ASSESSMENT OF THE POTENTIAL FOR GROUNDWATER CONTAMINATION DUE TO PROPOSED URBAN DEVELOPMENT IN THE VICINITY OF THE U.S. NAVY WAIAWA SHAFT, PEARL HARBOR, HAWAII

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EXECUTIVE SUMMARY

The concern over groundwater contamination in Hawaii has become most pronounced since the early 1980s with the discovery of various pesticide-related contaminants in the basal groundwaters of several of the state's aquifers. Two soil fumigants previously used by pineapple growers, 1,2-dibromo-3-chloropropane (DBCP) and 1,2-dibromoethane or ethylene dibromide (EDB), have been detected in several wells on Oahu and Maui. The compound 1,2,3-trichloropropane (TCP), which is an impurity of another soil fumigant DD, has also been detected in numerous wells on Oahu and Maui. The herbicide atrazine, commonly used by the sugarcane industry, has been found in wells on the islands of Hawaii, Maui, Oahu, and Kauai. In addition, the solvents trichloroethylene (TCE) and tetrachloroethylene (PCE) have been detected in Oahu groundwater samples.

Prior to the recent discoveries of pesticides in the state's groundwaters, it was felt that the great depth (hundreds of meters) between the ground surface and the basal waters of the state's aquifers was sufficient to prevent leaching of pesticide residues to the water table. Furthermore, it was believed that any residues which did reach the basal aquifers would become so greatly diluted as to be undetectable. It is now clear, however, that the overlying soil, saprolite, and basalt layers do not completely insulate Hawaii's groundwaters from contamination. Chemicals applied by man at the ground surface can potentially reach the groundwater table.

Although there is an accute need for affordable housing in Hawaii, the potential environmental impacts of a particular development must be considered prior to acceptance of that project. On the island of Oahu, nearly all of the potable water is derived from groundwater sources. Thus, proposed urban developments which could potentially impact our precious groundwater resources must be carefully examined.

The Gentry Companies' proposed Waiawa Master Plan community and the U.S. Navy (USN) proposed Waiawa Valley development overlie a portion of the Pearl Harbor aquifer, which is the most important potable water source on Oahu. The USN Waiawa infiltration tunnel and pumping station (well no. 2558-10), which is the largest potable water development station of the U.S. military forces in Hawaii, withdraws water from the basal lens of the Pearl Harbor aquifer and is situated near the eastern boundary of the proposed Waiawa Gentry development and just west of the USN proposed Waiawa Valley development. The USN Waiawa water development complex, commonly referred to as the Waiawa Shaft, was completed in 1951 and consists of a control building, a 30° inclined shaft leading down to a pump room, an unlined sump excavated to 6.1 m (20 ft) below sea level, and a 519 m (1,702 ft) long infiltration tunnel. The Waiawa Shaft typically supplies a total of about 0.66 m^3/s (15 million gallons per day) of water to the Pearl Harbor Naval Base complex and Hickam Air Force Base.

Precedence of water contamination of the Waiawa infiltration tunnel, which lies directly beneath land previously used for sugarcane cultivation by Oahu Sugar Company (OSC), is documented. Water from OSC Waipahu Pump 6 was used for furrow irrigation of sugarcane fields on Waiawa Ridge until about 1983. From 1902 until about 1951, the chloride concentration in Pump 6 water generally ranged from 200 to 400 mg/l. Due to the shrinking of the basal lens of the Pearl Harbor aquifer, the deep Waipahu Pump 6 wells began to withdraw water from the rising transition zone which eventually resulted in chloride concentrations in Pump 6 water in excess of 1 000 mg/l during the 1970s. As a result of the irrigation of Waiawa Ridge sugarcane fields with water from Pump 6, chlorides applied at the surface eventually leached through the 120 m (400 ft) thick vadose zone to the groundwater table. This irrigation return flow caused a rise in chloride concentration of water pumped by Waiawa Shaft until approximately 1983 when the overlying sugarcane fields were abandoned. Chlorides, being nonreactive, were expected to leach freely.

Up until the mid-1960s, water pumped from Waiawa Shaft generally had chloride concentrations between 70 and 100 mg/l. From the mid-1960s to the beginning of 1978 the chloride concentration rose to a level of about 210 mg/l, and by the end of 1978 the chloride concentration increased further to a level of 280 mg/l. Since 1983, when sugarcane fields on

Waiawa Ridge were abandoned, chloride concentrations have decreased to an acceptable level and unprecedented low of about 40 to 50 mg/l in 1989.

Recent detection of DBCP and TCP in water samples taken from Waiawa Shaft provides further evidence of the susceptibility of the USN well to anthropogenic surface activities. Although it is unknown when the first traces of DBCP and TCP were pumped from Waiawa Shaft, these organic chemicals were detected as early as 1983 when analyses for the compounds were initially performed. Sources of the DBCP and TCP are not absolutely identified, but these chemicals were used in the existing pineapple fields to the east and northeast of Mililani Town which are located hydraulically upgradient from the shaft and in nearby areas previously used for pineapple cultivation such as Pacific Palisades.

Past experience indicates that the USN Waiawa Shaft can potentially be impacted by nearby developments where pesticides and fertilizers will be applied to lawns and gardens, solvents and petroleum products may be illegally discarded, and leaky underground storage tanks may go undetected. Recognizing the possible environmental impact, the USN solicited the services of the University of Hawaii Water Resources Research Center (WRRC) to assess the potential for groundwater contamination due to proposed urban development in the vicinity of the Waiawa Shaft.

The project requires multidisciplinary expertise and is accomplished by a number of coordinated activities, each having its own scientific objectives but contributing to the overall project goals. Project personnel consisted of qualified researchers from the University of Hawaii. The expertise of each of the individual members of the research team was essential for the successful and timely completion of the project.

The overall objective of the study is to determine the long-term potential for contamination of pumped groundwater by major and representative chemicals applied in the proposed USN housing project and the Waiawa Gentry community. The investigation involves the extensive use of computer modeling techniques in conjunction with laboratory and field tests. The laboratory and field tests are designed to provide valuable input information necessary for increasing the accuracy of the modeling results. The specific objectives of the research activities are listed below.

1. Determine the types, quantities, and mode of application of pesticides and fertilizers that would most likely be used on the proposed sites of urbanization.
2. Calculate the amounts, including temporal and spatial variation, of water recharge by rainfall and irrigation in the proposed urban areas.
3. Adapt and apply models to assess potential contamination of the groundwater due to application of various pesticides and fertilizers which are likely to be applied in the area.
4. Estimate the amount of chemical transport in the basal water to the Waiawa Shaft to determine if any measurable contamination of the basal water occurs.

This document is the final summary report of the project whose activities were initiated in October 1987. Results of each primary research activity are summarized below.

1. Chemical Use in Proposed Development Areas

The first step in the asssessment approach involved the identification of pesticides and fertilizers which might be used in the proposed development areas. Although fertilizer products are composed primarily of nitrogen, phosphorus, and potassium, the pesticides which are likely to be used in the Waiawa developments contain a wide variety of active ingredients. The types of chemicals which will likely be used in the residential areas were identified by (1) surveying a number of local pest control companies which could conceivably apply chemicals, such as termiticides, in the proposed development areas, (2) conducting spot checks of various retail outlets in the central Oahu area to determine what types of commercial chemicals are readily available to home owners, and (3) surveying residents in the Waipio Gentry area to determine the types of pesticides and fertilizers currently being used in an area climatologically similar and geographically close to the proposed Waiawa developments. Chemical application rates and frequencies used by home owners were estimated from pesticide label information in conjunction with the results of the house-to-house survey of residents in the Waipio Gentry area.

Based on the survey of local pest control companies, the most commonly used termiticide is Dursban TC which contains chlorpyrifos as an active ingredient. Permethrin is another commonly and locally used termiticide. The chemicals cypermethrin and isofenphos may also be used in the proposed developments for termite control.

Results of the household survey clearly indicate that diazinon, malathion, and the herbicide glyphosate are the most popular pesticides used by home owners locally. In addition, chlorpyrifos, MCPP, and 2,4-D are also commonly used. Based on survey responses, estimated chemical application rates from house to house were estimated to vary over two orders of magnitude.

The chemicals selected for study by this project were chosen on the basis of their prevalent use and their transport behavior. For the long-term leaching simulations, the four nonvolatile chemicals tested were (1) chlorpyrifos, (2) nitrate, (3) metribuzin, and (4) diazinon. Chlorpyrifos was selected because it is the termiticide most commonly used by local pest control companies, it may be applied at high rates, and it is normally applied below the soil surface. Nitrate was chosen because it is recognized as the most mobile and persistent component of fertilizers and it is regulated for health reasons by the U.S. Environmental Protection Agency. The herbicide metribuzin was used to assess the impact of the proposed golf course areas because of its persistent and mobile nature. Diazinon was selected because of its relatively high persistence and mobility and its common household usage.

2. Water Recharge Estimation

To determine the fate of chemicals applied near the ground surface, a number of computer models were linked in series to trace the transport of chemicals downward through the unsaturated zone to the groundwater table and then their spreading in the saturated zone. Near the ground surface, recharge water emanating from just below the plant root zone was estimated with a water balance model. Water recharge, which is the primary advective mechanism by which chemicals are transported downward through the vadose zone, was estimated by accounting for water inputs to the pervious areas in the form of precipitation and irrigation, water losses due to evapotranspiration and runoff, and changes in soil moisture within a day. Different land use and soil type combinations behave differently to water inputs. Thus, the estimation of recharge requires (1) identification of the soil types and land uses within and surrounding the proposed Waiawa development areas, (2) determination of irrigation and precipitation over the region and period of interest, and (3) application of a water balance model to partition water inputs into runoff, evapotranspiration, soil moisture storage, and groundwater recharge.

Recharge was estimated for different land use scenarios on Waiawa Ridge and in Waiawa Valley. Rather than computing the water balance for each irregular zone representing a different combination of land use, soil type, and climate within the Waiawa area, recharge water was estimated for cells within a rectangular grid. The grid dimensions were chosen to minimize climate variations within a particular cell. A representative land use and soil type was assigned to each cell of the grid. This discretization of the development area was desirable and necessary to reduce the number of long-term pesticide leaching simulations. The water balance for each cell in the discretized development was estimated on a daily basis over a 37-yr period. The length of the period was selected to ensure that chemicals applied at the ground surface would have sufficient time to leach through the vadose zone and travel in the saturated zone towards Waiawa Shaft. The period also provided a realistic range of recharge conditions for pesticide leaching.

The recharge estimates reflect the spatial and temporal patterns of rainfall as well as the land use distribution. Within a particular land use designation, recharge increases toward the northeastern portion of the study area where rainfall is greatest. Golf course areas generally have the greatest recharge, with typical annual average recharge rates of about 1 200 mm.

3. Potential Leaching of Chemicals

Estimated chemical application rates and frequencies in conjunction with water recharge estimates were used as input to a numerical model designed to simulate transport of chemical residues in the unsaturated zone. The computer simulation model selected for this study is the U.S.

Environmental Protection Agency's Pesticide Root Zone Model (PRZM) which is a one-dimensional finite difference model. Before PRZM could be confidently used for long-term chemical leaching predictions, the model was calibrated and evaluated with observed field data obtained for and judged applicable to the project site.

The data were obtained by conducting field tests in Waiawa Valley and at Poamoho where selected chemicals were applied to the soil and allowed to move downward with rainfall and irrigation water. Conducting chemical leaching experiments on Waiawa Ridge, the site of the proposed Gentry development, proved to be impossible due to perceived liability problems by OSC which currently holds the lease to the land. Thus a field experiment was established at an alternate site at Poamoho in central Oahu, on a soil series which is also found on Waiawa Ridge.

After calibrating the model at the experimental test sites, PRZM was used for long-term leaching predictions under development conditions. For the long-term PRZM simulations, the development area was discretized into a manageable number of small areas (cells). Leaching of each test chemical was simulated with a daily time step within each cell of the grid over a 37-yr period by using the water recharge estimates developed by this project as input to PRZM. After the model was calibrated for the upper 3 m (10 ft) of soil, PRZM was used to simulate transport through the entire depth of the vadose zone above the basal water table. Due to the lack of detailed hydrogeological information characterizing the deeper vadose zone, use of a more sophisticated physically-based model to simulate solute transport through the subsoil, saprolite, and unweathered basalt would be neither justified nor possible. Tests were made to determine the sensitivity of PRZM to various property changes in the unsaturated zone profile, including the removal of the topsoil layer, which is a pesticide-transport deterrent, due to grading during construction.

PRZM results suggest that chlorpyrifos is not expected to be a significant threat to groundwater because of its immobile and nonpersistent behavior. However, consideration must be given to the metabolite of chlorpyrifos. Assuming that 3% of the applied nitrate is available for leaching, PRZM results indicate that nitrate concentrations introduced to the water table are near 1 mg/l (as nitrogen). Concentrations of diazinon reaching the groundwater table vary according to location, the amount of organic carbon in the surface soil, and the method of distributing the water and pesticide in the unsaturated zone profile. Metribuzin concentrations introduced to the water table are most significantly affected by the hydrolysis rate used. In general, simulated chemical loading rates at the water table reflect the temporal pattern of groundwater recharge.

4. Modeling of Contaminant Transport in Groundwater

Three different saturated zone models were evaluated using historical chloride concentrations at Waiawa Shaft. The models used to simulate solute transport in the saturated zone were (1) a two-dimensional, areal model based on the Konikow and Bredehoeft method of characteristics (MOC), (2) the MOC model in a vertical section orientation, and (3) a two-layered multiple mixing cell model.

For the long-term predictive simulations, the areal MOC model was selected due to its ability to account for spatial variations of recharge and chemical loading rates to the water table. These variations were obtained by PRZM simulations. The groundwater model was used to simulate movement of the chemicals through the saturated zone in the basal lens under the influence of pumping from Waiawa Shaft and other nearby wells. The areal MOC groundwater model was employed under a range of unsaturated zone inputs and pumping rates. Predicted groundwater quality impacts resulting from the proposed Gentry and USN developments in the Waiawa area are summarized below.

1. Termiticide Applications. The parent compound of chlorpyrifos, the most commonly used termiticide in Hawaii, should not pose a significant threat to groundwater quality in the study area. It is possible, however, that metabolites of chlorpyrifos may occur in significant quantities as a result of breakdown of the parent compound. Other more mobile termiticides could pose a threat to groundwater quality if subjected to unmitigated concentrated recharge conditions such as beneath areas where runoff from rooftops occurs.
2. Nitrogen Fertilizers. In terms of the nitrogen component, fertilizers applied in the USN Waiawa Valley development and the

Waiawa Master Plan development should not cause nitrate concentrations in the water pumped by Waiawa Shaft to exceed the drinking water limit of 10 mg/l. Under extreme conditions, nitrate concentrations might reach levels of about 5 mg/l if Waiawa Ridge is completely developed as planned.

3. Golf Course Pesticides. With regard to chemicals applied on the proposed golf courses of the Waiawa Master Plan, the impact on groundwater may be either minimal or significant depending on the chemical used. Metribuzin was used as a test chemical for the proposed golf course areas in the modeling analysis. When a hydrolysis half-life of about 1 year is assumed for the chemical, the relatively long travel time through the intermediate vadose zone below the soil enhances the opportunity for chemical decay. Resulting concentrations in water pumped by Waiawa Shaft could then be expected to range from nondetectable levels to a few ng/l (parts per trillion) depending on the amount of organic carbon maintained in the soil by golf course personnel. However, if metribuzin is assumed to be persistent once below the soil layer, concentrations in water pumped by Waiawa Shaft could reach a few thousand ng/l. Thus, the impacts of golf course applications on groundwater quality are very sensitive to assumed chemical characteristics.

4. Diazinon--Waiawa Ridge. Under extreme leaching conditions where the top soil layer is removed and concentrated recharge beneath residential areas occurs, diazinon applications in the proposed residential areas on Waiawa Ridge may result in concentrations in groundwater pumped by Waiawa Shaft to be on the order of tens to hundreds of ng/l. By retaining the top soil layer, and with it a significant amount of organic carbon, resulting concentrations at Waiawa Shaft can be reduced to levels below 20 ng/l. Because the severe recharge conditions mentioned above are not likely to occur over the entire development area, the concentrations are probably overestimated. It should be mentioned, however, that if a different, more persistent pesticide should become available and as popular as diazinon, the concentrations may be underestimated.

When recharge occurring beneath unpaved areas spreads laterally, the downward rate of water movement decreases and travel time through the vadose zone increases, thereby enhancing the opportunity for chemical decay. Thus, under conditions which are probably more representative of the spreading phenomenon of the recharge wetting front, diazinon applications in residential areas on Waiawa Ridge should result in concentrations in groundwater pumped by Waiawa Shaft below 5 ng/l.

5. Diazinon--Waiawa Valley. For the USN proposed Waiawa Valley development, the exact nature of the hydrologic connection between the alluvial groundwater body and the basal aquifer is not precisely known. For this study, an unimpeded interflow was assumed to exist between the two groundwater bodies. Under this condition, diazinon applications in the proposed Waiawa Valley development may result in concentrations in groundwater pumped by Waiawa Shaft to range between a few to a few hundred ng/l depending on the amount of top soil retained, the extent of lateral spreading of recharge in the vadose zone, and the degree of hydrolysis of diazinon in groundwater.
6. Diazinon--Waiawa Ridge and Waiawa Valley. If the hydrologic connection between the alluvial groundwater body and the basal aquifer is unimpeded, diazinon applications in both the Waiawa Ridge and Waiawa Valley developments may result in diazinon concentrations in groundwater pumped by Waiawa Shaft of a few hundred ng/l under extreme leaching conditions where the top soil layer is removed and no lateral spreading of recharge occurs. Under conditions which are probably more representative of the downward movement of the recharge wetting front, diazinon applications in both residential areas should result in concentrations in groundwater pumped by Waiawa Shaft below 25 ng/l. If there is no transfer between the alluvial groundwater body and the basal aquifer because of an impermeable weathered zone, recharge from the Waiawa Valley development will not contribute to the shaft output. Thus, concentrations in water pumped by Waiawa Shaft will likely be close to those predicted by

the Waiawa Ridge only development scenario, but may differ slightly because the zone of contribution of recharge water to the shaft will shift in the absence of recharge to the basal aquifer from portions of Waiawa Valley.

For this investigation, a modeling approach is taken to provide scientific information necessary to make an informed decision regarding the development/nondevelopment of the proposed Waiawa housing projects. It is generally accepted that modeling results cannot be considered as absolute. Model predictions should constantly be subjected to review as more scientific information is obtained and a better understanding of the underlying scientific processes is developed. Modeling does, however, represent the best approach available to provide necessary scientific information so that rational decisions can be made.

It should be noted that the health significance of various levels of chemical concentrations that may be encountered in the Waiawa water source is not the goal of this investigation. However, the results of this study will serve as a basis for risk assessment related to long-term exposure to these chemicals in a potable water supply.

Based on the results and conclusions of this study, the following general guidelines are recommended to help mitigate any negative impacts on groundwater quality:

1. In golf course areas where chemical applications can be somewhat regulated and controlled, an effort should be made to reduce the potential impact of pesticides by using only those chemicals which are not persistent and which have only harmless products after breakdown.
2. Because the frequency and rate of chemical applications in residential areas are difficult to control, the use of highly mobile and persistent chemicals should be restricted to reduce the potential for groundwater contamination.
3. In all areas where pesticides might be applied, removal of organic carbon with the topsoil layer should be avoided.
4. Concentrated recharge conditions and ponding of water around the periphery of houses should be avoided by incorporating gutters in building designs and properly sloping the ground away from buildings.

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1. INTRODUCTION

In the state of Hawaii, the housing supply is currently lagging behind both population growth and household formation (Office of State Planning 1989). Between 1980 and 1987, the resident population in the state of Hawaii increased by 12.3% with an increase in the number of households of 17.3%. During this same period, resident housing units increased by only 10.4%. As of January 1987, a shortfall of over 20,000 housing units, of which 14,000 were needed by low- to moderate-income families, was estimated to exist in Hawaii (Office of State Planning 1989).

On the island of Oahu, where approximately 80% of Hawaii's one million residents live (Office of State Planning 1989), numerous residential communities are currently being developed in the southern, Ewa portion of the island to help curb the housing shortage. These include the City and County of Honolulu's West Loch Estates subdivision, the State Housing Finance and Development Corporation's Kapolei Village residential community, and The Gentry Companies' Ewa by Gentry development.

The Honolulu City Council recently raised the central Oahu population limit established by the Oahu General Plan, thus opening the area to a total of 6,875 new housing units (Honolulu Star Bulletin, 3 February 1989). This action cleared the way for two proposed developments in central Oahu, the 3,500-unit Mililani Mauka project and the 2,000-unit Royal Kunia project. The 1,375-unit balance was allotted to The Gentry Companies, which hopes to build 7,900 housing units on 565 ha (1,395 acres) of land, currently owned by the Bernice Pauahi Bishop Estate, as the first increment of a master-planned community at Waiawa, central Oahu (Fig. 1). The U.S. Department of the Navy is also planning to develop a housing project in the Waiawa area of central Oahu. The U.S. Navy (USN) is currently considering construction of 114 family housing units on 16 ha (39 acres) of military land in Waiawa Valley just east of the proposed Waiawa Gentry community (Fig. 2).

Although there exists a tremendous shortage of affordable housing in Hawaii, development is controlled by the state Land Use Commission which

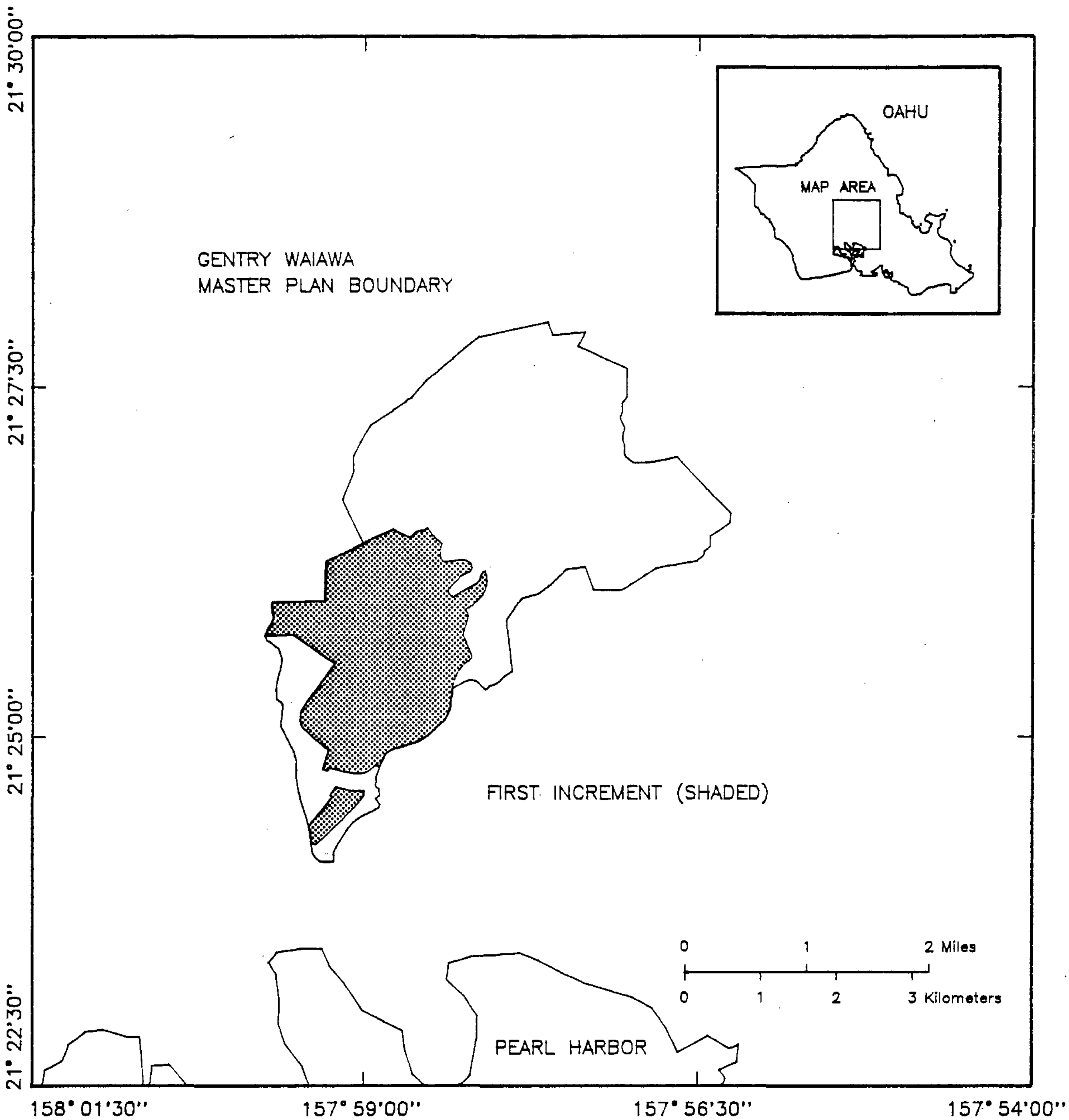


Figure 1. First increment of Gentry Waiawa Master Plan, Oahu, Hawaii

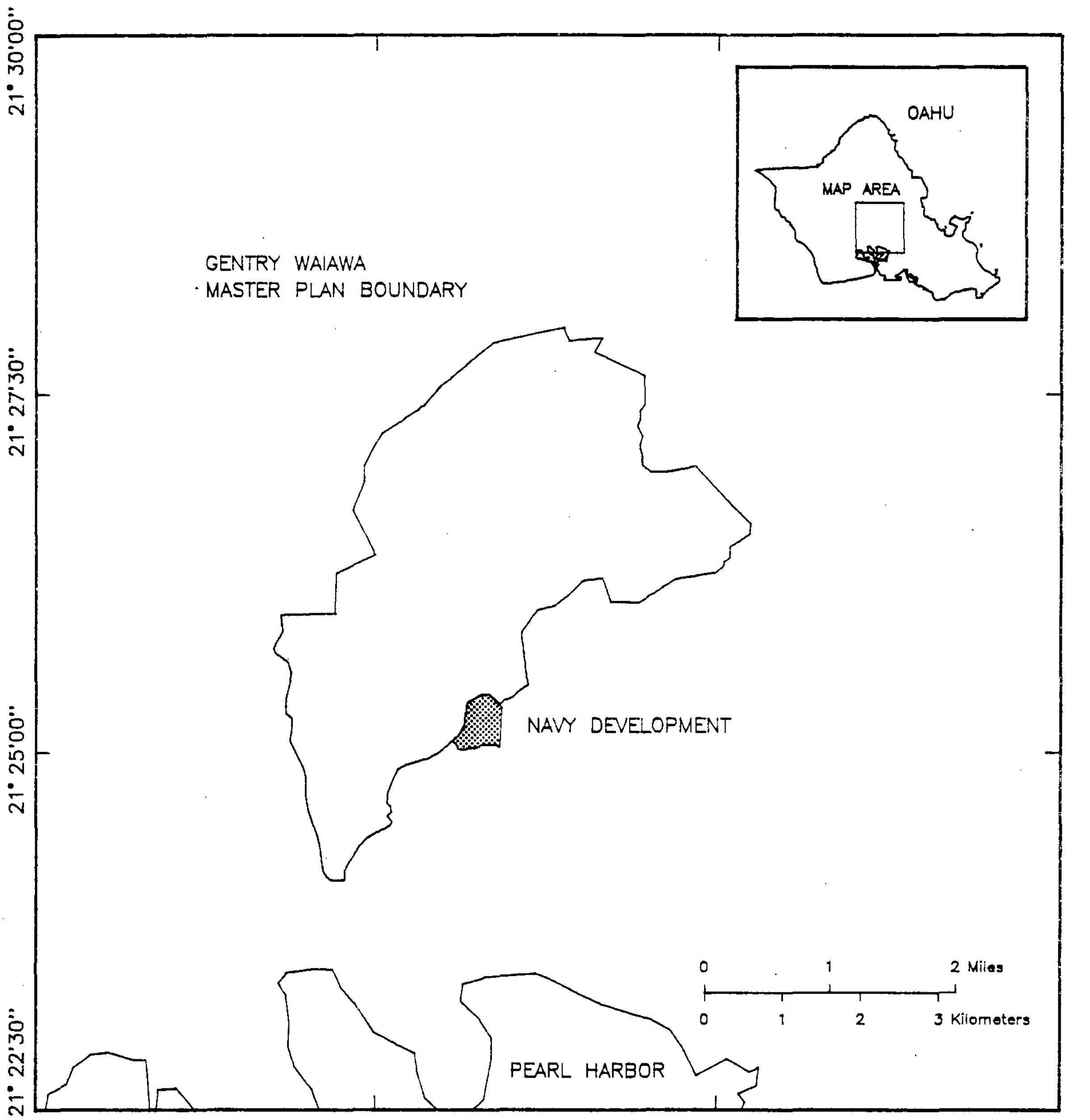


Figure 2. Proposed U.S. Navy Waiawa Valley development, Oahu, Hawaii

is responsible for districting the land within the state into urban, rural, agricultural, and conservation uses. Land use districting decisions are greatly influenced by water use decisions and environmental concerns. For instance, the first increment of the Gentry Waiawa Master Plan community was approved by the Land Use Commission on the condition that the housing development will not adversely impact the quality of the underlying groundwater. Final determination of whether the development will lead to undesirable groundwater contamination is to be made by the state Department of Health (DOH).

The state DOH Director, Dr. John Lewin, recently spoke against the city's request to permit development of the Kipapa Ridge Estates, located southwest of the proposed Waiawa Gentry community, arguing that the state would lose its ability to regulate chemical use once central Oahu is developed (Honolulu Advertiser, 22 June 1989). Whether residential development in central Oahu poses a greater threat to the Pearl Harbor aquifer than large-scale agriculture is debatable. Clearly, however, protection of Hawaii's high quality groundwater is of paramount importance since over 90% of the state's domestic water is derived from groundwater sources (Nakahara 1980). With the exception of isolated cistern catchments and a small amount (less than 0.0044 m^3/s) of Lulumahu Stream water*, groundwater is the sole source for domestic water on the island of Oahu.

PROBLEM IDENTIFICATION

The proposed location of the Waiawa Gentry housing development overlies a portion of the Pearl Harbor aquifer (Fig. 3), which is the most important potable water source for the island of Oahu. The USN Waiawa water development tunnel and pumping station (well no. 2558-10) withdraws water from the basal lens of the Pearl Harbor aquifer and is situated near the eastern boundary of the proposed Waiawa Gentry community (Fig. 4). The Waiawa tunnel is the largest potable water development station of the U.S. military forces in Hawaii (Mink 1985), supplying approximately 70% of the water demand of the Pearl Harbor Naval Base complex and Hickam Air Force Base (Eyre 1983b). The USN also operates water tunnels at Red Hill and Halawa which are used to supply additional water to the Pearl Harbor-Hickam complex.

*C. Lao (Board of Water Supply) 1989: personal communication.

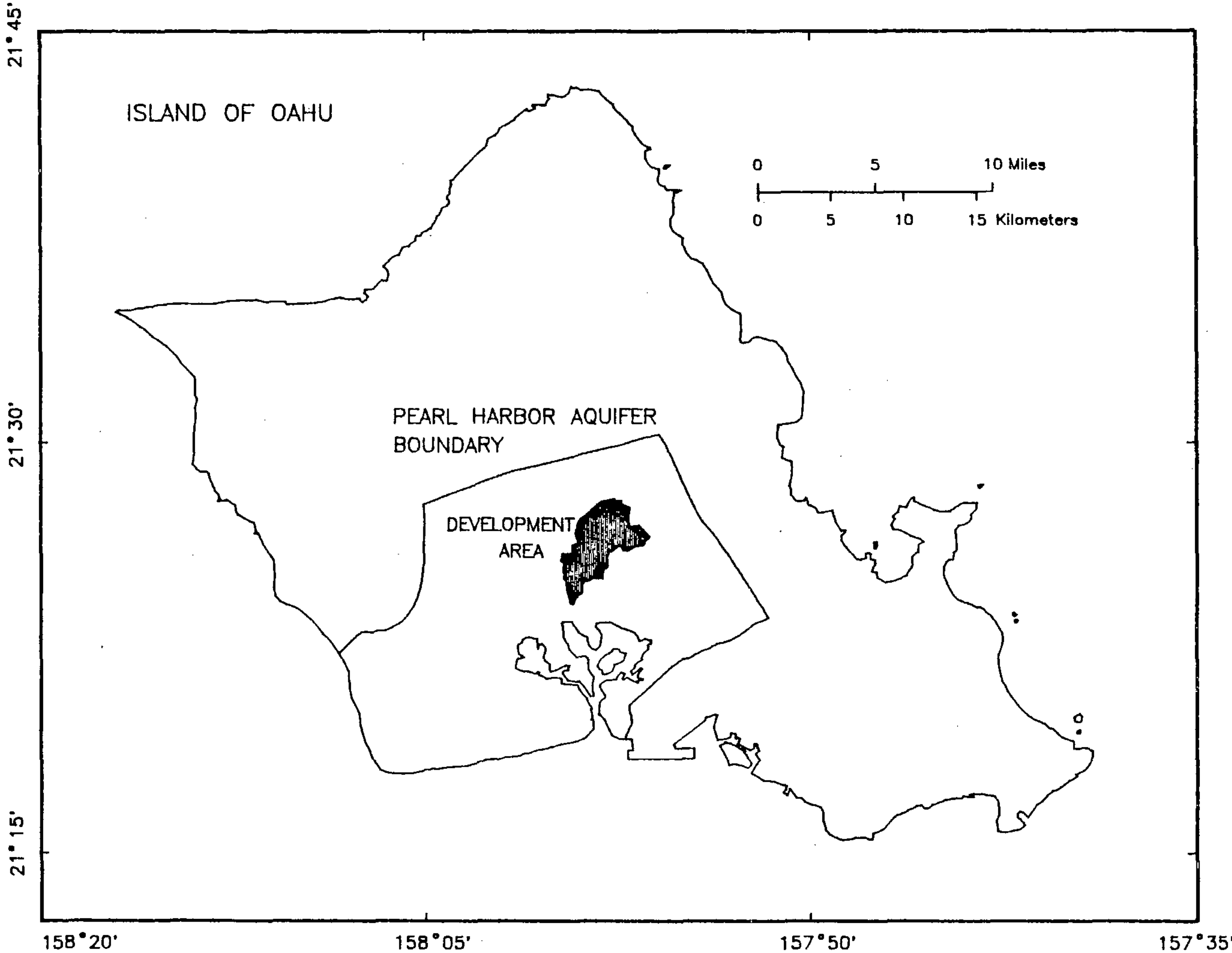


Figure 3. Pearl Harbor aquifer boundary and Waiawa development area, Oahu, Hawaii

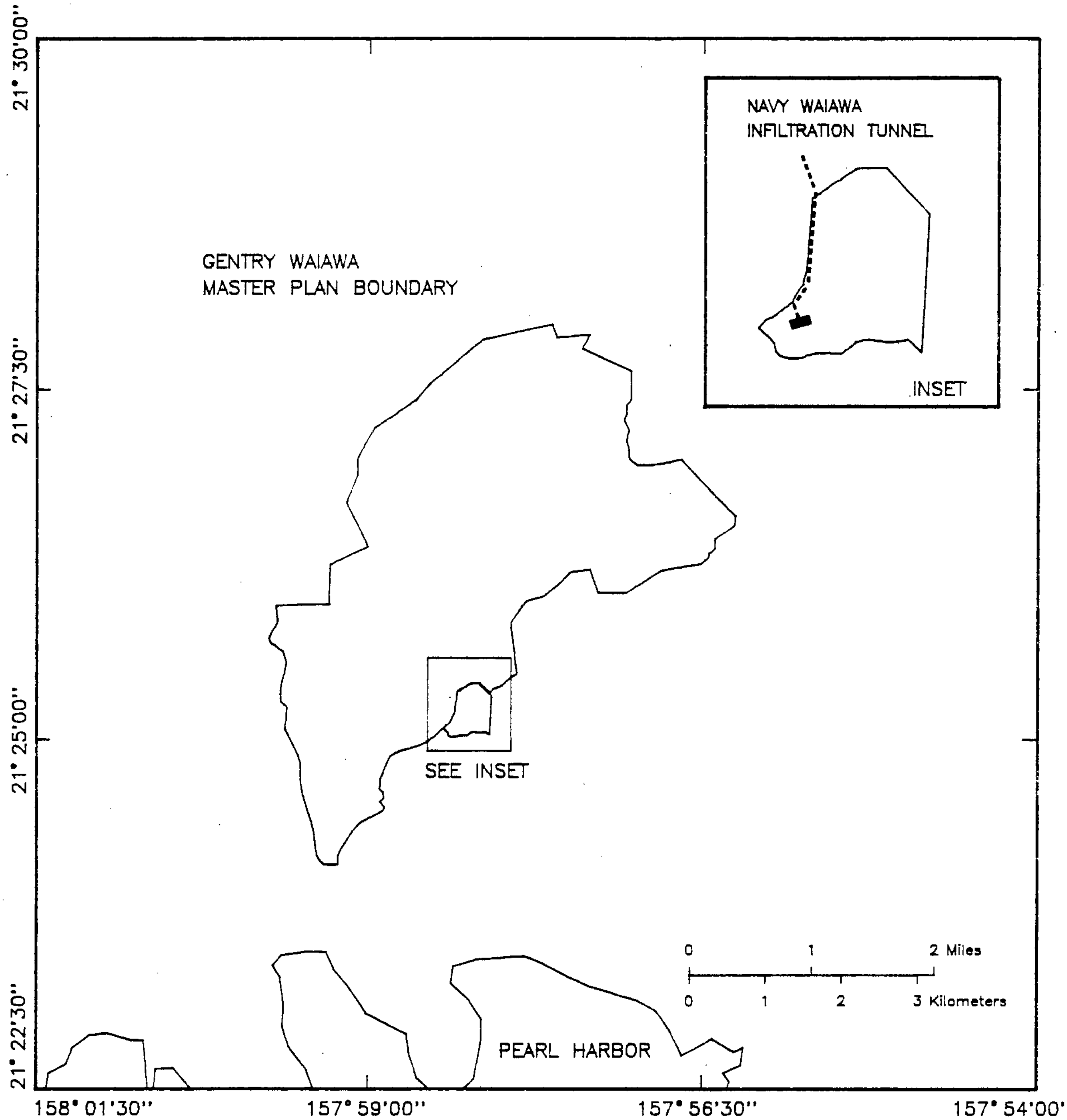


Figure 4. Location of U.S. Navy Waiawa infiltration tunnel, Oahu, Hawaii

Construction for the USN Waiawa water development complex started in 1949 and was completed in 1951. The complex consists of a control building at an elevation of about 43 m (140 ft) above mean sea level, a 77 m (254 ft) long, 30° inclined shaft leading down to a pump room at an elevation of 9.1 m (30 ft), an unlined sump excavated to 6.1 m (20 ft) below sea level, and a 519 m (1,702 ft) long infiltration tunnel (Fig. 5). The infiltration tunnel is 3.7 m (12 ft) wide by 3.7 m (12 ft) high near the tunnel entrance which has an invert 1.2 m (4 ft) below sea level and tapers to 2.1 m (7 ft) wide by 3.0 m (10 ft) high at its terminus which has an invert 1.2 m (4 ft) above mean sea level. Water collected in the infiltration tunnel flows toward the unlined sump where four deep well turbine pumps, each with a capacity of 0.41 m^3/s (9.36 million gallons per day [mgd]), lift the water up the inclined shaft.

The Waiawa infiltration tunnel lies directly beneath land previously used for sugarcane cultivation by Oahu Sugar Company (OSC). Water from OSC Waipahu Pump 6 was used for furrow irrigation of sugarcane fields on Waiawa Ridge until 1983. The Waipahu Pump 6 well field consists of 14 deep wells drilled to depths of 150 to 210 m (500-700 ft) below mean sea level. From 1902 until about 1951, the chloride concentration in Pump 6 water generally ranged from 200 to 400 mg/l (Eyre 1983b). Due to the shrinking of the basal lens of the Pearl Harbor aquifer (Soroos and Ewart 1979), Waipahu Pump 6 wells began to withdraw water from the rising transition zone which eventually resulted in chloride concentrations in Pump 6 water in excess of 1 000 mg/l during the 1970s. As a result of the irrigation of Waiawa Ridge sugarcane fields with water from Pump 6, chlorides applied at the surface eventually leached through the 120 m (400 ft) thick vadose zone to the groundwater table. This irrigation return flow caused the rise in chloride concentration of water pumped by Waiawa Shaft (Eyre 1983b) until approximately 1983 when the overlying sugarcane fields were abandoned.

Records from the excavation of the Waiawa infiltration tunnel indicate that the top of the basal lens in the vicinity of the shaft probably had a chloride concentration of approximately 250 mg/l during the early 1950s, attributable to the saltier sugarcane irrigation return flow discussed above. As excavation proceeded, greater amounts of water were pumped

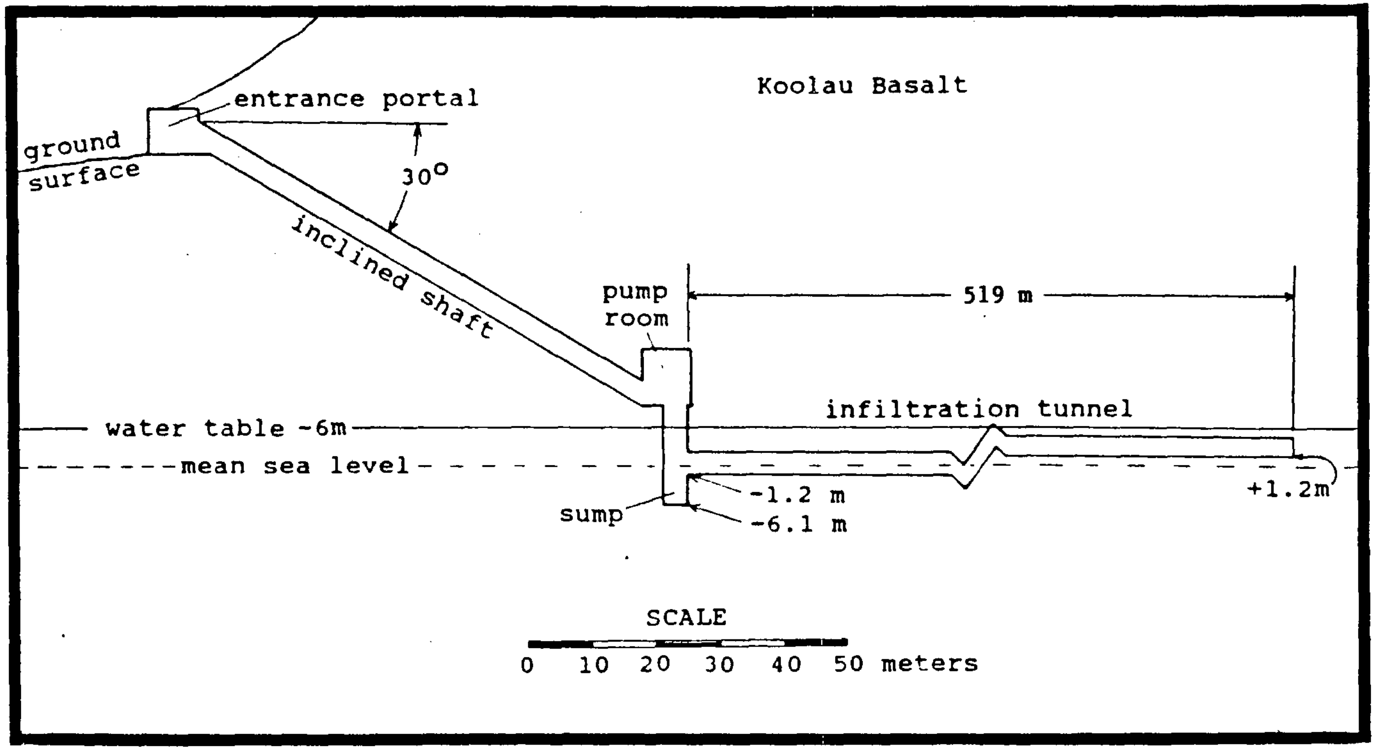


Figure 5. Diagram of U.S. Navy Waiawa Shaft and infiltration tunnel, Oahu, Hawaii

to dewater the infiltration tunnel. In March 1951, when excavation was completed, pumping rates in excess of 1.8 m^3/s (40 mgd) were required to dewater the tunnel. At this point, much of the accumulated sugarcane recharge water at the top of the basal lens in the vicinity of Waiawa Shaft had been removed so that the chloride concentration of the pumped water was reduced to approximately 70 mg/l (Fig. 6).

Up until the mid-1960s, water pumped from Waiawa Shaft generally had chloride concentrations between 70 and 100 mg/l. From the mid-1960s to the beginning of 1978 the chloride concentration rose to a level of about 210 mg/l, and by the end of 1978 the chloride concentration increased further to a level of 280 mg/l. Since 1983, when sugarcane fields on Waiawa Ridge were abandoned, chloride concentrations have decreased to an acceptable level and unprecedented low of about 40 to 50 mg/l in 1989 (Fig. 7).

The concern over groundwater contamination in Hawaii has become most pronounced since the early 1980s with the discovery of various pesticide-related contaminants in the basal groundwaters of several of the state's aquifers. Two soil fumigants previously used by pineapple growers, 1,2-dibromo-3-chloropropane (DBCP) and 1,2-dibromoethane or ethylene dibromide (EDB), have been detected in several wells on Oahu and Maui. The compound 1,2,3-trichloropropane (TCP), which is an impurity of the soil fumigant DD, has also been detected in numerous wells on Oahu and Maui (Oki and Giambelluca 1987). The herbicide atrazine, commonly used by the sugarcane industry, has been found in wells on the islands of Hawaii, Maui, Oahu, and Kauai. In addition, the presence of the solvent tetrachloroethylene (PCE) has been confirmed in groundwater samples from Hawaii and Oahu (Giambelluca, Leung, and Konda 1987).

The detection of DBCP and TCP in water samples taken from Waiawa Shaft provides further evidence of the susceptibility of the basal lens to anthropogenic surface activities. Although it is unknown when the first traces of DBCP and TCP were pumped from Waiawa Shaft, these organic chemicals were detected as early as 1983 when analyses for the compounds were initially performed. DBCP and TCP were used on existing pineapple fields, which are located hydraulically upgradient from the shaft, to the

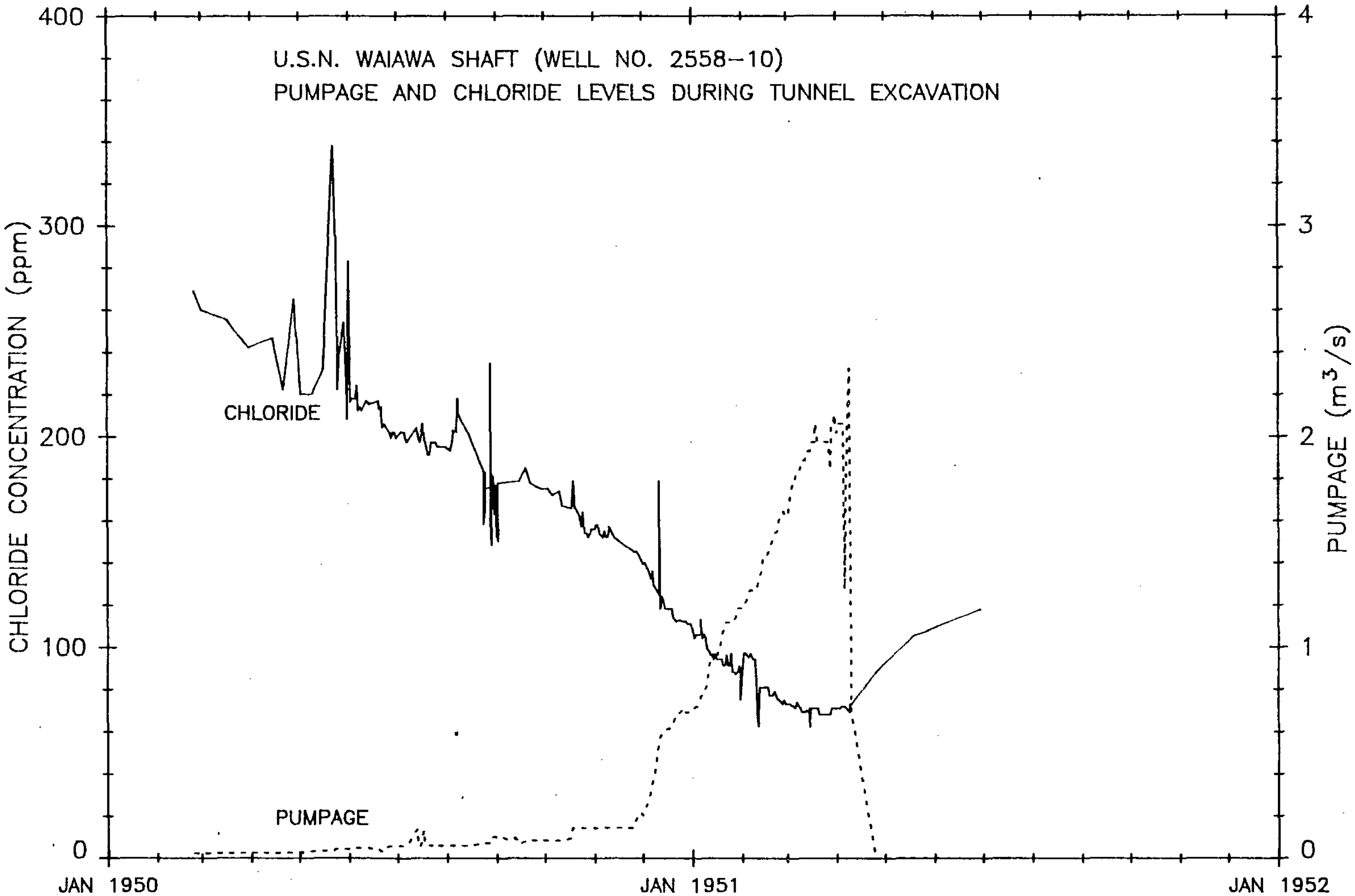


Figure 6. Pumpage and chloride concentrations at Waiawa Shaft during tunnel excavation

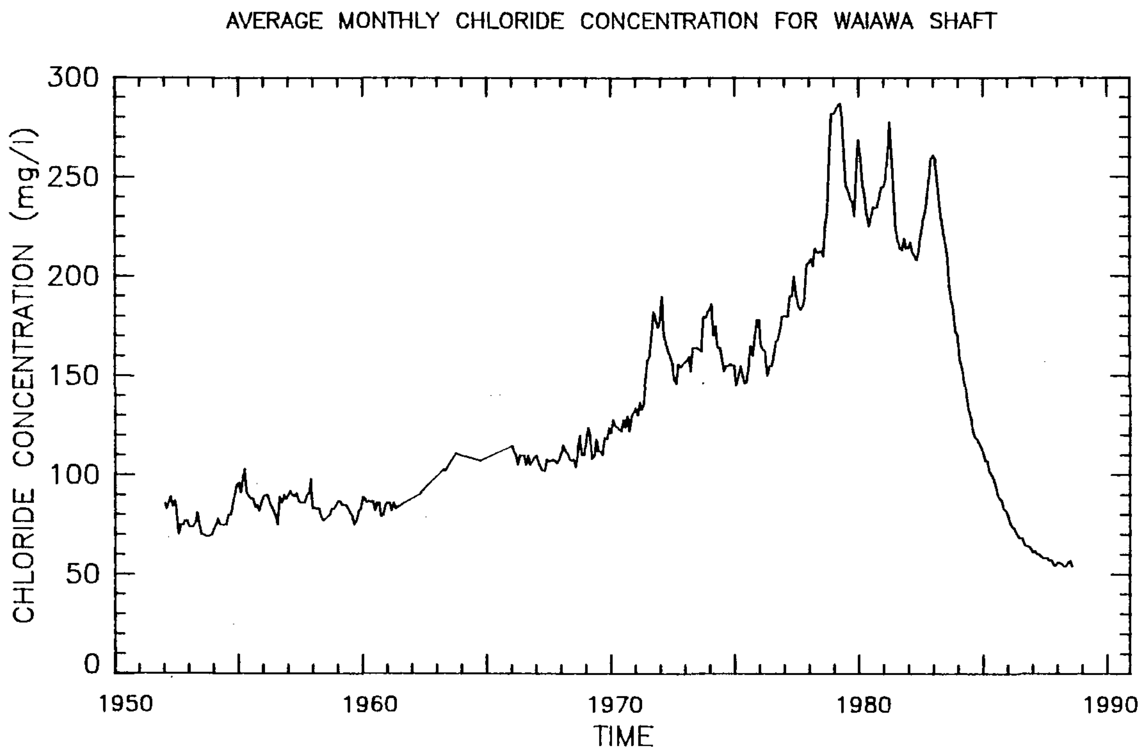


Figure 7. **Average monthly chloride concentrations at Waiawa Shaft, Oahu, Hawaii**

east and northeast of Mililani Town and in nearby areas previously used for pineapple cultivation such as Pacific Palisades.

Prior to the recent discoveries of pesticides in the state's groundwaters, it was felt that the great depth (hundreds of meters) between the ground surface and the basal waters of the state's aquifers was sufficient to prevent leaching of pesticide residues to the water table. Furthermore, it was believed that any residues which did reach the basal aquifers would become so greatly diluted as to be undetectable. It is now clear, however, that the overlying soil, saprolite, and basalt layers do not completely insulate Hawaii's groundwaters from contamination. Chemicals applied by man at the ground surface can potentially reach the groundwater table. The Waiawa Shaft, which has a history of susceptibility to anthropogenic surface activities, can potentially be impacted by development on nearby Waiawa Ridge or in Waiawa Valley where pesticides and fertilizers applied to lawns and gardens, solvents and petroleum products illegally discarded, and leaky underground storage tanks can contaminate the groundwater.

OBJECTIVES

Recognizing the possible environmental impact, the USN solicited the services of the University of Hawaii Water Resources Research Center (WRRC) (contract N62742-87-C-0510 awarded on 1 October 1987) to assess the potential for groundwater contamination due to proposed urban development in the vicinity of the Waiawa Shaft, Pearl Harbor, Oahu. Given the operating production rates from Waiawa Shaft, the overall objective of the study is to determine the long-term potential for contamination of pumped groundwater by chemicals applied in the proposed USN housing project and the Waiawa Gentry community. The investigation involves the use of computer modeling techniques in conjunction with laboratory and field tests. The laboratory and field tests are designed to provide valuable input information necessary for increasing the accuracy of the modeling results. The specific objectives of the research activities are listed below.

1. Determine the types, quantities, and mode of application of pesticides and fertilizers that would most likely be used on the proposed sites of urbanization.

2. Calculate the amounts, including temporal and spatial variation, of water recharge by rainfall and irrigation in the proposed urban areas.
3. Adapt and apply models to assess potential contamination of the groundwater due to application of various pesticides and fertilizers. The models shall assess the movement of the dominant pesticides and fertilizers which are likely to be applied in the area. The models shall also estimate the amount of chemical transport in the basal water to the Waiawa Shaft to determine if any measurable contamination of the basal water occurs.

NATURE AND SCOPE

This document is the final completion report of the project, whose activities were initiated in October 1987, to assess the potential for groundwater contamination due to proposed developments by the USN and The Gentry Companies in the Waiawa area of central Oahu. This report documents the assessment approach and methodology, field, laboratory, and modeling work performed, results, conclusions, and recommendations. The final recommendations of this investigation regarding the development/nondevelopment of the proposed Waiawa housing projects are based on the potential for contamination of the groundwater.

PROJECT MANAGEMENT AND PERSONNEL

The research requires multidisciplinary expertise and is accomplished by a number of coordinated activities, each having its own scientific objectives but contributing to the overall project goals. A list of the project personnel and their respective roles is presented in Table 1. Overall responsibility for the project is vested in the Principal Investigator. The Project Coordinator, in addition to conducting necessary research, is responsible for coordinating and executing on a day-to-day basis the numerous details for the project, organizing monthly meetings for project personnel, and interfacing with the funding agency of progress made and problems associated with the project. The expertise of each of the individual members of the research team was absolutely essential for the successful completion of this project.

TABLE 1. PROJECT PERSONNEL

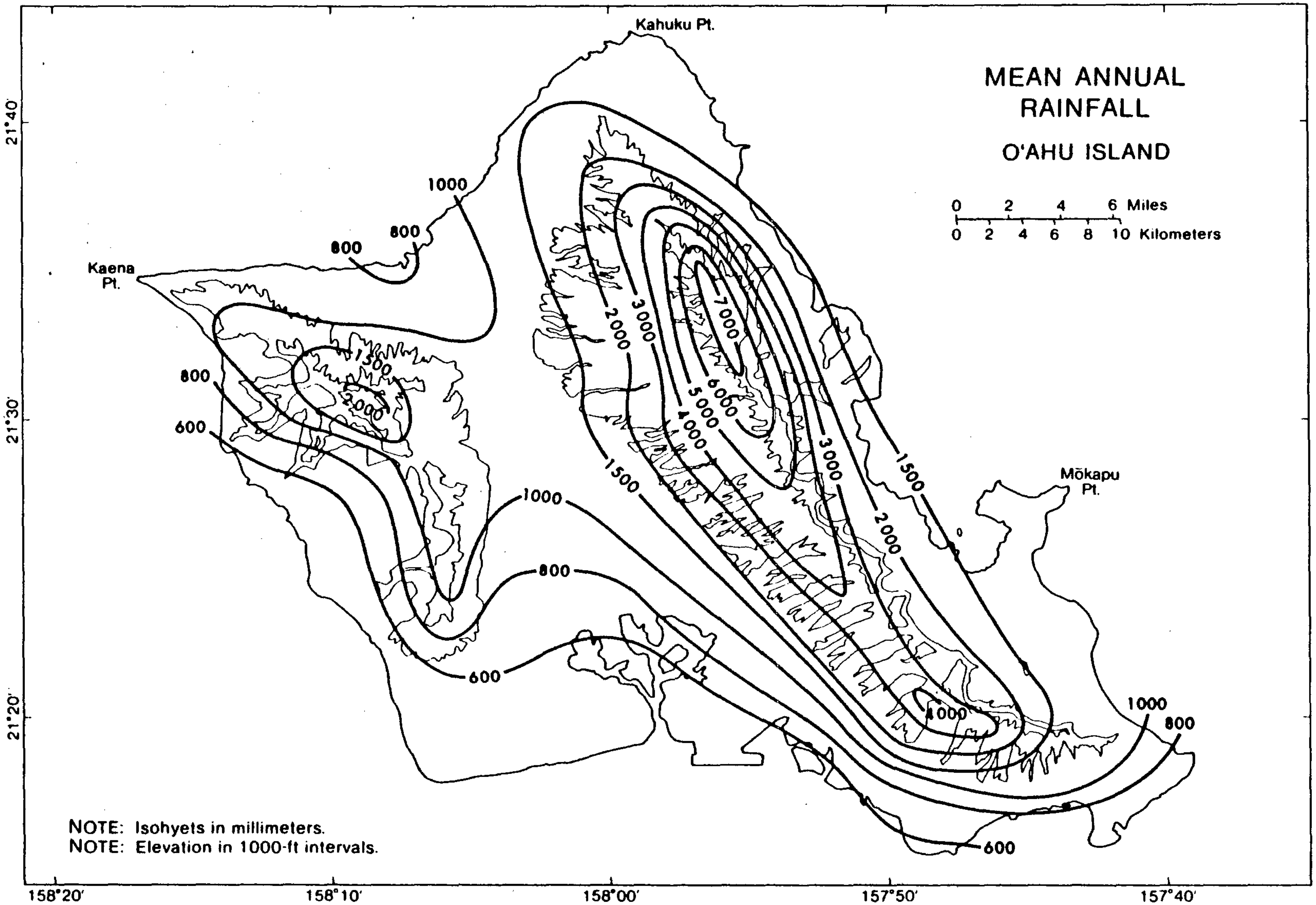
Dr.	L.	Stephen Lau, Director, Water Resources Research Center Project Principal Investigator
Dr.	R.E.	Green, Professor, Agronomy and Soil Science
Mr.	D.S.	Oki (Project Coordinator), WRRC Research Associate
Mr.	H.K.	Gee (Field Consultant), WRRC Research Associate
Dr.	T.W.	Giambelluca (Water Balance Modeler/Climatologist), Assistant Professor, Geography
Mr.	D.N.	Little, Project Chemist
Dr.	K.M.	Loague (Groundwater Modeler), Assistant Professor, Geology and Geophysics
Mr.	J.F.	Mink (Hydrologist-Geologist), WRRC Research Affiliate
Mr.	R.N.	Miyahira, Graduate Research Assistant
Mr.	E.T.	Murabayashi (Soils Specialist and Field Consultant), WRRC Research Associate
Ms.	R.C.	Schneider (Laboratory and Field Consultant), Junior Researcher, Agronomy and Soil Science

2. PHYSICAL SETTING

CLIMATE

The Hawaiian Archipelago is made up of 132 islands, reefs, and shoals stretching 2 451 km (1,523 miles) southeast to northwest across the Tropic of Cancer between 154°40' and 178°25'W longitude, and 18°54' to 28°15'N latitude (Armstrong 1983). Oahu, the third largest of the eight major Hawaiian islands, has a land area of 979 km^2 (378 $miles^2$) (Macdonald, Abbott, and Peterson 1983). Oahu's climate is characterized by mild and equable temperatures the year round (reflecting the high heat capacity of the surrounding ocean), moderate humidities, infrequent severe storms, and persistence of northeasterly trade winds. Air moving outward from the Pacific High or anticyclone flows past the island in the form of a persistent northeasterly trade wind which prevails approximately 90% of the time during the summer and 50% of the time during the winter (Blumenstock and Price 1967).

The climate on Oahu is greatly influenced by the island's topography. The steep Koolau Range is the dominant mountain range on Oahu, stretching northwest-southeast for 59.5 km (37 miles) from the tips of the island, and acts as a barrier which deflects the warm, moisture laden trade winds up its windward slopes. This orographic lifting cools the air, resulting in condensation and rainfall. Orographic rainfall over the older Waianae Range, which makes up the western bulwark of the island and lies leeward of the Koolau Range, is reduced by the dessication of the air as it flows over the Koolau Range. The rainfall gradient on Oahu is very steep. Mean annual rainfall is highest over the crest of the Koolau Range (7 000 mm) and lowest on the leeward coast of the island (600 mm) (Fig. 8). During the winter months between November and April when trade winds are less persistent, migratory cyclones from the north and Kona storms that form nearby often lead to storm rainfall (Armstrong 1983). The cyclonic pattern, most commonly occurring in winter, is less affected by topography and accounts for much of the annual rainfall over the drier areas of the island.



SOURCE: Giambelluca, Nullet, and Schroeder (1986).

Figure 8. Mean annual rainfall, Oahu, Hawaii

GEOLOGY

The island of Oahu is formed primarily from the lavas of the Waianae and Koolau shield volcanoes and to a lesser extent by the Honolulu Volcanic Series. The eroded remnants of the two great shield volcanoes are the Waianae and Koolau ranges (Fig. 9). The Waianae and Koolau volcanoes each have two principal rift zones, which roughly parallel the mountain ranges, and a lesser rift zone extending outward from collapsed calderas near their summits. The Waianae volcano consists of two principal rift zones extending northwestward and south-southeastward and one minor rift zone extending northeastward outward from the caldera area. The Koolau volcano was built primarily by eruptions along a northwest trending rift zone and a southeastward rift zone. A lesser rift zone extends south-southwestward from the Koolau caldera area which was about 13 km (8 miles) long and 6.5 km (4 miles) wide (Macdonald, Abbott, and Peterson 1983). Lava flows from the more recent Koolau volcano are banked against the eastern slope of the Waianae Range forming the broad, gently sloping Schofield plateau between the two ranges. The Koolau volcano and the lower portion of the Waianae volcano consist mainly of thin tholeiitic basalts (Macdonald, Abbott, and Peterson 1983). The thin basaltic lava flows are generally less than 3 m (10 ft) in thickness with slopes of 3 to 10° (Visher and Mink 1964). The middle and upper members of the Waianae Volcanic Series are generally thicker with massive flows in the upper member often reaching 15 to 30 m (50-100 ft) in thickness. Most of the flows emerged from the vent as pahoehoe, possibly changing to aa as they advanced downslope depending on the physical state of the liquid lava and on the amount of stirring it underwent (Macdonald, Abbott, and Peterson 1983).

A long period of quiescence followed the volcanic activity which formed the Waianae and Koolau shields. Fluctuations in relative sea level caused by submergence of the land mass and melting of glaciers during the Pleistocene era played a major role in the shaping of deep valley fills and the coastal plain. During the period when sea level was about 360 m (1,200 ft) below present sea level, intense erosion occurred which carved out deep valleys in the Koolau dome. Deposition of terrestrial sediments near the coast helped to build the southern coastal plain. As the sea level began to rise relative to the land mass, deep valleys were filled with

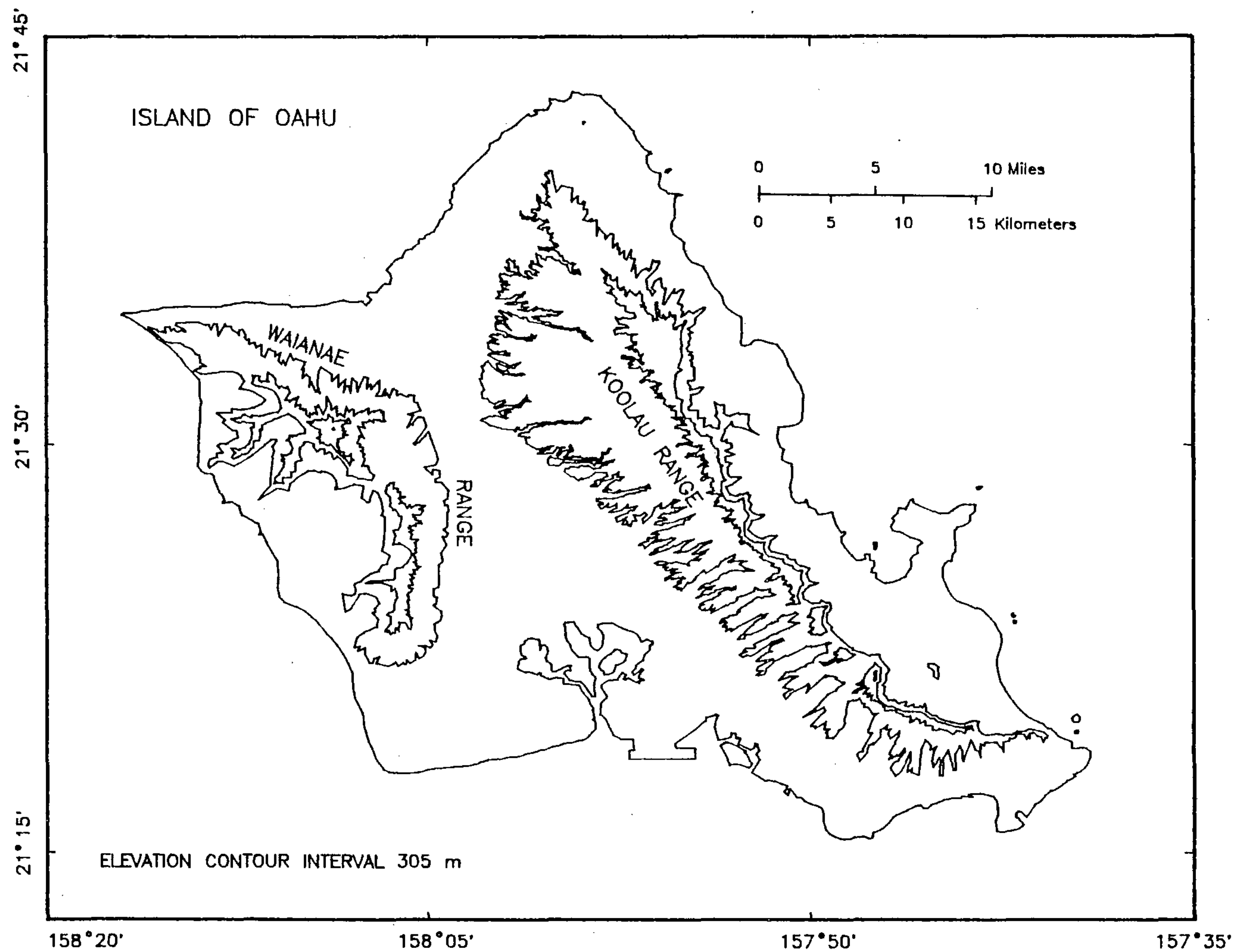


Figure 9. Koolau and Waianae ranges, Oahu, Hawaii

alluvium and the coastal plain was further developed as coral reefs grew and eroded and marine sedimentation occurred. Coral reef deposits, marine sediments, and terrestrial alluvium form the bulk of the southern coastal plain of Oahu and act as a caprock over the unweathered Koolau basalts.

