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

The Ewa caprock aquifer has been a long-standing water source for southern Oahu, but the freshwater viability of the aquifer is being threatened with the gradual increase in the salinity level of pumped caprock aquifer water in recent years. Concern over enhancing the freshwater quantity and quality of the Ewa caprock aquifer prompted a consortium of agencies to sponsor a demonstration Groundwater Recharge with Treated Wastewater Effluent project. The project, located in a sugarcane field on the Ewa Plain, consists of two California grass plots and four sugarcane plots, each approximately 0.5 acre in size. One of the California grass plots is to receive, by overhead sprinklers, 4 in./day of nearby Honouliuli WWTP primary effluent, 5 days/wk; the other, one-half this application rate. Two of the sugarcane plots are scheduled to receive 10 in. of primary effluent by flood irrigation twice a week, the other two plots, once a week. Shallow and deep monitoring wells within, upstream, and downstream of the plots will be sampled and analyzed for various constituents. Baseline analyses of monitoring wells and Honouliuli WWTP effluent samples have been conducted.

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GROUNDWATER RECHARGE WITH HONOULIULI WASTEWATER IRRIGATION, 'EWA PLAIN, SOUTHERN O'AHU, HAWAI'I

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Technical Memorandum Report No. 80

August 1986

First Progress Report

PREPARED FOR

State of Hawaii
Department of Land and Natural Resources
Division of Water and Land Development

and

The Estate of James Campbell

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ABSTRACT

The 'Ewa caprock aquifer has been a long-standing water source for southern O'ahu, but the freshwater viability of the aquifer is being threatened with the gradual increase in the salinity level of pumped caprock aquifer water in recent years. Concern over enhancing the freshwater quantity and quality of the 'Ewa caprock aquifer prompted a consortium of agencies to sponsor a demonstration Groundwater Recharge with Treated Wastewater Effluent project. The project, located in a sugarcane field on the 'Ewa Plain, consists of two California grass plots and four sugarcane plots, each approximately 0.5 acre in size. One of the California grass plots is to receive, by overhead sprinklers, 4 in./day of nearby Honouliuli WWTP primary effluent, 5 days/wk; the other, one-half this application rate. Two of the sugarcane plots are scheduled to receive 10 in. of primary effluent by flood irrigation twice a week, the other two plots, once a week. Shallow and deep monitoring wells within, upstream, and downstream of the plots will be sampled and analyzed for various constituents. Baseline analyses of monitoring wells and Honouliuli WWTP effluent samples have been conducted.

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INTRODUCTION

The uppermost unconfined limestone aquifer in 'Ewa, commonly known as the 'Ewa caprock aquifer, has been a long-standing water source for southern O'ahu. In recent years, it has provided 20 to 25 mgd for sugarcane irrigation. This source needs protection and enhancement as a viable and substantive water source inasmuch as 'Ewa is being planned for substantial near-future urban development. Furthermore, a possible O'ahu water shortage into the early part of the 21st century is now commonly acknowledged.

Management of the 'Ewa caprock aquifer water appears necessary because of two recent events: first, conversion from furrow irrigation to the water-use-efficient drip irrigation, which reduces the amount of irrigation return flow to recharge the aquifer; second, a gradual increase in the salinity level of the pumped caprock aquifer water in recent years. The first event may be related to the second.

Recycling of Sewage Effluent by Irrigation in Hawai'i

Recycling of sewage effluent in Hawai'i presently totals about 20 mgd at 23 sites, with major applications used for the irrigation of sugarcane and golf courses. Each county has one or more sites.

Associated with the practice is a major research program on recycling of sewage effluent by irrigation which has been in progress by the University of Hawaii's Water Resources Research Center (WRRC) since 1971 in Mililani, O'ahu. The program has developed the necessary technology for effluent irrigation of sugarcane and the requisite answer to crop yield and concerns for possible pollution of groundwater. Additional successful WRRC studies in Mililani were completed with Bermuda grass and California grass. Current pilot studies in Mililani include alfalfa, guinea grass, papaya, banana, and corn.

The "living filter" concept used for this project is based on the premise that the soil and vegetation will remove nutrients, organic matter, and viral and bacterial pathogens from the applied sewage effluent. At the project site, primary effluent from the Honouliuli Wastewater Treatment Plant (WWTP) will be applied at relatively high hydraulic loading rates to test plots of California grass and sugarcane in an effort to strip nutrients and organic matter from the effluent before it percolates to and recharges the underlying caprock aquifer shown in Figure 1. Conversely, the stripping process also provides the nutrients needed for crop growth.

In an earlier study, California grass showed excellent results when irrigated with secondary effluent as a means for high hydraulic loading rates, nitrogen removal, and high productivity of medium-grade fodder (Handley and Ekern 1981). However, the feasibility of that study is considered to be site specific because the soils are different; also, primary- rather than secondary-treated effluent will be used.

California grass (para grass) (Brachiaria mutica [Forsk.] Stapf = Panicum purpurascens Raddi) is well adapted to wet and high moisture areas. Although the experimental site is not naturally wet, the high hydraulic loading rates planned for this project will, in essence, provide the high moisture to which it is adapted. The Mililani study verified that this grass tolerates prolonged flooding, grows luxuriantly in dense stands in lowland and swampy areas, has excellent capacities for nutrient uptake, uses water efficiently, and is already well established in Hawai'i where it is used as pasturage and for fodder. California grass thrived under high rates of effluent application (4 in./day, 5 days/week) and consumed only 0.2 in./day of irrigation water. This infers a high rate of recharge (~77,500 gal/acre/day) and a relatively small land requirement (13.4 acres for 1 mgd). The study also shows low nitrate levels in the percolate (less than 10 mg/l as N) and high crop yield (50 dry tons/acre/yr), and yield quality meeting the limiting toxic level of nitrate for animal consumption.

The effectiveness of secondary effluent to irrigate sugarcane at Mililani in central O'ahu has been well proven at the pilot level by the use of various schemes of application (including rotation and dilution) by the furrow method since 1971 (Lau et al. 1972, 1974, 1975, 1977, 1980; Dugan et al. 1975) and also by applying secondary effluent to sugarcane by drip irrigation (Lau et al. 1978). The results of the pilot level research formed the basis for a current project for which Mililani WWTP secondary effluent was used by the Oahu Sugar Company for application to furrow irrigated sugarcane, as a supplement to potable quality irrigation water.

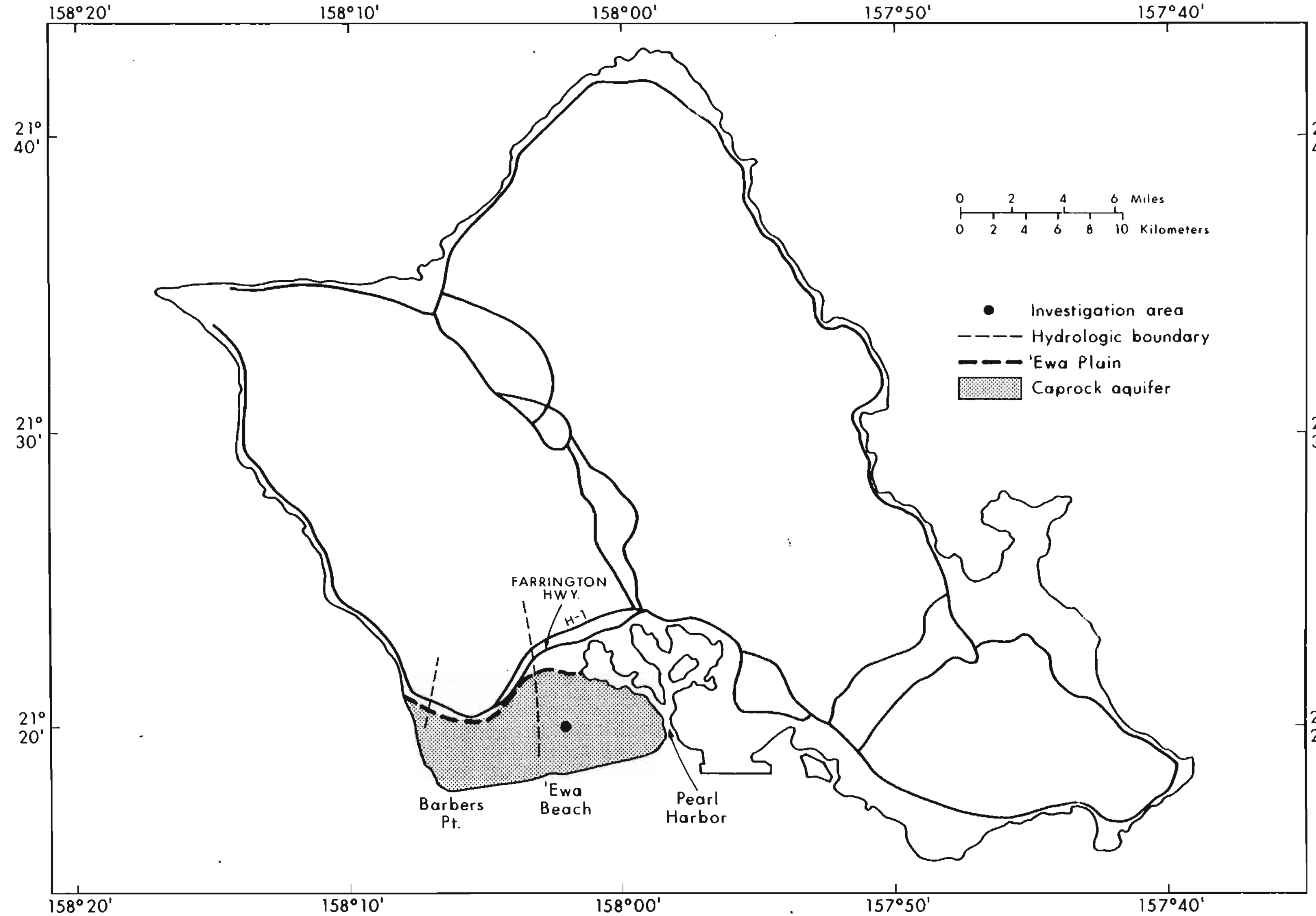


Figure 1. Map of Honouliuli investigation area, O'ahu, Hawai'i

Aquifer Recharge with Effluent

Some degree of incidental recharge of aquifers has undoubtedly occurred over the years as a result of utilizing wastewater effluent for sugarcane and golf course irrigation, as well as seepage from household cesspools and similar subsurface disposal methods. Until the present project, the state has not had a groundwater recharge project whose specific objective was the use of treated municipal effluent to recharge the aquifer. However, prior suggestions on recharge with effluent were advanced (Lau and Dugan 1979; Dugan and Lau 1981).

Project Organization

This project represents a consortium of agencies with different levels of involvement. The agencies and their personnel associated with the project are listed in the Project Personnel section. The lead agency is the Hawaii State Department of Land and Natural Resources, Division of Water and Land Development, a co-principal sponsor with The Estate of James Campbell. The University of Hawaii at Manoa's Water Resources Research Center, as the implementing agency coordinates the overall project and performs water quality and related monitoring.

Land for the pilot plots was provided by Oahu Sugar Company. The Oahu Sugar Company is also responsible for the design, installation, and operation of the irrigation aspects for the pilot plots, pipeline to the Honouliuli WWTP perimeter nearest the pilot plots, as well as for planting, harvesting, and determining the biomass constituents of the harvested California grass and sugarcane crops.

The Honouliuli WWTP, under the direction of the City and County of Honolulu Department of Public Works, is providing the primary effluent, pumping system, and power, as well as participating in the project's water quality analysis program. The Board of Water Supply is participating in the water quality analysis program. The Hawaii State Department of Health is a cooperating agency advising on aerosol quality and public health matters for the project. Two private consultants engaged for the project's planning and initiation phases are John F. Mink, for the geohydrology of the 'Ewa caprock; and Linda Handley-Raven, a specialist on California grass for wastewater reclamation in Hawai'i and Florida.

PURPOSE AND SCOPE

The general goals are to recharge the 'Ewa caprock aquifer in order to promote and/or maintain low groundwater salinity levels without causing other adverse impacts to the groundwater, to conserve water resources (both wastewater reuse and retardation of seawater intrusion), to utilize the effluent's nutrients, and to produce a usable biomass (e.g., California grass and/or sugarcane).

