and basin. If an ammonia-based fertilizer had been washed down the basin drain, the material would have reached the influent chamber since the drain connected to the cottages' waste water line. There were two distinct jumps in the influent total nitrogen levels. The rise in the middle of the sampling period may have resulted from the possible fertilizer addition. The initial rise could be attributed to the arrival of the houseguests.

The removal efficiencies for ammonia and organic N, and TKN averaged respectively 16, 70, and 24%. Again, the relatively higher organic nitrogen removal—as compared to the ammonia—was exhibited, similar to the Wahiawa soil lysimeter. However, a percentage of the organic nitrogen would be transformed to ammonia nitrogen. The low ammonia and TKN removals were probably due to the excessive loadings on the soil lysimeter. During the last week of sampling, ammonia in the leachate exceeded the influent values. Under the high loading conditions, excess ammonia nitrogen probably leached out of the soil lysimeter, causing higher values. In addition, ammonia can be produced during microbial degradation under anaerobic conditions as described by Miller (1974). Dissolved oxygen measurements were made only on a limited number of occasions but they all indicated that little or no dissolved oxygen was present in either the influent or the leachate. These results also agree with the low nitrite and nitrate nitrogen levels which were detected.

TOTAL PHOSPHORUS. Total phosphorus averaged approximately 14.2 mg/ℓ for the influent; however, the weekly averages show that the phosphorous concentrations increased to levels considerably higher than the mean value for the whole period. A noticeable increase occurred during the second week of operation which is close to the approximate period when the fertilizer was suspected to have entered the system. The additional loading due to the increase in residents may have also contributed to the observed increase and the high levels (>25 mg/ℓ) which were attained.

Despite the high loadings, the removal efficiencies still averaged about 96%. The data compare favorably with the phosphorous removal reported by Chu and Sherman (1952) and Lau et al. (1974, 1975, 1977) on studies involving similar soils. The results are again consistent with the high phosphorous fixation properties characteristic of the Hawaiian soils.

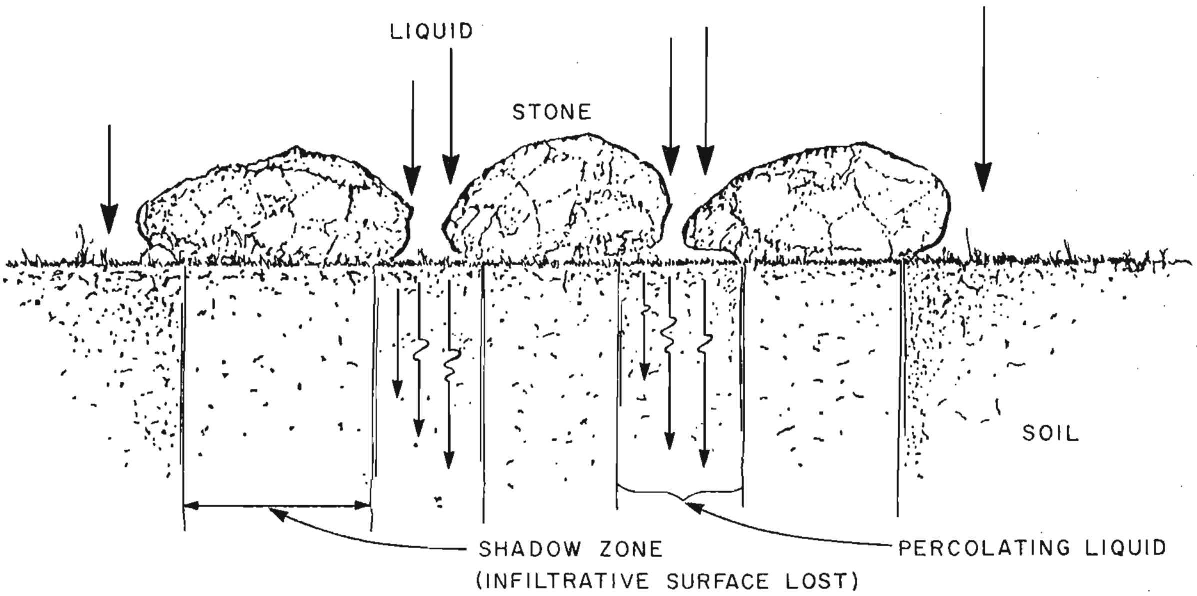
BACTERIA. Influent bacterial counts for the three parameters were all well within the normal ranges for domestic waste water. Fecal streptococcus counts were on an order of 10^5 per 100 mℓ while fecal coliform and total coliform values ranged from 10^7 to 10^8 per 100 mℓ. A fair amount of variation in the influent bacterial levels occurred throughout the sampling duration. The total coliform values decreased steadily for about the first 6 days before experiencing a sharp increase. These results do not seem to correlate with the fecal streptococcus and fecal coliform data as they both indicated an increase followed by a decrease during the same time period. However, these apparently conflicting trends may be of only limited significance since the order of magnitude for the variations is only a little more than 1 log. When considering that bacterial levels were as high as 10^8 per 100 mℓ, these variations may be due to the natural fluctuations in the bacterial populations.

Removal efficiencies for the bacterial indicators appeared to increase with time with overall averages of 78, 88, and 81% for the respective fecal streptococcus, fecal coliform, and total coliform. Although these values reflect fairly high removals, the leachate data revealed that significant numbers of the bacteria were still passing through the soil lysimeter. Actual reductions were only on the order of about 1 log between the influent and leachate.

SOIL CLOGGING. The graded rock over the soil surface was to be used as a physical screening mechanism to prevent the large solid materials and other debris from accumulating over the soil surface and also to provide a means for partial biodegradation of the organic material. This may have been successful to a limited extent as adequate outflow rates for leachate collection were maintained over a longer period of time. The initial and final flow rates were close to the rates observed for the Wahiawa soil lysimeter (about 1.7×10^{-5} m^3/s [0.264 gpm] and 2.8×10^{-7} m^3/s [0.044 gpm]) for the respective initial and final rates. Whereas sampling for the Wahiawa lysimeter lasted only 2 wk, sample collection was conducted for about 4 wk for the Lahaina treatment scheme.

Ponding over the soil-rock lysimeter occurred with greater frequency from about the second week of operation and was probably due to the higher flows generated by the additional occupants in the cottage. Soil clogging was not the primary cause of the ponding as leachate flow rates were still adequate for sample collection. However, clogging became evident as reductions in the outflow rates became more noticeable. When the leachate flow was reduced to less than 2.8×10^{-7} m^3/s (0.264 gpm), the decision was made to terminate sampling.

During the first half of the sampling period, the graded rock was moderately successful as a screening mechanism as large solids material and other debris were being trapped on the rock. However, because of the high overall loadings, ponding was sustained for long periods of time and anaerobic conditions probably led to the production of slime material, thus sealing effectively the infiltrative surface of the soil. In addition, the rocks themselves were directly placed on the soil and probably reduced the infiltration surface area (Fig. 7). Together, all of these factors probably accelerated the occurrence of clogging in the soil lysimeter.



Source: McGauhey and Winneberger (1965).

Figure 7. Loss of infiltrative capacity by abrupt change in particle size

Tantalus and Jaucas Lysimeters

The Tantalus and Jaucas waste water treatment lysimeters were simultaneously operated and the influent water for both was laterally received through the side of the compartment. Sample collection started on 16 July 1978 and continued until 14 August 1978. During this period, the E cottage was occupied by the resident and by another houseguest who was present on an intermittent basis. The cottage was thus occupied by one or two people throughout the sampling duration and also during the period of the flow determinations. The flow measurements were performed for about 1.5 wk. Estimates of the influent flows during the sampling period averaged approximately 3.68×10^{-6} m^3/s (84 gpd). The measured water quality constituents are presented in Table 5 in the form of weekly averages.

TEMPERATURE AND pH. The mean temperature of the influent was approximately 23.4°C while both the Tantalus and Jaucas lysimeters averaged about 23.2°C. As in the Wahiawa and Lahaina lysimeters, there were only minor variations in the temperatures of the influent and leachates for the entire sampling period.

The pH for the influent ranged from 7.3 to 8.3 which is within the usual pH range for domestic sewage. As described previously, the use of alkaline-based cleaners or other chemicals may have been responsible for the higher pH during the early weeks of sampling.

The Tantalus leachate pH averaged about 6.5 which was consistently lower than the influent pH. This result is comparable to the findings of the two previous soil lysimeters as the Tantalus soil is also quite acidic in nature. The weekly averages for the sand leachate show pH values of 7.8 to 8.3 for the whole sampling period. The higher pH was expected as the sand medium was relatively alkaline in nature, with a measured pH of 8.7.

RESIDUE. Residue determinations indicated that the total, dissolved, and suspended solids levels averaged respectively 427, 287, and 140 mg/ℓ for the influent. Influent values for the volatile and fixed suspended soils averaged respectively 132 and 8 mg/ℓ, thus indicating the suspended material to be primarily organic.

Removal efficiencies for dissolved solids average 45 and 2% for the respective Tantalus and Jaucas leachates. For the Jaucas leachate, the removals resulted in negative efficiencies for the first 2 wk. This may be attributed to salts which were in the beach sand and which may have been

TABLE 5. WEEKLY FLOW AVERAGES FOR INFLUENT AND LEACHATE, TANTALUS AND JAUCAS SERIES, 16 JULY-14 AUGUST 1978

		Week 1	Week 2	Week 3	Week 4	Mean*
Temperature (°C)	Infl.	23.2	23.7	23.0	23.4	23.4
	Leach. (T)†	23.1	23.5	22.9	23.2	23.2
	Leach. (J)‡	23.2	23.5	22.8	23.2	23.2
pH (units)	Infl	8.3	8.2	8.0	7.3	7.9
	Leach. (T)†	6.6	6.3	6.4	6.7	6.5
	Leach. (J)‡	8.2	8.2	8.3	7.8	8.1
Total Solids	Infl.	239	338	416	552	427
	Leach. (T)†	109 (54)	191 (43)	206 (39)	233 (58)	193 (55)
	Leach. (J)‡	233 (3)	266 (21)	250 (26)	347 (37)	296 (31)
Dissolved Solids	Infl.	214	195	243	362	287
	Leach. (T)†	105 (51)	165 (15)	178 (27)	181 (50)	259 (45)
	Leach. (J)‡	226 (-6)	248 (-27)	234 (1)	324 (10)	280 (2)
Suspended Solids	Infl.	25	143	173	191	140
	Leach. (T)†	4 (84)	26 (82)	28 (84)	52 (73)	34 (76)
	Leach. (J)‡	7 (72)	17 (88)	16 (91)	23 (88)	17 (88)
Volatile Suspended Solids	Infl.	22	139	166	178	132
	Leach. (T)†	3 (86)	25 (82)	26 (84)	50 (72)	32 (76)
	Leach. (J)‡	6 (73)	26 (88)	15 (91)	21 (88)	16 (88)
Fixed Suspended Solids	Infl.	2	4	7	13	8
	Leach. (T)†	1 (50)	1 (75)	1 (86)	2 (85)	2 (75)
	Leach. (J)‡	1 (50)	1 (75)	1 (86)	2 (85)	2 (75)
COD	Infl.	160	276	268	482	319
	Leach. (T)†	43 (73)	100 (64)	144 (46)	194 (60)	129 (60)
	Leach. (J)‡	37 (77)	146 (47)	126 (53)	126 (74)	112 (65)
BOD_5	Infl.	97	152	232	308	213
	Leach. (T)†	32 (67)	38 (75)	87 (63)	122 (60)	76 (64)
	Leach. (J)‡	32 (67)	69 (55)	84 (64)	95 (69)	75 (65)
TOC	Infl.	34	66	87	180	102
	Leach. (T)†	9 (74)	22 (67)	51 (41)	77 (57)	44 (57)
	Leach. (J)‡	19 (44)	40 (39)	45 (48)	41 (77)	37 (64)
Ammonia Nitrogen	Infl.	30.8	37.5	45.3	44.5	39.9
	Leach. (T)†	1.8 (94)	13.0 (65)	30.2 (33)	28.9 (35)	19.1 (52)
	Leach. (J)‡	11.4 (63)	30.7 (18)	31.2 (31)	27.2 (39)	25.6 (36)
Organic Nitrogen	Infl.	8.3	12.2	9.8	24.9	14.7
	Leach. (T)†	1.4 (83)	4.1 (66)	3.9 (60)	4.5 (82)	3.6 (76)
	Leach. (J)‡	2.9 (65)	3.1 (75)	3.5 (64)	3.1 (88)	3.1 (79)
Total Kjeldahl Nitrogen	Infl.	39.1	49.7	55.1	68.8	55.0
	Leach. (T)†	3.2 (92)	17.1 (66)	34.1 (38)	33.5 (51)	23.2 (58)
	Leach. (J)†	14.3 (63)	33.9 (32)	34.7 (37)	30.5 (56)	28.8 (48)
Nitrite + Nitrate Nitrogen§	Infl.	<0.04	<0.04	<0.04-0.15	<0.04-0.54	<0.04-0.54
	Leach. (T)†	<0.04-1.26	<0.04-1.22	<0.04	<0.04	<0.04-1.26
	Leach. (J)‡	<0.04-0.41	<0.04-0.97	<0.11-1.00	<0.10-0.63	<0.04-1.00
Total Nitrogen	Infl.	39.1	49.7	54.4	68.9	55.0
	Leach. (T)†	4.0 (90)	17.5 (65)	34.1 (38)	33.5 (51)	23.4 (57)
	Leach. (J)‡	14.4 (63)	34.4 (31)	35.1 (37)	30.5 (56)	29.2 (47)
Total Phosphorus	Infl.	5.3	7.1	7.6	13.3	8.9
	Leach. (T)†	0.2 (96)	0.5 (93)	0.6 (92)	0.7 (95)	0.5 (94)
	Leach. (J)‡	0.6 (89)	1.9 (73)	3.0 (61)	2.4 (82)	2.0 (78)
Fecal Streptococcus ($\times 10^4$/100 mℓ)	Infl.	33	76	16	47	46
	Leach. (T)†	0.8 (98)	5.4 (93)	2.4 (85)	5.0 (89)	3.8 (92)
	Leach. (J)‡	9.1 (72)	15 (80)	3.2 (80)	1.7 (96)	7.4 (84)
Fecal Coliform ($\times 10^6$/100 mℓ)	Infl.	90	77	130	73	90
	Leach. (T)†	5.3 (94)	12 (84)	19 (85)	10 (86)	12 (87)
	Leach. (J)‡	15 (83)	11 (86)	16 (88)	7.4 (90)	12 (87)
Total Coliform ($\times 10^6$/100 mℓ)	Infl.	160	117	230	230	180
	Leach. (T)†	10 (94)	16 (36)	47 (80)	46 (80)	30 (83)
	Leach. (J)‡	21 (87)	14 (88)	46 (80)	23 (90)	25 (86)

NOTE: All values in mg/ℓ unless indicated otherwise.
NOTE: Values in parentheses represent removal efficiencies in percent.
*Mean of entire sampling duration.