Strictly speaking, the poorly permeable caprock is made up of terrestrial alluvium, marine sediments, calcareous reef deposits, pyroclastic rocks of the Honolulu Volcanic Series, and weathered basalt (Visher and Mink 1964). The weathered basalt occurs as a thin continuous layer at the base of the caprock. This layer is overlaid by old alluvium which was deposited during the period of profound erosion of the Koolau shield. Toward its inland boundary, the caprock consists only of old alluvium overlying the weathered basalt. Near the southern coast, where the caprock may be several hundred meters thick, reef deposits and other marine sediments overlie and interfinger with old alluvium (Visher and Mink 1964). In the vicinity of Pearl Harbor, evidence of the Honolulu Volcanic Series is limited to the southern and eastern portions of the harbor.

HYDRAULIC CHARACTERISTICS OF BASALT

Extrusive Rocks. The permeability of the unweathered extrusive basalt that forms the basal aquifers of Oahu is generally high, with regional hydraulic conductivities lying in the range of 300 to 1 500 m/day (1,000-5,000 ft/day) with most probable values centering around 610 m/day (2,000 ft/day) (Mink and Lau 1980). The principal features of Hawaiian lava that contribute to the high permeability include clinker layers associated with aa, lava tubes in pahoehoe flows, irregular openings within and between flows, and contraction joints formed during cooling of the lavas (Visher and Mink 1964). The successive layering of lava flows suggests that the horizontal component of hydraulic conductivity is greater than the vertical component. However, since water does not flow strictly parallel to the formation units due to structural features such as cracks, joints, and bridging (Mink and Lau 1980), the vertical component is certainly significant.

Estimates of the porosity of unweathered Koolau basalts vary from 5.2 to 51.4% (Mink and Lau 1980). The effective porosity of the basaltic aquifers contributing to water flow is often assumed to be about 10% (Mink 1980).

The permeability of saprolite, which is highly weathered basalt that contains textural features of the parent material, is considerably lower than that of the fresh rock. This is because in the weathered material, the original permeability elements are clogged by chemical alteration and by clays and colloids which precipitate from percolating water. The effects of weathering on permeability are greatest near and beneath valleys where saturated sediments overlie the basalt. Estimates of the hydraulic conductivity of weathered Koolau basalts underlying older type sediments range from 8.5×10^{-8} to 0.039 m/day (2.8×10^{-7}-0.128 ft/day) (Mink and Lau 1980).

Intrusive Rocks. Numerous tabular, intrusive dike formations occur in the rift zones of the Waianae and Koolau volcanoes. The dikes are generally very dense basalt rock ranging in thickness from a few centimeters to about 4 m. Although they may have any attitude, most dikes are nearly vertical. Dike complexes, which make up more than 10% of the total rock volume, may contain in excess of 400 dikes per kilometer in some areas (Macdonald, Abbott, and Peterson 1983). Although dikes may occur extremely close to each other, compartments of extrusive layered lavas often do occur between them (Mink and Lau 1980). The vertical dikes are nearly impermeable and thus act as groundwater barriers capable of impounding water at high elevations.

HYDRAULIC CHARACTERISTICS OF SEDIMENTS

The older alluvium deposited on the coastal plain following the period of intense erosion on Oahu also filled the deeply cut valleys. This alluvium is hydrologically important because of its low permeability. Older alluvium along with weathered basalt in the caprock formation are the primary elements which retard the seaward movement of groundwater in the basal aquifers of Oahu. In addition, weathered basalt and older alluvium filling the deep valley cuts extend downward into the basal aquifers and may impede the lateral movement of groundwater near the top of the lens.

The older alluvium consists of basalt particles weathered under considerable load into a soft mass. The old alluvium is compact with no original spaces larger than vesicles remaining open (Wentworth 1951).

Wentworth (1938) measured the hydraulic conductivity of older alluvium samples in the laboratory and found a range of conductivities between 0.0057 and 0.11 m/day (0.019 and 0.37 ft/day).

GROUNDWATER OCCURRENCE

High-Level Groundwater. The groundwater of Oahu occurs in various forms. High-level groundwater occurs as dike-impounded water in the mountain regions, where relatively impermeable vertical dikes in the rift zones cut through permeable lava flows and, to a lesser extent, as perched water on relatively impermeable beds of soil, alluvium, or volcanic ash. Dike-impounded water develops as rainfall over the mountain areas recharges dike compartments. These dike compartments can be saturated to levels a few hundred meters above sea level. In general, the impounded water is probably separated from seawater by the dense dikes (Macdonald, Abbott, and Peterson 1983). Water development tunnels tapping the dikes of the Koolau Range can extract tremendous amounts of groundwater. The Waiahole System tunnels, for instance, drain an average of 1.2 m^3/s (28 mgd) of groundwater (Mink, Yuen, and Chang 1988).

A high-level water body of particular importance on Oahu is the Wahiawa high-level water body located beneath the Schofield plateau of central Oahu. This groundwater body underlies an area of approximately 88 km^2 (34 $miles^2$) and is impounded by dikes or other features concealed by highly permeable lava flows to an elevation of about 85 m (278 ft) above mean sea level (Shettigara and Peterson 1985). Draft from the system is typically between 0.35 and 0.48 m^3/s (8 and 11 mgd) (Mink, Yuen, and Chang 1988). Overflow from the Wahiawa aquifer is an essential component of recharge to the basal aquifers. Mink, Yuen, and Chang (1988) estimate that as much as 2.7 m^3/s (62 mgd) of water from the Wahiawa high-level aquifer may recharge the Pearl Harbor aquifer.

Basal Groundwater. The most important and extensive groundwater source on Oahu is basal water. Basal groundwater consists of a lens of fresh water floating on seawater due to the density difference between the two liquids. Under static conditions with a sharp interface between fresh water and seawater, the Ghyben-Herzberg relation can be used to estimate the thickness of the freshwater lens. Using the commonly accepted specific gravity of 1.025 for seawater and a specific gravity of 1.0 for fresh water, the Ghyben-Herzberg principle states that every meter of fresh water occurring above sea level will be balanced by 40 m of fresh water below sea level.

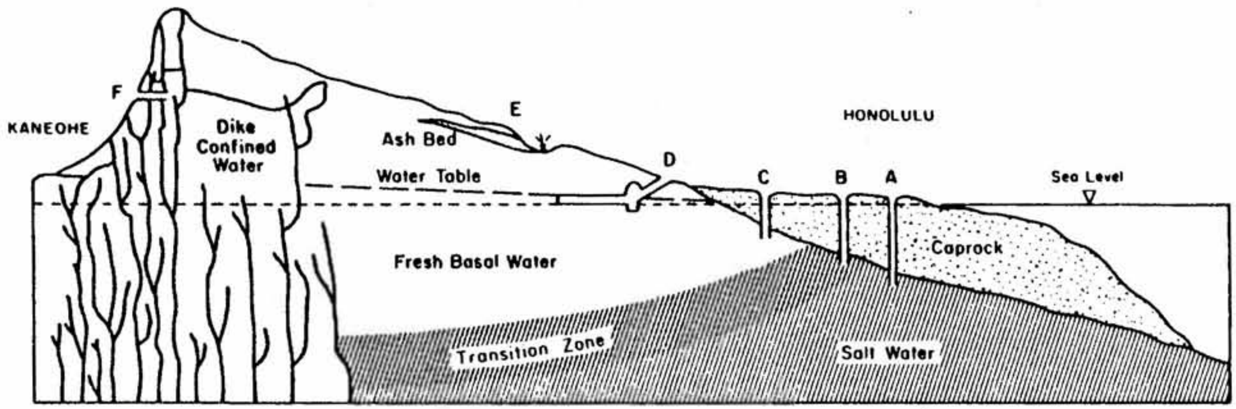
The basal lens underlying southern Oahu is dynamic in nature which results in an interface that is continually moving. Due to the action of density variations and seasonal fluctuations in recharge and discharge, the bottom of the lens may move vertically. This vertical fluctuation causes mixing of the seawater upward into the fresh water at the interface leading to the development of a transition zone between the freshwater lens and the underlying saltwater (Fig. 10).

The thickness of a freshwater lens is governed by (1) the recharge flux, (2) the aquifer permeability which controls the freshwater gradient and heads, and (3) the existence or absence of a coastal caprock of low permeability. The thickness of a freshwater lens increases as the recharge flux increases. Where a coastal caprock overlies the aquifer and separates it from the ocean (Fig. 10), the seaward movement of groundwater is restrained so that the freshwater lens is thicker than that which would exist if the caprock were not present. The caprock plays a major role in the groundwater occurrence in the southern Oahu basal lens.

The caprock is made up of weathered basalt at its base overlaid by terrestrial and marine sediments and reef deposits. Although the overall permeability of the caprock is low, controlled primarily by the weathered basalt and the old alluvium, limestone deposits within the caprock can be extremely permeable and successfully developed. The Ewa caprock aquifer of southern Oahu, for instance, has provided from 0.88 to 1.1 m^3/s (20-25 mgd) of irrigation water in recent years (Lau, Dugan, and Hardy 1986).

PEARL HARBOR AQUIFER

The southern Oahu basal aquifer consists of basaltic lava flows of high permeability extending to the eastern end of the island and westward to the crest of the Waianae Range. The southern Oahu aquifer can be divided into a number of hydraulically connected aquifers (Mink and Lau 1987). Aquifer boundaries consist of dike formations in volcanic rift zones and sedimentary deposits extending inland from the caprock, filling ancient



A Artesian well producing salt water

B Artesian well producing brackish water

C Artesian well producing fresh water

D Maui shaft

E Perched water spring

F High level tunnel tapping dike water

SOURCE: Macdonald, Abbott, and Peterson (1983).

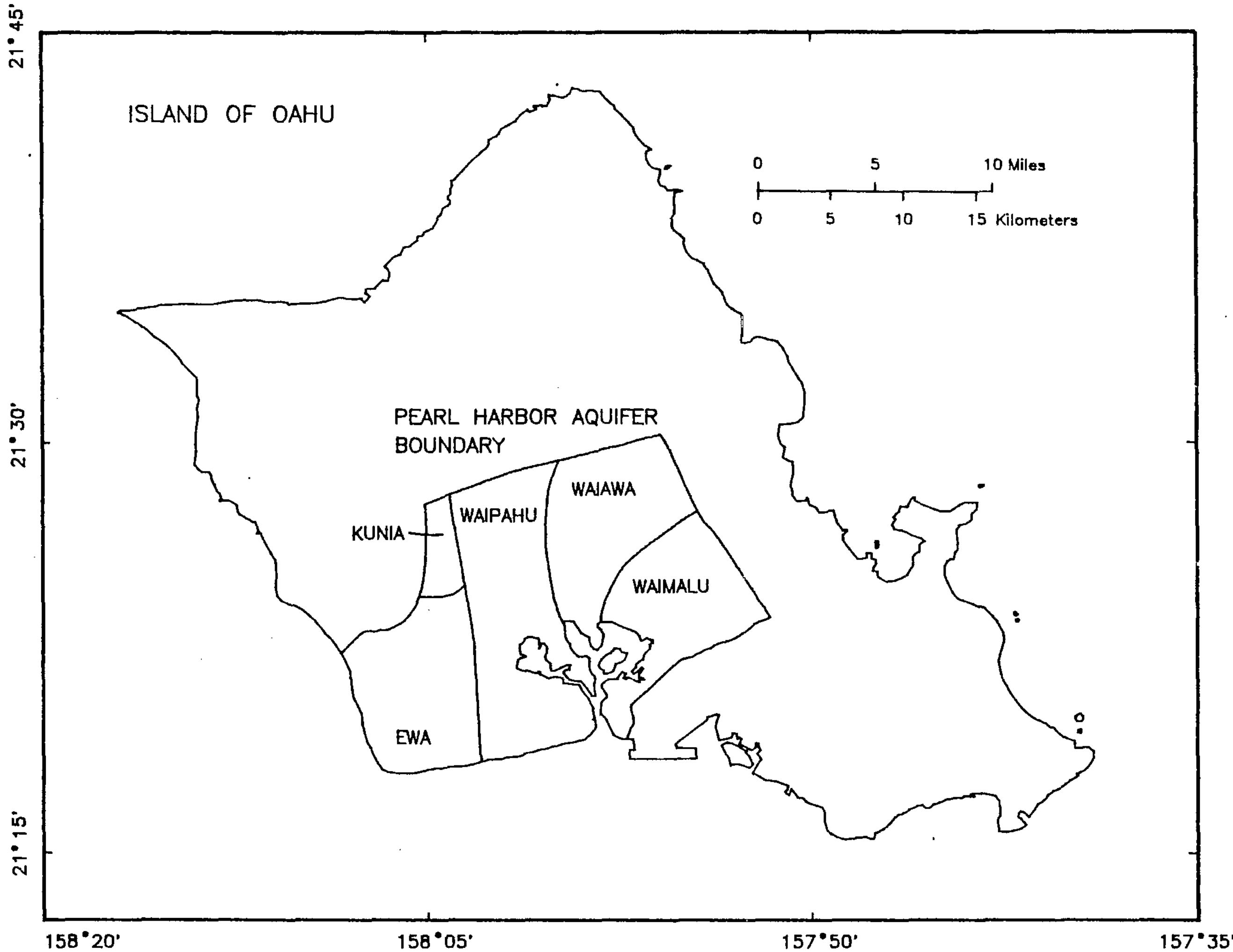
Figure 10. Cross section of basal lens, transition zone, and caprock formation

valleys. The largest and most important aquifer in southern Oahu occurs in the Pearl Harbor area and is named the Pearl Harbor aquifer.

The Pearl Harbor aquifer is geologically bounded by the dike zone of the Koolau Range toward the east and by the dike zone of the Waianae Range toward the west. The northern boundary, possibly formed by intrusive dike formations, is coincident with the southern extent of the Wahiawa high-level water body. Water from the rift zones of the Koolau and Waianae mountains and from the Wahiawa high-level water body contribute to the recharge of the Pearl Harbor aquifer. The boundary separating the Pearl Harbor aquifer from the Honolulu District is the Halawa Valley fill near Red Hill. The valley fill is an open boundary which does not completely preclude flow from one area to the other. The caprock which retards the flow of fresh water represents the southern boundary of the Pearl Harbor aquifer.

Mink and Lau (1987) further separate the Pearl Harbor aquifer into five aquifer systems (Fig. 11). The three systems occurring in the Koolau Volcanic Series are, from east to west, the Waimalu, Waiawa, and Waipahu systems. The dividing lines between these three systems are synthetic in nature and were chosen to reflect the general flow paths to principal spring discharges in the area. The western extent of the Waipahu system is the unconformity between the Koolau Volcanic Series and the Waianae Series. The unconformity is poorly permeable creating a discontinuity in groundwater levels on either side. The Kunia and Ewa aquifer systems lie to the west of the unconformity in the Waianae Volcanic Series. The Kunia and Ewa systems are hydraulically continuous, with the boundary chosen to reflect the source of irrigation water in the region (Mink, Yuen, and Chang 1988).

Recharge to the Pearl Harbor aquifer is primarily from deep percolation of rainfall, and is greatest in the high forested areas near the Koolau Range. Recharge to the basal lens also occurs as a result of inflow from dike compartments at the western, northern, and eastern boundaries of the aquifer, seepage of water through streambeds (Hirashima 1971), and flow from the Honolulu District beneath the valley fill at the southeastern boundary of the aquifer. Deep percolation of irrigation return water has also been shown to contribute to the recharge of the Pearl Harbor aquifer



SOURCE: Adapted after Mink and Lau (1987).

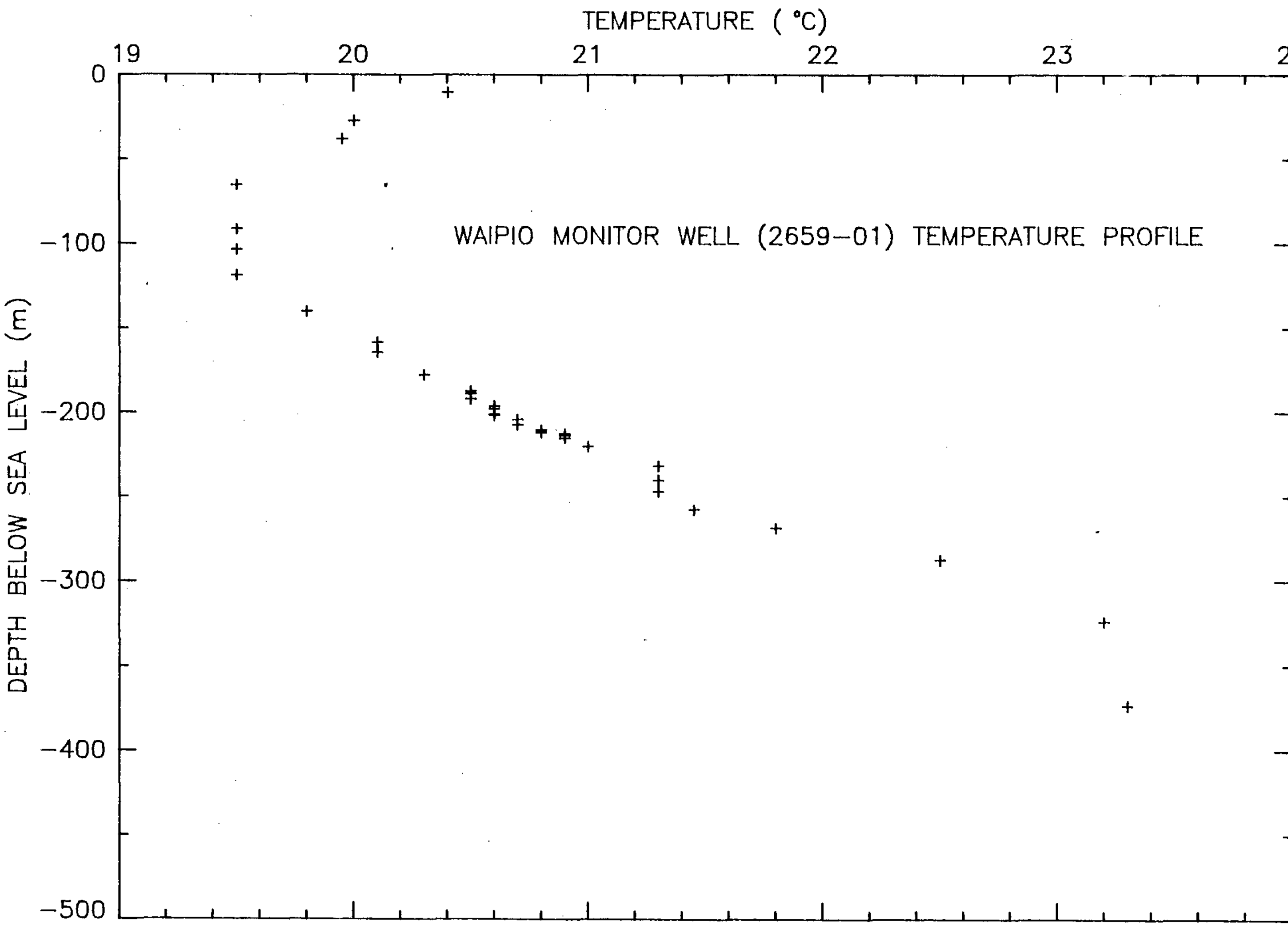
Figure 11. Aquifer systems of the Pearl Harbor aquifer, Oahu, Hawaii

(Tenorio, Young, and Whitehead 1969; Hufen, Eyre, and McConachie 1980; Eyre 1983b).

The basal lens of the Pearl Harbor aquifer can be divided into three layers (Mink 1964). The uppermost consists of a mixture of subsurface inflow, rainfall recharge, and irrigation return water and is slightly warmer than the middle layer, which consists primarily of cooler subsurface inflow from mountain recharge areas. The bottom layer is also slightly warmer than the middle reflecting the effect of the geothermal gradient. A recent temperature profile measured by the Honolulu Board of Water Supply on 23 April 1987 at the Waipio monitor well (well no. 2659-01) (Mink, Yuen, and Chang 1988) provides evidence of the layered basal lens system (Fig. 12).

Natural discharge from the Pearl Harbor basaltic aquifer occurs in the form of springs and diffuse seeps along the margins of the caprock, in streams cut below the basal water level, and from leakage through the caprock. Visher and Mink (1964) conservatively estimated spring discharge along the shore of Pearl Harbor as 3.8 m^3/s (87 mgd) for the period 1953 to 1957. Although spring discharge has been reduced by declining groundwater levels, substantial outflow still exists. Mink, Yuen, and Chang (1988) estimate the average outflow since 1980 to be about 2.6 m^3/s (60 mgd). Leakage through the caprock formation is difficult to quantify. Most of the leakage, however, probably occurs near the inland margin of the caprock where the formation is relatively thin. In the absence of external influences such as pumping, the ambient groundwater flow direction is from areas of high recharge toward the natural discharge points near the coast.

Groundwater withdrawal by pumping occurs throughout the Pearl Harbor aquifer but most heavily along the downgradient portion of the aquifer. The first successful development of basal groundwater in a drilled well on Oahu took place in 1879 at Honouliuli where artesian water was struck at a depth of about 67 m (220 ft) (Visher and Mink 1964). The basal groundwater head at Honouliuli at the time of this initial development was likely about 9.8 m (32 ft), increasing to about 12.2 m (40 ft) upgradient near the Wahiawa high-level water body (Mink 1980). The initial volume of groundwater storage in the basal lens declined as



SOURCE: Data from Mink, Yuen, and Chang (1988).

Figure 12. Temperature profile for Waipio monitor well (2659-01), Oahu, Hawaii

increasing numbers of wells were developed for agricultural, urban, industrial, and military uses. A history of the head decline experienced in the Pearl Harbor region is provided by Mink, Yuen, and Chang (1988). From 1910 to 1977, Soroos and Ewart (1979) estimate that the groundwater level in the Pearl Harbor aquifer declined at an average rate of about 9×10^{-10} m/s (0.09 ft/yr). Current operating head at the USN Waiawa Shaft is typically about 5.2 m (17 ft), varying seasonally with pumping and recharge rates.

The estimated water levels for the period of initial groundwater development 110 years ago represent heads which provide a true measure of the amount of groundwater stored in the basal lens. This groundwater storage can be estimated by the Ghyben-Herzberg relation. A clear distinction should be made between storage heads and the operating heads measured during periods of aquifer pumpage. Operating heads measure only the response of the top of the lens to seasonal fluctuations in pumping and recharge. Seasonal fluctuations of operating heads may be as great as a few meters. If the operating head did provide a true measure of water in storage, then based on the Ghyben-Herzberg principle, a decline of 2 m in the operating head would indicate that the bottom of the lens should rise about 80 m, releasing an unrealistically high amount of water. Clearly, seasonal fluctuations of pumping are felt most immediately by water near the top of the lens, with sluggish adjustment of the bottom of the lens. This concept was first proposed by Wentworth who summarized his "doctrine of bottom storage" in seven corollaries (Wentworth 1951). A fuller elucidation is presented by Mink (Mink and Lau 1980).

In response to the trend of declining heads in the region and increasing chloride concentrations in wells due to a rising transition zone, the State Water Commission appointed by the governor recommended that the groundwater resources of the Pearl Harbor basin be regulated to ensure the long-term integrity of the aquifer (State Water Commission 1979). In September 1979, the Board of Land and Natural Resources designated the Pearl Harbor basin as a "Ground Water Control Area" (GWCA) to control future development and use of groundwater in the area. The Pearl Harbor aquifer and a portion of the Wahiawa high-level water body are contained within this designated GWCA. The sustainable yield of the Pearl Harbor GWCA was originally estimated to be 9.9 m^3/s (225 mgd). Based on the sustainable yield estimate, original allocations for the Pearl Harbor basal aquifer portion of the GWCA amounted to 9.4 m^3/s (214 mgd). Allocations were subsequently modified to reflect actual conditions in the aquifer and changing pumping practices. Currently, allocations for the Pearl Harbor aquifer total 9.1 m^3/s (208 mgd) (Mink, Yuen, and Chang 1988). Most recently, Mink, Yuen, and Chang (1988) recalculated the sustainable yield of the Koolau and Waianae portions of the Pearl Harbor aquifer. Based on equilibrium storage heads of 4.3 m (14 ft) for the Waianae sector and 5.5 m (18 ft) for the Koolau sector near Waipahu, the natural sustainable yield for the Pearl Harbor aquifer was estimated to be 6.9 m^3/s (158 mgd). Based on a return irrigation flow of 1.0 m^3/s (23 mgd), the total allowable draft becomes 7.9 m^3/s (181 mgd).

NAVY WAIAWA VALLEY DEVELOPMENT

Development Description. One of the proposed developments overlying the Pearl Harbor aquifer which could adversely affect the quality of water pumped by the Waiawa Shaft is the proposed military housing development in Waiawa Valley (Fig. 13). The site occurs within the USN Pearl Harbor Water Supply Area which consists of 30.45 ha (75.231 acres) lying predominantly within Waiawa Valley. The valley floor where the proposed housing development will be located, consists primarily of flatter alluvial terraces with sloping rocky talus material adjoining the gulch wall periphery. The alluvial terraces occur at elevations of 30 to 50 m (100-160 ft) above mean sea level. Waiawa Stream, which has cut a channel about 3 to 5 m (10-15 ft) below the terraces, meanders through the USN property, flowing from the northern toward the southern boundary of the area. Waimano Stream, a principal tributary of Waiawa Stream, enters from the southeastern corner of the property and flows along the southern boundary until the confluence of the two streams. The salient features toward the east and west are steep valley walls rising approximately 60 m (200 ft) above the alluvial terraces. An urban residential area, Pacific Palisades, lies on the ridge above the eastern portion of the valley while the land on the western ridge is currently owned by the Bernice Pauahi Bishop Estate, leased by Amfac, and subleased by Circle 6 Ranch.

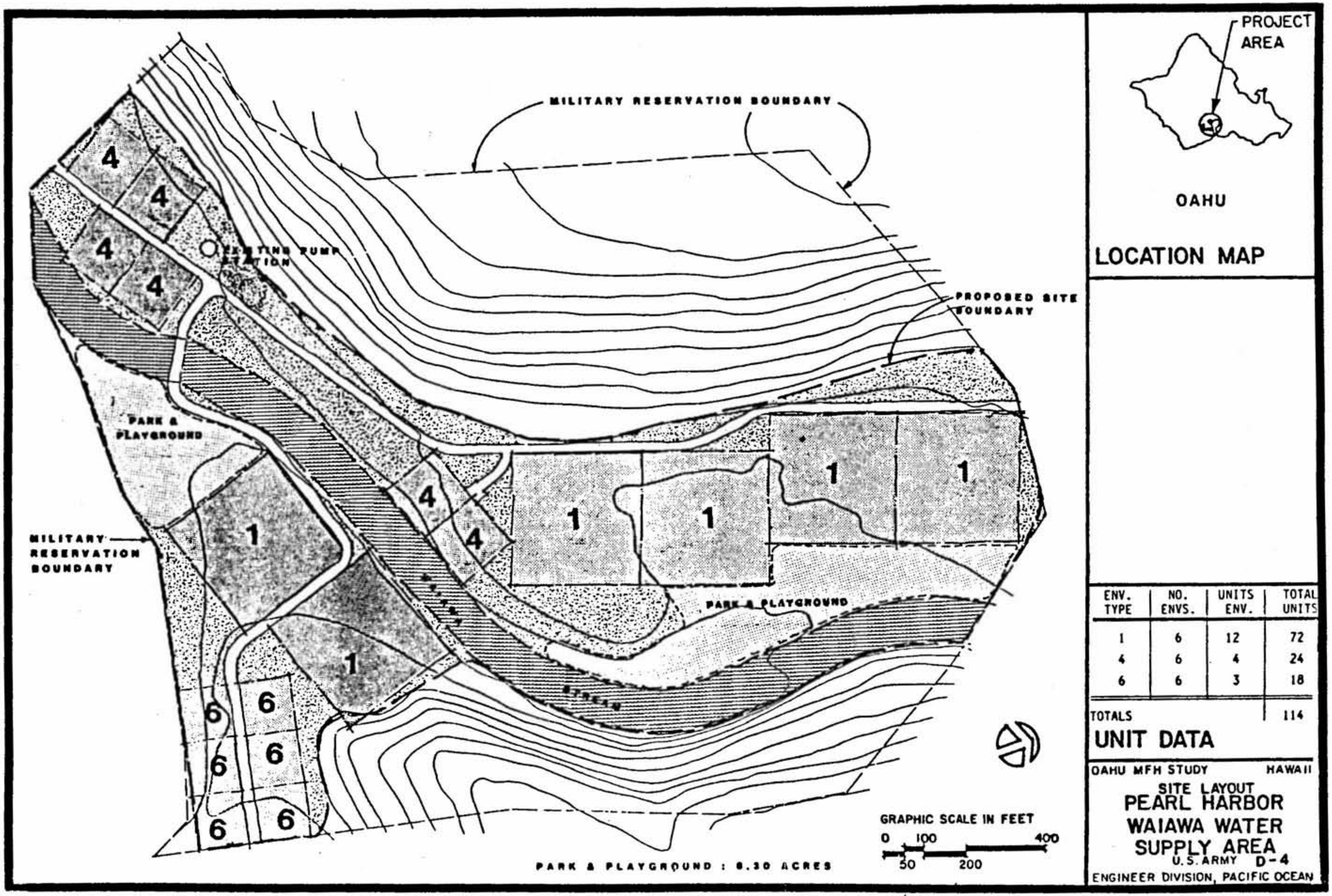


Figure 13. Land use distribution for U.S. Navy proposed Waiawa Valley development, Oahu, Hawaii

The USN proposed Waiawa Valley development consists of 114 housing units with 2.55 ha (6.30 acres) committed to park and playground areas. Housing units will be built south of the existing Waiawa Fresh Water Pumping Plant and toward the northern boundary of the military property on an older alluvial terrace. A proposed road and bridge will allow residents to cross Waiawa Stream to additional housing units and a park area between the confluence of Waiawa and Waimano streams. Although a small portion of the USN property extends above the western valley wall onto the ridge, the proposed development is limited to the alluvial terraces within the valley.

Land Use History. Examination of a historical map (14th Naval District Drawing No. OA-NI-779) indicates that prior to 1942, the area currently owned by the USN was used for pineapple and vegetable cultivation (Fig. 14). A road running along Waiawa Stream existed prior to the USN purchase of the land. Comparison of historical topographic contours with present-day relief indicates that the land was cut in certain areas, including along the western talus slope. In addition, just above the northern property boundary, a Waiawa Stream meander appears to have been cut off, either naturally or by man, which subsequently led to a straightening of the stream course.

The USN purchased the current Waiawa Water Supply Area from Bishop Estate in 1945 (title passed 13 August 1945). During World War II, however, it was necessary for the USN to lease the current property along with adjacent land to the south for storage purposes. During the war, the USN brought airplanes from the mainland in crates, stored them at Waiawa, and assembled them in Kunia.* Thus, the Waiawa Valley area was used as an aviation supply depot during the war.

Several buildings were erected within the current USN Waiawa land (Fig. 15). Buildings 31 and 32 (which are no longer standing) were used as general storehouses while building S62 (which still stands) was used as an incinerator. Building S71 is the Waiawa Fresh Water Pumping Plant which operates today. In addition to the structures, two open storage areas once existed between Waiawa and Waimano streams (Public Works Drawing No. OA-N25-1580). An asphalt road extends northward from the southern boundary of the area.

*J. Wallace (PACDIV) 1988: personal communication.

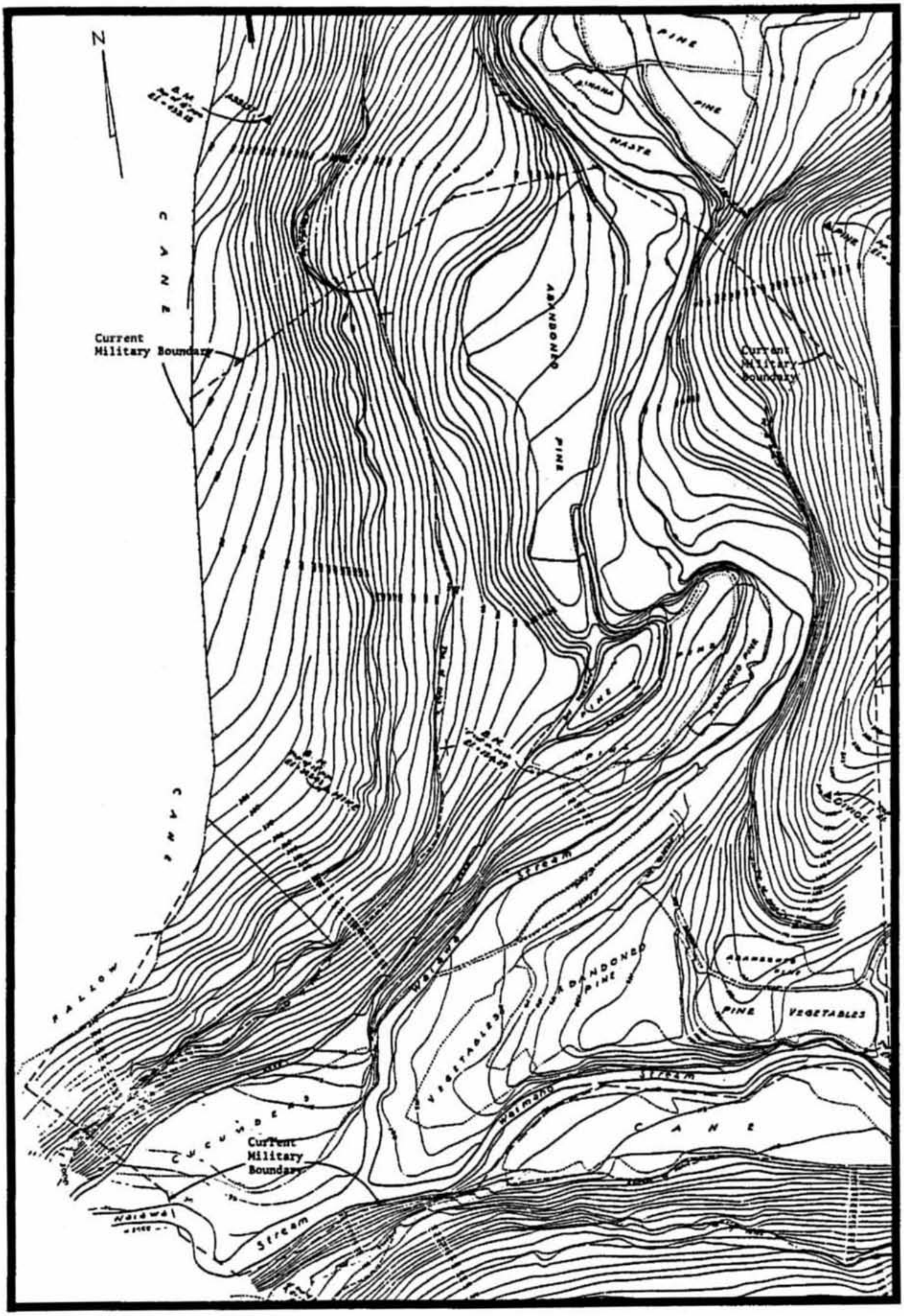
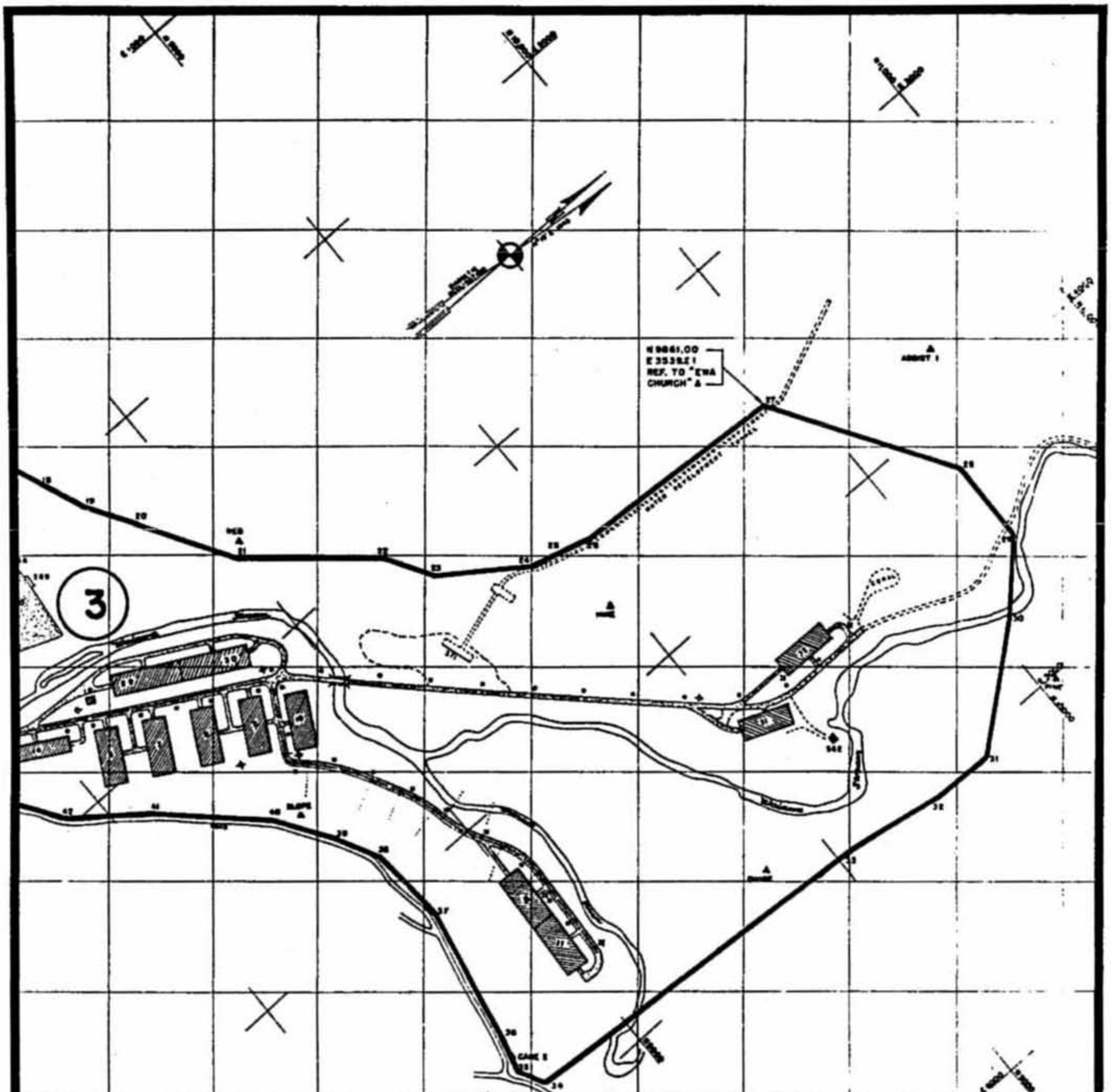


Figure 14. Historical map (ca. 1940) of U.S. Navy Waiawa Valley property, Oahu, Hawaii



SOURCE: Public Works Drawing No. OA-NI-1990.

Figure 15. Layout of Aviation Supply Depot, U.S. Naval Supply Center, Waiawa, Oahu, Hawaii, 30 June 1952

Location Relative to Waiawa Shaft. The Waiawa Fresh Water Pumping Plant lies within the military land where the USN is proposing to develop. A 30° inclined shaft was excavated into the western valley wall near the southwest boundary of the USN property. The shaft leads down to the pump room and sump which are located approximately beneath the edge of Waiawa Ridge. From the sump, the infiltration tunnel runs north beneath the western boundary line of the military's land on Waiawa Ridge for about 382 m (1,253 ft) until the edge of the property. At this point, the infiltration tunnel bends 30° west and continues beneath Waiawa Ridge land (owned by Bishop Estate) for approximately 137 m (449 ft) to its terminus.

Climate. No rain gage stations other than the short-term gage installed for this project are located in the proposed development area. Average annual rainfall in the region, however, is estimated to be about 1 100 mm (43 in.) (Giambelluca, Nullet, and Schroeder 1986). Rainfall occurring in Waiawa Valley may actually be slightly higher than this value due to a funneling effect created by the valley walls. The seasonal pattern of rainfall can be determined from data at existing and discontinued rain gages in the area and is presented in Figure 16. The area does receive orographic rainfall associated with the persistent northeasterly trade wind. Relative to areas deeper in the valley, however, a substantial portion of the annual rainfall total occurs as a result of seasonal migratory storms.

Although no evaporation records exist for the proposed development area, annual pan evaporation in the region is estimated to be about 1 900 mm (75 in.) (Ekern and Chang 1985). This value may slightly underestimate evaporative conditions in the valley since increased trapping of outgoing radiation by the gulch walls and possible subsidence warming of air in descent from the ridge crest add to the energy available for evaporation (Ekern 1983). The seasonal evaporation pattern in the area can be determined from monthly potential evapotranspiration maps (Giambelluca 1983) and is presented in Figure 17. Actual evapotranspiration will be less than the pan value due to soil moisture limitations in the area (see App. C).

Soils. The valley floor consists primarily of flatter alluvial terraces grading into moderately sloping, rocky talus material at the base of the

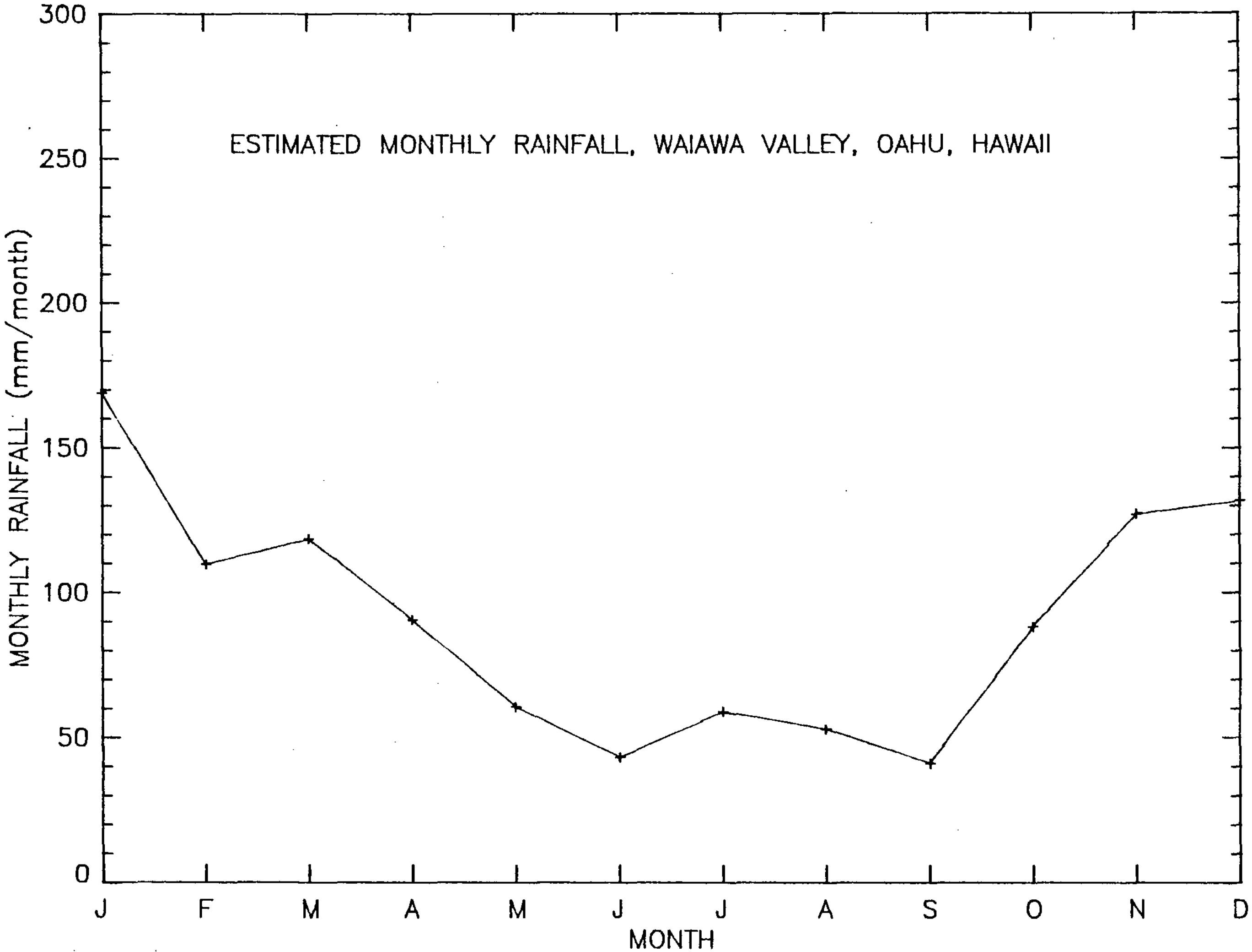


Figure 16. Estimated seasonal rainfall pattern at proposed U.S. Navy development site in Waiawa Valley, Oahu, Hawaii

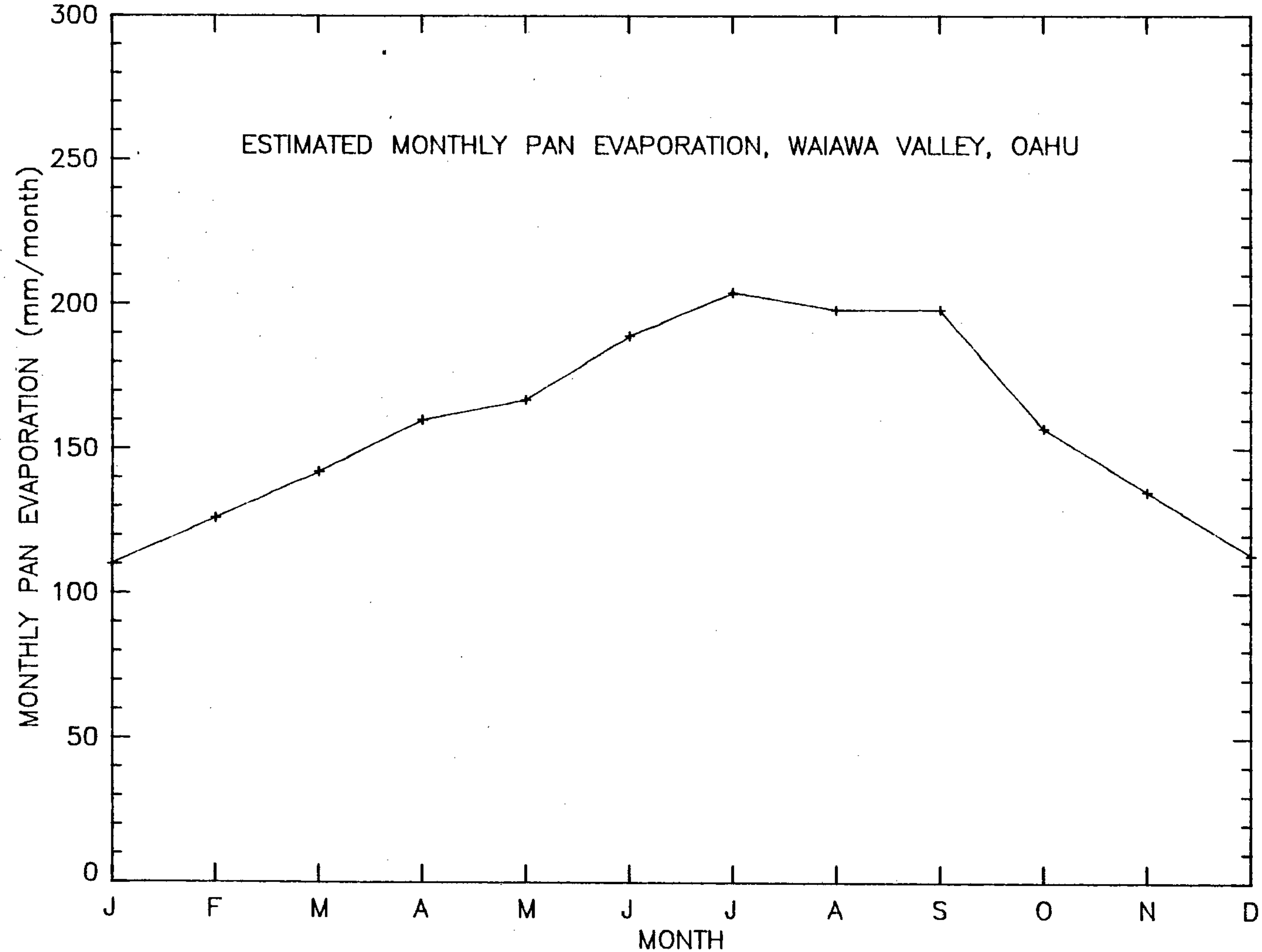


Figure 17. Estimated seasonal pan evaporation pattern at proposed U.S. Navy development site in Waiawa Valley, Oahu, Hawaii

gulch wall. In the more recent past, there has been some grading of these talus slopes, evidently to enlarge the usable flatter terrace area. Also, a small knoll where Building 31 was formerly situated has been flattened for the same purpose. The rocky debris from this earth moving has been scattered through much of the valley floor to establish the desired grade. In addition, some of the rock spoils from the shaft excavation were deposited adjacent to the portal. As a result, the surface of the valley floor is disturbed, which has added to the highly heterogeneous characteristics normal to alluvial-laid soils.

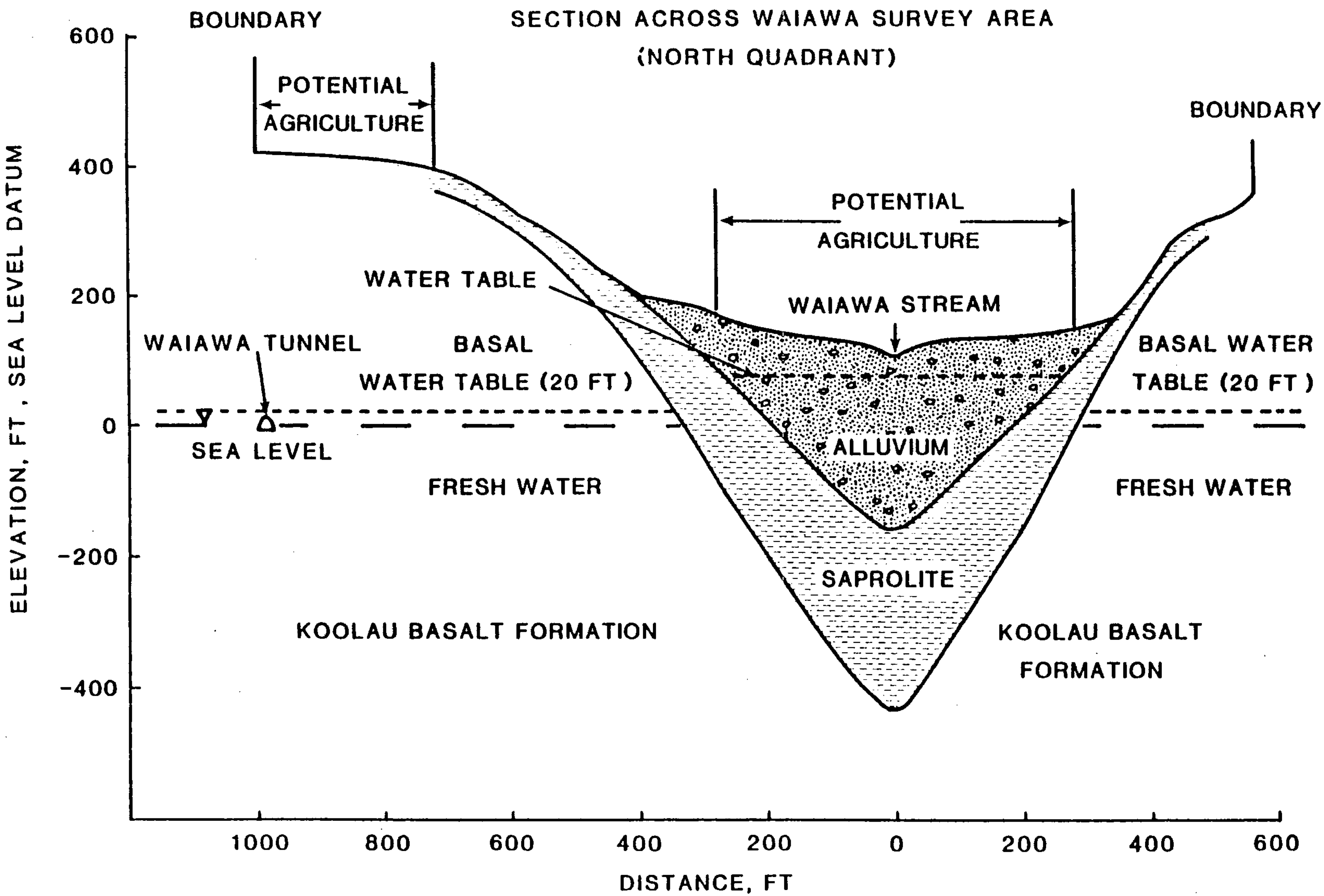
The predominant soil on the valley floor has been mapped as an inclusion with Kawaihapai stony clay loam, 2 to 6% slopes, of the Kawaihapai series (Foote et al. 1972). The valley walls have been classified either as Helemano silty clay of the Helemano series or as rock land. On the western ridge top above the valley floor, Lahaina silty clay of the Lahaina series occurs within the military property. Toward the east, Wahiawa silty clay of the Wahiawa series occurs in the Pacific Palisades area near the edge of the ridge.

The Kawaihapai soils, formed from well-drained alluvium, are medium textured and exhibit moderate levels of infiltration and permeability. Stones commonly occur within the soil and hinder workability. Runoff from the Kawaihapai soil is slow and the erosion hazard slight (Foote et al. 1972). Based on a field reconnaissance survey through the proposed development area, soils of the Kaena series may also exist in Waiawa Valley.* In contrast to the Kawaihapai soils, the characteristically rocky Kaena soils generally associated with talus slopes consist predominantly of fine-textured smectitic (montmorillonitic) clays that have relatively low permeability levels when wet. The Kaena soils also exhibit considerable expansion and contraction on wetting and drying, with wide cracks formed on drying into which pesticide-laden surface soils can mechanically fall in especially from along the edges. At the driest times of the year, these cracks are as wide as 0.025 to 0.05 m at the top and taper downward to a depth of 0.45 to 0.60 m at its narrow lower level. In contrast, the Kawaihapai soils do not crack extensively; consequently, pesticide movement in that soil would occur primarily through percolation.

*E. Murabayashi 1988: personal communication.

Geology. The recent alluvium occurring on the valley floor has a thickness of about 1 m (3 ft) and consists of clay, silt, sand, gravel, cobbles, and boulders (Mink 1985). Soils overlie this alluvium on the terraces. The recent alluvium lies above older alluvium and is distinguished from the latter by having been deposited after the major erosional stage of island development. The older alluvium deposited in deeply eroded valleys after the intense erosional period typically consists of ill-sorted material and is generally weathered to a soft, ferruginous mass (Wentworth 1951). Test borings drilled in the military land in Waiawa Valley during 1948 indicate the presence of soft weathered material to depths in excess of 76 m (250 ft) (Public Works Drawing No. OA-N25-1581). The subsurface geology in Waiawa Valley 760 m (2,500 ft) upstream of the northern boundary of the proposed USN housing development was investigated by R. M. Towill Corporation (1978) using geophysical survey techniques in conjunction with borehole drilling data. Based on that study, Mink (1985) extrapolated results downstream to the proposed housing development area and determined that total alluvium thickness is greater than 61 m (200 ft) near the valley center thinning toward the edges of the terrace (Fig. 18). Beneath the older alluvium, heavily weathered Koolau basalt grades into fresh unweathered rock. Due to the presence of saturated sediments above the basalt, weathering of the underlying rock has been very effective, extending to depths greater than 61 m (200 ft) below the older alluvium. Chemical alteration and precipitation of clays and colloids with percolating water have occurred in the original basalts to reduce the permeability of the formation. Injection well tests conducted in a Waiawa Valley borehole on a 48 m (158 ft) thick column of weathered rock yielded an average hydraulic conductivity of 0.018 m/day (0.058 ft/day) (R.M. Towill Corp. 1978). The most permeable section of the borehole was found to have an average hydraulic conductivity of 0.088 m/day (0.288 ft/day). Subtle weathering effects have probably penetrated 15 to 30 m (50-100 ft) into the valley wall even in places where exposed rock appears to be unweathered (R.M. Towill Corp. 1978).

Groundwater Occurrence. In Waiawa Valley proper, two separate aquifers occur beneath the proposed USN housing development. The first



SOURCE: Mink (1985).

Figure 18. Geologic section of Waiawa Valley at proposed U.S. Navy development site, Oahu, Hawaii

is a relatively small aquifer formed in the alluvium. The alluvial groundwater body is recharged by rainfall, flood waters of Waiawa Stream, and leakage from beneath the streambed. The water table in the alluvial aquifer is about 15 m (50 ft) below the terrace surface. The aquifer is 30 to 60 m (100-200 ft) thick and has a hydraulic conductivity of less than 0.3 m/day (1 ft/day) and an effective porosity of 5 to 10% (Mink 1985). The second aquifer beneath the proposed Waiawa Valley development is a small portion of the Pearl Harbor basal aquifer which lies beneath the alluvial aquifer. The heads in the alluvial and basal aquifers remain distinct due to the low permeability of the saturated saprolite separating them. The alluvial aquifer heads may be up to 25 m (80 ft) higher than those in the basal aquifer (Public Works Drawing No. OA-N25-1581). Some flow of groundwater from the alluvial aquifer to the basal aquifer, however, may occur.

GENTRY WAIAWA RIDGE DEVELOPMENT

Development Description. The proposed Waiawa Master Plan development by The Gentry Companies is located on Waiawa Ridge and will cover an area of about 1 000 ha (2,500 acres) when completed. The proposed development is roughly triangular in shape and is bounded toward the west by the H2 freeway and Panakauahi Gulch, to the north by Dole Company pineapple fields and the forest reserve boundary, and to the east by Pacific Palisades, military land, and the Pearl City Industrial Park. Waiawa Stream is included in the eastern portion of the development in an area designated as open space. Military reservation land occurs within the proposed development area toward the northern boundary.

The Waiawa Master Plan can stand alone as a self-contained community and would include single family detached units, low- and medium-density apartments, retail commercial spaces, mixed commercial and industrial areas, school and park areas, golf courses, a botanical garden, and trails leading through large open spaces (Fig. 19). Although numerous gulches exist in the area, the developable portions of Waiawa Ridge are generally level to mildly sloping. The steeper-sloped gulches have been designated as open areas. Ground elevations toward the southern extent of the development are less than 61 m (200 ft) rising to approximately 300 m (1,000 ft) toward the north.

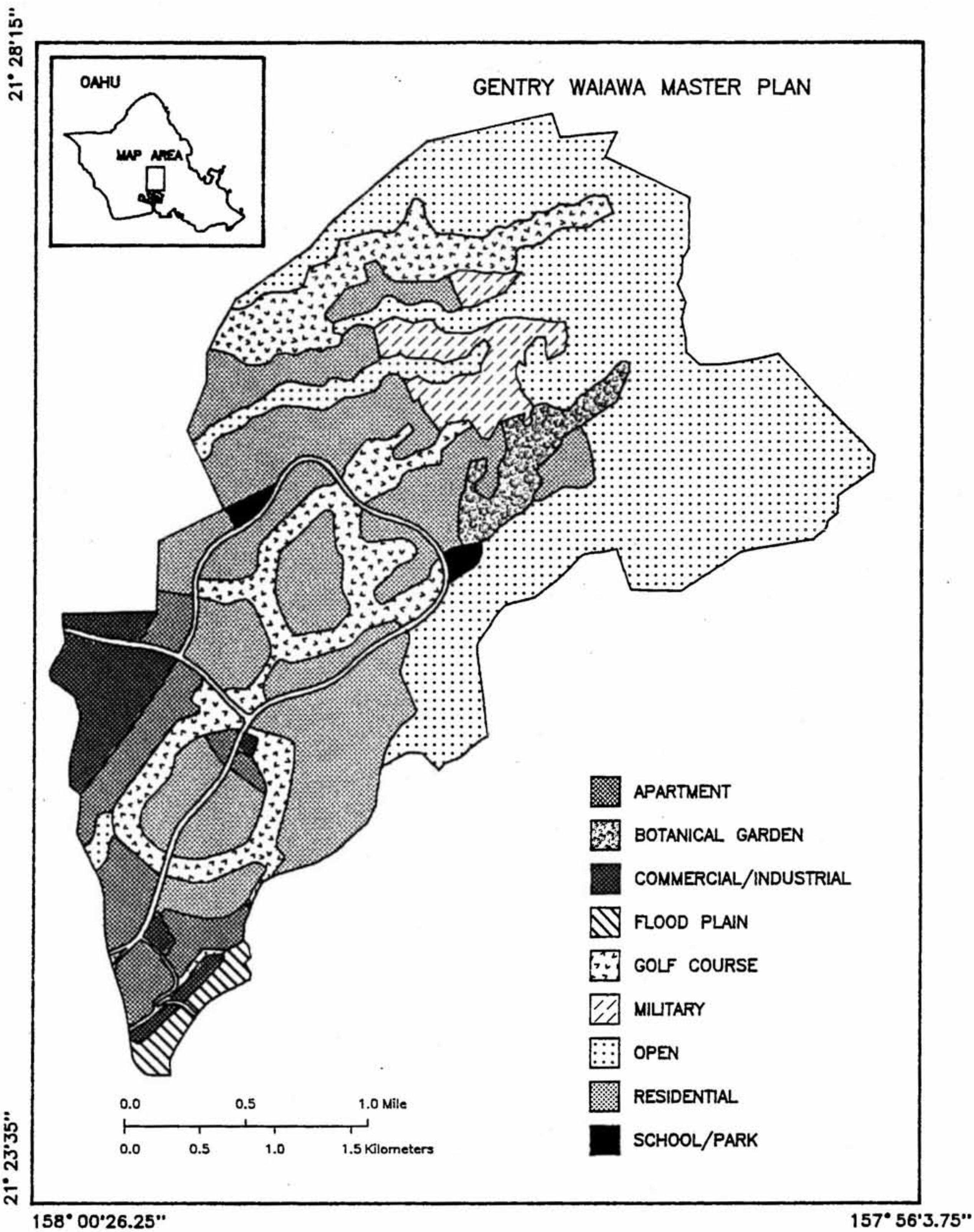


Figure 19. Proposed Gentry Waiawa Master Plan land use distribution

Land Use History. Based on historical maps and aerial photographs, a large portion of the land on Waiawa Ridge within the proposed development boundary was planted in sugarcane until about 1983. Oahu Sugar Company, which currently leases the land from Bishop Estate, abandoned sugarcane cultivation over a period of years. Portions of the property are currently being used for cattle grazing by Circle 6 Ranch as a sublessee. In addition, Dole Company currently grows pineapple near Panakauahi Gulch. The State of Hawaii Department of Corrections is currently leasing military reservation land (toward the northern boundary of the proposed development) for the minimum security Waiawa Correctional Facility.

Location Relative to Waiawa Shaft. The Waiawa infiltration tunnel runs beneath the eastern edge of Waiawa Ridge where the ground surface is at an elevation of approximately 120 m (400 ft) above mean sea level. About 382 m (1,253 ft) of the infiltration tunnel lies beneath military land adjacent to the proposed Waiawa Gentry development (see Fig. 4). The remaining length of the tunnel was excavated directly beneath land near the eastern border of the proposed Gentry development. Based on the Waiawa by Gentry development plan, the land directly above the end of the infiltration tunnel is to be used for single family residential units.

Climate. The prevailing winds occurring over the proposed Waiawa Gentry development area are brisk to gentle, averaging about 2.2 m/s (5 mph) from the northeast. The average annual temperature in the area is about 23.7°C (74.6°F) (Nakagawa 1986).

Mean annual rainfall over the proposed development area varies from 800 mm (30 in.) near the southwest extent to about 2 500 mm (100 in.) at the northeast end of the development toward the crest of the Koolau Range (Giambelluca 1986). Numerous rain gages were maintained by OSC within the area. Station 752.3 (Field 500) and station 834.7 (Adit 8) are located near the southern and northern portions of the development. The seasonal pattern of rainfall at these two sites is presented in Figure 20.

Mean annual pan evaporation on Waiawa Ridge varies from a low of about 1 270 mm (50 in.) in the higher rainfall region in the northeast to a high exceeding 2 030 mm (80 in.) in the western portion of the proposed

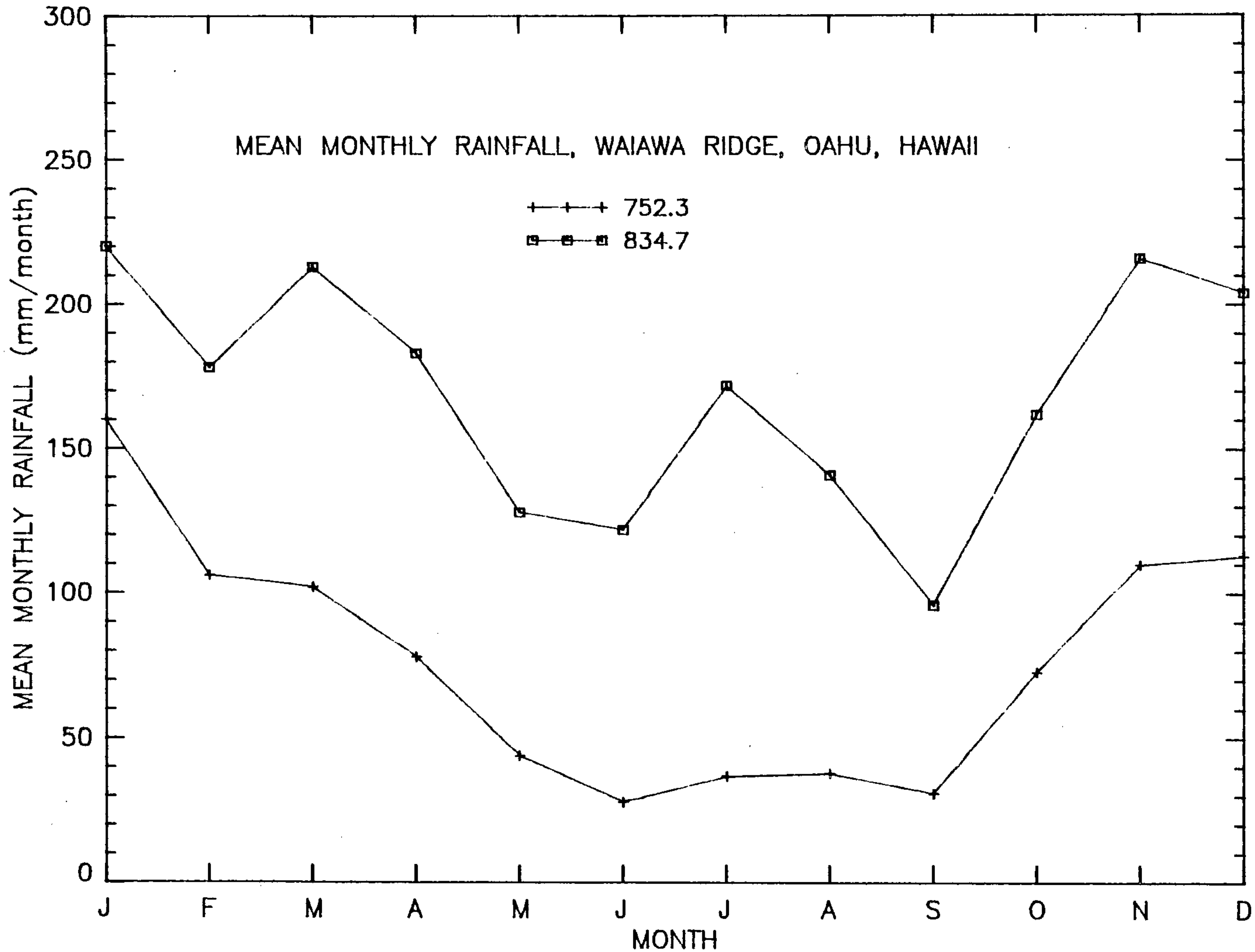


Figure 20. Seasonal rainfall pattern at Stations 752.3 and 834.7, Waiawa Ridge, Oahu, Hawaii

development. The seasonal pattern of pan evaporation at station 825.3 (Field 540) is presented in Figure 21.