The project will utilize the relatively low salinity level, primary effluent from the Honouliuli WWTP and will apply it to the nearby pilot plots (OSC Field No. 49) of California grass and sugarcane at various hydraulic loading rates in order to ascertain the optimal effectiveness of the crops and soil to recharge the caprock water, process the effluent, and produce the crop yield. Information will be developed, through monitoring, on the optimal irrigation rate and schedule and corresponding land requirement, the water quality, the distribution and flow pattern of the recharge water in the caprock aquifer, the quantity and quality of the biomass produced, and general aesthetics factors and related public health considerations.

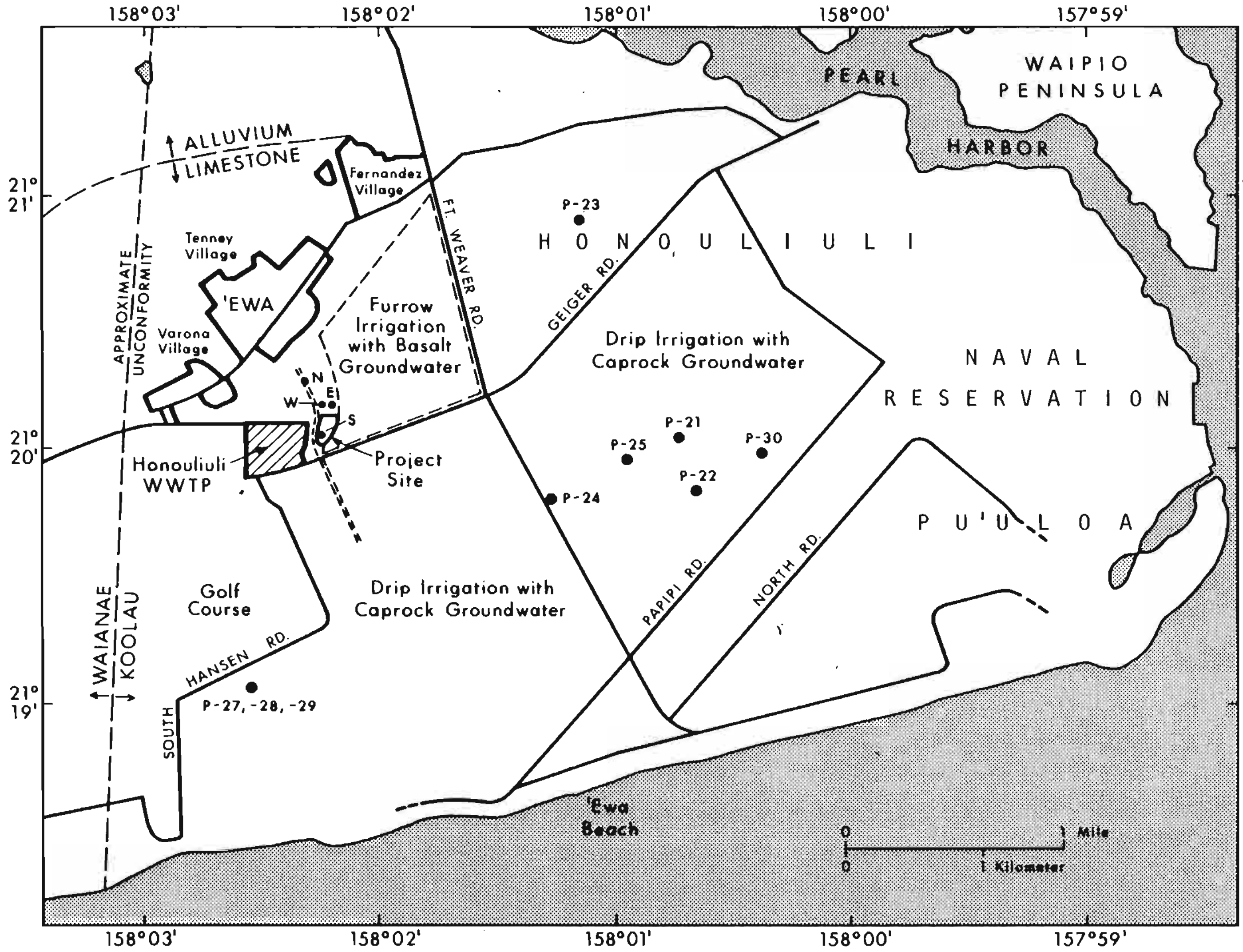
In addition to the technical aspects, the project will consider the management objectives of institution, financing, and water rights.

CAPROCK WATER IN 'EWA PLAIN

The 'Ewa Plain covers an area of approximately 28 miles^2 of which about 75% is underlaid by limestone (Fig. 2). The terrain of the area is gently sloping to relatively level with the inland boundary approximately parallel to Farrington Highway. About one-third of the limestone area is planted in sugarcane, with the remainder apportioned among military controlled land and the communities of 'Ewa and 'Ewa Beach (Mink 1985).

The 'Ewa caprock aquifer, which is 100 to 200 ft thick throughout most of its extent, either crops out at the surface or is beneath a shallow alluvium. The limestone aquifer thins out inland where it interfingers with the alluvium (Mink 1985).

According to Mink (1985), under pre-development natural conditions the caprock aquifer contains relatively brackish water, the natural hydrologi-



NOTE: P-21 to P-30 are Oahu Sugar Co. irrigation well pumps.

Figure 2. Land use and irrigation methods in project vicinity site, 'Ewa Plain, southern O'ahu, Hawai'i

cal inputs to the aquifer are relatively small, consisting of meager infiltration from low rainfall (estimated maximum annual average of 6 mgd to percolate to the aquifer) and upward seepage from the deeper Waianae and Ko'olau aquifers in the narrow zone of thin alluvial cover at the inland margin of the 'Ewa Plain. Seepage from the deep aquifer is estimated to be in the order of 5 to 10 mgd and occurs primarily in the landward portion of the aquifer where the caprock is thin (Mink 1985). However, the average draft for irrigation over the last 25 years has been 20 to 25 mgd, thus suggesting a deficit (Mink 1985). The aquifer can be pumped at a rate exceeding natural recharge only because other inputs, principally irrigation return, have been added. For furrow irrigation, the return flow is about 50% of the applied amount and, thus, covers the deficit. However, in the past few years throughout the 'Ewa Plain, except for 300 acres, furrow irrigation has been replaced by the more water-use-efficient drip irrigation method which returns less water to the aquifer. Therefore, conversion to drip can create a water imbalance in the caprock aquifer. Return water also adds salinity to the receiving groundwater and could possibly contribute to some of the salt increase in the pumped water salinity. An exception is possibly the sugarcane land irrigated with low-salinity basaltic aquifer water, such as the 300 acres located adjacent to the northeast side of the project plots.

From the foregoing it appears that, in terms of the 'Ewa Plain, the continued use of drip irrigation for sugarcane cultivation or the discontinuation of low salinity water originating from basaltic sources, or the complete termination of sugarcane cultivation will eventually lead to increased salinity of the 'Ewa caprock aquifer water unless the pumping draft from the aquifer is severely restricted, or another suitable source of water for recharge is found. An obvious potential candidate for the supplemental recharge water is the low salinity treated effluent from the nearby Honouliuli WWTP.

HONOULIULI WASTEWATER TREATMENT PLANT

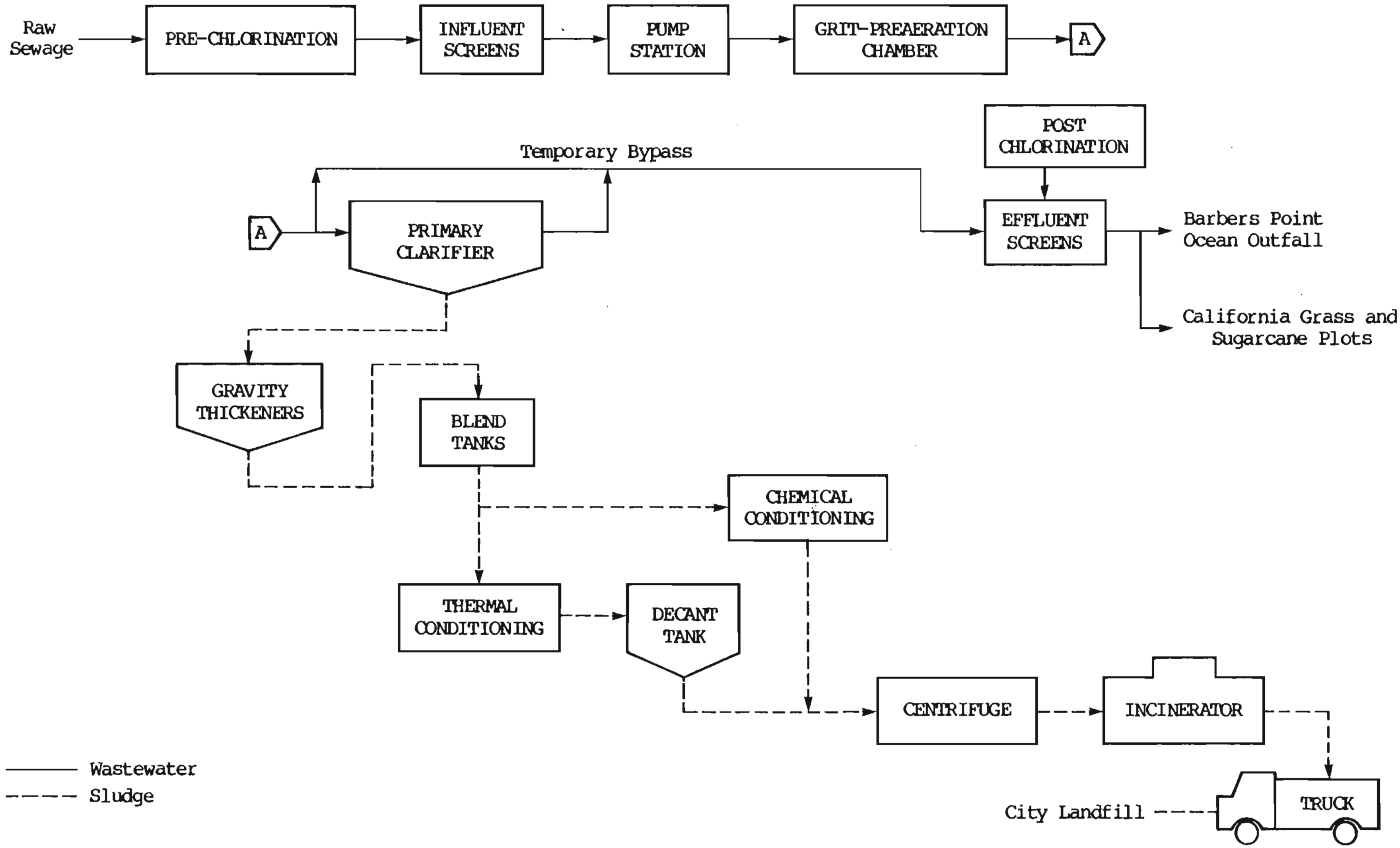
The regional Honouliuli WWTP has a present average daily flow of approximately 17 mgd. The chloride level of the Honouliuli WWTP effluent is only about 250 mg/l, a relatively low salinity level suitable for the irrigation and adequate growth of nearly all commercial crops. Effluent from the Honouliuli WWTP is treated to the primary level and discharged through deep ocean outfalls.

The Honouliuli WWTP is presently designed to treat an average daily flow of 25 mgd. Through planned expansion the average design flow can be increased to 51 mgd for the year 2020. The plant serves a geographical area of O'ahu that extends from Halawa Hills to the east, to Makakilo to the west, and Mililani to the north. The only exception is a portion (0.5 mgd) of the Mililani wastewater that is treated by the Mililani WWTP and used by Oahu Sugar Company for furrow irrigation of cane fields under a previous agreement with OSC which was terminated 31 July 1986.

The Honouliuli WWTP was originally designed to provide secondary treatment in accordance with federal legislation (PL 92-500). Supported by scientific information that discharge of primary effluent into the deep ocean outfalls does not cause significant impact on the indigeneous biological population in the zone of initial dilution, the City and County of Honolulu submitted an application to the U.S. EPA for a waiver of secondary treatment.