†Tantalus.
‡Jaucas.
§Weekly range of values.

eluted into the leachate in significant quantities during the early sampling periods. Elution into the leachate may have continued to a limited extent since dissolved solids removal remained very low for the duration of the sampling period. Suspended solids removal averaged 76 and 88% for the respective Tantalus and Jaucas waste water treatment lysimeters. Some distinct variations in the suspended solids concentrations with time were noted. These variations may reflect the intermittent occupancy of the houseguest in the E cottage. Changes in the flow pattern from the office in the D cottage due to meetings or social gatherings may have also contributed to the variations. The removals obtained for the volatile suspended solids were almost identical to the suspended solids removals. This might be expected as practically all of the suspended solids material was comprised of volatiles. Removals for the fixed suspended material ranged from 50 to 86% (weekly averages) with an overall average of 75% for both lysimeters. However, it should be noted that these removals are based on relatively low values (as in the Lahaina soil lysimeter). Averages for fixed suspended solids ranged from 2 to 13 mg/ℓ for the influent and from 1 and 2 mg/ℓ for the leachates. Slight changes in these values would reflect relatively large variations in the removal efficiencies.

All of the residue parameters revealed increased concentrations with time. In the Tantalus soil lysimeter, removal averages for suspended solids (as well as volatile suspended solids) remained fairly constant for most of the period with a moderate decrease during the last week. The trend for the total and dissolved solids, however, was one of decrease followed by an increase during the last week.

ORGANICS. The COD, BOD_5, and TOC in the influent averaged respectively 319, 213, and 102 mg/ℓ for the entire period. Removal efficiencies in the Tantalus soil lysimeter averaged 60, 64, and 57% for the respective COD, BOD_5, and TOC; removals in the Jaucas lysimeter averaged slightly higher—65, 65, and 64% for the same respective parameters. Based on the weekly data, the COD loading showed a moderate decrease between the second and third week, with a "leveling off" of the increase in influent loads during this same period. Again, these changes may be due to the variable occupancy of the cottage. However, the overall trend was still one of increasing concentrations in the organic loads. Removal efficiencies for the organic material followed a common trend in both complexes—a pattern of decreasing removals followed by an increase during the last quarter of sampling.

NITROGEN. As in the results of the Wahiawa and Lahaina lysimeters, the nitrogen content of both the Tantalus and Jaucas influent and leachates is almost completely in the form of total Kjeldahl nitrogen. Ammonia nitrogen was the primary constituent in the influent and in both leachates. The oxidizable nitrogen forms (nitrite and nitrate) again comprised only a small fraction of the total nitrogen content, although the values were slightly higher than previously observed in the Wahiawa and Lahaina soil lysimeters, with a maximum of 0.54 mg/ℓ in the leachate. For the Tantalus leachate, the nitrite and nitrate nitrogen levels reached a maximum value of 1.26 mg/ℓ early in the sampling period. After the second week, however, the values were consistently lower than 0.04 mg/ℓ. Nitrite and nitrate nitrogen concentrations in the Jaucas leachate ranged from less than 0.04 to 1.00 mg/ℓ. Unlike the Tantalus leachate, detectable levels of the oxidizable nitrogen forms were present in the Jaucas leachate for most of the sampling period. It appears that the lysimeter design using the stratified gravel and the lateral flow application was somewhat more conducive to the nitrification processes within the lysimeters since the maximum values of the nitrite and nitrate nitrogen in the Wahiawa and Lahaina leachates were respectively only 0.12 and 0.22 mg/ℓ. The nitrite and nitrate nitrogen levels detected in the Jaucas leachate were probably due to the more pervious nature of the sand material which may have induced a higher transfer of dissolved oxygen. This could not be confirmed, however, through the limited dissolved oxygen determinations since they all indicated that practically no oxygen was present in either the influent or the leachates. These results are still plausible as the observed nitrite and nitrate nitrogen levels in both leachates are still relatively low. It is possible that limited amounts of dissolved oxygen were available for nitrification—via the pore sapces between the gravel—but by the time the influent had percolated through the lysimeters, this dissolved oxygen had been completely consumed by nitrifying bacteria.

Removal efficiencies for the ammonia fractions averaged 52 and 36% for the respective Tantalus and Jaucas lysimeters. Organic nitrogen removals were higher and averaged 76 and 79% for the respective lysimeters. This characteristic of higher organic nitrogen removals was also noted in the previous two soil series lysimeters. Total nitrogen removals (essentially equal to the TKN removals) averaged 57 and 47% for the respective Tantalus soil and Jaucas lysimeters. The nitrogen removals followed the characteristic trend of decreased efficiencies followed by an increase in the last week of sampling. The other trend of increased loadings, especially for total nitrogen, with time was also observed.

TOTAL PHOSPHORUS. Influent values for total phosphorus ranged from 4.6 to 17.4 mg/ℓ, with an average of 8.9 mg/ℓ for the entire period. The weekly data are indicative of the trend of increasing phosphorous concentrations in the influent. Removal efficiencies in the Tantalus lysimeter remained fairly constant, averaging 94% for the entire period, with an average leachate value of 0.5 mg/ℓ. Removal in the Jaucas lysimeter seemed to decrease over the first 3 wk but later increased during the last week. The total phosphorus in the Jaucas leachate averaged 2.0 mg/ℓ which represented an overall removal of 78%. These relatively high removals compare favorably with the findings of Chu and Sherman (1952) on phosphate fixation studies. The results are again indicative of the high percentage of phosphorous removals attained in treatment studies involving Hawaiian soils.

BACTERIA. The influent values for all three bacteriological parameters were well within the ranges typical of domestic sewage. Fecal streptococcus levels were on the order of 10^5 per 100 mℓ while fecal coliform and total coliform both ranged from 10^7 to 10^8 per mℓ. A noticeable variation in the influent and leachates for all three parameters can be seen. These variations are only on the order of about 1 log and thus may be due to the normal fluctuations in the bacterial populations. The intermittent occupancy of the E cottage houseguest may have also contributed to the observed variation.

Removal efficiencies for fecal streptococcus, and fecal and total coliform in the Tantalus lysimeter averaged respectively 92, 87, and 83%. Removals in the Jaucas lysimeter averaged 84, 87, and 86% for the same respective parameters. These removals appear quite high on a percentage basis but actual reductions were only on the order of about 1 log. Thus, significant numbers of the bacteria were being passed through both lysimeters.

SOIL CLOGGING. The application scheme of lateral flow from the central or influent reservoir chamber was used in both the Tantalus and Jaucas lysimeters. As a result, the sustained water levels in the influent chamber could be used as an indicator of clogging in the soil compartments. An increase in the water level would be indicative of clogging in successive layers of the lysimeter. For the first 2 wk of the sampling period, the influent level remained fairly constant at the second row of distribution ports—the first row of ports were left stoppered. This represented a standing water height of about 0.36 m (14 in.) as measured from the bottom of the chamber. During the last half of the sampling duration, some clogging was evident as 0.15 to 0.20 m (6-8 in.) rises in the influent water were observed, with the water reaching the third row of distribution ports on several occasions. These increases were only intermittent, however, as the water level frequently returned to its original level (second row of ports).

Leachate outflows rates in both lysimeters were considerably higher than observed previously. Initial flow rates averaged about 3×10^{-5} and 5×10^{-5} m^3/s (0.52 and 0.79 gpm) for the respective Tantalus and Jaucas lysimeters. Flow reductions were observed during the last 2 wk with the final outflows averaging roughly 2×10^{-5} and 3×10^{-5} m^3/s (0.26 and 0.52 gpm) for the respective Tantalus and Jaucas leachates. The increased influent levels and the decreased leachate outflows both indicated that soil clogging had occurred to some degree. However, the flow reductions observed here were not as severe as the reductions experienced in the Wahiawa and Lahaina lysimeters (final flows of approximately 3×10^{-7} m^3/s [0.52 gal/hr]). Despite the relatively high leachate outflows, sample collection was not continued beyond mid-August as the E cottage resident anticipated an extended leave-of-absence beginning in the latter half of the month. Sampling was thus terminated to insure that sufficient time was available for the influent flow determinations before the cottage was vacated.

General Characteristics Among the Waste Water Treatment Lysimeters

INFLUENT CHARACTERISTICS. Almost all of the measured influent constituents showed considerable variation throughout each of the sampling periods. These variations were not expected as the two cottages were the only sources generating the influent flow. Besides the normal fluctuations in the waste water constituents, factors such as varying occupancy and the use of household cleaners or other chemicals could also cause noticeable variations in the day-to-day characteristics of the influent. Such variations would be less pronounced in the influent at a waste water treatment plant where the varying inputs from individual households are diluted or "averaged" into the total flow of the collection system.

Despite the observed fluctuations in the influent, a general trend of increased loadings with time was still discernable. In each lysimeter, the weekly data generally indicated increases in the constituent levels, particularly solids, organics, and nutrients. These increases were probably due to the accumulation of the solid and organic material within the central reservoir. A substantial amount of the solids material was held in the reservoir compartment due to the coarse screening effect of the distribution ports. Significant portions of this matter also settled out in the compartment due to sedimentation. In addition, the sludge material remained in the compartment for the duration of the sampling period. During periods of incoming flow, some mixing of all the accumulated material inevitably occurred, although the rubber tubing (over the PVC inlet pipe) minimized this effect to some degree.

Based on the overall averages, the general characteristics of the influents could be considered typical of the domestic waste waters in Hawai'i. Most of the averaged data fell within the constituent ranges as characterized by Young and Chan (1970) and Chun, Young, and Anderson (1972). The relative strengths of the waste water as reported in the literature placed the Wahiawa lysimeter influent in the weak to medium range while the influents for the Lahaina, Tantalus, and Jaucas lysimeters were in the medium to medium-strong ranges (Metcalf and Eddy 1972; Pound and Crites 1973*b*). Some typical characteristics of untreated domestic waste water are given in Appendix Table D.1. Although most of the influent values were within the normal ranges for domestic waste waters, strict comparisons between the typical literature values and the values obtained in this study would not be totally justified. The influent data for this study represents a relatively small and isolated waste water source while literature values are usually based on averages from large municipal flows.