Soils. The vast majority of the developable upland ridge soils found within the proposed Waiawa Gentry development boundary are Oxisols of the Molokai, Lahaina, Wahiawa, and Helemano series (Fig. 22). Ultisols of the Manana series are scattered in the middle and northern sections of the proposed development, with smaller amounts of Ultisols belonging to the Leilehua, Lolekaa, and Paaloa series occurring in the wetter northern sector. The steep undevelopable gulch walls are classified as rock land. Alluvial soils of the Kawaihapai series (order Mollisols) are mapped just within the eastern boundary of the proposed development in the bottom of Waiawa Valley. An isolated pocket of fill land (Fd) occurs around an area previously used as a surface water reservoir by OSC. Thus, this area may contain materials associated with the excavation of the reservoir. Toward the southern tip of the development, a narrow strip of Ewa silty clay loam, 3 to 6% slopes (EaB), of the Ewa soil series (order Mollisols) is found in the broader mouth of Waiawa Valley.

The Molokai soils found in the drier southern portion of the proposed development belong to the clayey, kaolinitic, isohyperthermic family, of the subgroup Typic Torrox, great group and suborder Torrox, and order Oxisols. The Molokai silty clay loam soils formed in material weathered from basic igneous rock and have slopes of 3 to 7% (MuB), 7 to 15% (MuC), and 15 to 25% (MuD) (Foote et al. 1972). Runoff is slow to medium on the MuB soils and the erosion hazard is slight to moderate. On MuC soils, runoff is medium and the erosion hazard is moderate. Runoff is medium and the erosion hazard severe on the small areas classified as MuD. On Waiawa Ridge, the Molokai soils are found between elevations of 37 and 107 m (120 and 350 ft) where annual rainfall ranges from about 850 to 1 050 mm (33-41 in.). Permeability of these soils is moderate, 0.0044 to 0.014 mm/s (0.63-2.0 in./hr), and the available water capacity is between 0.11 and 0.13 mm/mm soil (Foote et al. 1972).

Lahaina soils occur near the southern portion of the proposed Waiawa development at slightly higher elevations than the Molokai soils. The Lahaina silty clay soils belong to the clayey, kaolinitic, isohyperthermic

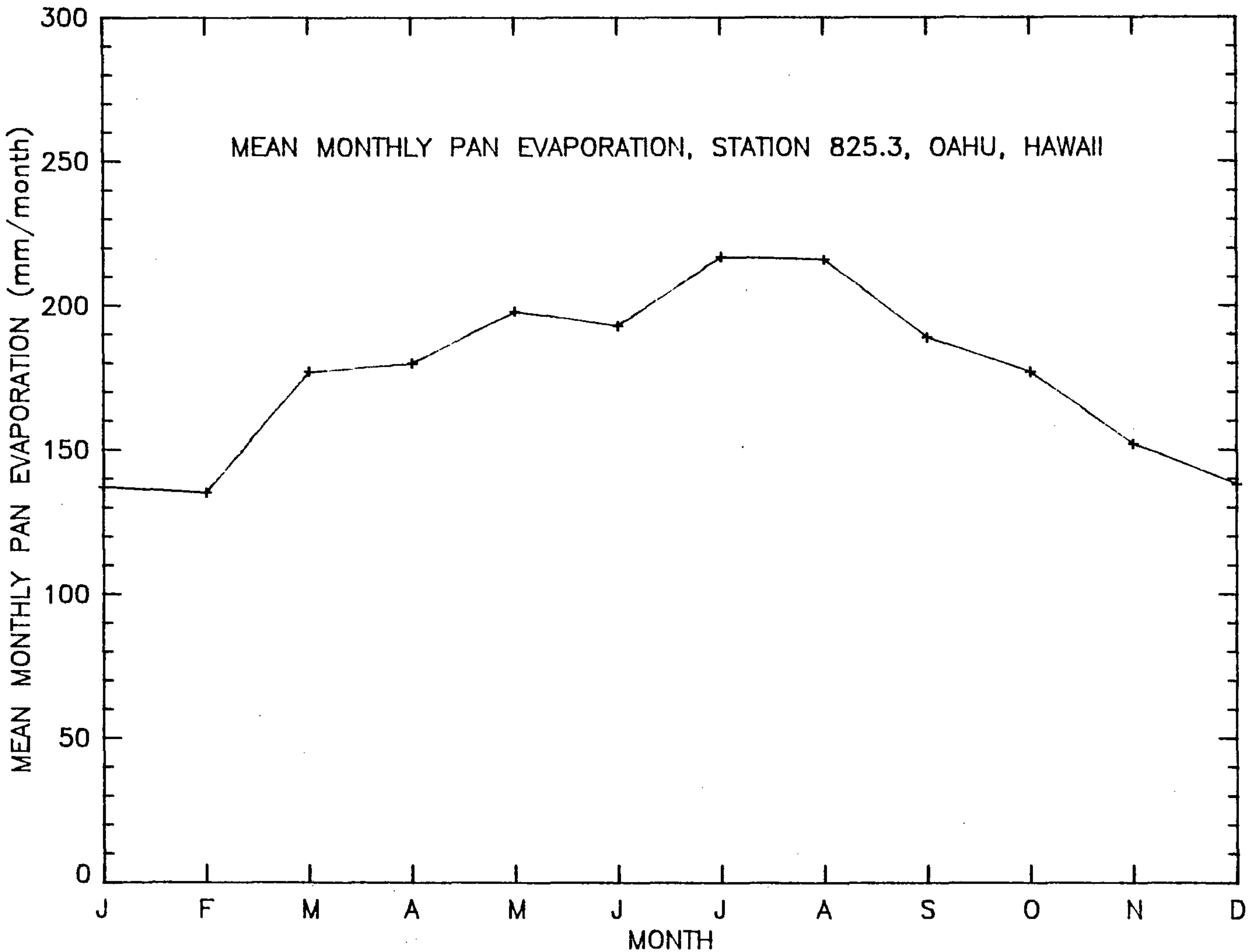


Figure 21. Seasonal pan evaporation pattern at Station 825.3, Oahu, Hawaii

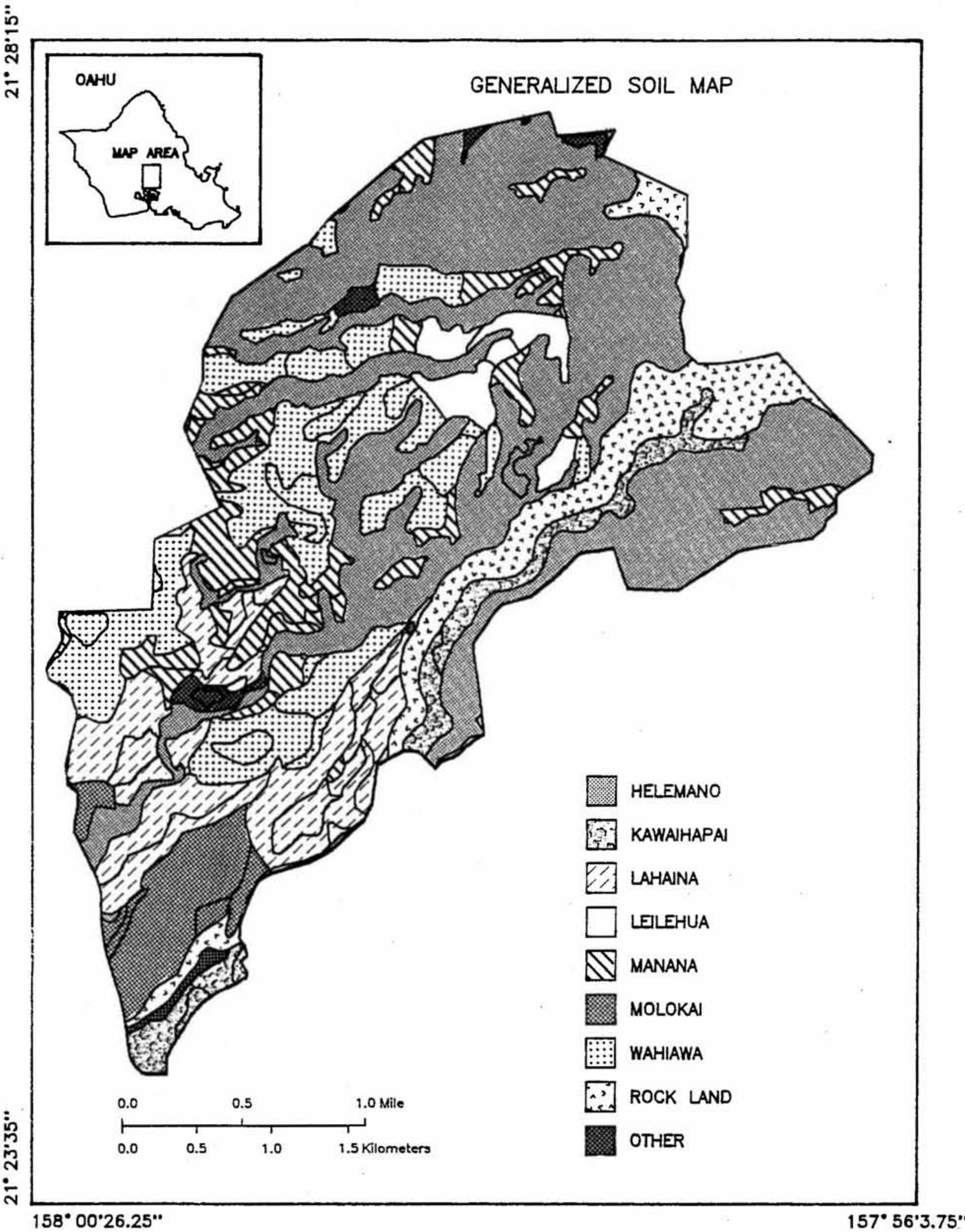


Figure 22. Generalized soil map for Waiawa Master Plan development area, Oahu, Hawaii

family, of the subgroup Tropeptic Haplustox, great group Haplustox, suborder Ustox, and order Oxisols (U.S. Department of Agriculture, 1990) and formed in material weathered from basic igneous rock. The Lahaina series found within the proposed development area have slopes of 0 to 3% where the runoff is slow and the erosion hazard is no more than slight (LaA), 3 to 7% where runoff is slow and the erosion hazard slight (LaB), and 7 to 15% where the runoff is medium and the erosion hazard is moderate (LaC) to severe (LaC3) (Foote et al. 1972). Within the Waiawa Gentry development boundaries, these soils are found between elevations of 61 and 167 m (200 and 550 ft) where annual rainfall ranges from about 900 to 1 250 mm (35-49 in.). Permeability of these soils is moderate, 0.0044 to 0.014 mm/s (0.63-2.0 in./hr), and the available water capacity is between 0.10 and 0.12 mm/mm soil in the top 0.79 m (31 in.) of the profile (Foote et al. 1972).

Soils of the Wahiawa series are found in the middle section of the proposed Gentry development on Waiawa Ridge between elevations of 98 and 260 m (320 and 850 ft) where annual rainfall averages respectively 1 050 and 1 740 mm (41 and 69 in.). Wahiawa silty clay soils developed in residuum and in old alluvium derived from basic igneous rock, and belong to the clayey, kaolinitic, isohyperthermic family, of the subgroup Tropeptic Eutrustox, great group Eutrustox, suborder Ustox, and order Oxisols (U.S. Department of Agriculture, 1990). The Wahiawa series found within the development boundaries have slopes of 0 to 3% (WaA) and 3 to 8% (WaB) where runoff is slow and the erosion hazard is slight, and slopes of 8 to 15% (WaC) where the runoff is medium and the erosion hazard is moderate (Foote et al. 1972). Wahiawa soils typically have permeabilities ranging from 0.014 to 0.044 mm/s (2.0 to 6.3 in./hr) and an available water capacity of 0.11 to 0.13 mm/mm soil (Foote et al. 1972).

In the proposed development, soils of the Helemano series occupy much of the gulch areas designated mainly as open spaces and golf courses. These soils developed in alluvium and colluvium derived from basic igneous rock and have slopes of 30 to 90%. Runoff is medium to very rapid and the erosion hazard is considered to be severe to very severe. Helemano silty clay (HLMG) soils are classified in the clayey, kaolinitic, isohyperthermic family, of the subgroup Tropeptic Haplustox, great group Haplustox, suborder Ustox, and order Oxisols. Helemano soils typically have moderately rapid permeabilities ranging from 0.014 to 0.044 mm/s (2.0-6.3 in./hr) and an available water capacity of 0.11 to 0.13 mm/mm soil (Foote et al. 1972).

Soils of the Manana series occur in the middle and northern sections of the proposed development area. The Manana series developed in material weathered from basic igneous rock and are classified in the clayey, oxidic, isohyperthermic family, of the subgroup Orthoxic Tropohumults, great group Tropohumults, suborder Humults, and order Ultisols (U.S. Department of Agriculture, 1990). Runoff on Manana silty clay loam having 2 to 6% slopes (MoB) is slow and the erosion hazard is slight. On Manana silty clay loam having 6 to 12% slopes (MoC), runoff is medium and the erosion hazard is moderate. Manana silty clay with slopes of 3 to 8% (MpB), 8 to 15% (MpC), and 15 to 25% (MpD), and eroded slopes ranging from 12 to 25% (MpD2) can be found within the development boundary. The top 0.38 m (15 in.) of the soil profile has a permeability ranging from 0.014 to 0.044 mm/s (2.0-6.3 in./hr) and an available water capacity of 0.09 to 0.11 mm/mm soil. A pan layer typically beneath the top 0.38 m has a permeability less than 0.0004 mm/s (0.06 in./hr) (Foote et al. 1972). Within the development area the Manana series occurs at elevations between 116 and 305 m (380 and 1,000 ft) where annual rainfall averages respectively 1 100 and 2 200 mm (43 and 87 in.).

The Leilehua soil series occurs near the northernmost extent of the Wahiawa series within the development area and is found primarily in military reservation land. The Leilehua series belongs to the clayey, oxidic, isothermic family, of the subgroup Humoxic Tropohumults, great group Tropohumults, suborder Humults, and order Ultisols. Leilehua soils having slopes of 2 to 6% (LeB) and 6 to 12% (LeC) occur in the area. Runoff is slow and the erosion hazard slight on the LeB soils. On the LeC soils, runoff is medium and the erosion hazard is moderate. The permeability of the Leilehua series ranges between 0.014 to 0.044 mm/s (2.0-6.3 in./hr) and the available water capacity between 0.10 and 0.12 mm/mm soil (Foote et al. 1972). Within the development area the Leilehua series occurs at elevations between 220 and 305 m (720 and 1,000 ft) where annual rainfall averages respectively 1 800 and 2 100 mm (71 and 83 in.).

Geology. The proposed Waiawa Gentry development is located on land built by successive lava flows from the Koolau shield volcano. The unsaturated zone beneath Waiawa Ridge consists of a layer of soil and saprolite approximately 30 m (100 ft) thick overlying unweathered basalt. In some places where weathering is less extensive, the soil and saprolite may be as thin as 11 m (35 ft) (Public Works Drawing No. OA-N25-1582). In areas of low permeability within the saprolite material, perched water conditions may occur above the unweathered basalt layer.

A portion of the Pearl Harbor basal aquifer lies beneath the proposed development area. Based on a groundwater head of about 4.6 to 6.1 m (15-20 ft), the water table lies less than 46 m (150 ft) beneath the ground surface near the southern tip of the development. At the northern boundary of the development, the depth to the groundwater table exceeds 305 m (1,000 ft).

3. ASSESSMENT APPROACH

To assess the potential impact of urban development on the quality of water pumped by the USN Waiawa Shaft, a number of separate yet interrelated project tasks were linked together. The overall assessment approach can be divided into four broad areas: (1) pesticide and fertilizer use estimation, (2) water recharge estimation, (3) pesticide leaching estimation from the soil and vadose zone, and (4) groundwater quality modeling. Each of these project areas is described briefly below to provide an overview of the assessment approach. Detailed descriptions and results of the various tasks are covered in subsequent chapters and appendices of this report.

PESTICIDE USE ESTIMATION

The first step in the asssessment approach involved the identification of pesticides and fertilizers which might be used in the proposed development areas. Although fertilizer products are composed primarily of nitrogen, phosphorus, and potassium, the pesticides which are likely to be used in the Waiawa developments contain a wide variety of active ingredients. The types of chemicals which will likely be used in the residential areas were identified by (1) surveying a number of local pest control companies which could conceivably apply chemicals, such as termiticides, in the proposed development areas; (2) conducting spot checks of various retail outlets in the central Oahu area to determine what types of commercial chemicals are readily available to home owners; and (3) surveying residents in the Waipio Gentry area to determine the types of pesticides and fertilizers currently being used in an area climatologically similar and geographically close to the proposed Waiawa developments. Chemical application rates and frequencies used by home owners were estimated from pesticide label information in conjunction with the results of the house-to-house survey of residents in the Waipio Gentry area. For golf courses and parks, pesticide and fertilizer use estimates were based on the work of Murdoch and Green (1989). Pesticide and fertilizer use estimates are presented in chapter 4 of this report.

WATER RECHARGE ESTIMATION

To determine the fate of chemicals applied near the ground surface, a number of computer models were linked in series to trace the transport of chemicals downward through the unsaturated zone to the groundwater table and then their spreading in the saturated zone. Near the ground surface, recharge water emanating from just below the plant root zone was estimated with a water balance model (App. C). Water recharge, which is the primary advective mechanism by which chemicals are transported downward through the vadose zone, was estimated by accounting for water inputs to the pervious areas in the form of precipitation and irrigation, water losses due to evapotranspiration and runoff, and changes in soil moisture within a specified time interval. Different land use and soil type combinations behave differently to water inputs. Thus, the estimation of recharge requires (1) identification of the soil types and land uses within and surrounding the proposed Waiawa development areas; (2) determination of irrigation and precipitation over the region and period of interest; and (3) application of a water balance model to partition water inputs into runoff, evapotranspiration, soil moisture storage, and groundwater recharge. Rather than computing the water balance for each irregular zone representing a different combination of land use, soil type, and climate within the development area, recharge water was estimated over a rectangular grid. The grid dimensions were chosen to minimize climatic variations within a particular cell. A representative land use and soil type were assigned to each cell of the grid. This discretization of the development area was desirable and necessary to reduce the number of long-term pesticide leaching simulations. A complete description of the input data and parameters used for the water balance model over the study area as well as the water balance results are presented in chapter 5.

PESTICIDE LEACHING ESTIMATION

The estimated chemical application rates and frequencies and water recharge can be used as input to a numerical model designed to simulate solute transport in the unsaturated zone. The computer simulation model selected for this study is the U.S. Environmental Protection Agency's Pesticide Root Zone Model (PRZM) which is a one-dimensional finite difference model. Before PRZM could be confidently used for long-term chemical leaching predictions, the model was calibrated and evaluated with observed field data.

The data were obtained by conducting field tests in Waiawa Valley and at Poamoho where selected chemicals were applied to the soil and allowed to move downward with rainfall and irrigation water (App. A). Conducting chemical leaching experiments on Waiawa Ridge, the site of the proposed Gentry development, proved to be impossible due to perceived liability problems by OSC, which currently holds the lease to the land. Thus, a field experiment was established at an alternate site at Poamoho on a soil series which is also found on Waiawa Ridge. Of the major developable soils on Waiawa Ridge, the Wahiawa series, which is the soil series also occurring at the Poamoho field site, represents an extreme in terms of leaching potential. Of the primary soils found on Waiawa Ridge, the Wahiawa series was generally formed in areas of highest rainfall and exhibits greater macroporosity in the surface zone and higher hydraulic conductivities. Thus, the Poamoho field site is a conservative representation of conditions on Waiawa Ridge. Together, the Waiawa Valley and Poamoho field plots provided a wide range of soil types with which to evaluate PRZM.

At the Waiawa Valley and Poamoho experimental sites, chemical movement was monitored for 318 and 100 days, respectively, by collecting soil samples at depths of up to 3 m (10 ft) at various times following the chemical applications. All soil samples were analyzed at the University of Hawaii Agronomy and Soil Science laboratory for the pertinent chemical constituents.

During the calibration phase, model performance was assessed by comparing observed concentration profiles at particular times with simulated results from PRZM. Model input parameters used to quantify chemical degradation rates and adsorption characteristics were measured in the laboratory using soils obtained at various depths at both experimental sites (App. B). Model calibration at each experimental site involved adjustment of the different model parameters, including those measured in the laboratory, within reasonable ranges until acceptable model performance was achieved.

After obtaining a satisfactory calibration, a simulation model is commonly subjected to a validation process. During model validation, the best parameter estimates obtained from the calibration run are used to check whether the model can successfully simulate observed concentration profiles at a time other than that used for the calibration phase. Although it is possible to validate a single-process model, a multiple-process model like PRZM, which accounts for advection, dispersion, adsorption, and chemical decay, cannot be truly validated. It is possible, however, to evaluate the model in terms of the conditions under which it is valid. Model calibration and evaluation results at each experimental site are presented in Appendix D.

After calibrating the model at the experimental test sites, PRZM was used for long-term leaching predictions under development conditions. Although the model was calibrated for the upper 3 m (10 ft) of soil, PRZM was used to simulate transport through the entire depth of the vadose zone above the basal water table. Due to lack of detailed hydrogeological information characterizing the deeper vadose zone, use of a more sophisticated physically-based model to simulate solute transport through the subsoil, saprolite, and unweathered basalt would be neither justified nor possible.

For the long-term leaching simulations, four different chemicals were tested. The test chemicals were selected based on predicted use patterns and leaching potential (chap. 6). For the long-term PRZM simulations, the development area was discretized into a manageable number of cells. Leaching of each test chemical was simulated with a daily time step within each cell of the grid over a 37-yr period by using the water recharge estimates developed by this project as input to PRZM. The sensitivity of PRZM to various property changes in the unsaturated zone profile, including the removal of the top soil layer due to grading during construction, is described in chapter 6.

GROUNDWATER QUALITY MODELING

Three different saturated zone models were calibrated and evaluated using historical chloride concentrations at Waiawa Shaft in conjunction with recharge estimates of Giambelluca (1983) (App. E). The models used to simulate solute transport in the saturated zone were (1) the two-dimensional, areal method of characteristics (MOC) model (Konikow and Bredehoeft 1978); (2) the MOC model in a vertical section orientation; and (3) a two-layered multiple mixing cell model.

For the long-term predictive simulations, the areal MOC model was selected due to its ability to account for spatial variations of recharge and chemical loading rates to the water table. These variations were obtained by the PRZM simulations. The groundwater model was used to simulate movement of the chemicals through the saturated zone in the basal lens under the influence of pumping from Waiawa Shaft and other nearby wells. The groundwater model was used under a range of unsaturated zone inputs and pumping rates. Predicted groundwater quality impacts resulting from the proposed Gentry and USN developments in the Waiawa area are presented in chapter 7.

The final chapters of this report include a discussion of the sources of uncertainty, discussion of results, conclusions, and recommendations.

For this investigation, a modeling approach is taken to provide scientific information necessary to make an informed decision regarding the development/nondevelopment of the proposed Waiawa housing projects. It is generally accepted that modeling results cannot provide absolute answers. Model predictions should constantly be subjected to review as more scientific information is obtained and a better understanding of the underlying processes is developed. Modeling does, however, represent the best approach available to provide necessary scientific information so that rational decisions can be made. Modeling in itself cannot, and indeed should not, be used to provide a final yes or no answer to the development/nondevelopment question. This simplistic "safe or unsafe" dichotomy "does not accurately portray either the spectrum of chemical risks or the limits of our scientific information" (Tomboulian 1989, p. 1041).

It should be emphasized that this report stops short of a risk assessment analysis. In general, risk assessment is the process which defines the relationship between the harm to humans and the exposure or dose received (Tomboulian 1989). A groundwater risk assessment analysis might utilize scientific information from an environmental study, such as this one, in conjunction with assumed risk levels (most often extrapolated from animal studies) associated with consuming certain quantities of contaminated water over a specified period of time. Taken one step further, the risk management decision-making process must analyze the economic costs and benefits, potential environmental impacts, public health considerations, as well as public attitudes associated with any development scheme. Clearly, this is a subjective process involving value judgements. Nevertheless, all of the factors mentioned above must be considered in making a final decision on the development or nondevelopment of the proposed housing projects.

4. PESTICIDE AND FERTILIZER USE

A wide variety of chemicals including pesticides and fertilizers are available for use in urbanized areas. In order to assess the potential for groundwater contamination resulting from proposed urban developments in the vicinity of the USN Waiawa Shaft, these chemicals must be identified. The pesticides which will most likely be used in the Waiawa area were identified using three separate approaches. Firstly, a number of local pest control companies which could conceivably apply chemicals, such as termiticides, in the proposed development areas were surveyed. Secondly, several spot checks of various retail outlets in the central Oahu area were made to determine what types of commercial chemicals are readily available to home owners. And thirdly, a house-to-house survey of residents in the Waipio Gentry area was used to determine the types of pesticides and fertilizers currently being used at a nearby development. Chemical use on the proposed golf course areas in the Waiawa Gentry development was estimated based on the work of Murdoch and Green (1989).

PEST CONTROL OPERATOR SURVEY

In the past, chlordane was widely used by pest control companies on Oahu to control subterranean termites. Recent studies, however, revealed that levels of chlordane found in the air of properly treated houses posed a health risk to occupants (U.S. EPA 1987). As a result, the use of chlordane was banned after 15 April 1988 by the EPA [Federal Register, 52(212):42145-42149]. A number of registered pest control operators on Oahu who treat homes and construction projects in central Oahu were contacted in November 1987 to determine the termiticides currently being used and those which may be used in the future. The termiticides which could be used in the proposed Waiawa developments represent EPA-registered pesticides which are currently commercially available. Results of the survey of pest control operators are presented in Table 2. Based on the results of the survey, Dursban TC manufactured by The Dow Chemical Company appears to be the termiticide most often selected as the replacement chemical for chlordane. The active ingredient in Dursban

TABLE 2. SURVEY RESULTS OF PEST CONTROL COMPANIES

Company	Termiticides	General Use Pesticides
A To Z Fumigation (Kane Pest)		Demon, Dursban, Knox Out, Vaponite
Advance Termite	Dragnet, Dursban TC Torpedo	Dursban, Safrotin
Aladdin Inc.	Dursban TC, Torpedo	
Chemipure	Chlordane, Dursban TC	Dursban 4E, Ficam Gencor, Safrotin
Hauoli Pest Control	Chlordane/Heptachlor Dursban TC, Torpedo	Baygon, Demon wettable powder, Diazinon, Dursban 50W, Ditox Plus, Ficam, Precor 5E, Safrotin
Interisland Termite	Chlordane, Torpedo	Dursban LO, Dursban Granules, Diazinon
Island Termite	Demon, Dursban TC Torpedo	
No Ka Oi Termite and Pest Control, Inc.	Chlordane/Heptachlor	Dursban LO, Dursban ME, Sevin
Rainbow Exterminator	Chlordane, Dursban TC Torpedo	Deltic, Demon, Sevin
Randy's Termite and Pest Control	Dursban TC	Dursban 2E, Knox Out
Terminix International, Inc.	Pryfon 6	Baygon, Diazinon, Dursban, Sevin
The Help Squad Exterminators	Dursban TC, Torpedo	Dursban 50W

NOTE: Survey conducted in November 1987.

is chlorpyrifos which is an organophosphate compound. Torpedo Insecticide manufactured by ICI Americas, Inc. contains permethrin as an active ingredient and is also commonly used locally. Other termiticides which could be used in the Waiawa area include Demon TC manufactured by ICI Americas, Inc., Dragnet FT manufactured by FMC Corporation, and Pryfon 6 Insecticide manufactured by Mobay Corporation. The active ingredients in Demon, Dragnet, and Pryfon 6 are respectively cypermethrin, permethrin, and isofenphos. Cypermethrin and permethrin are both pyrethroids whereas isofenphos is an organophosphate.

A more recent national survey indicates that Dursban TC is the principal termiticide of 69.5% of pest control operators (Mix 1989). The same poll indicated that 16% of the pest control operators listed Demon TC as their principal termiticide. Tribute (Roussel Bio Corporation), containing fenvalerate as an active ingredient, Pryfon 6, Dragnet FT, and Torpedo were used as principal termiticides to a lesser extent. According to the survey, 95.3% of the pest control operators applied the termiticides at the label rate for pre-construction treatments.

In addition to termiticides, those chemicals likely to be used for general pest control by the surveyed companies are also presented in Table 2. It should be noted that choice of pesticides may depend heavily on the existing problem. Thus, the general use pesticides listed in Table 2 merely represent the primary chemicals which a particular company may use.

RETAIL OUTLET SURVEY

In addition to surveying registered pest control operators, various retail outlets which are likely to be frequented by home owners in the proposed development sites were checked to determine the types of pesticides which may be available. Available pesticides at seven retail outlets (City Mill Co., Ltd., Waimalu; Gem Department Stores, Waipahu; Holiday Mart, Pearl City; Longs Drugs Stores, Pearl City; Longs Drugs Stores, Pearl Ridge; Pay 'n Save, Waimalu; Sears Roebuck and Co., Pearl Ridge) were noted during checks at each store in January 1988 and April 1988. A list of active ingredients contained in the pesticides encountered at the seven surveyed retail outlets was compiled by examining labels available at the state Department of Agriculture, Pesticides Branch. A summary list of active ingredients contained in available pesticide products is presented in Table 3.

Unlike active ingredients which are listed on the individual product labels, detailed information regarding inert ingredients is not provided. Although the state Department of Agriculture, Pesticides Branch, has information concerning inert ingredients in the various products, such information is confidential* and is therefore not available for public scrutiny.

WAIPIO GENTRY HOUSEHOLD CHEMICAL USE SURVEY

To better determine expected pesticide and fertilizer use patterns in the Waiawa area, door-to-door surveys were conducted in Waipio Gentry, central Oahu on Friday, 5 May 1989 and Saturday, 20 May 1989 between the hours of 09:00 and 15:00. The purpose of the survey was to obtain information regarding types of chemicals used and chemical application rates and frequencies. A total of 113 responses were obtained on these two dates. Three households indicated that they had hired professional pest control operators to treat their lawns. These households were not included in the following analysis since the occupants were not certain what chemicals the pest control operator applied. Thus, 110 usable responses were obtained. All survey results, with the exception of two survey forms which were mailed in, were obtained by direct personal communication. Of the approximately 30 forms left with household occupants for mail-in responses, only two were returned.

Pesticides. The surveyed households can be separated into three categories with regard to pesticide use: (1) no pesticide usage, (2) spot pesticide usage, and (3) lawn application of pesticides. Spot usage of pesticides includes applications on or around ornamental plants and fruit trees as well as in vegetable gardens. Lawn applications of pesticides include spray, granular, and dust formulations as well as combinations of pesticides with fertilizers. The percentage of surveyed households in each use category is presented in Table 4. The survey results indicate that approximately 50% of the households in the Waipio Gentry area do not use pesticides. Numerous individuals cited health concerns for children and pets as a primary reason for their avoidance of pesticides.

*D. Yoshizu (Department of Agriculture) 1988: personal communication.

TABLE 3. ACTIVE INGREDIENTS IN PESTICIDE PRODUCTS AVAILABLE AT SURVEYED RETAIL OUTLETS

2-hydroxyethyl-n-octyl sulfide
2,4-D (2,4-dichlorophenoxyacetic acid)
AMS (ammonium sulfamate)
acephate (O,s-dimethyl acetylphosphoramidothioate)
acifluorfen-sodium [sodium 5-(2-chloro-4-[trifluoromethyl]phenoxy)-2-nitrobenzoate]
allethrin [(RS)-3-allyl-2-methyl-4-oxocyclopent-2-enyl (1RS)-cis,trans-chrysanthemate]
amitrole (1H-1,2,4-triazol-3-ylamine)
aromatic petroleum hydrocarbons
bacillus thuringiensis berliner, var. kurstaki
bendiocarb (2,2-dimethyl-1,3-benzodioxol-4-yl methylcarbamate)
benomyl [methyl 1-(butylcarbamoyl)benzimidazol-2-ylcarbamate]
CAMA (calcium acid methanearsonate)
captan [N-(trichloromethylthio)cyclohex-4-ene-1,2-dicarboximide]
carbaryl (1-napthyl methylcarbamate)
chlorothalonil (tetrachloroisophthalonitrile)
chlorpyrifos (O,O-diethyl O-3,5,6-trichloro-2-pyridyl phosphorothioate)
chlorthal-dimethyl (dimethyl tetrachloroterephthalate) (dacthal)
DDVP (2,2-dichlorovinyl dimethyl phosphate)
diazinon [O,O-diethyl O-(2-isopropyl-6-methyl-4-pyrimidinyl) phosphorothioate]
dicamba (3,6-dichloro-o-anisic acid)
dicofol [2,2,2-trichloro-1,1-bis(4-chlorophenyl)ethanol]
fluazifop-butyl [butyl (RS)-2-[4-(5-trifluoromethyl-2-pyridyloxy)phenoxy]propionate]
folpet [n-(trichloromethylthio) phthalimide] (phaltan)
glyphosate [N-(phosphonomethyl)glycine]
hydorprene [ethyl (E,E)-3,7,11-trimethyldodeca-2,4-dienoate]
MSMA (monosodium methanearsonate)
malathion [S-1,2-bis(ethoxycarbonyl)ethyl O,O-dimethyl phosphorodithioate]
mancozeb [mangenese ethylenebis (dithiocarbamate) (polymeric) complex with zinc salt]
mecoprop [2,(4-chloro-o-tolyl)oxypropionic acid]
metaldehyde (r-2,c-4,c-6,c-8-tetramethyl-1,3,5,7-tetroxocane)
methiocarb (4-methylthio-3,5-xylyl methylcarbamate) (mesurol)
methoprene [isopropyl (E,E)-(RS)-11-methoxy-3,7,11-trimethyldodeca-2,4-dienoate]
methoxychlor [1,1,1-trichloro-2,2-bis(4-mehtoxyphenyl)ethane]
n-alkyl dimethyl benzyl ammonium chlorides
n-alkyl dimethyl ethylbenzyl ammonium chlorides
n-octyl bicycloheptene dicarboximide
naled (1,2-dibromo-2,2-dichloroethyl dimethyl phosphate)
nicotine [(S)-3-(1-methylpyrrolidin-2-yl)pyridine]
orthoboric acid
oxyfluorfen [2-chloro-1-(3-ethoxy-4-nitrophenoxy)-4-(trifluoromethyl) benzene]
permethrin [3-phenoxybenzyl (1RS)-cis,trans-3-(2,2-dichlorovinyl)-2,2-dimethylcyclopropanecarboxylate]
petroleum hydrocarbons
phenothrin [3-phenoxybenzyl 2,2-dimethyl-3-(2-methylprop-1-enyl)cyclopropanecarboxylate] (sumithrin)
piperonyl butoxide [5-(2-[2-butoxyethoxy]ethoxymethyl)-6-propyl-1,3-benzodioxole]
plant spray oil
potassium salts of fatty acids (potassium oleate and potassium salts of other fatty acids)
prometon [2,4-bis (isopropylamino)-6-methoxy-1,3,5-triazine]
propoxur (2-isopropoxyphenyl methylcarbamate)
pyrethrins
resmethrin [5-benzyl-3-furylmethyl (1RS)-cis,trans-chrysanthemate]
rotenone [(2R,6aS,12aS)-1,2,6,6a,12,12a-hexahydro-2-isopropenyl-8,9-dimethoxychromeno (3,4-b)furo (2,3-h)chromene-6-one]
sulfur
tetramethrin [cyclohex-1-ene-1,2-dicarboximidomethyl (1RS)-cis,trans-2,2-dimethyl-3-(2-methylprop-1-enyl)cyclopropanecarboxylate]
thiram (tetramethylthiuram disulfide)
triclopyr (3,5,6-trichloro-2-pyridyloxyacetic acid)
triforine [1,1'-piperazine-1,4-diyldi-(N-[2,2,2]-trichloroethyl)formamide]
xylene

TABLE 4. PESTICIDE USE SUMMARY

Pesticide Usage	Number	% of Households
No Usage	55	50
Spot Usage	12	11
Lawn Application	43	39
Total	110	100

TABLE 5. PESTICIDES USED BY HOUSEHOLDS

Chemical	No. of Households
2,4-D	5
acephate	3
calcium acid methanearsonate	2
captan	2
carbaryl	3
chlorpyrifos	7
diazinon	23
dicamba	3
glyphosate	9
MCPP	6
MSMA	3
malathion	13
mesurol	2
metaldehyde	3
methoxychlor	2
petroleum oil	2
piperonyl butoxide	1
pyrethrins	1
resmethrin	2
rotenone	2
triforine	1
unknown	18

A list of the pesticides used by surveyed home owners for both spot treatments and lawn applications is presented in Table 5. It should be noted that many of the surveyed households use more than one of the chemicals listed. Clearly, the most popular pesticides used by surveyed residents of Waipio Gentry are diazinon, malathion, and the herbicide glyphosate (Roundup). In addition, chlorpyrifos, MCPP, and 2,4-D are also commonly used.

Estimated application rates and frequencies for those residents who use pesticides on their lawns are presented in Table 6. Many of the surveyed home owners could not provide accurate information relating to types, amounts, and frequencies of chemicals used. Thus, quantitative estimates of pesticide use could not be determined for all households. Based on the usable responses, estimated application rates for diazinon ranged from a minimum of 1.6 kg/ha (1.3 lb/acre) to a maximum of 200 kg/ha (180 lb/acre). Estimated application rates for malathion ranged from a minimum of 3.2 kg/ha (2.9 lb/acre) to a maximum of 68 kg/ha (61 lb/acre). Clearly, a wide range of chemical application rates is likely to be found within any residential area.

Fertilizers. The fertilizer results are separated into three categories: (1) no fertilizer usage, (2) spot fertilizer usage, and (3) lawn application of fertilizers. The percentage of surveyed households in each category is presented in Table 7. Of the surveyed households, 35% do not use fertilizers. Those home owners who do apply fertilizers on their lawns use formulations with varying nitrogen-phosphorus-potassium (N-P-K) ratios. Because potassium is affected by ion exchange processes in soil, any portion of the applied potassium unconsumed by plants will likely remain in the soil. In terms of groundwater contamination, the components of greatest concern are nitrogen and phosphorus. Phosphorus binds very tightly with iron and alluminum hydroxides which are abundant in soils occurring on Waiawa Ridge (Murdoch and Green 1989) and will not likely leach to any significant degree. Although ammonium nitrogen (NH_4) is also unlikely to leach downward, nitrogen applied in the ammonium form is rapidly converted to the nitrate (NO_3) form by nitrifying bacteria. Because it is relatively unaffected by adsorptive processes nitrate leaching could occur if significant recharge occurs prior to plant consumption. In

TABLE 6. ESTIMATED LAWN PESTICIDE APPLICATION RATES

HOUSE ID	CHEMICAL	APPLICATION Amount (kg)	APPLICATION Area (m^2)	APPLICATION Rate (kg/ha)	FREQUENCY (appl./yr)
1	glyphosate				2
2	diazinon	0.059	74	7.9	2
5	diazinon		325		
	glyphosate		325		
6	diazinon	0.077	56	14.	6
	malathion	0.16	56	28.	3
7	chlorpyrifos		65		2
	Green Light product		65		2
8	2,4-D	0.043	74	5.7	12
	chlorpyrifos	0.025	74	3.4	12
	MCPP	0.045	74	6.1	12
	malathion	0.24	74	32.	12
	resmethrin	0.0012	74	0.16	12
12	MSMA	0.15	186	8.1	3
	metaldehyde		186		
17	diazinon	0.16	46	34.	3
	malathion	0.32	46	68.	3
22	diazinon (Ortho Diazinon Insect Spray)	0.059	93	6.3	4
	diazinon (Spectracide 6000)	0.038	93	4.1	3
	malathion	0.12	93	13.	4
23	MSMA	0.16	56	28.	6
24	mesurol		93		
	chlorpyrifos	0.025	93	2.7	12
25	diazinon	0.044	93	4.8	4
28	Weed and Feed		46		
29	glyphosate	0.059	28	21.	12
31	chlorpyrifos		186		
	Dexol product		186		
	glyphosate		186		
32	2,4-D		139		
	diazinon	0.023	139	1.6	2
	dicamba		139		
	MCPP		139		
36	chlorpyrifos		46		36
37	chlorpyrifos[1]	0.017	93	1.8	12
	diazinon[2]	0.077	93	8.3	12
38	diazinon	0.077	93	8.3	2
39	dicamba	0.0025	93	0.27	6
	MSMA	0.037	93	4.0	6
	Weed and Feed		93		12
42	diazinon	0.38	19	200.	6
43	Spectracide product		19		
44	calcium acid methanearsonate	0.00073	37	0.20	26
	glyphosate		37		
	Weed and Feed		37		8
55	diazinon	0.059	56	11.	12
56	glyphosate		19		

TABLE 6--Continued

HOUSE ID	CHEMICAL	------- APPLICATION ------- Amount (kg)	Area (m^2)	Rate (kg/ha)	FREQUENCY (appl./yr)
57	Weed and Feed		14		4
58	unknown grass killer				
63	diazinon		28		
64	chlorpyrifos		19		1
68	unknown termiticide		93		
70	diazinon	0.16	46	34.	6
72	diazinon	0.020	19	10.	6
	mesurol	0.0023	19	1.2	4
75	diazinon		158		3
77	diazinon	0.030	37	8.2	6
	malathion	0.24	37	63.	1
78	2,4-D		139		
	diazinon	0.029	139	2.1	4
	malathion	0.12	139	8.5	4
	MCPP		139		
	Spectracide product				
79	malathion	0.077	242	3.2	6
	glyphosate		242		
80	diazinon	0.11	93	12.	4
84	glyphosate	0.068	33	21.	2
88	diazinon[2]	0.059	139	4.2	4
	malathion		139		
	weed killer		139		
93	2,4-D	0.043	65	6.6	2
	MCPP	0.045	65	7.0	2
96	2,4-D	0.0086	112	0.77	6
	diazinon (Spectracide 6000)	0.15	112	13.	6
	diazinon[2]	0.12	112	11.	6
	dicamba	0.0054	112	0.49	6
	MCPP	0.0027	112	0.24	6
	malathion[3]	0.24	112	21.	6
99	calcium acid methanearsonate		84		
100	Weed and Feed		56		

[1]5.3% active ingredient (Ortho product) assumed for calculation.
[2]25% active ingredient (Ortho product) assumed for calcuation.
[3]50% active ingredient (Ortho product) assumed for calculation.

TABLE 7. FERTILIZER USE SUMMARY

Fertilizer Usage	Number	% of Households
No Usage	38	35
Spot Usage	8	7
Lawn Application	64	58
Total	110	100

a study of California grass irrigated with secondary sewage effluent and grown in soil of the Lahaina series, Handley and Ekern (1981) used lysimeters and found nitrogen removals of about 69%. In that study, 28% of the nitrogen was lost as gas and only 3% of the applied nitrogen was collected in the lysimeter leachate. However, the timing of recharge events following the nitrogen application could play a significant role in determining the amount of nitrogen leached relative to plant uptake.

Based on the house-to-house survey, the typical home owner in the Waipio Gentry area applies fertilizers six times a year over a lawn area of approximately 80 m^2 (860 ft^2). During each fertilizer application, the average nitrogen use is about 155 kg/ha (140 lb/acre).

CHEMICAL USE ON GOLF COURSES

Pesticides. Typical fertilizer and pesticide use practices on golf courses in Hawaii were reported by Murdoch and Green (1989). According to their study, pesticides (including herbicides) are generally not applied in a regularly scheduled, preventative program. Due to the weed, insect, and disease pests of turf grasses in Hawaii, however, it is almost impossible to completely avoid the use of pesticides and still maintain a high quality turf. Thus, on golf courses, pesticides are normally applied in response to the inevitable problem situations.

A variety of chemicals are available for use on turf grasses. A lengthy list of the pesticides registered in Hawaii for use on turf grasses was compiled by Tarutani and Brennan (1986). In practice, a typical golf course will use no more than about six of the chemicals registered for use on turf grasses over a period of a few years (Murdoch and Green 1989).

A typical pesticide program for the various portions of a golf course in Hawaii was presented by Murdoch and Green (1989) and is reproduced here as Table 8. It should be noted that there are a number of other chemicals which may be used instead of or in addition to those listed in Table 8.

Fertilizers. In terms of both application amount on golf courses and leaching potential, nitrogen is the fertilizer component which represents the greatest threat to groundwater. To ensure efficient nitrogen uptake and minimal leaching, Murdoch and Green (1989) recommend the use of a slow-release nitrogen fertilizer on golf courses. In their study, Murdoch and Green also estimated the nitrogen application rates for a typical nine-hole golf course in Hawaii (Table 9).

TABLE 8. TYPICAL PESTICIDE PROGRAM FOR 9-HOLE GOLF COURSE IN HAWAII

Turfgrass Area	Area (ha)	Chemical	Applications per year	Rate/Appl. (kg ai/ha)	Annual Total (kg ai/yr)
Herbicides					
Greens	0.6	MSMA	6	2.24	8.1
		bensulide	2	13.45	16.3
Tees	0.6	MSMA	6	2.24	8.1
		Trimec	3	1.17*	2.1 l ai
		bensulide	2	13.45	16.3
Fairways	10.1	MSMA	6	2.24	136
		Trimec	3	1.17*	35.5 l ai
		metribuzin	2	0.84	17.0
Perimeter Areas	4.0	glyphosate	3	1.68	20.4
Insecticides					
Greens	0.6	chlorpyrifos	as needed	1.12	about 4.1
Tees	0.6	chlorpyrifos	as needed	1.12	about 4.1
Fairways	spot	chlorpyrifos	as needed	1.12	about 11.3
Fungicides					
Greens	0.6	metalaxyl	as needed	1.46	about 5.4
		chlorothalonil	as needed	8.97	about 16.3
Tees	0.6	metalaxyl	as needed	1.46	about 5.4
		chlorothalonil	as needed	8.97	about 16.3
Fairways	spot	chlorothalonil	as needed	8.97	about 56.7

NOTE: Adapted after Murdoch and Green (1989).
NOTE: ai indicates active ingredient.
*Liter/hectare.

TABLE 9. APPROXIMATE FERTILIZER USE RATES FOR DIFFERENT AREAS OF A TYPICAL 9-HOLE GOLF COURSE IN HAWAII

Type of Turf	Area (ha)	APPLICATION Rate (kg N/ha)	APPLICATION Frequency	Annual Total (kg N)
Greens	0.6	24.4	2 wk	380
Tees	0.6	48.8	3 wk	510
Fairways	10.1	73.2	8 wk	4500
Roughs	6.1	48.8	3 mo	1200
Total	17.4			6590

NOTE: Adapted after Murdoch and Green (1989).

5. RECHARGE

WATER BALANCE MODEL

Downward percolating water, or recharge, is an important mechanism affecting the transport of chemicals through the unsaturated zone to the groundwater table. Efforts to model the downward movement of applied chemicals in urban areas must inevitably take into account the spatial and temporal variations of downward water movement through the soil layer. To estimate the temporal and spatial variation of water recharge by rainfall and irrigation in the proposed urban areas, a water balance model was developed. The water balance may be defined as the exchange of moisture that occurs at the surface, through the vegetation, and within the root zone of the soil.

The water balance model used to estimate recharge for this study is described fully in Appendix C of this report. It is a variant of the Thornthwaite and Mather (1955) bookkeeping procedure. At a given location, the model keeps account of the moisture exchanges that occur within the soil-plant system over a particular time interval. Water inputs over the study area consist of rainfall and irrigation. Outputs from the system include surface runoff and evapotranspiration. Groundwater recharge and end-of-interval soil moisture storage are assigned after estimating rainfall, irrigation, runoff, and evapotranspiration for the time interval.

The water balance analysis was carried out over portions of a 9 x 10 rectangular grid encompassing the proposed development area as well as the zone of contribution of Waiawa Shaft (Fig. 23). The grid dimensions, 40" of latitude by 37.5" of longitude, were selected to minimize climate, soil, and land use heterogeneity within a particular cell. The discretization of the development area was necessary to reduce the number of computer intensive simulation runs of pesticide leaching.

IDENTIFICATION OF LAND USES

The proposed Waiawa Master Plan development by The Gentry Companies consists of single family detached units, low-density and

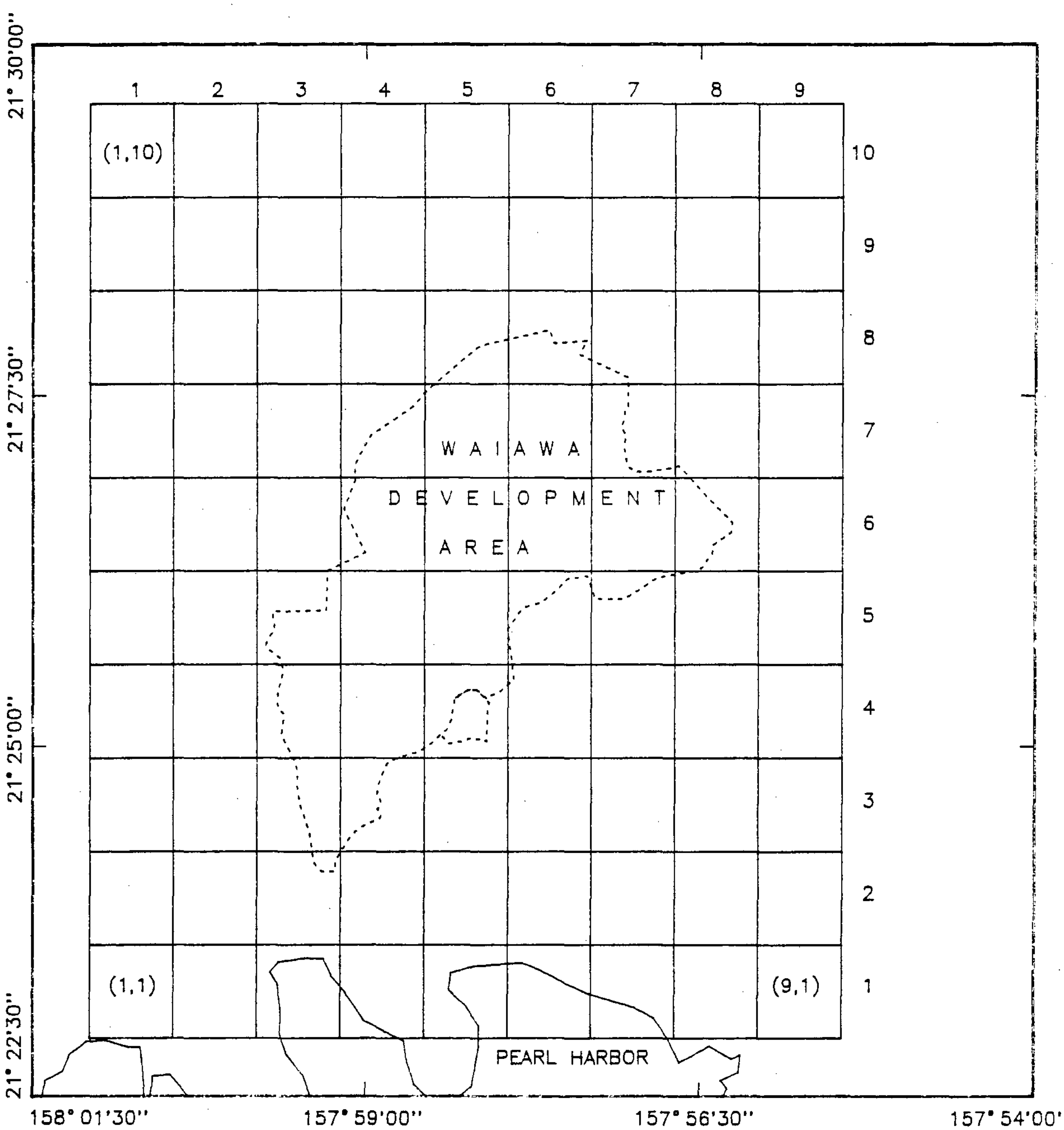


Figure 23. Water balance grid in relation to Waiawa development area

medium-density apartments, retail commercial spaces, mixed commercial and industrial areas, school and park areas, golf courses, a botanical garden, and trails leading through large open areas (Fig. 19). Each of the different land uses in the proposed development must be treated separately in the water balance analysis to account for such factors as irrigation and paved areas. In addition, within any of the land use areas delineated in Figure 19 there may exist several different soil types. Ideally, each combination of land use and soil type should be handled separately. Fortunately, however, many of the different soil series found on Waiawa Ridge behave similarly with regard to runoff potential and soil moisture storage so that they may be grouped together without much loss in accuracy.

The soils within each cell of the water balance grid were defined according to the Soil Conservation Service (SCS) hydrologic soil group classification (U.S. Department of Agriculture 1972). The hydrologic soil group assignments to the water balance cells are presented in Figure 24. The soil series found in the Waiawa area belong primarily to hydrologic soil groups B and C. Group B soils are characterized as having moderate infiltration and water transmission rates whereas group C soils have slow infiltration rates when thoroughly wetted and slow water transmission rates.

For the water balance runoff computations throughout the proposed development, the SCS runoff model was employed (U.S. Department of Agriculture 1972). Based on the hydrologic soil group and land use assignments for each cell of the water balance grid, runoff curve numbers were determined. A complete description of the runoff model and the curve number assignments for the different land uses is presented in Appendix C of this report.

CLIMATOLOGICAL DATA GENERATION

To run the water balance model, climatological input data must be obtained for the period of interest. The current research investigation attempts to predict the long-term effects of future urban development and chemical use on the groundwater using simulated data.

Precipitation. To minimize water balance biases associated with longer time intervals, a daily time step should be used in the water balance

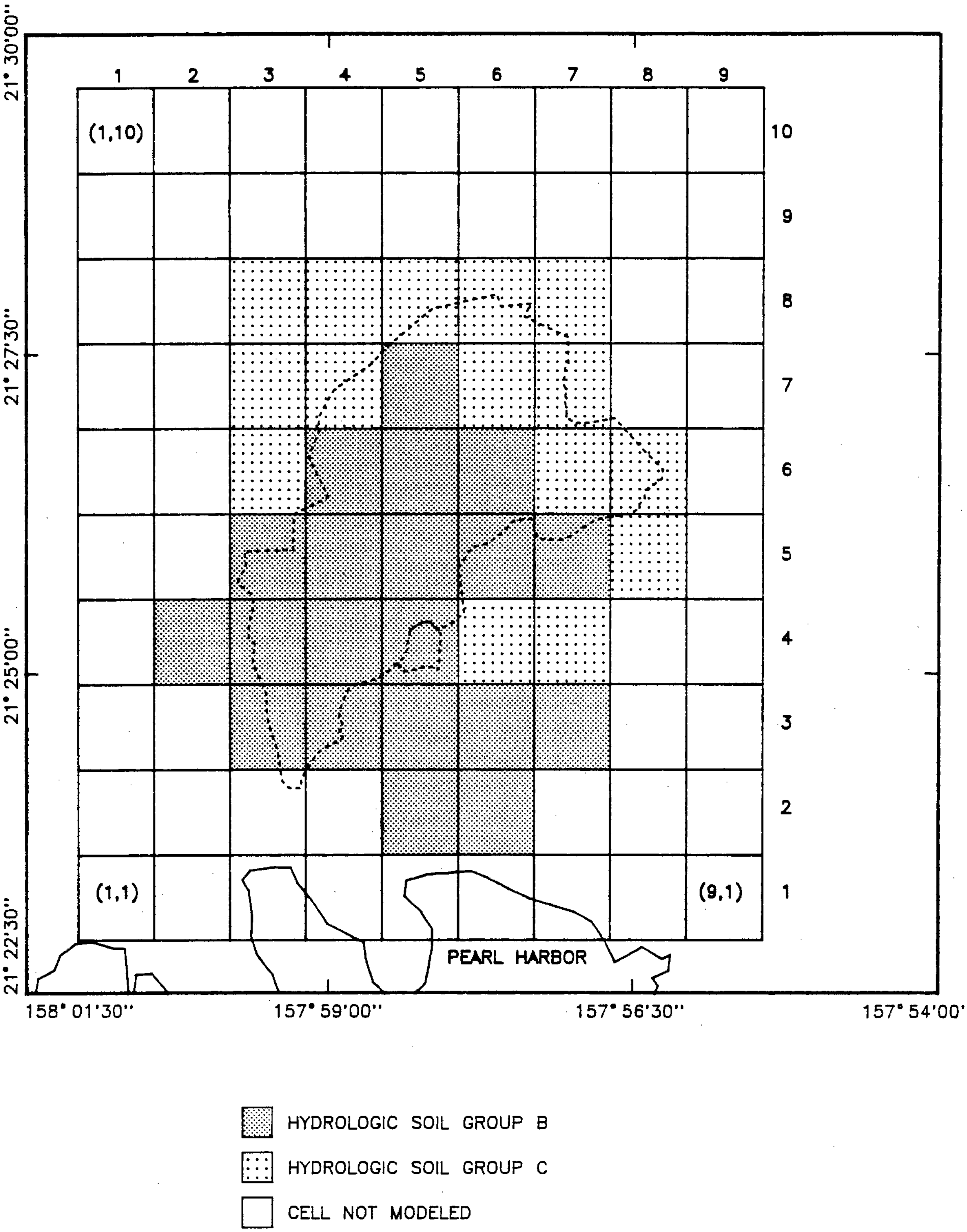


Figure 24. Hydrologic soil group assignments for modeled water balance cells

computations (see App. C). The approach taken in this investigation was to utilize historical monthly rainfall records and generate daily rainfall based on the monthly rainfall totals with a disaggregation model. Rather than generating synthetic monthly rainfall data, actual historical monthly rainfall between 1946 to 1982 was used. During this 37-yr period, adequate monthly records existed to facilitate the interpolation of monthly rainfall within the water balance grid. Rainfall during this period was felt to be sufficiently diverse as to offer a representative range of recharge conditions. The length of the period was selected to allow adequate time for leaching of chemicals through the vadose zone and movement of the chemicals within the groundwater.

Although an extensive network of rain gages exists in central Oahu, there are few rain gage stations with complete monthly records for the entire 37-yr period of interest. Based on monthly records at existing and discontinued rain gage stations in central Oahu, a computer interpolation scheme was able to calculate monthly rainfall within the 90 cells of the water balance grid for the 444 months of interest (Fig. 25). The ZGRID subroutine of the PLOT88 Software Library (Young and Van Woert 1987), which employs a combination of Laplacian and spline interpolation, was utilized to estimate monthly rainfall within each cell of the 9 x 10 grid. In general, interpolated mean annual rainfall compares favorably with rainfall isohyets determined by Giambelluca, Nullet, and Schroeder (1986) for the central portion of the grid where the proposed developments are located (Fig. 26).

Daily rainfall was generated using the simulated fragments disaggregation model described in Appendix C. In the simulated fragments model, daily rainfall is simulated by first generating a sequence of wet and dry days and then apportioning the monthly rainfall total to the wet days in the month. The disaggregation model uses a first-order Markov chain model to generate sequences of wet and dry days. Based on the relatively complete historical daily rainfall record at station 863 (Wahiawa Dam), beta distributions of the dimensionless parameter Y, where Y is given as the ratio of daily rainfall (mm) to monthly rainfall (mm), were formed for each possible number of rainy days in a month. For each month the proper beta distribution was invoked to generate a sequence of simulated

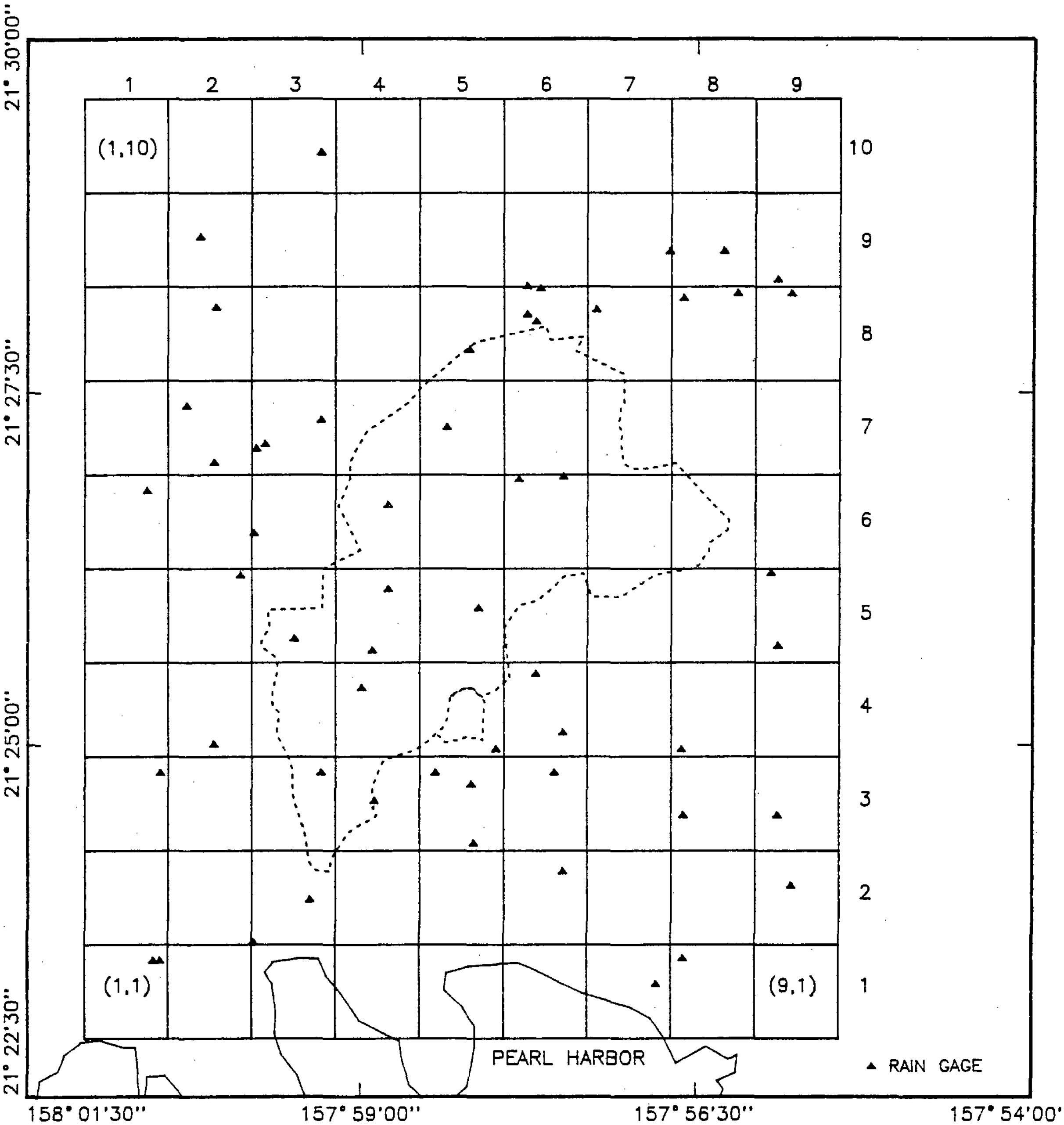
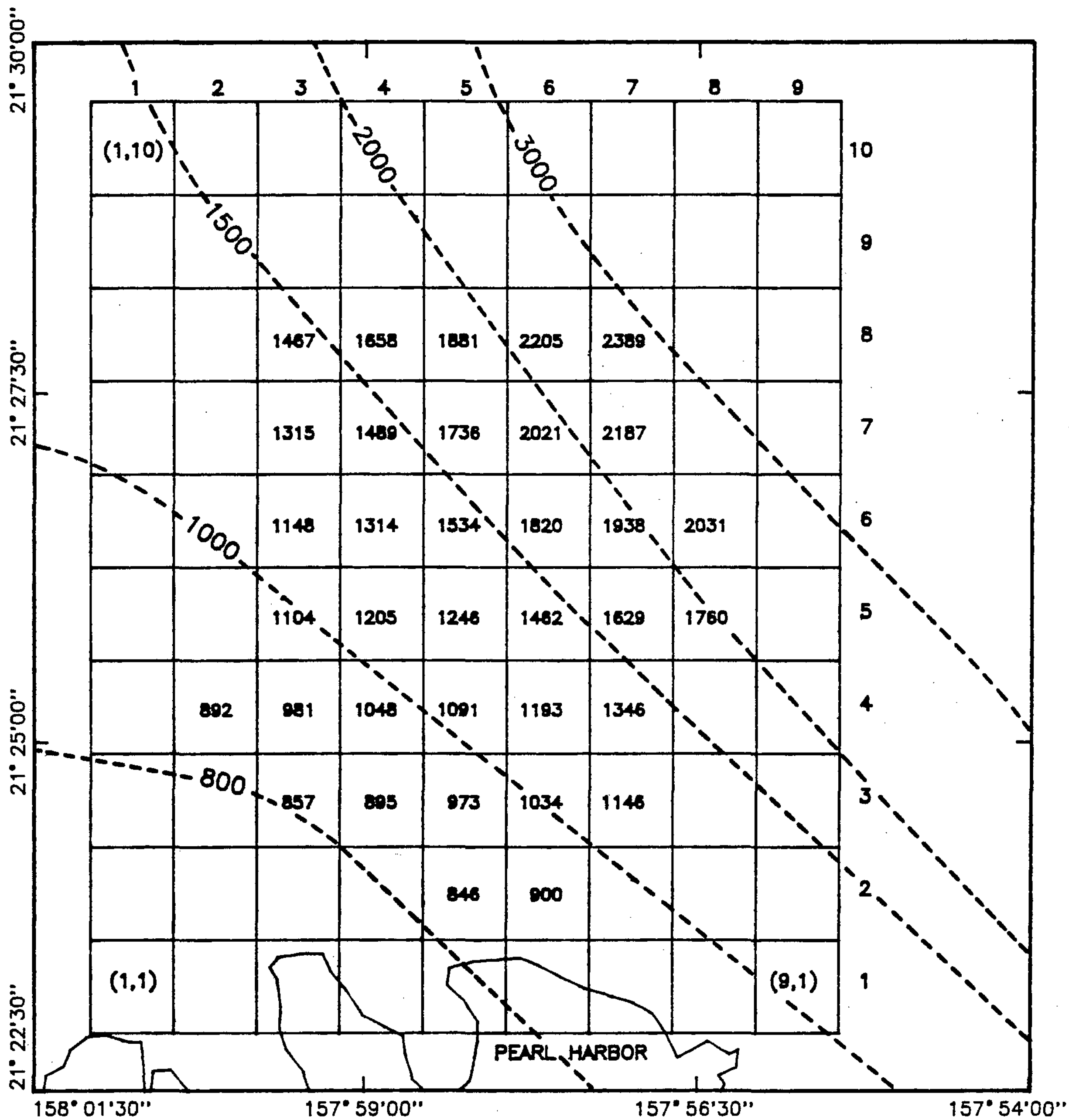


Figure 25. Existing and discontinued rain gage stations within water balance grid



SOURCE: Adapted after Giambelluca, Nullet, and Schroeder (1986).
NOTE: Rainfall in mm.

Figure 26. Mean annual interpolated rainfall in relation to rainfall isohyets

fragments for the period of interest. Within each month, the simulated fragments were then multiplied by the monthly rainfall to produce a sequence of daily rainfall. The same sequence of fragments was used for each cell of the water balance grid to maintain the spatial integrity of the rainfall process. Note that an infinite number of different fragment sequences, and therefore daily rainfall scenarios, could be generated. However, the long-term impact on transport processes of the differences among sequences does not appear to be significant (Loague et al. 1989d).

Evapotranspiration. Actual evapotranspiration in the water balance is determined as a function of environmental demand, potential evapotranspiration, and soil moisture availability. The actual evapotranspiration model used for this investigation is detailed in Appendix C. Potential evapotranspiration, which is the maximum amount of evapotranspiration possible under prevailing atmospheric conditions and surface characteristics given that soil moisture stress is nonlimiting, is used as input to the actual evapotranspiration model. The spatial and seasonal patterns of potential evapotranspiration for the study area were obtained from monthly potential evapotranspiration maps developed by Giambelluca (1983). The potential evapotranspiration maps represent atmospheric demand and ignore spatial variation in surface characteristics (Giambelluca 1983) which can be taken into account with a crop coefficient. Daily potential evapotranspiration was assumed to be uniformly distributed throughout the month.

IRRIGATION

Irrigation in the proposed golf course areas was estimated with a model relating annual rainfall with annual irrigation. The irrigation model developed for this study is based on golf course irrigation data obtained from a survey conducted by Hollyer and Cox (1988) and is presented in detail in Appendix C. Mean annual golf course irrigation rates were obtained for the relevant cells of the water balance grid based on the mean annual rainfall in the cell. Annual irrigation totals were then disaggregated into monthly values by first assuming that total water input to the cell was distributed uniformly over the 12 months of the year. An unadjusted monthly irrigation total was computed as the difference between average monthly water input and the mean monthly rainfall. Finally, the monthly irrigation totals were adjusted to reflect the annual irrigation amount. Daily irrigation was assumed to be uniformly distributed throughout the month. Golf course irrigation rates were also extrapolated to the urban areas within the study area.