The City and County of Honolulu was granted a temporary partial waiver for secondary treatment of the Honouliuli WWTP effluent subsequent to the design of secondary facilities, but prior to the construction of the units. In the interim the City and County has authorized a study to reevaluate the treatment process in order to meet the partial waiver discharge requirements, in addition to reevaluating the need for secondary treatment. Consequently, considerations for the construction of the secondary treatment facilities will await the outcome of the on-going reevaluation study (Division of Wastewater Management n.d.).

Construction of the Honouliuli WWTP commenced originally in late 1976 with three increments, with a fourth increment designated for secondary treatment facilities. The total capital investment for the three increments (from federal, state, and City and County funds) exceeded $89 million. The third increment was completed in October 1984 with actual operations beginning in December 1984. A schematic flow diagram of the present Honouliuli WWTP's primary treatment system is shown in Figure 3. At the present time an odor control system is being installed under an increment denoted as 3A (Division of Wastewater Management n.d.).



SOURCE: Division of Wastewater Management (n.d.).

Figure 3. Schematic flow diagram of Honouliuli WWTP, southern O'ahu, Hawai'i

The WWTP's first treatment commenced in January 1982 with the screening and degritting of the raw wastewater prior to discharge through the Barbers Point Ocean Outfall. Effluent is presently discharged after primary treatment without post-chlorination. However, that portion of the effluent to be used by this project will be disinfected by chlorination.

PROJECT LAYOUT AND MONITORING

The project field site is located at the Honouliuli Wastewater Treatment Plant (WWTP) and the adjoining Oahu Sugar Company's Field No. 49 on the 'Ewa Plain, O'ahu. The principal elements in the field layout consist of two California grass plots, four sugarcane plots, an effluent irrigation supply pipeline and accessories, in-field piping (valves, meters, pipes, sprinklers and risers, and flood risers), monitoring wells, and percolate samplers (Fig. 4). The site selection was principally based on proximity to the WWTP and land available to the project.

The basic field operations consist of two principal components:

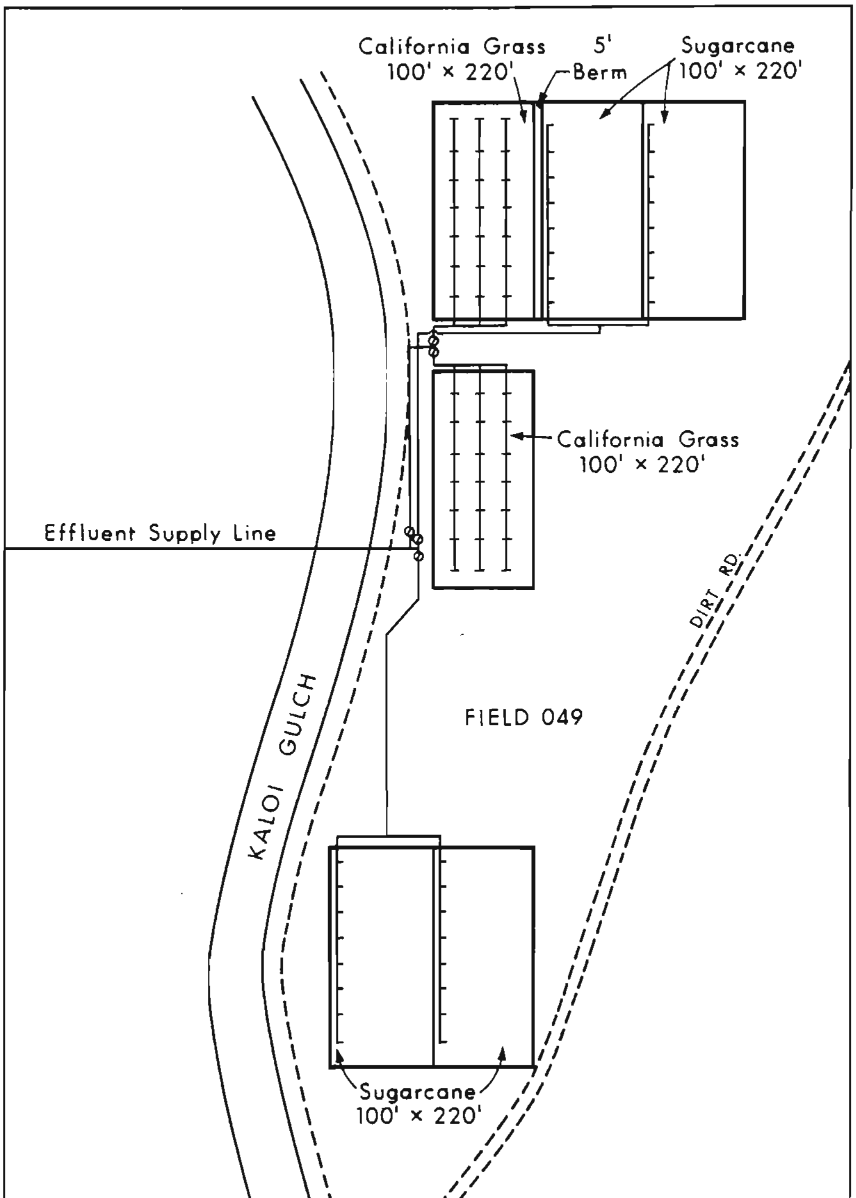
1. Cultivation (crop planting, irrigating, logging, harvesting)
2. Monitoring (water quality, water table elevation, aerosol bacterial quality, general aesthetics).

The two California grass plots are laid out in a rectangular configuration (100 ft by 220 ft) with an approximate area of 0.5 acre surrounded by a berm. The two plots are to be irrigated by overhead sprinklers with different amounts of effluent: 4 in./day for the high rate plot and 2 in./day for the low-rate plot. Irrigation is scheduled for five days per week from Monday through Friday.

The optimum irrigation application rate for growth of California grass should be approximately 360 gpm/acre, or 2.5 hr to irrigate the low-rate plot and 5.0 hr to irrigate the high-rate plot on each irrigation day.* The sprinkler nozzles on risers 8 ft above ground are uniformly spaced (approximately 28 ft apart).

The wet-dry cycle created on each irrigation day should induce an aerobic condition in the soil system for enhancing biodegradation and denitrification. The practice should reduce the incidence of ponding, odor

*L. Handley-Raven 1985: unpublished notes.



NOTE: All plots surrounded by low berms.

Figure 4. Location and layout of project plots of California grass and sugarcane, Oahu Sugar Company Field 049

emissions, and soil clogging by particulates.

By project plan, the California grass plots are scheduled to be optimally harvested when the stand reaches approximately 6 ft and to be cut down to a height of 5 to 6 in. The harvesting frequency is expected to be approximately every 4 to 5 weeks in warm weather and every 6 to 8 weeks in cool weather. Various methods of harvesting have been considered but a final choice has not yet been made. General sanitation during harvest will follow the practice developed for the Mililani study. The harvested grass will be sampled for quality analysis but the bulk is presently planned to be trucked to a landfill site for disposal.

The four sugarcane plots are identical in size and shape to the California grass plots. Two plots will be flood-irrigated with effluent for the first year, then drip-irrigated with water for the second year. Of the two plots, one will be irrigated twice a week on Monday and Friday at high-rate irrigation (10 in./day or 20 in./wk); the other once a week on Wednesday only at low-rate irrigation (10 in./wk). The other two sugarcane plots will be cultivated on the same high- and low-rate basis, but will be flood-irrigated with effluent for the full 2-yr period without switching to water. The sugarcane will be cultivated and harvested consistent with Oahu Sugar Company's (OSC) best field practice.

The OSC completed the design of the irrigation systems for the California grass and sugarcane plots. The personnel at the Honouliuli WWTP, in cooperation with the City and County's Department of Public Works design engineers, designed and modified the WWTP's effluent wash-down system, which enabled sufficient pumping head and flow for the chlorinated irrigation of the pilot plots. An estimated pumping head of 115 ft is required for the overhead-sprinkled California grass pilot plot, whereas only 30 ft of head is necessary for the flood-irrigated sugarcane pilot plots. The piping system will be equipped with sufficient valves and meters to enable accurate application of the primary effluent. As previously indicated, OSC is scheduled to install the irrigation/piping system starting from the Honouliuli WWTP, plant the California grass and sugarcane, irrigate the pilot plots, harvest the crops, and determine the quality biomass parameters for both crops. The start-up time for California grass is expected to require 4 to 6 weeks.

Monitoring Program

The principal element of the monitoring program is water quality. This is accomplished by sampling the effluent, in-field caprock water and percolate water, and near-field caprock water, and by analyzing for selected water quality factors. Planning considerations include selection of water quality factors, monitoring sites, and frequency, sampling methods, laboratory analytical procedures, cooperative agencies' laboratories, and, above all, project funds allocated to monitoring. In addition to water quality, groundwater head and aerosol bacterial quality are also important parts of the overall monitoring program.

The percolate quality below the root zone is monitored with the WRRC porvic samplers. These samplers are 1.25-in. diameter, 3-ft long PVC pipes with two 1-ft sections perforated with holes, covered with screen, and tightly wrapped with porous membrane (porvic). One sampler is implanted approximately 3 ft below the ground surface and just above the limestone rock formation in three selected plots: high-rate California grass plot (W), high-rate sugarcane plot (E), and low-rate sugarcane plot (S). The vacuum needed to extract the soil water is supplied by a Well Wizard™ pump (Model No. 3013). Sampling time is scheduled immediately following irrigation when the soil water content is high.

For caprock water monitoring, a set of two piezometer wells, one deep and one shallow, was drilled in each of the same three plots where the porvic samplers are located. Each well is open to the aquifer by a 1-ft perforated section located at the bottom of the well casing. The shallow wells draw water approximately 2 ft below the water table and the deep wells approximately 30 ft below the water table. The selection of the depth and location of the wells was, in part, aided by a simulation model of the expected plume (Domenico and Robbins 1985a). Use of the model for the project is summarized in Appendix A.

As a control, an additional well is located to the north of these wells. The well, which is perforated throughout the entire casing, is drilled to the bottom of the aquifer approximately 80 ft below mean sea level at the site.

All well casings are 2-in. PVC pipes. The well is backfilled with gravel for the perforated section, sealed at the bottom with a cap, and covered with a concrete apron. The wells were developed by pumping and disinfected with chlorine. The monitoring wells are sampled using a Well Wizard™ pump designed to exclude contamination of the samples.

Well locations are shown in Figure 5. The well logs, construction details, and initial water levels in these wells are given in Figures 6 and 7. The soil types shown in these figures were taken from the Foote et al. (1972) Soil Survey which provides general information. An on-site soil survey will be conducted to verify the soil types.

Near-field wells, yet to be drilled, will be located at two locations down gradient from the plots.

In summarizing the soil water and caprock water sampling, the immediate effect of the living filter is indicated by the porvic sampler results. Additional effects from the limestone rock above the water table and the ambient caprock water are reflected by in-field well results. Finally, the mixing effects of the recharge water with the caprock water beyond the irrigated (recharge) plots will be assessed by the near-field wells.

The WWTP effluent is monitored by sampling the effluent downstream of the effluent screen of the WWTP, by either grab or compositing as needed.

The sampling and analysis schedule is presented in Table 1. WRRC is scheduled to collect and analyze samples from the various sources on a weekly basis, whereas the quarterly analyses are anticipated to be primarily conducted by the combined efforts of the Division of Wastewater Management and the Board of Water Supply. The allocation of the analyses to be conducted on the quarterly samples are still being negotiated at the present time. The sequence and frequency of sample collection and the type of analysis performed may change as conditions warrant and initial results may suggest.

RESULTS AND DISCUSSIONS

Monitoring caprock water conditions prior to effluent application provides the necessary baseline data for determining the effects of recharge. The data include the groundwater flow pattern (head and gradient) and the water quality. Pre-application monitoring also aids in the selection of water quality factors as tracers of the recharge water.