One notable deviation from the typical literature characteristics was revealed in the TOC results obtained for each of the waste water treatment lysimeters. Metcalf and Eddy (1972) state that, normally, the TOC and BOD_5 of a waste water should be about equal. In this study the BOD_5 and COD results were within the expected ranges but the values for the TOC were consistently lower than the BOD_5. The organics data in Table 6 indicate that

TABLE 6. COMPARISON OF THE RANGE AND MEAN VALUES FOR THE WAHIAWA, LAHAINA, TANTALUS, AND JAUCAS SERIES, O'AHU, HAWAI'I, 1978

		WAHIAWA		LAHAINA		TANTALUS		JAUCAS	
		Range	Mean	Range	Mean	Range	Mean	Range	Mean
Temperature (°C)	Infl.	22.0-23.3	22.9	22.0-24.5	22.8	22.0-24.5	23.4	22.0-24.5	23.4
	Leach.	22.0-23.3	22.8	22.0-24.0	22.6	22.0-24.0	23.2	22.0-24.0	23.2
pH (units)	Infl.	7.1-8.6	7.6	7.6-8.7	8.4	6.9-8.7	7.9	6.9-8.7	7.9
	Leach.	7.1-7.7	7.4	6.4-7.9	7.4	5.8-7.0	6.5	7.6-8.4	8.1
Total Solids	Infl.	---	---	236-616	464	224-612	427	224-612	427
	Leach.	---	---	112-509	316 (32)	76-270	193 (55)	208-379	296 (31)
Dissolved Solids	Infl.	---	---	200-484	372	184-376	287	184-376	287
	Leach.	---	---	106-479	299 (20)	69-195	159 (45)	203-358	280 (2)
Suspended Solids	Infl.	---	---	36-132	92	21-248	140	21-248	140
	Leach.	---	---	6-30	16 (83)	2-79	34 (76)	5-42	17 (88)
Volatile Susp. Solids	Infl.	---	---	36-132	88	21-223	132	21-223	132
	Leach.	---	---	6-30	14 (84)	2-73	32 (76)	4-38	16 (88)
Fixed Susp. Solids	Infl.	---	---	0-12	4	0-25	8	0-25	8
	Leach.	---	---	0-12	3 (25)	0-6	2 (75)	0-5	2 (75)
COD	Infl.	170-289	198	47-569	370	114-517	319	114-517	319
	Leach.	69-192	107 (46)	31-352	182 (51)	8-239	129 (60)	16-188	112 (65)
BOD_5	Infl.	136-209	160	50-260	199	92-316	213	92-316	213
	Leach.	59-110	84 (48)	21-176	102 (49)	7-128	76 (64)	29-104	75 (65)
TOC	Infl.	65-155	91	24-153	99	23-202	102	23-202	102
	Leach.	31-72	45 (51)	14-93	59 (40)	5-92	44 (57)	7-60	37 (64)
Ammonia Nitrogen	Infl.	9.7-44.8	25.6	10.4-92.8	61.9	19.6-64.1	39.9	19.6-64.1	39.9
	Leach.	4.3-38.0	19.2 (25)	2.1-110.0	51.9 (16)	1.0-34.3	19.1 (52)	1.4-35.3	25.6 (36)
Organic Nitrogen	Infl.	3.3-34.4	10.0	1.8-25.8	12.5	6.2-45.9	14.7	6.2-45.9	14.7
	Leach.	1.0-8.8	3.1 (69)	1.8-5.0	3.8 (70)	0.8-7.8	3.6 (76)	2.0-4.9	3.1 (79)
Total Kjeldahl Nitrogen	Infl.	13.2-55.8	35.6	13.3-107.9	78.8	29.3-86.6	5.5	29.3-86.6	55.0
	Leach.	5.4-39.0	22.3 (37)	4.1-112.9	59.7 (24)	1.9-40.1	23.2 (58)	4.1-39.1	28.8 (48)
Nitrite + Nitrate Nitrogen	Infl.	<0.04-0.06	---	<0.04-0.10	---	<0.04-0.54	---	<0.04-0.54	---
	Leach.	<0.04-0.12	---	<0.04-0.22	---	<0.04-1.26	---	<0.04-1.00	---
Total Nitrogen	Infl.	13.3-55.8	35.6	13.4-105.0	78.8	29.3-86.8	55.0	29.3-86.8	55.0
	Leach.	5.5-39.0	22.3 (37)	1.0-112.9	59.2 (25)	1.9-40.1	23.4 (57)	4.4-40.1	29.2 (47)
Total Phosphorus	Infl.	2.1-7.0	4.5	5.1-26.5	14.2	4.6-17.4	8.9	4.6-17.4	8.9
	Leach.	0.2-0.6	0.3 (93)	0.3-1.0	0.5 (96)	0.1-1.2	0.5 (94)	0.5-4.8	2.0 (78)
Fecal Strep. (× 10^4/100 mℓ)	Infl.	0.30-1.8	1.3	1.0-75	37	1.2-200	46	1.2-200	46
	Leach.	0.20-0.51	0.4 (69)	0.2-24	8.3 (78)	0.2-12	3.8 (92)	0.2-29	7.4 (84)
Fecal Coliform (× 10^6/100 mℓ)	Infl.	6.4-48	29	0.8-250	81	7.0-310	90	7.0-310	90
	Leach.	2.4-9.1	4.6 (84)	0.11-25	9.4 (88)	0.8-32	12 (87)	0.15-42	12 (87)
Total Coliform (× 10^6/100 mℓ)	Infl.	10-64	40	17-460	210	11-470	180	11-470	180
	Leach.	3.2-5.1	4.3 (89)	6-180	39 (81)	0.8-96	30 (83)	2.0-94	25 (86)

NOTE: All values in mg/ℓ unless indicated otherwise.
NOTE: Values in parentheses represent removal efficiencies in percent.

the average TOC values are about 50% less than the corresponding BOD_5 results. These results may be part of the differences or variations characteristic of the particular isolated influent source used in this study. In addition, the results are still plausible as similar results have been obtained in studies involving the domestic waste waters of Hawai'i. Kumagai (1967), in characterizing the organic levels in both raw and treated sewage from several municipal STPs, produced TOC results which were 30 to 88% lower than the corresponding BOD_5 values. In the same study, samples from operating cesspools also showed a tendency for lower TOC levels by 16 to 40%. In a study by Griffith, Young, and Chun (1978), organic characterization of a municipal waste water source revealed TOC data 35 to 50% lower than the corresponding BOD_5 results. Based on these findings, the relatively low TOC results obtained in this study are consistent with the organic character of the domestic waste waters in Hawai'i.

Other deviations from the usual constituent values were the exceedingly high nitrogen and phosphorous values—in excess of 100 and 25 mg/ℓ, respectively—obtained from the Lahaina lysimeter influent. As discussed previously, these results have been attributed to the possible introduction of fertilizer material into the influent collection system. The increase in the number of occupants in the E cottage may also have been a contributing factor to the high loadings.

REMOVAL EFFICIENCIES. The overall removal efficiencies attained in all of the waste water treatment lysimeters were only fair to moderate. The lysimeters employing the lateral flow scheme, Tantalus and Jaucas, seemed to average slightly higher removals than the surface flow lysimeters, Wahiawa and Lahaina. Removal for total solids averaged 32, 55, and 31% for the respective Lahaina, Tantalus, and Jaucas series, while dissolved solids removal averaged 20, 45, and 2% for the same lysimeters. Organic removal for the Wahiawa and Lahaina series averaged respectively about 40 and 25%, and for the Tantalus and Jaucas series, approximately 60 and 50% respectively.

The bacteriological indicators in all of the lysimeters showed fairly high removals based on percentage values. However, significant numbers of bacteria passed through all of the lysimeters and actual reductions were generally on the order of 1 log.

These removal efficiencies are especially low in comparison to the results obtained in recycling and reuse studies of land treatment. Typically, these studies report about 70 to 90% removals for constituents such as organics, suspended solids, TKN, and phosphorus. Bacterial reductions are also significant in that negligible counts are usually reported in the percolate or "soil-treated" waters (Pound and Crites 1973*a*; McMichael and McKee 1966). One of the contributing factors to these relatively high removals has been the aerobic conditions generally maintained in these systems. These conditions are particularly conducive towards the biodegradation of the organic materials and also towards the nitrification of ammonia nitrogen to the nitrate forms The relatively anaerobic conditions in all of the tested lysimeters no doubt contributed to the low organic and ammonia removals. Similar results, with low organic removal in particular, have been reported by Koizumi, Burbank, and Lau (1966) and Kumagai (1967).

Perhaps the most significant factor for the high removals in the reported land treatment studies is the quality of the applied waste water. In most cases, domestic waste waters have been subjected to secondary treatment, which result in fairly low constituent levels, particularly for the organics, suspended solids, and TKN. Bacterial levels in the waste waters are also quite low due to the conventional disinfection practices employed in waste water treatment. Some typical characteristics of treated effluent are provided in Appendix Table D.2. Investigations by Lau et al. (1975) and Chang (1976) on the reuse of sewage effluent for irrigation revealed negligible amounts of organics, TKN, phosphorus, and bacteria in the percolate waters. In both cases, the applied effluents were characterized by relatively low amounts of BOD_5 and TKN values. The excellent removals reported in these two studies were also aided by nutrient uptake of the irrigated vegetation. In studies of rapid infiltration basins by Bouwer, Lance, and Riggs (1974) and McMichael and McKee (1966), there was little or no opportunity for vegetal assimilation of nutrient material. However, high removal were again obtained with highly treated secondary effluents.

In contrast to the land treatment systems, the designed lysimeters in this study were all loaded with an untreated waste water which was generally typical of raw domestic sewage. Most of the constituent levels were thus considerably higher than those of the other investigations. Thus, the soil lysimeters were probably excessively loaded resulting in the moderate overall removals. In a discussion on organic loading rates for land treatment, Pound and Crites (1973*a*) suggested a maximum rate of about 2×10^{-7} kg/m^2/s

(164 lb/acre/day) for BOD_5 loadings. In the Wahiawa lysimeter the average influent BOD_5 was approximately 160 mg/ℓ. Based on the average daily flow of 3.2×10^{-6} m^3/s (72 gpd) and a surface area of 0.31 m^2 (3.3 ft^2) the BOD_5 loading on the lysimeter was nearly 1.65×10^{-6} $kg/m^2/s$ (1270 lb/acre/day). For nitrogen loadings, the irrigation study by Lau et al. (1975) reported a value of 0.071 kg/m^2 (634 lb/acre)—including fertilizer—over an 18-mo period. This translates into an average figure of approximately 1.56×10^{-9} $kg/m^2/s$ (1.2 lb/acre/day). In high rate infiltration studies, Bouwer, Lance, and Riggs (1974) reported a loading of about 8.55×10^{-8} $kg/m^2/s$ (66 lb/acre/day). The applied nitrogen in both of these systems was primarily in the ammonia and organic nitrogen forms (TKN). For the Wahiawa lysimeter, TKN averaged 35.6 mg/ℓ and resulted in a loading of 3.65×10^{-7} $kg/m^2/s$ (282 lb/acre/day). Based on these figures, both the organic and nitrogen loadings in the Wahiawa lysimeter were at least five to eight times the loadings cited in the literature. The loadings were compared with the Wahiawa influent because it was the weakest influent encountered among all the lysimeters. The higher constituent levels, and also higher flows, of the remaining lysimeters would indicate even greater influent loadings. The comparison figures should not be considered as exacting values as both the constituent levels and the influent flows (in the study) showed fair amounts of variation throughout the sampling period. However, the values are indicative of the excessive loadings placed on all of the lysimeters.

It should be noted that the application surface for the Tantalus and Jaucas lysimeters was the lateral soil-water interface in the compartments. However, if the maximum height of influent water (about 0.51 m [20 in.]) denotes the upper boundary of the soil-water interface, the area of the application surface is the same as in the Wahiawa and Lahaina lysimeters (0.51 × 0.61 m [20 × 24 in.] or about 0.31 m^2 [3.3 ft^2]). Actual loading figures for the Tantalus and Jaucas lysimeters would be difficult to calculate due to changing water levels which would vary the loading per unit area. In addition, both lysimeters were simultaneously run, thus splitting the influent flow by about one-half for each lysimeter (actual flow distribution would be closer to 60% through sand and 40% through soil based on initial leachate outflows). Despite the lowered flows through each compartment, the constituent levels (Table 6) still indicate extremely high loadings for both soils.

The high loading conditions probably overtaxed the removal mechanisms in all of the designed lysimeters resulting in the moderate reductions of organics, nitrogen, dissolved solids, and bacteria. The primary mechanisms for these particular constituents were essentially physical filtering or straining and adsorption-precipitation reactors (including ion exchange and Van der Waal's forces). Physical straining at the soil-water interface would have accounted for the removal of solid organics, organic nitrogen, and also bacteria. Adsorption-precipitation reactions were probably responsible for the removal of dissolved matter (solids and organics), ammonia nitrogen (primarily in the ammonia ion form), and also bacteria to some degree. For the ammonia, removals may have been accomplished through adsorption by clays and organic colloids, fixation by organic fraction (forming chemical complexes resistant to leaching and decomposition), incorporation into microbial cell tissue, and volatilization to ammonia gas as described by Lance (1972). With the exception of the Jaucas sand, all of the soils utilized are characterized by a fairly high clay and organic content (Ahuja and El-Swaify 1975; Young, Lau, and Burbank 1967). The other mechanisms, such as biological degradation of organics and nitrification, were severely limited by the anaerobic conditions observed in all of the lysimeters. In the Wahiawa and Lahaina soil lysimeters, the high loadings caused fairly rapid clogging with ponding of the influent water over the soil surfaces. The anaerobic conditions, which developed as well as the increases in the constituent level, led progressively to reduced organic removals. The reduced removals may be also attributed to the equilibrium condition in the ion exchange phenomenon. The exchange mechanism would be effective only until an equilibrium between the exchangeable ions in the water and the ions in the soil matrix has been reached. Subsequently, the ions would simply pass through the exchange medium (McGauhey and Krone 1967). The high loads probably accelerated the occurrence of this equilibrium condition in the Wahiawa and Lahaina soil lysimeters. As a result, ammonia nitrogen and the dissolved constituents showed a decreasing trend in removal efficiencies which accompanied the increased loadings.

In the Tantalus and Jaucas lysimeters, decreased removals were also observed with increased loadings. However, most of the removal efficiencies also revealed an increase during the latter part of the operation. The decreases were probably due to the same factors as in the Wahiawa and Lahaina lysimeters. The increases in removal efficiencies may have been the result of the lateral flow design of the Tantalus and Jaucas lysimeters. As clogging occurred in the bottom layers of the lysimeters, the influent waste water level rose. These higher levels would have allowed contact with relatively "fresh" or previously unloaded portions of the soil lysimeter, thus providing additional opportunities for ion exchange or other adsorption reactions. This may account for the increase in removal efficiencies noted for dissolved solids, organics (in dissolved forms), and ammonia nitrogen.