RECHARGE ESTIMATES

Six different recharge scenarios were generated for subsequent input to PRZM in order to estimate pesticide leaching through the unsaturated zone. Each scenario represents a different land use distribution and hence a spatially different recharge pattern. For Waiawa Ridge, the land use pattern ranged from one which maximized recharge (scenario 1) to those which represented no development (scenarios 3, 4). Between these two extremes, a distributed land use pattern similar to the proposed Waiawa Master Plan was used (scenarios 2, 5). An additional scenario was devised to test the possibility of concentrated recharge occurring near the periphery of a house due to runoff from rooftops. The six scenarios provide a range of recharge estimates which may be used for modeling of chemical transport in the unsaturated zone. Each of the scenarios is described below.

<u>Recharge Scenario 1: Waiawa Ridge Irrigated Lawn Without Runoff</u>. Recharge scenario 1 was devised to provide a condition conducive to leaching of chemicals. In this scenario, all water balance cells in the proposed Waiawa Gentry development area were either designated as open (with runoff) or treated as irrigated lawn (Fig. 27). Zero runoff was assigned to irrigated lawn areas, thus assuming an unlimited soil infiltration capacity and maximizing recharge. Those cells designated as irrigated lawn roughly correspond in location to the developed areas of the proposed Gentry Waiawa Master Plan community. Water balance cells representing existing urban areas were unaffected by the assumptions of scenario 1. That is, recharge from existing urban areas was based on an urban water balance rather than the irrigated lawn (without runoff) water balance.

Average annual recharge by cell for recharge scenario 1 is presented in Figure 28. Recharge estimates for existing urban areas reflect the depth of water over the entire area of the water balance cell including the paved and unpaved areas. The annual recharge time series for each of the water balance cells depicted in Figure 27 are presented in Appendix C.

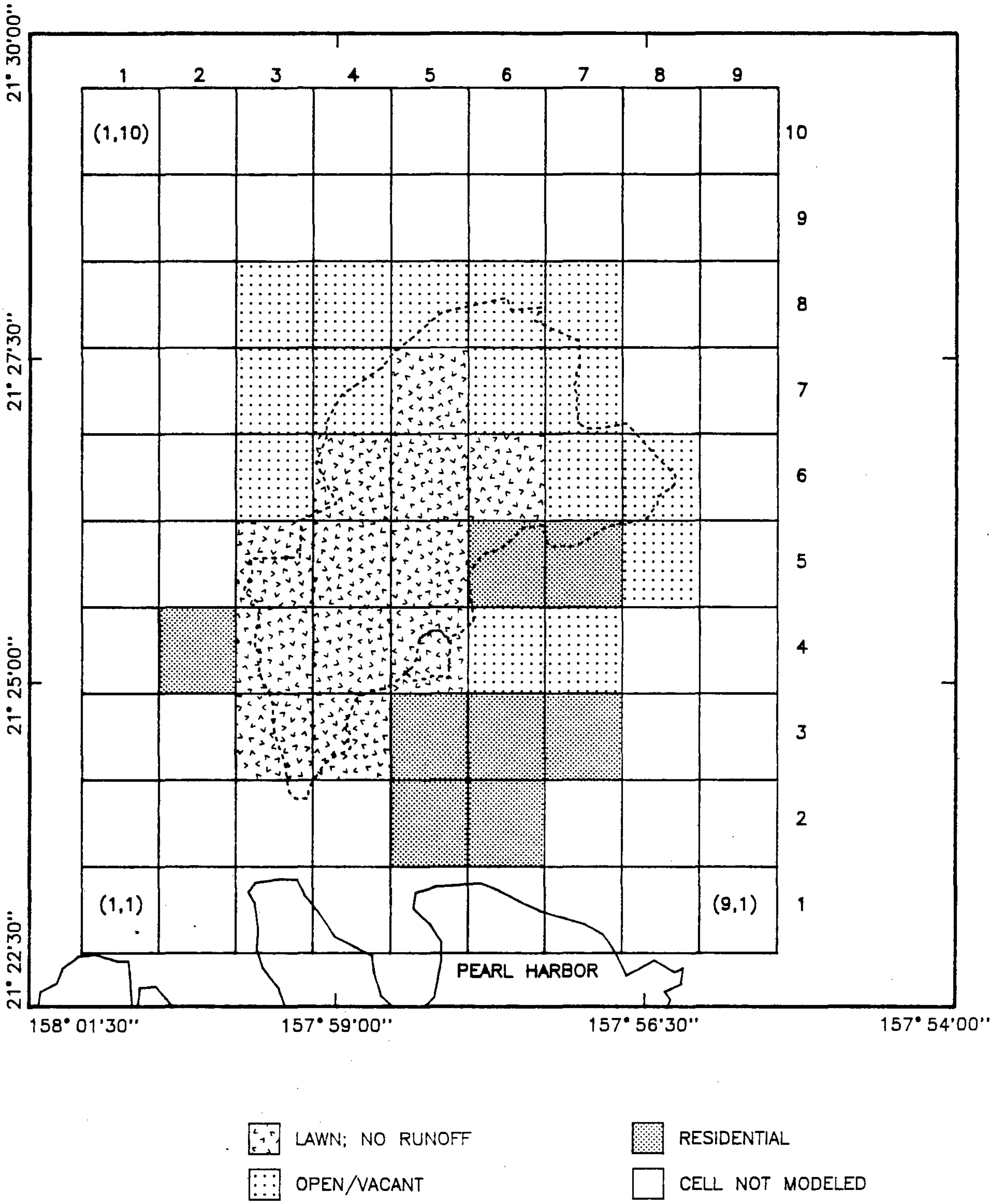
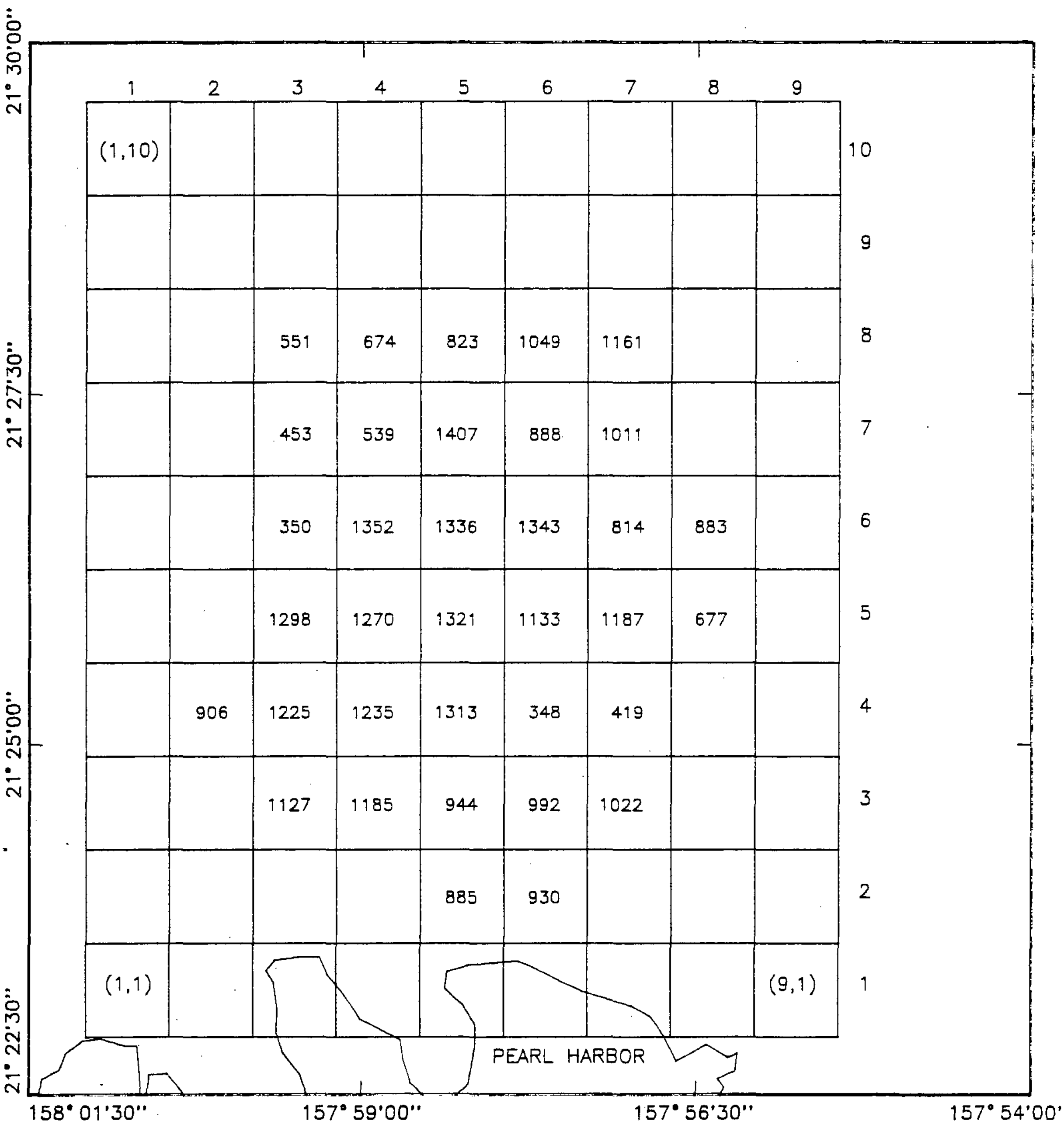


Figure 27. Land use and recharge scenario 1



NOTE: Recharge in mm.

Figure 28. Estimated mean annual recharge for land use scenario 1

TABLE 10. AVERAGE MONTHLY RECHARGE BY CELL FOR SCENARIO 1

Cell x	Cell y	Land Use*	Average Monthly Recharge (mm) 1	2	3	4	5	6	7	8	9	10	11	12	Avg. Ann. (mm)
2	4	4	100	95	88	79	52	47	55	53	55	75	93	109	906
3	3	1	139	129	97	84	72	64	54	54	69	97	128	140	1127
3	4	1	143	128	111	101	83	70	70	63	81	101	129	144	1225
3	5	1	146	130	118	105	90	79	84	72	90	105	133	148	1298
3	6	3	81	42	43	28	11	2	5	9	3	19	50	60	350
3	7	3	91	51	56	31	16	6	13	13	5	27	62	82	453
3	8	3	98	60	68	39	23	10	20	21	8	37	73	93	551
4	3	1	143	128	109	83	91	73	55	60	73	101	126	142	1185
4	4	1	148	129	112	99	96	73	63	63	76	104	127	145	1235
4	5	1	151	128	115	101	102	74	69	66	84	104	133	144	1270
4	6	1	154	131	118	107	108	88	74	72	91	111	145	154	1352
4	7	3	97	57	65	41	22	11	20	19	8	37	76	88	539
4	8	3	105	66	84	52	30	19	31	28	12	52	89	107	674
5	2	4	100	90	89	74	58	50	47	49	51	73	91	107	885
5	3	4	104	93	94	80	64	56	55	54	53	79	95	112	944
5	4	1	151	133	123	108	103	85	72	77	77	110	128	146	1313
5	5	1	151	132	119	107	108	83	71	79	80	113	130	147	1321
5	6	1	153	127	121	108	105	81	80	81	81	111	138	150	1336
5	7	1	155	126	132	115	105	91	94	89	89	117	142	150	1407
5	8	3	113	74	104	70	41	29	44	39	18	69	101	118	823
6	2	4	98	92	95	82	61	55	54	52	55	77	94	110	930
6	3	4	105	95	98	87	67	61	61	57	59	83	98	115	992
6	4	3	75	39	42	29	14	3	7	9	3	22	47	58	348
6	5	4	112	104	108	98	83	76	85	73	64	95	108	120	1133
6	6	1	150	124	130	111	97	83	100	87	70	113	134	144	1343
6	7	3	114	85	103	81	46	33	63	45	19	73	103	123	888
6	8	3	126	97	130	92	54	47	72	56	29	89	118	140	1049
7	3	4	104	96	100	91	69	64	67	60	64	83	102	116	1022
7	4	3	76	44	50	37	16	6	16	14	5	30	56	69	419
7	5	4	112	106	112	103	86	85	92	76	70	98	115	126	1187
7	6	3	107	79	93	71	39	31	60	41	16	64	97	116	814
7	7	3	121	96	121	91	52	44	74	52	25	86	113	136	1011
7	8	3	132	109	141	102	60	56	83	65	33	103	124	153	1161
8	5	3	96	66	72	59	30	20	42	31	12	54	86	107	677
8	6	3	111	85	98	75	42	36	63	43	20	74	107	129	883

*1 irrigated lawn; no runoff
2 golf course
3 open/vacant
4 residential
5 apartment
6 commercial/industrial.

The seasonal pattern of recharge by cell is provided in Table 10. As in Figure 28, estimates in Table 10 for water balance cells representing existing urban areas reflect the depth of recharge water over the entire cell area.

Recharge Scenario 2: Waiawa Ridge Distributed Land Use. Recharge scenario 2 represents the estimated future recharge condition following the completion of the Waiawa Master Plan community. In this scenario, water balance cells are assigned land uses in accordance with Figure 29. An effort was made in assigning each cell a land use to approximate the actual expected areas of each different land use. However, an exact correspondence of actual and discretized areas could not be maintained due to the relatively coarse nature of the water balance grid. Note that existing urban areas such as Pacific Palisades, Pearl City, and Waipio Gentry are represented in Figure 29. Runoff is allowed to occur from all areas. The open areas and existing urban areas produce the same recharge as in scenario 1.

Average annual recharge by cell for recharge scenario 2 is presented in Figure 30. Recharge estimates for urban areas presented in Figure 30 represent the depth of water over the entire water balance cell. The annual recharge time series for each of the water balance cells depicted in Figure 29 are presented in Appendix C. The seasonal pattern of recharge by cell is provided in Table 11. As in Figure 30, estimates presented in Table 11 for water balance cells representing urban areas were adjusted to reflect the depth of recharge water over the entire cell area.

Recharge Scenario 3: Waiawa Valley Irrigated Lawn Without Runoff. Recharge scenario 3 was devised to isolate the effects of the proposed USN Waiawa Valley development under high recharge conditions. In this scenario the proposed Waiawa Valley development area was assigned a land use corresponding to an irrigated lawn condition without runoff. Note that the Waiawa Valley development occupies three MOC grid cells which represents just a fraction of the area of a water balance cell (Fig. 31). Under recharge scenario 3, the existing vacant land use for Waiawa Ridge was maintained so that all water balance cells covering the proposed Waiawa Master Plan community were designated as open undeveloped areas. All

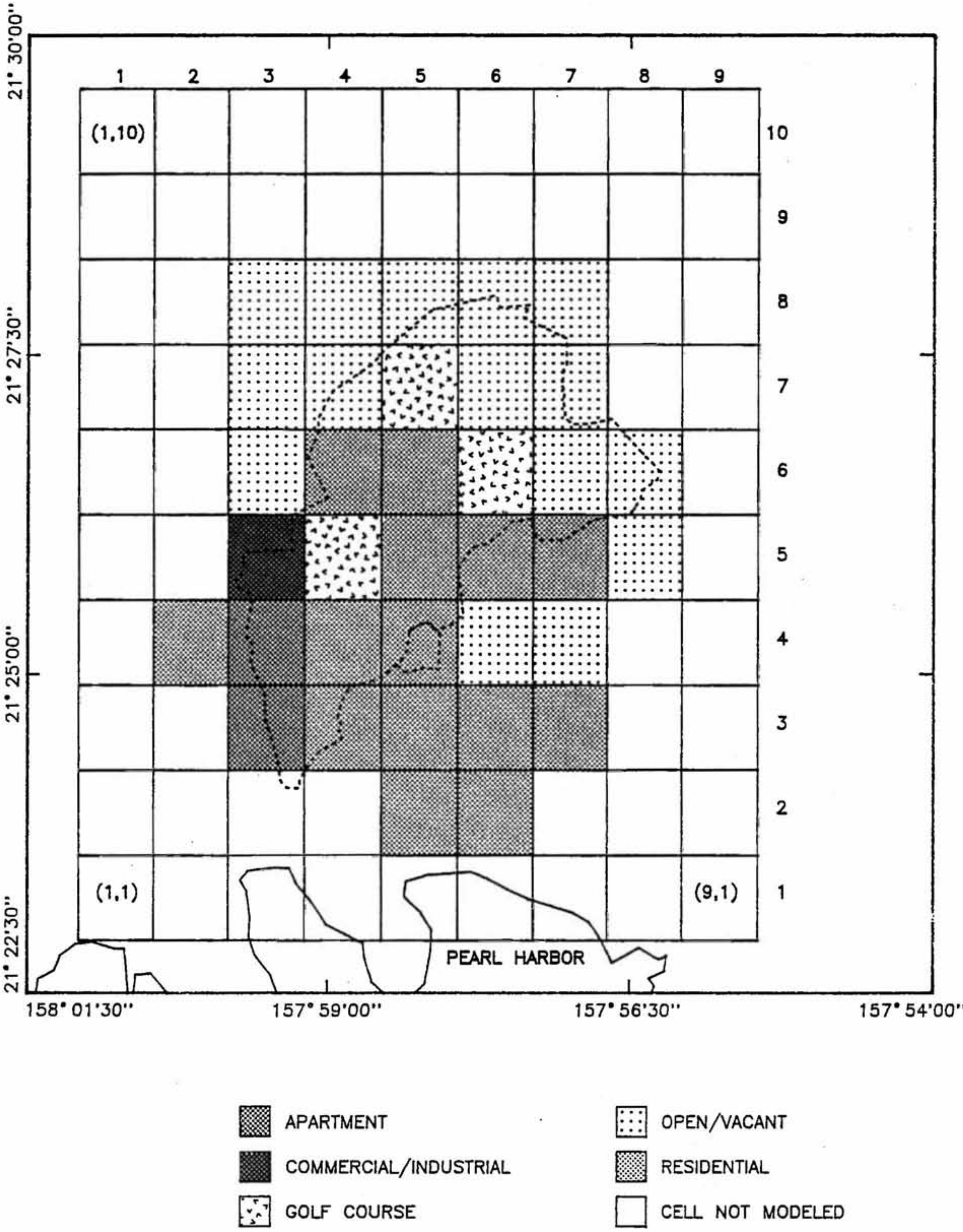
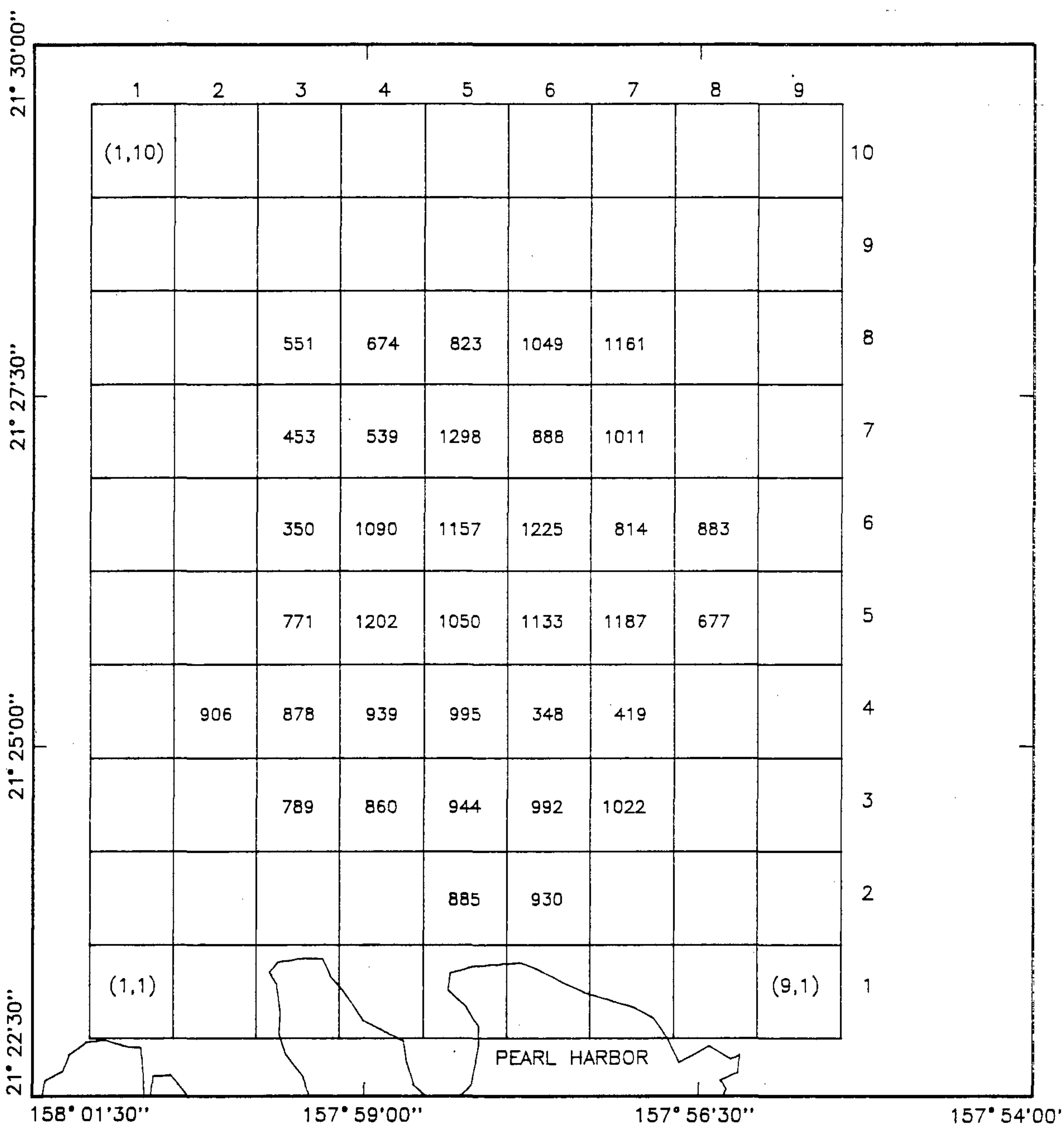


Figure 29. Land use and recharge scenario 2



NOTE: Recharge in mm.

Figure 30. Estimated mean annual recharge for land use scenario 2

TABLE 11. AVERAGE MONTHLY RECHARGE BY CELL FOR SCENARIO 2

Cell x	Cell y	Land Use*	1	2	3	4	5	6	7	8	9	10	11	12	Avg. Ann. (mm)
			------------ Average Monthly Recharge (mm) ------------												
2	4	4	100	95	88	79	52	47	55	53	55	75	93	109	906
3	3	5	99	88	77	65	46	37	39	37	41	68	86	101	789
3	4	5	102	91	86	77	55	44	51	45	49	74	92	106	878
3	5	6	85	75	78	68	49	41	52	43	42	64	80	90	771
3	6	3	81	42	43	28	11	2	5	9	3	19	50	60	350
3	7	3	91	51	56	31	16	6	13	13	5	27	62	82	453
3	8	3	98	60	68	39	23	10	20	21	8	37	73	93	551
4	3	4	102	90	86	68	60	46	43	43	48	73	89	107	860
4	4	4	107	94	91	80	66	52	54	50	52	79	97	112	939
4	5	2	129	121	108	97	99	74	68	65	84	101	120	136	1202
4	6	4	112	103	100	93	79	70	73	64	66	89	114	122	1090
4	7	3	97	57	65	41	22	11	20	19	8	37	76	88	539
4	8	3	105	66	84	52	30	19	31	28	12	52	89	107	674
5	2	4	100	90	89	74	58	50	47	49	51	73	91	107	885
5	3	4	104	93	94	80	64	56	55	54	53	79	95	112	944
5	4	4	109	98	98	86	70	59	61	58	54	84	99	114	995
5	5	4	111	101	100	91	76	64	68	63	59	89	104	119	1050
5	6	4	116	105	107	99	86	76	84	74	67	96	116	125	1157
5	7	2	128	117	117	109	102	90	91	85	88	108	126	138	1298
5	8	3	113	74	104	70	41	29	44	39	18	69	101	118	823
6	2	4	98	92	95	82	61	55	54	52	55	77	94	110	930
6	3	4	105	95	98	87	67	61	61	57	59	83	98	115	992
6	4	3	75	39	42	29	14	3	7	9	3	22	47	58	348
6	5	4	112	104	108	98	83	76	85	73	64	95	108	120	1133
6	6	2	125	114	114	104	94	82	94	81	69	103	117	127	1225
6	7	3	114	85	103	81	46	33	63	45	19	73	103	123	888
6	8	3	126	97	130	92	54	47	72	56	29	89	118	140	1049
7	3	4	104	96	100	91	69	64	67	60	64	83	102	116	1022
7	4	3	76	44	50	37	16	6	16	14	5	30	56	69	419
7	5	4	112	106	112	103	86	85	92	76	70	98	115	126	1187
7	6	3	107	79	93	71	39	31	60	41	16	64	97	116	814
7	7	3	121	96	121	91	52	44	74	52	25	86	113	136	1011
7	8	3	132	109	141	102	60	56	83	65	33	103	124	153	1161
8	5	3	96	66	72	59	30	20	42	31	12	54	86	107	677
8	6	3	111	85	98	75	42	36	63	43	20	74	107	129	883

*1 irrigated lawn; no runoff
2 golf course
3 open/vacant
4 residential
5 apartment
6 commercial/industrial.

water balance cells representing existing urban areas remain unaffected in recharge scenario 3.

Average annual recharge by cell for recharge scenario 3 is presented in Figure 32. Recharge estimates for existing urban areas reflect the depth of water over the entire area of the water balance cell. The annual recharge time series for each of the water balance cells depicted in Figure 31 are presented in Appendix C. The seasonal pattern of recharge by cell is provided in Table 12. For water balance cells representing urban areas, Table 12 presents the depth of recharge water over the entire cell area.

Recharge Scenario 4: Waiawa Valley Distributed Land Use. Recharge scenario 4 represents the case in which the USN develops their Waiawa Valley property and Waiawa Ridge remains vacant. Thus, recharge scenario 4 is similar to recharge scenario 3 except that the USN Waiawa Valley property is treated as a residential area rather than as an irrigated lawn without runoff (Fig. 33).

Average annual recharge by cell for recharge scenario 4 is presented in Figure 34. The annual recharge time series for each of the water balance cells depicted in Figure 33 are presented in Appendix C. The seasonal pattern of recharge by cell is provided in Table 13. Estimates in Figure 34 and Table 13 for water balance cells representing urban areas reflect the depth of recharge water over the entire cell area.

Recharge Scenario 5: Waiawa Ridge Distributed Land Use. Recharge scenario 5 is identical to recharge scenario 2 except that no runoff from golf course areas is assumed to occur. Thus, scenario 5 utilizes water balance estimates from scenario 1 for the golf course cells and recharge estimates from scenario 2 elsewhere.

Recharge Scenario 6: Unguttered Roof Condition. Recharge scenarios 1 to 5 utilize a large-scale approach to analyzing the water balance of the proposed developments. In recharge scenario 6, a single residence is isolated to determine the amount of recharge occurring over a lawn as a result of irrigation and rainfall. This scenario was designed specifically to test the potential for leaching of termiticides applied around the periphery of a house where concentrated recharge conditions may exist due to runoff from rooftops without a gutter system.

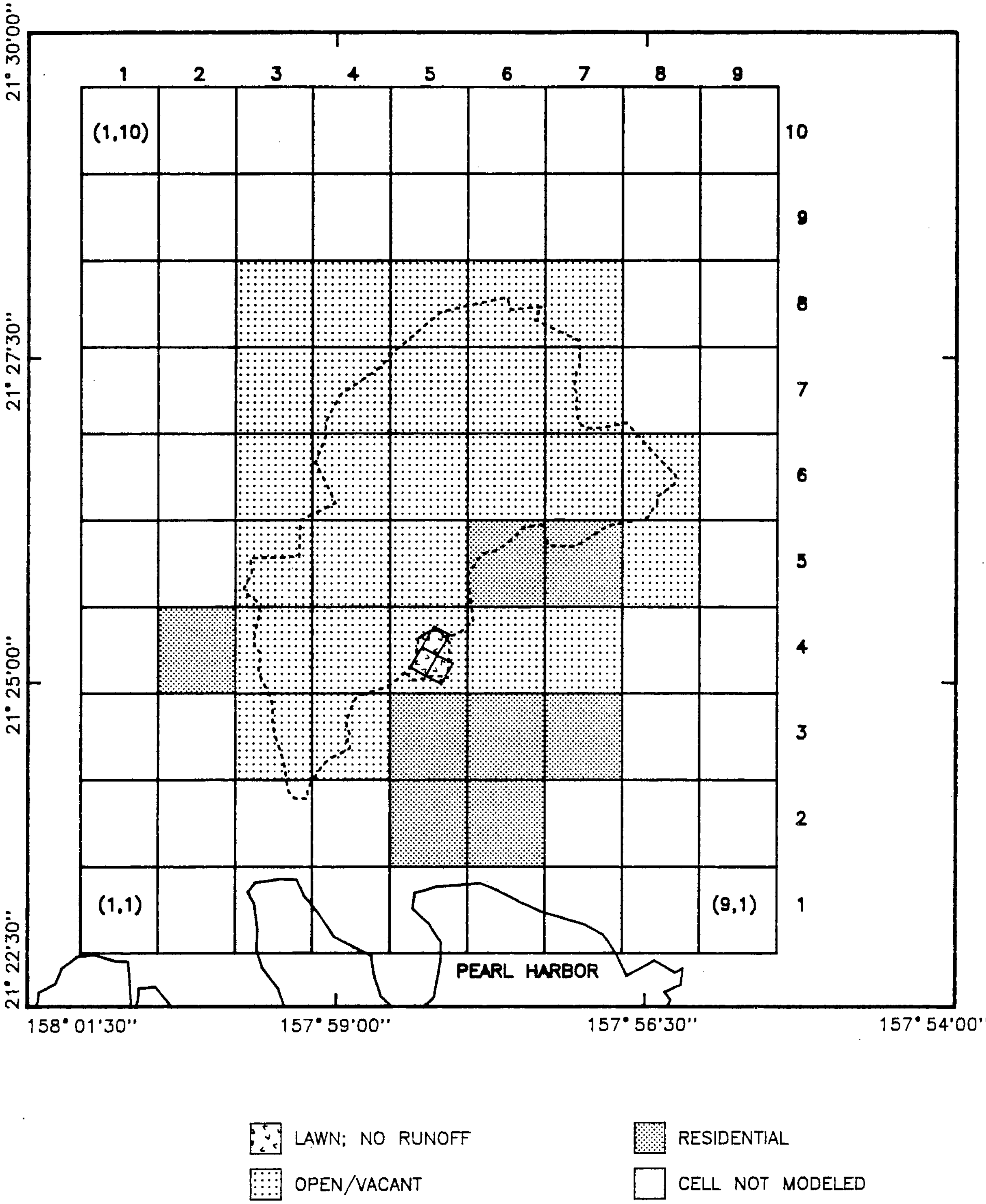
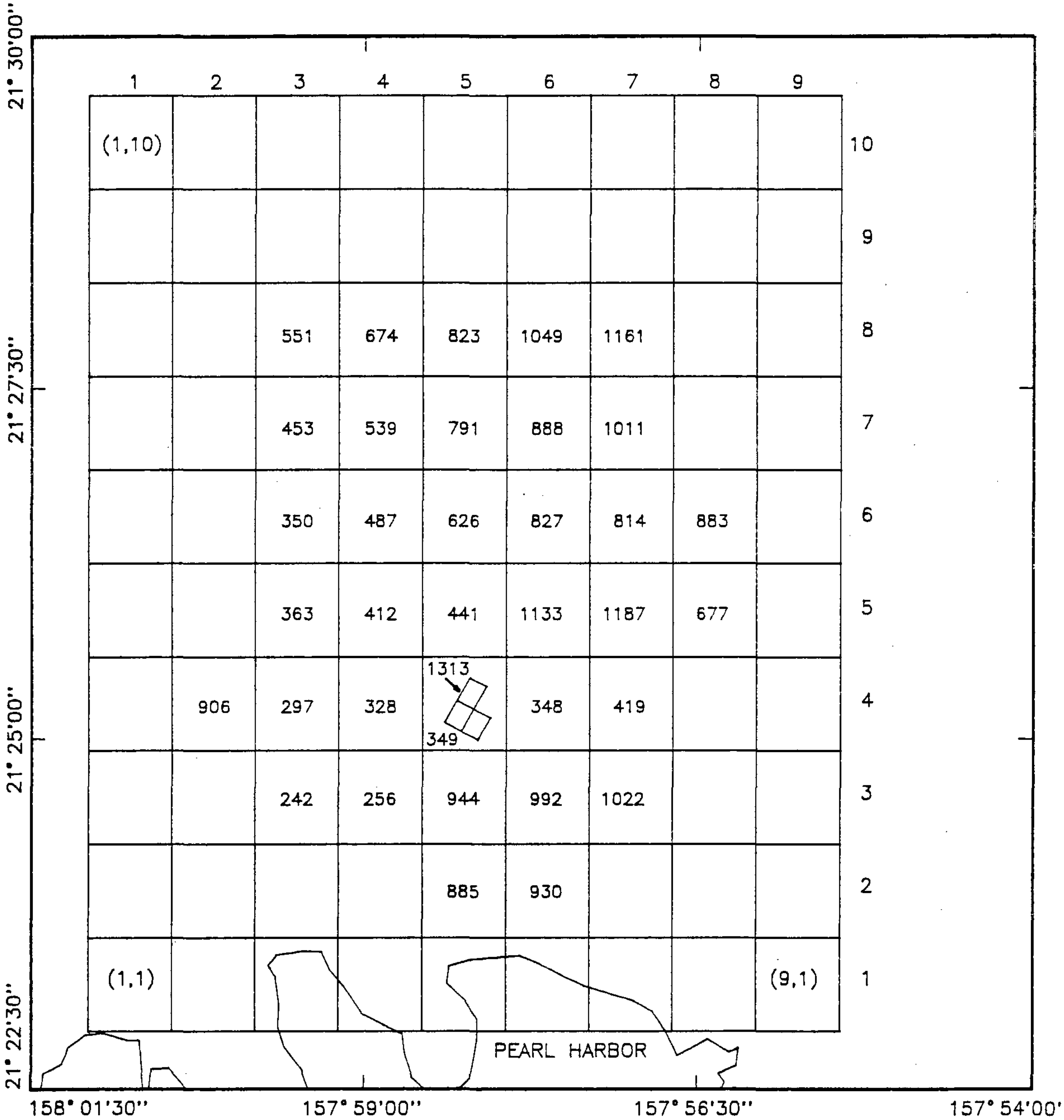


Figure 31. Land use and recharge scenario 3



NOTE: Recharge in mm.

Figure 32. Estimated mean annual recharge for land use scenario 3

TABLE 12. AVERAGE MONTHLY RECHARGE BY CELL FOR SCENARIO 3

Cell x	Cell y	Land Use*	1	2	3	4	5	6	7	8	9	10	11	12	Avg. Ann. (mm)
			Average Monthly Recharge (mm)												
2	4	4	100	95	88	79	52	47	55	53	55	75	93	109	906
3	3	3	73	33	29	16	5	0	0	2	2	13	34	36	242
3	4	3	83	39	36	22	7	0	1	4	2	16	41	47	297
3	5	3	91	46	43	30	11	1	3	7	2	20	50	59	363
3	6	3	81	42	43	28	11	2	5	9	3	19	50	60	350
3	7	3	91	51	56	31	16	6	13	13	5	27	62	82	453
3	8	3	98	60	68	39	23	10	20	21	8	37	73	93	551
4	3	3	75	32	31	15	5	0	0	2	2	14	38	40	256
4	4	3	89	40	39	23	11	1	1	6	2	19	45	54	328
4	5	3	98	51	47	32	14	2	7	10	3	25	57	66	412
4	6	3	108	58	55	38	17	4	13	14	5	29	69	77	487
4	7	3	97	57	65	41	22	11	20	19	8	37	76	88	539
4	8	3	105	66	84	52	30	19	31	28	12	52	89	107	674
5	2	4	100	90	89	74	58	50	47	49	51	73	91	107	885
5	3	4	104	93	94	80	64	56	55	54	53	79	95	112	944
5	4	1	151	133	123	108	103	85	72	77	77	110	128	146	1313
5	4	3	90	41	42	26	13	2	3	6	2	20	46	58	349
5	5	3	99	50	52	37	18	4	9	11	3	27	58	72	441
5	6	3	114	68	72	51	25	11	29	25	8	42	84	94	626
5	7	3	126	79	96	67	35	19	42	35	13	62	102	114	791
5	8	3	113	74	104	70	41	29	44	39	18	69	101	118	823
6	2	4	98	92	95	82	61	55	54	52	55	77	94	110	930
6	3	4	105	95	98	87	67	61	61	57	59	83	98	115	992
6	4	3	75	39	42	29	14	3	7	9	3	22	47	58	348
6	5	4	112	104	108	98	83	76	85	73	64	95	108	120	1133
6	6	3	123	84	96	72	36	27	59	43	14	58	102	113	827
6	7	3	114	85	103	81	46	33	63	45	19	73	103	123	888
6	8	3	126	97	130	92	54	47	72	56	29	89	118	140	1049
7	3	4	104	96	100	91	69	64	67	60	64	83	102	116	1022
7	4	3	76	44	50	37	16	6	16	14	5	30	56	69	419
7	5	4	112	106	112	103	86	85	92	76	70	98	115	126	1187
7	6	3	107	79	93	71	39	31	60	41	16	64	97	116	814
7	7	3	121	96	121	91	52	44	74	52	25	86	113	136	1011
7	8	3	132	109	141	102	60	56	83	65	33	103	124	153	1161
8	5	3	96	66	72	59	30	20	42	31	12	54	86	107	677
8	6	3	111	85	98	75	42	36	63	43	20	74	107	129	883

*1 irrigated lawn; no runoff
2 golf course
3 open/vacant
4 residential
5 apartment
6 commercial/industrial.

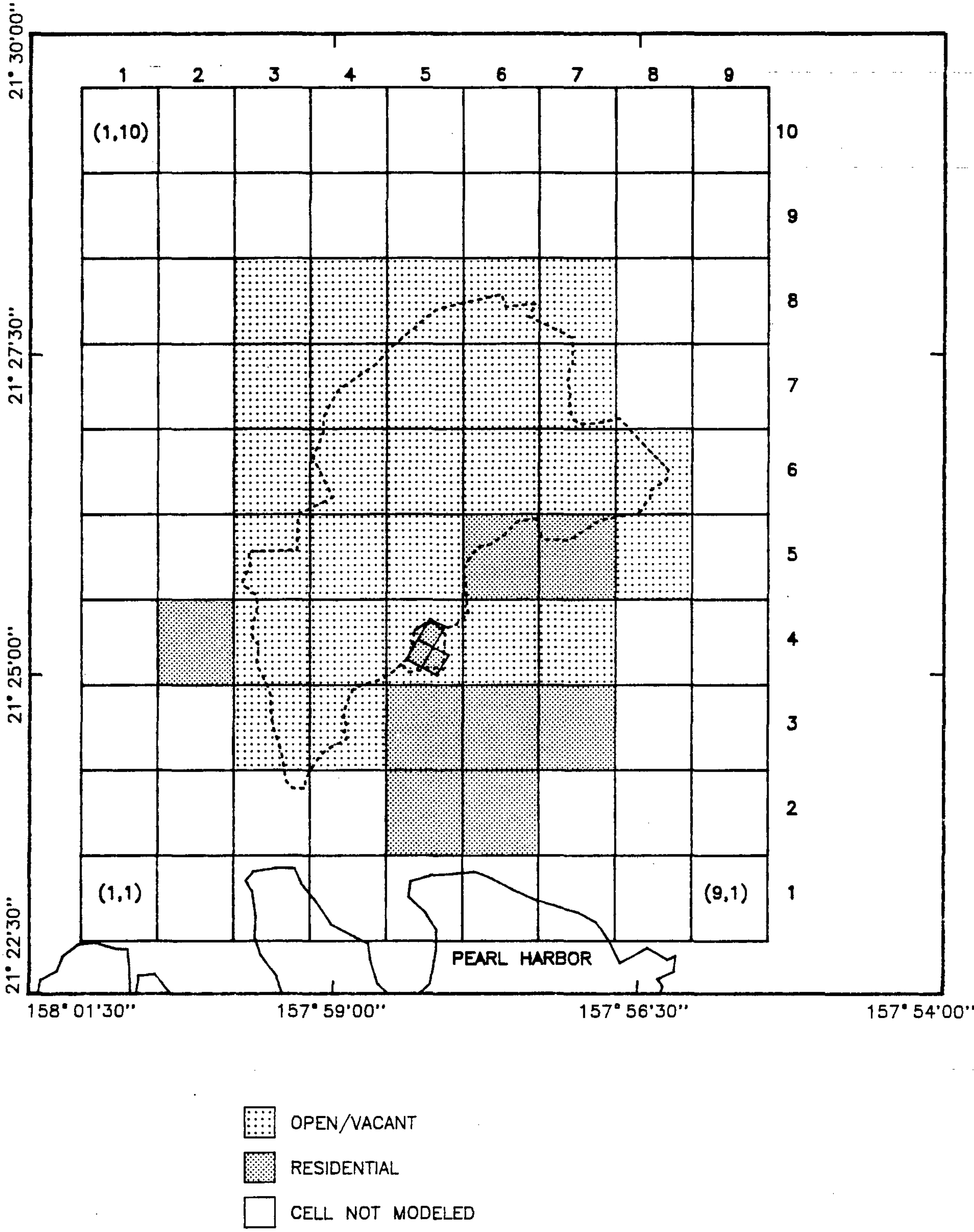
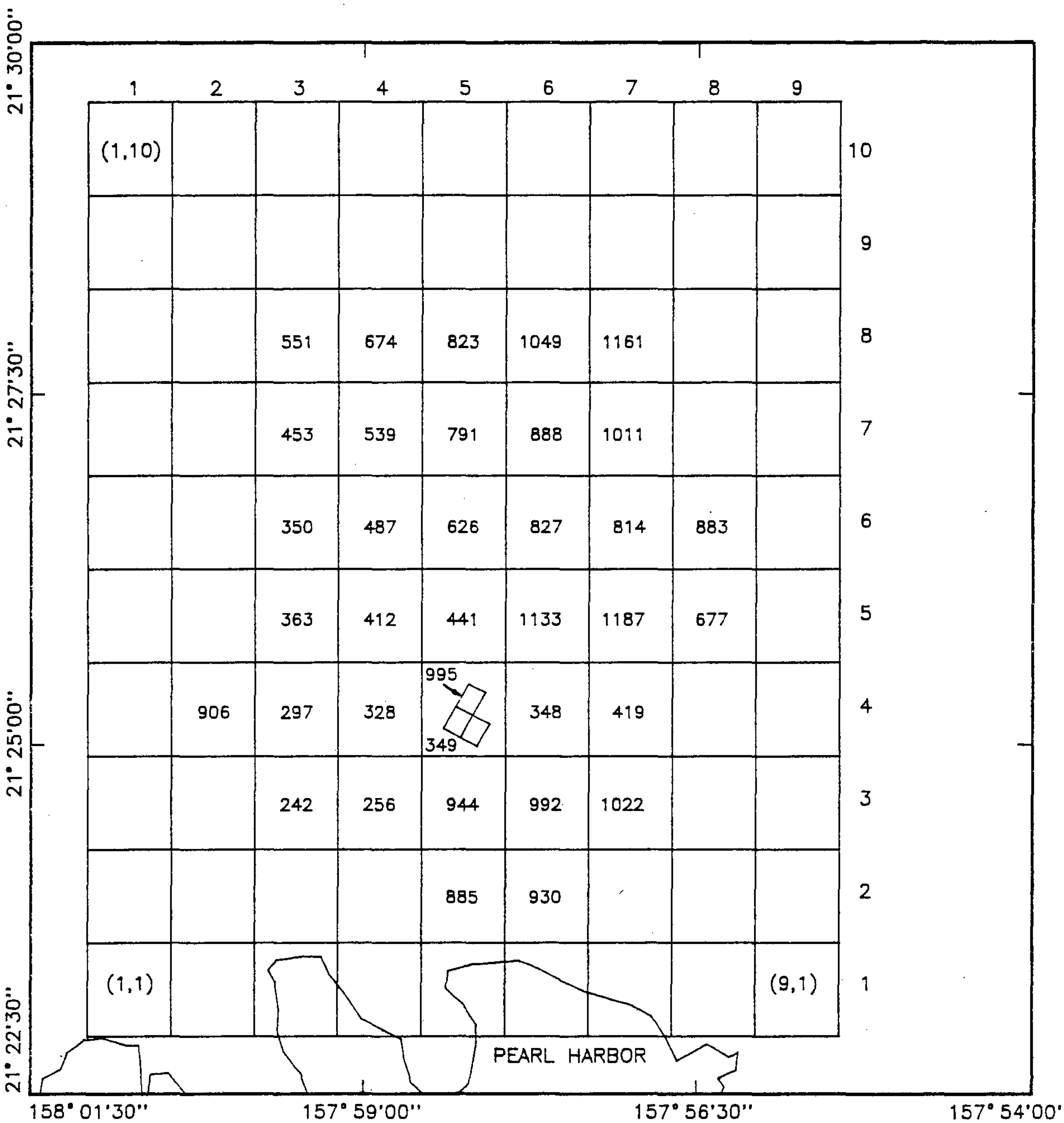


Figure 33. Land use and recharge scenario 4



NOTE: Recharge in mm.

Figure 34. Estimated mean annual recharge for land use scenario 4

TABLE 13. AVERAGE MONTHLY RECHARGE BY CELL FOR SCENARIO 4

Cell x	Cell y	Land Use*	1	2	3	4	5	6	7	8	9	10	11	12	Avg. Ann. (mm)
			Average Monthly Recharge (mm)												
2	4	4	100	95	88	79	52	47	55	53	55	75	93	109	906
3	3	3	73	33	29	16	5	0	0	2	2	13	34	36	242
3	4	3	83	39	36	22	7	0	1	4	2	16	41	47	297
3	5	3	91	46	43	30	11	1	3	7	2	20	50	59	363
3	6	3	81	42	43	28	11	2	5	9	3	19	50	60	350
3	7	3	91	51	56	31	16	6	13	13	5	27	62	82	453
3	8	3	98	60	68	39	23	10	20	21	8	37	73	93	551
4	3	3	75	32	31	15	5	0	0	2	2	14	38	40	256
4	4	3	89	40	39	23	11	1	1	6	2	19	45	54	328
4	5	3	98	51	47	32	14	2	7	10	3	25	57	66	412
4	6	3	108	58	55	38	17	4	13	14	5	29	69	77	487
4	7	3	97	57	65	41	22	11	20	19	8	37	76	88	539
4	8	3	105	66	84	52	30	19	31	28	12	52	89	107	674
5	2	4	100	90	89	74	58	50	47	49	51	73	91	107	885
5	3	4	104	93	94	80	64	56	55	54	53	79	95	112	944
5	4	3	90	41	42	26	13	2	3	6	2	20	46	58	349
5	4	4	109	98	98	86	70	59	61	58	54	84	99	114	995
5	5	3	99	50	52	37	18	4	9	11	3	27	58	72	441
5	6	3	114	68	72	51	25	11	29	25	8	42	84	94	626
5	7	3	126	79	96	67	35	19	42	35	13	62	102	114	791
5	8	3	113	74	104	70	41	29	44	39	18	69	101	118	823
6	2	4	98	92	95	82	61	55	54	52	55	77	94	110	930
6	3	4	105	95	98	87	67	61	61	57	59	83	98	115	992
6	4	3	75	39	42	29	14	3	7	9	3	22	47	58	348
6	5	4	112	104	108	98	83	76	85	73	64	95	108	120	1133
6	6	3	123	84	96	72	36	27	59	43	14	58	102	113	827
6	7	3	114	85	103	81	46	33	63	45	19	73	103	123	888
6	8	3	126	97	130	92	54	47	72	56	29	89	118	140	1049
7	3	4	104	96	100	91	69	64	67	60	64	83	102	116	1022
7	4	3	76	44	50	37	16	6	16	14	5	30	56	69	419
7	5	4	112	106	112	103	86	85	92	76	70	98	115	126	1187
7	6	3	107	79	93	71	39	31	60	41	16	64	97	116	814
7	7	3	121	96	121	91	52	44	74	52	25	86	113	136	1011
7	8	3	132	109	141	102	60	56	83	65	33	103	124	153	1161
8	5	3	96	66	72	59	30	20	42	31	12	54	86	107	677
8	6	3	111	85	98	75	42	36	63	43	20	74	107	129	883

*1 irrigated lawn; no runoff
2 golf course
3 open/vacant
4 residential
5 apartment
6 commercial/industrial.

In recharge scenario 6, rainfall occurring on a rooftop is assumed to run off two sides of the house (Fig. 35). If the recharge area along each side of the house is approximately 0.6 m (2 ft) wide by 13.7 m (45 ft) long, rainfall occurring over a 140 m^2 (1,500 ft^2) roof area is concentrated over an area of 16.4 m^2 (180 ft^2) (Fig. 35). Thus, direct rainfall occurring over the concentrated recharge strip area must be increased by a factor of 9.3 to account for runoff from the rooftop. In addition, urban irrigation rates were assumed to be applicable to the concentrated recharge strip. In computing the water balance for the strip, potential evapotranspiration was reduced by a factor of 0.5 to account for the shielding effect of the house. Runoff from the strip was computed with the SCS runoff curve number model. The water balance for the remaining lawn area was assumed to be similar to the golf course water balance. Monthly recharge estimates for proposed urban water balance cells are presented in Table 14. Concentrated recharge estimates in Table 14 represent the depth of water over the isolated pervious strip area.

DISCUSSION

The recharge estimates presented in Figures 28, 30, 32, and 34 reflect the spatial patterns of land use and rainfall. Within a particular land use designation, recharge increases toward the northeastern portion of the study area where rainfall is greatest. Water balance cells treated as irrigated lawn without runoff have the greatest amount of recharge. Water balance cells designated as golf courses produce slightly less recharge due to runoff losses. Within the climate regime of the study area, recharge estimates for residential areas are greater than corresponding recharge estimates for open areas. This latter effect is due to the irrigation of lawns in residential areas. Although urbanization increases the amount of runoff due to the covering of land with impervious surfaces and the reduction of soil infiltration rates in pervious areas (Murabayashi and Fok 1979), there is no simple relationship between recharge and urbanization. Giambelluca (1986) suggests that recharge is a function of the level of urbanization and the climate.

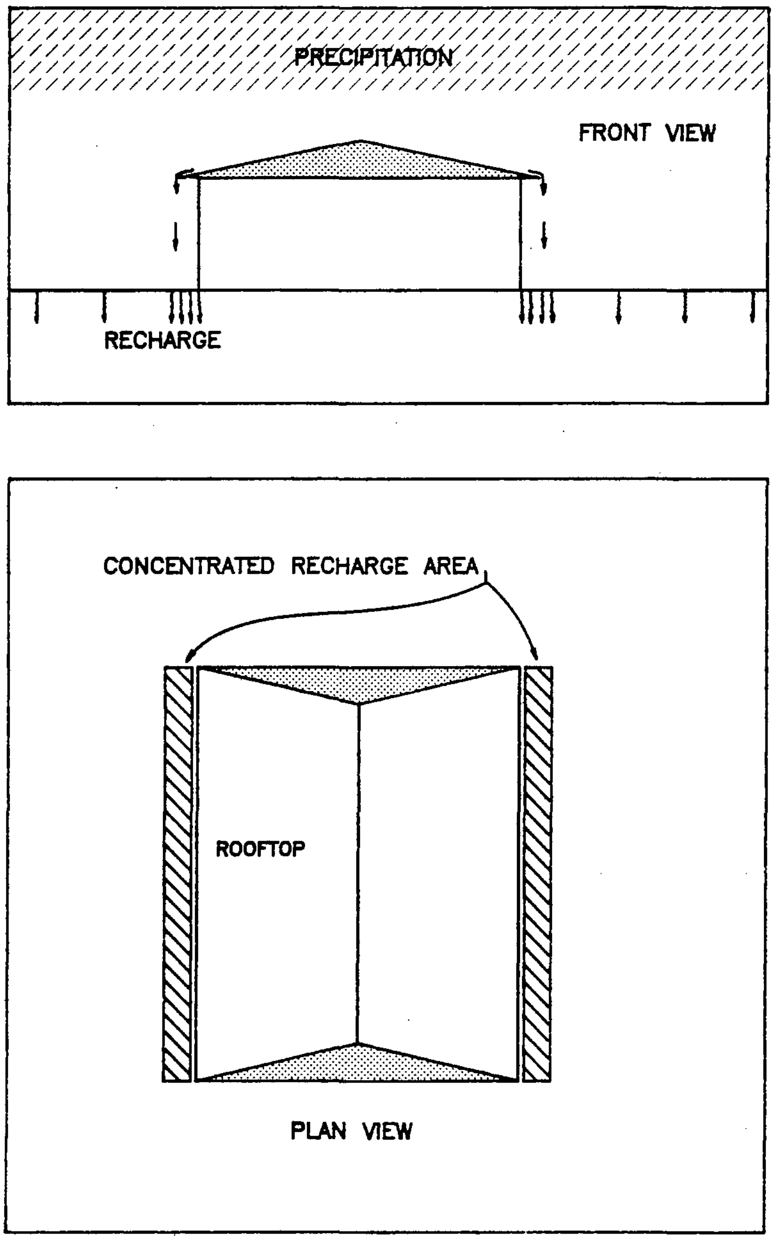


Figure 35. Unguttered roof, recharge scenario 6

TABLE 14. AVERAGE MONTHLY RECHARGE BY CELL FOR SCENARIO 6

Cell x	Cell y	Land Use*	Average Monthly Recharge (mm) 1	2	3	4	5	6	7	8	9	10	11	12	Avg. Ann. (mm)
4	3	4	245	210	226	191	161	137	155	149	146	198	230	252	2306
4	4	4	251	221	235	212	178	158	178	168	159	213	243	261	2482
4	5	4	254	230	244	227	193	178	198	187	176	224	256	268	2641
4	6	4	255	233	248	236	207	199	210	200	184	233	266	274	2752
5	3	4	248	219	235	205	175	157	171	165	156	212	238	259	2446
5	4	4	253	227	244	218	185	170	188	178	165	219	247	264	2564
5	5	4	257	233	249	228	198	185	206	192	177	229	255	270	2685
5	6	4	262	241	262	247	225	217	229	220	199	247	273	283	2909

*1 irrigated lawn; no runoff
2 golf course
3 open/vacant
4 residential
5 apartment
6 commercial/industrial.

6. CHEMICAL LEACHING ESTIMATES

OVERVIEW OF PESTICIDE FATE IN THE UNSATURATED ZONE

As reviewed by Wagenet and Rao (1985) and Donigian and Rao (1986), the major processes which describe pesticide fate under field conditions are transport, transformation, retention, plant uptake, and volatilization. Transport includes surface runoff, erosion, and leaching. The leaching process is typically assumed to conform to Darcian principles, however the significance of leaching via preferential flow has received considerable attention.

Preferential flow through structured porous media involves flow through a network of continuous channels or macropores. A review paper by Beven and Germann (1982) indicates that structured flow through soils is not adequately described by a Darcian approach. White (1985) summarizes the possible effects on the leaching of fertilizers and pesticides via this bypassing mechanism. Data from scanning electron microscopy by Miller (1987) on central Oahu subsoil and saprolite show that preferential flow occurs along joints and in channels between macropores. Loague et al. (1989c,d) discuss the need to characterize and account for preferential flow in Hawaiian soils.

Transformation of pesticides may occur via microbiological or chemical pathways which are spatially and temporally variable depending on factors such as soil type, soil moisture, initial pesticide concentration, temperature, and pH. The transformation rate is commonly expressed as k, a first-order decay rate, or by $t_{1/2}$, the apparent half-life. Hydrolysis is a significant transformation process for organic compounds in aqueous environments (Harris 1982). Hydrolysis becomes especially important below the soil layer where photolysis is negligible and biological pathways are retarded. It is important to keep in mind that the transformation process may result in degradation to nontoxic products as well as the production of toxic metabolites.

The retention of pesticides by porous media refers to the phenomenon of sorption, which includes the effects of absorption and adsorption.

Sorption may be characterized by a linear sorption partition coefficient, K_d, which relates the sorbed and dissolved pesticide concentrations by equation D.3 (App. D). Organic carbon content is recognized as the single most important soil characteristic influencing sorption of pesticides (Rao et al. 1983). Organic carbon content is commonly expressed as f_{oc}, the mass fraction of organic carbon to dry soil. Due to the dominant effect of f_{oc} on sorption, the sorption partition coefficient is often based on soil organic carbon and expressed as K_{oc}. The relationship between K_{oc} and K_d is usually assumed to be linear and expressed as

$$K_d = K_{oc} \cdot f_{oc} \qquad (6.1)$$

The transport of pesticides by surface runoff and erosion is dependent upon the pesticide formulation, application method, and timing of rainfall/irrigation events. In general, the resulting losses are in the order of 0.5% or less of the amounts applied (Wauchope 1978). The effects of plant uptake on pesticide fate are dependent upon characteristics of the vegetation, but few quantified results have been documented. The importance of volatilization is dependent on properties of the selected chemical and prevailing meteorologic conditions.

A useful tool for determining the leaching potential of chemicals is the attenuation factor (AF) described by Rao, Hornsby, and Jessup (1985). The AF is a simple yet useful index which can be used to rank chemicals according to their potential to cause groundwater contamination. Chemicals with AF values close to 1.0 are expected to pose a significant threat whereas those with AF values approaching zero are generally considered safe.

The AF does not include dispersion or temporal variation in recharge, but otherwise treats pesticide fate in a manner very similar to PRZM. Using both PRZM and AF, Kleveno (1990) determined that the two models produced nearly identical rankings.

Table 15 ranks AF values of selected chemicals through a soil depth of 0.5 m assuming an average urban recharge rate of 1 m/yr. Chemicals listed in Table 15 include those used in simulations for this study as well as those currently used by residents of Waipio Gentry (see Chapter 4) if estimates for the AF model parameters were available. Also included in Table 15 are the commonly used golf course pesticides metribuzin, MSMA,

TABLE 15. ATTENUATION FACTOR OF SELECTED CHEMICALS IN SOIL

CHEMICAL	K_{oc} (m^3/kg)	k (yr^{-1})	Attenuation Factor
nitrate	0.000	0.00	1.00
DBCP	0.070	1.41	4.4×10^{-1}
metribuzin	0.041	8.44	2.8×10^{-2}
dicamba	0.002	18.1	2.2×10^{-2}
diazinon	0.085	8.44	3.6×10^{-3}
fenamiphos	0.171	12.7	5.4×10^{-7}
2,4-D	0.020	50.6	1.5×10^{-7}
methiocarb	0.300	12.7	6.8×10^{-11}
triforine	0.500	12.1	3.6×10^{-16}
metaldehyde	0.240	25.3	1.9×10^{-17}
carbaryl	0.229	36.2	1.2×10^{-23}
acephate	0.100	84.4	3.3×10^{-28}
chlorothalonil	1.380	12.7	1.5×10^{-43}
MSMA	10.00	2.53	2.0×10^{-61}
petroleum oil	1.000	25.3	2.1×10^{-63}
chlorpyrifos	6.070	8.44	$<1.0 \times 10^{-99}$
glyphosate	10.00	8.44	$<1.0 \times 10^{-99}$
malathion	1.797	253	$<1.0 \times 10^{-99}$

NOTE: K_{oc} and k values from Wauchope (1988); Rao, Hornsby, and Jessup (1985); Ou et al. (1979); and Rao and Davidson (1979).

NOTE: The following assumptions were made:
bulk density = 1100 kg/m^3
f_{oc} = 0.01 kg/kg
θ_{fc} = 0.40 m^3/m^3
depth of profile = 0.5 m
recharge rate = 1.0 m/yr.

and chlorothalonil and a chemical, DBCP, which has been detected in groundwater samples from the Pearl Harbor aquifer. Rankings based on AF provide a general perspective on the relative leaching potential of different chemicals. Of the pesticides listed in Table 15, DBCP has the highest AF ranking, which is consistent with its known leaching potential and presence in groundwater. The AF for the chemical 2,4-D is considerably lower than that of DBCP. Although 2,4-D is a popular herbicide with widespread use, it has not been detected in groundwater samples from Waiawa Shaft and other wells on Oahu (Giambelluca, Leung, and Konda 1987).

The herbicide MSMA (monosodium methanearsonate) is an organic arsenical which is commonly used on lawns and golf courses in Hawaii. Degradation of MSMA may lead to the production of inorganic forms of arsenic more toxic and persistent than the parent compound. In soils, both oxidative and reductive transformations of methanearsonates may occur. Reductive methylation of arsenic compounds has been shown to produce volatile dimethylarsine and trimethylarsine (Woolson 1977; Braman 1975). The primary mechanism of MSMA degradation in soils is oxidative demethylation of the molecule by microorganisms, with the products of metabolism being CO_2 and inorganic arsenate (Shariatpanahi, Anderson, and Abdelghani 1981; Abdelghani et al. 1977; Von Endt, Kearney, and Kaufman 1968).

Inorganic arsenate is highly sorbed, and thus, has limited mobility in highly weathered oxidic soils. Livesey and Huang (1981) determined that soil retention of arsenate at low concentrations proceeds through adsorption mechanisms rather than through the precipitation of sparingly soluble arsenate compounds. Arsenate sorption in soil is related to the aluminum and iron oxides and clay minerals present (Goldberg and Glaubig 1988; Livesey and Huang 1981; Frost and Griffen 1977; Wauchope 1975; Woolson, Axley, and Kearney 1973, 1971; Jacobs, Syers, and Keeney 1970). Frost and Griffen (1977) determined that arsenate adsorption on the clay minerals montmorillonite and kaolinite is pH dependent, with sorption being greater on montmorillonite than kaolinite and exhibiting a maximum between pH 4 and 6. Sorption of arsenate may occur on both crystalline (Hingston, Posner, and Quirk 1971) and amorphous (Pierce and Moore 1982; Anderson, Ferguson, and Gavis 1976) forms of iron and aluminum oxides.

Like arsenate, phosphate sorption is highly correlated with iron and aluminum oxides in soil (see Wild [1950] and references cited therein). Adsorption of phosphate on hydroxylated mineral surfaces occurs via a ligand exchange mechanism (Goldberg and Sposito 1985). Similarly, Lumsdon et al. (1984) showed that arsenate is adsorbed on synthetic goethite by a ligand exchange mechanism.

McLaughlin, Ryden, and Syers (1981) found that sorption of inorganic phosphate was greater on amorphous forms of iron and aluminum containing components than on their crystalline analogues. Using x-ray diffraction line profile analysis, Jones (1981) determined that phosphorus sorption on 11 Puerto Rican soils was due principallly to goethite, and to a lesser extent gibbsite, and was insignificant on hematite. Curi and Franzmeier (1984) and Bigham et al. (1978) found that yellower soils containing goethite were more efficient adsorbers of phosphate than redder soils dominated by hematite. Thus, it appears that sorption of arsenate in soil will be dependent on the form of the iron and aluminum oxides present.

The low humic latasol soils which predominate on Waiawa Ridge contain significant amounts of clay minerals, including kaolinite, as well as secondary aluminum and iron oxide minerals, which are primarily crystalline. However, amorphous minerals such as allophane may also be present (Tenma 1965; Tamura, Jackson, and Sherman 1953). X-ray analysis of soil samples from the Wahiawa and Manana series on Waiawa Ridge indicate that kaolinite/dehydrated halloysite are the predominant clay minerals. Hematite and maghemite appear to be the predominant secondary minerals present. However, goethite and gibbsite were also found in the soil samples.* Miller (1987) used x-ray diffraction to determine the mineralogy of soil and saprolite samples collected to depths of 18.3 and 12.2 m from nearby Dole pineapple fields 4101 and 4111, respectively. The soils in fields 4101 and 4111 are of the Wahiawa and Lahaina series, respectively. In general, kaolinite/halloysite were the most abundant minerals identified throughout the profiles. Hematite occurred in high concentrations especially in the upper portions of the profiles. Goethite was identified throughout much of the sampled profiles at lower concentrations, while gibbsite was found to depths of 0.3 and 7.6 m in respectively fields 4101 and 4111.

Based on the presence of iron and aluminum oxide minerals throughout the soil and saprolite in conjunction with the lack of evidence of phosphate contamination of groundwater on Oahu, it is apparent that organic arsenicals applied in the proposed Waiawa development areas will not threaten groundwater quality.

SUMMARY OF CHEMICAL LEACHING EXPERIMENTS

For this study the fate of chemicals in the unsaturated zone was simulated with PRZM, a relatively rigorous model which incorporates many

*B. Gavenda (1990) unpublished data.

of the processes mentioned above. PRZM is described in Appendix D. The data used to evaluate PRZM were collected from field plots at Waiawa and Poamoho. The Waiawa plot received two chemical applications and was sampled on five different days over a 318-day period. The Poamoho plot received a single application and was sampled three times over a 100-day interval. The three chemicals applied on each plot were (1) a tracer in the form of sodium bromide, (2) the termiticide chlorpyrifos, and (3) the nematicide fenamiphos. Figure 36 shows time series of the chemical application and sampling dates in relation to daily rainfall and irrigation at each plot. Descriptions of the field plots and the experiments performed on them are presented in Appendix A.

Bromide. The bromide profiles at Waiawa show a considerable amount of variation between quadrants and even between profiles of the same quadrant (see quadrant #1 in App. Fig. A.6). On the fourth and fifth sampling dates, background concentrations of about 0.5 mg/kg make it difficult to identify the bromide peak from the initial application (App. Figs. A.8, A.9). It appears that the first peak may have moved below the maximum sampling depth on these two occasions.

The mass balance of bromide reveals low recoveries versus the amount applied for all five sampling dates, with an increase in lost mass with time. Table 16 lists the approximate fractions of bromide recovered in the field versus the amount applied. These findings suggest one or more of the following: mass loss due to lateral dispersion, preferential flow which transported the unaccountable mass of bromide below the maximum sampling

TABLE 16. BROMIDE RECOVERY AT FIELD PLOTS

Sampling Date	Waiawa Plot	Poamoho Plot
1	0.76	0.70
2	0.17	0.49
3	0.24	0.49
4	0.39	---
5	0.25	---

NOTE: Recoveries expressed as fraction of amount applied; 1.0 would indicate 100% recovery.

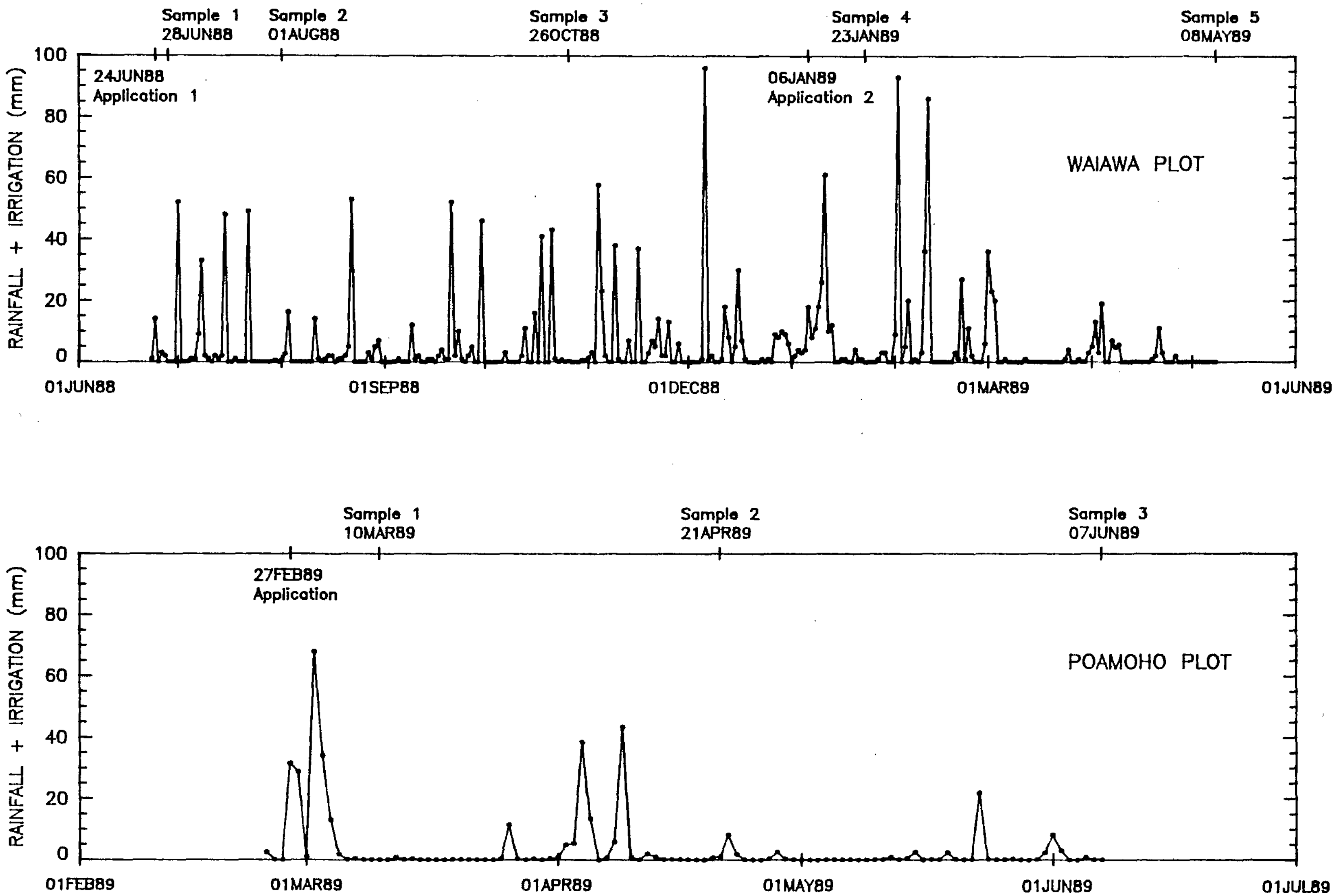


Figure 36. Daily rainfall and irrigation time series at field plots

depths, nonrepresentative sampling within the plot, and nonuniform chemical application. Errors introduced by the application method are probably the least significant. Most samples were collected within 2.5 m of the plot boundaries. This may have resulted in mass being lost to lateral dispersion, especially for the later, deeper samples.