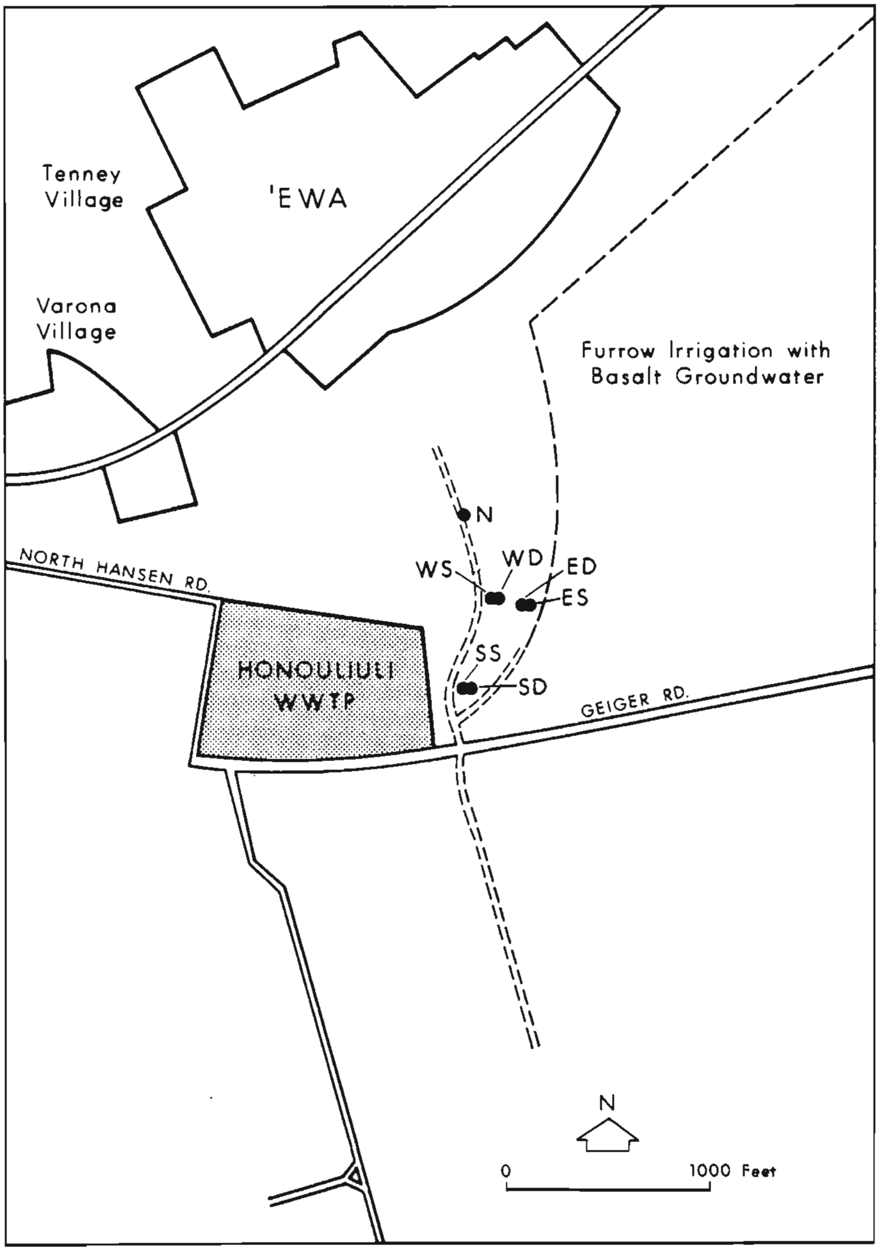
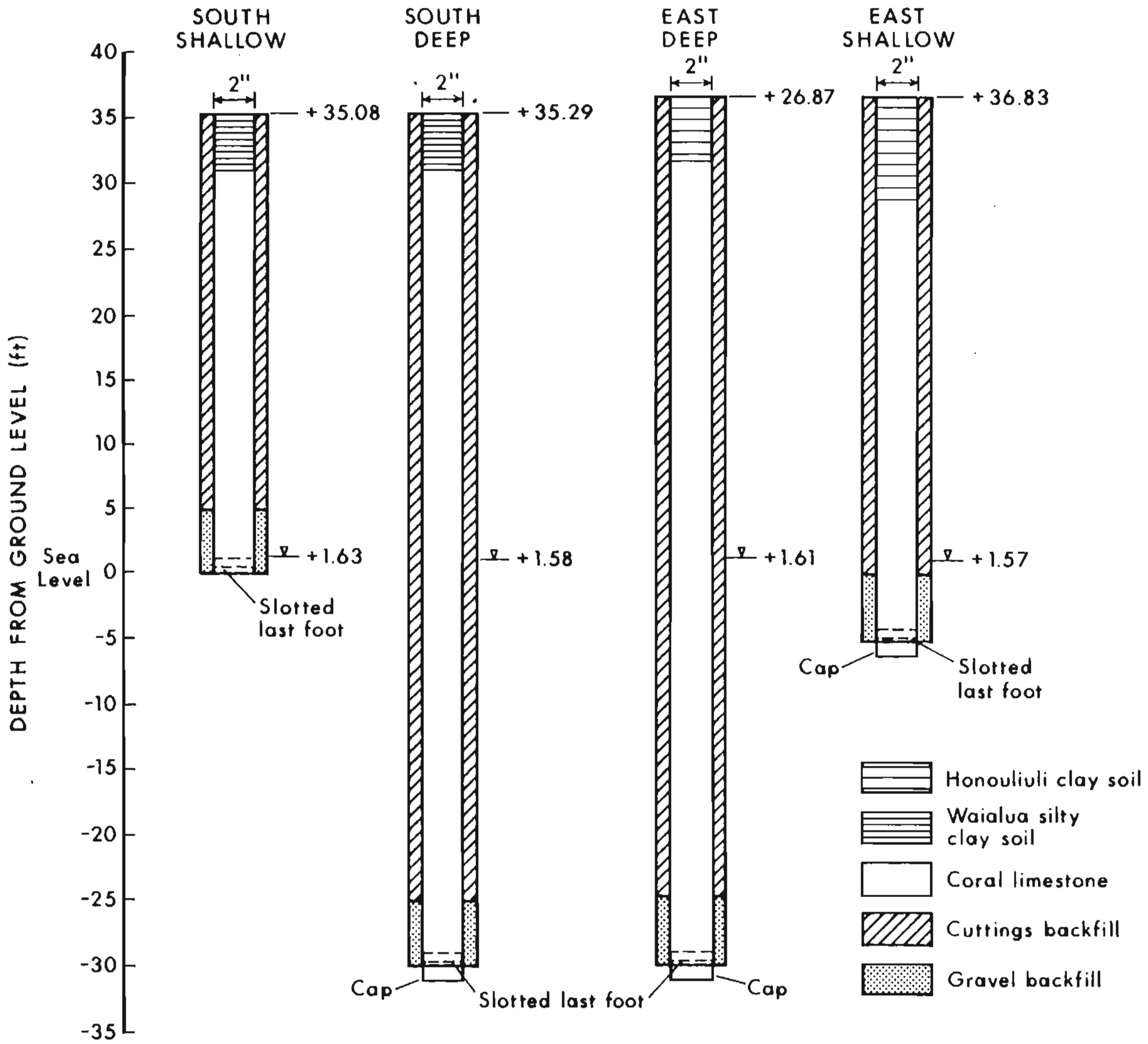
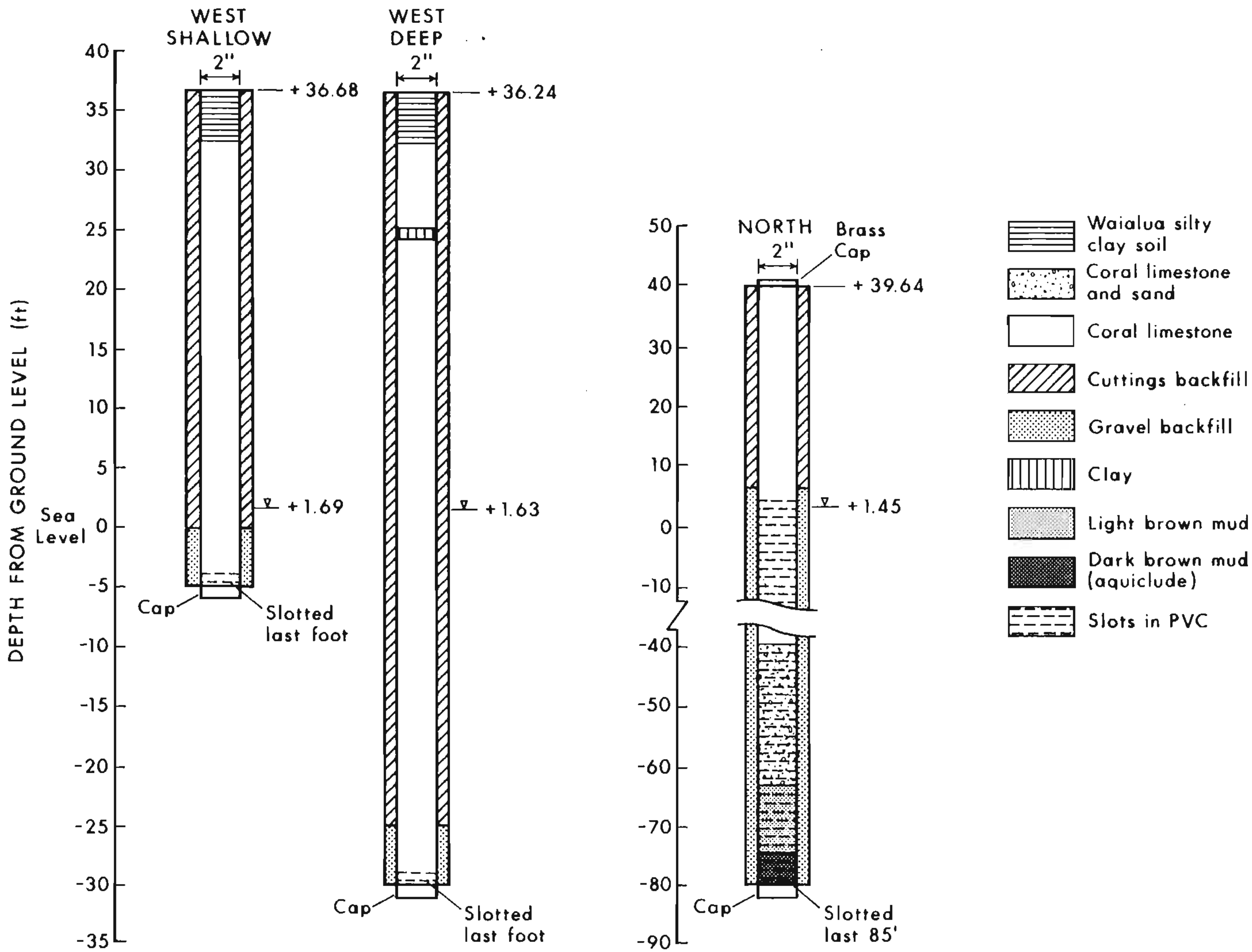


Figure 5. Location of project monitoring wells in Honouliuli, O'ahu, Hawai'i



NOTE: Soil types from Foote et al. (1972).

Figure 6. Well logs of project monitoring wells, south and east



NOTE: Soil types from Foote et al. (1972).

Figure 7. Well logs of project monitoring wells, west and north

TABLE 1. SAMPLING AND ANALYSIS SCHEDULE (TENTATIVE), HONOULIULI TEST SITES

ANALYSIS PARAMETER	SAMPLE COLLECTION & ANALYSIS FREQUENCY	SAMPLE SOURCE			AGENCY CONDUCT'G ANALYSIS
		WWTP Effl.[1]	Soil Water[2]	Ground-water[3]	
Temperature[4]	1/wk	X	X	X	WRRC
pH[4]	1/wk	X	X	X	WRRC
Chemical					
Electrical Conductivity	1/wk	X	X	X	WRRC
Chloride	1/wk	X	X	X	WRRC
Total Dissolved Solids	1/wk	X	X	X	WRRC
BOD_5	1/wk	X	X	X	WRRC
Suspended Solids	1/wk	X	X	X	WRRC
Total Nitrogen	1/wk	X	X	X	WRRC
Bacteria	1/wk	X	X	X	WRRC
Total Coliform	1/wk	X	X	X	WRRC
Fecal Coliforn	1/wk	X	X	X	WRRC
Heavy Metals[5]	1/wk	X	X	X	WRRC
Complete Analysis					
Ca, Mg, Na, K, CO_3, HCO_3, SO_4, NO_3, T-P, Grease/Oil	1/3 mo	X	X	X	DPW
SiO_2, B	1/3 mo	X	X	X	BWS
Pesticides[6]	1/3 mo	X	X	X	BWS

[1]Composite samples during irrigation of California grass and sugarcane test plots (total 1 site).