Bacterial removals did not appear to follow any discernable trends since actual reductions were quite poor in all of the lysimeters. In all probability, the poor removals were caused by the high loadings in the influent waters, as bacteria levels were on the order of 10^7 or 10^8/100 mℓ (fecal and total coliform). The low total coliform removals could also be attributed to the presence of coliform bacteria naturally present in the soil which had leached into the percolate waters.

The Tantalus and Jaucas lysimeters averaged higher removal efficiencies for ammonia nitrogen and organics. In addition, the Tantalus lysimeter resulted in higher efficiencies for dissolved solids. One of the primary factors for higher removals in the Tantalus lysimeter would be the cation exchange potential of the soil. Kanehiro and Chang (1956) characterized the cation exchange potential of the Wahiawa and Lahaina soils as ranging from about 12 to 20 me/100 g. For the soils which are similar to the Tantalus soil in classification (Latosolic Brown Forest soils), the range is between 40 and 60 me/100 g. This higher cation exchange capacity would account for the higher removal in the dissolved constituents, solids and organics, and also the ammonia, in ammonium ion form.

In the Jaucas lysimeter, the higher ammonia removals may have been due to volatilization of ammonia to ammonia gas under alkaline conditions as described by Lance (1972). The sand was quite alkaline, with a measured 8.7 pH. The higher organics removal was possibly the result of biodegradation of the organic material. Although the dissolved oxygen determinations showed little or no oxygen present, the increase in nitrite and nitrate nitrogen indicates that some oxygen might have been available. This oxygen may have been used for limited biological stabilization of the organic matter.

The higher removals attained in these two lysimeters may also be due to the simultaneous operation of the lysimeters which split the influent flow by a factor of about one-half for each lysimeter. Even with the relatively high removal efficiencies for the Tantalus and Jaucas lysimeters, the overall removals for these particular constituents (organics, dissolved solids, ammonia, and bacteria) were quite low for all of the lysimeters.

The only constituents for which high removal efficiencies were attained were suspended solids (including volatile suspended solids) and total phosphorus. The overall average for suspended solids removal ranged from roughly 75 to 90% for all of the lysimeters, excluding the Wahiawa lysimeter. Total phosphorous removals exceeded 90% for the Wahiawa, Lahaina, and Tantalus soils. Considerable phosphorous removal was also attained in the Jaucas lysimeter as an efficiency of 78% was averaged.

The removal of suspended solids was caused by the physical straining action of the soil media in all of the lysimeters. Even with the increased loadings, sharp decreases in removal efficiencies were not observed. Decreases would not have been expected as the accumulation of solid material on the soil surface would have aided the filtering action of the entire lysimeter. Slight reductions in the removal efficiencies were noted, however, in the Tantalus and Jaucas lysimeters during the latter period of sampling. This may have been due to the rising influent waste water level which reached the previously unloaded, or less frequently loaded, portions of the soil mass. These sections of the two lysimeters would have contained less accumulated material to aid in the infiltration process.

The phosphorous removals were not unexpected in light of the similar results obtained in various studies utilizing Hawaiian soils. The investigation by Chu and Sherman (1952) in particular, describes the high affinity of Hawaiian soils for phosphate fixation due to high iron and aluminum oxides content. The acid Hawaiian soils were found to be expecially conducive for phosphate fixation through anionic exchange of the iron and aluminum oxides. In this study, the Wahiawa, Lahaina, and Tantalus soils all indicated acid pH values. Since the Jaucas sand was quite alkaline (8.7 pH), phosphorous removals were probably due to the formation of calcium phosphate precipitates, as described by Bouwer, Lance, and Riggs (1974). The beach sands of Hawai'i are predominantly of calcium carbonate material (coral and limestone) and would probably form tri-calcium phosphate under alkaline conditions.* Chu and Sherman (1952) also reported on the affinity of phosphate fixation by chemical precipitation with calcium ions in the alkaline

*P.C. Ekern: personal communication (1977).

soils of Hawai'i.

SOIL CLOGGING. To a limited extent, soil clogging was observed in all of the waste water treatment lysimeters. The most severe clogging occurred in the Wahiawa and Lahaina lysimeters, which employed top surface application schemes. This "clogged" condition was characterized by sustained ponding of the influent water over the lysimeter soils and also by a marked reduction in the leachate outflow rates (from approximately 1.6×10^{-4} m^3/s [0.26 gpm] to less than 2.7×10^{-6} m^3/s [0.26 gal/hr]). In the Tantalus and Jaucas lysimeters which employed a lateral flow application scheme, at least partial clogging was evidenced by the rising influent levels in the central reservoir and by the decrease in leachate flow rates (from about 3.3×10^{-4} m^3/s [0.52 gpm] to 1.6×10^{-4} m^3/s in the Tantalus lysimeter and from 4.9×10^{-4} m^3/s [0.77 gpm] to 3.3×10^{-4} m^3/s in the Jaucas lysimeter).

It should be noted that the term "clogging" has been used in this study to describe the conditions of markedly reduced flows through the soil lysimeters. These conditions have been solely characterized on the physical observations of influent ponding, decreased leachate flow rates, and organic slime layers (visible in the Wahiawa lysimeter). The clogging phenomena could have been better characterized if the physical observations were supplemented with more extensive dissolved oxygen measurements and also with monitoring of oxidation-reduction potentials and sulfides generation. Although not included in this particular study, these biochemical parameters have been incorporated in related studies by Kumagai (1967) and McGauhey and Krone (1967).

All of the waste water treatment lysimeters experienced reductions in the leachate outflow rates, but none were operated for a sufficient length of time to reach a zero or no-flow condition. Both the Wahiawa and Lahaina soil lysimeters experienced the most severe leachate reductions. When the leachate outflow of these lysimeters decreased to less than 2.7×10^{-6} m^3/s (0.26 gal/hr), sampling was terminated. Based on the surface area of each lysimeter the 2.7×10^{-6} m^3/s value translates to approximately 8.8×10^{-7} m^3/s (3 in./day), which still represents a fair amount of water passing through the unit. This value could also represent the maximum water intake rate of the lysimeters under a steady-state condition, i.e., sustained ponding. However, the influent flow to the unit ranged from 3.2 to 5.0×10^{-6} m^3/s (72-115 gpd). These values would be equivalent to a range of 1.0 to 1.6×10^{-5} m/s (35-56 in./day) for the influent application rates. It is recognized that these values are based on the average flows to the unit and that the actual loadings are intermittent rather than continuous. In addition, since the units were covered to prevent rainfall from entering, a natural source of dilution was lost, which would not be the case for a prototype unit. However, it was still apparent that when sampling was terminated, the lysimeters were severely overloaded for both hydraulic and constituent loadings.

If more time had been allotted to the operation of each lysimeter, it is highly probable that the zero or no-flow leachate condition would eventually have been reached. It is also probable that, in general, reduced treatment efficiencies would also become manifest, as indicated by the observed trends in the data.

The no-flow condition in the lysimeters would necessitate some type of rehabilitation to restore the water intake rates and to improve treatment efficiency. Chemical treatment or natural "resting" of the soil lysimeter or a combination of both could be utilized to regenerate the infiltrative capacity of the soil. Resting of the lysimeters could be accomplished by using dual or multiple treatment units. This would permit a schedule of alternate loadings for the units, by loading one or more while resting the remaining units, and thus permit the natural biodegradation of the accumulated waste materials to proceed under aerobic conditions. This would help restore both the infiltrative capacity and the treatment capabilities of the soil lysimeters.

SUMMARY AND CONCLUSIONS

1. Based on the overall averages, the influent applied to the waste water treatment lysimeters could be considered typical of untreated domestic waste water.
2. Although the influent constituent levels in all of the lysimeters showed fair amounts of variation, an increasing concentration trend was still discernable. This increasing trend seemed to coindide with a trend of decreased removal efficiencies.
3. On the whole, the overall averages indicate that only moderate removals were attained, particularly for dissolved solids, organics, ammonia nitrogen, and bacteria. The only constituents which were effectively

removed were suspended solids and phosphorus. The moderate removals were probably the result of high constituent loadings (per unit area) and anaerobic conditions within all of the lysimeters. A primary factor for the high loadings was the relatively limited surface area afforded by each individual lysimeter (maximum of 0.31 m^2 [3.3 ft^2]) and the organic loading rates that were at least eight times higher than the maximum recommended limit for continental U.S. conditions (Pounds and Crites 1973*a*). The decision to run individually each lysimeter resulted in a four-fold increase in the organic loading and probably contributed significantly to the subsequent low removals.

4. It is recognized that direct comparisons between the individual lysimeters are difficult to assess because of the multiple variations among the flows, loadings, soil media, and application schemes. However, based on the overall removal efficiencies, the soil lysimeters employing the lateral flow application (Tantalus and Jaucas series) attained better constituent removals for dissolved solids, organics, ammonia, and organic nitrogen. The Tantalus lysimeter achieved higher removals for the ammonia nitrogen and dissolved solids constituents while removals for the organics and organic nitrogen were slightly higher in the Jaucas lysimeter. In addition, the clogging problem was not as extensive in these two lysimeters as was experienced in the Wahiawa and Lahaina units. None of the waste water treatment lysimeters, however, were operated on the no-flow condition for the leachates.
5. As tested, the lysimeters produced only moderate treatability to raw domestic sewage, probably a direct result of operating only one or two compartments instead of all four. Any further investigations with this particular unit should consider utilizing simultaneously all four compartments in a lateral flow application scheme and/or reducing the organic application rate. Other possibilities include the design of either larger or more numerous compartments, or a combination of both, to increase the usable surface area and thus reduce the loading (per unit area) on the lysimeters. Consideration should also be given to the use of multiple units which would permit loading and resting of the lysimeters on an alternating basis.

ACKNOWLEDGMENTS

The faculty and staff of the University of Hawaii Water Resources Research Center, The Department of Civil Engineering, and Harold L. Lyon Arboretum are acknowledged for their assistance. Special recognition is extended to Mr. Robert T. Hirano, Assistant Researcher, Harold L. Lyon Arboretum; Mr. Andrew H. Oshita, Laboratory Technician, Department of Civil Engineering; Mr. Henry K. Gee, Research Associate, Water Resources Research Center; and Dr. Paul C. Ekern, Professor of Soils, Department of Agronomy and Soil Science, and Hydrologist, Water Resources Research Center, University of Hawaii at Manoa.

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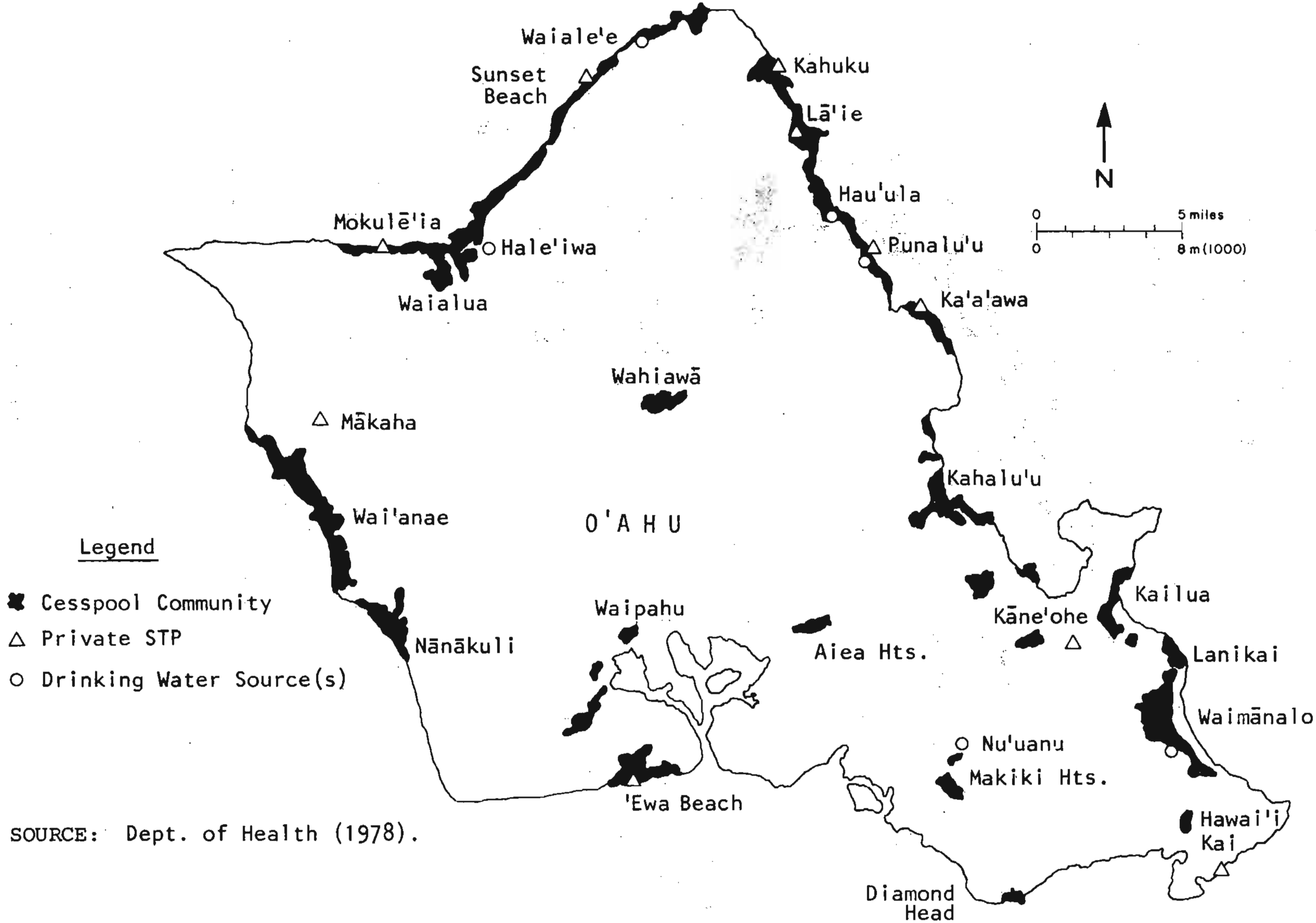
APPENDICES