Bromide profiles at Poamoho (App. Figs. A.23-A.25) also reveal similar mass balance discrepancies. The lower background concentrations at Poamoho (typically 0.2 mg/kg) allow the observation of a more discernable bromide peak. This increased sensitivity in detecting the applied bromide suggests that unless there is a very tenuous and extended tailing of the concentration profile with depth, preferential flow is not evident at the Poamoho site. Another complication is observed during the third sampling (App. Fig. A.25) where bromide has moved upward toward the surface. This was apparently caused by a capillary transport process. Unfortunately the plot received very little rainfall and no irrigation between the second and third sampling dates, allowing the soil to become very dry at the surface which resulted in the transport of bromide by this wick-like process.

Chlorpyrifos and Fenamiphos. The amount of chlorpyrifos leaching below 0.5 m was negligible at both plots, with the great majority of mass remaining within the top 0.2 m for all sampling dates (App. Figs. A.10-A.14, A.26-A.28). Fenamiphos showed greater variability than chlorpyrifos in its concentration profiles and was even less persistent. Fenamiphos also showed minimal leaching, although the first sampling at Poamoho (App. Fig. A.29) showed detectable levels down to about 0.7 m. In either case, both chlorpyrifos and fenamiphos behaved as relatively immobile and nonpersistent pesticides. The extended tailing in some of the observed pesticide profiles indicate that preferential flow may have occurred.

EVALUATION OF PRZM

The effort to evaluate PRZM was simplified by isolating and reducing the number of pesticide fate processes involved. Isolating the transport of pesticides by leaching was accomplished by preventing surface runoff and erosion on the field plots. Losses due to volatilization were avoided by using nonvolatile chemicals. A conservative tracer was also applied to observe transport without the effects of sorption and transformation. The primary processes evaluated by this study are transport by leaching, sorption, and transformation. However, PRZM does not incorporate the effects of preferential flow. The model evaluation process is discussed in Appendix D.

PRZM accurately simulated the locations of peaks in the bromide concentration profiles sampled closest to the application dates (App. Fig. D.3). In general, the shapes of the observed and simulated bromide concentration profiles are also similar. PRZM also accurately simulated the observed bromide profiles for the first two Poamoho samplings, especially when viewed with respect to the ranges in observed concentrations. By isolating these two Poamoho samplings it appears that PRZM has been successfully calibrated and validated. However, with the exception of these two samplings PRZM significantly over-predicted most of the observed mean concentrations. Another discrepancy with the field data is observed for the third Poamoho sampling. PRZM was unable to simulate the observed upward capillary transport of bromide. Despite these discrepancies and with the possible exception of preferential flow, the empirical drainage algorithm employed by PRZM appears to be at least marginally adequate in simulating bromide transport. However, it does not seem appropriate to state that PRZM has been validated with respect to bromide transport in this study.

While attempting to validate PRZM with the chlorpyrifos and fenamiphos concentration profiles, it became apparent that PRZM could not be definitively validated for each of the sampling dates. With this in mind, the chemical properties input to PRZM to simulate the field data were selected such that they would result in a simulation which would best describe pesticide leaching over the entire test period. This modified approach to simulating the field data resulted in a single "best estimate" set of parameters at each of the sites (App. Tables D.3, D.4).

PRZM simulations for chlorpyrifos and fenamiphos are shown in Appendix Figures D.4 and D.5. When compared with field data collected shortly after a pesticide application, PRZM tended to over predict near surface concentrations, but as time progressed it underestimated the concentrations. This trend is probably caused by variable transformation and sorption of pesticides. The greater persistence of observed pesticide concentrations with time may also suggest that desorption is occurring at a lower rate and/or the pesticides are being trapped in "dead end" pores or within soil aggregates. PRZM cannot account for variable and nonlinear pesticide characteristics as it assumes constant first-order relationships.

Statistical evaluation methods described by Loague and Green (1989b) were performed for the three chemicals using average field concentration profiles. These results, summarized in Appendix Table D.5, quantify the discrepancies between predicted and observed concentrations. Although PRZM simulated some of the pesticide profiles to a reasonable extent, it would again be inappropriate to claim that PRZM has been strictly validated. This was particularly evident when PRZM was evaluated by the statistical criteria. However, when the range of observed concentrations is considered, the simulated results are reasonable.

LONG-TERM SIMULATIONS WITH PRZM

Upon its evaluation, PRZM was used to predict the long-term effects of chemical applications in the proposed Waiawa Ridge and Waiawa Valley developments. Although PRZM was only evaluated through a depth of about 0.5 m, it was extended and used as a predictive tool for profiles up to 240 m thick.

Chemicals. The four nonvolatile chemicals used for the long-term PRZM simulations were (1) chlorpyrifos; (2) diazinon, an insecticide; (3) metribuzin, an herbicide; and (4) nitrate, a component of fertilizers. Table 17 summarizes the chemical properties used in the long-term simulations. From the AF rankings in Table 15 nitrate, metribuzin, and diazinon have high leaching potentials through the soil relative to chlorpyrifos. It must be emphasized that the AF indices presented in Table 15 were calculated only for the top 0.5 m of soil. A more comprehensive AF ranking should include the entire unsaturated profile but is not presented here due to the scarcity of published data on chemical transformation rates at greater depths.

Chlorpyrifos was selected for the long-term simulations based on three factors: (1) it is the termiticide most commonly used by local treatment companies, (2) it is applied at relatively high rates, and (3) it is applied below the soil surface (below the highest concentrations of organic

TABLE 17. CHEMICAL PROPERTIES USED IN LONG-TERM SIMULATIONS

CHEMICAL	Chlorpyrifos	Diazinon	Metribuzin	Nitrate*
USE	termiticide	insecticide	herbicide	fertilizer
APPLICATION RATE (kg/ha)	3125	2.242	0.841	2.20**
APPLICATION FREQUENCY	every 2 years	4 times per year	2 times per year	6 times per year
K_{oc} (kg/m^3)	6.07	0.085	0.041	0.000
$t_{1/2}$ (days)				
0.0 - 0.3 m	30	30	30	∞***
0.3 - 0.5 m	60	60	60	∞
>0.5 m	100	200	365 & ∞	∞

*Nitrate expressed as nitrogen.
**Nitrate application rate reflects reduction to 3%.
***No decay.

carbon). Diazinon was selected because of its relatively high persistence and mobility and its very common usage, as revealed by the household survey. Metribuzin, although used primarily on golf courses, was also selected because of its persistent and mobile nature. Nitrate was chosen because it is recognized as the most mobile and persistent component of fertilizers and has been identified as the source of elevated nitrate levels in Hawaiian groundwater (Green and Young 1970).

The application rate and incorporation depth used in the long-term chlorpyrifos simulations approximate the maximum allowable rates as they would be used to provide a vertical barrier to subterranean termites. The application frequency of two years represents a typical case of persistent termite infestation.

Rao and Davidson (1979) have shown that the K_{oc} values obtained by assuming a linear relationship between C and C_s at low concentrations will under-predict the mobility of pesticides applied at high concentrations. For this reason, the K_{oc} for chlorpyrifos was decreased by an order of magnitude in the top 0.3 m of the profile. This decrease in magnitude is estimated from the Freundlich equation using a conservative value of 0.7 for N. The Freundlich equation is given by

$$C_s = KC^N \qquad (6.2)$$

where C_s is the sorbed concentration, K is the sorption partition coefficient, C is the dissolved concentration, and N is the empirically fitted exponent.

Diazinon application rates and frequencies are based on those specified on the product label. The simulated applications of nitrogen fertilizers and metribuzin are based on those typically used for golf courses (Murdoch and Green 1989). The actual amount of nitrate-nitrogen leached below the root zone and made available for transport to the water table is assumed to be 3% of the application rate, as measured by Handley and Ekern (1981) in a study on California grass. This was simulated by reducing the actual application to 3% of its original rate and then treating the nitrate as a conservative chemical (i.e., no sorption or degradation).

The values used for K_{oc}, and decay of pesticides in soil are conservative yet reasonable estimates from Wauchope (1988), Rao and Davidson (1982), and Ou et al. (1982). Below a depth of 0.5 m hydrolysis was assumed to be the only process contributing to decay of pesticides. Unfortunately there are very few published hydrolysis rate data for pesticides.

The hydrolysis rates used for the long-term PRZM simulations were obtained from published laboratory experiments conducted in the dark with distilled water at temperatures and pH values consistent with those found in natural groundwater systems. These conditions eliminate the effects of biological and photochemical decay.

The 100 day apparent hydrolysis half-life of chlorpyrifos is a conservative estimate based on the results of Freed, Chiou, and Schmedding (1979), Macalady and Wolfe (1983), and Meikle and Youngson (1978). The hydrolysis half-life of 200 days ($k = 0.0035\ day^{-1}$) for diazinon is a value estimated from Harris (1982).

The hydrolysis rate of metribuzin was not readily available so a half-life of 1 yr was estimated based on transformation studies with sterilized soils kept in the dark (Savage 1977; Webster, Sarna, and Macdonald 1978). Due to the uncertainty of this estimated half-life for metribuzin, a set of conservative long-term simulations assuming an infinite half-life (k = 0) was also simulated.

Nitrate was modeled as a conservative chemical that does not sorb or decay, although retarded leaching has been observed in Hawaiian soils (Balasubramanian et al. 1973).

Unsaturated profiles. Three different unsaturated profiles, summarized in Table 18, were used to approximate various conditions. The profiles represent different degrees of surface grading, which affect the amount of organic carbon in the profiles. Profiles 1, 2, and 3 assume that the top 0.0, 0.2, and 0.5 m of soil will be lost during surface grading, respectively. The f_{oc} values above a depth of 1.0 m are estimated from organic carbon transects on Waiawa Ridge (App. A), while data from Peterson et al. (1985) are used below a depth of 1 m. The organic carbon content of unweathered basalt is assumed to be negligible.

Bulk densities and field capacities above the unweathered basalt are based on the work of Green et al. (1982) and Miller (1987). The bulk density of basalt is from a gravity survey at the Schofield shaft #4 (Huber and Adams 1971). The field capacity of basalt is assumed to be equal to its specific yield which was estimated from Visher and Mink (1964), and Williams and Soroos (1973).

The diffusion-dispersion coefficient, D, is estimated to be 0.001 m^2/day in soil and subsoil. This value is somewhat smaller than the value used in the evaluation simulations, but the larger compartment size used in the long-term simulations increased the numerical dispersion by an approximately equal amount. Khan (1979) reports a value similar to this for a Hawaiian soil. The values of 0.003 and 0.01 m^2/day for saprolite and basalt, respectively, are consistent with those used by Loague and Green (1989a) for deep PRZM simulations.

Profile 3 utilizes conservative (yet realistic) estimates for field capacity, f_{oc} in saprolite, and saprolite thickness. The saprolite thickness was estimated from logs of exploratory wells drilled in the vicinity of the Waiawa Shaft just prior to its construction (Public Works Center 1951).

The proposed USN development site was treated as a special case because drill logs (Public Works Center 1951) from the valley floor indicate an alluvial aquifer at about 30 m above sea level. In this case PRZM was

TABLE 18. CHARACTERISTICS OF UNSATURATED PROFILES USED IN LONG-TERM SIMULATIONS

DEPTH (m)	f_{oc} (kg/kg)	ρ_b (kg/m³)	θ_{fc} (m³/m³)	D (m²/day)	DESCRIPTION
PROFILE #1: no f_{oc} loss from grading; 20 m saprolite					
0.0 - 0.1	0.022	1100	0.38	0.001	soil
0.1 - 0.3	0.017	1100	0.38	0.001	soil
0.3 - 0.5	0.010	1200	0.40	0.001	soil
0.5 - 1.2	0.005	1350	0.42	0.001	subsoil
1.2 - 2.7	0.002	1400	0.42	0.001	subsoil
2.7 - 5.2	0.001	1400	0.42	0.001	subsoil
5.2 - 25.0	0.0002	1100	0.50	0.003	saprolite
> 25.0	0.0000	2400	0.05	0.010	basalt
PROFILE #2: 0.2 m f_{oc} loss from grading; 20 m saprolite					
0.0 - 0.3	0.010	1200	0.40	0.001	soil
0.3 - 1.0	0.005	1350	0.42	0.001	subsoil
1.0 - 2.5	0.002	1400	0.42	0.001	subsoil
2.5 - 5.0	0.001	1400	0.42	0.001	subsoil
5.0 - 25.0	0.0002	1100	0.50	0.003	saprolite
> 25.0	0.0000	2400	0.05	0.010	basalt
PROFILE #3: 0.5 m f_{oc} loss from grading; 10 m saprolite; lower θ_{fc}					
0.0 - 0.5	0.005	1300	0.40	0.001	subsoil
0.5 - 2.0	0.002	1400	0.40	0.001	subsoil
2.0 - 4.5	0.001	1400	0.40	0.001	subsoil
4.5 - 14.5	0.0001	1100	0.45	0.003	saprolite
> 14.5	0.0000	2400	0.04	0.010	basalt

NOTE: f_{oc} = mass fraction of organic carbon to dry soil
ρ_b = bulk density
θ_{fc} = volumetric water content at field capacity
D = hydrodynamic dispersion coefficient.

TABLE 19. THICKNESSES OF WAIAWA RIDGE PROFILES USED IN LONG-TERM SIMULATIONS

Cell I.D. (x,y)*	Thickness (m)	Cell I.D. (x,y)	Thickness (m)
33	85	55	115
34	100	56	210
35	135	57	240
43	50	63	85
44	100	65	115
45	140	66	215
46	190	73	85
53	55	75	155
54	115		

*Coordinates are from water balance grid (see Fig. 23) used to simulate the 15 m of unsaturated profile from soil surface to the top of the alluvial aquifer. It was also assumed that the parameters used for saprolite extend to this 15 m depth (i.e., no unweathered basalt in the profile).

The thicknesses of the other unsaturated profiles used in the long-term simulations are listed in Table 19. The representative surface elevation for each of these profiles is 5 m more than their thickness due to the approximate basal water table elevation of 5 m.

The method of distributing water through the profiles of land areas with impermeable surfaces was also varied. Figure 37 illustrates the two scenarios. In case A of Figure 37 the wetting front of recharge from permeable surfaces is evenly distributed at the top of the saprolite over the entire areal extent of the profile. This allows at least a rough approximation of the effects of lateral dispersion which would otherwise be unaccounted for by the PRZM one-dimensional algorithm. The top of the saprolite was chosen because it marks a boundary with the overlying subsoil of lower permeability (Miller 1987). Case B is advection dominated and does not allow the infiltrating water and solutes to spread beneath the impermeable surfaces until the water table is reached. This case is analogous to a vertical channel between the ground surface and the water table.

Case A required the execution of two PRZM simulations for each profile. The first assumed advection dominated transport through the soil and subsoil. The recharge and leaching rates output from this first simulation were then distributed by using a reduction factor, equivalent to the fraction of total area which is paved, and input to the second simulation.

Recharge. For all long-term simulations, chemical losses due to runoff, erosion, and plant uptake were assumed to be negligible. Thus, daily recharge from the water balance model described in Appendix C was input directly into PRZM. The only foreseeable error introduced by this procedure is that it will underestimate the amount of infiltration above the maximum depth of evapotranspiration extraction (0.3 m depth). This effect was assumed to be minimal when compared with the extended depths which were simulated.

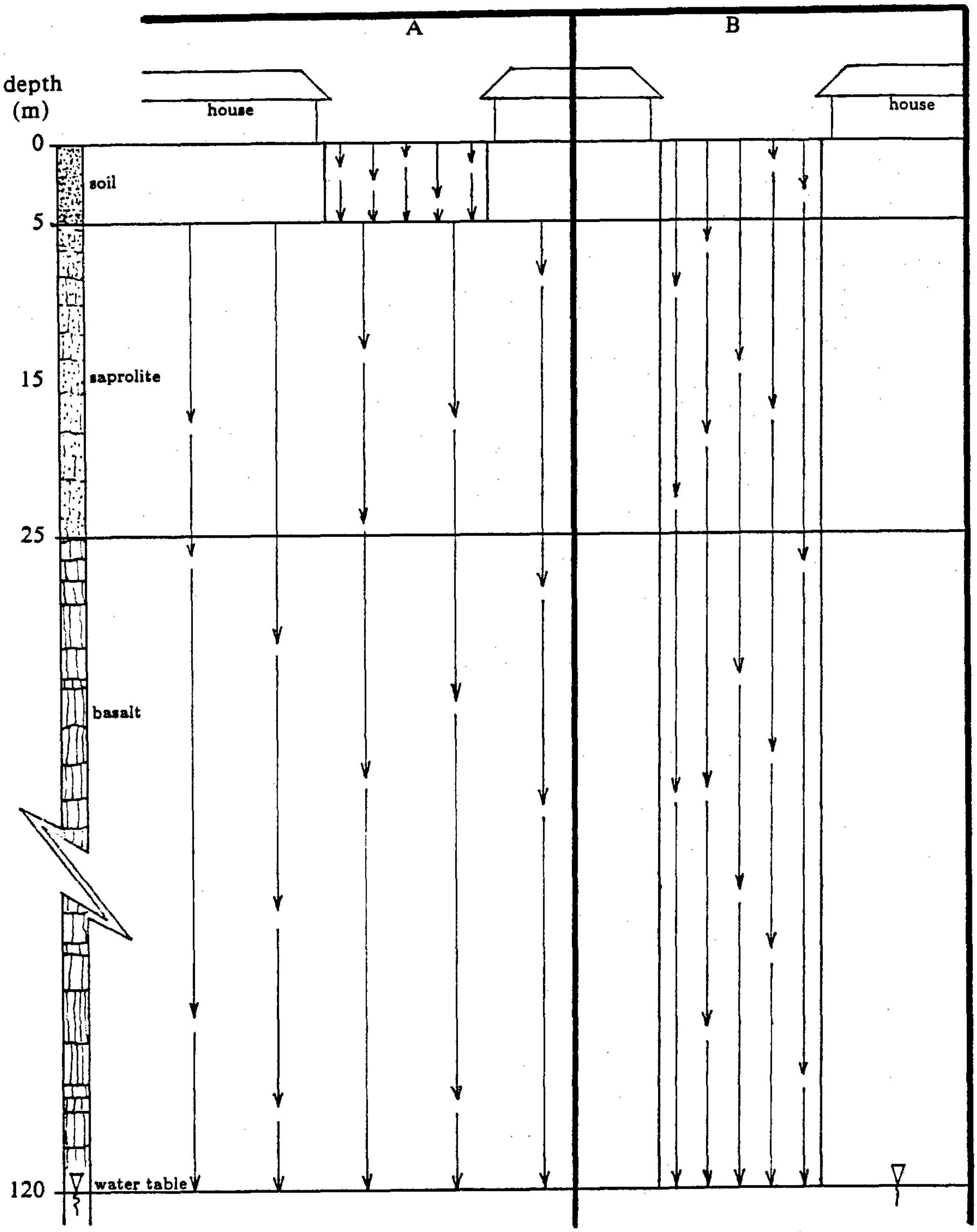


Figure 37. Cross section of water distribution methods: (A) distributed at top of saprolite; (B) advection dominated (distributed at water table)

The chlorpyrifos simulations received a special recharge scenario which considered unique and localized applications. Recharge was increased along the foundation of a house (where chlorpyrifos is applied) to account for the concentration of rainfall from rooftops.

Summary of results. Annual loading rates of diazinon, metribuzin, and nitrate (as nitrogen) to the water table for various scenarios and grid locations are listed in Appendix Tables D.6 to D.9.

Long-term loading rates of chlorpyrifos to the water table are not presented in tabular format because there were no significant concentrations even at the shallow depth of 5 m. The maximum average annual dissolved concentration at 5 m, when distributed at the saprolite, is below 0.011 μg/l. This maximum average annual leaching of chlorpyrifos below 5 m is about ten orders of magnitude lower than the application rate. In view of this, chlorpyrifos is not expected to be a threat to groundwater. The immobile and nonpersistent behavior of chlorpyrifos can be directly attributed to its very high K_{oc} value and high soil degradation and hydrolysis decay rates. However, consideration must be given to the toxic metabolite of chlorpyrifos. No information on decay or sorption was found in the literature for the metabolite 3,5,6-trichloro-2-pyridinol. If this metabolite is mobile and persistent, then chlorpyrifos may pose a threat to groundwater in a less direct but equally significant manner.

Based on application rates in Table 17, the maximum diazinon concentrations leached to the water table were on the order of a few μg/l. The method of distributing the water and pesticide in the profile decreased this maximum level by a few orders of magnitude by increasing the travel time through the vadose zone. The amount of organic carbon in the surface soil also had a significant effect on these concentrations.

Simulation cases 635.d3 and 635.d2 (see App. Fig. D.6 for description of case identifiers) which represent a land use with large fractions of impermeable surfaces and advection dominated flow illustrate the bias of this water distribution scheme. The travel times to groundwater were significantly shorter than if water had been distributed at the saprolite.

Metribuzin concentrations to the water table were most significantly affected by the hydrolysis rate used. The assumption of no hydrolysis increased the concentrations at the water table by several orders of magnitude. This observation underlines the importance of determining pesticide decay rates below the soil.

Nitrate concentrations introduced to the water table are near 1 mg/l (as nitrogen) for the assumed 3% leaching rate. The nitrate simulations illustrate that the method used to distribute water within the profile can significantly affect travel time in the vadose zone. Longer travel times provide a reduction buffer for those chemicals which decay below the soil. However, for chemicals with negligible decay rates, longer travel times merely result in longer residence times within the profile for any particular application. Thus, a longer period would be required to "flush out" the profile even after all chemical applications have ceased.

The long-term results presented above are given on an average annual basis. Significant variations from these annual averages can be expected on a smaller time scale. A comparison of the daily time series vs. annual values for recharge and loading rates for a particular nitrate simulation on selected years is shown in Appendix Figure D.7. Also note that these time series illustrate the "piston displacement" nature of the PRZM drainage algorithm.

7. PREDICTED GROUNDWATER QUALITY IMPACTS

The calibrated areal MOC model described in Appendix E was used to simulate the long-term groundwater quality impact of development on Waiawa Ridge and in Waiawa Valley over a 37-yr period. Note that the vertical MOC model and the mixing cell model do not adequately account for the spatial distribution of chemical inputs to the groundwater. In addition, the vertical MOC model and the mixing cell model rely on the areal MOC model to define the zone of contribution of Waiawa Shaft. Thus, for the long-term predictive simulations, only the areal MOC model was used. Groundwater pumping rates from existing wells within the areal MOC grid were assumed to be 0.044, 0.088, and 0.044 m^3/s for the respective Pearl City Wells I (2458-03, -04), Pearl City Wells II (2457-01 to -03), and Pearl City Well III (2457-03). These pumping rates are representative of existing pumping rates at each well site and were held constant for all simulations. Pumpage at Waiawa Shaft was assumed to be either 0.66 m^3/s (15 mgd) or 0.88 m^3/s (20 mgd). The former rate represents an average existing pumping rate at Waiawa Shaft which is likely to be maintained based on water allocations in the area. Existing groundwater heads are used as an initial condition. All simulations implicitly assume that the proposed developments are completed at time zero and do not contribute any contaminants prior to time zero.

Daily recharge estimates were supplied to PRZM by the water balance model described in chapter 5. Annual chemical input estimates to the areal MOC model were supplied by PRZM. Separate PRZM simulations were run for each of the water balance cells described in chapter 5 which contribute chemical input above the background level to the groundwater. All PRZM simulations covered a 37-yr period. The areal MOC grid was superimposed on the water balance grid (Fig. 38) to determine the relative contribution of each water balance cell to each MOC cell. The chemical loading input to a given MOC cell was computed as the recharge weighted average of the water balance cells occuring over that particular MOC cell.

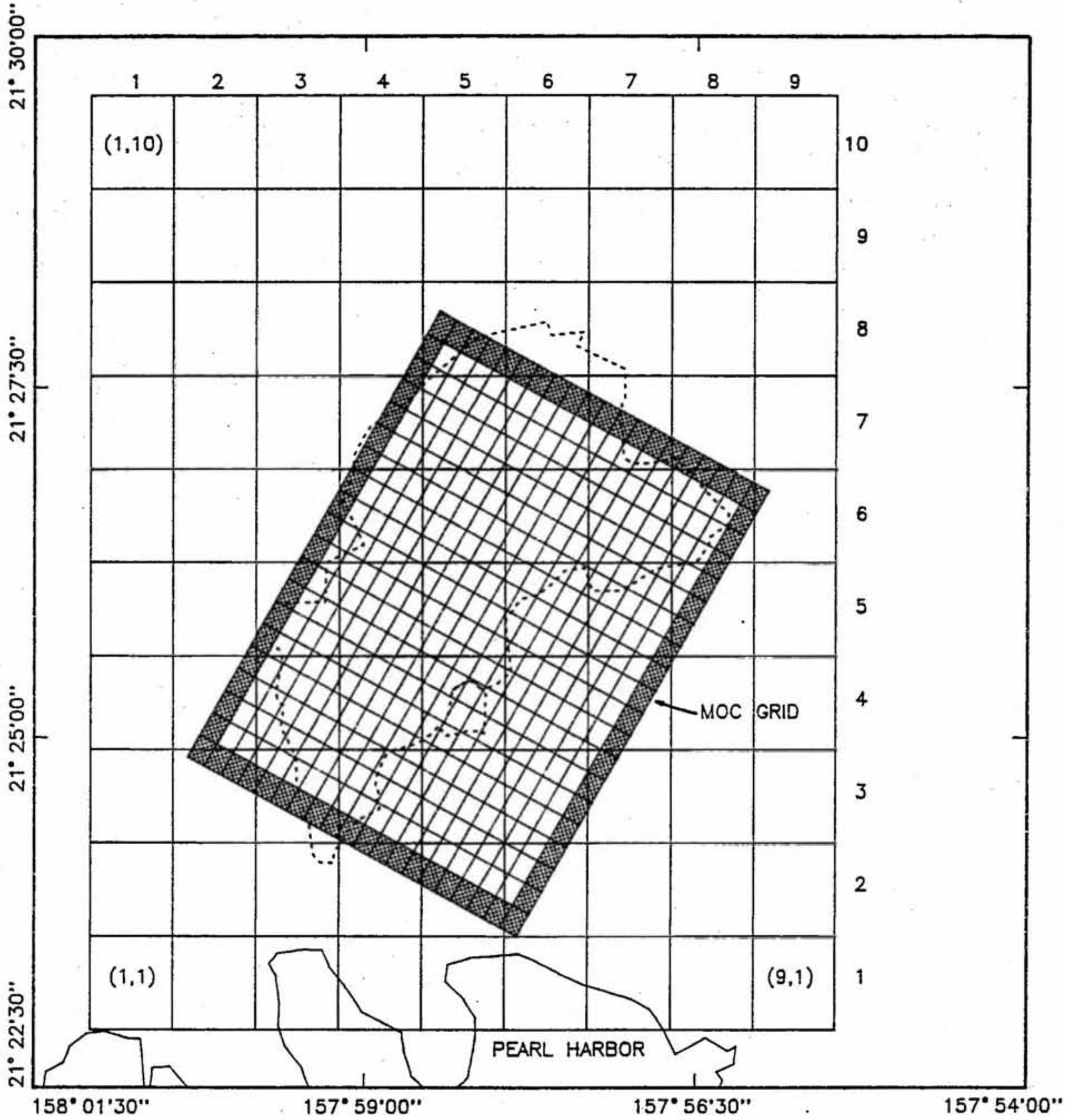


Figure 38. Areal MOC grid in relation to water balance grid

Three different chemicals were used as input to the groundwater model. Nitrogen is probably one of the most heavily applied chemicals on urban lawns and grassy areas. From a groundwater quality standpoint, the nitrate form of nitrogen, due to its mobility and high usage, is the most worrisome fertilizer component. Thus, nitrate-nitrogen was selected as a test chemical for long-term groundwater quality simulations and was assumed to be applied over golf courses as well as residential, apartment, and commercial land uses. The second chemical tested, metribuzin, is an herbicide associated with golf course use. The pesticide diazinon is one of the most common general use insecticides associated with residential areas and was the final chemical used in the long-term predictive simulations.

NITRATE SIMULATIONS

For golf course fairways in Hawaii, Murdoch and Green (1989) report six applications of nitrogen per year at a rate of about 73.25 kg/ha. If 3% of the applied nitrogen is available for leaching (Handley and Ekern 1981), an effective application rate of 2.20 kg/ha can be used as input to PRZM. Output from PRZM can then be scaled accordingly if greater fractions of the applied nitrogen are available for leaching. The nitrogen application rate determined from the house-to-house survey is about 155 kg/ha and is used for residential, apartment, and commercial areas with 60% of the population applying the fertilizer six times per year. Within the unsaturated and saturated zones, nitrate is assumed to be nonreactive so that no adsorption or degradation occurs.

The nitrate simulations can be separated into three groups. The first group of simulations assumes that Waiawa Ridge is developed and that the entire water balance cell overlying Waiawa Shaft possesses the vadose zone properties of the ridge. Thus, the proposed Waiawa Valley development is basically ignored in order to isolate the effects of the proposed Waiawa Gentry development. In the second group of simulations, the water balance cell overlying Waiawa Shaft is separated into two parts, with one part representing the proposed USN Waiawa Valley development (covering just three of the MOC cells) and the remaining portion representing the ridge areas. In the second group of simulations, the effects of the Waiawa Valley development are isolated by assuming an open or vacant land use for Waiawa Ridge which is representative of the current land use there.

In the third group of simulations, both Waiawa Ridge and Waiawa Valley are assumed to be developed. In all simulations, nitrate loading to the groundwater from existing urban areas near the Waiawa area was taken into consideration. The same nitrate loading from existing urban areas was maintained for all groundwater simulations. Recharge from areas unaffected by man was assumed to have a constant natural background nitrate concentration of 0.25 mg/l (as nitrogen) (Visher and Mink 1964). This background level was added to the groundwater loading from urban and golf course areas and was also used as an initial condition throughout the aquifer.

Each of the three groups of simulations described above can be further divided according to the assumed recharge scenario, recharge distribution depth, and groundwater pumping rates. In addition, simulations were conducted by assuming either 3, 15, or 30% of the applied nitrogen to be available for leaching. A summary of the long-term groundwater simulations is provided in Table 20. Minimum, maximum, and average concentrations presented in Table 20 are valid for the final 20 years of the 37-yr simulation to allow for adequate leaching of the chemical.

In all simulations, nitrate concentrations remain below the drinking water standard of 10 mg/l, and in fact do not exceed 5 mg/l even under conditions conducive to leaching. Nitrate analyses of groundwater samples from wells and shafts on Oahu (Giambelluca, Leung, and Konda 1987; Hufen, Eyre, and McConachie 1980; Swain 1973; Tenorio, Young, and Whitehead 1969) indicate that nitrate concentrations in urban and agricultural areas may reach about 1.7 and 3.5 mg/l, respectively. Thus, the simulated concentrations (Table 20) are reasonable. Each of the nitrate simulations is described in the paragraphs below.

Nitrate Simulations 1-9. Nitrate simulations 1 to 9 were designed to isolate the impact of the proposed Waiawa Ridge development under an average groundwater pumping rate of 0.66 m^3/s (15 mgd) at Waiawa Shaft.

Simulations 1, 2, and 3 represent recharge scenario 1 using the unsaturated zone profile 3 for Waiawa Ridge assuming 3, 15, and 30%, respectively, of the applied nitrogen to be available for leaching. Recall that recharge scenario 1 assumes an irrigated lawn condition without runoff

TABLE 20. SUMMARY OF SIMULATED NITRATE CONCENTRATIONS AT WAIAWA SHAFT

SIM.	PUMPAGE (m^3/s)	---------RECHARGE--------- Scenario	Distrib. Depth	PROFILE	% AVAIL. FOR LEACHING	----CONC. (mg/l) ---- Min.	Max.	Avg.
1	0.66	1	water table	3	3	0.5	0.7	0.6
2	0.66	1	water table	3	15	1.6	2.5	2.0
3	0.66	1	water table	3	30	3.0	4.8	3.7
4	0.66	2	water table	2	3	0.4	0.5	0.5
5	0.66	2	water table	2	15	0.9	1.6	1.4
6	0.66	2	water table	2	30	1.6	2.9	2.5
7	0.66	2	5 m	2	3	0.3	0.5	0.5
8	0.66	2	5 m	2	15	0.7	1.6	1.4
9	0.66	2	5 m	2	30	1.1	2.9	2.5
10	0.88	1	water table	3	3	0.5	0.7	0.6
11	0.88	1	water table	3	15	1.7	2.6	2.0
12	0.88	1	water table	3	30	3.2	4.9	3.8
13	0.88	2	water table	2	3	0.4	0.5	0.5
14	0.88	2	water table	2	15	1.0	1.6	1.4
15	0.88	2	water table	2	30	1.7	3.0	2.6
16	0.88	2	5 m	2	3	0.3	0.5	0.5
17	0.88	2	5 m	2	15	0.7	1.6	1.4
18	0.88	2	5 m	2	30	1.1	2.9	2.5
19	0.66	3	water table	3	3	0.3	0.3	0.3
20	0.66	3	water table	3	15	0.4	0.5	0.4
21	0.66	3	water table	3	30	0.5	0.7	0.6
22	0.66	4	water table	2	3	0.3	0.3	0.3
23	0.66	4	water table	2	15	0.3	0.4	0.4
24	0.66	4	water table	2	30	0.4	0.6	0.5
25	0.66	4	5 m	2	3	0.3	0.3	0.3
26	0.66	4	5 m	2	15	0.3	0.4	0.4
27	0.66	4	5 m	2	30	0.4	0.6	0.5
28	0.66	1	water table	3	3	0.5	0.7	0.6
29	0.66	1	water table	3	15	1.6	2.5	2.0
30	0.66	1	water table	3	30	3.0	4.8	3.8
31	0.66	2	water table	2	3	0.4	0.5	0.5
32	0.66	2	water table	2	15	0.9	1.6	1.4
33	0.66	2	water table	2	30	1.6	2.9	2.5
34	0.66	2	5 m	2	3	0.3	0.5	0.5
35	0.66	2	5 m	2	15	0.7	1.5	1.4
36	0.66	2	5 m	2	30	1.1	2.8	2.5

NOTE: Simulations 1-9 represent development of only Waiawa Ridge while simulations 28-36 represent development of both Waiawa Ridge and Waiawa Valley.

for all urban areas, including golf courses, on Waiawa Ridge. Under this scenario, all urban areas are assumed to be 100% pervious and receive the same nitrogen loading as the golf course areas. The 37-yr time series of nitrate concentrations pumped by Waiawa Shaft are presented in Figure 39 for simulations 1, 2, and 3. Even if 30% of the applied nitrogen is available for leaching, nitrate concentrations at Waiawa Shaft do not exceed the health standard of 10 mg/l as nitrogen. After the initial contamination period when applied nitrate begins to enter the groundwater, concentrations remain relatively stable reflecting the high frequency of fertilizer applications which creates a nearly steady loading to the groundwater.

Inspection of U.S. Geological Survey files reveals concentrations of about 1 to 2 mg/l nitrate (as nitrogen) in water pumped by Waiawa Shaft during the 1970s when sugarcane was being cultivated on Waiawa Ridge. Sugarcane crops generally require 18 to 24 mo for maturity and are given a total of four nitrogen applications at a rate of about 85 kg/ha (75 lb/acre) per application during the first eight months (Tenorio, Young, and Whitehead 1969). Over a two-yr period, a total of 340 kg/ha nitrogen is applied to sugarcane crops. Using lysimeters and sugarcane, Lau et al. (1975) collected between 15 and 23% of the applied nitrogen in the leachate. If 20% of the applied nitrogen is available for leaching beneath sugarcane crops, a total of 68 kg/ha is expected to leach over a two-yr period. Under the simulated conditions, 12 applications occur over a two-yr period yielding a total nitrogen loading of 880 kg/ha for that period. If the simulated loading rates are to be comparable to the sugarcane loading rates, the simulations should be conducted under the assumption that about 8% of the applied nitrogen is available for leaching. Interpolating between the 3 and 15% lines shown in Figure 39 yields nitrate concentrations between 1 to 2 mg/l which is consistent with the concentrations found during the period of sugarcane cultivation.

Simulations 4, 5, and 6 utilize unsaturated zone profile 2 in conjunction with recharge scenario 2, which corresponds to the distributed land use case in which the proposed Waiawa Ridge development is discretized into golf course, residential, apartment, commercial/industrial, and open land uses. Note that for nitrate, the choice of unsaturated zone

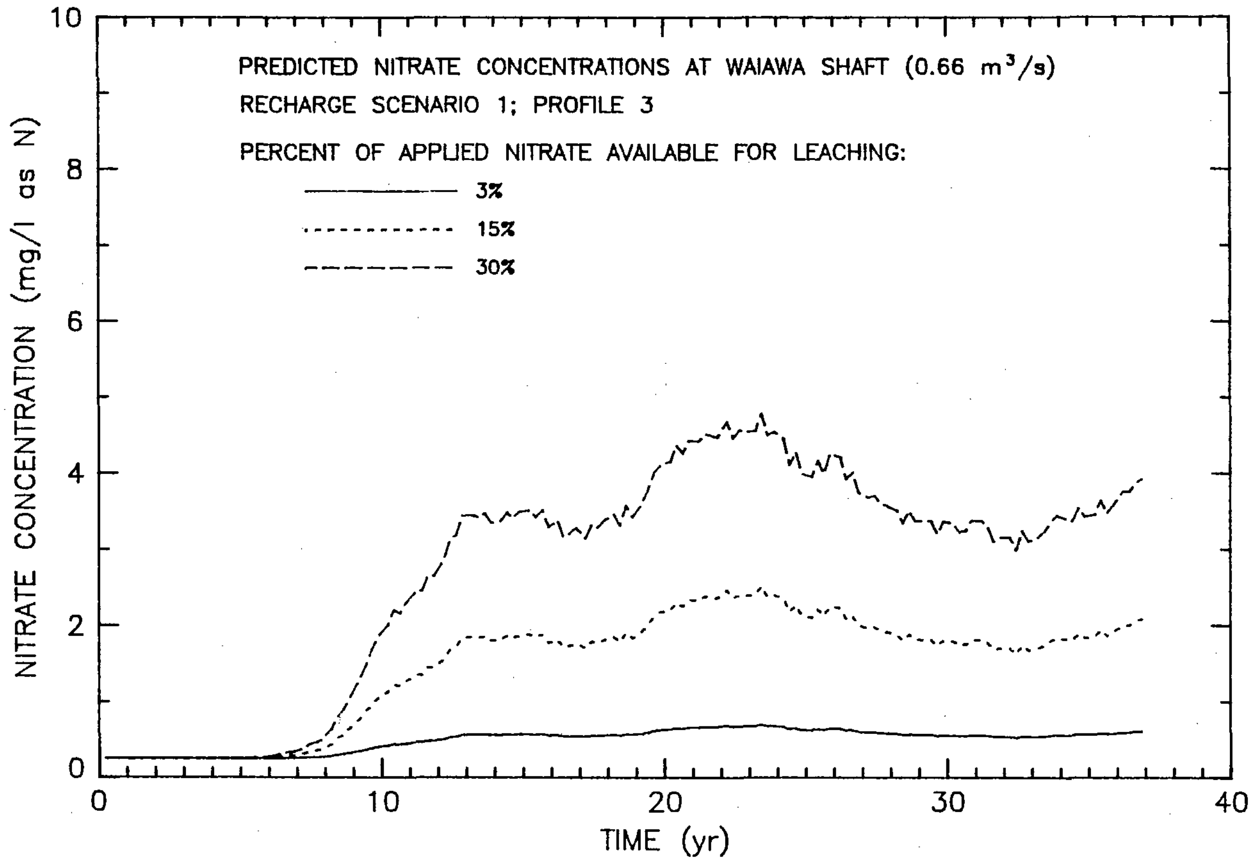


Figure 39. Nitrate simulations 1, 2, and 3, Waiawa Shaft, Oahu, Hawaii

profile is relatively unimportant since the chemical is assumed to be conservative. Beneath urban areas on Waiawa Ridge, recharge is assumed to move vertically downward beneath the pervious areas without lateral spreading of the wetting front. Thus, for the PRZM simulations, recharge is concentrated over the pervious areas. For the groundwater simulations, recharge is subsequently spread laterally at the water table so that a uniform input to the groundwater is obtained throughout the entire area of the water balance cell. The simulated 37-yr nitrate time series at Waiawa Shaft are presented in Figure 40 for simulations 4, 5, and 6 which assume 3, 15, and 30%, respectively, of applied nitrogen available for leaching. Concentrations presented in Figure 40 are lower than concentrations for simulations 1 to 3 since in the distributed land use scenario only pervious areas may contribute nitrate. If lawns and grassy areas are as efficient as California grass at removing nitrogen, only 3% of the applied nitrogen is expected to be available for leaching (Handley and Ekern 1981) so that resulting concentrations at Waiawa Shaft are barely above the natural background level of about 0.25 mg/l.

Simulations 7, 8, and 9 also utilize recharge scenario 2 with unsaturated zone profile 2. The PRZM simulations, however, were carried out by assuming recharge beneath the pervious areas to move vertically downward only to a depth of 5 m. At that depth the occurrence of saprolite material may result in a perched water condition. To account for this phenomenon, recharge beneath pervious areas was allowed to spread laterally throughout the entire area of the water balance cell at a depth of 5 m. The distributed recharge for each urban water balance cell was then used below a depth of 5 m in the PRZM simulations. Note that this condition was used for all existing urban areas in the vicinity of the Waiawa area for all of the nitrate simulations. The simulated 37-yr nitrate time series at Waiawa Shaft are presented in Figure 41 for simulations 7, 8, and 9 which assume 3, 15, and 30%, respectively, of applied nitrogen available for leaching. Note that the resulting concentrations at Waiawa Shaft are similar to those in Figure 40 since the same loading rates are used. However, the applied nitrogen reaches the shaft much later since the recharge from the pervious areas is dispersed (reduced) at a depth of 5 m below the ground surface.

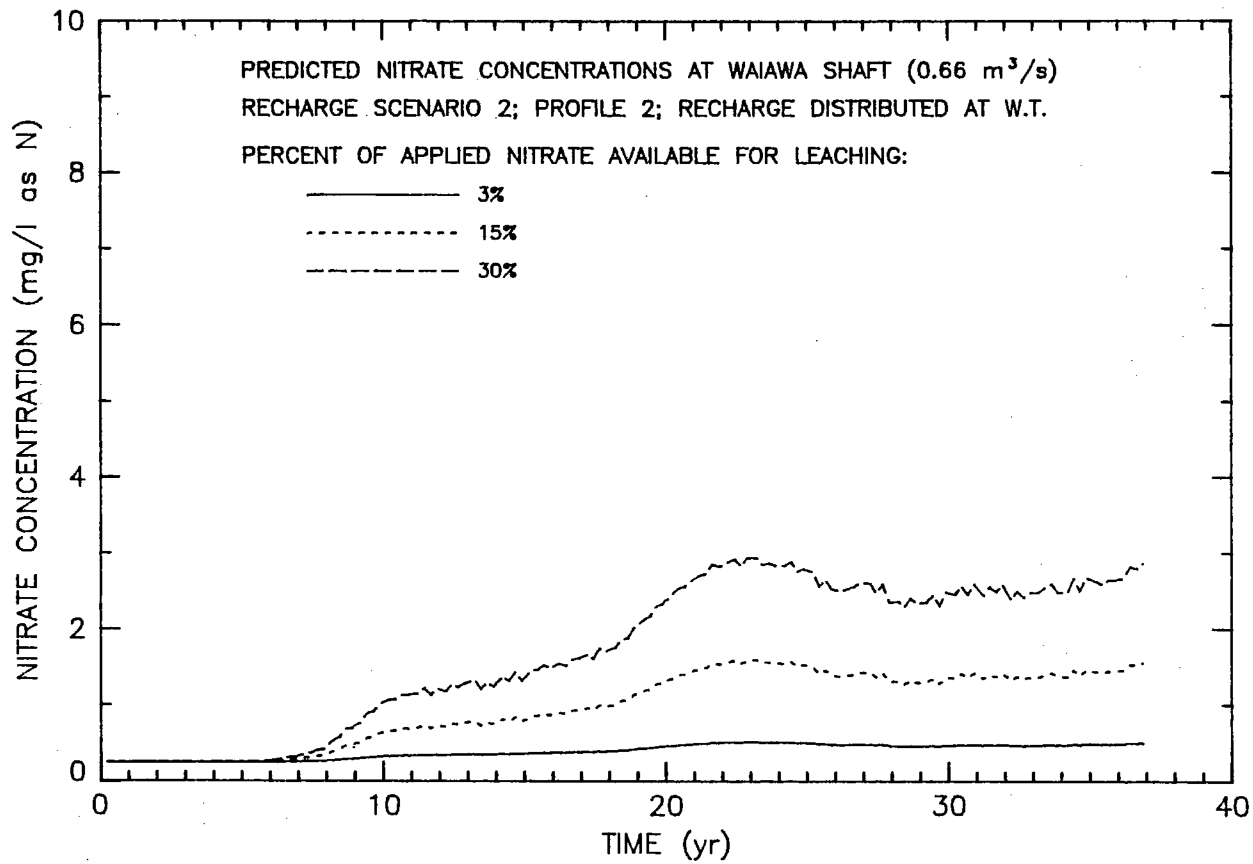


Figure 40. Nitrate simulations 4, 5, and 6, Waiawa Shaft, Oahu, Hawaii

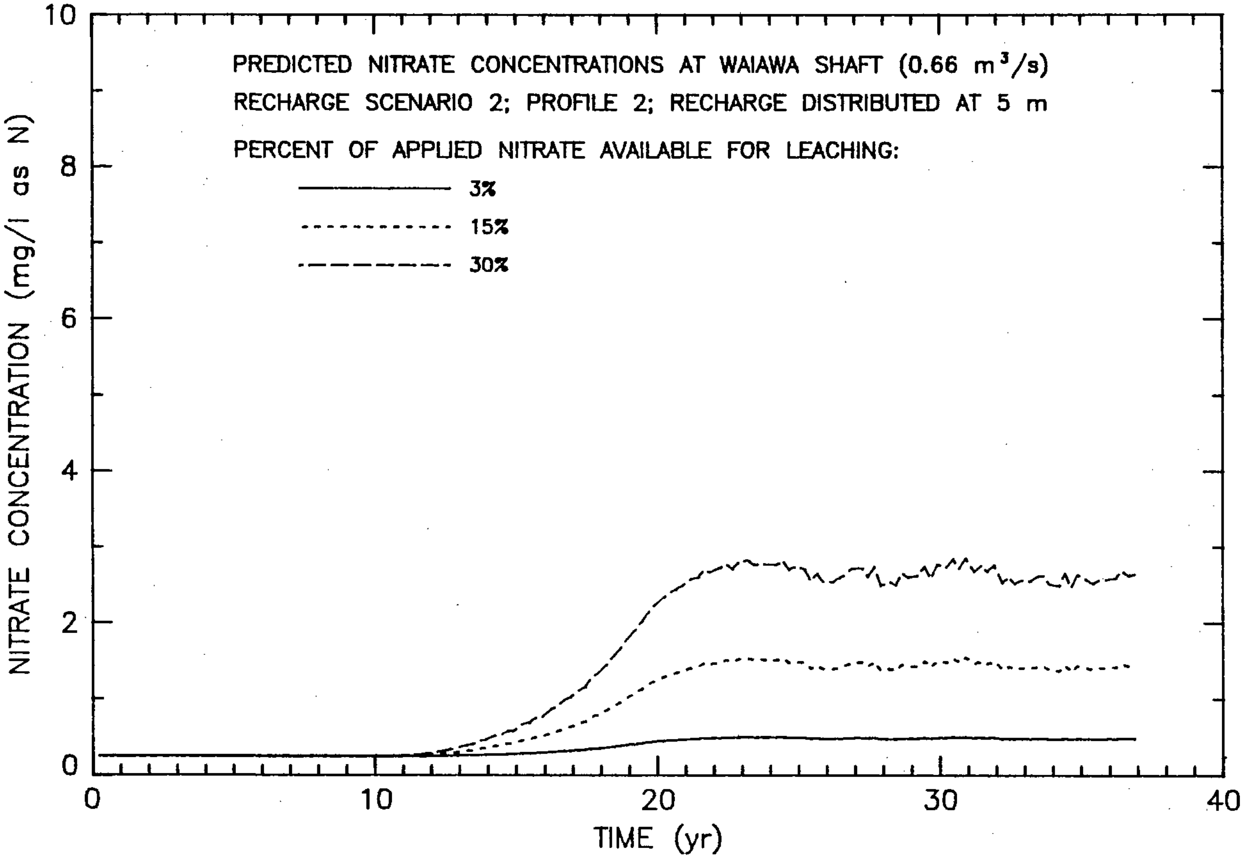


Figure 41. Nitrate simulations 7, 8, and 9, Waiawa Shaft, Oahu, Hawaii

Nitrate Simulations 10-18. Nitrate simulations 10 to 12, 13 to 15, and 16 to 18 are similar to simulations 1 to 3, 4 to 6, and 7 to 9, respectively, with the only change being that pumpage at Waiawa Shaft was increased to 0.88 m^3/s (20 mgd). Note that the same calibrated areal MOC model was used for the higher pumping condition. At higher pumping rates the depth of contribution of Waiawa Shaft should increase, thus resulting in a greater amount of deeper, fresh water entering the shaft. Due to a lack of calibration data at the higher pumping rate, however, the same model calibrated at a typical pumping rate of 0.66 m^3/s (15 mgd) was used for simulations 10 to 18 at a pumping rate of 0.88 m^3/s (20 mgd). This scenario thus represents a condition in which the horizontal zone of contribution of Waiawa Shaft increases to include a greater portion of the proposed development without a corresponding increase in the depth of contribution. The resulting nitrate time series for simulations 10 to 12, 13 to 15, and 16 to 18 are presented respectively in Figures 42, 43, and 44. The simulated time series at a pumping rate of 0.88 m^3/s are similar to the time series at a pumping rate of 0.66 m^3/s. The concentrations at the higher pumping rate, however, are slightly higher as expected.

Nitrate Simulations 19-27. Simulations 19 to 27 assume that Waiawa Ridge remains vacant and that the USN Waiawa Valley property is developed. The Waiawa Valley development is represented by three cells of the areal MOC grid (Fig. 45). A small aquifer exists in the alluvium beneath the valley floor and is assumed to be hydrologically connected to the basal aquifer. The extent to which water in the alluvium enters the basal aquifer through the weathered basalt is unknown. Based on the relative permeabilities of the alluvium and weathered basalt, it is conceivable that the majority of the water is held within the confines of the weathered basalt until it escapes at downgradient discharge points beyond the zone of contribution of Waiawa Shaft. For the current investigation, however, interflow between the alluvial groundwater body and the basal aquifer is assumed to be unimpeded. Recharge from the valley floor is assumed to be undiluted by the pre-existing water stored in the alluvium. Under long-term chemical inputs to the alluvial aquifer, a relatively steady groundwater concentration should ultimately be attained. Thus, by assuming no dilution with pre-existing water in storage, this

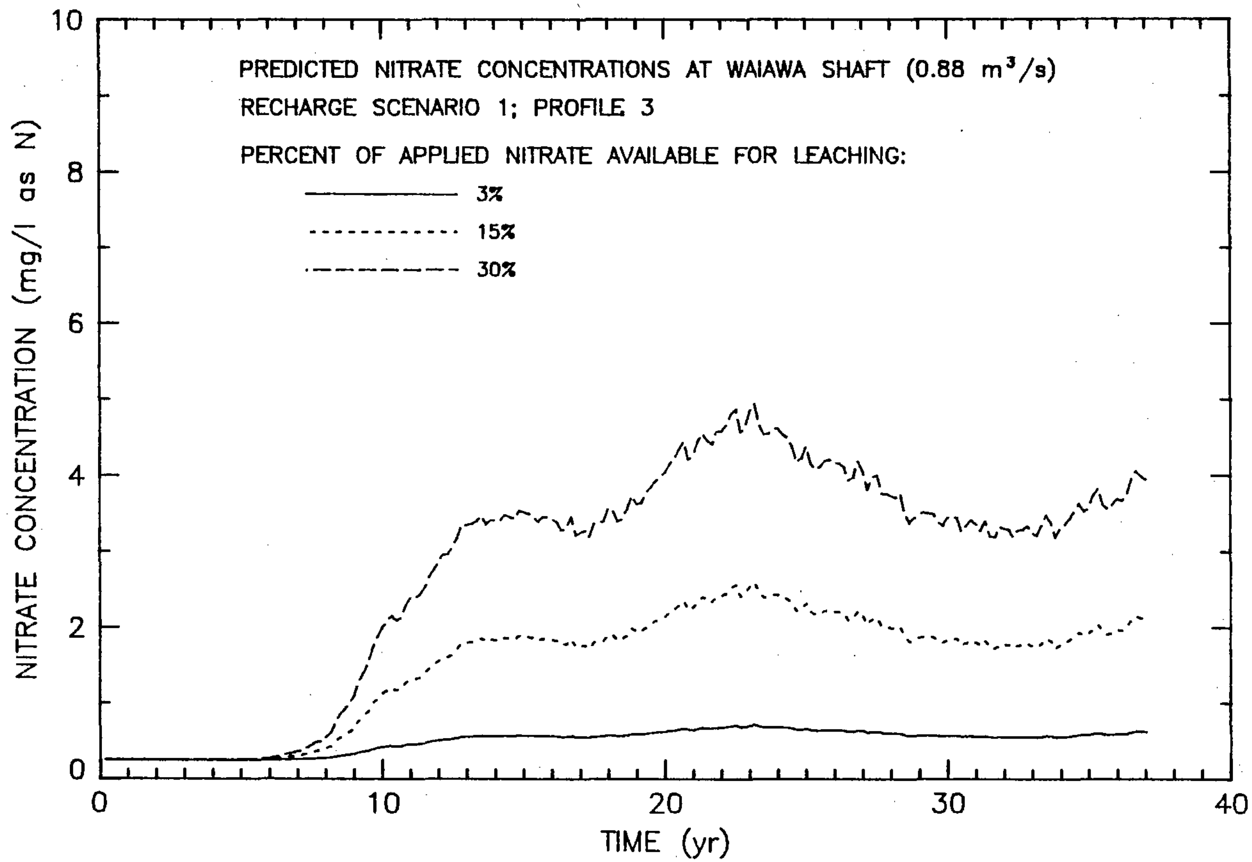


Figure 42. Nitrate simulations 10, 11, and 12, Waiawa Shaft, Oahu, Hawaii

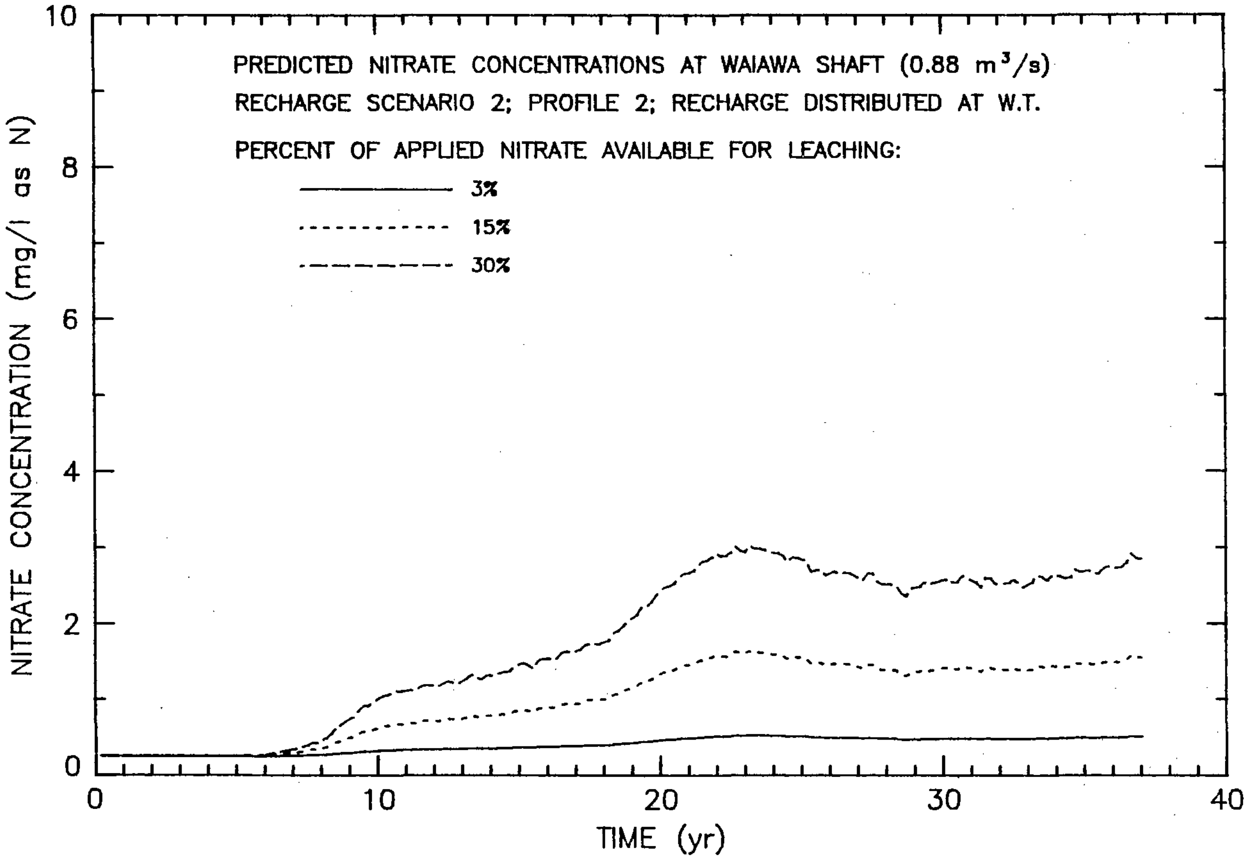


Figure 43. Nitrate simulations 13, 14, and 15, Waiawa Shaft, Oahu, Hawaii

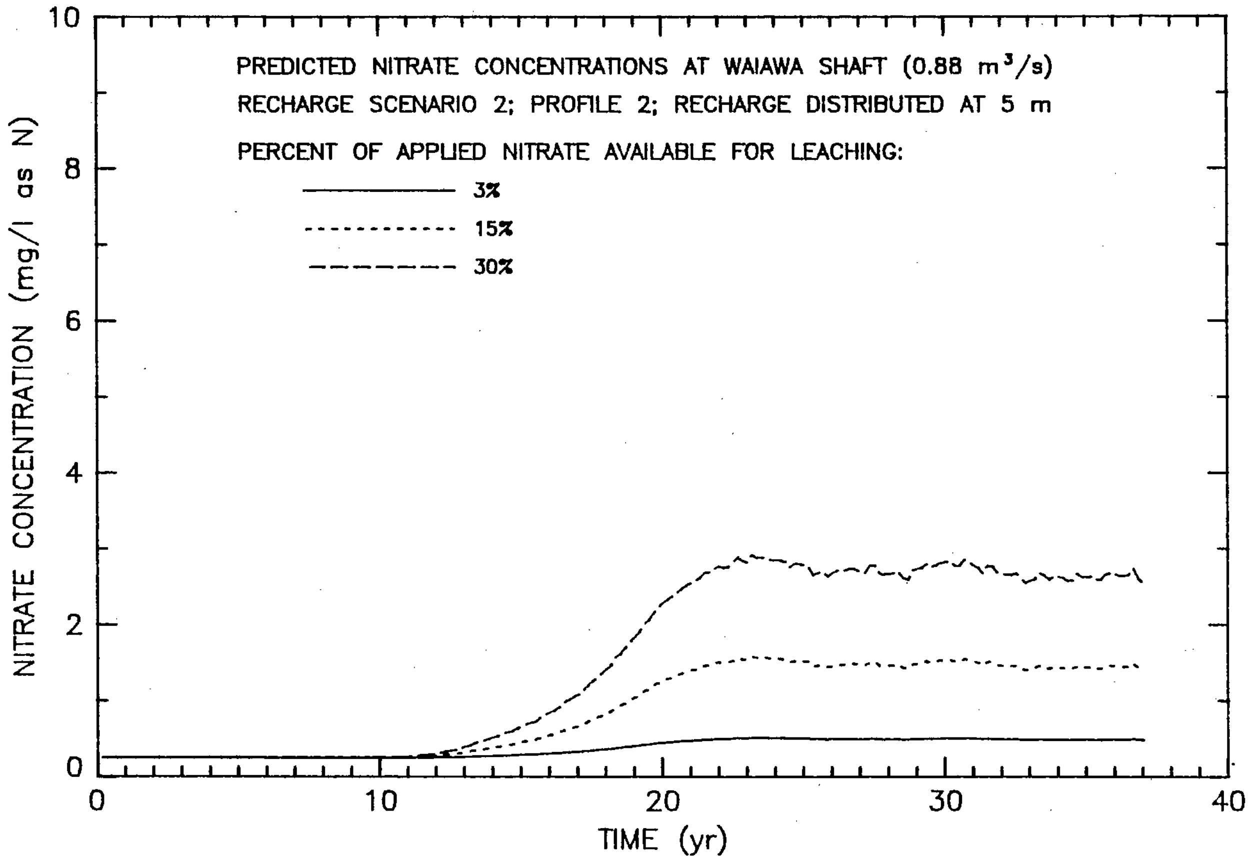


Figure 44. Nitrate simulations 16, 17, and 18, Waiawa Shaft, Oahu, Hawaii

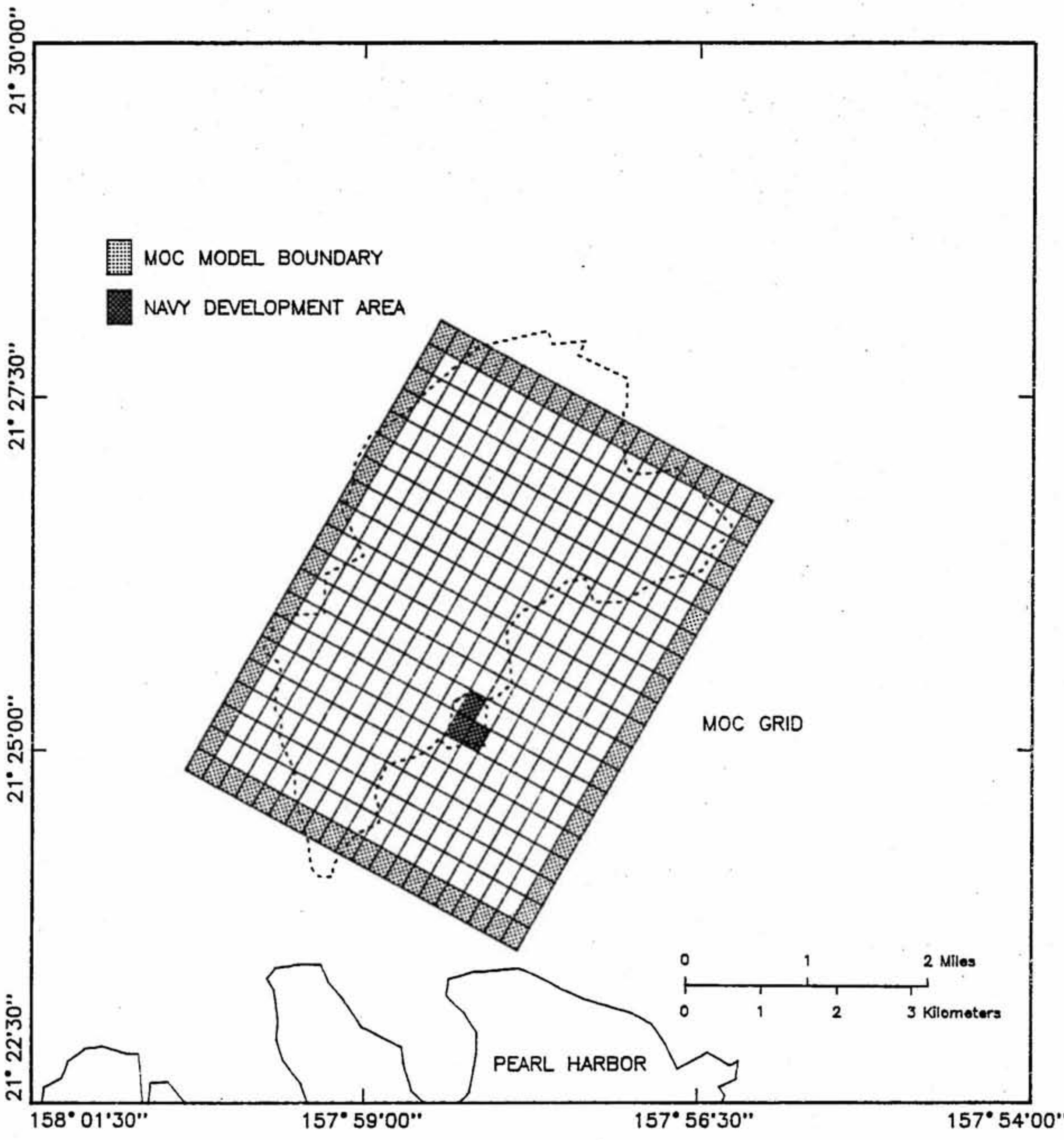


Figure 45. U.S. Navy Waiawa Valley development area in relation to MOC grid

steady state condition is assumed to be rapidly attained. Note that for simulations 19 to 27, as with simulations 1 to 18, nitrate loading from existing urban areas is based on unsaturated zone profile 2 with recharge distributed at a depth of 5 m beneath the ground surface.

Based on the assumptions described above, the simulated chemical travel time through the unsaturated zone to the perched water body and then to the basal aquifer is probably much shorter than expected. Since leached nitrate is relatively nonreactive, however, the simulated time series provide a reasonable estimate of the long-term effects of the proposed USN development on the quality of water pumped by Waiawa Shaft if the alluvial aquifer is hydrologically connected to the basal aquifer.

Simulations 19 to 21 represent the case of treating the entire Waiawa Valley development as an irrigated lawn which receives the same chemical input as a golf course but has no runoff. Results of the groundwater simulations under recharge scenario 3 in conjunction with unsaturated zone profile 3 for Waiawa Valley are presented in Figure 46. Even in the case where 30% of the applied nitrogen is available for leaching, nitrate levels at Waiawa Shaft remain well below 1 mg/l. The low concentrations reflect the relatively small loading to the basal aquifer from the proposed USN development.

Simulations 22 to 24 and 25 to 27 were conducted with recharge scenario 4 in which the USN development is treated as a residential area. Simulations 22 to 24 assume that recharge is distributed at the perched water table, whereas simulations 25 to 27 assume that recharge is distributed at a depth of 5 m beneath the ground surface. The nitrate time series for simulations 22 to 24 and 25 to 27 are presented in Figures 47 and 48, respectively. The concentrations presented in Figures 47 and 48 are similar. However, the applied nitrate reaches Waiawa Shaft later in Figure 48 than in Figure 47 due to the assumption that recharge is distributed at a depth of 5 m. All nitrate levels remain well below 1 mg/l due to the limited extent of the nitrate loading.