[2]One sampler each in high- and low-rate plots of California grass and sugarcane (total 4 sites).

[3]At 5- and 30-ft depths below water table for 3 sites: one each in high-rate plots of California grass and sugarcane, and one each at down gradient site; one up gradient control at 30-ft depth below water table (total 7 sites).

[4]To be determined in field at time of collection.

[5]Ag, B, Cd, Cr, Cu, Fe, Zn.

[6]EDB, DBCP, TCP, TCE, PCE, atrazine.

Groundwater Flow Condition

Three sets of head measurements were made at the monitoring wells on different days. Although the three sets of values for the same wells differ somewhat, the relative values among these wells are consistent. Ocean tidal influence at the project site should be negligible since the nearest shoreline is almost two miles away. Also, each set of measurements was made within one hour and, thus, minimized the effects of tidal phase lagging. The EDM (electronic distance measurement) instrument, which is extremely precise, was used for head measurements.

Based on the measured heads, the general groundwater flow direction is approximately in the southeast direction (Fig. 8), a result that suggests the influence of the composite pumping stress imposed by the Oahu Sugar Company wells. This interpretation is confirmed by a composite pumping drawdown analysis of these wells. Although the analysis involves a simplified model and assumptions, the computed flow directions, which reflect the composite effect of pumping of the Oahu Sugar Company wells (Pumps 21-24, 27-30), coincided generally with those based on measured heads. Information on the general flow direction served as a guide to the location of near field monitoring wells.

The groundwater head in the project monitoring area is approximately 1.6 ft above the mean sea level (MSL). Since the water immediately below the water table is relatively fresh, the water quality in a water column that extends to approximately 64 ft below MSL should continue to be relatively fresh, based on the Ghyben-Herzberg relation. This expectation based on hydraulic consideration is generally supported by the water quality data at the north monitoring well which indicates a relatively fresh water-column that extends to -79 ft below MSL. The existence of such a relatively freshwater body is not totally unexpected because the irrigation water used on the adjacent sugarcane field (Fig. 2) is from fresher basaltic water sources.

Water Quality Condition

Pre-application water quality was principally monitored at the project monitoring wells and also, to a minor extent, at the Oahu Sugar Company wells. The water quality factors analyzed thus far by University of Hawaii

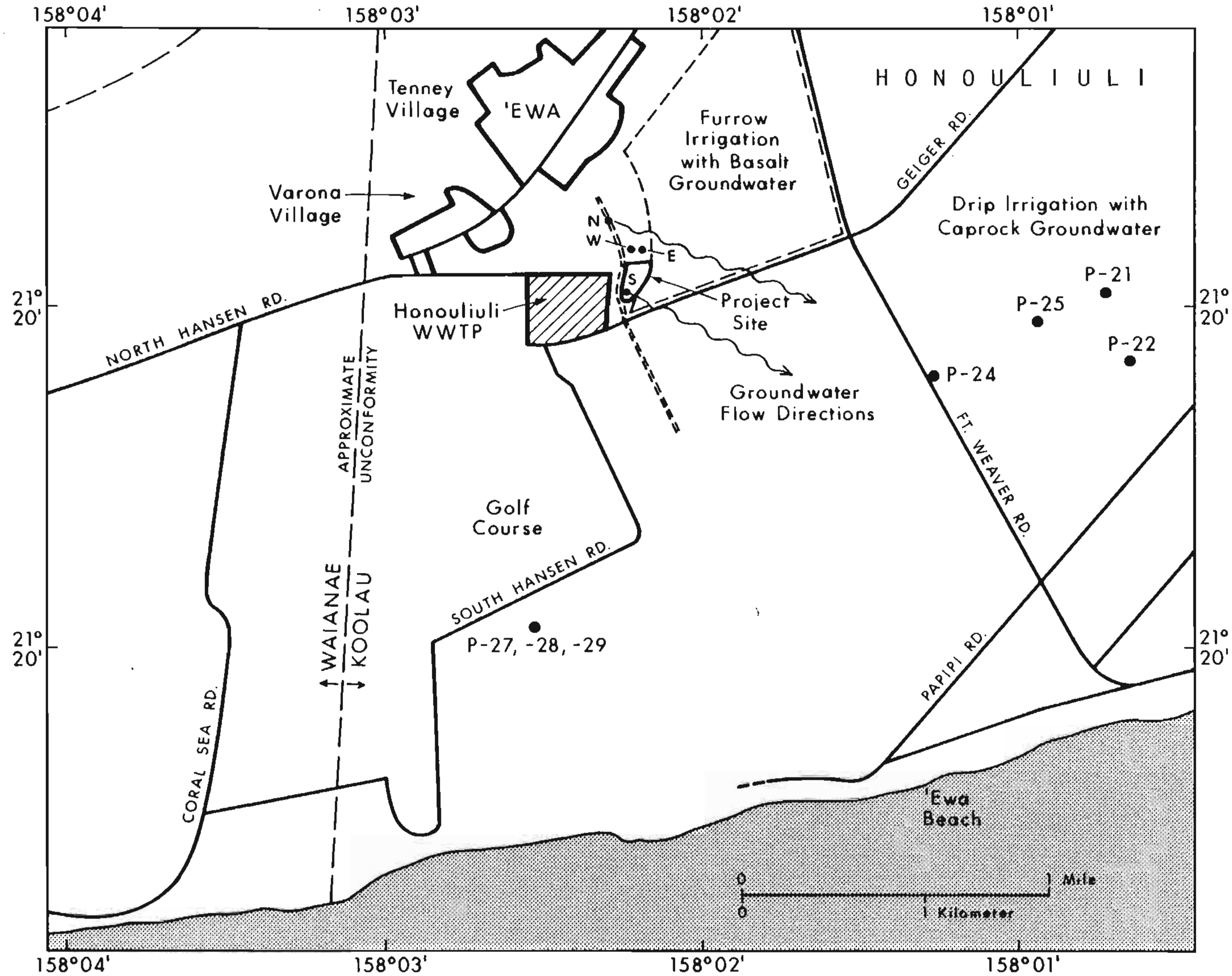


Figure 8. General groundwater flow directions in Honouliuli project vicinity

TABLE 2. INORGANIC AND NITROGEN LEVELS IN HONOULIULI WWTP EFFLUENT AND PROJECT MONITORING WELL WATER

DATE 1986	SOURCE*	Ca	Mg	TOTAL HARDNESS†	K	Cl^-	SO_4	TDS	EC (μmhos/cm)	TURBIDITY (NTU)	SiO_2 (mg/l)	NITROGEN Kjeld.	NITROGEN NO_3-N	NITROGEN Total	ALKALINITY† Carb.	ALKALINITY† Bicarb.	ALKALINITY† Total
		(mg/l)										(mg/l)			(mg/l)		
05/29	East-Shallow	88.8	29.3	342	...	207	..	...	720	...	24	...	...	...	.	...	...
06/30		....	....	...	...	200	60	...	...	...	26	...	0.2	...	.	...	...
07/16		....	....	...	...	220	..	...	...	...	23	...	...	...	.	...	...
07/21		....	....	...	...	250	..	...	...	6.5	26	...	2.5	...	.	...	...
07/29		....	....	...	...	212	..	...	...	...	22	...	2.8	...	0	280	280
05/29	East-Deep	116	25.1	393	...	282	43	680	960	...	35	...	...	...	.	...	...
06/30		...	....	...	...	270	66	...	...	...	48	3.9	2.9	6.8	.	...	...
07/16		...	....	...	...	250	..	...	...	...	31	...	...	...	.	...	...
07/21		...	....	...	...	270	..	...	...	2.1	30	0.2	2.8	3.0	.	...	...
07/29		...	....	...	...	230	..	...	...	...	28	...	3.4	...	0	235	235
05/29	West-Shallow	...	....	...	...	332	..	...	1410	...	20	...	...	...	.	...	...
06/30		...	....	...	...	280	65	...	....	...	40	...	...	...	.	...	...
07/16		...	....	...	...	270	..	...	....	....	31	...	...	...	.	...	...
07/21		...	....	...	...	290	..	...	...	5.0	25	...	4.0	...	.	...	...
07/29		...	....	...	...	287	..	...	...	...	29	...	4.5	...	0	281	281
05/29	West-Deep	123.2	16.6	376	...	287	48	700	1180	...	27	....	...	....	.	...	...
06/30		.....	....	...	...	287	48	...	....	...	27	22.7	0.2	22.9	.	...	...
07/16		.....	....	...	...	280	..	...	....	...	25	....	...	....	.	...	...
07/21		.....	....	...	...	270	..	...	....	5.7	23	0.0	4.0	4.0	.	...	...
07/29		.....	....	...	...	282	..	...	....	...	22	...	4.0	...	0	236	236
05/29	South-Deep	102.2	25.1	359	...	227	51	500	910	...	32	....	...	....	.	...	...
06/27		.....	....	...	103	...	..	...	...	...	..	....	...	....	.	...	...
06/30		.....	....	...	...	220	58	...	...	...	36	18.7	0.0	18.7	.	...	...
07/16		.....	....	...	...	240	..	...	...	...	29	....	...	....	.	...	...
07/21		.....	....	...	...	210	..	...	...	5.6	27	3.3	0.0	3.3	.	...	...
07/29		.....	....	...	...	237	..	...	...	...	25	...	0.7	...	.	...	...

*Refer to Figs. 5-7 for locations and depths of monitoring wells.
†As $CaCO_3$.

TABLE 2.—Continued

DATE 1986	SOURCE	Ca	Mg	TOTAL HARDNESS	K	Cl^-	SO_4	TDS	EC (µmhos/cm)	TURBIDITY (NTU)	SiO_2 (mg/l)	NITROGEN Kjeld.	NITROGEN NO_3-N	NITROGEN Total	ALKALINITY Carb.	ALKALINITY Bicarb.	ALKALINITY Total
		(mg/l)										(mg/l)			(mg/l)		
05/29	North-70'	....	....	...	..	240	..	...	...	...	29	...	3.4	...	..	...	...
	North-60'	....	....	...	..	235	..	...	...	...	33	...	3.2	...	..	...	...
	North-50'	....	....	...	..	236	..	...	...	...	30	...	3.2	...	..	...	...
	North-40'	....	....	...	..	234	..	...	...	...	29	...	3.3	...	..	...	...
	North-35'	....	....	...	..	267	..	...	...	...	24	...	4.2	...	..	...	...
05/29	North-80'	....	....	...	..	490	..	...	...	...	31	...	2.4	...	..	...	...
06/27		....	....	...	64	...	..	...	...	...	..	...	...	...	..	...	...
06/30		....	....	...	..	230	55	...	...	...	36	...	3.4	...	..	...	...
07/16		....	....	...	..	210	..	...	...	...	37	...	...	...	..	...	...
07/21		....	....	...	..	210	..	...	...	5.5	36	0.0	5.2	5.2	..	...	...
07/29		....	....	...	..	227	..	...	...	...	27	...	5.3	...	12	213	225
05/29	Primary WW	27.2	33.4	205	..	239	44	620	990	....	58	....	3.9	....	..	...	...
06/30		....	....	...	..	180	52	...	...	....	80	69.8	2.0	71.8	..	...	...
07/10		....	....	...	..	230	..	...	...	....	..	29.2	...	31	..	...	...
07/11		....	....	...	..	210	..	...	...	....	..	25.2	...	27	..	...	...
07/16		....	....	...	..	220	..	...	...	....	49	....	...	....	..	...	...
07/21		....	....	...	..	230	..	...	...	36.0	61	24.3	1.6	25.9	..	...	...