FIGURES

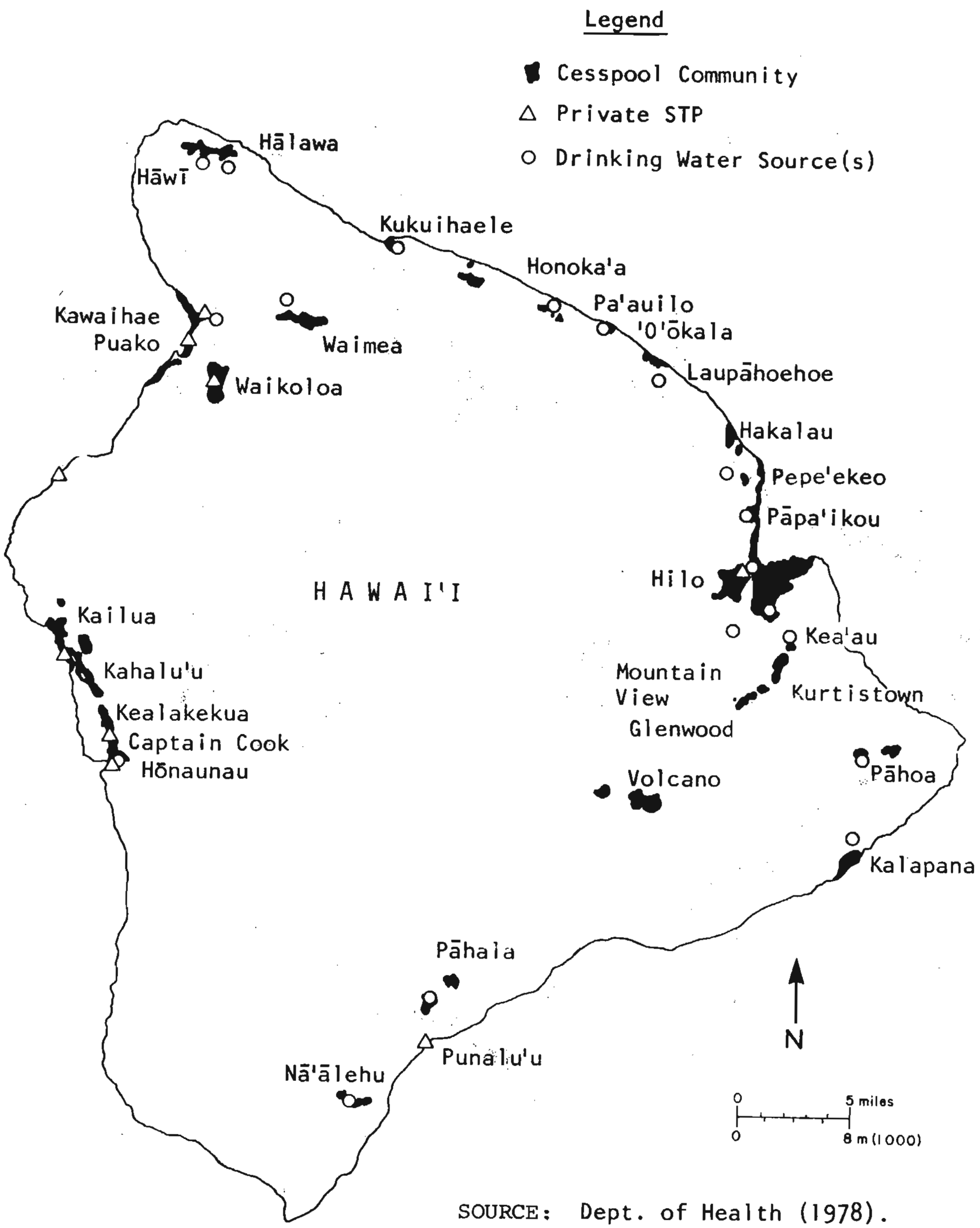
TABLES

APPENDIX A. MAPS OF CESSPOOL DISTRIBUTION



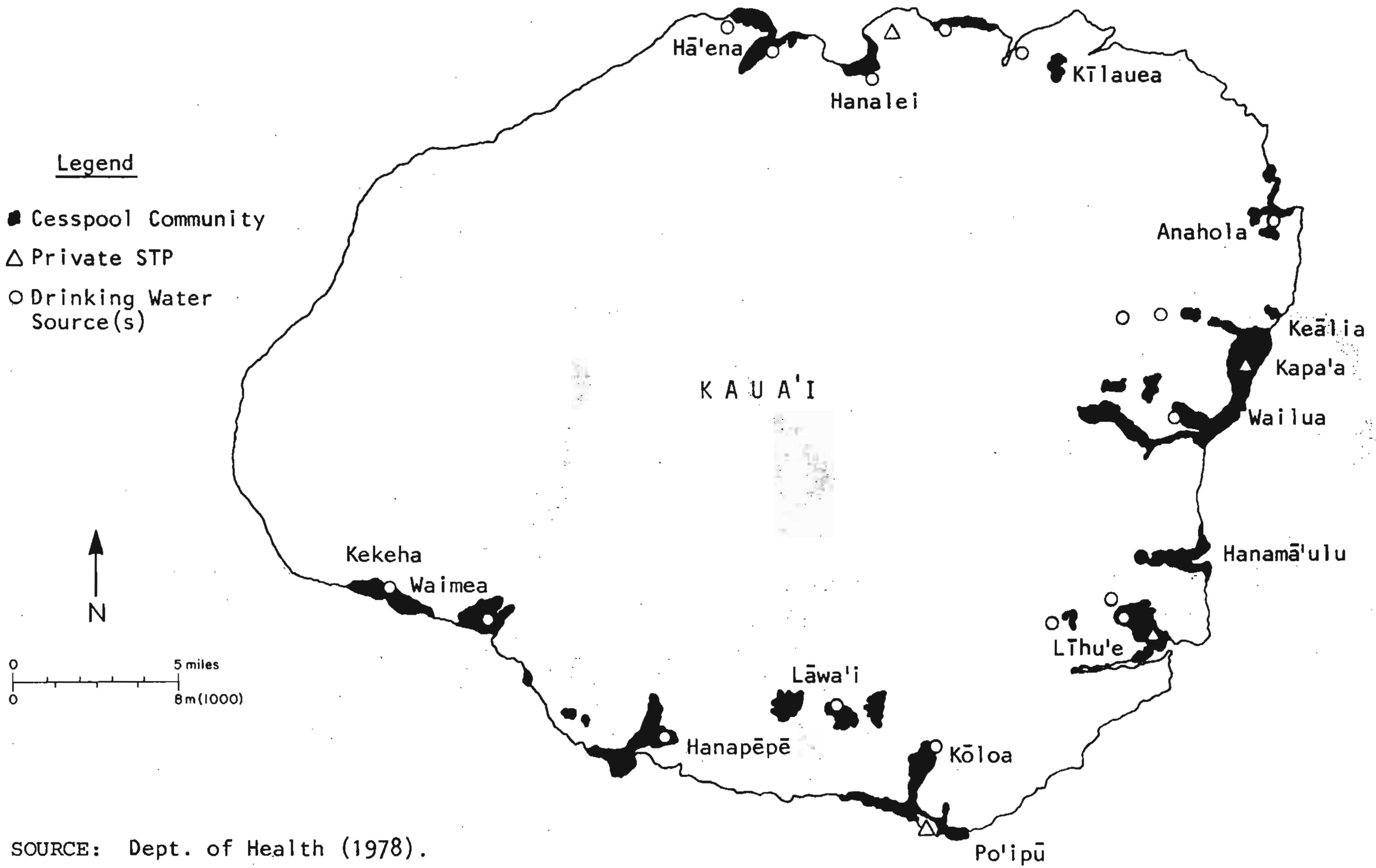
SOURCE: Dept. of Health (1978).

Appendix Figure A.1. Map of cesspool distribution, O'ahu Island, Hawai'i



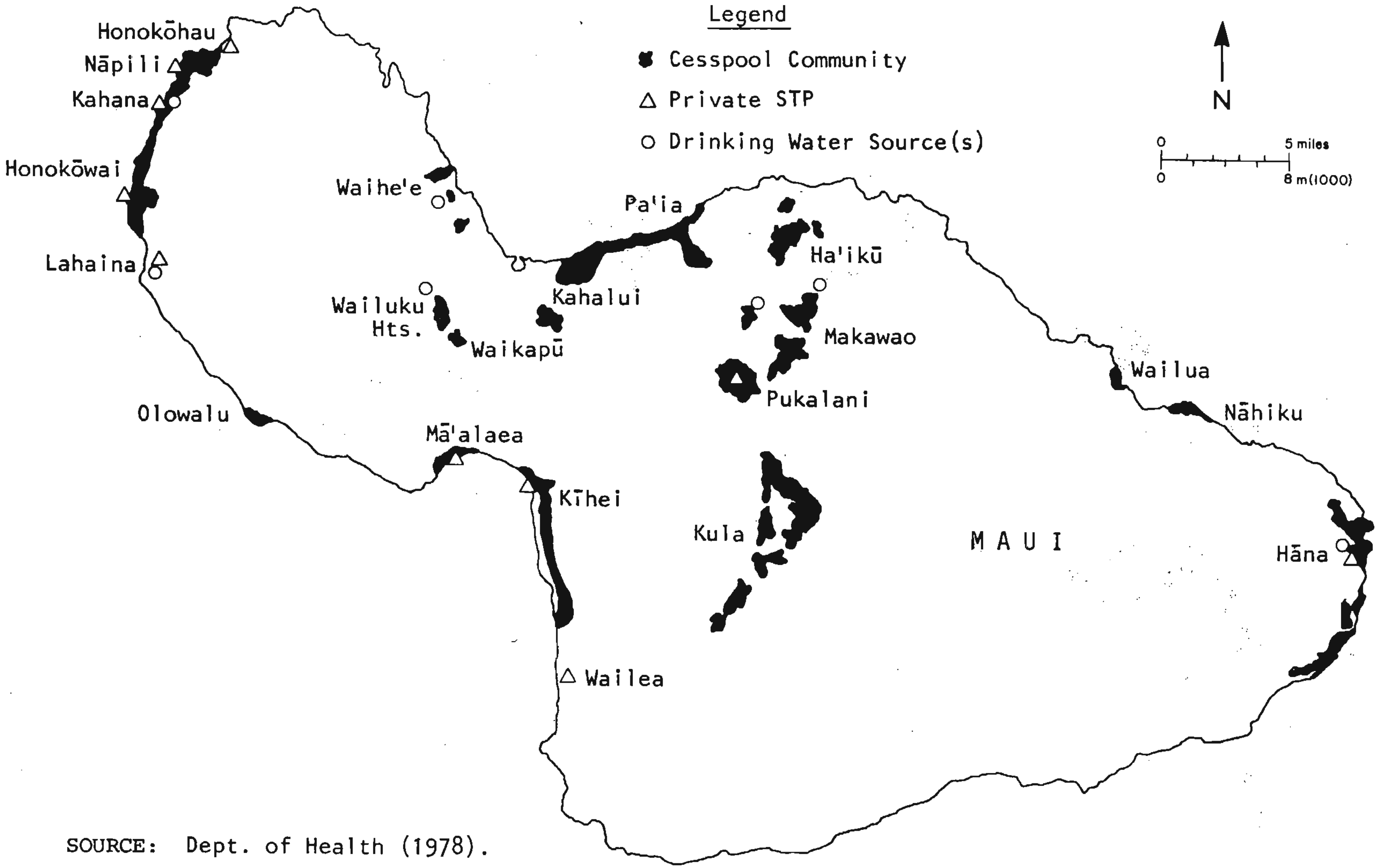
SOURCE: Dept. of Health (1978).