Nitrate Simulations 28-36. Simulations 28 to 36 assume that both Waiawa Ridge and the USN Waiawa Valley property are developed. The water balance cell overlying Waiawa Shaft (cell [5,4]) is separated into two parts, with one part representing the proposed Waiawa Valley development

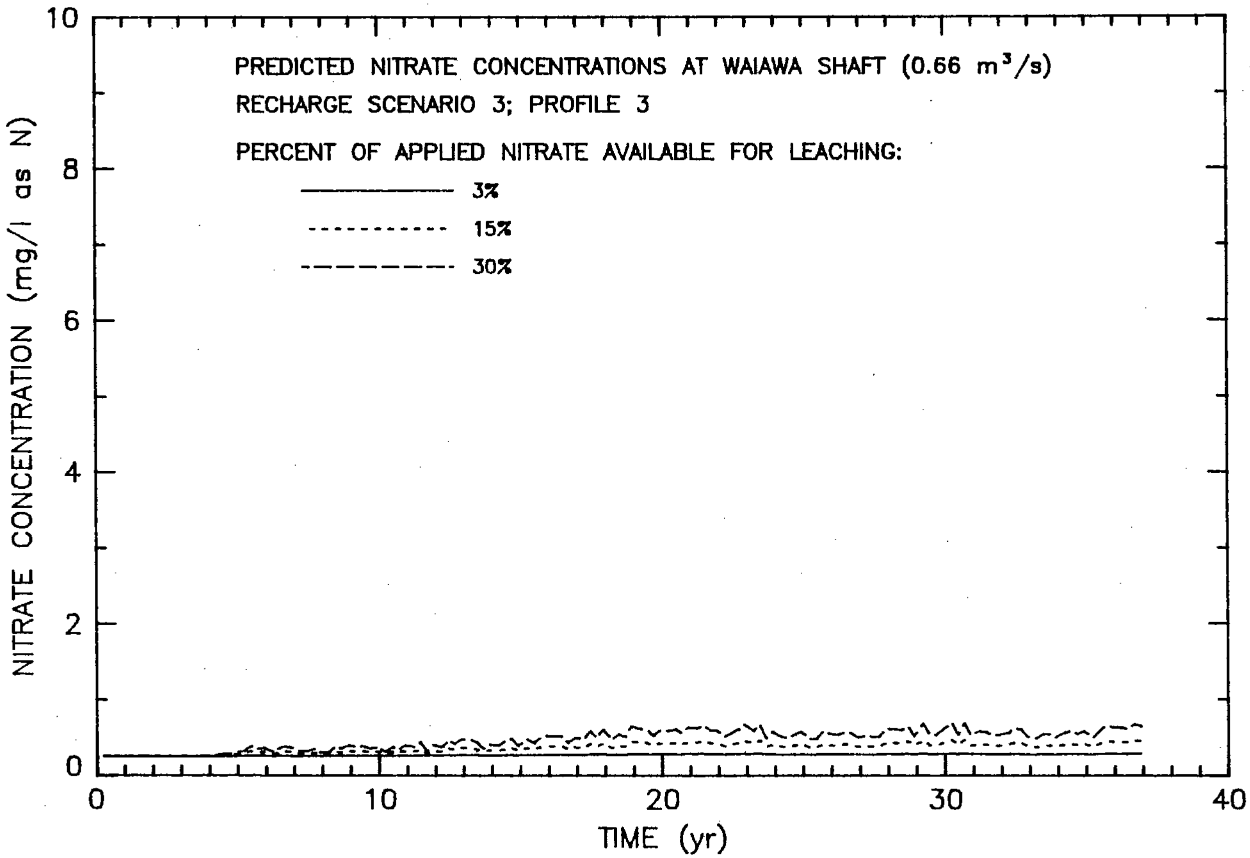


Figure 46. Nitrate simulations 19, 20, and 21, Waiawa Shaft, Oahu, Hawaii

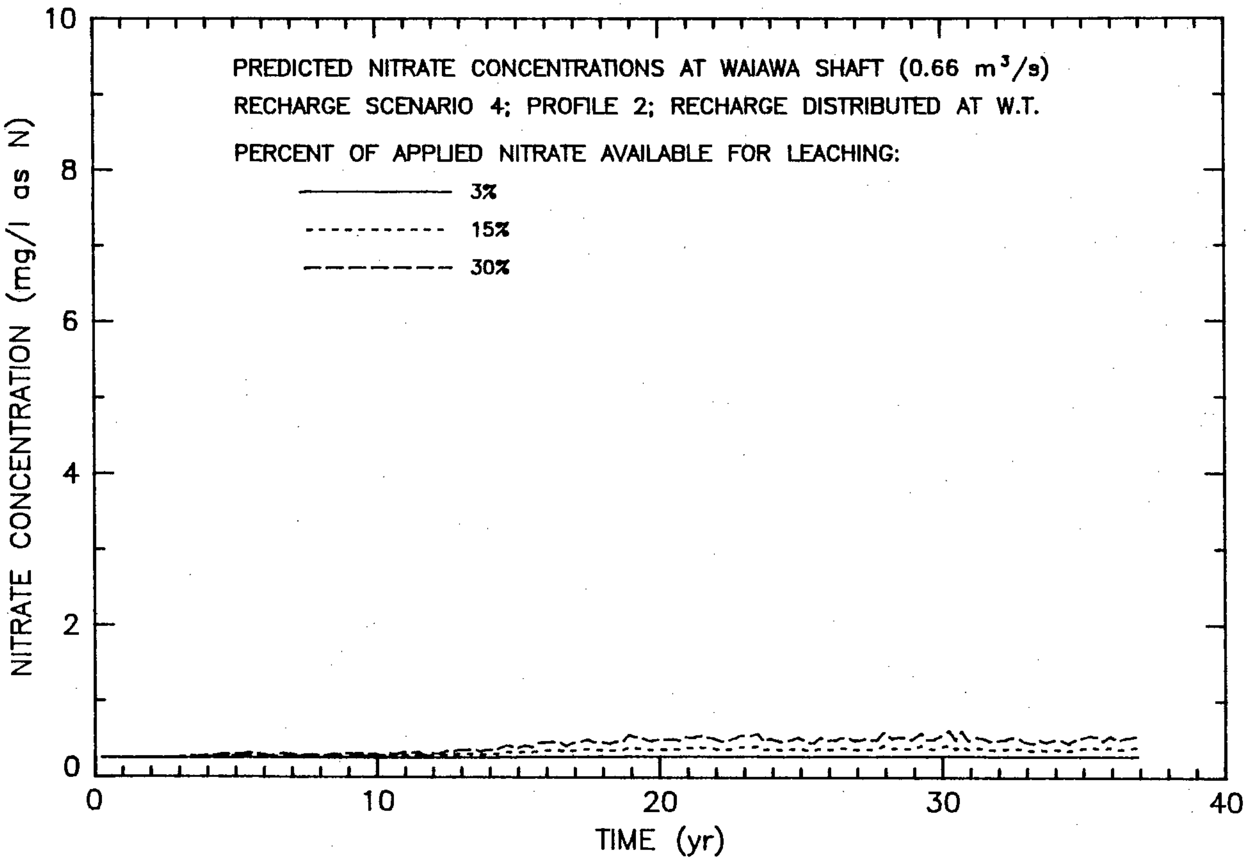


Figure 47. Nitrate simulations 22, 23, and 24, Waiawa Shaft, Oahu, Hawaii

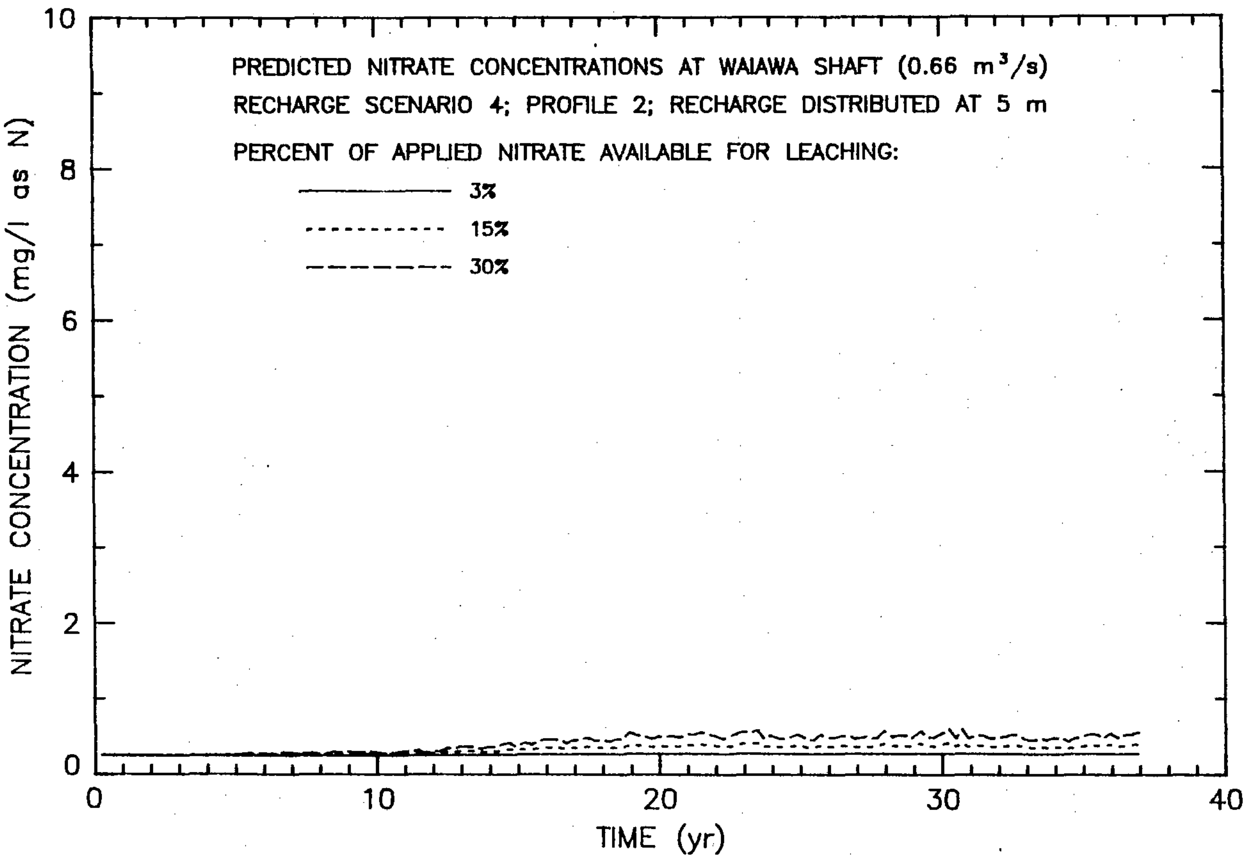


Figure 48. Nitrate simulations 25, 26, and 27, Waiawa Shaft, Oahu, Hawaii

(covering three cells of the areal MOC grid) and the remaining portion being assigned to the proposed Waiawa Ridge development. Since they occur within the same water balance cell, the Waiawa Valley development and a portion of the Waiawa Ridge development have the same recharge pattern. However, because of the elevation difference between the valley and the ridge, chemical travel times through the unsaturated zone will differ. As with nitrate simulations 19 to 27, interflow between the alluvial groundwater body and the basal aquifer is assumed to be unimpeded. Recharge from the valley floor is assumed to be undiluted by the pre-existing water stored in the alluvial aquifer. Note that nitrate loading from existing urban areas is based on unsaturated zone profile 2 with recharge distributed at a depth of 5 m beneath the ground surface.

Comparison of simulations 28 to 36 with simulations 1 to 9 (Table 20) reveals that concentrations resulting from simulations employing similar parameters are nearly identical. Thus, it is apparent that simulations 28 to 36 are dominated by the effects of nitrate loading from the Waiawa Ridge development, with the Waiawa Valley development contributing relatively little nitrate to the shaft output. This result is expected since the proposed Waiawa Ridge development is considerably larger than the proposed USN development and will thus contribute significantly more nitrate. Furthermore, because nitrate is relatively conservative once beneath the root zone, the shorter travel time through the unsaturated zone associated with the Waiawa Valley development will not result in higher concentrations to the groundwater relative to the Waiawa Ridge nitrate inputs.

All factors being equal, nitrate concentrations at Waiawa Shaft are expected to be higher if both Waiawa Ridge and Waiawa Valley are developed rather than if just Waiawa Ridge is developed. Thus, simulations 28 to 36 should have higher concentrations than their corresponding simulations employing similar parameters which assume development on Waiawa Ridge only (simulations 1-9). However, comparison of simulations 8 and 9 with simulations 35 and 36, respectively, indicates otherwise. This is due to two factors. Firstly, the entire area of water balance cell (5,4) was assigned to the Waiawa Ridge development in simulations 1 to 9, without subtracting the undeveloped area of the USN

Waiawa Valley property. Although simulations 1 to 9 appear to have the same land use distribution as simulations 28 to 36, the three MOC cells representing the USN Waiawa Valley property will have different elevations in the two sets of simulations. Thus, the second factor contributing to the discrepancy is related to the difference in travel times associated with the ridge and valley.

METRIBUZIN SIMULATIONS

Metribuzin, like the compounds atrazine and simazine which have been detected in Hawaii's groundwater as a result of sugarcane cultivation, is a triazine compound used as an herbicide. For the current study, metribuzin was assumed to be applied on the proposed golf course areas only. For each year of the 37-yr simulation period, it was assumed that the herbicide would be applied twice a year at a rate of 0.841 kg/ha. For the metribuzin groundwater simulations, output from PRZM using each of the three unsaturated zone profiles with recharge scenario 2 was tested. In addition, the impact of chemical application timing was tested using unsaturated zone profile 2 in conjunction with recharge scenario 2. Output generated by PRZM with unsaturated zone profile 3 and recharge scenario 5, which assumes no golf course runoff, was also tested. Each of the simulations mentioned above was conducted with and without decay of metribuzin below the soil layer. A hydrolysis half-life of 1 yr in the groundwater was assumed for those simulations which included decay below the soil. For all simulations, existing background concentrations of metribuzin were assumed to be zero throughout the aquifer, and pumpage from Waiawa Shaft was assumed to be steady at 0.66 m^3/s (15 mgd). A summary of the conditions used in each simulation along with minimum, maximum, and average concentrations for the final 15 years of each simulation is presented in Table 21. Each of the simulations is discussed below. It should be noted that all simulated metribuzin concentrations remain below the EPA's drinking water lifetime health advisory of 200 μg/l (U.S. Environmental Protection Agency 1988b). Unfortunately, there have been no known analyses for metribuzin in groundwater samples on Oahu which would help verify the simulated concentrations.

Metribuzin Simulations 1-6. Metribuzin simulations 1 to 3 were designed to test the impact of the golf course unsaturated zone profile on

TABLE 21. SUMMARY OF SIMULATED METRIBUZIN CONCENTRATIONS AT WAIAWA SHAFT

SIM.	RECHARGE SCENARIO	PROFILE	APPLICATION TIMING	HYDROLYSIS HALF-LIFE	----CONC. (ng/l) ---- Min.	Max.	Avg.
1	2	1	Jan-Jul	1 year	<0.1	<0.1	<0.1
2	2	2	Jan-Jul	1 year	<0.1	<0.1	<0.1
3	2	3	Jan-Jul	1 year	0.4	1.8	1.0
4	2	1	Jan-Jul	infinite	2172.3	2832.2	2475.6
5	2	2	Jan-Jul	infinite	3033.6	3874.1	3408.6
6	2	3	Jan-Jul	infinite	3239.4	5015.0	4158.5
7	5	3	Jan-Jul	1 year	0.6	3.5	1.8
8	5	3	Jan-Jul	infinite	3074.0	5545.2	4282.1
9	2	2	Apr-Oct	1 year	<0.1	<0.1	<0.1
10	2	2	Apr-Oct	infinite	2728.4	3440.5	3034.4

the groundwater quality. Simulations 1 to 3 were carried out assuming a hydrolysis half-life of 1 yr in the intermediate vadose zone as well as in the groundwater. Simulations 4 to 6 were similar to simulations 1 to 3 except that no decay was assumed to occur in the intermediate vadose zone and in the saturated zone. Recharge scenario 2 was used for simulations 1 to 6. Results of groundwater simulations 1 to 3 and 4 to 6 are presented as metribuzin time series at Waiawa Shaft in Figures 49 and 50, respectively. If metribuzin is assumed to have a hydrolysis half-life of 1 yr (Fig. 49), metribuzin concentrations in water pumped by Waiawa Shaft remain below 2 ng/l. The effect of the unsaturated zone profile on the groundwater quality is evident as only profile 3 allows metribuzin to reach Waiawa Shaft at levels above 0.1 ng/l if a hydrolysis half-life of 1 yr is used. If metribuzin proves to be persistent in the intermediate vadose zone and groundwater, resulting concentrations at Waiawa Shaft increase significantly (Fig. 50). The impact of the soil layer properties is evident in Figure 50 in terms of the magnitude of the concentrations as well as the timing of the contamination.

Metribuzin Simulations 7-8. Metribuzin simulations 7 and 8 were designed to test the impact of increased recharge to golf course areas due

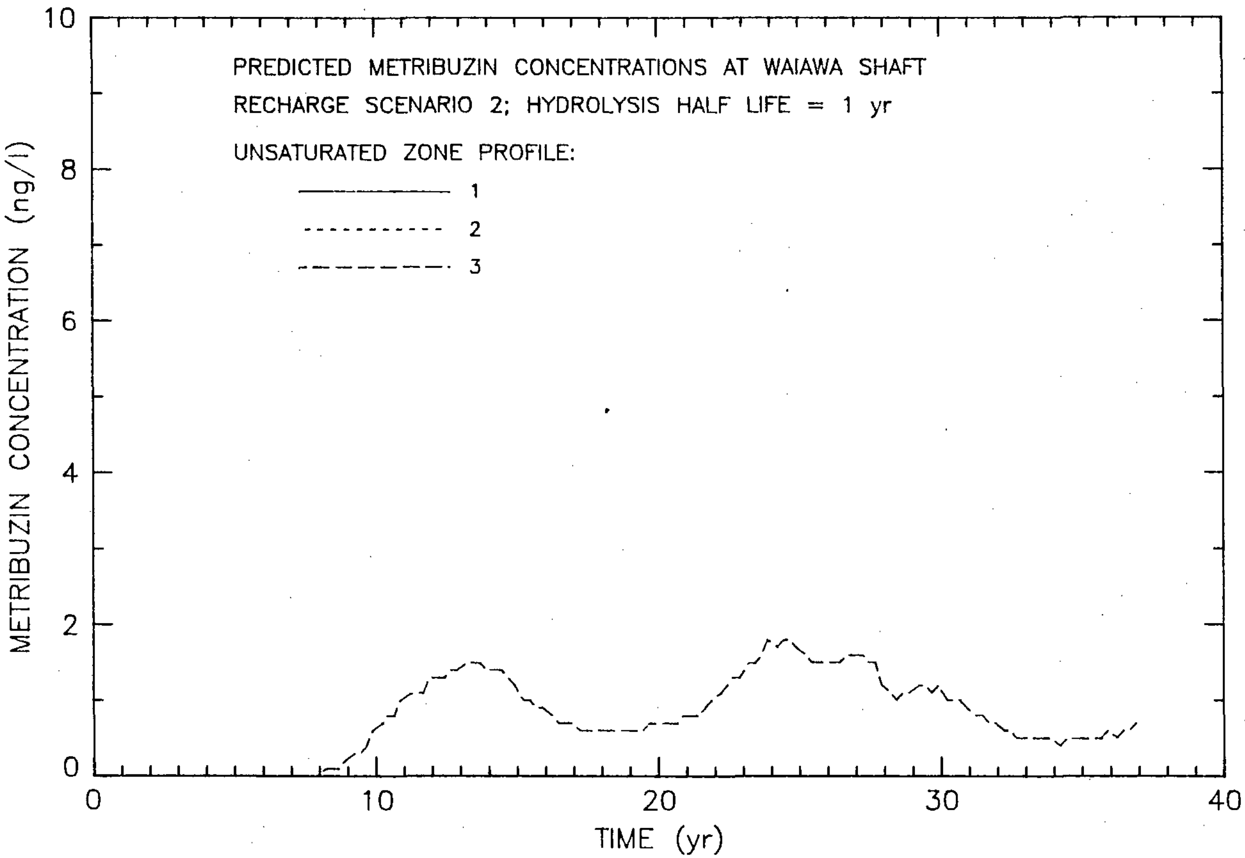


Figure 49. Metribuzin simulations 1, 2, and 3, Waiawa Shaft, Oahu, Hawaii

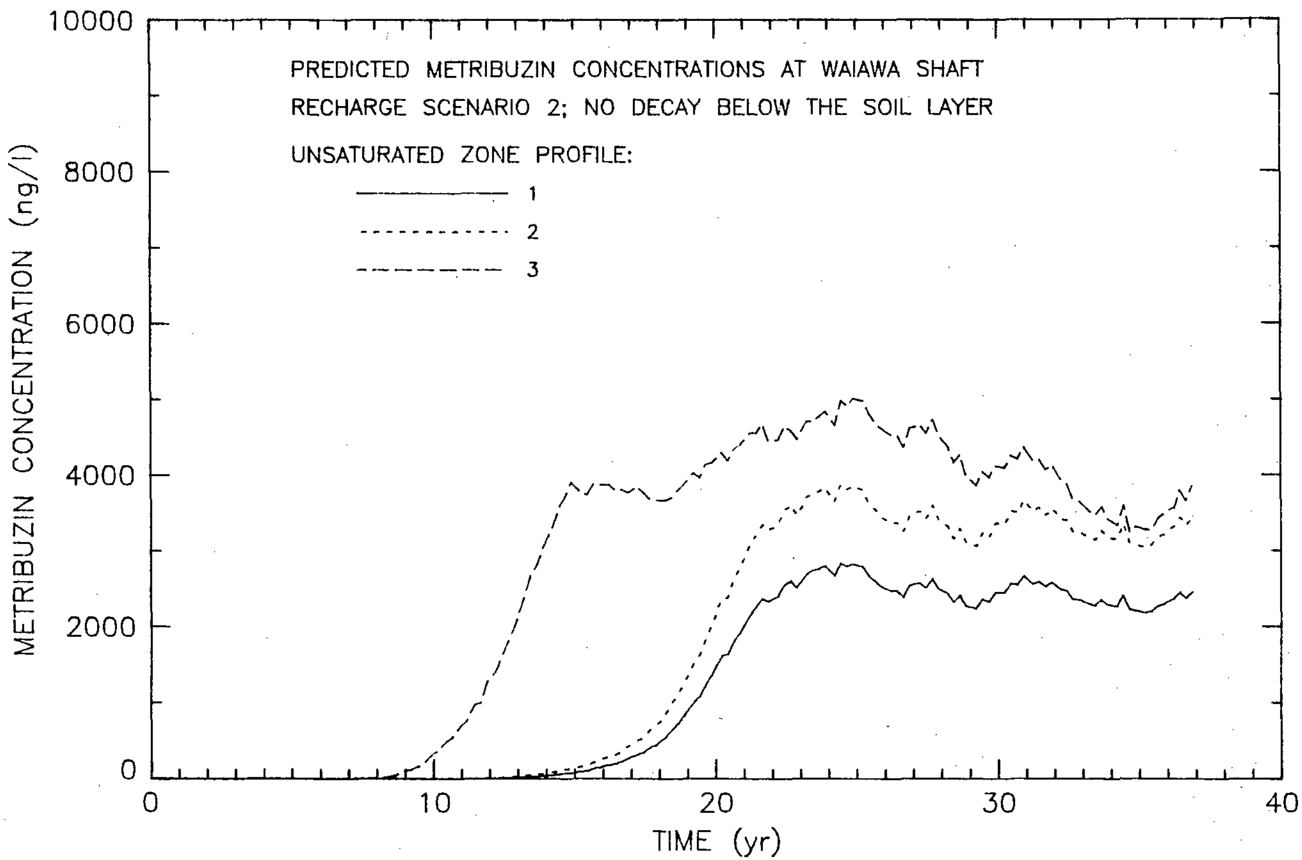


Figure 50. Metribuzin simulations 4, 5, and 6, Waiawa Shaft, Oahu, Hawaii

to the elimination of runoff. Simulations 7 and 8 also use PRZM output generated using unsaturated zone profile 3 for golf course areas. Figure 51 compares metribuzin simulations 3 and 7 which differ only in the assumed recharge scenario. Simulation 3 employs recharge scenario 2 which allows runoff from golf course areas, whereas simulation 7 uses recharge scenario 5 which assumes no runoff from golf course areas. As expected, increasing the recharge by eliminating runoff, results in greater transport of metribuzin to the groundwater. This manifests itself in the higher concentrations in water pumped by Waiawa Shaft (Fig. 51). Metribuzin simulations 3 and 7 assume a hydrolysis half-life of 1 yr. If hydrolysis is negligible, the metribuzin time series presented in Figure 52 might be representative of the groundwater impact. Figure 52 compares metribuzin simulations 6 and 8 which are analogous to the simulations presented in Figure 51. However simulations 6 and 8 assume that the chemical is persistent once it is below the soil layer. Without decay in the intermediate vadose zone and groundwater, metribuzin concentrations at Waiawa Shaft might increase significantly (Figs. 51, 52).

Metribuzin Simulations 9-10. Metribuzin predictions 9 and 10 were designed to test the impact of chemical application timing. In all golf course areas, metribuzin was assumed to be applied twice a year. In simulations 1 to 8, chemical applications occurred on the first day of the months of January and July throughout the 37-yr simulation period. Simulations 9 and 10 assumed the applications were shifted to the months of April and October. Both simulations utilize recharge scenario 2 in conjunction with unsaturated zone profile 2. Simulation 9 assumes a hydrolysis half-life of 1 yr below the soil layer whereas simulation 10 assumes no decay once the chemical leaches below the soil layer. Simulations 2 (presented above) and 9 differ only in the timing of the chemical applications. Both simulations assumed a hydrolysis half-life of 1 yr beneath the soil and resulted in extremely low concentrations (less than 0.1 ng/l) arriving at Waiawa Shaft. A comparison of simulations 5 and 10 reveals the impact of application timing if no decay occurs below the soil. The comparison, presented in Figure 53, reveals that the January-July applications result in slightly greater leaching.

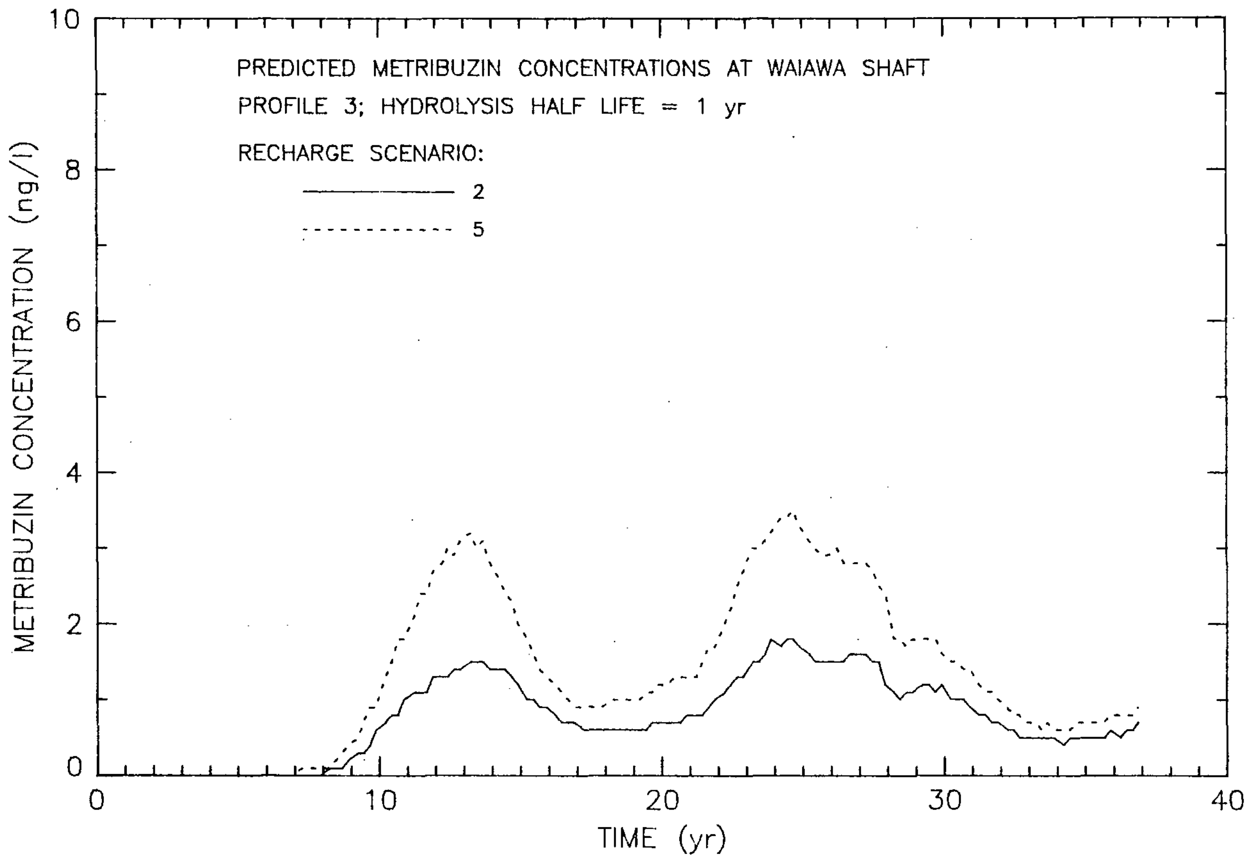


Figure 51. **Metribuzin simulations 3 and 7, Waiawa Shaft, Oahu, Hawaii**

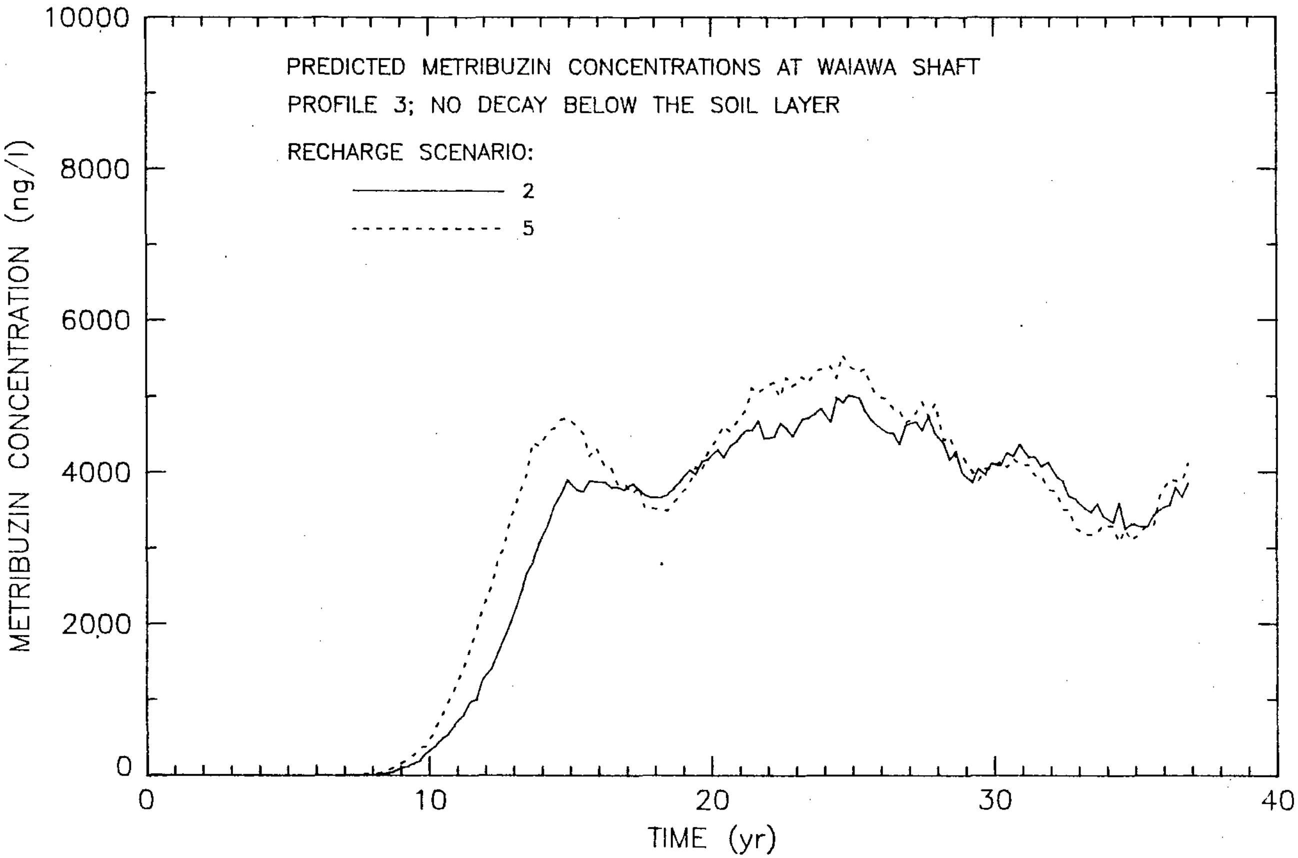


Figure 52. Metribuzin simulations 6 and 8, Waiawa Shaft, Oahu, Hawaii

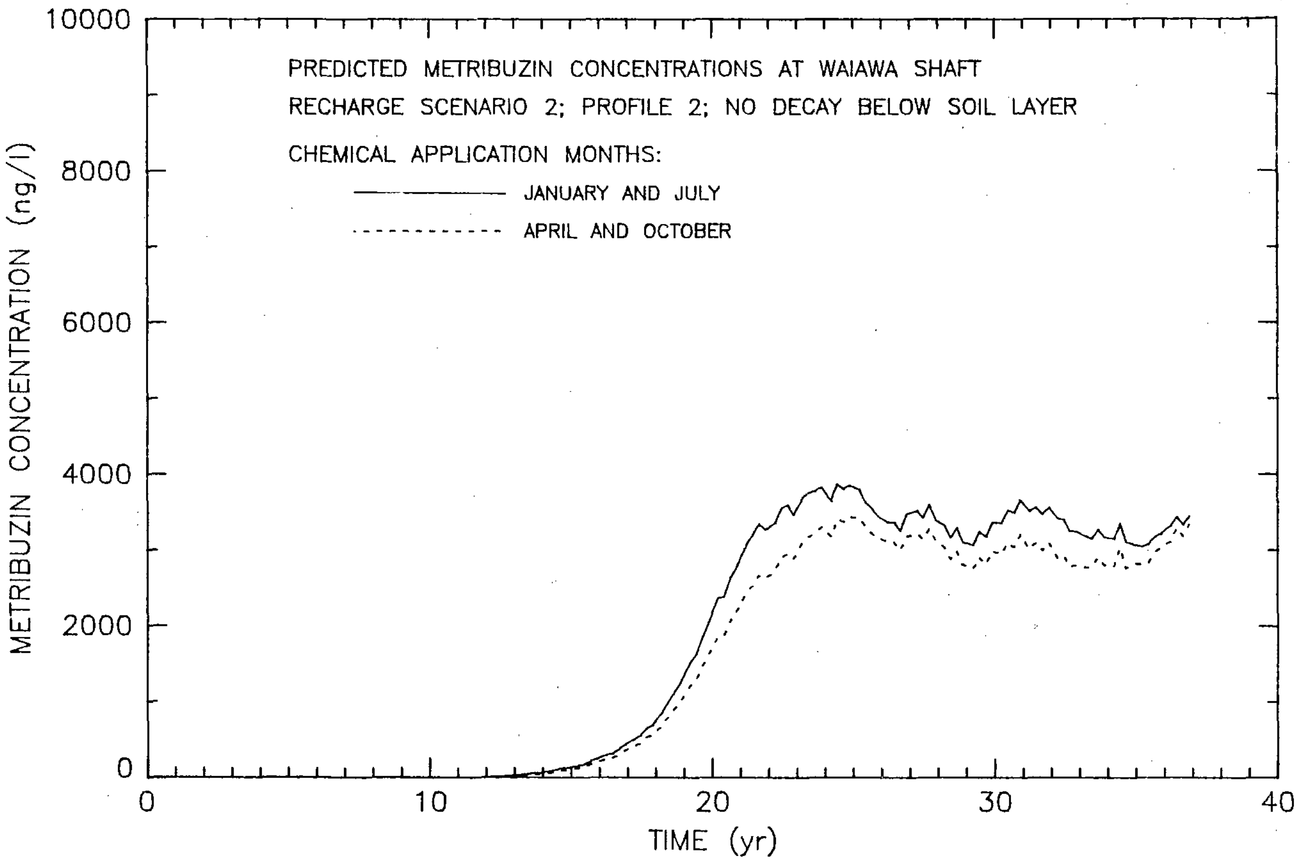


Figure 53. Metribuzin simulations 5 and 10, Waiawa Shaft, Oahu, Hawaii

DIAZINON SIMULATIONS

Based on the results of the chemical use survey above, diazinon is the most popular pesticide used in residential areas. For the groundwater predictive simulations, diazinon output from PRZM was adjusted to reflect an urban application rate of 10.8 kg/ha obtained from the survey. In addition, 50% of households were assumed to use diazinon a total of four times a year. Diazinon was not applied on golf course areas. As with the nitrate simulations, the diazinon simulations can be separated into three groups: (1) those which isolate the effects of the proposed Waiawa Ridge development; (2) those which assess the impact of the USN Waiawa Valley development; and (3) those which assume that both Waiawa Ridge and Waiawa Valley are developed. The groundwater simulations can be further separated into those which include the effects of hydrolysis in the saturated zone and those which assume no decay. Note that all PRZM simulations with diazinon employed a hydrolysis half-life of 200 days below the soil layer. For all simulations, pumpage from Waiawa Shaft is assumed to be steady at 0.66 m^3/s (15 mgd). Diazinon input from existing urban areas is based on unsaturated zone profile 2 with recharge being distributed at a depth of 5 m below the ground surface.

A summary of the diazinon simulations is presented in Table 22. Minimum, maximum, and average concentrations presented in Table 22 are valid for the final 15 years of the 37-yr simulation period. For all simulations, average diazinon concentrations are below the EPA drinking water lifetime health advisory of 0.6 μg/l (U.S. Environmental Protection Agency 1988a). However, under certain simulated conditions, maximum diazinon concentrations in water pumped by Waiawa Shaft may approach the lifetime health advisory (see simulations 7 and 27 in Table 22).

Analyses of a limited number of groundwater samples from Oahu for diazinon have not found the compound above the laboratory detection limit of 0.01 μg/l (Giambelluca, Leung, and Konda 1987; Chinn, Tateishi, and Yee 1986). In general, the average concentrations for the diazinon simulations which assumed lateral spreading of recharge were also below 0.01 μg/l. Although this result is consistent with actual analyses for diazinon in groundwater, it must be emphasized that sampling and testing for diazinon has thus far been limited both spatially and temporally. In

TABLE 22. SUMMARY OF SIMULATED DIAZINON CONCENTRATIONS AT WAIAWA SHAFT

	--------RECHARGE ---------			HYDROLYSIS	----CONC. (ng/l) ----		
SIM.	Scenario	Distrib. Depth	PROFILE	HALF-LIFE	Min.	Max.	Avg.
1	2	water table	2	200 days	0.9	5.8	2.6
2	2	water table	3	200 days	38.0	199.3	83.9
3	2	5 m	1	200 days	<0.1	<0.1	<0.1
4	2	5 m	2	200 days	<0.1	<0.1	<0.1
5	2	5 m	3	200 days	0.2	1.5	0.7
6	2	water table	2	infinite	3.5	15.6	8.1
7	2	water table	3	infinite	110.6	500.6	242.9
8	2	5 m	1	infinite	<0.1	<0.1	<0.1
9	2	5 m	2	infinite	<0.1	<0.1	<0.1
10	2	5 m	3	infinite	0.8	3.9	2.1
11	4	water table	2	200 days	5.2	61.1	20.9
12	4	water table	3	200 days	12.6	125.6	47.3
13	4	5 m	1	200 days	0.3	3.5	1.2
14	4	5 m	2	200 days	0.5	5.8	2.0
15	4	5 m	3	200 days	1.3	15.5	5.1
16	4	water table	2	infinite	9.8	103.3	36.5
17	4	water table	3	infinite	23.5	214.4	82.5
18	4	5 m	1	infinite	0.6	6.0	2.0
19	4	5 m	2	infinite	0.9	10.0	3.4
20	4	5 m	3	infinite	2.5	25.9	8.9
21	2	water table	2	200 days	5.3	45.5	18.1
22	2	water table	3	200 days	49.9	270.1	114.7
23	2	5 m	1	200 days	0.2	2.4	0.9
24	2	5 m	2	200 days	0.4	3.9	1.5
25	2	5 m	3	200 days	1.4	11.6	4.6
26	2	water table	2	infinite	12.3	83.6	36.0
27	2	water table	3	infinite	143.9	612.4	298.2
28	2	5 m	1	infinite	0.5	4.0	1.6
29	2	5 m	2	infinite	0.8	6.8	2.6
30	2	5 m	3	infinite	3.0	20.8	8.9

NOTE: Simulations 1-9 represent development of only Waiawa Ridge while simulations 21-30 represent development of both Waiawa Ridge and Waiawa Valley.

addition, conditions at the sampled sites are not identical to the conditions which may exist in the Waiawa area if it is developed. Each of the diazinon simulations is discussed more fully below.

Diazinon Simulations 1-10. Diazinon simulations 1 to 10 utilize recharge scenario 2 and were designed to test the impact of development of Waiawa Ridge. Simulations 1 to 5 include a hydrolysis half-life of 200 days in the groundwater whereas simulations 6 to 10 assume no decay in the saturated zone.

Figure 54 presents the results of simulations 1 and 6 which utilize output from PRZM generated using unsaturated zone profile 2, with concentrated recharge from pervious urban areas being allowed to move vertically downward to the water table without lateral spreading. Recharge for each urban water balance cell was then dispersed at the water table over the entire area of that cell. The effects of decay in groundwater result in reduced concentrations of diazinon in water pumped at Waiawa Shaft. Simulations 2 and 7, presented in Figure 55, are similar to predictions 1 and 6 except that they utilize output from PRZM generated with unsaturated zone profile 3 instead of 2. As expected, concentrations at Waiawa Shaft are higher using profile 3 than with profile 2. A comparison of the results using the two profiles for the cases including hydrolysis in groundwater is presented in Figure 56.

Note that the concentration peaks between simulation years 20 and 30 depicted in Figures 54 to 56 reflect the large chemical loading to the groundwater occurring during that period as a result of increased recharge. Because PRZM assumes that the entire unsaturated zone profile will drain if it is at its field capacity, a large recharge event occurring during a given time period will result in an equal amount of water being drained at the bottom of the profile within that same time period. Thus, large recharge events occurring during a certain time period could result in a large chemical loading to the groundwater table over that same time period if the bottom of the profile contains the solute of interest.

Simulations 1, 2, 6, and 7 all assume recharge beneath the pervious areas to move down to the water table without lateral spreading. However, spreading of the wetting front undoubtedly occurs due to moisture gradients and the occurrence of low permeability layers in the

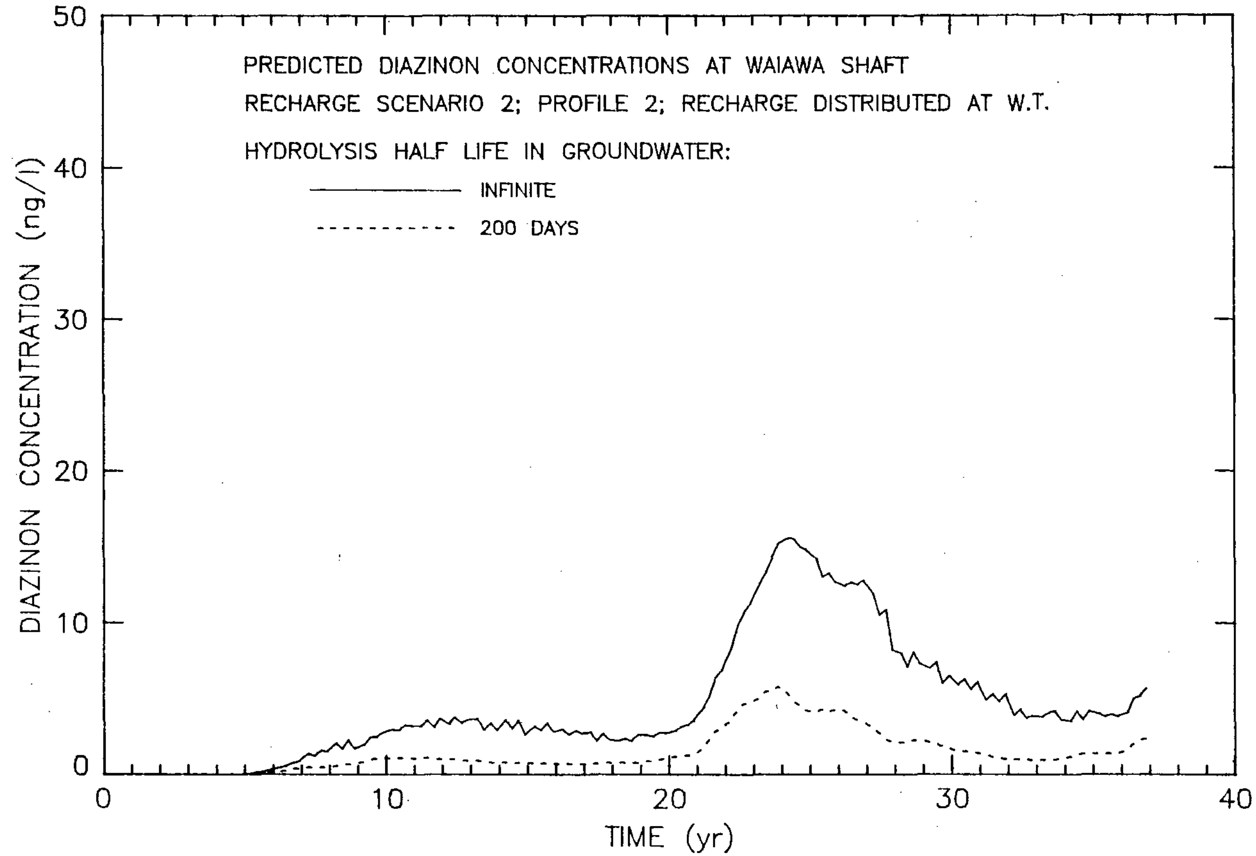


Figure 54. Diazinon simulations 1 and 6, Waiawa Shaft, Oahu, Hawaii

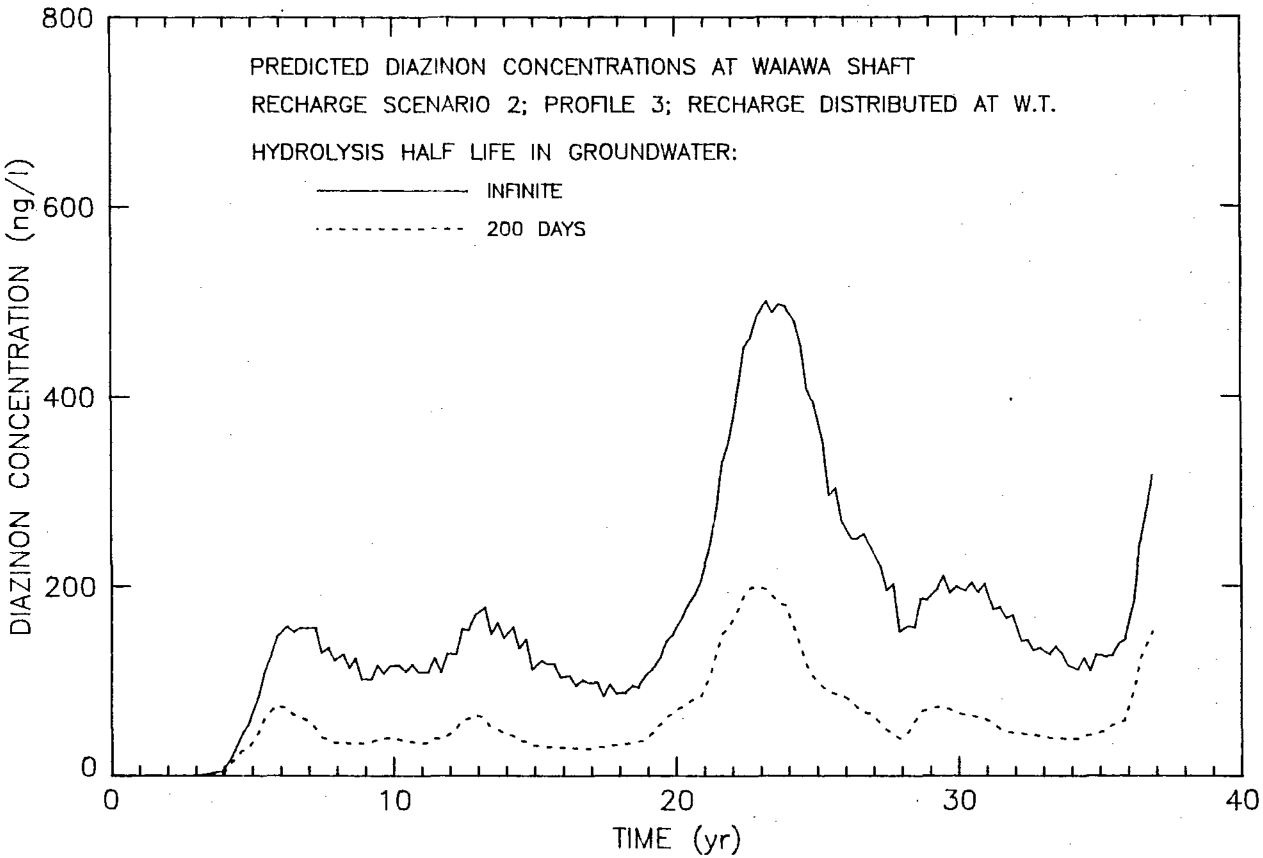


Figure 55. Diazinon simulations 2 and 7, Waiawa Shaft, Oahu, Hawaii

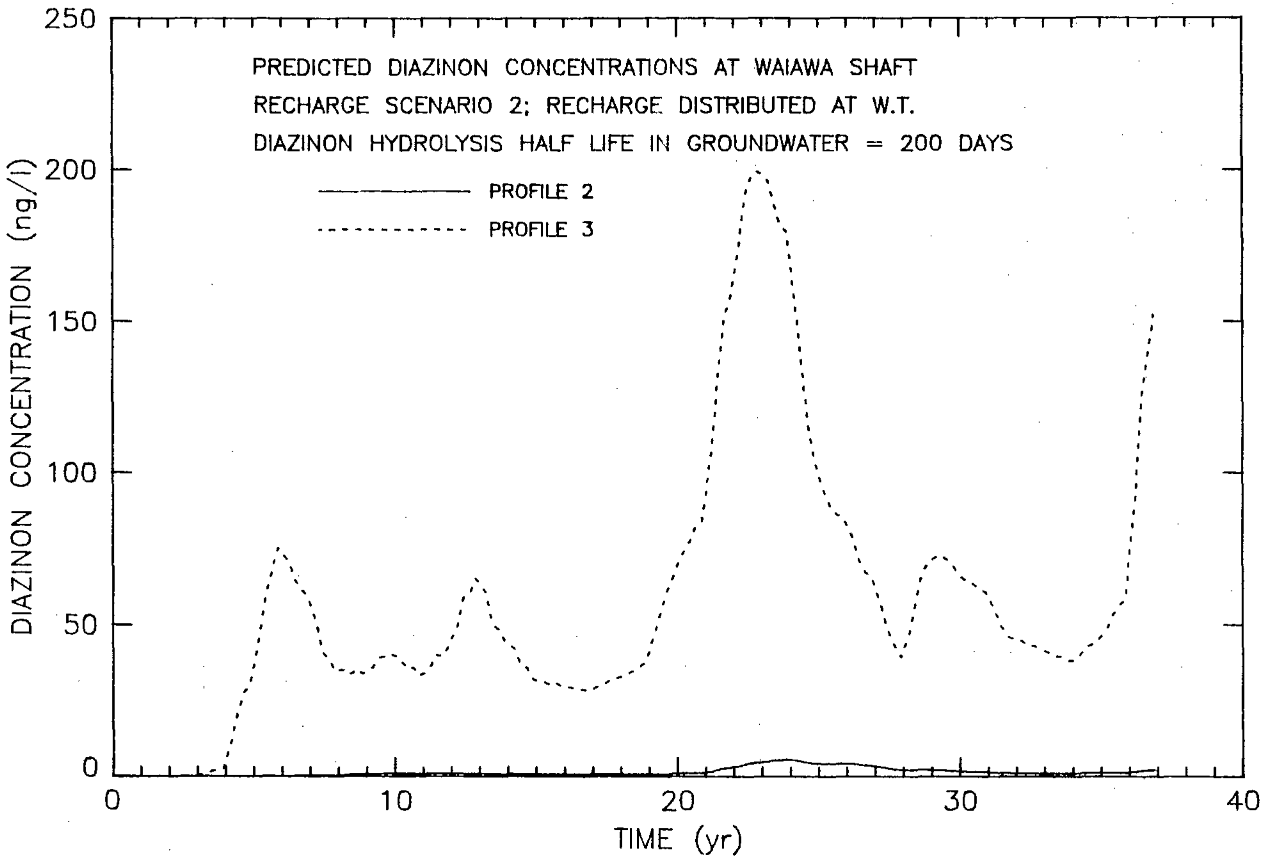


Figure 56. Diazinon simulations 1 and 2, Waiawa Shaft, Oahu, Hawaii

unsaturated zone. This phenomenon is accounted for with PRZM by assuming that recharge beneath pervious areas is dispersed at a depth of 5 m below the ground surface where the saprolite layer begins. Using this assumption with unsaturated zone profiles 1 and 2 results in insignificant loading rates of diazinon at the groundwater table. With recharge beneath urban areas dispersed at a depth of 5 m below the ground surface, profile 3 resulted in diazinon concentrations in the ng/l range at the groundwater table. The long-term groundwater predictions using unsaturated zone profile 3 with recharge dispersed at 5 m are presented in Figure 57. Diazinon concentrations at Waiawa Shaft remain below 5 ng/l throughout the duration of the 37-yr prediction period even in the absence of hydrolysis in groundwater. Figure 58 compares the effects of the recharge distribution assumptions for profile 3 with a hydrolysis half-life of 200 days in the saturated zone. Clearly, distributing the recharge at the top of the saprolite results in reduced recharge rates so that travel time through the unsaturated zone is increased. If recharge beneath pervious areas is allowed to move vertically downward to the water table without lateral spreading, travel time and diazinon decay are reduced in the unsaturated zone which results in higher concentrations in water pumped by Waiawa Shaft.

Diazinon Simulations 11-20. Diazinon simulations 11 to 20 were designed to isolate the effects of the USN proposed Waiawa Valley development by maintaining the current open land use for Waiawa Ridge. Waiawa Valley diazinon simulations 11 to 15 assume a hydrolysis half-life of 200 days in the groundwater while simulations 16 to 20 assume no decay in the groundwater. As previously described in the nitrate simulations, unimpeded interflow was assumed to exist between the alluvial aquifer in the valley and the basal groundwater body.

Figure 59 presents the results of simulations 11 and 16 which utilize PRZM output corresponding to unsaturated zone profile 2 without lateral spreading of recharge beneath pervious areas in the valley. Hydrolysis in the groundwater reduces the simulated concentrations at Waiawa Shaft. However, because of the proximity of the shaft in relation to the Waiawa Valley development, travel time in the groundwater from the diazinon

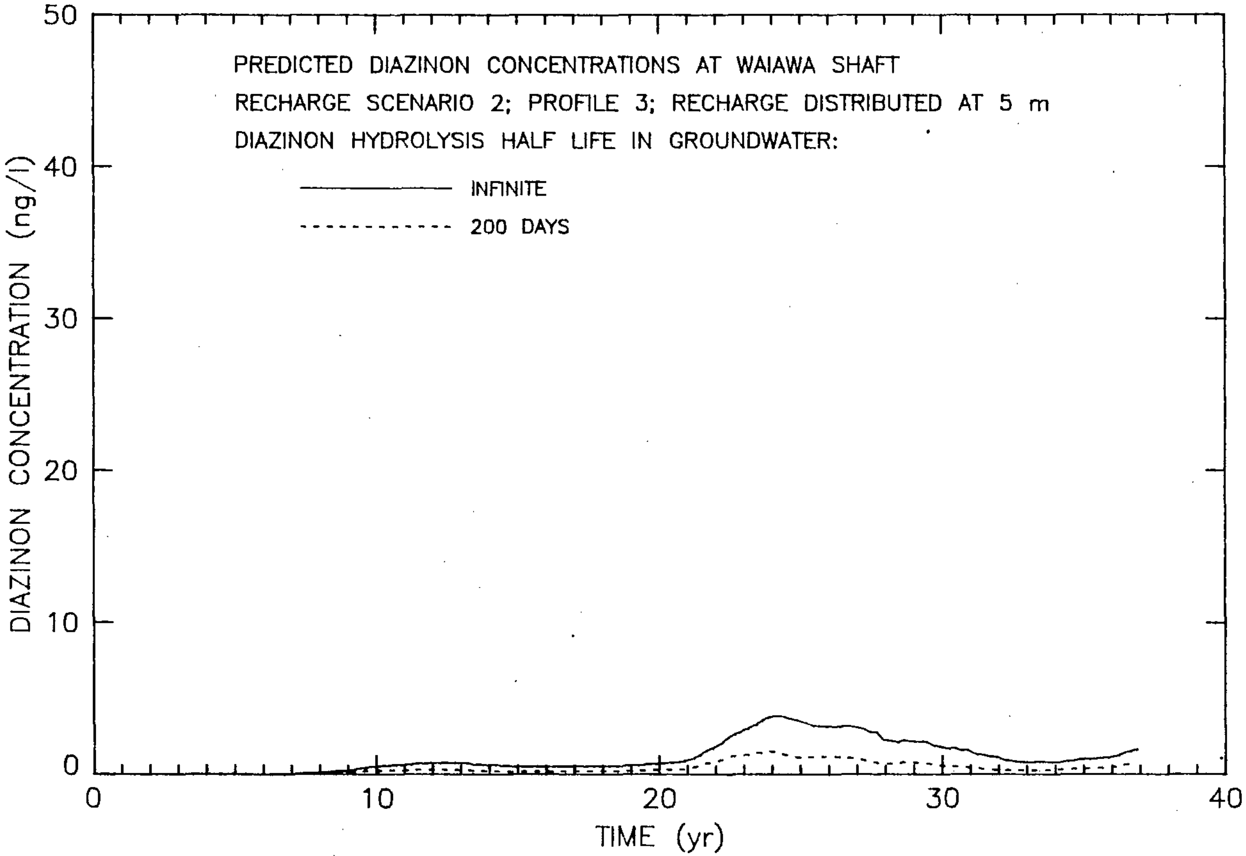


Figure 57. Diazinon simulations 5 and 10, Waiawa Shaft, Oahu, Hawaii

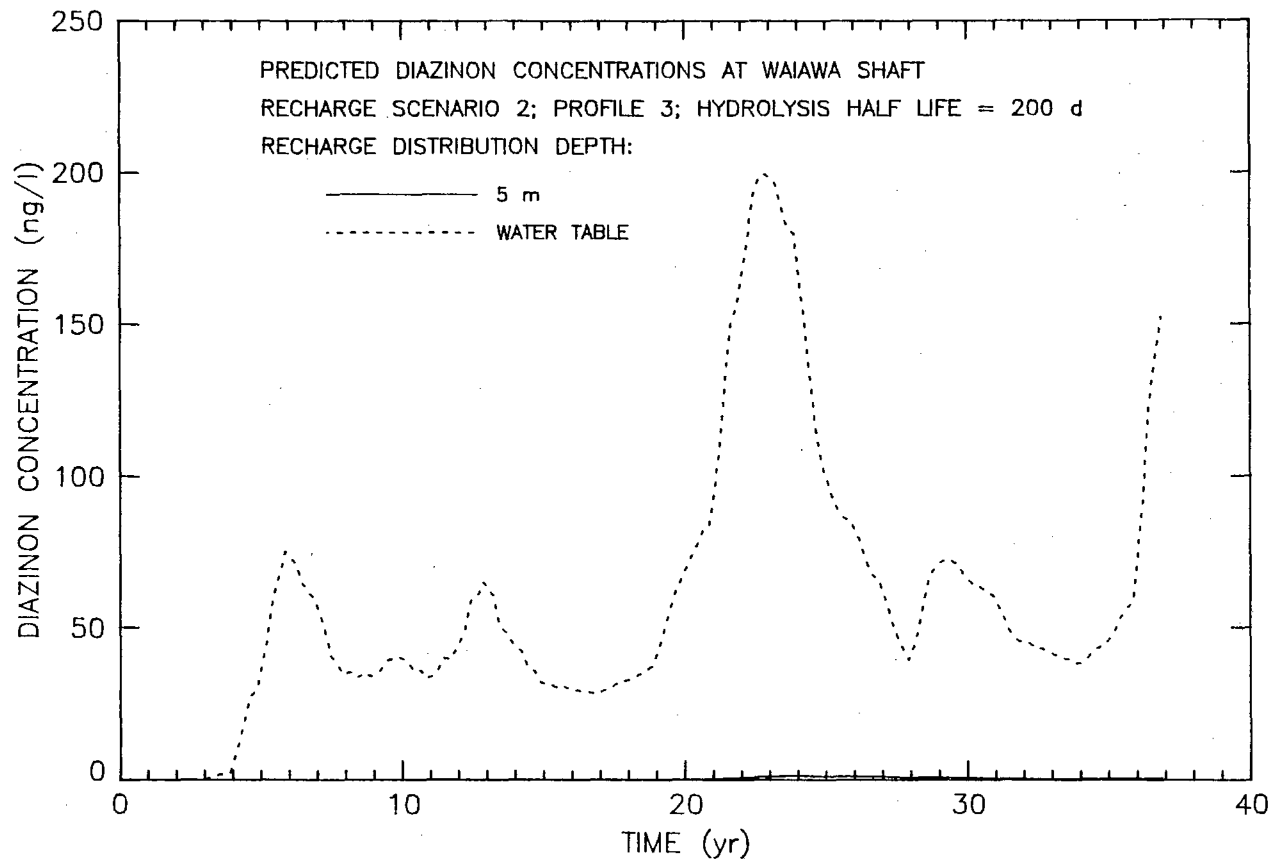


Figure 58. Diazinon simulations 2 and 5, Waiawa Shaft, Oahu, Hawaii

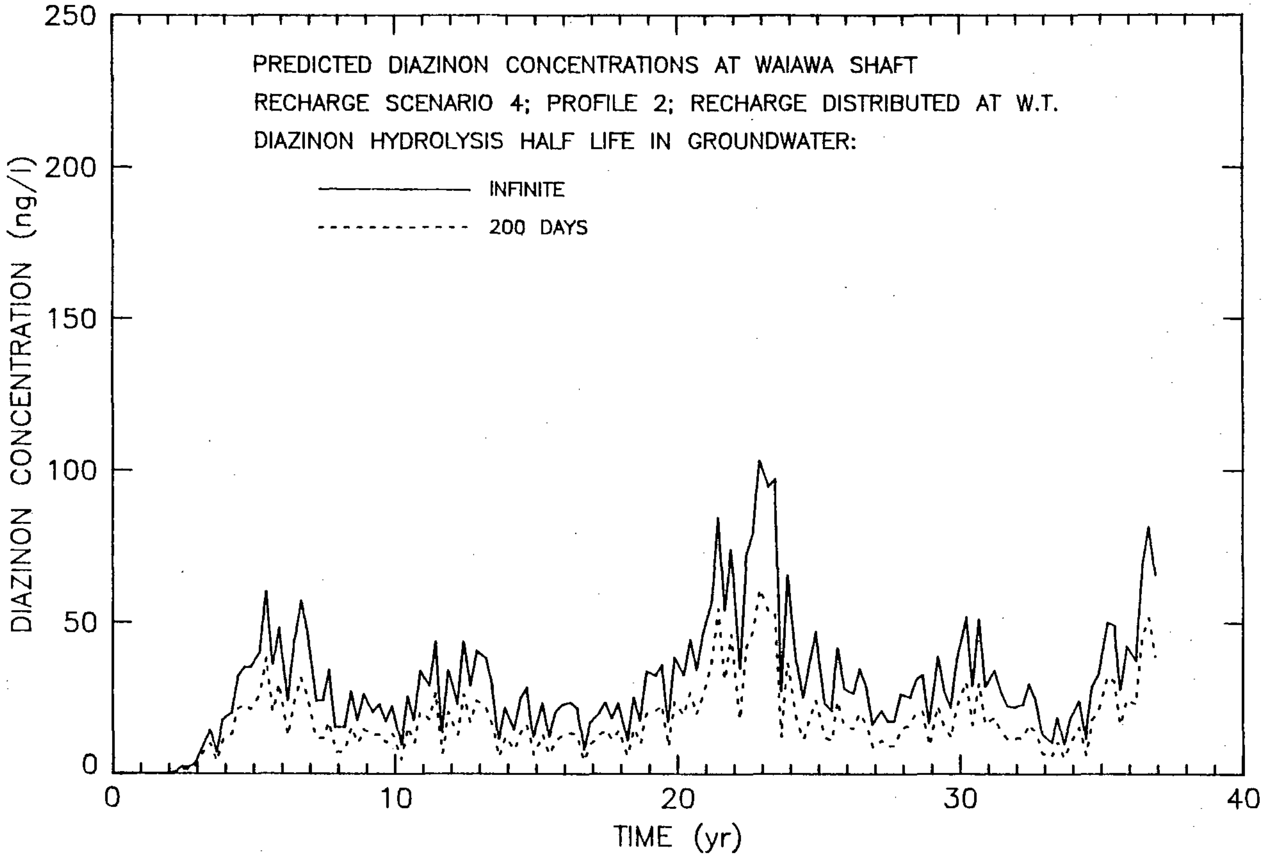


Figure 59. Diazinon simulations 11 and 16, Waiawa Shaft, Oahu, Hawaii

source areas is relatively short; consequently, the effects of hydrolysis are somewhat reduced.

Simulations 12 and 17 are similar to simulations 11 and 16 with the exception that PRZM output corresponding to profile 3 was used. The results of simulations 12 and 17, which assume recharge beneath pervious areas to move vertically downward to the alluvial aquifer without lateral spreading, are presented in Figure 60. Fluctuations in diazinon concentrations reflect the short distance between the diazinon source areas and Waiawa Shaft as well as the assumed unimpeded interflow between the alluvial aquifer and the basal aquifer (see earlier explanation on the nitrate simulations). A comparison between simulations 11 and 12, presented in Figure 61, demonstrates the effect of the soil layer on the groundwater quality.

Simulations 13 and 18 utilize PRZM output corresponding to unsaturated zone profile 1 with recharge dispersed at a depth of 5 m beneath the ground surface. Resulting diazinon concentrations in water pumped by Waiawa Shaft are presented in the time series of Figure 62. Even without decay in the groundwater, simulated diazinon concentrations at Waiawa Shaft do not exceed 10 ng/l. Simulations 14 and 19 are similar to simulations 13 and 18, respectively, except that unsaturated zone profile 2 is used instead of profile 1. Similarly, predictions 15 and 20 represent the case of utilizing profile 3 with recharge distributed at a depth of 5 m beneath the groundwater surface. Results of simulations 14 and 19 are presented in Figure 63, and simulated time series from runs 15 and 20 are presented in Figure 64. Only when profile 3 is used and no diazinon decay occurs in groundwater do simulated concentrations at Waiawa Shaft exceed a level of 20 ng/l. Figure 65 presents the results of using vadose zone profiles 1, 2, and 3 with a diazinon hydrolysis half-life of 200 days. The time series presented in Figure 65 correspond to simulations 13, 14, and 15. Clearly, profile 1, which possesses the greatest amount of organic carbon in the soil layer, enhances the opportunity for diazinon degradation so that subsequent leaching to the groundwater is reduced.