TABLE 3. HEAVY METALS AND TRACE ORGANIC LEVELS IN HONOULIULI WWTP EFFLUENT AND PROJECT MONITORING WELL WATER

DATE 1986	SOURCE*	HEAVY METALS (mg/l)								ORGANICS (ppt)						
		Ag	B	Cd	Cr	Cu	Fe	Pb	Zn	EDB	DBCP	TCP	PCE	TCE	Atrazine	Ametryn
05/29	East-Deep	0.0	0.0	0.0	0.0	0.0	0.2	0.1	0.0	....	....	....	..	....	...	...
	West-Deep	0.0	...	0.0	0.0	0.0	0.6	0.0	0.0	....	....	....	..	....	...	...
	Primary WW	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.2	....	....	....	40	....	< 0.1	< 0.1
	Pump 27	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0	....	....	....	..	....	...	...
	North-35'	...	...	...	...	...	...	...	...	....	....	....	..	....	...	...
	North-60'	...	...	...	...	...	...	...	...	....	....	....	..	....	...	...
06/04	North-80'	...	...	...	...	...	...	...	...	N.D.†	N.D.	N.D.	N.D.	N.D.	13.0	13.6
	North-40'	...	...	...	...	...	...	...	...	N.D.	N.D.	N.D.	N.D.	N.D.	12.6	8.2
	Primary WW	...	...	...	...	...	...	...	...	N.D.	N.D.	N.D.	40	N.D.	....	...
06/19	Pump 20	...	...	...	...	...	...	...	...	....	....	....	..	....	1.4	0.45
	Pump 21	...	...	...	...	...	...	...	...	....	....	....	..	....	1.1	0.34
	Pump 22	...	...	...	...	...	...	...	...	....	....	....	..	....	1.3	0.34
	Pump 23	...	...	...	...	...	...	...	...	....	....	....	..	....	2.3	1.1
	Pump 24	...	...	...	...	...	...	...	...	....	....	....	..	....	1.8	0.59
	Pump 27	...	...	...	...	...	...	...	...	....	....	....	..	....	0.4	0.64
	Pump 30	...	...	...	...	...	...	...	...	....	....	....	..	....	1.9	0.34

NOTE: Limit of detectability: EDB = 20 ppt, DBCP = 10 ppt, TCP = 50 ppt, PCE = 10 ppt, TCE = 100 ppt, atrazine = 2 ppb, and ametryn = 2 ppb.

*See Figs. 5-7 for locations and depths of monitoring wells.

†N.D. = None detectable.

TABLE 4. BACTERIOLOGICAL QUALITY OF PROJECT MONITORING WELL WATERS

1986 (mo/ day)	MONITORING WELL	BACTERIA					
		Fecal Coliform	Total Coliform	Fecal Strep.	Entero-coccus	Total Bacteria	Clostridium perfringens
		(Organisms/100 ml)					
06/04	North-38'*	52	> 500	126	81	29 600	< 1
06/23	North-55'*	< 1	500	2	2	112 000	< 1
07/08	East-Shallow	< 1	< 1	920	< 1		< 1
	East-Deep	< 1	< 1	< 1	< 1		< 1
	West-Shallow	< 1	< 1	40	< 1		< 1
	West-Deep	< 1	< 1	< 1	< 1		< 1
	North-80'	< 1	< 1	< 1	< 1		< 1
	South-Deep	< 1	< 1	< 1	< 1		< 1

*Sample-collection depth.

laboratories are inorganics, trace organics, heavy metals, and bacteria. Data are tabulated by inorganics and nitrogen (Table 2), heavy metals and trace organics (Table 3), and bacteriological quality (Table 4).

Based on the project data, the WWTP effluent has expected low salinity, as reflected by chlorides, total dissolved solids, and electrical conductivity (EC); however, the average value of chlorides, 220 mg/l, is slightly lower than expected. The initial silica (SiO_2) in the effluent is approximately 62 mg/l, a value that falls within the expected order of magnitude and reflects basaltic water origin. Eight heavy metals (Ag, B, Cd, Cr, Cu, Fe, Pb, Zn) are below detection levels. Trace organics (EDB, DBCP, TCP, TCE, atrazine, ametryn) are similarly all below detection limits. The only exception is the PCE value of 40 ppt (ng/l) which is being confirmed by resampling.

Based on the project data, the caprock water chlorides at the project monitoring wells range between 220 and 290 mg/l. These values are considerably lower than those reported for the Oahu Sugar Company wells tapping the eastern part of the 'Ewa Plain's caprock water which ranges between 800 and 1100 mg/l according to unpublished 1986 data from Dames and Moore. This apparent distribution of areal chlorides, yet to be fully confirmed, may be attributed to (1) the differences in chlorides in the irrigation water, as applied from one area to another area; (2) the close proximity of the Oahu Sugar Company wells to the coastline; (3) the pumping stress imposed by these wells; or (4) any combination of these possibilities. Further investigation is underway.

Although chlorides will still serve as indicators of recharge for this project, other water quality factors are being examined for this purpose. Potential candidates include silica and nitrogen because the level of both are considerably higher in the effluent than in the caprock water. However, their effectiveness for such use in this project is pending further assessments because, in a previously completed project in Mililani (Lau et al. 1975), the levels of silica and nitrogen in the percolate were considerably reduced after passing through the living filter. Some similar reductions could occur at the project site and, thereby, possibly render silica and nitrogen less effective as indicators.

As expected for limestone, the calcium and alkalinity levels in the caprock water are high. In fact, their levels are much higher in the caprock water than in the effluent. Thus, although they may be useful as tracers for this project, further assessment is necessary.

It is interesting to note that atrazine and ametryn levels in the north monitoring well ranged above 10 ppb (μg/l) as compared with those in the Oahu Sugar Company well waters which are about one order of magnitude lower. These organics are regularly used as herbicides in sugarcane cultural practices. The range mentioned above is presently considered to be below health significance.

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APPENDIX CONTENTS

Figures

Tables

APPENDIX A. MODELING A PLUME FROM PRIMARY EFFLUENT APPLICATION TO A CROP PLOT

This summarizes an attempt to estimate the resulting plume shape and concentration formation by using a three-dimensional model proposed by Domenico and Robbins. The primary goal of this investigation is to provide information that will aid in the determination of observation well placement. This report explains the procedure used to obtain results using the three-dimensional model.

Model

Two papers by Domenico and Robbins in 1985 advanced a different approach towards plume analysis in groundwater. In their first paper, "A New Method of Contaminant Plume Analysis" (Domenico and Robbins 1985a), an analytical expression is developed to estimate the plume resulting from a three-dimensional source rather than the commonly used point source models. The usual assumptions are made: isotropic and homogeneous aquifer formation properties, constant ambient flow velocity, and constant concentrations of the contaminant source and ambient waters. The model only addresses plume formation that results from advective and dispersive phenomena. The model ignores chemical reactions and is thus valid only for conservative contaminants such as chlorides.

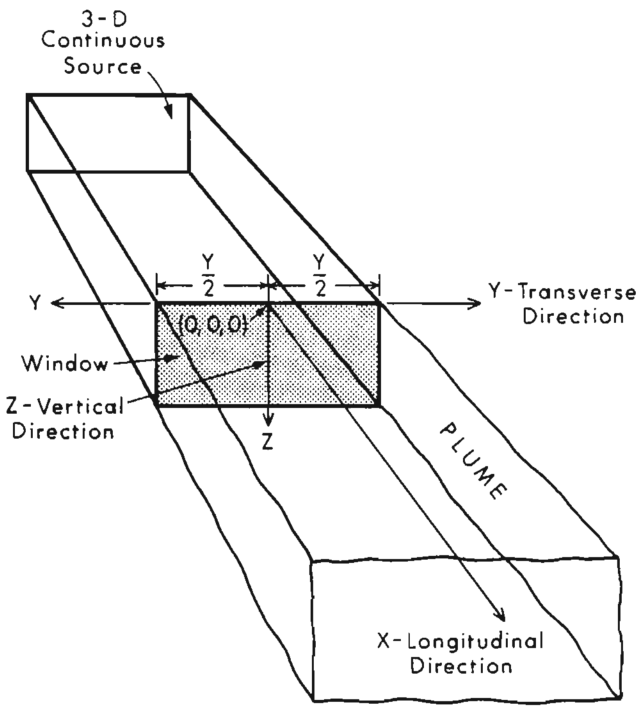
In essence, the model provides a window through which a continuous source of a pollutant enters the ambient groundwater environment (see App. Fig. A.1). This model can represent an actual physical condition if one can estimate the actual horizontal and vertical dimensions of a contaminant source. By using an extended pulse type of approach and mathematical integration, the resulting analytical expression derived by Domenico and Robbins (1985a) is

$$
\begin{aligned}
C(x,y,z,t) = (C_0/8) \\
& \{\mathrm{erfc}[(x - vt)/2(Dxt)^{1/2}]\} \\
& \{\mathrm{erf}[y + Y/2)/2(Dy/v)^{1/2}] - \\
& \ \mathrm{erf}[(y - Y/2)/2(Dy/v)^{1/2}]\} \\
& \{\mathrm{erf}[(z + Z)/2(Dz/v)^{1/2}] - \\
& \ \mathrm{erf}[(z - Z)/2(Dz/v)^{1/2}]\}
\end{aligned}
$$

where

x, y, z, t = space and time variables to be investigated
C = resulting aquifer water concentration
G_0 = ambient aquifer water concentration
v = ambient longitudinal groundwater velocity
Dx = longitudinal dispersion coefficient
Dy = transverse dispersion coefficient
Dz = vertical dispersion coefficient
Y = horizontal dimension of source
Z = vertical dimension of source.

The model can be alternately expressed by replacing D/v terms by dispersivity coefficients Ax, Ay, and Az.



Appendix Figure A.1. Modified definition sketch of source and plume for unconfined aquifer model by Domenico and Robbins (1985a)

The second paper presented by Domenico and Robbins (1985b) entitled "The Displacement of Connate Water from Aquifers" basically modifies the original analytical solution by incorporating actual concentrations in the groundwater and the contaminating percolate. This was done to provide a model that could handle situations where the displacing contaminant was either of higher or lower concentrations relative to the ambient aquifer water concentrations of the same chemical pollutant. The resulting model, which was used to estimate the plume formation for the project, has the following form,

$$\begin{aligned} C(x,y,z,t) = {} & Co - [(Co - Ci)/8] \\ & \{erfc[(x - vt)/2(A_x vt)^{\frac{1}{2}}]\} \\ & \{erf[(y + Y/2)/2(A_y x)^{\frac{1}{2}}] \\ & - erf[(y - Y/2)/2(A_y x)^{\frac{1}{2}}]\} \\ & \{erf[(z + Z)/2(A_z x)^{\frac{1}{2}}] \\ & - erf[(z - Z)/2(A_z x)^{\frac{1}{2}}]\} \end{aligned}$$

where

x,y,z,t = space and time variables to be investigated
C = resulting aquifer water concentration
Co = ambient aquifer water concentration
Ci = displacement water concentration
v = ambient longitudinal groundwater velocity
A_x = longitudinal dispersivity coefficient
A_y = transverse dispersivity coefficient
A_z = vertical dispersivity coefficient
Y = horizontal dimension of source
Z = vertical dimension of source.

Domenico and Robbins Model

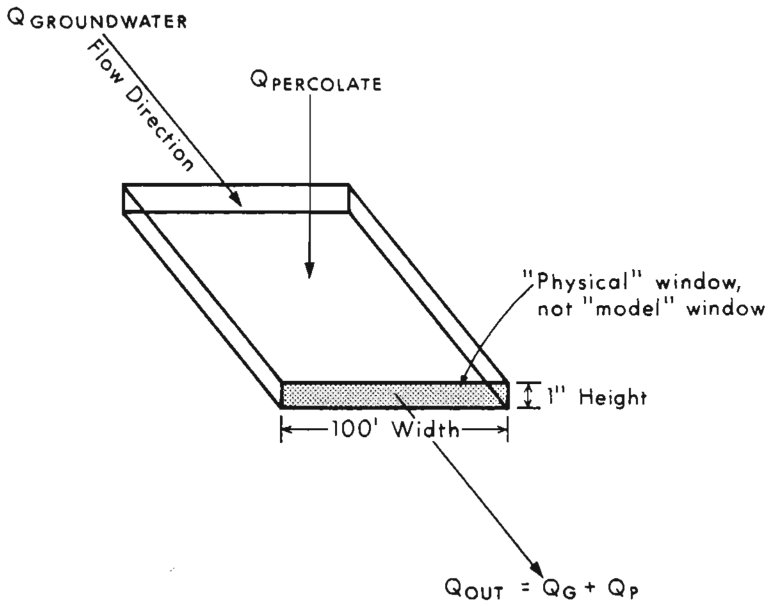
The primary project objective is to recharge the brackish caprock aquifer with primary treated wastewater effluent from the Honouliuli Wastewater Treatment Plant. However, it appears that chlorides would have limited usefulness as a viable tracer since the caprock chloride concentrations are surprisingly similar to the effluent concentration. Further chemical analysis suggests that silica, nitrogen, and temperature could be used as tracers to help define the resulting plume.