Appendix Figure A.2. Map of cesspool distribution, Hawai'i Island



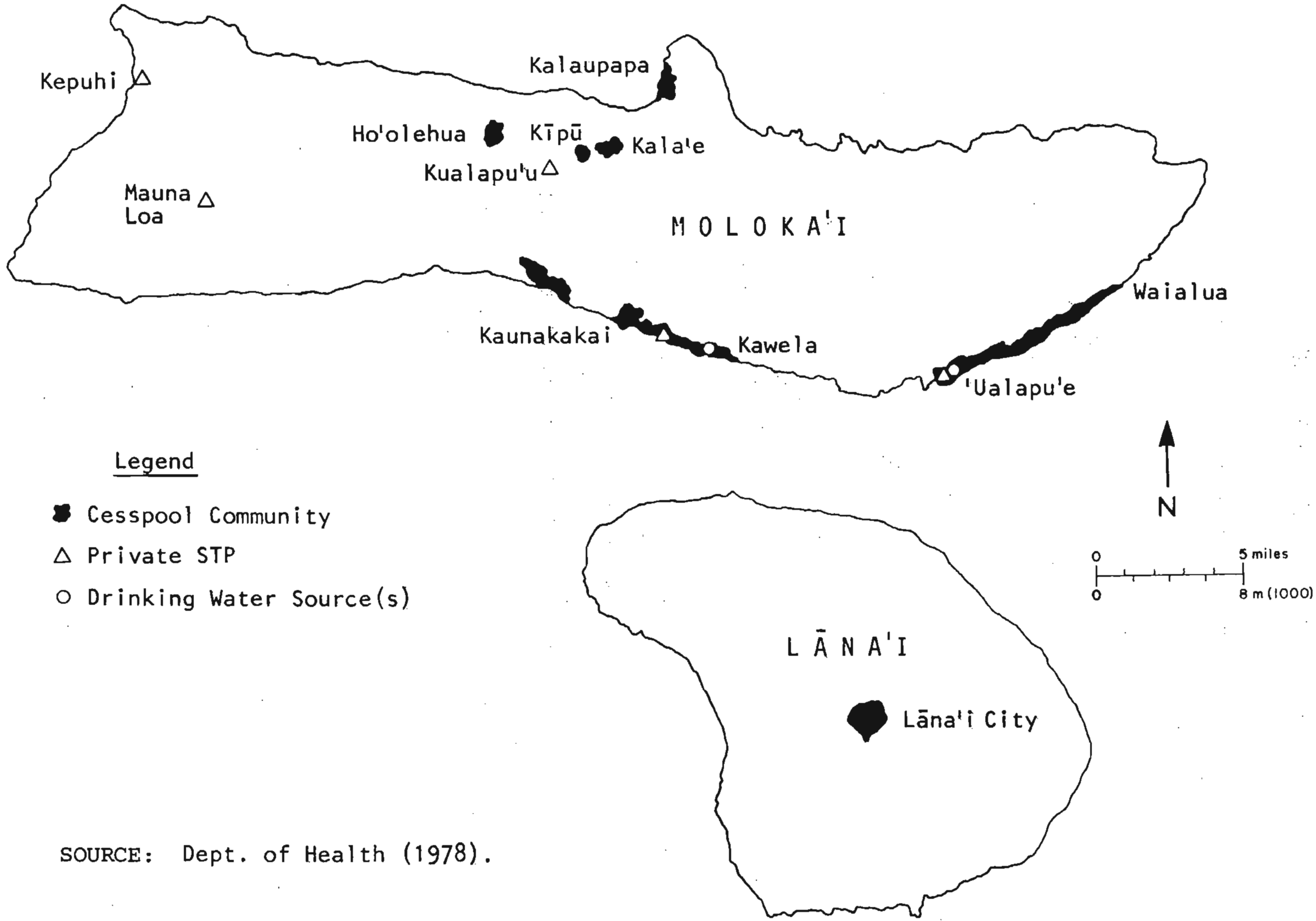
SOURCE: Dept. of Health (1978).

Appendix Figure A.3. Map of cesspool distribution, Kaua'i Island, Hawai'i



SOURCE: Dept. of Health (1978).

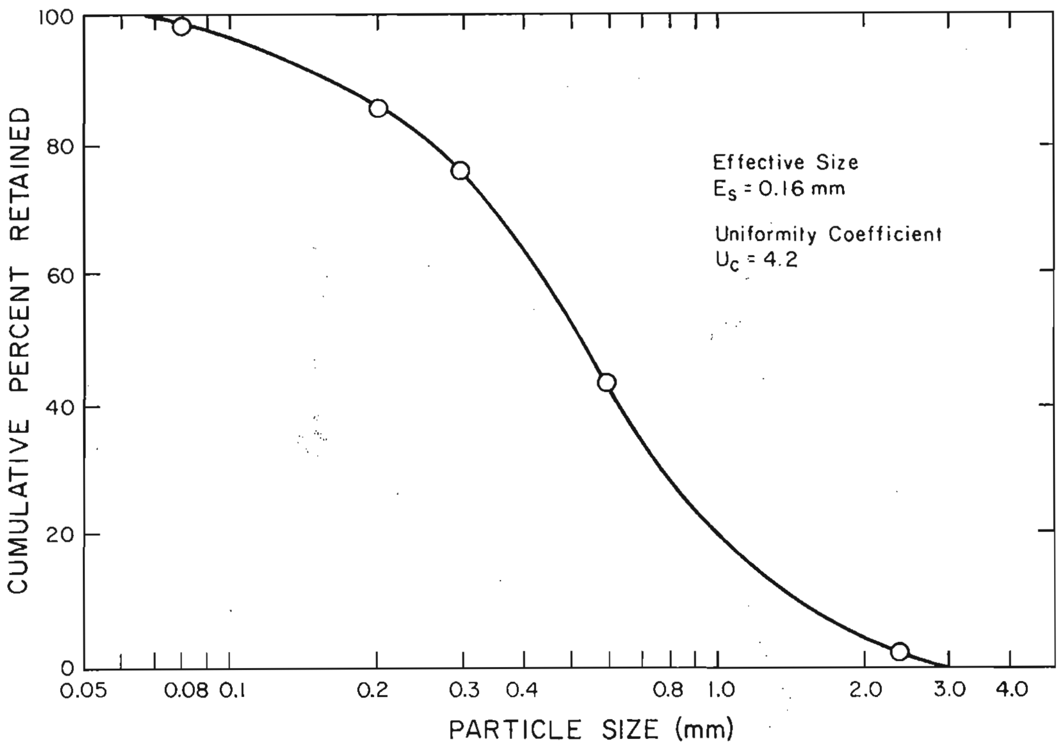
Appendix Figure A.4. Map of cesspool distribution, Maui Island, Hawai'i



SOURCE: Dept. of Health (1978).

Appendix Figure A.5. Map of cesspool distribution, Moloka'i and Lāna'i Islands, Hawai'i

APPENDIX B. SOIL DESCRIPTIONS



Appendix Figure B.1. Gradation curve for beach sand

APPENDIX TABLE B.1. CHARACTERIZATION OF SOIL pH FROM VARIOUS STUDIES

Soil Series	pH		
	(1)	(2)	(3)
Wahiawa	5.0-6.5	5.6-7.3	6.3
Lahaina	5.5-6.5	5.6-6.5	5.9
Tantalus	5.5-6.0	6.1-7.3	5.5
Jaucas	-------	7.9-8.4	8.7

(1) USDA (1955).
(2) Foote et al. (1972).
(3) This study.

APPENDIX TABLE B.2. CHARACTERIZATION OF CLAY AND ORGANIC CONTENTS

Soil Series	Clay	Organic	Clay	Organic
	(%)			
Wahiawa (1)	52	3.1	-----	---
Lahaina (1)	47	4.1	-----	---
Tantalus (2)	--	---	40-60	5-8

(1) Young, Lau, and Burbank (1967).
(2) Ahuja and El-Swaify (1975).

APPENDIX TABLE B.3. CHARACTERIZATION OF SOIL PERMEABILITY FROM VARIOUS STUDIES

Soil Series	Permeability (in./hr)			
	(1)	(2)	(3)	(4)
Wahiawa	2.0 - 6.3	4.3	-------	----
Lahaina	0.63- 2.0	4.3	-------	----
Tantalus	2.0 - 6.3	---	2.0-3.9	----
Jaucas	6.3 -20.0	---	-------	10.2

NOTE: In./hr × (7.05×10^{-6}) = m/s.
(1) Foote et al. (1972).
(2) Young, Lau, and Burbank (1967)
(3) Ahuja and El-Swaify (1975).
(4) Johnson Division (1975).

APPENDIX C. TABULATED DATA

APPENDIX TABLE C.1. TEMPERATURE AND pH, WAHIAWA LYSIMETER, O'AHU, HAWAI'I

1978	TEMPERATURE (°C)		pH	
	Infl.	Leach.	Infl.	Leach.
Feb.*				
2	22.1	22.0	7.1	7.1
4	23.0	23.0	7.6	7.3
6	23.3	23.2	7.4	7.2
7	22.8	22.8	7.2	7.1
9	22.0	22.0	7.3	7.4
10	23.0	23.0	7.2	7.1
13	23.0	23.0	7.3	7.3
14	24.2	24.1	7.2	7.1
15	23.5	23.4	7.3	7.3
Apr.				
6	23.2	23.2	7.1	7.1
8	23.3	23.3	7.3	7.1
10	22.8	22.7	7.2	7.2
13	22.0	22.0	7.2	7.3
15	23.0	22.9	7.4	7.3
17	23.3	23.2	7.7	7.6
19	22.6	22.6	8.6	7.7
20	22.8	22.7	8.2	7.6

*Office in D cottage single source of influent.

APPENDIX TABLE C.2. ORGANICS DATA, WAHIAWA LYSIMETER, O'AHU, HAWAI'I, 1978

1978	COD		BOD_5		TOC	
	Infl.	Leach.	Infl.	Leach.	Infl.	Leach.
	(mg/ℓ)					
Feb.*						
2	58	4	48	4	--	--
4	31	6	21	2	--	--
6	46	2	--	-	--	--
7	21	7	--	-	--	--
9	48	2	--	-	--	--
10	79	11	39	7	--	--
13	124	14	62	10	--	--
14	130	16	--	--	--	--
15	140	16	71	11	--	--
Apr.						
6	170	69	136	59	65	31
8	179	78	140	61	74	43
10	175	74	---	--	70	37
13	170	75	---	--	70	41
15	209	108	162	89	102	43
17	289	192	209	110	155	72
19	220	139	---	---	110	55
20	172	118	155	101	79	35

*Office in D cottage single source of influent.

APPENDIX TABLE C.3. NITROGEN AND PHOSPHORUS DATA, WAHIAWA LYSIMETER, O'AHU, HAWAI'I, 1978

1978	AMMONIA N Infl.	AMMONIA N Leach.	ORGANIC N Infl.	ORGANIC N Leach.	TOTAL KJELDAHL N Infl.	TOTAL KJELDAHL N Leach.	$NO_2 + NO_3$ N Infl.	$NO_2 + NO_3$ N Leach.	TOTAL N Infl.	TOTAL N Leach.	TOTAL P Infl.	TOTAL P Leach.
	(mg/ℓ)											
Feb.*												
2	0.4	0.2	1.6	1.1	2.0	1.3	----	----	----	---	1.3	0.1
4	10.4	0.0	5.3	0.1	15.7	0.1	----	----	----	---	2.5	0.1
6	1.4	0.0	12.5	0.1	13.9	0.1	----	----	----	---	2.4	0.2
7	2.4	1.3	17.6	5.5	20.0	6.8	----	----	----	---	3.8	0.4
9	10.6	1.2	3.0	0.8	13.6	2.0	----	----	----	---	2.7	0.4
10	6.2	2.3	4.9	1.0	11.1	3.3	----	----	----	---	3.0	0.2
13	3.9	2.2	7.9	0.6	11.8	2.8	----	----	----	---	3.0	0.2
14	1.1	2.4	4.0	0.7	5.1	3.1	----	----	----	---	1.8	0.1
15	1.5	2.5	3.0	0.8	4.5	3.3	----	----	----	---	1.9	0.1
Apr.												
6	9.7	4.3	4.7	1.1	14.4	5.4	0.06	0.12	14.5	5.5	2.1	0.2
8	9.9	5.6	3.3	1.2	13.2	6.8	0.06	0.10	13.3	6.9	2.4	0.2
10	10.6	6.4	5.4	1.8	16.0	8.2	<0.04	0.08	16.0	8.3	3.0	0.2
13	15.1	13.8	34.4	8.8	49.5	22.6	<0.04	<0.04	49.5	22.6	5.5	0.3
15	36.4	19.6	8.7	3.6	45.1	23.2	<0.04	<0.04	45.1	23.2	5.5	0.3
17	44.8	34.6	11.0	4.4	55.8	39.0	<0.04	<0.04	55.8	39.0	6.2	0.6
19	44.5	38.0	8.9	1.0	53.4	39.0	<0.04	<0.04	53.5	39.0	7.0	0.4
20	33.9	31.5	3.5	2.7	37.2	34.2	<0.04	<0.04	37.2	34.2	4.0	0.3

NOTE: Infl. = Influent,
Leach. = Leachate.

*Office in D cottage single source of influent.