Simulations 11 and 14 are compared in Figure 66, and simulations 12 and 15 are presented in Figure 67. Figures 66 and 67 demonstrate the significance of lateral spreading of the recharge wetting front using

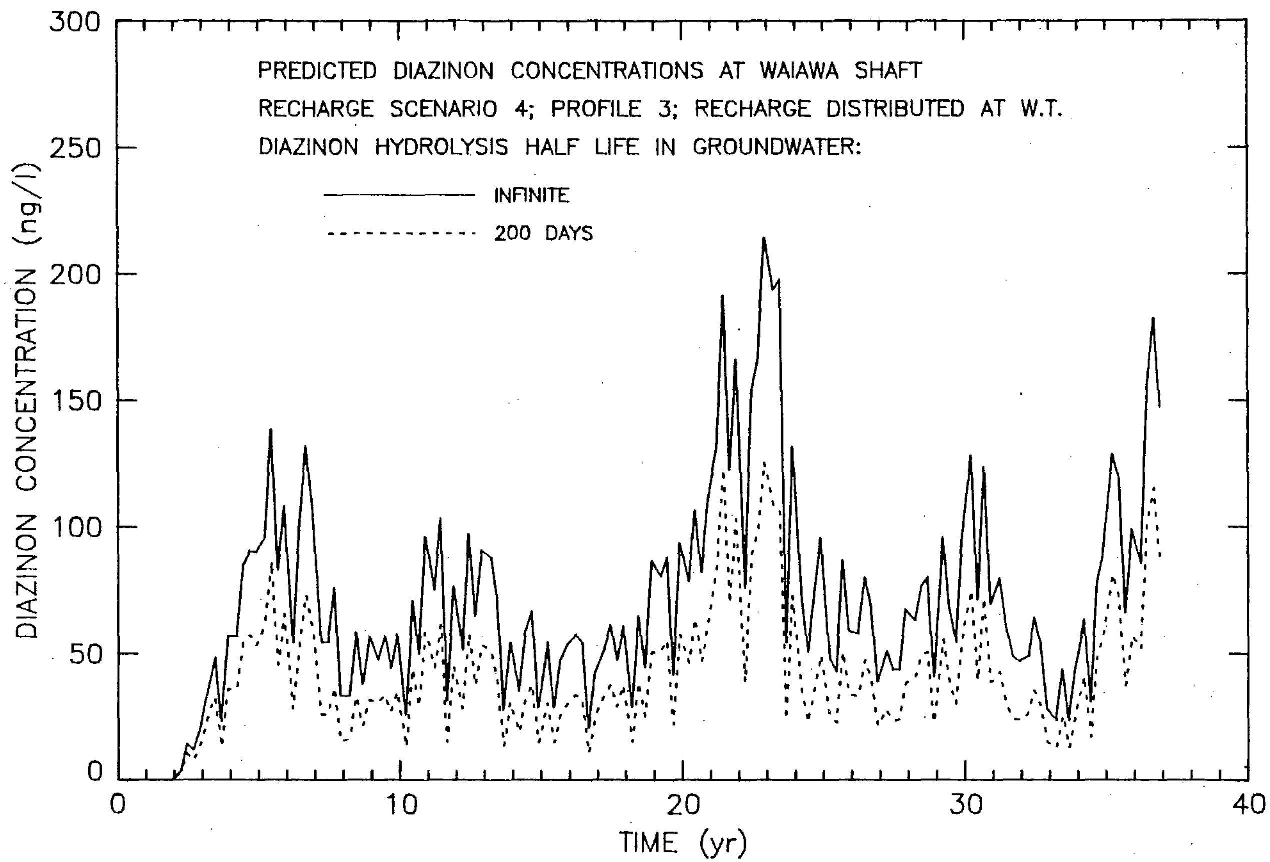


Figure 60. Diazinon simulations 12 and 17, Waiawa Shaft, Oahu, Hawaii

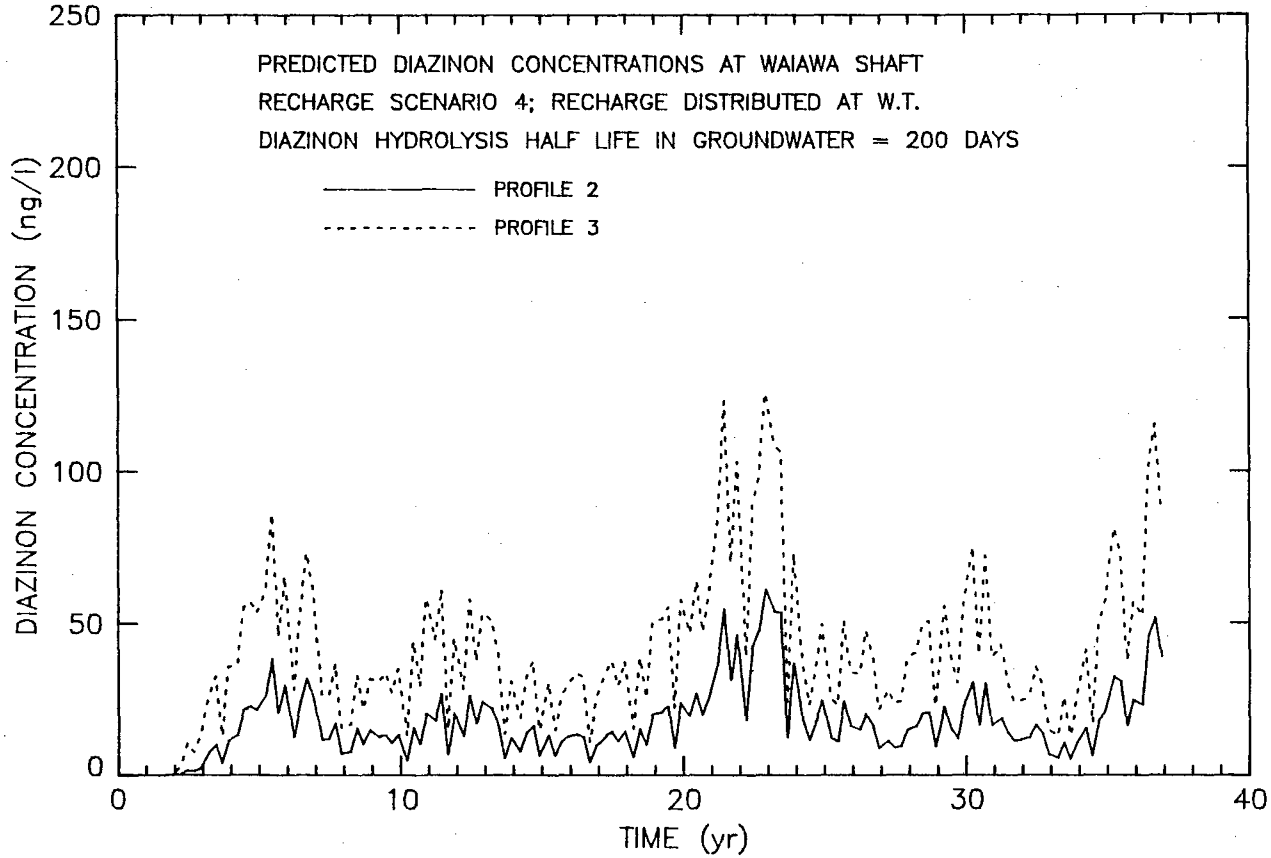


Figure 61. Diazinon simulations 11 and 12, Waiawa Shaft, Oahu, Hawaii

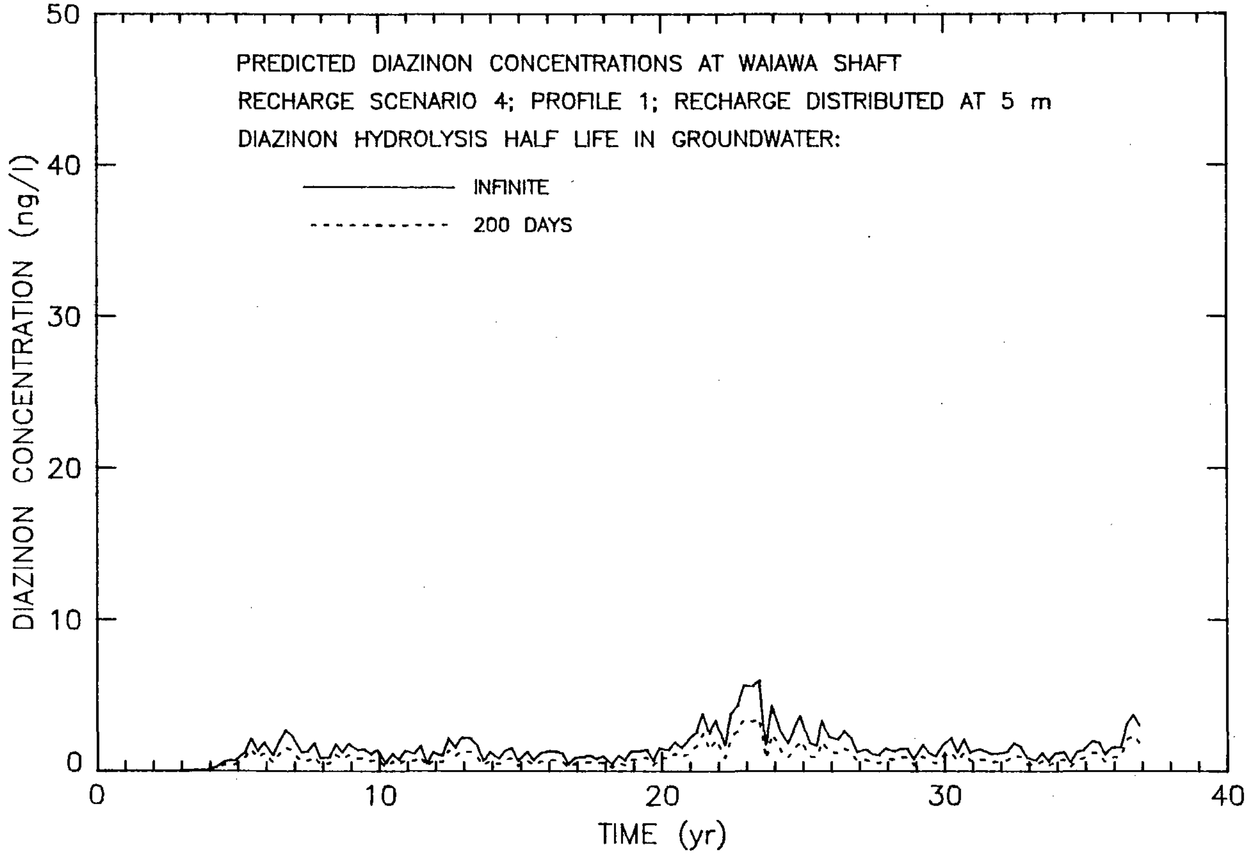


Figure 62. Diazinon simulations 13 and 18, Waiawa Shaft, Oahu, Hawaii

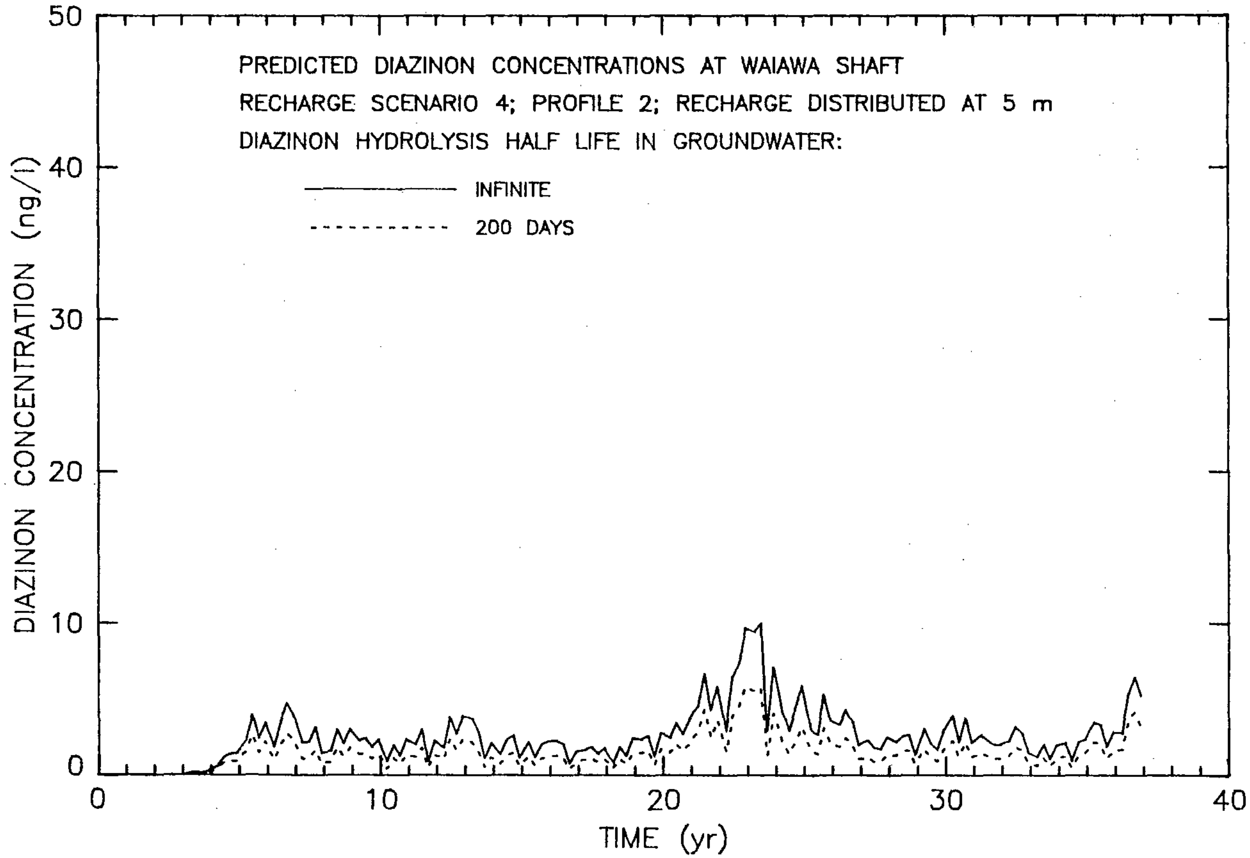


Figure 63. Diazinon simulations 14 and 19, Waiawa Shaft, Oahu, Hawaii

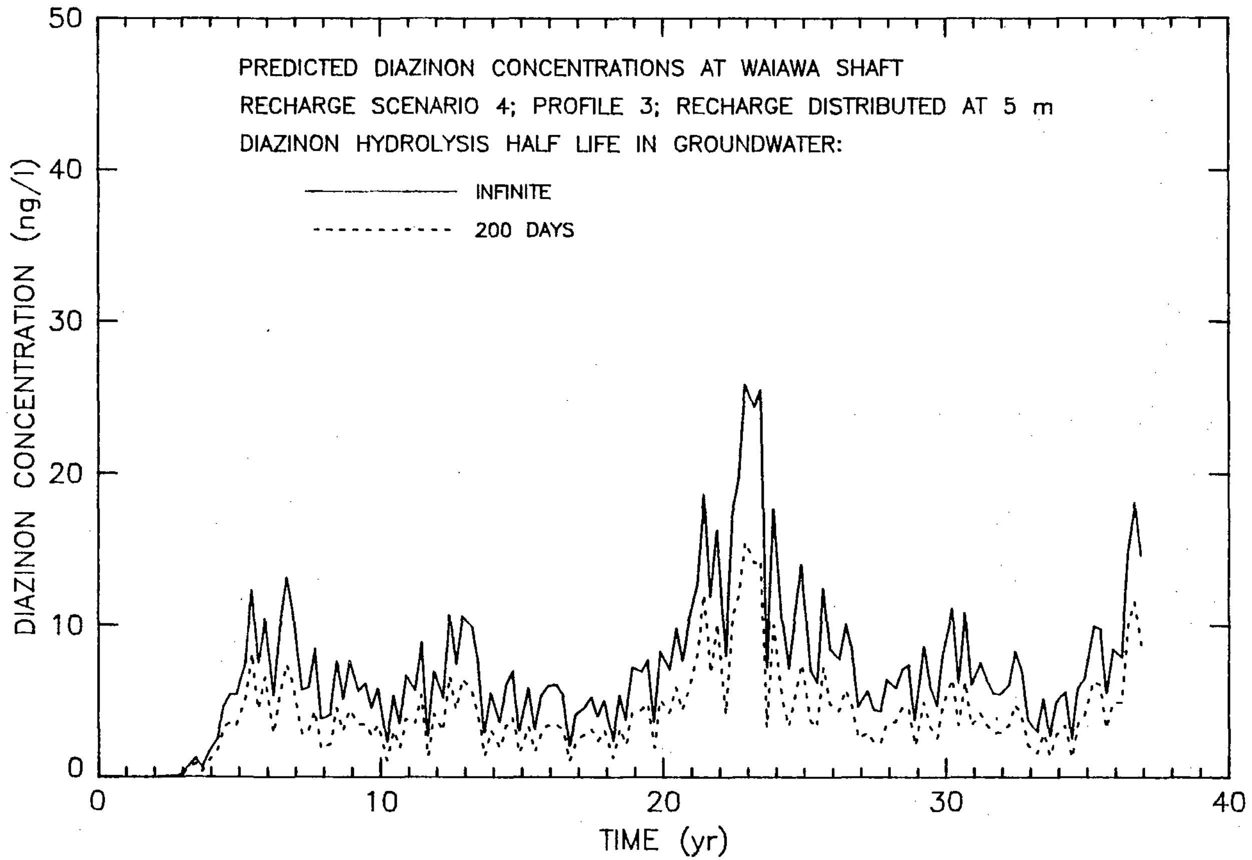


Figure 64. Diazinon simulations 15 and 20, Waiawa Shaft, Oahu, Hawaii

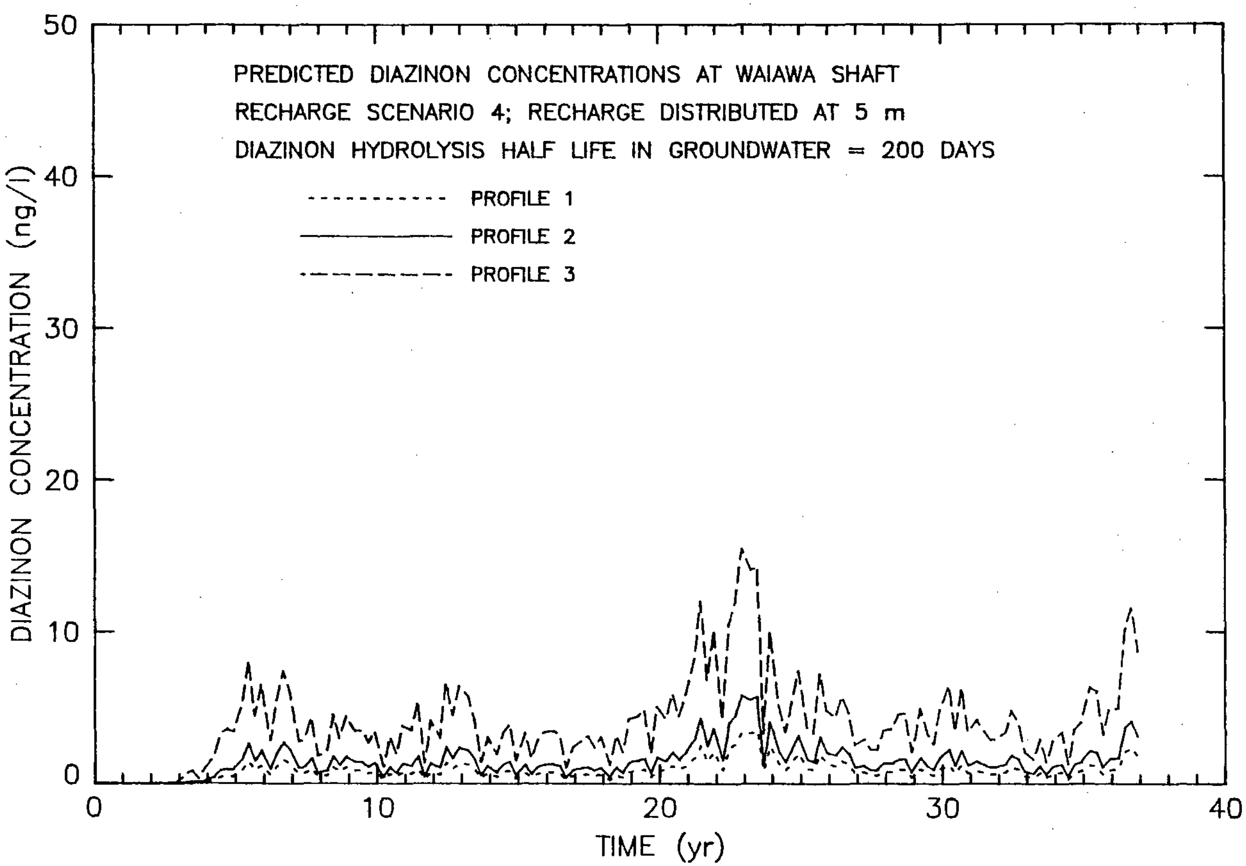


Figure 65. Diazinon simulations 13, 14, and 15, Waiawa Shaft, Oahu, Hawaii

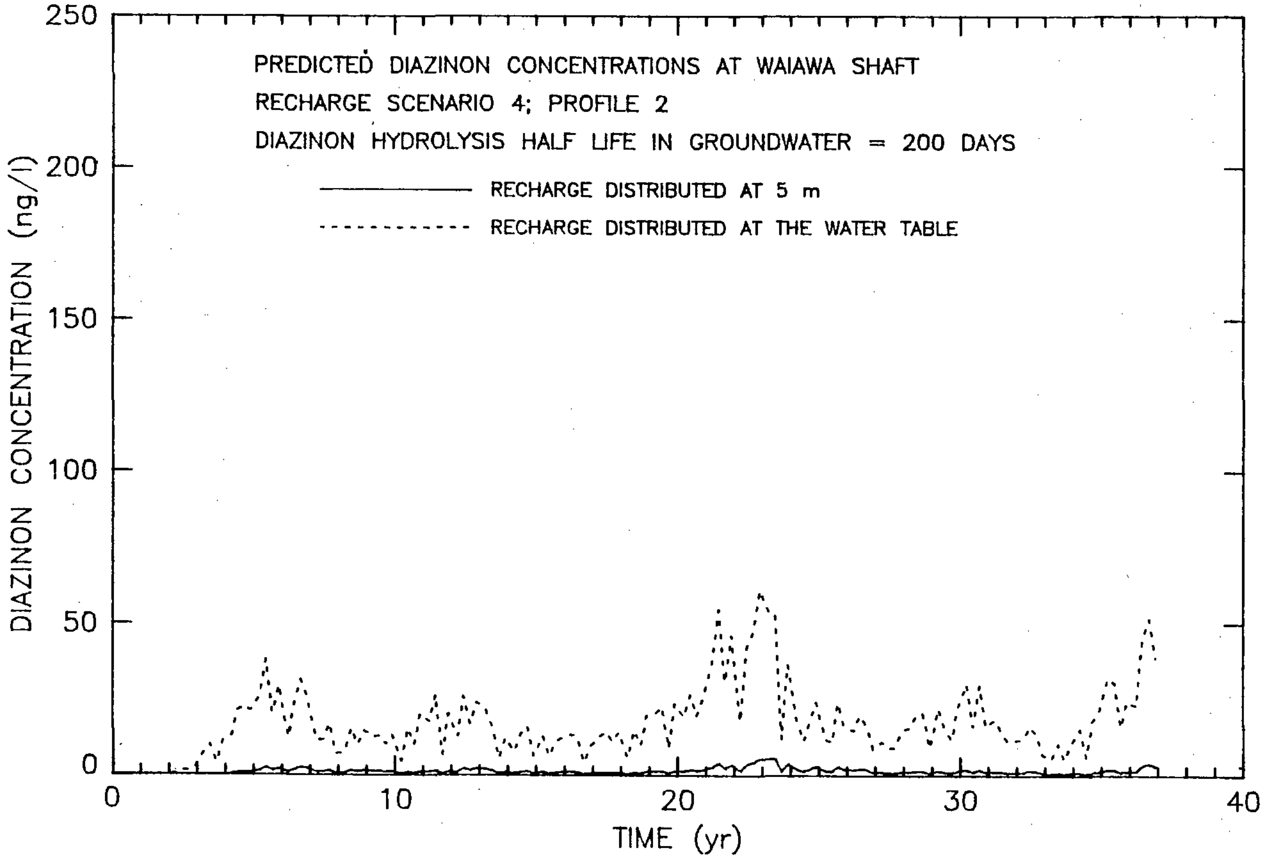


Figure 66. Diazinon simulations 11 and 14, Waiawa Shaft, Oahu, Hawaii

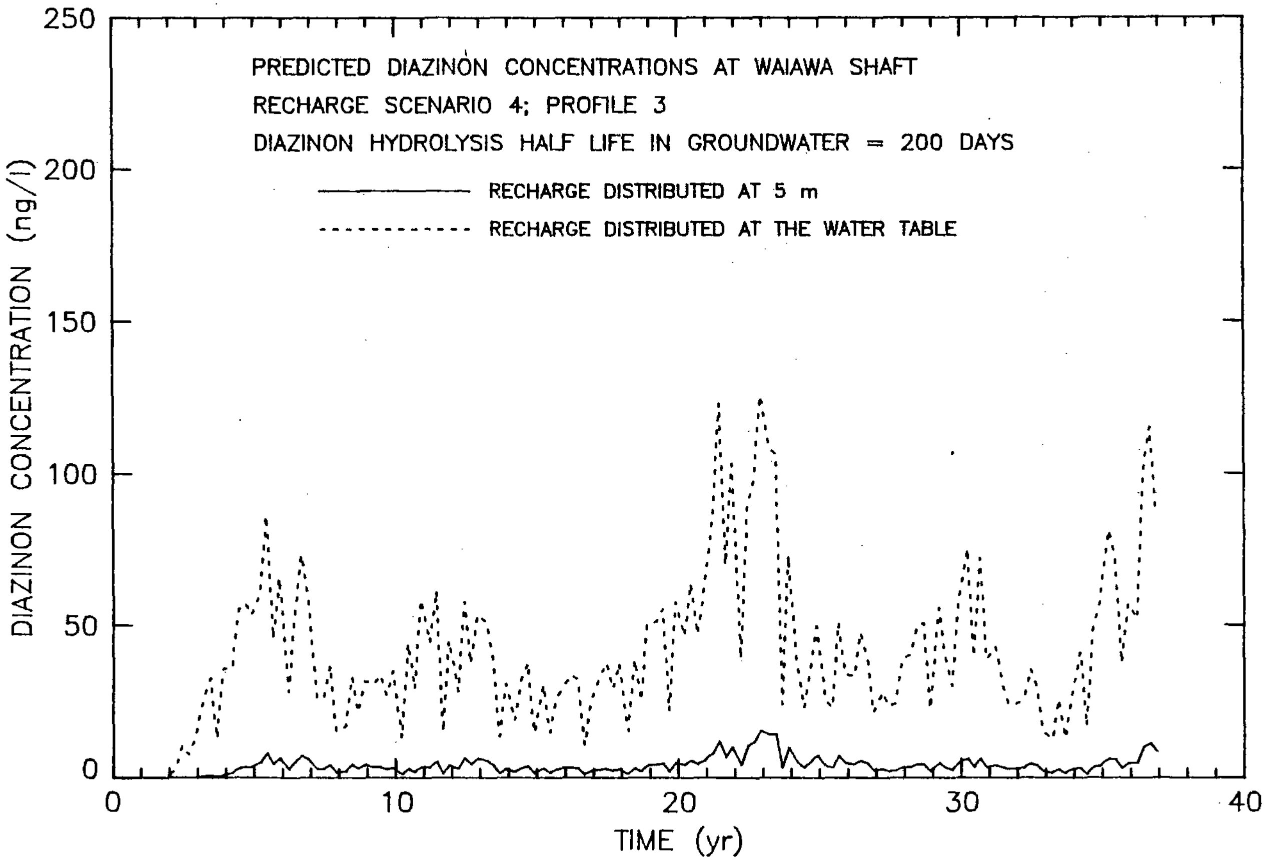


Figure 67. Diazinon simulations 12 and 15, Waiawa Shaft, Oahu, Hawaii

unsaturated zone profiles 2 and 3, respectively. In both cases, if no lateral spreading occurs, resulting concentrations at Waiawa Shaft are significantly increased.

Diazinon Simulations 21-30. Like diazinon simulations 1 to 10, simulations 21 to 30 utilize recharge scenario 2. However, simulations 21 to 30 were designed to test the combined impact of development on Waiawa Ridge and in Waiawa Valley. Unlike simulations 1 to 10, which assume that the USN Waiawa Valley property is part of the Waiawa Ridge development, simulations 21 to 30 treat the USN property separately. Thus, the three affected MOC grid cells representing the Waiawa Valley development will have an elevation representative of the valley and not the ridge. Simulations 21 to 25 include a hydrolysis half-life of 200 days in the saturated zone while simulations 26 to 30 assume no decay in the saturated zone. The hydrologic connection between the alluvial aquifer in the valley and the basal groundwater body is assumed to be unimpeded.

In general, simulations 21 to 30 are dominated by the effects of the Waiawa Valley development. Because diazinon applied in the proposed Waiawa Valley development will have a short travel time to Waiawa Shaft, chemical attenuation is reduced relative to the ridge inputs. Thus, in terms of diazinon concentrations, Waiawa Shaft is expected to be most influenced by the proposed Waiawa Valley development. The exceptions are simulations 22 and 27 which utilize unsaturated zone profile 3 and assume that recharge is distributed at the water table. Under such conditions, chemical attenuation is reduced to the extent that the diazinon contribution from Waiawa Ridge begins to be the significant factor.

Diazinon concentrations in water pumped by Waiawa Shaft will vary depending on whether Waiawa Valley, Waiawa Ridge, or both areas are developed. Development of Waiawa Ridge will affect the zone of contribution of Waiawa Shaft due to changes in the recharge pattern caused by the land use change from its current vacant condition. Due to the limited recharge on Waiawa Ridge associated with the current vacant land use condition, the zone of contribution of Waiawa Shaft will include much of the area beneath the proposed Waiawa Valley development. If Waiawa Ridge is developed, the effect of urban irrigation may cause a shift in the zone of contribution of Waiawa Shaft to the west. Thus, the zone of contribution may not include as much of the area beneath the proposed Waiawa Valley development. As a result, if both Waiawa Valley and Waiawa Ridge are developed, diazinon concentrations in water pumped by the shaft may be lower than those resulting from development of Waiawa Valley only, provided that the chemical input to the groundwater table from the ridge is low relative to the valley input. If the diazinon input to the groundwater table from the ridge is high (simulations 22, 27), then development of Waiawa Ridge and Waiawa Valley will cause an increase of concentrations relative to the case of development of Waiawa Valley only.

ZONE OF CONTRIBUTION SIMULATIONS

A number of simulations were run using diazinon as a test chemical to determine the impact of developing beyond the assumed zone of contribution of Waiawa Shaft. Prior to running these simulations, however, the impact of existing urban areas was assessed using diazinon. It should be noted that water samples collected at Waiawa Shaft have been analyzed twice in the past for diazinon. Analyses of water samples collected in October 1982 and November 1983 from Waiawa Shaft indicated no detectable levels of diazinon at a laboratory detection limit of 10 ng/l (see Giambelluca, Leung, and Konda 1987).

For all background simulation runs, application rates and frequencies of diazinon were assumed to be the same as those used above for urban areas, and a diazinon hydrolysis half-life of 200 days was assumed to be applicable in the groundwater. Only water balance cells (5,3), (6,3), (6,5), (7,3), and (7,5) corresponding to the existing Pacific Palisades and Pearl City urban areas were assumed to be potential source areas of diazinon. All simulations were carried out with recharge scenario 2, with the proposed Waiawa Ridge and Waiawa Valley developments contributing no diazinon to the groundwater. When recharge beneath the pervious areas was distributed at a depth of 5 m beneath the ground surface, simulated diazinon concentrations in water pumped by Waiawa Shaft did not exceed 1 ng/l even when unsaturated zone profile 3 was employed. Although the simulated recharge conditions for Waiawa Ridge are different from those that existed at the time of the 1982 and 1983 analyses, this result is consistent with the nondetectable diazinon levels in actual water samples collected at Waiawa Shaft. In addition, with unsaturated zone profile 2 and recharge beneath pervious areas distributed at the water table, simulated diazinon concentrations at Waiawa Shaft remained below 1 ng/l. With vadose zone profile 3 and recharge distributed at the water table, the average simulated concentration over the final 15 years of the 37-yr simulation was about 9 ng/l with a maximum concentration of 21 ng/l. Even under simulated conditions conducive to chemical leaching, average simulated diazinon concentrations remained below a level of 10 ng/l. Thus, the simulated results appear to be consistent with actual analyses of water samples collected at Waiawa Shaft.

The zone of contribution of Waiawa Shaft changes in response to varying recharge and pumping conditions. Several typical zones of contribution for Waiawa Shaft as estimated with the groundwater flow submodel of the MOC model are presented in Appendix E of this report. These zones of contribution are generally consistent with the zone of contribution as determined with an analytical solution (Bear 1979) by Paul Eyre of the U.S. Geological Survey (Fig. 68). In order to test the impact of those portions of the Waiawa Gentry development beyond the assumed zone of contribution of Waiawa Shaft, only the western portions of the proposed development were allowed to contribute diazinon to the groundwater. That is, although the entire development was assumed to be in place, only certain areas near the western boundary of the development were considered potential source areas of chemicals. In all of the zone of contribution test simulations described below, recharge scenario 2 was employed. Selected output from PRZM, corresponding to unsaturated zone profile 3 without lateral spreading of recharge beneath pervious areas, was used as input to the solute transport groundwater model.

Apartment and Commercial/Industrial Areas. The proposed apartment and commercial/industrial areas were assigned to the extreme western portion of the development in the discretized water balance land use assignment scheme. For the zone of contribution test, the apartment areas in water balance cells (3,3) and (3,4) were first isolated. The commercial/industrial area corresponding to water balance cell (3,5) was then tested as a source area. The apartment and commercial/industrial areas were then both allowed to contribute diazinon to the groundwater. In all three cases, simulated diazinon concentrations at Waiawa Shaft did

SOURCE: Eyre (1989).

Figure 68. Estimated zone of contribution for Waiawa Shaft

not exceed 1 ng/l when a hydrolysis half-life of 200 days was used. If diazinon is assumed to be persistent in groundwater, however, simulated concentrations at Waiawa Shaft exceed 10 ng/l when all apartment and commercial/industrial cells are considered source areas.

Residential Areas. The proposed residential areas near the western portion of the development were assigned to water balance cells (4,3), (4,4), and (4,6). Diazinon was applied only over these residential areas to test the impact of the residential areas at the periphery of the assumed zone of contribution of Waiawa Shaft. With a 200 day hydrolysis half-life of diazinon in groundwater, the average simulated concentration at Waiawa Shaft over the final 15 years of the 37-yr simulation period was about 16 ng/l. If the chemical is persistent in groundwater, the average simulated concentration at Waiawa Shaft increases to 39 ng/l with a maximum of about 100 ng/l being attained over the final 15 years of the simulation.

GOLF COURSE WATER HAZARDS

The effect of surface runoff, which enters golf course water hazards, on groundwater quality was not simulated. Runoff from proposed golf courses on Waiawa Ridge, however, is not expected to be high. Furthermore, pesticides entering surface water impoundments will be degraded by processes such as hydrolysis and photodecomposition. It should be mentioned, however, that unlined surface water impoundments on Waiawa Ridge may leak where soil permeablity is high. Thus, from both a water conservation and a groundwater quality protection standpoint, lining of golf course water hazards should be considered, especially in areas within the zone of contribution of Waiawa Shaft.

8. UNCERTAINTY ANALYSIS

For this investigation, a modeling approach is taken to assess the potential for groundwater contamination due to proposed urban development in the vicinity of the USN Waiawa Shaft. The overall assessment approach utilized computer models in conjunction with the best available data (historical and by measurement), parameter estimates, and scientific understanding of the underlying processes affecting water and chemical movement through the unsaturated and saturated zones. Using computer models, the impact of various land use and chemical use scenarios on the quality of water pumped at Waiawa Shaft may be represented by concentration time series at the shaft. It is recognized, however, that there is uncertainty associated with the predictive simulations leading to the concentration time series presented in chapter 7 of this report. Thus, caution must be exercised in interpreting the results.

Although it is beyond the scope of this project to undertake an extensive and quantitative uncertainty analysis, it is important to at least identify and discuss the various forms of uncertainty which may have an impact on the interpretation of the results. The uncertainty involved in the overall assessment approach for this investigation can be divided into four broad categories: (1) geology associated uncertainty, (2) model associated uncertainty, (3) input data associated uncertainty, and (4) model parameter associated uncertainty. Each of these four broad uncertainty categories can be further divided into their component parts as presented in Table 23. Each area of uncertainty presented in Table 23 is briefly discussed below in terms of its impact on the long-term predictive simulations designed to assess the potential for groundwater contamination due to urbanization.

GEOLOGY ASSOCIATED UNCERTAINTY

Geology associated uncertainty may affect simulations involving the proposed Gentry Waiawa Ridge development as well as the USN Waiawa Valley development. On Waiawa Ridge, soil, saprolite, and unweathered basalt thicknesses vary throughout the proposed development area. The

TABLE 23. SOURCES OF UNCERTAINTY

GEOLOGY ASSOCIATED UNCERTAINTY

A. Waiawa Ridge - Unsaturated Zone
   1. Soil Thickness
   2. Saprolite Thickness
   3. Unweathered Basalt Thickness

B. Waiawa Valley
   1. Alluvium Thickness
   2. Saprolite Thickness
   3. Hydraulic Connection Between the Alluvial and Basal Groundwater Bodies

INPUT DATA ASSOCIATED UNCERTAINTY

A. Water Balance Model
   1. Precipitation
   2. Irrigation
   3. Potential Evapotranspiration

B. Unsaturated Zone Solute Transport Model (PRZM)
   1. Recharge
   2. Chemical Application
      a. Rates
      b. Frequencies
      c. Dates

C. Saturated Zone Solute Transport Model (MOC)
   1. Recharge
   2. Upgradient Influx
   3. Well Pumpage
   4. Chemical Loading

MODEL ASSOCIATED UNCERTAINTY

A. Water Balance Model
   1. SCS Runoff Curve Number Model
   2. Evapotranspiration Model
   3. Threshold Concept for Recharge

B. Unsaturated Zone Solute Transport Model (PRZM)
   1. Flow Model
      a. One-Dimensional Flow Conditions
      b. Validity of Simple Drainage Rule
   2. Advection-Dispersion Transport Model
   3. Linear Equilibrium Adsorption/Desorption Model
   4. First-Order Chemical Decay Model

C. Saturated Zone Solute Transport Model (MOC)
   1. Two-Dimensional Flow Conditions
   2. Simulated Flow Tube Concept

MODEL PARAMETER ASSOCIATED UNCERTAINTY

A. Water Balance Model
   1. SCS Runoff Curve Number Model
      a. SCS Curve Number
   2. Evapotranspiration Model
      a. Root Constant Submodel
      b. Root Depth
      c. Crop Factor
   3. Recharge Model
      a. Available Moisture Capacity of Soil
      b. Percent of Total Area Paved

B. Unsaturated Zone Solute Transport Model (PRZM)
   1. Soil Field Capacity
   2. Soil Bulk Density
   3. Soil Adsorption
      a. K_{oc}
      b. f_{oc}
   4. Dispersion Coefficient
   5. Chemical Half-Life

C. Saturated Zone Solute Transport Model
   1. Hydraulic Conductivity
      a. Longitudinal or Horizontal Component
      b. Transverse or Vertical Component
   2. Dispersivity
      a. Longitudinal Component
      b. Transverse Component
   3. Aquifer Depth
   4. Effective Porosity

extent of chemical weathering may extend to as little as 11 m (35 ft) below the ground surface in some places to a depth in excess of 30 m (100 ft) in others. Representative soil and saprolite layer thicknesses were estimated from available boring logs from locations on Waiawa Ridge. At various locations on Waiawa Ridge, the unweathered basalt thickness was then determined from the known ground surface elevation, estimated soil and saprolite layer thicknesses, and assumed groundwater level. In terms of the long-term predictive PRZM simulations, the use of average soil and saprolite layer thicknesses probably has only a small effect on the results. In those areas with thinner weathered zones, chemicals may arrive at the water table sooner than predicted. However, in areas with thicker weathered zones, chemicals will have a longer transit time through the vadose zone. Thus, the primary effect of using average soil and saprolite thicknesses is to underestimate the initial arrival time of the chemicals to the groundwater table. For the long-term predictive simulations, however, the average concentrations in water pumped by Waiawa Shaft should not be influenced greatly by the use of average soil and saprolite layer thicknesses. In any event, there is insufficient data curently available to make more detailed estimates of the depth of weathering at all locations of interest. Furthermore, detailed information regarding the soil and saprolite layer thicknesses will never be available to eliminate all uncertainty. Thus it is reasonable to aggregate available information and utilize average values for soil and saprolite layer thicknesses.

For the long-term predictive simulations relevant to the Waiawa Valley development, there also exists uncertainty associated with the alluvium and saprolite thicknesses. However, the primary area of geological uncertainty associated with Waiawa Valley is the nature of the hydrologic connection between the alluvial and basal groundwater bodies. For the long-term simulations, it was assumed that the hydrologic connection was unimpeded. Thus, chemicals applied in Waiawa Valley which leached through the vadose zone into the alluvial aquifer were assumed to be readily transported to the basal aquifer. It is as reasonable to assume, however, that the alluvial and basal groundwater bodies are effectively separated by a relatively impermeable zone of weathering so that little transfer occurs from the alluvial aquifer to the basal groundwater body. Clearly, there is uncertainty associated with the nature of the hydrologic connection between the two groundwater bodies.

MODEL ASSOCIATED UNCERTAINTY

To minimize model associated uncertainty, ideally an integrated three-dimensional, saturated/unsaturated zone model which extends to the natural boundaries of the system should be employed. Due to time and data constraints, however, for the long-term predictive simulations three separate models were used in this study. These models were (1) a water balance model, (2) an unsaturated zone solute transport model (PRZM), and (3) a saturated zone solute transport model (MOC). Model associated uncertainty can be separated into these three areas.

Water Balance Model. The water balance model used in this study is similar to the model used by Giambelluca (1983, 1986). The model used in this study consists of a number of different submodels including (1) a runoff submodel, (2) an evapotranspiration submodel, and (3) a recharge submodel.

The SCS runoff curve number model was used to estimate runoff due to rainfall and irrigation water inputs to the soil. The SCS model assumes that runoff is a function of soil type, rainfall, and antecedent rainfall. The SCS model does not directly account for surface slope which may contribute to model uncertainty. Using observed rainfall and runoff data, Cooley and Lane (1982) calibrated the SCS model for pineapple and sugarcane watersheds in Hawaii. Giambelluca (1983) utilized a modified SCS model to disaggregate basin runoff as well as to estimate runoff in areas lacking streamflow data within the Pearl Harbor-Honolulu basin. Runoff estimates computed by Giambelluca (1983) compared favorably with the results of other studies. For this study, runoff estimates from urban areas were needed. Due to a lack of detailed rainfall, irrigation, and runoff measurements for urban areas on Oahu, the SCS model could not be calibrated for this study. However, in terms of its impact on the long-term chemical leaching simulations, the SCS model probably produces reasonable if not conservative estimates of runoff.

The evapotranspiration model developed for this study is discussed in detail in Appendix C of this report. Actual evapotranspiration is determined as a function of potential evapotranspiration and soil moisture availability during a given time interval. Actual evapotranspiration is assumed to occur at the potential rate for soil moisture conditions above the root constant. The model does consider the important factors influencing evapotranspiration rates. The model does not, however, directly account for local variations of such factors as net radiation, wind, and temperature which could affect evapotranspiration estimates. Such small-scale variations are impossible to predict. The impact of the uncertainty in the evapotranspiration model on the long-term chemical leaching simulations is thus difficult to assess.

For this study, recharge is assumed to occur at the end of a given time interval, after accounting for runoff and evapotranspiration water losses, if the soil water in the plant root zone is in excess of the available moisture capacity. It is likely that some recharge occurs even if the soil system has not reached its moisture capacity. However, for long-term simulations, the threshold concept of recharge has been successfully used for the Pearl Harbor-Honolulu basin (Giambelluca 1983).

For the long-term water balance simulations, there are a number of factors which contribute to uncertainty in the recharge estimates. For instance, the degree of hydraulic connectivity between the paved and unpaved areas in the proposed developments is not currently known and therefore cannot be accounted for by the model. In spite of the model uncertainties, the long-term predictive simulations appear to yield reasonable recharge estimates.

Unsaturated Zone Solute Transport Model (PRZM). The flow submodel of PRZM assumes one-dimensional flow conditions and employs a simple drainage rule to distribute water throughout the unsaturated zone profile. Uncertainty in the one-dimensional flow assumption was addressed in this study by simulating lateral spreading of recharge water occurring beneath unpaved areas of the proposed developments. The degree of lateral spreading of recharge can have a significant effect on the resulting chemical loading to the groundwater table for compounds that undergo hydrolysis in the unsaturated zone. Lateral spreading is likely in both project areas, thus the non-spreading scenario may be overly conservative in terms of groundwater protection.

The simple drainage rule used in the PRZM simulations does not account for macropore flow nor does it allow for the occurrence of perched water conditions. Thus, PRZM may underestimate the initial arrival of chemicals at the groundwater table because of macropore flow or because of exceptional vertical flow through the unweathered basalt. Although the presence of macropores may result in faster chemical transport to the groundwater table, the bulk of the solute mass may travel slower through the vadose zone which would lead to greater opportunity for chemical attenuation. Thus, the overall effect of PRZM's drainage rule may be an underestimation of the initial arrival time but an overestimation of long-term concentrations. PRZM may also overestimate chemical transport to the groundwater table by neglecting the retention of percolating water by perching members. The presence of a perching member was simulated by assuming that recharge occurring beneath unpaved areas would be distributed at the top of the saprolite.

It should be noted that the free drainage rule employed by PRZM may not realistically simulate the temporal response of water movement in the unsaturated zone due to recharge events occurring near the ground surface. In particular, the delayed effect of water movement at the bottom of the unsaturated zone column due to water input at the top of the column may not be accurately simulated with the free drainage assumption.

It should also be mentioned that PRZM does not simulate the upward movement of water due to moisture gradients. For long-term simulations, this leads to conservative estimates of chemical transport to the groundwater table.

The advection-dispersion equation used by PRZM assumes that chemicals are transported downward by both advection with the percolating water and by hydrodynamic dispersion. There does exist uncertainty as to the applicability of the advection-dispersion equation to the structured soils of the proposed Waiawa development areas. In some simulations, advection was enhanced by assuming no lateral spreading of recharge occurring beneath unpaved areas. Thus, chemical transport is allowed to occur rapidly beneath unpaved areas. This condition most likely overestimates the effects of macropore flow since the bulk of the water, rather than just a portion of it, is allowed to move down rapidly.

The linear adsorption/desorption model used by PRZM is expected to overestimate sorption for high chemical concentrations and underestimate sorption for low concentrations. For the long-term leaching simulations, the overall impact of the linear equilibrium adsorption model remains uncertain. Increased sorption over time in the near-surface soil probably reduces leaching more than the model predicts with laboratory values of sorption so that model estimates of leaching are conservative.

The uncertainty associated with the use of a first-order chemical decay model is difficult to assess due to the complex nature of the chemical degradation process. Microorganisms play a significant role in determining the persistence of organic chemicals in the soil layer. Where pesticides are able to absorb sunlight, photodecomposition may be a significant process. In addition, chemical reactions such as hydrolysis, oxidation, and reduction may also be important factors affecting the fate of chemicals in the unsaturated zone. Chemical transformations of pesticides may be affected by such factors as adsorption, temperature, pH, and moisture content. Uncertainty in published degradation rates, which were measured under conditions different than those existing in the study area, require caution in the interpretation of predicted chemical concentrations in percolating water. Where no data are available, order of magnitude estimates must be used with caution.

<u>Saturated Zone Solute Transport Model (MOC)</u>. The saturated zone solute transport model used for this study assumes that two-dimensional flow conditions exist in the study area. In the immediate vicinity of Waiawa Shaft, the flow pattern is probably not well represented by the two-dimensional MOC model.

The modeling effort in the saturated zone isolates a portion of the aquifer rather than extending to the natural boundaries of the aquifer. Thus, the choice of the model grid orientation becomes very significant. By orienting the grid in the direction of groundwater flow in the Waiawa area, lateral transfer of water into and out of the grid system can be minimized and the uncertainty associated with the flow tube concept of the modeling effort is reduced.

Ideally, a three-dimensional model which incorporates the natural boundaries of the aquifer should be used to minimize model uncertainty.

Based on the calibration simulations, however, the MOC model is capable of accurately simulating the magnitude of chemical concentrations at Waiawa Shaft. Thus, the uncertainty associated with the use of the MOC model may not be excessive.

INPUT DATA ASSOCIATED UNCERTAINTY

Each of the models used for the long-term predictive simulations in this study required input data to run. Input data associated uncertainty can be grouped by model.

Water Balance Model. The input data necessary for the water balance model include daily rainfall, irrigation, and potential evapotranspiration. Daily rainfall estimates were obtained by disaggregating monthly rainfall values, which were obtained with a computer interpolation scheme using historical monthly rainfall records. The underlying assumption of this approach is that the historical pattern of rainfall will accurately reflect conditions in the future. The input data used for this study thus do not account for the possible effects of future climate change on precipitation patterns.

The golf course irrigation rates used as input to the water balance model were based on actual golf course irrigation rates used throughout Hawaii. These golf course rates were then extrapolated to the residential areas of the proposed Waiawa developments. Future climatic conditions and water availability will influence irrigation rates, making it difficult to predict the exact irrigation patterns throughout the proposed development areas. However, irrigation practices will be adjusted to climatic conditions, with less water being applied when rainfall increases.

As with rainfall and irrigation, potential evapotranspiration is highly dependent on future climatic conditions which are difficult to accurately predict at this time. Thus, because all of the input data for the water balance model were based on historical records, there does exist some input data associated uncertainty. If the effects of global warming were incorporated into the input data estimates, uncertainty could conceivably be even greater. Again, irrigation management will likely compensate for most climatic variability.

Unsaturated Zone Solute Transport Model (PRZM). The uncertainty associated with the recharge estimates input to PRZM are discussed under the water balance model sections of this chapter. Other inputs to PRZM include estimates of chemical application rates, frequencies, and dates. Chemical applications in the surveyed Waipio Gentry area varied widely from household to household, which may indicate a large degree of uncertainty associated with the assumed chemical inputs from residential areas for the long-term predictive leaching simulations. There is also uncertainty associated with the assumed golf course chemical applications since chemical use patterns vary from course to course depending on the existing problems as well as the philosophy of the golf course manager.

Saturated Zone Solute Transport Model (MOC). The MOC model requires recharge estimates from the unsaturated zone as well as influx rates to the upgradient boundary of the model. Uncertainty in the recharge estimates is primarily linked to the water balance model. Since annual recharge values were used as input to the MOC model, the drainage rule employed by PRZM probably does not have a major impact on the timing of water inputs to the groundwater table from the unsaturated zone. The upgradient influx estimates are also based on a water balance computation and correspond well to current thinking on groundwater fluxes in that portion of the aquifer.

Well pumpage estimates were also required inputs to the MOC model. Based on existing well pumping patterns and current groundwater allocations, there does not appear to be a large amount of uncertainty associated with the pumpage estimates. However, possible climate changes in the future could alter recharge rates and groundwater usage patterns in the vicinity of the proposed Waiawa developments.

Annual chemical loading rates used as input to the long-term predictive simulations were obtained from PRZM output. Thus, any uncertainty associated with the chemical inputs to the groundwater table are linked to PRZM.

MODEL PARAMETER ASSOCIATED UNCERTAINTY

In addition to the model and input data associated uncertainties, there exists uncertainty associated with the selection of model parameters. As with the input data associated uncertainty, the parameter uncertainty may be grouped by model.

Water Balance Model. Each of the submodels of the water balance model requires parameter estimates. The runoff model requires estimates of runoff curve numbers for the different surface and soil conditions expected in the proposed developments. There have been no studies to optimize curve numbers for urban areas in Hawaii so the uncertainty associated with the estimated curve numbers may be significant. In terms of the overall effect on the long-term water balance simulations, however, the uncertainty in the runoff curve numbers may not have a large impact.

The evapotranspiration model used in this study requires estimates for plant root depth and crop factor as well as parameter estimates for the root constant model. Uncertainty in the plant root depth and crop factor parameters results from our inability to accurately predict the spatial and temporal distributions of vegetation types in the proposed development areas. Parameter estimates for the root constant model were obtained from Giambelluca (1983) who calibrated the model based on lysimeter studies by Ekern (1966b). Site specific information to validate the root constant model for future conditions is impossible to obtain. Thus the overall uncertainty in the evapotranspiration parameter estimates is difficult to assess.

The estimation of urban recharge for the long-term predictive simulations requires estimates for the available moisture capacity of the soils in the Waiawa study area as well as the extent of paving expected in the proposed developments. Soils within the proposed Waiawa developments generally have similar available moisture capacities so that uncertainty associated with this parameter is probably small. The extent of paving in the proposed developments can significantly affect recharge. Detailed plans of the proposed developments do not currently exist. Thus, the estimation of paved area was based on existing urban areas. Uncertainty in the paved area in the proposed developments is probably not large.

Unsaturated Zone Solute Transport Model (PRZM). PRZM requires estimates for field capacity, bulk density, and organic carbon content for each identified layer of the vadose zone profile. Much of the information used to identify these parameters was obtained from a study of core samples by Miller (1987). Thus, although there does exist some uncertainty associated with these parameters, there is some basis for establishing the approximate relationship of these parameters with depth.

There have been only limited studies in Hawaii to quantify dispersion in the unsaturated zone. In general, field-scale dispersivity has been shown to be directly related to distance. For the PRZM simulations, this phenomenon was simulated by increasing the dispersion coefficient with depth in the vadose zone profile. It should be noted, however, that PRZM employs time invariant dispersion coefficients which are independent of velocity fluctuations.

Chemical-related parameters required by PRZM include adsorption coefficients and first-order decay coefficients. In the case of the former, parameter estimates were obtained from laboratory experiments in conjunction with published literature values. Although there exists a wide range of uncertainty in adsorption coefficients, in general conservative values were used for this study.

In terms of the overall results of the predictive simulations, the chemical half-life probably contributes as much uncertainty as any other factor in this study. In particular, published values for hydrolysis rates of many pesticides are scarce. Thus, precise estimates of chemical loadings to the groundwater table remain uncertain. For metribuzin, uncertainty in the hydrolysis rate was addressed by assuming a range of chemical half-lives, which led to a wide range of chemical concentrations in water pumped by Waiawa Shaft. In addition to the hydrolysis rate, uncertainty associated with the mobility and persistence of the breakdown products of pesticides can make management decisions extremely difficult.

Saturated Zone Solute Transport Model (MOC). For the long-term predictive simulations, the MOC model appears to be relatively insensitive to the hydraulic conductivity, dispersivity, and effective porosity estimates. That is, changes in these model parameters appear to have minimal impact on the chemical concentrations in the aquifer and in water pumped by Waiawa Shaft. The parameter which has the greatest effect on model output is the effective aquifer depth. The depth of extraction of Waiawa Shaft was determined by model calibration. However, physical evidence to support the choice of effective aquifer depth for the long-term simulations does not exist. Thus, there remains some uncertainty as to the actual depth of extraction of the shaft.

SUMMARY

There are three primary areas of uncertainty associated with the overall assessment approach used in this study.

1. In terms of the predicted impacts of the proposed developments on the quality of water pumped by Waiawa Shaft, the greatest amount of uncertainty seems to be tied to the chemical half-life. In particular, the hydrolysis rates of the different pesticides in vadose zone water and groundwater can have a significant impact on the overall predictions. Uncertainty associated with the breakdown products of some chemicals reduces the level of confidence in model predictions for these chemicals.
2. Because the behavior of the overall modeled system is dependent on climate, our current inability to accurately predict future climatic conditions contributes to uncertainty in the results.
3. Finally, the uncertainty associated with the hydrologic connection between the Waiawa Valley alluvial aquifer and the basal groundwater body must be considered when interpreting model results.

9. RESULTS AND DISCUSSION

The long-term groundwater impact of development on Waiawa Ridge and in Waiawa Valley was assessed over the 37-yr simulation period using nitrate, metribuzin, and diazinon as test chemicals. In terms of health effects, application amounts in residential and golf course areas, and potential for leaching, nitrate-nitrogen is the fertilizer component of greatest concern. The herbicide metribuzin was used to assess the impact of pesticide use on the proposed golf courses in the Waiawa Master Plan, based on the quantity normally applied and its relative persistence and low sorption tendencies in soil. Diazinon is one of the more commonly used pesticides in residential areas and was therefore selected as the final test chemical for the groundwater simulations. In addition to the three chemicals mentioned above, potential leaching of the termiticide chlorpyrifos applied in trenches around the periphery of houses was tested.

The downward transport of chemicals in the unsaturated zone was simulated with PRZM. Chemical loading rates at the groundwater table from PRZM output were used as input to the areal MOC groundwater model. It should be mentioned that the models are capable of simulating chemicals other than those tested which may be of concern in the future. The models, however, are not currently suited to simulation of two-phase flow which would occur with immiscible liquids.

Since both land use patterns and the nature of water movement in the subsurface unsaturated zone were not well defined for the physical situation being modeled, it was necessary to examine several combinations of surface and subsurface conditions to determine those conditions under which undesirable impacts of chemical use could occur. Some conditions are less realistic than others. Different land use scenarios were tested, with each land use distribution resulting in a spatially different chemical loading from the unsaturated zone to the groundwater table. Three different unsaturated zone profiles possessing varying amounts of organic carbon in the soils were also employed. Possible effects of land grading were thus tested by using the different unsaturated zone profiles. In addition, the effect of the lateral spreading depth of recharge occurring beneath unpaved areas was tested. The various scenarios examined by modeling and the results obtained are presented in Tables 24 to 26. The results in the tables are summarized for each chemical in the text following the tables.

TABLE 24. SUMMARY OF PREDICTED LONG-TERM NITRATE CONCENTRATIONS UNDER TYPICAL PUMPING RATES AT WAIAWA SHAFT, OAHU, HAWAII

Land Use Scenario[1]	Plant Uptake Efficiency[2]	Conc. (mg/l) Avg.	Conc. (mg/l) Max.
Waiawa Ridge Urbanized and Waiawa Valley Open	High	0.5	0.5
	Low	2.5	2.9
Waiawa Ridge Irrig. Lawn and Waiawa Valley Open	High	0.6	0.7
	Low	3.7	4.8
Waiawa Valley Urbanized and Waiawa Ridge Open	High	0.3	0.3
	Low	0.5	0.6
Waiawa Valley Irrig. Lawn and Waiawa Ridge Open	High	0.3	0.3
	Low	0.6	0.7
Waiawa Ridge and Waiawa Valley Urbanized	High	0.5	0.5
	Low	2.5	2.9
Waiawa Ridge and Waiawa Valley Irrigated Lawn	High	0.6	0.7
	Low	3.8	4.8

[1]Urbanized land use scenarios correspond to proposed development land use distributions, whereas irrigated lawn land use scenario treats entire development area as pervious irrigated lawn area.

[2]High and low plant uptake efficiencies correspond to having 3% and 30%, respectively, of applied nitrogen available for leaching.

TABLE 25. SUMMARY OF PREDICTED LONG-TERM METRIBUZIN CONCENTRATIONS UNDER TYPICAL PUMPING RATES AT WAIAWA SHAFT, OAHU, HAWAII

Chemical Persistence[1]	Soil Layer[2]	Application Months	Golf Course Runoff[3]	Conc. (ng/l) Avg.	Conc. (ng/l) Max.
Medium	Partial	Apr., Oct.	yes	<0.1	<0.1
Medium	Partial	Jan., July	yes	<0.1	<0.1
Medium	Scraped	Jan., July	yes	1.0	1.8
Medium	Scraped	Jan., July	no	1.8	3.5
High	Retained	Jan., July	yes	2480.	2830.
High	Partial	Apr., Oct.	yes	3030.	3440.
High	Partial	Jan., July	yes	3410.	3870.
High	Scraped	Jan., July	yes	4160.	5020.
High	Scraped	Jan., July	no	4280.	5550.

NOTE: Land use scenario based on proposed Waiawa Master Plan. Metribuzin 1assumed to be applied only on golf courses.

[1]Refers to metribuzin persistence once beyond the soil layer. Medium persistence corresponds to a hydrolysis half-life of 200 days whereas high persistence corresponds to an infinite half-life.

[2]A partial soil layer is one in which 0.2 m of the original soil is lost to land grading, whereas a scraped soil layer is one in which 0.5 m is lost to grading.

[3]Pesticide losses from golf courses due to runoff are assumed to be negligible. However, runoff affects the amount of water available for recharge.

TABLE 26. SUMMARY OF PREDICTED LONG-TERM DIAZINON CONCENTRATIONS UNDER TYPICAL PUMPING RATES AT WAIAWA SHAFT, OAHU, HAWAII

Land Use Scenario	Recharge Spreading[1]	Persistence in Groundwater[2]	Soil Layer[3]	Conc. (ng/l) Avg.	Conc. (ng/l) Max.
Waiawa Ridge Urbanized and Waiawa Valley Open	yes	Medium	Retained	<0.1	<0.1
	yes	Medium	Partial	<0.1	<0.1
	yes	Medium	Scraped	0.7	1.5
	yes	High	Retained	<0.1	<0.1
	yes	High	Partial	<0.1	<0.1
	yes	High	Scraped	2.1	3.9
	no	Medium	Partial	2.6	5.8
	no	Medium	Scraped	83.9	199.3
	no	High	Partial	8.1	15.6
	no	High	Scraped	242.9	500.6
Waiawa Valley Urbanized and Waiawa Ridge Open	yes	Medium	Retained	1.2	3.5
	yes	Medium	Partial	2.0	5.8
	yes	Medium	Scraped	5.1	15.5
	yes	High	Retained	2.0	6.0
	yes	High	Partial	3.4	10.0
	yes	High	Scraped	8.9	25.9
	no	Medium	Partial	20.9	61.1
	no	Medium	Scraped	47.3	125.6
	no	High	Partial	36.5	103.3
	no	High	Scraped	82.5	214.4
Waiawa Ridge and Waiawa Valley Urbanized	yes	Medium	Retained	0.9	2.4
	yes	Medium	Partial	1.5	3.9
	yes	Medium	Scraped	4.6	11.6
	yes	High	Retained	1.6	4.0
	yes	High	Partial	2.6	6.8
	yes	High	Scraped	8.9	20.8
	no	Medium	Partial	18.1	45.5
	no	Medium	Scraped	114.7	270.1
	no	High	Partial	36.0	83.6
	no	High	Scraped	298.2	612.4

[1]Recharge beneath unpaved areas is assumed to either spread laterally at a depth of 5 m below the ground surface or move downward to the water table without spreading beneath the paved areas.

[2]Chemical persistence refers to diazinon persistence in the groundwater. Medium persistence corresponds to a hydrolysis half-life of 200 days whereas high persistence corresponds to an infinite half-life.

[3]A partial soil layer is one in which 0.2 m of the original soil is lost to land grading, whereas a scraped soil layer is one in which 0.5 m is lost to grading.

NITROGEN FERTILIZERS

1. Nitrate concentrations in Waiawa Shaft water under typical pumping conditions should remain within 0.5 mg/l of the existing background level if lawns in the Waiawa Master Plan land use distribution effectively uptake nitrogen such that only 3% of the applied amount is available for leaching. With efficient plant uptake and denitrification, 3% nitrogen availability for leaching is achievable with such plants as California grass.
2. Nitrogen fertilizers applied on Waiawa Ridge should not cause nitrate levels in water pumped by Waiawa Shaft to exceed the drinking water standard of 10 mg/l under a land use pattern and recharge condition conducive to leaching even for low nitrogen plant uptake efficiencies.
3. For nitrogen fertilizers applied in the proposed Waiawa Valley development, nitrate concentrations in water pumped by Waiawa Shaft under typical operating conditions should remain well within 0.1 mg/l of the existing background level if interflow between the alluvial groundwater body of Waiawa Valley and the basal aquifer is complete and rapid, and if lawns planted in the proposed Waiawa Valley development effectively uptake nitrogen such that only 3% of the applied amount is available for leaching.
4. Nitrogen applied in the proposed Waiawa Valley development should not cause nitrate concentrations in Waiawa Shaft water to increase by more than 1 mg/l above the existing background level at typical operating withdrawal rates even for a land use pattern, recharge condition, and nitrogen plant uptake efficiency conducive to leaching.
5. The effect of development of both Waiawa Ridge and Waiawa Valley on the nitrate concentrations in water pumped by Waiawa Shaft will likely be dominated by the nitrogen applications on Waiawa Ridge. Nitrogen fertilizers applied in the proposed Waiawa Ridge and Waiawa Valley developments should not cause nitrate levels in water pumped by Waiawa Shaft to exceed the drinking water standard of 10 mg/l.

6. Since nitrate is relatively unaffected by adsorption to organic carbon, the amount of grading during construction of the proposed developments should not significantly affect the nitrate leaching process, provided that enough soil is available for healthy plant growth.
7. The amount of lateral spreading of the recharge wetting front affects the timing of nitrate loading to the groundwater table but has little long-term influence on the nitrate concentrations in water pumped by Waiawa Shaft.

METRIBUZIN

1. Typical semiannual chemical applications of metribuzin on golf course areas should not produce concentrations exceeding 0.1 ng/l in groundwater pumped by Waiawa Shaft at typical extraction rates if an adequate amount of organic carbon exists in the soil profile to retard the downward movement of chemicals and if the hydrolysis half-life of metribuzin is less than 1 yr.
2. Semiannual chemical applications of metribuzin on golf courses may produce concentrations on the order of approximately 1 ng/l in groundwater pumped by Waiawa Shaft at typical pumping rates if the top soil layer is removed from golf course areas, and if metribuzin has a hydrolysis half-life of 1 yr. Metribuzin concentrations at Waiawa Shaft could approach a few ng/l if, in addition to the above conditions, there are no water losses due to runoff from golf courses.
3. Semiannual metribuzin applications on golf courses could result in concentrations of a few thousand ng/l in water pumped by Waiawa Shaft under typical operating conditions if metribuzin is assumed to be persistent once beyond the soil layer. The extent of the contamination can be reduced considerably by maintaining a top soil layer. Persistence of metribuzin in groundwater is not known.
4. If metribuzin applications occur on a semiannual basis, applications occurring in the months of April and October produce slightly less leaching and consequently lower groundwater

concentrations than similar applications in the months of January and July.

5. As a result of semiannual chemical applications of metribuzin on proposed Waiawa Ridge golf courses, concentrations in water pumped by Waiawa Shaft should not exceed the EPA lifetime health advisory for drinking water of 200 µg/l. Current data are inadequate to determine the carcinogenicity of metribuzin. If metribuzin is found to be carcinogenic as more data become available, the lifetime health advisory will likely be set at a much lower level.

DIAZINON

1. Diazinon applied in the proposed Waiawa Ridge development should not cause concentrations in Waiawa Shaft water to exceed 0.1 ng/l if soil containing organic carbon is retained at the surface and lateral spreading of recharge beneath paved areas is assumed to occur at a depth of 5 m below the ground surface.
2. Diazinon applications in urban areas on Waiawa Ridge could result in concentrations of about 1 ng/l in water pumped by Waiawa Shaft under typical operating conditions if soil containing organic carbon is scraped from the surface, lateral spreading of recharge beneath paved areas is assumed to occur at a depth of 5 m below the ground surface, and diazinon has a hydrolysis half-life of 200 days in groundwater. In addtion to the above conditions, if diazinon is persistent in the groundwater, concentrations at Waiawa Shaft could reach a few ng/l.
3. Diazinon applications in urban areas on Waiawa Ridge could result in concentrations of a few to several ng/l in water pumped by Waiawa Shaft at typical operating conditions if there is only a partial loss of the soil layer due to grading, lateral spreading of recharge beneath paved areas is minimal, and diazinon has a hydrolysis half-life of 200 days in groundwater. Completely scraping off the soil layer may result in concentrations at Waiawa Shaft to reach about 200 ng/l. If, in addition, diazinon is persistent in groundwater, concentrations at Waiawa Shaft may approach 500 ng/l.