The effluent will be applied over six individual 0.5 acre plots that will be irrigated up to 5 hr/day, at a low rate of 2 in./day and a high rate of 4 in./day and will result in a three dimensional essentially continuous source.

The necessary parameters for input to the model are

1. Horizontal and vertical dimensions
2. Hydraulic gradient
3. Hydraulic conductivity
4. Formation dispersivities
5. Formation and percolate silica concentrations
6. Porosity
7. Time.

The 100-ft width of each of the 0.5-acre plots easily defines the horizontal dimension of the source. The vertical dimension of the source was more difficult to estimate but was accomplished as follows. In a seminar report by a graduate student, Bert Saito, the Hantush model was used to estimate the resulting mounding effect upon the water table due to the infiltration rate of the percolate. His results suggested a mound of approximately 1 in. would result from the proposed irrigation rate for the project. However, this value cannot be used as the vertical dimension of the source since conservation of mass will be violated. In other words, the amount of daily irrigation and groundwater flow through a window of 100 ft by 1 in. will not be possible at the calculated groundwater flow velocity. Either the velocity or the window through which the flow occurs must be increased sufficiently to accommodate the entire mass flux. The most reasonable candidate to change should be the window dimensions. Since the horizontal dimension is already known to be 100 ft, the vertical dimension for the model window will be altered. This is done by estimating the contribution of groundwater and irrigation percolate water to a control volume of 100 ft x 232 ft x 1 in. (see App. Fig. A.2). Groundwater contribution is estimated by taking the calculated groundwater flow velocity and multiplying it by the 100 ft x 1 in. physical window through which the groundwater will pass. Irrigation percolate contribution is estimated by multiplying the plot area (0.5 acre) by the daily application rate of effluent. Holding the ambient groundwater flow velocity constant, the resulting vertical dimension necessary to allow this volume of water to



Appendix Figure A.2. Control volume used to calculate model window

pass through is then calculated. This is the vertical dimension used in the model.

The maximum and minimum conditions for plume formation were investigated by lumping together all the reasonable respective maximum and minimum non-variable coefficients for the model. Hydraulic conductivity in the caprock aquifer has been estimated to be between 1000 (min) and 5000 (max) ft/day. The hydraulic gradient computed with measured groundwater table values by surveying on three separate dates was found to range between 0.0004 (min) and 0.0007 (max). The porosity was held constant for both maximum and minimum conditions at a value of 0.2. From these parameters the actual flow velocity was computed, at a minimum of 2.0 ft/day to a maximum of 17.5 ft/day, which in turn was used to compute the vertical dimension of the model's window. The resulting vertical dimensions were 18.23 ft (min) and 4.23 ft (max). Also, dispersivity values were estimated from an unpublished WRRC report on macrodispersivity characteristics of selected Hawaii aquifers. These values corresponded to longitudinal values between hundreds to tens of feet while transverse and vertical values were estimated to be equal and between a few to tenths of feet. The final values chosen were longitudinal values between 300 (max) and 10 (min) ft. and transverse and vertical values between 3.0 (max) and 0.1 (min) ft.

These maximum and minimum values were grouped accordingly and used together with the average concentrations found by chemical analysis for silica in the ambient caprock water (30.6 mg/l) and the sewage effluent (62.1 mg/l). Finally, the time period over these parameters was varied between 90 and 365 days to estimate steady-state conditions. Results from the various computer runs can be found in Appendix Table A.1.

Discussion and Results

The size of the plume resulting from both minimum and maximum conditions was defined by the point at which the silica concentration returned to the ambient caprock silica concentration. To begin, the minimum conditions at t = 90 days produced a plume which was small in the transverse and vertical directions, less than 75 ft and 30 ft respectively, and along the longitudinal center line reached a distance between 350 to 400 ft down gradient. Silica concentrations near the plot source were essentially the same as percolate concentrations within a distance approximately 100 ft down gradient. Beyond 100 ft down gradient, the silica concentrations rapidly decreased approaching the ambient caprock water conditions. This would imply a plug-flow type of phenomenon where little mixing is occurring. At t = 365 days the plume for the minimized conditions is still quite small in the transverse and vertical directions, essentially the same as t = 90 days, while the longitudinal distance of the plume extends between 1050 and 2000 ft down gradient. Thus, it appears that the plume is elongating further, an implication that steady-state conditions do not occur at t = 90 days for the minimum conditions.

The maximized conditions at t = 90 days resulted in a plume which is slightly wider in both the transverse and vertical directions, slightly greater than 100 ft and 35 ft, respectively. The plume was more elongated down gradient along the longitudinal center line, slightly greater than 2000 ft, than the minimized conditions presented earlier. However, silica concentrations near the plot source, at a distance of 100 ft down gradient, were much reduced and approached the ambient caprock concentrations for the maximized conditions. Also, the silica concentrations decreased gradually along the longitudinal axis which makes the plume appear to be "stretched out" compared to the plume resulting from the minimum conditions. This suggests that much more mixing is occurring between the percolate and ambient groundwater in the maximized case. This makes sense since the dispersivities and flow velocity are so great that much mixing is expected to take place between the caprock and percolate waters. The difference between the plume size and silica concentrations for t = 90 and t = 365 days was very little and suggests that at t = 90 days the plume is already near steady-state conditions.

The results are summarized as follows:

Extreme Limits of Ambient Silica
Concentrations at t = 90 Days

	Long. Dist.	Trans. Dist.	Depth
Minimum	< 350 ft	< 75 ft	< 30 ft
Maximum	2000 ft	100 ft	35 ft

Conclusion

The size of the actual plume will most likely be closer to the minimum condition. This is due to the fact that at the maximized conditions it is very rare to encounter a high hydraulic conductivity coupled with a high hydraulic gradient. For this reason it is advisable to place the downgradient observation wells close to the project plots at distances less than 350 ft along the longitudinal direction. The resulting plume will probably be quite thin in width and depth thus these wells should be placed near the longitudinal center line and be made shallow in depth, i.e., between 5 and 30 ft deep.

APPENDIX TABLE A.1. PARAMETER VALUES FOR MINIMUM PLUME SIMULATION AT 90 DAYS

3-D Plume Analysis Input Data

Hydraulic Conductivity, K (L/T)	1000.00
Hydraulic Gradient, J	0.0004
Porosity, n	0.20
Actual Flow Velocity (L/T)	2.00
Longitudinal Dispersivity (L)	10.00
Transverse Dispersivity (L)	0.10
Vertical Dispersivity (L)	0.10
Time (T)	90.00
Formation Concentration, Co (M/L^3)	30.60
Pollutant Concentration, Ci (M/L^3)	62.10
Rectangular Source Dimensions	
Width of Source (L)	100.00
Height of Source (L)	18.23

NOTE: X = longitudinal position of plume
Y = transverse position of plume at X from center line
Z = vertical position of plume at X from center line (refer to App. Fig. A.1).

NOTE: Model is valid for any consistent length measurement for x, y, z directions.

$\frac{Y}{2}$ (ft)	SiO_2 CONCENTRATION (mg/l) Z (ft)							
	Z=0	Z=5	Z=10	Z=15	Z=20	Z=25	Z=30	Z=35
				X = 50 ft				
0.0	61.6	61.6	61.5	56.9	39.5	31.1	30.6	30.6
25.0	61.6	61.6	61.5	56.9	39.5	31.1	30.6	30.6
50.0	46.1	46.1	46.0	43.7	35.1	30.9	30.6	30.6
75.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
100.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
				X = 100 ft				
0.0	59.2	59.2	58.3	52.5	40.5	32.5	30.7	30.6
25.0	59.2	59.2	58.3	52.5	40.5	32.5	30.7	30.6
50.0	44.9	44.9	44.4	41.5	35.6	31.5	30.7	30.6
75.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
100.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
				X = 150 ft				
0.0	52.4	52.2	50.9	46.3	38.7	33.0	30.9	30.6
25.0	52.4	52.2	50.9	46.3	38.7	33.0	30.9	30.6
50.0	41.5	41.4	40.8	38.5	34.7	31.8	30.8	30.6
75.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
100.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6

APPENDIX TABLE A.1.—Continued

Y/2 (ft)	SiO$_2$ CONCENTRATION (mg/l) Z (ft)							
	Z=0	Z=5	Z=10	Z=15	Z=20	Z=25	Z=30	Z=35
				X = 200 ft				
0.0	42.2	42.0	41.1	38.7	35.1	32.3	31.0	30.6
25.0	42.2	42.0	41.1	38.7	35.1	32.3	31.0	30.6
50.0	36.4	36.3	35.9	34.6	32.9	31.4	30.8	30.6
75.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
100.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
				X = 250 ft				
0.0	34.4	34.3	34.0	33.2	32.1	31.2	30.8	30.6
25.0	34.4	34.3	34.0	33.2	32.1	31.2	30.8	30.6
50.0	32.5	32.5	32.3	31.9	31.4	30.9	30.7	30.6
75.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
100.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
				X = 300 ft				
0.0	31.3	31.3	31.2	31.1	30.9	30.7	30.6	30.6
25.0	31.3	31.3	31.2	31.1	30.9	30.7	30.6	30.6
50.0	31.0	30.9	30.9	30.8	30.7	30.7	30.6	30.6
75.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
100.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
				X = 350 ft				
0.0	30.7	30.7	30.7	30.6	30.6	30.6	30.6	30.6
25.0	30.7	30.7	30.7	30.6	30.6	30.6	30.6	30.6
50.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
75.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
100.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
				X = 400 ft				
0.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
25.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
50.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
75.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
100.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
				X = 450 ft				
0.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
25.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
50.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
75.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
100.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
				X = 500 ft				
0.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
25.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
50.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
75.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
100.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6

APPENDIX TABLE A.2. PARAMETER VALUES FOR MINIMUM PLUME SIMULATION AT 365 DAYS

3-D Plume Analysis Input Data

Hydraulic Conductivity, K (L/T).............	1000.00
Hydraulic Gradient, J.......................	0.0004
Porosity, n.................................	0.20
Actual Flow Velocity (L/T)..................	2.00
Longitudinal Dispersivity (L)...............	10.00
Transverse Dispersivity (L).................	0.10
Vertical Dispersivity (L)...................	0.10
Time (T)....................................	365.00
Formation Concentration, Co (M/L^3)..........	30.60
Pollutant Concentration, Ci (M/L^3)..........	62.10
Rectangular Source Dimensions	
Width of Source (L).........................	100.00
Height of Source (L)........................	18.23

NOTE: X = longitudinal position of plume
Y = transverse position of plume at X from center line
Z = vertical position of plume at X from center line (refer to App. Fig. A.1).

NOTE: Model is valid for any consistent length measurement for X, Y, Z directions.