APPENDIX TABLE C.4. BACTERIOLOGICAL DATA, WAHIAWA LYSIMETER, O'AHU, HAWAI'I, 1978

1978	FECAL STREP. Infl.	FECAL STREP. Leach.	FECAL COLIFORM Infl.	FECAL COLIFORM Leach.	TOTAL COLIFORM Infl.	TOTAL COLIFORM Leach.
	(mg/ℓ)					
	($\times 10^2$)		($\times 10^3$)		($\times 10^3$)	
Feb.*						
2	25	1.0	37	0.02	200	0.30
4	11	1.5	26	0.02	180	0.39
6	17	1.5	19	0.06	22	0.29
9	32	3.0	900	40	1000	73
10	67	7.8	1500	6.9	2400	81
13	35	4.0	300	32	500	42
14	10	1.4	40	12	50	8
15	10	1.2	30	11	40	6
	($\times 10^3$)		($\times 10^6$)		($\times 10^6$)	
Apr.						
6	14	4.2	28	3.7	32	4.5
8	15	4.3	28	3.8	35	4.3
10	14	4.1	30	4.2	41	5.1
13	18	5.0	48	4.8	63	5.0
15	17	5.1	43	6.2	64	4.6
17	16	4.9	39	9.1	61	4.0
19	5.2	2.0	9.7	2.9	10	3.2
20	3.0	2.0	6.4	2.4	12	3.8

*Office in D cottage single source of influent.

APPENDIX TABLE C.5. TEMPERATURE AND pH DATA, LAHAINA LYSIMETER, O'AHU, HAWAI'I

1978	TEMPERATURE (°C) Influent	TEMPERATURE (°C) Leachate	pH Influent	pH Leachate
05/28	23.0	23.0	7.9	6.4
05/30	23.0	23.0	7.6	6.5
06/01	24.0	24.0	8.7	7.0
06/02	24.0	24.0	8.6	7.0
06/04	23.0	23.0	8.5	6.9
06/06	24.5	24.0	8.1	7.3
06/07	23.0	23.0	7.7	7.4
06/09	23.0	23.0	7.9	7.5
06/10	22.5	22.0	8.6	7.6
06/13	22.5	22.0	8.4	7.4
06/14	22.0	22.0	8.7	7.8
06/15	22.0	22.5	8.6	7.5
06/17	22.0	22.0	8.7	7.7
06/19	22.0	22.0	8.4	7.8
06/20	22.0	22.0	8.5	7.9
06/21	22.0	22.0	8.6	7.8
06/22	22.5	22.0	8.5	7.6
06/23	23.0	22.0	8.4	7.6
06/25	22.0	22.0	8.2	7.7
06/26	23.0	22.5	8.4	7.8

APPENDIX TABLE C.6. RESIDUE DATA, LAHAINA LYSIMETER, O'AHU, HAWAI'I, 1978

1978	TOTAL SOLIDS		DISSOLVED SOLIDS		SUSPENDED SOLIDS		VOLATILE SUSP. SOLIDS		FIXED SUSP. SOLIDS	
	Infl.	Leach.	Infl.	Leach.	Infl.	Leach.	Infl.	Leach.	Infl.	Leach.
	(mg/ℓ)									
05/28	236	112	200	106	36	6	36	6	0	0
05/30	---	---	---	---	--	--	--	-	-	-
06/01	---	---	---	---	--	--	--	-	-	-
06/02	287	140	238	133	49	7	47	7	2	0
06/04	---	---	---	---	--	--	--	-	-	-
06/06	---	---	---	---	--	--	--	-	-	-
06/07	392	199	316	189	76	10	70	8	6	2
06/09	---	---	---	---	--	--	--	-	-	-
06/10	---	---	---	---	--	--	--	-	-	-
06/13	463	292	351	268	112	24	100	18	12	6
06/14	---	---	---	---	---	--	--	--	--	-
06/15	---	---	---	---	---	--	--	--	--	-
06/17	560	380	459	362	101	18	94	16	7	2
06/19	---	---	---	---	---	--	--	--	-	-
06/20	---	---	---	---	---	--	--	--	-	-
06/21	596	444	475	429	121	15	117	15	4	0
06/22	---	---	---	---	---	--	---	--	-	-
06/23	564	448	456	426	108	22	108	10	0	12
06/25	---	---	---	---	---	--	---	--	-	-
06/26	616	509	484	479	132	30	132	30	0	0

NOTE: Infl. = Influent,
Leach. = Leachate.

APPENDIX TABLE C.7. ORGANICS DATA, LAHAINA LYSIMETER, O'AHU, HAWAI'I, 1978

1978	COD		BOD_5		TOC	
	Infl.	Leach.	Infl.	Leach.	Infl.	Leach.
	(mg/ℓ)					
05/28	76	34	50	21	24	14
05/30	47	31	---	--	40	18
06/01	415	58	210	97	99	60
06/02	287	69	---	--	--	--
06/04	291	82	167	39	61	32
06/06	475	45	245	107	98	45
06/07	267	150	---	--	75	60
06/09	300	198	178	47	87	62
06/10	266	189	---	--	67	51
06/13	321	192	---	--	90	58
06/14	358	208	204	108	97	62
06/15	407	201	---	---	--	--
06/17	412	226	208	109	125	73
06/19	435	247	---	---	110	61
06/20	441	278	212	152	109	72
06/21	488	222	---	---	129	79
06/22	451	262	---	---	126	68
06/23	534	275	252	160	152	69
06/25	552	352	---	---	146	89
06/26	569	320	260	176	153	93

NOTE: Infl. = Influent,
Leach. = Leachate.

APPENDIX TABLE C.8. NITROGEN AND PHOSPHORUS DATA, LAHAINA LYSIMETER, O'AHU, HAWAI'I, 1978

1978	AMMONIA N		ORGANIC N		TOTAL KJELDAHL N		$NO_2 + NO_3$ N		TOTAL N		TOTAL P	
	Infl.	Leach.	Infl.	Leach.	Infl.	Leach.	Infl.	Leach.	Infl.	Leach.	Infl.	Leach.
	(mg/ℓ)											
05/28	11.7	2.2	1.8	1.9	13.5	4.1	0.10	0.22	13.6	4.3	5.1	1.0
05/30	10.4	2.1	2.9	4.5	13.3	6.6	0.06	<0.04	13.4	6.6	5.5	0.6
06/01	51.1	5.5	16.0	4.3	67.1	9.8	<0.04	0.19	67.1	10.0	10.4	0.6
06/02	48.3	8.3	13.3	4.2	61.6	12.5	<0.04	<0.04	61.6	12.5	8.6	0.6
06/04	47.3	14.0	10.5	4.3	57.8	18.3	<0.04	<0.04	57.8	18.3	8.4	0.8
06/06	50.5	44.3	25.8	5.0	76.3	49.3	0.07	<0.04	76.4	49.3	9.7	0.6
06/07	53.6	34.9	13.5	3.8	67.1	38.7	<0.04	<0.04	67.1	38.7	6.2	0.7
06/09	60.2	39.3	10.6	3.6	70.8	42.9	0.05	0.06	70.9	43.0	7.3	0.7
06/10	65.7	54.9	8.8	3.9	74.5	58.8	<0.04	<0.04	74.5	58.8	8.5	0.5
06/13	52.6	55.3	14.0	3.5	66.6	58.8	<0.04	<0.04	66.6	58.8	11.2	1.0
06/14	92.8	65.5	10.9	3.7	103.7	69.2	<0.04	<0.04	103.7	69.2	13.2	0.5
06/15	----	----	----	---	-----	----	----	----	-----	----	14.1	0.5
06/17	91.5	72.6	16.4	4.8	107.9	77.4	<0.04	<0.04	107.9	77.4	17.1	0.3
06/19	----	----	----	---	99.8	70.2	<0.04	<0.04	99.8	70.2	14.7	0.3
06/20	----	----	----	---	101.6	80.7	<0.04	<0.04	101.6	80.7	19.1	0.3
06/21	----	----	----	---	104.7	92.3	<0.04	<0.04	104.7	92.3	20.4	0.3
06/22	89.0	108.0	13.0	2.4	102.0	110.4	<0.04	<0.04	102.0	110.4	26.5	0.3
06/23	87.6	108.0	15.0	4.9	102.6	112.9	<0.04	<0.04	102.6	112.9	24.4	0.3
06/25	86.8	110.0	13.7	1.8	100.5	111.8	<0.04	<0.04	100.5	111.8	26.2	0.3
06/26	90.7	106.0	14.3	3.4	105.0	109.4	<0.04	<0.04	105.0	109.4	26.4	0.4

NOTE: Infl. = Influent, Leach. = Leachate.

APPENDIX TABLE C.9. BACTERIOLOGICAL DATA, LAHAINA LYSIMETER, O'AHU, HAWAI'I, 1978

1978	FECAL STREPTOCOCCUS (× 10^3)		FECAL COLIFORM (× 10^6)		TOTAL COLIFORM (× 10^6)	
	Infl.	Leach.	Infl.	Leach.	Infl.	Leach.
	(/100 mℓ)					
05/28	10	2	0.8	0.1	110	43
05/30	25	4	33	8.0	49	31
06/01	500	240	9.2	0.8	22	9
06/02	390	180	10	1.0	17	6
06/04	500	200	11	4.0	260	90
06/06	210	40	1.0	0.1	330	76
06/07	190	110	1.2	0.8	340	180
06/09	---	--	---	---	---	--
06/10	150	94	9.0	0.2	230	64
06/13	130	40	120	21	210	35
06/14	530	150	160	20	230	30
06/15	540	120	160	22	210	28
06/17	570	65	140	20	170	21
06/19	750	46	150	25	460	13
06/20	240	35	250	18	340	19
06/21	410	29	220	16	310	17
06/22	430	57	84	6.4	130	14
06/23	590	15	43	2.0	120	13
06/25	---	--	--	--	---	--
06/26	570	62	52	3.0	230	16

NOTE: Infl. = Influent,
Leach. = Leachate.

APPENDIX TABLE C.10. TEMPERATURE AND pH DATA, TANTALUS AND JAUCAS LYSIMETERS, O'AHU, HAWAI'I, 1978

1978	TEMPERATURE (°C)			pH		
	Infl.	Leach.		Infl.	Leach.	
		Tantalus	Jaucas		Tantalus	Jaucas
07/16	24.0	24.0	24.0	8.0	6.8	8.3
07/18	23.0	23.0	23.0	8.2	6.8	8.1
07/19	23.5	23.0	23.5	8.5	7.0	8.1
07/20	22.5	22.5	22.0	8.4	6.7	8.2
07/22	23.0	23.0	23.5	8.3	5.9	8.3
07/23	23.0	23.0	23.0	8.2	6.2	8.2
07/24	23.0	22.5	23.0	8.7	6.6	8.2
07/26	24.0	23.5	23.0	8.1	6.2	8.2
07/27	23.5	24.0	24.0	7.4	5.8	8.2
07/28	24.0	24.0	24.0	7.9	6.6	8.1
07/29	24.5	24.0	24.0	8.6	6.4	8.2
07/31	23.0	23.5	23.0	8.5	6.4	8.3
08/01	22.5	22.0	22.5	8.6	6.3	8.4
08/02	22.0	22.0	22.5	7.8	6.4	8.4
08/03	24.0	24.0	23.5	7.7	6.4	8.1
08/05	23.5	23.0	22.5	7.6	6.5	8.1
08/06	23.0	23.0	23.0	7.6	6.6	8.0
08/07	23.0	23.0	23.0	7.0	6.6	8.0
08/08	23.0	22.5	23.0	6.9	6.6	8.0
08/09	23.0	22.5	22.5	7.3	6.7	7.9
08/11	24.0	24.0	23.5	7.6	6.8	7.8
08/12	24.5	24.0	23.5	7.4	6.8	7.8
08/13	23.0	23.0	23.0	7.5	6.7	7.6
08/14	24.0	24.0	24.0	7.2	6.7	7.7

NOTE: Infl. = Influent,
Leach. = Leachate.

APPENDIX TABLE C.11. RESIDUE DATA, TANTALUS AND JAUCAS LYSIMETERS, O'AHU, HAWAI'I, 1978

1978	TOTAL SOLIDS			DISSOLVED SOLIDS			SUSPENDED SOLIDS			VOL. SUSP. SOLIDS			FIXED SUSP. SOLIDS		
	Infl.	Leachate		Infl.	Leachate		Infl.	Leachate		Infl.	Leachate		Infl.	Leachate	
		Tant.	Jauc.		Tant.	Jauc.		Tant.	Jauc.		Tant.	Jauc.		Tant.	Jauc.
	(mg/ℓ)														
07/16	224	76	236	196	69	229	28	7	7	25	5	7	3	2	0
07/18	---	--	---	---	--	---	--	--	--	--	--	--	--	--	--
07/19	260	133	256	235	129	247	25	4	9	21	3	6	4	1	3
07/20	---	---	---	---	---	---	--	--	--	--	--	--	--	--	--
07/22	232	118	208	211	116	203	21	2	5	21	2	4	0	0	1
07/23	---	---	---	---	---	---	--	--	--	--	--	--	--	--	--
07/24	---	---	---	---	---	---	--	--	--	--	--	--	--	--	--
07/26	368	186	291	206	159	275	162	27	16	158	25	15	4	2	1
07/27	---	---	---	---	---	---	---	--	--	---	--	--	--	--	--
07/28	---	---	---	---	---	---	---	--	--	---	--	--	--	--	--
07/29	308	196	240	184	171	222	124	25	18	120	25	18	4	0	0
07/31	---	---	---	---	---	---	---	--	--	---	--	--	--	--	--
08/01	---	---	---	---	---	---	---	--	--	---	--	--	--	--	--
08/02	410	206	250	243	178	234	173	28	16	166	26	15	7	2	1
08/03	---	---	---	---	---	---	---	--	--	---	--	--	--	--	--
08/05	---	---	---	---	---	---	---	--	--	---	--	--	--	--	--
08/06	436	164	280	334	134	269	102	30	11	102	30	11	0	0	0
08/07	540	226	324	354	186	310	186	40	14	180	40	14	6	0	0
08/08	---	---	---	---	---	---	---	--	--	---	--	--	--	--	--
08/09	575	247	379	376	195	358	199	52	21	183	47	16	16	5	5
08/11	564	244	362	364	190	339	200	54	23	188	52	21	12	2	2
08/12	---	---	---	---	---	---	---	--	--	---	--	--	--	--	--
08/13	584	249	368	375	191	342	209	58	26	191	56	25	18	2	1
08/14	612	270	370	364	191	328	248	79	42	223	73	38	25	6	4

NOTE: Infl. = Influent,
Tant. = Tantalus,
Jauc. = Jaucas.