$\frac{Y}{2}$ (ft)	SiO_2 CONCENTRATION (mg/l) Z (ft)							
	Z=0	Z=5	Z=10	Z=15	Z=20	Z=25	Z=30	Z=35
				X = 150 ft				
0.0	62.1	61.9	60.0	53.4	42.4	34.0	31.1	30.6
25.0	62.1	61.9	60.0	53.4	42.4	34.0	31.1	30.6
50.0	46.3	46.2	45.3	42.0	36.5	32.3	30.8	30.6
75.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
100.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
				X = 300 ft				
0.0	61.5	60.7	57.6	51.4	43.5	36.6	32.6	31.1
25.0	61.5	60.7	57.5	51.4	43.5	36.6	32.6	31.1
50.0	46.1	45.6	44.1	41.0	37.1	33.6	31.6	30.8
75.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
100.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
				X = 450 ft				
0.0	60.1	59.0	55.7	50.3	43.9	38.0	33.9	31.8
25.0	59.9	58.9	55.6	50.3	43.8	38.0	33.9	31.8
50.0	45.3	44.8	43.2	40.5	37.2	34.3	32.3	31.2
75.0	30.7	30.7	30.7	30.7	30.7	30.6	30.6	30.6
100.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6

APPENDIX TABLE A.2.—Continued

$\frac{Y}{2}$ (ft)	SiO$_2$ CONCENTRATION (mg/l) Z (ft)							
	Z=0	Z=5	Z=10	Z=15	Z=20	Z=25	Z=30	Z=35
				X = 600 ft				
0.0	55.1	54.1	51.4	47.2	42.4	37.9	34.4	32.3
25.0	54.8	53.9	51.2	47.0	42.3	37.8	34.4	32.3
50.0	42.8	42.4	41.0	38.9	36.5	34.2	32.5	31.5
75.0	30.9	30.9	30.8	30.8	30.7	30.7	30.6	30.6
100.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
				X = 750 ft				
0.0	42.4	42.0	40.7	38.8	36.6	34.6	32.9	31.8
25.0	42.2	41.7	40.5	38.6	36.5	34.5	32.9	31.7
50.0	36.5	36.3	35.7	34.7	33.6	32.6	31.8	31.2
75.0	30.8	30.8	30.8	30.8	30.7	30.7	30.6	30.6
100.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
				X = 900 ft				
0.0	32.7	32.6	32.4	32.1	31.7	31.4	31.1	30.9
25.0	32.6	32.5	32.3	32.0	31.7	31.3	31.1	30.9
50.0	31.6	31.6	31.5	31.3	31.2	31.0	30.8	30.7
75.0	30.7	30.7	30.7	30.6	30.6	30.6	30.6	30.6
100.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
				X = 1050 ft				
0.0	30.7	30.7	30.7	30.7	30.7	30.6	30.6	30.6
25.0	30.7	30.7	30.7	30.7	30.7	30.6	30.6	30.6
50.0	30.7	30.6	30.6	30.6	30.6	30.6	30.6	30.6
75.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
100.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
				X = 1200 ft				
0.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
25.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
50.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
75.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
100.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
				X = 1350 ft				
0.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
25.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
50.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
75.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
100.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
				X = 1500 ft				
0.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
25.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
50.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
75.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6
100.0	30.6	30.6	30.6	30.6	30.6	30.6	30.6	30.6

APPENDIX TABLE A.3. PARAMETER VALUES FOR MAXIMUM PLUME SIMULATION AT 90 DAYS

3-D Plume Analysis Input Data

Hydraulic Conductivity, K (L/T)	5000.00
Hydraulic Gradient, J	0.0007
Porosity, n	0.20
Actual Flow Velocity (L/T)	17.50
Longitudinal Dispersivity (L)	300.00
Transverse Dispersivity (L)	3.00
Vertical Dispersivity (L)	3.00
Time (T)	90.00
Formation Concentration, Co (M/L^3)	30.60
Pollutant Concentration, Ci (M/L^3)	62.10
Rectangular Source Dimensions	
Width of Source (L)	100.00
Height of Source (L)	4.23

NOTE: X = longitudinal position of plume
Y = transverse position of plume at X from center line
Z = vertical position of plume at X from center line (refer to App. Fig. A.1).

NOTE: Model is valid for any consistent length measurement for X, Y, Z directions.

$\frac{Y}{2}$ (ft)	SiO_2 CONCENTRATION (mg/l) Z (ft)							
	Z=0	Z=5	Z=10	Z=15	Z=20	Z=25	Z=30	Z=35
				X = 200 ft				
0.0	33.0	33.0	32.9	32.8	32.6	32.5	32.3	32.0
25.0	32.7	32.7	32.6	32.5	32.4	32.2	32.1	31.9
50.0	32.0	32.0	31.9	31.9	31.8	31.7	31.6	31.4
75.0	31.3	31.3	31.2	31.2	31.2	31.1	31.1	31.0
100.0	30.8	30.8	30.8	30.8	30.8	30.8	30.7	30.7
				X = 400 ft				
0.0	31.9	31.9	31.9	31.9	31.8	31.8	31.7	31.6
25.0	31.8	31.8	31.8	31.8	31.7	31.7	31.6	31.5
50.0	31.5	31.5	31.5	31.5	31.4	31.4	31.4	31.3
75.0	31.2	31.2	31.2	31.1	31.1	31.1	31.1	31.0
100.0	30.9	30.9	30.9	30.9	30.9	30.9	30.8	30.8
				X = 600 ft				
0.0	31.5	31.5	31.5	31.5	31.4	31.4	31.4	31.3
25.0	31.4	31.4	31.4	31.4	31.4	31.4	31.3	31.3
50.0	31.3	31.3	31.3	31.3	31.2	31.2	31.2	31.2
75.0	31.1	31.1	31.1	31.1	31.1	31.0	31.0	31.0
100.0	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.8

APPENDIX TABLE A.3.—Continued

$\frac{Y}{2}$ (ft)	SiO_2 CONCENTRATION (mg/l) Z (ft)							
	Z=0	Z=5	Z=10	Z=15	Z=20	Z=25	Z=30	Z=35
				X = 800 ft				
0.0	31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.2
25.0	31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.1
50.0	31.1	31.1	31.1	31.1	31.1	31.1	31.1	31.1
75.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	30.9
100.0	30.9	30.9	30.9	30.9	30.9	30.8	30.8	30.8
				X = 100 ft				
0.0	31.1	31.1	31.1	31.1	31.1	31.1	31.0	31.0
25.0	31.1	31.1	31.1	31.0	31.0	31.0	31.0	31.0
50.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0
75.0	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.9
100.0	30.8	30.8	30.8	30.8	30.8	30.8	30.8	30.8
				X = 1200 ft				
0.0	31.0	31.0	31.0	31.0	31.0	30.9	30.9	30.9
25.0	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.9
50.0	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.9
75.0	30.9	30.9	30.9	30.9	30.8	30.8	30.8	30.8
100.0	30.8	30.8	30.8	30.8	30.8	30.8	30.8	30.8
				X = 1400 ft				
0.0	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.9
25.0	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.8
50.0	30.8	30.8	30.8	30.8	30.8	30.8	30.8	30.8
75.0	30.8	30.8	30.8	30.8	30.8	30.8	30.8	30.8
100.0	30.8	30.8	30.8	30.8	30.8	30.8	30.8	30.7
				X = 1600 ft				
0.0	30.8	30.8	30.8	30.8	30.8	30.8	30.8	30.8
25.0	30.8	30.8	30.8	30.8	30.8	30.8	30.8	30.8
50.0	30.8	30.8	30.8	30.8	30.8	30.8	30.8	30.8
75.0	30.8	30.8	30.8	30.8	30.8	30.8	30.8	30.7
100.0	30.7	30.7	30.7	30.7	30.7	30.7	30.7	30.7
				X = 1800 ft				
0.0	30.8	30.8	30.8	30.8	30.8	30.7	30.7	30.7
25.0	30.8	30.8	30.7	30.7	30.7	30.7	30.7	30.7
50.0	30.7	30.7	30.7	30.7	30.7	30.7	30.7	30.7
75.0	30.7	30.7	30.7	30.7	30.7	30.7	30.7	30.7
100.0	30.7	30.7	30.7	30.7	30.7	30.7	30.7	30.7
				X = 2000 ft				
0.0	30.7	30.7	30.7	30.7	30.7	30.7	30.7	30.7
25.0	30.7	30.7	30.7	30.7	30.7	30.7	30.7	30.7
50.0	30.7	30.7	30.7	30.7	30.7	30.7	30.7	30.7
75.0	30.7	30.7	30.7	30.7	30.7	30.7	30.7	30.7
100.0	30.7	30.7	30.7	30.7	30.7	30.7	30.7	30.7

APPENDIX TABLE A.4. PARAMETER VALUES FOR MAXIMUM PLUME SIMILATION AT 365 DAYS

3-D Plume Analysis Input Data

Hydraulic Conductivity, K (L/T).............	5000.00
Hydraulic Gradient, J.........................	0.000
Porosity, n...................................	0.20
Actual Flow Velocity (L/T)...................	17.50
Longitudinal Dispersivity (L)...............	300.00
Transverse Dispersivity (L).................	3.00
Vertical Dispersivity (L)...................	3.00
Time (T)......................................	365.00
Formation Concentration, Co (M/L^3)..........	30.60
Pollutant Concentration, Ci (M/L^3)..........	62.10
Rectangular Source Dimensions	
Width of Source (L).........................	100.00
Height of Source (L)........................	4.23

NOTE: X = longitudinal position of plume
Y = transverse position of plume at X from center line
Z = vertical position of plume at X from center line (refer to App. Fig. A.1).

NOTE: Model is valid for any consistent length measurement for X, Y, Z directions.

Y/2 (ft)	SiO_2 CONCENTRATION (mg/l)							
	Z (ft)							
	Z=0	Z=5	Z=10	Z=15	Z=20	Z=25	Z=30	Z=35
				X = 200 ft				
0.0	33.2	33.2	33.1	33.0	32.8	32.6	32.4	32.2
25.0	32.9	32.9	32.8	32.7	32.5	32.4	32.2	32.0
50.0	32.1	32.1	32.1	32.0	31.9	31.8	31.6	31.5
75.0	31.3	31.3	31.3	31.3	31.2	31.2	31.1	31.0
100.0	30.8	30.8	30.8	30.8	30.8	30.8	30.8	30.7
				X = 400 ft				
0.0	32.1	32.1	32.1	32.0	32.0	31.9	31.8	31.8
25.0	32.0	32.0	31.9	31.9	31.9	31.8	31.7	31.7
50.0	31.6	31.6	31.6	31.6	31.6	31.5	31.5	31.4
75.0	31.2	31.2	31.2	31.2	31.2	31.2	31.1	31.1
100.0	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.9
				X = 600 ft				
0.0	31.7	31.6	31.6	31.6	31.6	31.6	31.5	31.5
25.0	31.6	31.6	31.6	31.6	31.5	31.5	31.5	31.4
50.0	31.4	31.4	31.4	31.4	31.4	31.3	31.3	31.3
75.0	31.2	31.2	31.2	31.1	31.1	31.1	31.1	31.1
100.0	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.9

APPENDIX TABLE A.4.—Continued

$\frac{Y}{2}$ (ft)	SiO$_2$ CONCENTRATION (mg/l) Z (ft)							
	Z=0	Z=5	Z=10	Z=15	Z=20	Z=25	Z=30	Z=35
				X = 800 ft				
0.0	31.4	31.4	31.4	31.4	31.4	31.4	31.3	31.3
25.0	31.4	31.4	31.4	31.3	31.3	31.3	31.3	31.3
50.0	31.3	31.2	31.2	31.2	31.2	31.2	31.2	31.2
75.0	31.1	31.1	31.1	31.1	31.1	31.1	31.1	31.0
100.0	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.9
				X = 1000 ft				
0.0	31.3	31.3	31.3	31.2	31.2	31.2	31.2	31.2
25.0	31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.2
50.0	31.1	31.1	31.1	31.1	31.1	31.1	31.1	31.1
75.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0
100.0	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.9
				X = 1200 ft				
0.0	31.2	31.2	31.2	31.1	31.1	31.1	31.1	31.1
25.0	31.1	31.1	31.1	31.1	31.1	31.1	31.1	31.1
50.0	31.1	31.1	31.1	31.1	31.1	31.1	31.0	31.0
75.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0
100.0	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.9
				X = 1400 ft				
0.0	31.1	31.1	31.1	31.1	31.1	31.1	31.1	31.0
25.0	31.1	31.1	31.1	31.1	31.1	31.0	31.0	31.0
50.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0
75.0	31.0	31.0	31.0	30.9	30.9	30.9	30.9	30.9
100.0	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.9
				X = 1600 ft				
0.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0
25.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0
50.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	30.9
75.0	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.9
100.0	30.9	30.9	30.9	30.9	30.9	30.9	30.8	30.8
				X = 1800 ft				
0.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.0
25.0	31.0	31.0	31.0	31.0	31.0	31.0	30.9	30.9
50.0	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.9
75.0	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.9
100.0	30.8	30.8	30.8	30.8	30.8	30.8	30.8	30.8
				X = 2000 ft				
0.0	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.9
25.0	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.9
50.0	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.9
75.0	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.9
100.0	30.9	30.9	30.9	30.9	30.9	30.9	30.9	30.9