APPENDIX TABLE C.12. ORGANICS DATA, TANTALUS AND JAUCAS LYSIMETERS, O'AHU, HAWAI'I, 1978

1978	COD Infl.	COD Leach. Tant.	COD Leach. Jauc.	BOD_5 Infl.	BOD_5 Leach. Tant.	BOD_5 Leach. Jauc.	TOC Infl.	TOC Leach. Tant.	TOC Leach. Jauc.
	(mg/ℓ)								
07/16	155	8	43	102	7	29	34	9	31
07/18	264	33	26	---	-	--	61	8	33
07/19	114	54	16	---	-	--	25	10	12
07/20	119	70	62	92	59	36	23	15	11
07/22	150	49	39	---	--	--	26	5	7
07/23	232	17	106	111	14	57	42	5	18
07/24	251	35	139	---	--	--	58	11	33
07/26	260	60	169	164	32	88	61	14	48
07/27	386	191	150	---	--	--	71	16	50
07/28	299	157	187	---	--	--	95	47	44
07/29	229	139	124	180	68	63	72	42	48
07/31	219	130	110	---	--	--	76	42	46
08/01	209	151	133	---	--	--	72	45	60
08/02	226	134	122	181	72	71	78	48	40
08/03	337	128	114	---	--	--	100	50	31
08/05	351	178	150	284	102	97	110	71	49
08/06	492	118	92	---	---	--	152	48	26
08/07	458	203	93	---	---	--	160	64	45
08/08	502	232	93	305	128	85	180	77	36
08/09	500	216	130	---	---	--	184	75	49
08/11	480	197	188	300	120	88	186	84	50
08/12	416	129	118	310	115	102	183	82	40
08/13	493	216	132	---	---	---	192	91	36
08/14	517	239	159	316	123	104	202	92	44

NOTE: Infl. = Influent,
Leach. = Leachate,
Tant. = Tantalus,
Jauc. = Jaucas.

APPENDIX TABLE C.13. NITROGEN DATA, TANTALUS AND JAUCAS LYSIMETERS, O'AHU, HAWAI'I, 1978

1978	AMMONIA NITROGEN			ORGANIC NITROGEN			TOTAL KJELDAHL N			$NO_2 + NO_3$ NITROGEN			TOTAL NITROGEN		
	Infl.	Leachate		Infl.	Leachate		Infl.	Leachate		Infl.	Leachate		Infl.	Leachate	
		Tant.	Jauc.		Tant.	Jauc.		Tant.	Jauc.		Tant.	Jauc.		Tant.	Jauc.
	(mg/ℓ)														
07/16	29.7	1.0	13.9	12.8	2.1	4.9	42.5	3.1	18.8	<0.04	1.26	0.41	42.5	4.4	19.2
07/18	19.6	1.1	1.4	9.7	0.8	2.7	29.3	1.9	4.1	<0.04	<0.04	0.31	29.3	1.9	4.4
07/19	33.4	3.0	15.7	6.5	1.4	2.2	39.9	4.4	17.9	<0.04	0.57	<0.04	39.9	5.0	17.9
07/20	35.0	2.0	11.2	6.2	1.7	2.0	41.2	3.7	13.2	<0.04	0.10	<0.04	41.2	3.8	13.2
07/22	36.2	1.9	14.9	6.4	1.0	2.5	42.6	2.9	17.4	<0.04	0.22	<0.04	42.6	3.1	17.4
07/23	26.0	3.9	25.8	9.6	1.7	3.3	35.6	5.6	29.1	<0.04	1.22	0.51	35.6	6.8	29.6
07/24	59.0	6.0	35.4	10.5	1.9	3.7	69.5	7.9	39.1	0.04	<0.04	0.12	69.5	7.9	39.2
07/26	39.2	9.2	30.1	9.6	4.5	3.0	48.8	13.7	33.1	<0.04	<0.04	0.07	48.8	13.7	33.2
07/27	29.6	17.5	28.3	10.3	4.3	2.6	39.9	21.8	30.9	0.04	<0.04	<0.04	39.9	21.8	30.9
07/28	27.1	19.0	32.2	22.6	7.8	3.3	49.7	26.8	35.5	0.04	0.84	0.97	49.7	27.6	36.5
07/29	44.1	22.4	32.6	10.3	4.6	2.8	54.4	27.0	35.4	<0.04	<0.04	0.57	54.4	27.0	36.0
07/31	48.0	22.6	33.7	10.6	5.1	3.0	58.6	27.7	36.7	0.06	<0.04	0.40	59.7	27.7	37.1
08/01	54.2	34.1	35.3	9.8	4.6	3.8	64.0	38.7	39.1	0.15	<0.04	1.00	64.2	38.7	40.1
08/02*	39.1	30.7	30.3	8.0	2.9	3.0	47.1	33.6	33.3	<0.04	<0.04	0.11	47.1	33.6	33.4
08/03*	39.1	30.7	30.3	8.0	2.9	3.0	47.1	33.6	33.3	<0.04	<0.04	0.32	47.1	33.6	33.6
08/05	46.0	32.8	26.6	12.7	4.1	4.6	58.7	36.9	31.2	<0.04	<0.04	0.24	58.7	36.9	31.4
08/06	64.1	25.8	24.3	14.2	1.9	3.9	78.3	27.7	28.2	<0.04	<0.04	0.33	78.3	27.7	28.5
08/07	34.6	23.9	13.3	31.0	4.2	3.5	65.6	28.1	16.8	0.54	<0.04	0.63	66.1	28.1	17.4
08/08	40.7	34.3	25.2	45.9	5.8	1.5	86.6	40.1	26.7	0.23	<0.04	0.14	86.8	40.1	26.9
08/09	42.6	28.2	32.6	20.2	7.2	2.8	62.8	35.4	35.4	<0.04	<0.04	0.10	62.8	35.4	35.5
08/11	41.5	28.0	32.5	8.3	1.7	2.4	49.8	29.7	34.9	<0.04	<0.04	0.52	49.3	29.7	35.4
08/12	----	----	----	----	---	---	63.7	34.3	32.4	<0.04	<0.04	0.21	63.7	34.3	32.6
08/13	43.7	30.2	31.6	26.3	6.3	3.2	70.0	36.5	34.8	0.30	<0.04	0.50	70.3	36.5	35.3
08/14	44.6	31.7	30.9	28.7	4.3	4.1	73.3	36.0	35.0	<0.04	<0.04	0.29	73.3	36.0	35.3

NOTE: Infl. = Influent,
Tant. = Tantalus,
Jauc. = Jaucas.

*Composite sample for 2 days.

APPENDIX TABLE C.14. PHOSPHORUS DATA, TANTALUS AND JAUCAS LYSIMETERS, O'AHU, HAWAI'I, 1978

1978	TOTAL PHOSPHORUS		
	Infl.	Leachate	
		Tant.	Jauc.
	(mg/ℓ)		
07/16	6.2	0.3	0.5
07/18	5.6	0.3	0.6
07/19	5.1	0.2	0.5
07/20	5.2	0.2	0.6
07/22	4.6	0.1	0.6
07/23	5.2	0.3	1.0
07/24	6.6	0.4	1.9
07/26	7.1	0.5	1.9
07/27	10.1	0.7	1.9
07/28	6.4	0.7	2.0
07/29	6.9	0.6	2.6
07/31	7.3	0.6	2.1
08/01	7.3	0.4	4.8
08/02	5.0	0.5	3.2
08/03	8.2	0.5	2.3
08/05	10.3	0.8	2.7
08/06	17.4	0.9	4.6
08/07	8.3	0.7	2.4
08/08	14.4	1.2	1.8
08/09	13.5	0.9	1.7
08/11	10.9	0.3	2.2
08/12	11.6	0.3	2.5
08/13	14.0	0.8	1.7
08/14	16.1	0.9	2.0

NOTE: Infl. = Influent,
Tant. = Tantalus,
Jauc. = Jaucas.

APPENDIX TABLE C.15. BACTERIOLOGICAL DATA, TANTALUS AND JAUCAS LYSIMETERS, O'AHU, HAWAI'I, 1978

1978	FECAL STREPTOCOCCUS (× 10^4)			FECAL COLIFORM (× 10^6)			TOTAL COLIFORM (× 10^6)		
	Infl.	Leach.		Infl.	Leach.		Infl.	Leach.	
		Tant.	Jauc.		Tant.	Jauc.		Tant.	Jauc.
	(/100 mℓ)								
07/16	1.2	0.2	0.3	110	4.7	3.8	260	14	3.6
07/18	11	1.0	3.0	160	5.7	42	210	9.0	58
07/19	--	---	---	---	---	--	---	--	--
07/20	50	1.1	14	70	10	12	130	18	15
07/22	68	1.0	19	19	0.8	4.0	20	0.8	6.0
07/23	28	3.0	4.5	8.0	2.0	1.0	11	6.0	2.0
07/24	69	0.8	19	130	1.0	35	180	2.0	40
07/26	99	6.2	13	120	19	9.1	190	16	13
07/27	200	12	22	93	17	5.5	170	21	5.0
07/28	43	8.2	14	59	15	12	83	20	17
07/29	14	2.0	5.0	54	16	6.0	68	24	9.1
07/31	13	2.0	4.2	72	13	11	99	17	19
08/01	8.0	1.0	3.0	310	32	30	470	31	94
08/02	12	4.0	3.0	77	17	12	250	60	41
08/03	--	---	---	--	--	--	---	--	--
08/05	30	2.8	2.8	75	15	12	120	29	30
08/06	2.0	0.2	0.2	24	3.0	1.0	160	49	14
08/07	52	10	3.0	52	2.0	1.0	79	7.3	9.0
08/08	150	6.0	2.2	210	29	18	460	96	52
08/09	--	---	---	--	--	--	---	--	--
08/11	11	3.0	1.0	7.0	1.0	0.15	110	26	4.6
08/12	23	4.0	2.0	62	12	13	280	32	29
08/13	--	---	---	--	--	--	---	--	--
08/14	43	7.0	2.0	82	15	11	300	64	32

NOTE: Infl. = Influent,
Leach. = Leachate,
Tant. = Tantalus,
Jauc. = Jaucas.

APPENDIX D. WASTE WATER CHARACTERISTICS

APPENDIX TABLE D.1. TYPICAL COMPOSITION OF DOMESTIC SEWAGE

CONSTITUENT	CONCENTRATION		
	Strong	Medium	Weak
Solids, Total	1 200	700	350
Dissolved, Total	850	500	250
Fixed	525	300	145
Volatile	325	200	105
Suspended, Total	350	200	100
Fixed	75	50	30
Volatile	275	150	70
Settleable Solids, (mℓ/ℓ)	20	10	5
Biochemical Oxygen Demand, 5-day, 20°C (BOD_5-20°)	300	200	100
Total Organic Carbon (TOC)	300	200	100
Chemical Oxygen Demand (COD)	1 000	500	250
Nitrogen, (Total as N)	85	40	20
Organic	35	15	8
Free Ammonia	50	25	12
Nitrite	0	0	0
Nitrate	0	0	0
Phosphorus (Total as P)	20	10	6
Organic	5	3	2
Inorganic	15	7	4
Chlorides*	100	50	30
Alkalinity (as $CaCO_3$)*	200	100	50
Grease	150	100	50

SOURCE: Metcalf and Eddy (1972).
NOTE: All values except settleable solids in mg/ℓ.
*Values should be increased by amount in carriage water.

APPENDIX TABLE D.2. AVERAGE EFFLUENT CHARACTERISTICS FROM VARIOUS TREATMENT PLANTS

CONSTITUENT	PRIMARY EFFLUENT	SECONDARY EFFLUENT		
		Trickling Filter	Activated Sludge	Ponds
Chemical				
Specific Conductivity, μmhos/cm	---	1,663	--	---
Total Dissolved Solids	1,402	1,166	917	1,330
pH, units	---	--	--	--
BOD	152	17	20	70
Total Nitrogen	37	16	23	23
Nitrate Nitrogen	0.3	6.3	3.9	0.7
Ammonia Nitrogen	23	5.9	17	8
Total Phosphorus	11	13	12.9	6.7
Chlorides	461	176	185	138
Sulfate	180	317	224	360
Alkalinity ($CaCO_3$)	635	491	--	682
Boron	1.2	0.7	0.7	1.2
Sodium	329	267	192	257
Potassium	22	14	20	14
Calcium	96	80	52	92
Magnesium	34	50	57	48
Sodium Adsorption Ratio	7.5	5.6	5.0	5.0

SOURCE: Pound and Crites (1973).
NOTE: All values in mg/ℓ unless indicated otherwise.