4. Diazinon applications in the USN property could result in concentrations of a few ng/l in water pumped by Waiawa Shaft at typical pumping rates if (1) there is an adequate amount of organic carbon in the soil, (2) recharge beneath paved areas in the proposed Waiawa Valley development spreads laterally at a depth of 5 m below the ground surface, (3) interflow between the alluvial groundwater body of Waiawa Valley and the basal aquifer is assumed to be unimpeded, and (4) diazinon has a hydrolysis half-life of 200 days in groundwater. If the soil layer is scraped from the surface, resulting concentrations at Waiawa Shaft could exceed 10 ng/l.
5. If recharge beneath the pervious areas in the proposed Waiawa Valley development does not move laterally to a significant extent, diazinon applications in the USN property could result in concentrations of a few to several tens of ng/l in water pumped by Waiawa Shaft at typical pumping rates if (1) the top soil layer containing organic carbon is only partially scraped, (2) interflow between the alluvial groundwater body of Waiawa Valley and the basal aquifer is assumed to be unimpeded, and (3) diazinon has a hydrolysis half-life of about 200 days in groundwater. If the soil layer is scraped from the surface, resulting concentrations at Waiawa Shaft may exceed 100 ng/l.
6. Because of the relatively close distance between the diazinon source areas and the Waiawa infiltration tunnel, travel time in the saturated zone for diazinon applied in the USN Waiawa Valley development is fairly short. Thus, all other factors being equal, the difference between a 200 day and an infinite hydrolysis half-life in the groundwater is less than a doubling of concentrations at Waiawa Shaft for diazinon applied in Waiawa Valley.
7. Diazinon applications in the proposed Waiawa Ridge and Waiawa Valley developments could result in concentrations of a few ng/l in water pumped by Waiawa Shaft at typical pumping rates if (1) there is an adequate amount of organic carbon in the soil, (2) recharge beneath paved areas in the proposed Waiawa Valley

development spreads laterally at a depth of 5 m below the ground surface, (3) interflow between the alluvial groundwater body of Waiawa Valley and the basal aquifer is assumed to be unimpeded, and (4) diazinon has a hydrolysis half-life of 200 days in groundwater. If the soil layer is scraped from the surface, resulting concentrations at Waiawa Shaft could exceed 10 ng/l.

8. If recharge beneath the pervious areas in the proposed Waiawa Ridge and Waiawa Valley developments does not move laterally to a significant extent, diazinon applications in the two developments could result in concentrations of a few tens of ng/l in water pumped by Waiawa Shaft at typical pumping rates if (1) the top soil layer containing organic carbon is only partially scraped during grading, (2) interflow between the alluvial groundwater body of Waiawa Valley and the basal aquifer is assumed to be unimpeded, and (3) diazinon has a hydrolysis half-life of about 200 days in groundwater. If the soil layer is scraped from the surface, resulting concentrations at Waiawa Shaft may exceed 250 ng/l.
9. Diazinon concentrations in water pumped by Waiawa Shaft may exceed the EPA lifetime health advisory for drinking water of 600 ng/l if (1) Waiawa Ridge and Waiawa Valley are developed, (2) conditions are conducive to chemical leaching (no lateral spreading of recharge and low organic carbon in the top soil), and (3) diazinon is persistent in groundwater.
10. For diazinon applied only in the apartment and commercial/industrial areas near the western boundary of the proposed Waiawa Ridge development, model results indicate that concentrations at Waiawa Shaft should remain below 1 ng/l under typical operating conditions provided that a hydrolysis half-life of 200 days is appropriate for diazinon.
11. For diazinon applied only in the apartment and commercial/industrial areas near the western boundary of the proposed Waiawa Ridge development, concentrations at Waiawa Shaft may exceed 10 ng/l under typical operating conditions if it is assumed that (1) no hydrolysis of diazinon occurs in

groundwater, (2) soil organic carbon is significantly depleted, and (3) lateral spreading of recharge is minimal.

12. For diazinon applied only in the proposed residential areas toward the periphery of the zone of contribution of Waiawa Shaft, diazinon concentrations at Waiawa Shaft may average about 15 ng/l under typical operating conditions if it is assumed that (1) soil organic carbon is significantly depleted, (2) lateral spreading of recharge is minimal, and (3) a hydrolysis half-life of 200 days is appropriate for diazinon in the saturated zone. If hydrolysis of diazinon in groundwater is minimal but the other conditions mentioned above remain unchanged, concentrations at Waiawa Shaft may average about 40 ng/l.

CHLORPYRIFOS

1. Leaching of the termiticide chlorpyrifos applied in trenches around the periphery of a house is minimal even under concentrated recharge conditions due to runoff from rooftops. More mobile termiticides, however, may pose a more significant threat especially if subjected to concentrated recharge conditions.

In general, for chemicals which are affected by adsorption, maintaining an adequate top soil layer which contains organic carbon can have a positive effect in terms of groundwater quality protection. The effectiveness of the top soil layer is dependent on the amount of organic carbon present as well as the characteristics of the chemical being used. Because chemical degradation in soil varies with the pesticide being considered, it would be difficult to specify a minimum amount of organic carbon which would result in concentrations on the order of 1 ng/l in water pumped by Waiawa Shaft for all possible chemicals. However, if it is possible, an adequate top soil layer which contains organic carbon should be maintained. Thus, any imported soil which may be used for the proposed golf courses on Waiawa Ridge should be monitored to ensure that the material is not subsoil lacking organic carbon. In addition to chemical retention and degradation in the soil, hydrolysis of chemicals during the long downward transit through the vadose zone can further limit the potential for groundwater contamination.

Lateral spreading of recharge occurring beneath pervious areas is an extremely important mechanism controlling transport of chemicals through the unsaturated zone. In the absence of such spreading of the recharge wetting front, chemical loading rates to the groundwater could significantly increase. Although it would be difficult to control the lateral spreading of the recharge water in the vadose zone, it is possible to avoid recharge conditions at the ground surface which are conducive to chemical leaching. For instance, the use of gutters to divert the rain water received on rooftops can eliminate concentrated recharge conditions around the periphery of buildings.

10. CONCLUSIONS AND RECOMMENDATIONS

For this study, a modeling approach was used to determine the potential for groundwater contamination due to proposed urban development in the Waiawa area of central Oahu. Specifically, it was the goal of this research to assess the potential impact of development on the quality of groundwater pumped by the USN Waiawa Shaft. It must be empahsized that it was neither the intent nor the goal of this study to conduct a risk assessment. Results of this study, however, could be used as input to a risk assessment to determine the potential harm to humans as a result of exposure to chemicals in the potable water supply.

A water balance model was employed to obtain estimates of groundwater recharge for various future land use scenarios in the study area. Recharge estimates from the water balance model were used as input to a one-dimensional finite difference model, PRZM, designed to simulate solute transport in the unsaturated zone. Different test chemicals were simulated to determine the chemical loading rates to the groundwater table. The test chemicals ranged from the highly mobile (nitrate) to the highly immobile (chlorpyrifos). Spatially varying chemical loading rates determined from PRZM were used as input to the two-dimensional areal MOC model in order to simulate solute transport in the saturated zone. The chemicals nitrate, metribuzin, and diazinon were tested individually in the saturated zone simulations, and long-term results for the various scenarios were presented as time series of chemical concentrations in water pumped by Waiawa Shaft. The test chemicals selected appeared to be those most likely to impact groundwater quality.

Although there exists uncertainty in the models and data used, a wide range of conditions and assumptions was tested to ensure that the various solute transport phenomena and potential impacts were adequately addressed. It should be noted that some of the assumptions, such as the assumption that recharge does not move laterally beneath pervious areas, may be conservative. However, it is necessary to demonstrate the possible effects of urbanization with conservative assumptions to account for uncertainty. This approach also proved to be instructive in identifying areas where possible managemant practices could be implemented to reduce the potential for groundwater contamination. Based on the modeling results of this study, the following conclusions resulted.

1. Nitrogen Fertilizers. In terms of the nitrogen component, fertilizers applied in the USN Waiawa Valley development and the Waiawa Master Plan development should not cause nitrate concentrations in the water pumped by Waiawa Shaft to exceed the drinking water limit of 10 mg/l. Under extreme conditions, nitrate concentrations might reach levels of about 5 mg/l if Waiawa Ridge is developed.

2. Golf Course Pesticides. With regard to chemicals applied on the proposed golf courses of the Waiawa Master Plan, the impact on groundwater may be minimal or significant depending on the chemical used. Metribuzin was used as a test chemical for the proposed golf course areas in the modeling analysis. When a hydrolysis half-life of about 1 yr is assumed for the chemical, the relatively long travel time through the intermediate vadose zone below the soil enhances the opportunity for chemical decay. Resulting concentrations in water pumped by Waiawa Shaft could then be expected to range from nondetectable levels to a few ng/l depending on the amount of organic carbon maintained in the soil by golf course personnel. However, if metribuzin is assumed to be persistent once below the soil layer, concentrations in water pumped by Waiawa Shaft could approach a few thousand ng/l. Thus, the impacts of golf course applications on groundwater quality are very sensitive to assumed chemical characteristics.

3. Diazinon--Waiawa Ridge. Under extreme leaching conditions where the top soil layer is removed and lateral spreading of recharge beneath residential areas does not occur, diazinon applications in the proposed residential areas on Waiawa Ridge may result in concentrations in groundwater pumped by Waiawa Shaft to be on the order of tens to hundreds of ng/l. By retaining the top soil layer, and with it a significant amount of organic carbon, resulting concentrations at Waiawa Shaft can be reduced to levels below 20 ng/l. Because the severe recharge conditions mentioned above are not likely to occur over the entire development area, the concentrations are probably overestimated. It should be mentioned, however, that if a different, more persistent pesticide should become available and as popular as diazinon, the concentrations may even be underestimated. When recharge occurring beneath unpaved areas spreads laterally, the downward rate of water movement decreases and travel time through the vadose zone increases, thereby enhancing the opportunity for chemical decay. Thus, under conditions which are probably more representative of the spreading phenomenon of the recharge wetting front, diazinon applications in residential areas on Waiawa Ridge should result in concentrations in groundwater pumped by Waiawa Shaft below 5 ng/l.

4. Diazinon--Waiawa Valley. For the USN proposed Waiawa Valley development, the exact nature of the hydrologic connection between the alluvial groundwater body and the basal aquifer is not precisely known. For this study, an unimpeded interflow was assumed to exist between the two groundwater bodies. Under this condition, diazinon applications in the proposed Waiawa Valley development may result in concentrations in groundwater pumped by Waiawa Shaft to range between a few to a few hundred ng/l depending on the amount of top soil retained, the extent of lateral spreading of recharge in the vadose zone, and the degree of hydrolysis of diazinon in groundwater.
5. Diazinon--Waiawa Ridge and Waiawa Valley. If the hydrologic connection between the alluvial groundwater body and the basal aquifer is unimpeded, diazinon applications in both the Waiawa Ridge and Waiawa Valley developments may result in diazinon concentrations in groundwater pumped by Waiawa Shaft of a few hundred ng/l under extreme leaching conditions where the top soil layer is removed and no lateral spreading of recharge occurs. Under conditions which are probably more representative of the downward movement of the recharge wetting front, diazinon applications in both residential areas should result in concentrations in groundwater pumped by Waiawa Shaft below 25 ng/l. If there is no transfer between the alluvial groundwater body and the basal aquifer because of an impermeable weathered zone, recharge from the Waiawa Valley development will not contribute to the shaft output. Thus, concentrations in water pumped by Waiawa Shaft will likely be close to those predicted by the Waiawa Ridge only development scenario, but may differ slightly because the zone of contribution of the shaft will shift in the absence of recharge to the basal aquifer from portions of Waiawa Valley.
6. Termiticide Applications. The parent compound of chlorpyrifos, the most commonly used termiticide in Hawaii, should not pose a significant threat to groundwater quality in the study area. It is possible, however, that metabolites of chlorpyrifos may occur in significant quantities as a result of breakdown of the parent compound. Other, more mobile termiticides could pose a threat to groundwater quality if subjected to concentrated recharge conditions such as where roofs are not equipped with a gutter system.

Based on the results and conclusions of this study, the following general guidelines are recommended:

1. Results of the nitrate simulations indicate that persistent chemicals applied in either of the proposed development areas have the potential of contaminating the groundwater. The historical rise and then decline of chloride concentrations in water pumped by Waiawa Shaft supports the results of the potential threat of highly persistent and mobile chemicals. Fortunately, however, most of the pesticides currently used in urban areas are

not highly persistent and mobile. In golf course areas where chemical applications can be somewhat regulated and controlled, an effort should be made to reduce the potential impact of pesticides by using only those chemicals which are not persistent and which have only harmless products after breakdown. Because residential areas are difficult to control, the use of highly mobile and persistent chemicals should be restricted to reduce the potential for groundwater contamination.

2. In all areas where pesticides might be applied, removal of organic carbon with the top soil layer should be avoided since the organic carbon can effectively reduce leaching of some problematic chemicals. Any imported soil which is to be used as top soil should be monitored to ensure that the material is not subsoil with a low organic carbon content.

3. Because termiticides applied in trenches around the periphery of houses may be subjected to concentrated recharge events from rooftop runoff, gutters should be incorporated in the design of buildings. In addition, ponding of water above the termiticide applications should be avoided by proper sloping of the ground away from the building.

4. If it is the intent of decision makers to absolutely avoid <u>any</u> risk of potential groundwater contamination, then the only possible land uses for Waiawa Ridge are those which altogether preclude chemical usage. The potential for groundwater contamination, however, can be greatly reduced with proper urban management practices. The extent to which the groundwater is impacted is highly dependent on the chemical properties of the pesticide as well as the conditions in the soil. In addition, management practices to control excessive recharge in problem areas can reduce potential leaching.

Studies such as this one help to delineate areas where the quality and quantity of existing data are deficient. Further research is needed to help better our undertanding of the physical and chemical processes which affect solute transport in the unsaturated and saturated zones. In particular, the following research needs should be addressed.

1. If the persistence of a particular pesticide which could be used heavily in the development areas is unknown, further quantitative studies should be conducted to obtain this information. In particular, hydrolysis studies are much needed to quantify the extent of chemical transformation during the long transit time through the intermediate vadose zone. The U.S. Environmental Protection Agency (EPA) is currently attempting to determine hydrolysis rates based on the molecular structure of different pesticides. When available, results of the EPA study should be extremely informative. It is beyond the scope and capability of this study to determine hydrolysis rates.

2. Behavior of many of the breakdown products of pesticides in the unsaturated and saturated zones is largely unknown. If the breakdown products of pesticides are a health hazard, emphasis should be placed on characterizing their mobility and persistence in the vadose and saturated zones.

3. The results of this study indicate that certain pesticides applied in either the Waiawa Master Plan community or the USN Waiawa Valley development can reach the groundwater. The use of persistent and mobile chemicals in the USN Waiawa Valley property may result in no or minimal basal groundwater contamination to undesirable contamination levels depending on the nature of the interflow between the alluvial and basal aquifers. The use of persistent and mobile chemicals on Waiawa Ridge will likely lead to measureable concentrations at Waiawa Shaft. Whether or not these levels are acceptable will depend on the results of a risk assessment. A risk assessment and risk management analysis should be conducted to fully assess the impacts of the proposed developments.

4. If there is an unimpeded interflow between the alluvial groundwater body and the basal aquifer, pesticides applied in the USN proposed Waiawa Valley development may result in measureable concentrations at Waiawa Shaft. This is due partially to the shallow depth below the ground surface to the saturated zone as well as the short distance from the chemical source areas and the discharge point at Waiawa Shaft. Because travel times are reduced, chemical decay is also reduced. It should be emphasized, however, that the exact nature of the hydrologic pathways between the two groundwater bodies is not precisely known. It is likely that the weathered basalt separating the two is an effective barrier reducing flow from the alluvial aquifer to the basal aquifer. If this is the case, most of the groundwater in the alluvium will be expected to move downgradient, within the confines of the weathered basalt, to discharge points beyond the zone of contribution of Waiawa Shaft. Without further information on the subsurface valley geohydrology, however, it is difficult to assess the amount of chemical transfer from the alluvial to the basal aquifer. Thus, a geological investigation to quantify the extent of interflow between the two groundwater bodies should be conducted.

5. The importance of macropore flow in the unsaturated zone and the behavior of chemicals in the deeper vadose zone remains largely unknown. Field work should be conducted to better characterize chemical transport in the unsaturated zone under Hawaii's unique conditions.

6. Other methods of reducing recharge in chemical application areas could be studied. For instance, growing xerophytic plants which require less irrigation could be studied as an alternative to current urban lawn and garden plants. The impact of a xerophytic plant cover on recharge, however, should be studied since evapotranspiration is greatly suppressed. In addition, the nature and amounts of chemicals used to cultivate such plants must be studied.

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APPENDIX A. FIELD STUDIES

WAIAWA VALLEY CHEMICAL LEACHING STUDY

To obtain observed field data necessary for computer model calibration and validation, chemical leaching experiments were conducted in Waiawa Valley where the USN is planning to develop. One experimental test site, which was divided into four separate subplots, was established in Waiawa Valley. One of the subplots was reserved for soil hydraulic tests. Selected chemicals were applied on the three remaining test subplots and allowed to move downward through the soil with rainfall and irrigation water. Soil samples were collected periodically at various depths to determine the extent of chemical movement through the soil. The field study setup and methodology are explained in detail below.

Site Selection. In December 1987, a reconnaissance investigation was conducted to determine preliminary locations of the field test plots in Waiawa Valley. A second site investigation was conducted in February 1988 to better determine the locations of the field test plots in the USN proposed development area. A walk-through survey revealed a wide variety of existing flora, including extremely dense growths of guinea grass and koa-haole. In addition, five double rows of large concrete bomb shelter parts, including parabolic-shaped shelters lying on their front edges along with slab end pieces, extend along the bottom of the western talus slope for a distance of approximately 180 m toward the northern boundary of the area. The concrete shelters were apparently designed to stand vertically as parabolic-shaped arches with a height of approximately 2.7 m. The outside dimension of the base of each arch is approximately 4 m. The arches, which are 1.4 m long, were designed to stand face to face and form a tunnel-like shelter. Concrete thickness varies from 0.25 m at the base to 0.4 m at the arch invert.

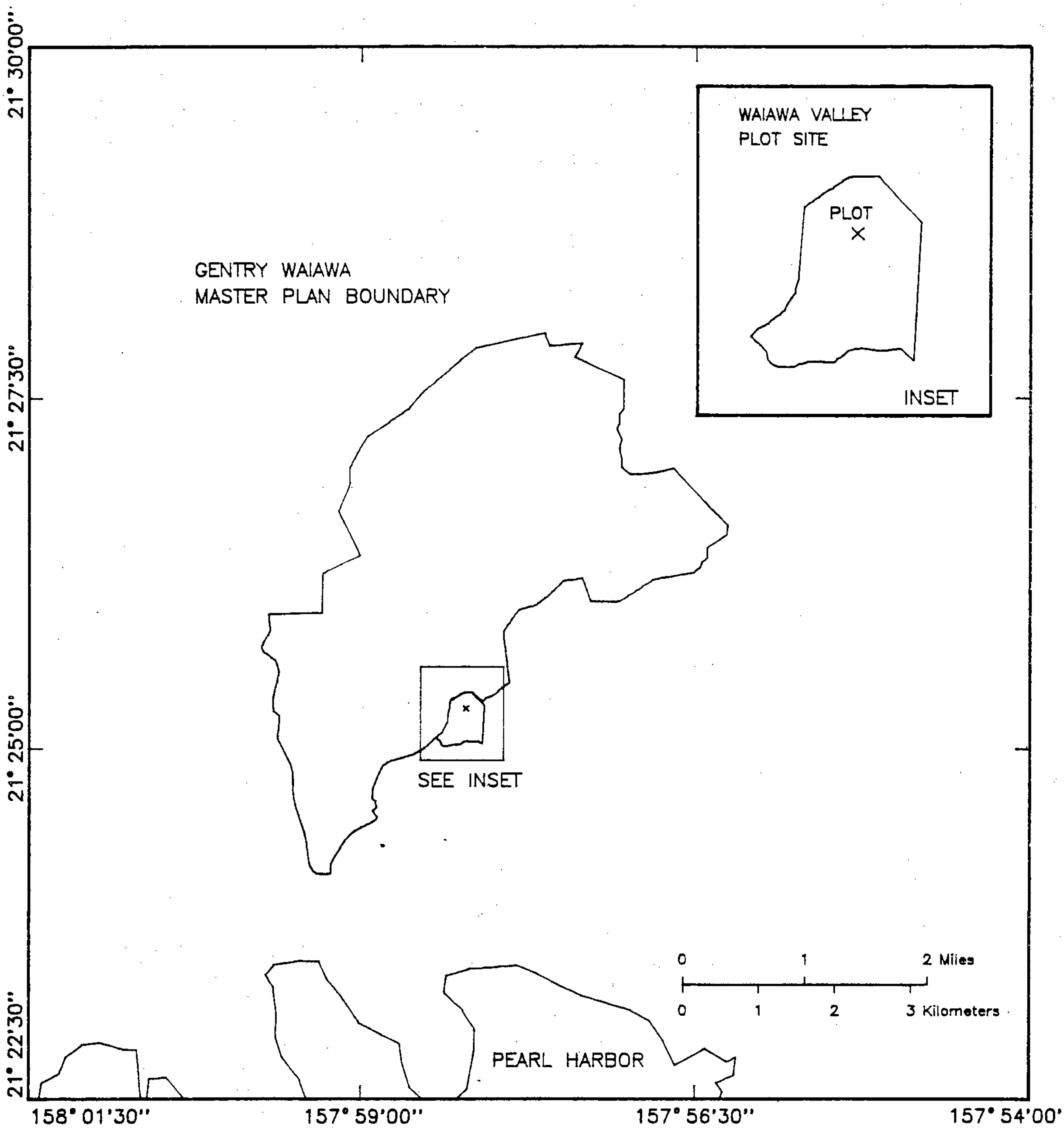
A number of factors were considered in selecting a particular plot location. First, only those areas affected by the proposed USN development were considered. Thus, the small portion of USN land on the western ridge and the steeper-sloped areas were not considered. Second, in order to obtain meaningful temporal leaching data for model calibration, the plot had to possess relatively uniform areal soil conditions. Third, areas with very sticky soils were avoided because pesticide residues would not likely leach significantly within the study period to allow for model calibration. In addition, from a practical standpoint, it was necessary to avoid extremely rocky areas to collect intact or uncontaminated soil samples with hand augers. Finally, only those areas with reasonable acccessibility were considered because plot establishment, maintenance, and irrigation require transportation of equipment.

The transport of equipment and safety were considerations, thus, the selection of desirable locations was based on proximity to an existing road and not having to cross Waiawa Stream. A number of test holes were augered at various locations within the USN Waiawa study area to obtain information regarding existing soil conditions. Augering at locations between the existing road and Waiawa Stream was severely hindered by the presence of rocks and fill material. (Inspection of an aerial photograph taken in 1951 indicates that construction fill or perhaps excavation material from the Waiawa development tunnel may have been deposited near the road toward the southern boundary of the area.) Test holes were also augered on the west side of the road (approximately 420 m up the road from the bridge crossing Waiawa Stream at the southern boundary of the area) in an area with relatively sparse vegetation. From a practical standpoint, taking into consideration land clearing and accessibility, this area appeared to be an ideal location for a test plot. However, several holes which were augered throughout the area revealed why the vegetation had not proliferated as in an adjacent area to the north. Soils were very sticky, with the consistency of modeling clay, and gray in color. These soils may have originated from the cut made along the western talus slope. Pesticides applied onto such soils would not be expected to leach sufficiently to allow for proper model calibration. Toward the northern boundary of the USN property lie perhaps thousands of concrete shelter structures. These large concrete structures preclude the placement of a plot toward the northern boundary of the property. In addition, the presence of metal landing mats and rocks near the northern boundary greatly hampered augering.

South of the concrete shelters and west of the existing road, six test holes were augered (5 February 1988) successfully to depths exceeding 1 m. Three of the holes, spaced approximately 10 m apart, were augered along a line running roughly east-west which was about 20 m south of the bunkers. The remaining three holes were similarly spaced and located along a line 20 m further south. None of the test holes gave any indication of major problems such as the presence of heavy clays. The soil in the area appeared to be spatially uniform. Soil was typically dark brown near the surface with some rocks. Once below the top 0.1 m, material encountered was generally loose weathered subsoil ranging in color from light brown to orange. The hand augers were able to cut through weathered basalt rock when encountered. Occasionally, a thin layer of darker brown material was found at approximately 1 m.

Plot Preparation. The overall uniformity of soil conditions in the vicinity of the test holes south of the concrete shelters made this particular location a prime candidate for a plot (App. Fig. A.1). In addition, the soil was relatively loose which would enhance the likelihood for measurable pesticide leaching. Vegetation in the area, which consisted primarily of a dense growth of 2 m tall guinea grass, koa-haole trees, and guava trees, was cut by hand or with the aid of gasoline powered weed cutters, equipped with circular blades, and a chain saw. Although the clearing process took a crew of four several days to complete, hand clearing was preferred to avoid the use of heavy equipment which would disturb the soil and leave voids with the uprooting of trees.

Existing vegetation over a total area of approximately 25 m x 25 m was cut. After hauling off the grass and trees from the cleared area, the plot corners were marked. Actual plot dimensions were 10.6 m x 10.6 m. An effort was then made to rake the excess organic matter from the soil surface of the plot. The major concern was that large amounts of organic matter which would not be present under developed conditions would tend to adsorb excessive quantities of applied pesticides. Holes were then augered at the plot corners, at the midpoints between plot corners, and at the center of the plot to further check soil uniformity. This series of holes thus formed a three by three sampling grid over the plot area. Soil was spatially uniform over the plot. A typical profile consisted of brown



Appendix Figure A.1. Experimental field plot site in Waiawa Valley, Oahu, Hawaii to dark brown soil (mapped as Kawaihapai stony clay loam [Foote et al. 1972]) at the surface, with some rocks occurring within the top 0.05 to 0.1 m, grading into light brown to orange-brown weathered soil beneath 0.1 m. Soil samples were collected every 0.3 m and were analyzed for organic carbon. Markers, including steel posts at the corners, were placed in each of the augered holes.

To prevent unquantifiable amounts of surface runoff from entering the plot, a berm and interception ditch system was constructed around all four sides of the plot. A continuous interception ditch, 0.1 to 0.15 m deep and 0.45 m wide, was dug along the four sides of the plot and an earthen berm approximately 0.15 to 0.2 m high was built inside the trench (between the plot boundary and the interception ditch) around the plot periphery. By building the berm and interception ditch system, runoff into or off of the plot cannot occur, thus eliminating it as a factor in the plot water balance.

Preparation of the field plot in the USN development area required a tremendous amount of manpower to remove considerable amounts of existing vegetation. Although additional plots could have been prepared within the USN land, desirable areas were not available from both a practical as well as a scientific standpoint. Rather than committing valuable resources to additional field plots which would not yield any useful scientific information, the selected site was divided into three independent subplots and one hydraulic test plot for the chemical leaching study. This approach allowed for greater replication of results at the one selected test site rather than poorer replication at more test sites.

Soil Classification. In order to have a representative of the U.S. Soil Conservation Service (SCS) classify the soil in the vicinity of the Waiawa Valley plot, a rectangular pit approximately 1.65 m deep was manually dug near the southwest corner of the plot. Mr. Saku Nakamura, a soil scientist with the SCS, examined the pit on 16 February 1989. His soil description is provided as Attachment A.1.

Selection of Test Chemicals. Only pesticides which are registered by the EPA were considered for the Waiawa Valley field study. The chemicals which were selected for use include bromide and the pesticides chlorpyrifos (typically used in urban areas and currently the most popular termiticide nationwide [Mix 1989]) and fenamiphos (a much studied agricultural chemical). The trade names for chlorpyrifos and fenamiphos are Dursban and Nemacur, respectively.

Selection of chemicals was based on practical as well as scientific considerations. Bromide, which is found in soils cultivated with pineapple and which occurs naturally in groundwater, served as a conservative tracer for this investigation. Bromide is not a known water contaminant.

Under field conditions, the two organophosphate pesticides chosen for this study were expected to behave quite differently, which creates a desirable condition for model calibration. Chlorpyrifos has a relatively low solubility in water estimated to be between 0.4 mg/l at 23°C (Chiou et al. 1977) and 2 mg/l at 25°C (Neely 1980) and a vapor pressure of 1.87 x 10^{-5} mm Hg at 25°C (Worthing 1979). Under the chemical mobility classification of McCall et al. (1980), chlorpyrifos is considered to be immobile in soil due to its high adsorption potential.

Fenamiphos is a nematicide which is used by both Dole and Del Monte plantations on the island of Oahu. The solubility of fenamiphos in water has been estimated to be between 400 mg/l (no temperature specified) (Sine 1987) and 700 mg/l at room temperature (Worthing 1979). Its vapor pressure is 1 x 10^{-6} mm Hg at 30°C (Worthing 1979). In soil, fenamiphos is transformed rapidly to a persistent product, fenamiphos sulfoxide, which is then slowly transformed to fenamiphos sulfone. According to the pesticide mobility classification scheme of McCall et al. (1980), fenamiphos and its metabolites can be grouped under medium- and high-mobility classes, respectively (Lee, Green, and Apt 1986). Current research being conducted by the University of Hawaii, Department of Agronomy and Soil Science, indicates that fenamiphos residues can leach below the crop root zone.* Thus, for model calibration, fenamiphos represents a mobile pesticide while chlorpyrifos represents a relatively immobile pesticide.

Background Soil Sampling. Prior to applying the pesticides and chemical tracer to the plot, soil samples were collected to determine background concentrations of fenamiphos, chlorpyrifos, and bromide. Holes were augered near the northern, western, and eastern borders of the plot to depths of 1.2 m, 1.2 m, and 0.9 m, respectively. Soil samples at 0.3, 0.9, and 1.2 m for the north hole, the surface and 0.9 m for the

*R.C. Schneider, WRRC Seminar, 7 April 1988.

west hole, and the surface and 0.3 m for the east hole were analyzed. Neither of the pesticides fenamiphos or chlorpyrifos could be detected in the background soil samples at a detection limit of 0.007 μg/g. Bromide analyses suggested background levels between 0.37 and 0.88 μg/g in the soil.

Chemical Applications. The initial application of chemicals on the Waiawa Valley plot occurred on 24 June 1988 and was carried out by project chemist D.N. Little, who was training to become a certified pesticide applicator at the time, under the supervision of registered pesticide applicator R.C. Schneider. On 22 June 1988, two days prior to the scheduled chemical application date, the Waiawa Valley plot was irrigated with 5.87 m^3 (1550 gal) of water, equivalent to a water depth of approximately 50 mm (2 in.). Including transport time, it took approximately 4 hrs to apply the 50 mm of water through a portable sprinkler irrigation system. By initially wetting the soil prior to the pesticide application, a condition relatively conducive to chemical leaching was created. Under drier initial soil conditions, applied pesticides may become bound in soil near the surface and be unavailable for subsequent leaching. In addition to the pre-application irrigation, 2 mm of rainfall occurred during the early morning hours on 24 June 1988, prior to the chemical application.

Prior to the application on 24 June 1988, the application equipment was calibrated to deliver the desired amount of chemicals as the applicator paced a specified distance. To facilitate the application process, parallel lengths of string oriented east-west were stretched across the plot at 0.51-m (20-in.) intervals and secured at their ends around wooden stakes driven into the ground. At the field site, the chemicals were mixed in a CO_2-pressurized backpack tank and applied with a hand-held sprayer equipped with two output nozzles spaced at 0.51 m (20 in.). A delivery pressure or nozzle pressure of 103 kPa (15 psi) was used with a second stage pressure of 207 kPa (30 psi). The applicator, wearing complete protective garb, walked at a constant speed while delivering the chemicals within the series of 0.51 m parallel paths marked with string. The sprayer nozzles were aligned to provide 50% overlap between adjacent paths in order to attain a uniform application. Enough chemicals were mixed in the tank to cover one quadrant of the plot.

A total of 27 ml of Nemacur 3E containing 0.36 kg/l (3 lb/gal) fenamiphos, 114 ml of Dursban 2E containing 0.24 kg/l (2 lb/gal) chlorpyrifos, and 82 g of NaBr were mixed into 7.6 l (2 gal) of water in the backpack tank and applied to one quadrant of the plot. Chemicals were applied only in the northeast, northwest, and southwest quadrants of the plot. The southeast quadrant was used as a test plot for soil hydraulic experiments. Final pesticide loading rates were 3.5 kg/ha (3 lb/acre) fenamiphos and 9.8 kg/ha (8.7 lb/acre) chlorpyrifos.

The loading rates were chosen to provide sufficient and measureable quantities of leached residues. The fenamiphos loading rate used corresponds to the maximum recommended dosage for postplant broadcast spray on pineapple crops in Hawaii. The loading rate used, however, is considerably less than the maximum allowable total quantity per pineapple crop of 44.8 kg/ha (40 lb/acre).

For preconstruction subterranean termite treatment, chlorpyrifos (in the form of Dursban TC Termiticide Concentrate) may be used at a rate of 390 kg/ha (350 lb/acre) to form a horizontal barrier prior to the pouring of the slab. If the concrete slab cannot be poured over the soil the same day it has been treated, a waterproof material is generally placed over the soil. Loading rates for vertical barriers and postconstruction treatments vary with the structural situation. The chlorpyrifos loading rate of 9.8 kg/ha chosen for the Waiawa Valley plot is considerably lower than the allowable preconstruction treatment of 390 kg/ha. The two loading rates, however, should not be compared due to the vastly different post-application conditions. Whereas leaching is prevented by covering the soil following preconstruction subterranean termite treatments to form a horizontal barrier, leaching is purposefully allowed to occur in the Waiawa Valley plot by exposing the treated soil to rainfall and irrigation.

Immediately following the chemical application, approximately 12 mm of irrigation water was applied on the plot through a portable sprinkler irrigation system. The purpose of this post-application irrigation was to wash the chemicals off of the existing vegetation and into the soil. The vegetation on the plot, which consists primarily of guinea grass, had been cut the previous day to a height of approximately 0.01 to 0.02 m.

Results of soil sampling conducted during October 1988 revealed that very low quantities of pesticide residues remained in the soil profile in the Waiawa Valley plot four months after the initial chemical application. Rather than attempting to sample immeasureable amounts of residues, a second application of pesticides and bromide was made on 6 January 1989. This second application was designed to yield additional information to facilitate the calibration of the unsaturated zone solute transport model being used.

The methodology used for the second application was essentially the same as that used for the initial application. On 5 January 1989, one day prior to the second application, the existing vegetation on the plot was cut. Because the soil was already very wet, a pre-application irrigation of the plot, as was done before the initial application on 24 June 1988, was felt to be unnecessary. On 6 January 1989, prior to the chemical application, the grass cuttings from the previous day were raked off the plot. Soil samples were collected from the southeastern quadrant of the plot to determine initial soil moisture conditions. Parallel lengths of string spaced 0.25 m (10 in.) apart were stretched across the plot in an east-west orientation to help delineate paths for the pesticide applicator.

The 6 January 1989 application of chemicals on the Waiawa Valley plot was carried out by trained pesticide applicator D.N. Little. The chemicals were mixed in a CO_2-pressurized backpack tank and applied with a hand-held sprayer equipped with two output nozzles spaced at 0.51 m (20 in.). Prior to the application, the equipment was calibrated to deliver the desired amount of chemicals as the applicator paced a specified distance at a constant rate. A delivery pressure (nozzle pressure) of 103 kPa (15 psi) was used with a second stage pressure of 207 kPa (30 psi).

A total of 27 ml of Nemacur 3E containing 0.36 kg/l (3 lb/gal) fenamiphos, 114 ml of Dursban 2E containing 0.24 kg/l (2 lb/gal) chlorpyrifos, and 164 g of NaBr were mixed into 7.6 l (2 gal) of water in the backpack tank and applied to one quadrant of the plot. Chemicals were applied only in the northeast, northwest, and southwest quadrants of the plot. The southeast quadrant was used as a soil hydraulic test plot.

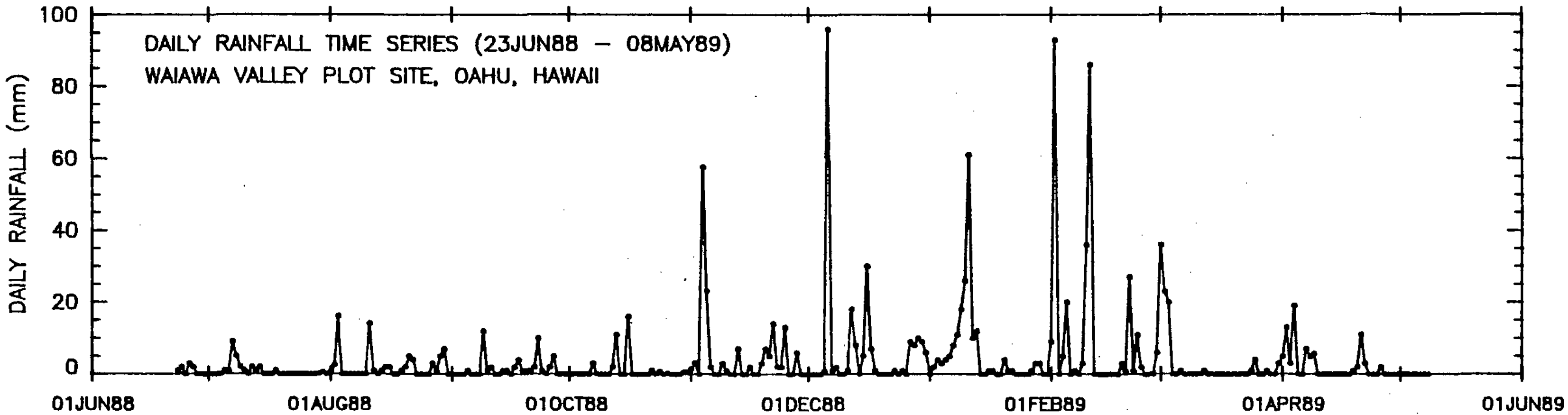
Final pesticide loading rates were 3.5 kg/ha (3 lb/acre) fenamiphos and 9.8 kg/ha (8.7 lb/acre) chlorpyrifos.

The fenamiphos and chlorpyrifos loading rates were the same as those used in the initial chemical application of June 1988. The bromide dosage, however, was doubled to provide an amount significantly above the background level.

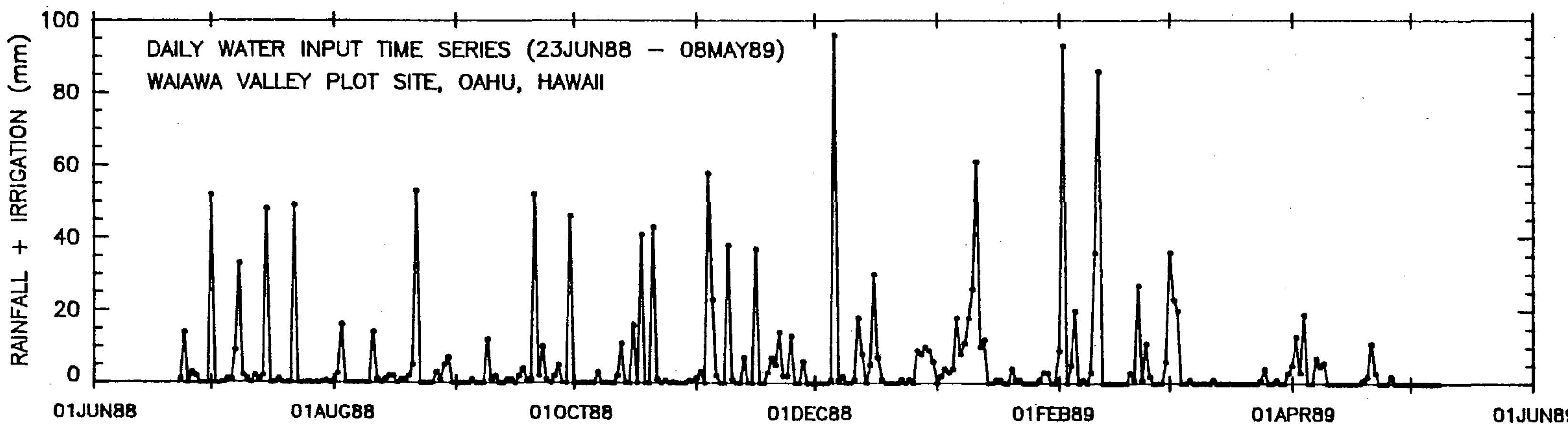
Immediately following the chemical application of 6 January 1989, approximately 12 mm of water was applied on the plot through the sprinkler irrigation system. The purpose of the post-application irrigation was to wash the chemicals off of the existing vegetation and into the soil.

Weather Station. Throughout the duration of the field study in Waiawa Valley, a weather station was maintained to record necessary climatological data. The weather station was established near the southeastern boundary of the plot to measure rainfall, wind, and net radiation. Hourly measurements of rainfall were recorded with a tipping bucket rain gage sensitive to 1 mm. Wind and radiation were measured with an anemometer and Fritschen-type net radiometer, respectively. All instruments were connected to a LI-COR LI-1000 data logger concealed in a protective steel box. Recorded data were downloaded to a portable computer as frequently as possible to check equipment operation and thereby minimize the inevitable occurrences of data gaps.

A summary of the daily rainfall occurring at the Waiawa Valley plot site between 23 June 1988 and 8 May 1989 is presented in Appendix Figure A.2. Battery failures caused the loss of data from 27 July 1988 through 3 August 1988 and from 7 October 1988 through 15 October 1988. The cumulative rainfall total between 27 July 1988 and 3 August 1988, however, was retained in the data-logger's memory. After the second battery failure, a manual rain gage was placed near the tipping bucket gage as a backup. Although data between 16 October 1988 and 7 November 1988 were recorded by the data logger, a software problem prevented downloading of the data. The data logger was subsequently sent directly to the manufacturer to determine if the data could be recovered. LI-COR acknowledged that problems existed with the software and was unable to recover the data. Data between 7 April 1989 and 19 April 1989 were also lost due to data-logger problems of an unknown origin. Daily rainfall was



Appendix Figure A.2. Daily rainfall, 23 June 1988-8 May 1989, at Waiawa Valley plot, Oahu, Hawaii



Appendix Figure A.3 Daily rainfall and irrigation, 23 June 1988-8 May 1989, at Waiawa Valley plot, Oahu, Hawaii estimated during the gaps with daily rainfall measurements at a nearby Pacific Palisades rain gage in conjunction with available readings from the backup manual rain gage. Data from the Pacific Palisades gage were obtained from the U.S. National Weather Service.*

Plot Maintenance and Irrigation. To ensure measureable and sufficient chemical movement for computer model calibration purposes, irrigation was applied whenever possible during periods of low or no rainfall. Growing vegetation was periodically cut to maintain a relatively constant stand of grass and weeds. The periodic trimming of vegetation with gasoline powered weed cutters was also necessary to prevent blockage of sprinklers.

Due to the lack of a water source in the immediate vicinity of the Waiawa Valley plot site, water was trucked from the USN Waiawa pumping station to provide irrigation for the plot. Water taken off the shaft header prior to any chlorination or fluoridation was transported to the plot in a 1.04 m^3 (275 gal) capacity water bag loaded on a pickup truck. The water was then gravity drained into a 0.38 m^3 (100 gal) capacity pool, from where it was pumped into a sprinkler system with a 3730 watt (5 HP) gasoline powered centrifugal pump. The irrigation system developed was portable (assembling the components took approximately 15 min) and was also designed to be used at other sites.

The primary reason for irrigating the plot was to provide a sufficient driving mechanism for the downward transport of the applied chemicals. The intent of the irrigation was not necessarily to simulate a specific climatic setting, but rather to produce measureable amounts of leaching within the relatively short time frame of the research effort. Irrigation generally took place on a weekly basis; however, pump failure and unforeseen transportation problems sometimes disrupted the schedule. The objective on each outing was to apply approximately 50 mm of water over the entire plot area. This quantity of water was felt to be sufficiently in excess of the evapotranspiration demand so as to produce recharge. A summary of the total water input, which includes rainfall and irrigation, to the Waiawa Valley plot site between 23 June 1988 and 8 May 1989 is provided in Appendix Figure A.3. It should be noted that with the exception of the irrigation immediately following the second application of

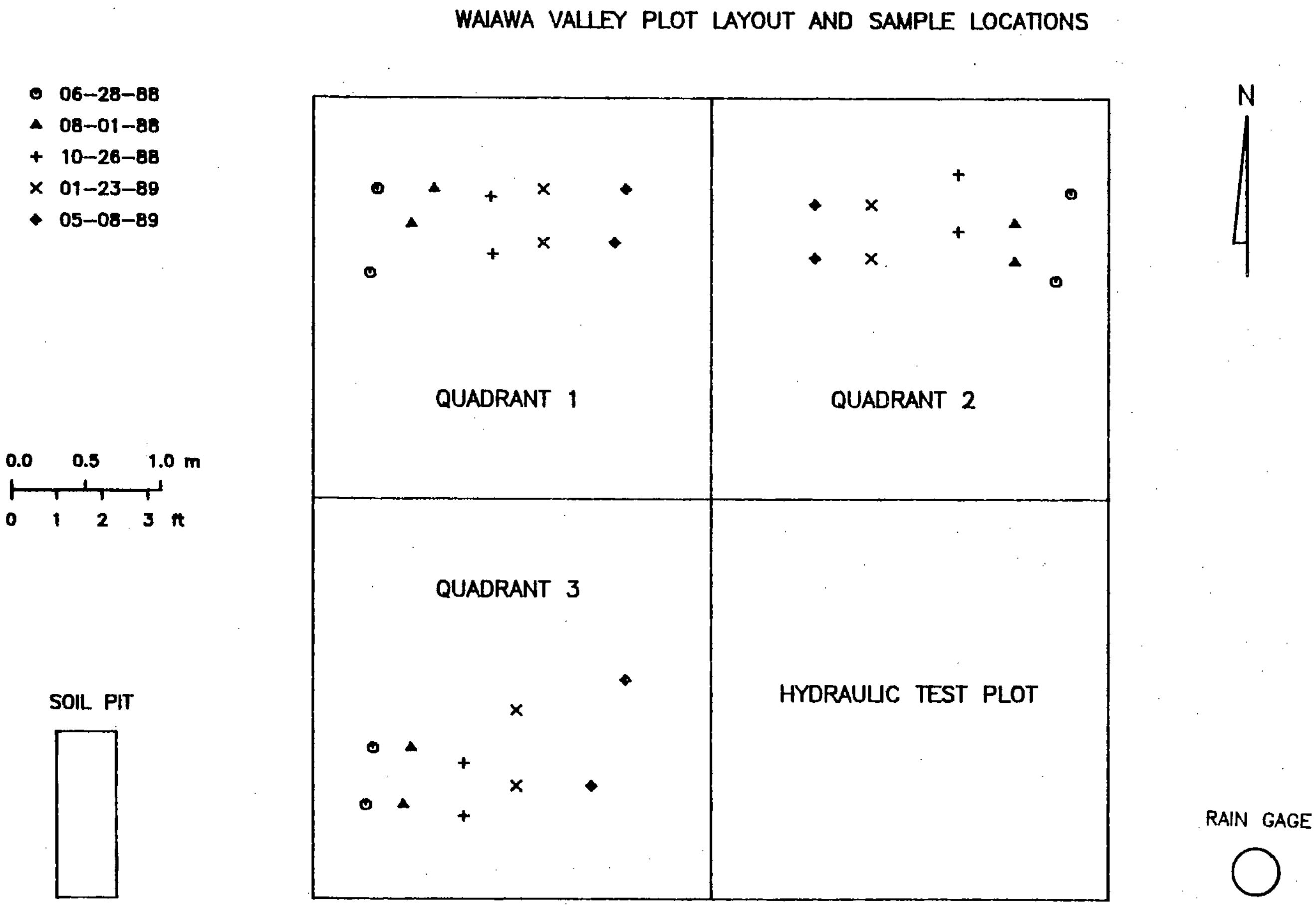
*B. Hablutzel 1989: personal communication.

chemicals on 6 January 1989, no irrigation was applied from the latter portion of November 1988 due to sufficient rainfall.

Pesticide/Bromide Sampling. A total of three soil samplings occurred between the initial chemical application of 24 June 1988 and the second application of 6 January 1989. Following the chemical application of 6 January 1989, the Waiawa Valley plot was sampled two more times. The five sampling dates were 28 June 1988, 1 August 1988, 26 October 1988, 23 January 1989, and 8 May 1989. On each occasion, duplicate holes were augered in the northwest, northeast, and southwest quadrants of the plot, which are labeled respectively quadrants 1, 2, and 3 in Appendix Figure A.4. The sampling locations were selected to minimize the need to walk on the intact portions of the plot. Thus, sampling generally proceeded from the outer edges of the plot inward as time progressed (App. Fig. A.4). In addition, sampling depths were generally increased with time from the applications. Immediately after each sampling, all augered holes were backfilled with untreated soil obtained from outside the plot and marked with ribbon tied to heavy-gage wire to prevent future sampling at the same locations. All soil samples were collected in plastic ziplock bags properly labeled with sample information and stored in a cooler for transport to the University of Hawaii, Agronomy and Soil Science laboratory where samples were analyzed.

Great care was taken while augering each hole to minimize the possibility of surface or inter-sample contamination. Prior to collecting each sample, augers were cleaned beyond the plot boundaries with a scrubbing brush and water. When possible, the bottom of the hole was gently scraped and cleaned to remove any surface soil which may have spilled into the hole when the auger was removed. For all samples other than the initial sample from a particular hole, the top few millimeters of soil in the auger, which represented the interface between two samples, was discarded to further reduce the possibility of inter-sample contamination.

The initial soil sampling for pesticide residues occurred four days post-application on 28 June 1988. It was desired to sample for pesticides relatively soon after application prior to excessive degradation losses. Two holes were augered in each of the three treated quadrants of the plot



Appendix Figure A.4. Waiawa Valley experimental field plot layout and sample locations to a depth of approximately 0.5 m. Between the chemical application date and the initial sampling date, a total of approximately 17 mm of water (rainfall and irrigation) wetted the plot. Due to the limited recharge following the application, it was not necessary to sample to greater depths. Two holes, spaced approximately 1 m apart, were augered approximately 0.75 m from the edge of each treated quadrant.

The actual sampling process involved the use of three augers for each hole. Since it was felt that most of the recently applied chemicals would be found near the surface, a 0.05 m sampling interval was used for the first 0.2 m. If a larger interval had been used for the surface, the bulk of the residues likely to be found within the top 0.05 m would have been greatly diluted by the underlying soil. Especially for the top 0.1 m where rocks were encountered, sampling at 0.05-m increments required the use of an auger with a diameter small enough to retain the 0.05-m layer of soil. A 0.04 m (1.5 in.) tube auger allowed accurate collection of 0.05 m soil samples. The downward driving force was supplied by pressing down on a foot pedal attached to the extension of the auger. Due to the small diameter of the tube auger, it was necessary to collect several cores (6-10) at each sample location to provide enough soil for the laboratory analyses. All of the cores for a particular sample location were augered within a 0.3 m diameter area. When enough soil for the 0 to 0.05 m depth had been collected in a plastic ziplock bag, the sample was labeled and stored in an ice chest. The augered area was then cleared with a small hand-held garden spade to form a 0.05 m deep pit. Care was taken to remove all of the top 0.05 m of soil from the pit to avoid surface contamination in the next sampling increment. Prior to sampling for the 0.05 to 0.1 m depth range, the tube auger was cleaned beyond the plot boundaries with a scrubbing brush and water. Sampling for the 0.05 to 0.1 m increment was carried out using the same procedure described for the top 0.05 m. Approximately 0.003 m from the top of each core, however, was discarded to eliminate the possibility of surface contamination. After collecting enough soil for the 0.05- to 0.1-m sample, the augered area was cleared with the garden tool to form a 0.1 m deep pit.

Below the top 0.1 m, soil cohesiveness made it possible to sample with bucket augers having larger diameters. Prior to using a 0.08 m (3.25 in.) bucket auger, the cleared pit was cased with a short length of 0.1 m (4 in.) PVC pipe to prevent surface soil from falling into the augered hole. The 0.08 m bucket auger was used to a depth of approximately 0.3 m where a second casing consisting of 0.08 m (3 in.) PVC pipe was lowered into the hole. Between 0.3 and 0.5 m, soil samples were collected with a 0.05 m (2 in.) bucket auger in an uncased hole. The telescoping casing system described above was developed by R.C. Schneider of the University of Hawaii, Department of Agronomy and Soil Science, and has been successfully used for pesticide sampling in pineapple fields. Care was taken to wash and scrub the augers after each sampling increment to avoid contamination of deeper soil layers by upper soil.

The second post-application sampling effort at the Waiawa Valley plot site was conducted on 1 August 1988. Between the first and second sampling dates, a known total of approximately 202 mm of water in the form of rainfall and irrigation occurred over the plot. Due to data logger problems, the hourly rainfall data between 27 July and 3 August 1988 were lost. During this period, however, the cumulative rainfall total of 20 mm was retained in the logger's memory.

As with the first sampling, two holes were augered in each of the three treated quadrants of the plot. Sampling depths were 0.73 and 0.94 m in quadrant 1, 1.05 and 1.09 m in quadrant 2, and 0.5 and 1.04 m in quadrant 3. Maximum sampling depths were chosen based on results of chemical movement from the initial sampling effort. In some cases, the presence of rocks prevented further augering to the desired depth.

The sampling technique used on 1 August 1988 differed slightly from the initial sampling method. Due to expected spreading of the chemical profile, the fine sampling interval (employed four days post-application) of 0.05 m used to a depth of 0.2 m was deemed to be unnecessary. For the second effort, a sampling interval of 0.1 m was used for the first 0.4 m. At greater depths, a sampling interval of 0.15 m was employed. As the sampling depth was increased, the interval was also increased to avoid taking more samples than could be analyzed in a timely manner.

In general, the top 0.2 to 0.3 m was sampled with a 0.1 m (4 in.) bucket auger at 0.1 m sampling increments. The relatively large diameter auger was able to retain a 0.1-m core of soil. Prior to collecting the next sample (0.1-0.2 m depth range), the auger was cleaned beyond the plot boundaries with a scrubbing brush and water. The bottom of the hole was gently scraped and cleaned to remove any surface soil which may have spilled into the hole upon removal of the auger. In addition, loose material on the sides of the hole was removed to prevent contamination upon reinsertion of the auger. After carefully reinserting the auger and collecting the next 0.1-m core of soil, the top few millimeters of soil in the auger, which represented the interface between the first two samples, was discarded to further reduce the possibility of inter-sample contamination. The same precautions mentioned above were followed for all subsequent samples from a particular hole.

After employing the 0.1-m auger to collect the top two or three soil samples, the bottom and sides of the hole were carefully cleaned and the hole was cased with a short length of 0.1 m (4 in.) diameter PVC pipe to prevent surface soil from falling into the augered hole. Below the top 0.2 to 0.3 m, soil was sampled with a 0.08 m (3.25 in.) bucket auger at 0.1-m increments. After augering to a depth of approximately 0.45 m, the bottom and sides of the hole were again carefully cleaned and the hole was cased with a length of 0.08 m (3 in.) diameter PVC pipe nested inside the 0.1-m casing. Once the 0.08-m casing was lowered into the hole, all augering was conducted with a 0.05 m (2 in.) bucket auger. The lower portion of the hole remained uncased when sampling with the 0.05-m auger. Beyond a depth of approximately 0.4 m, the sampling increment was increased from 0.1 to 0.15 m. The increased sampling interval was necessary because the 0.05-m auger was unable to collect a sufficient volume of soil for the laboratory analyses in a 0.1-m core. The increased interval also made it possible for the laboratory to analyze the samples in a timely manner.

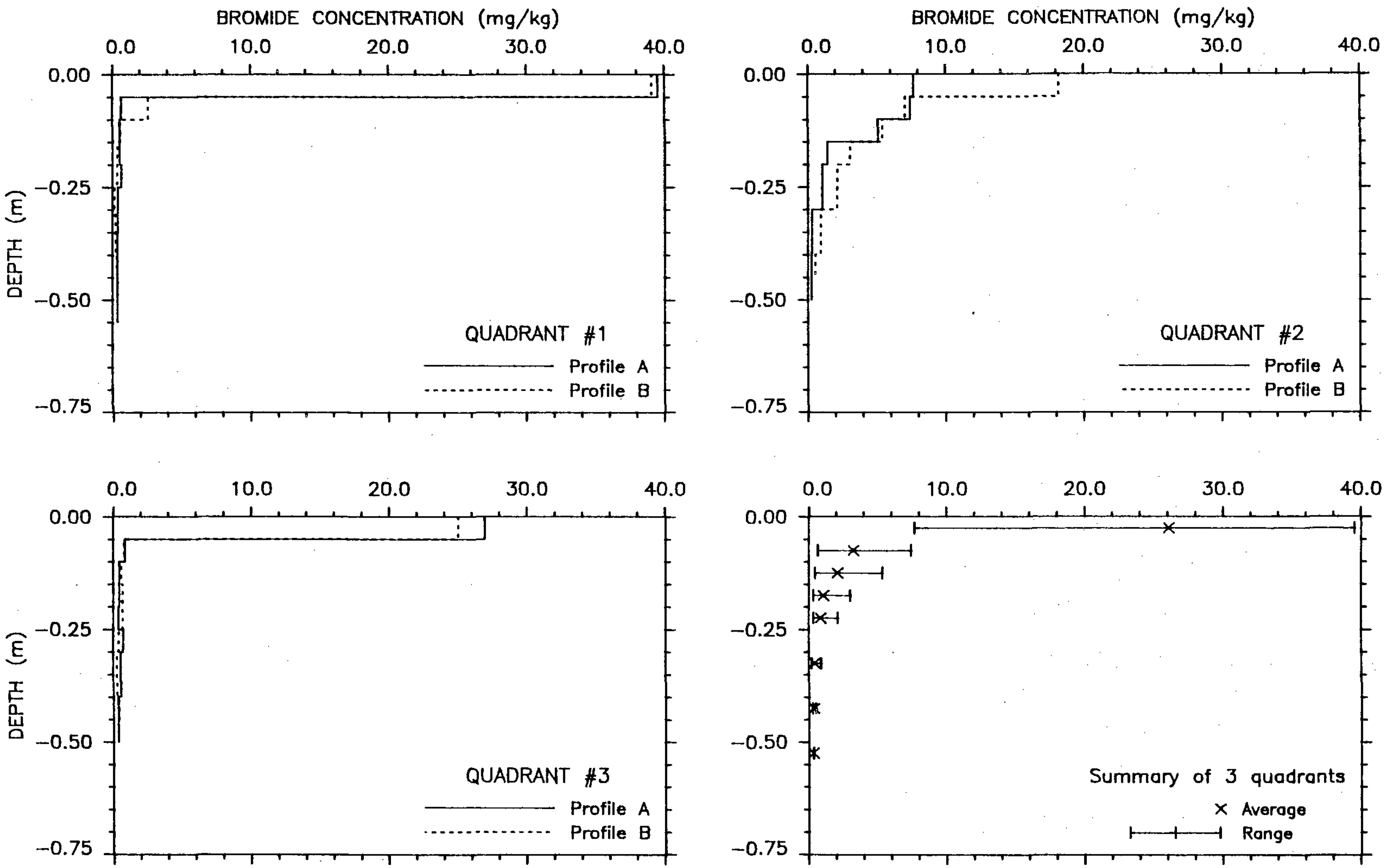
Between the second and third sampling efforts, a known total of 329 mm of water wetted the plot. Sampling depths on 26 October 1988 were 1.35 and 1.45 m in quadrant 1, 0.73 and 1.20 m in quadrant 2, and 1.05 and 1.25 m in quadrant 3. The sampling technique used on 26 October

1988 was similar to the technique used on 1 August 1988 which was detailed above. For the third effort, a sampling interval of 0.1 m was used for the first 0.3 m. At greater depths, a sampling interval of approximately 0.15 to 0.3 m was used. Generally, the top 0.2 to 0.3 m was sampled with a 0.1 m (4 in.) bucket auger at 0.1 m sampling increments. Below the top 0.2 to 0.3 m, soil was sampled with a 0.08 m (3 in.) bucket auger at 0.15-m increments in a cased hole. After augering to a depth of approximately 0.7 m, the hole was cased with a 0.8-m length of 0.08 m (3 in.) diameter PVC pipe nested inside the 0.1-m casing. After the 0.08 m diameter casing was lowered into the hole, all augering was conducted with a 0.05 m (2 in.) bucket auger in an uncased hole. Sampling intervals with the 0.05-m auger were from 0.2 to 0.3 m.

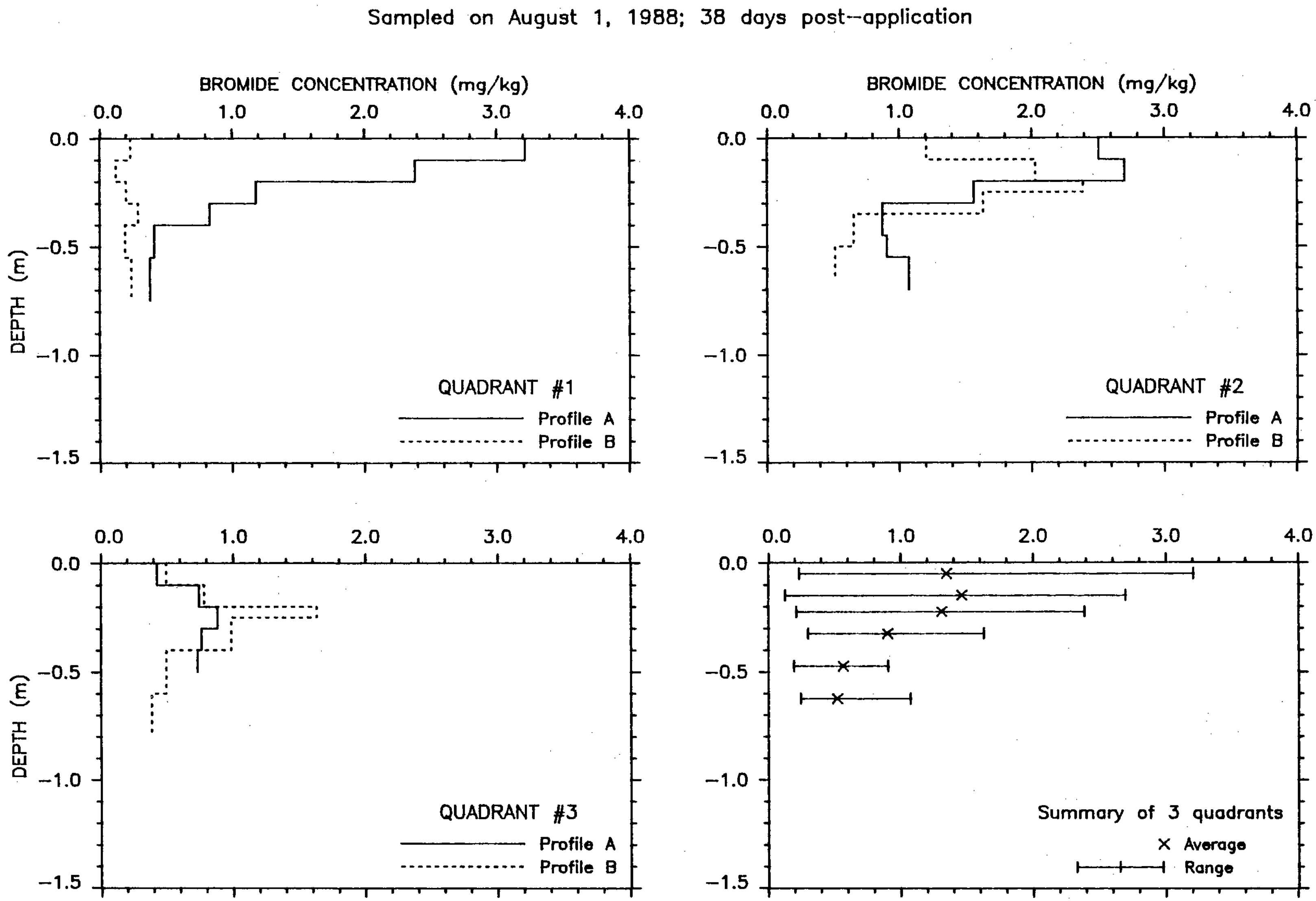
From the second chemical application on 6 January 1989 to the sampling of 23 January 1989, a total of 170 mm of water occurred on the plot. Between the 23 January 1989 sampling and the 8 May 1989 sampling, a total of 478 mm of water wetted the plot. The sampling techniques used on 23 January 1989 and 8 May 1989 were essentially similar to the technique used on 26 October 1988. Final sampling depths on 23 January 1989 were 2.02 and 2.19 m in quadrant 1, 0.57 and 0.83 m in quadrant 2, and 1.37 and 2.01 m in quadrant 3. In quadrant 2, numerous attempts to auger to greater depths were prevented by the presence of rocks. On 8 May 1989, final sampling depths were 1.5 and 3.0 m in quadrant 1, 1.52 and 1.69 m in quadrant 2, and 1.61 and 2.62 m in quadrant 3.

The soil samplings of 28 June 1988, 1 August 1988, and 26 October 1988 occurred 4 days, 38 days, and 124 days, respectively, after the initial chemical application of 24 June 1988. The samplings of 23 January 1989 and 8 May 1989 occurred 17 days and 122 days, respectively, after the second chemical application of 6 January 1989. All soil samples were analyzed for bromide, chlorpyrifos, and fenamiphos at the University of Hawaii, Agronomy and Soil Science laboratory. The analytical methodologies for the three chemicals are presented in Appendix B of this report. Results of the soil samplings are presented in Appendix Figures A.5 to A.19. Sampling results for bromide, chlorpyrifos, and total fenamiphos are presented for each hole in each of the three treated quadrants of the plot. Arithmetically averaged profiles for each chemical

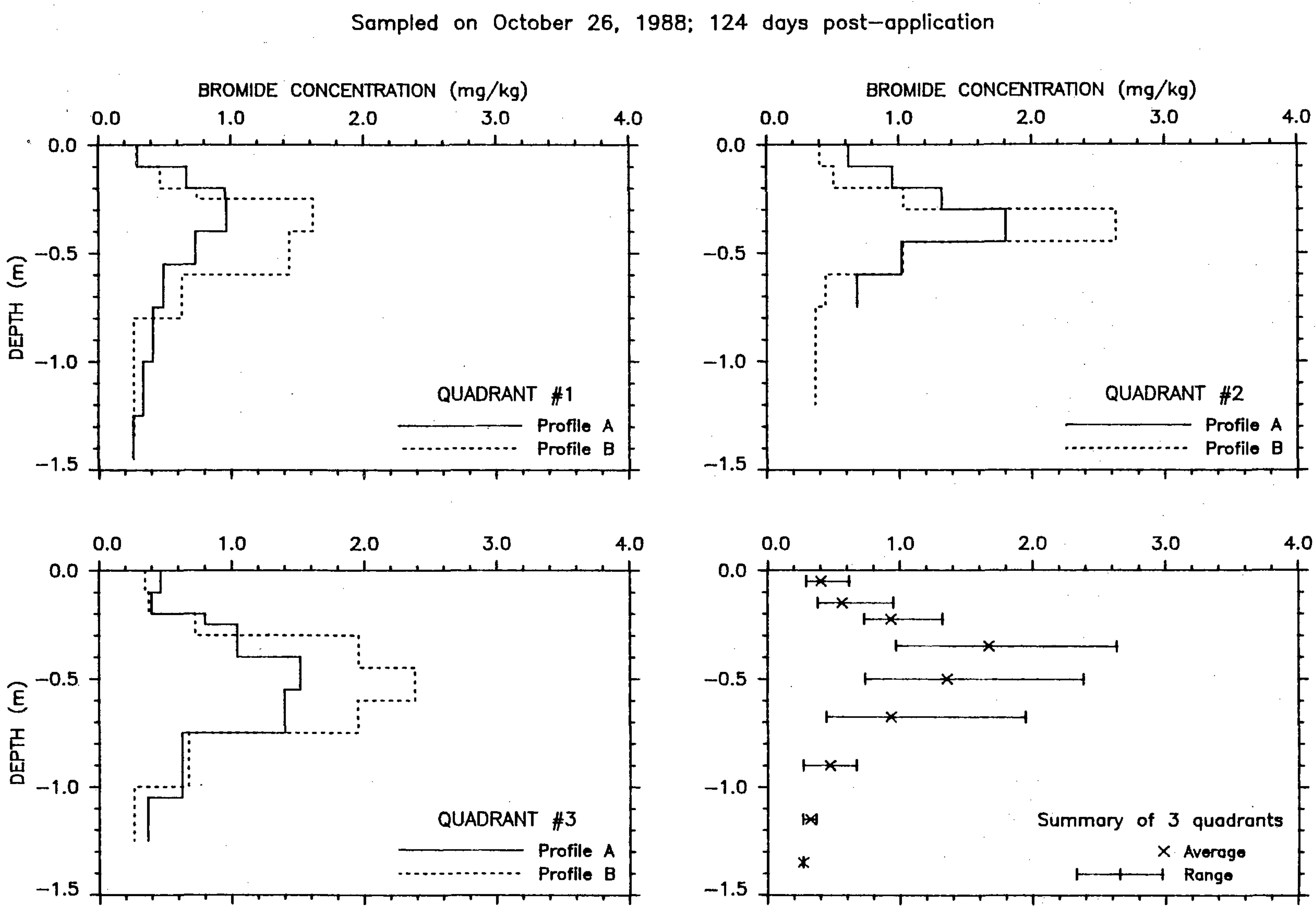
Sampled on June 28, 1988; 4 days post-application



Appendix Figure A.5. Bromide concentration profiles at Waiawa plot, first sampling (28 June 1988), 4 days post-application

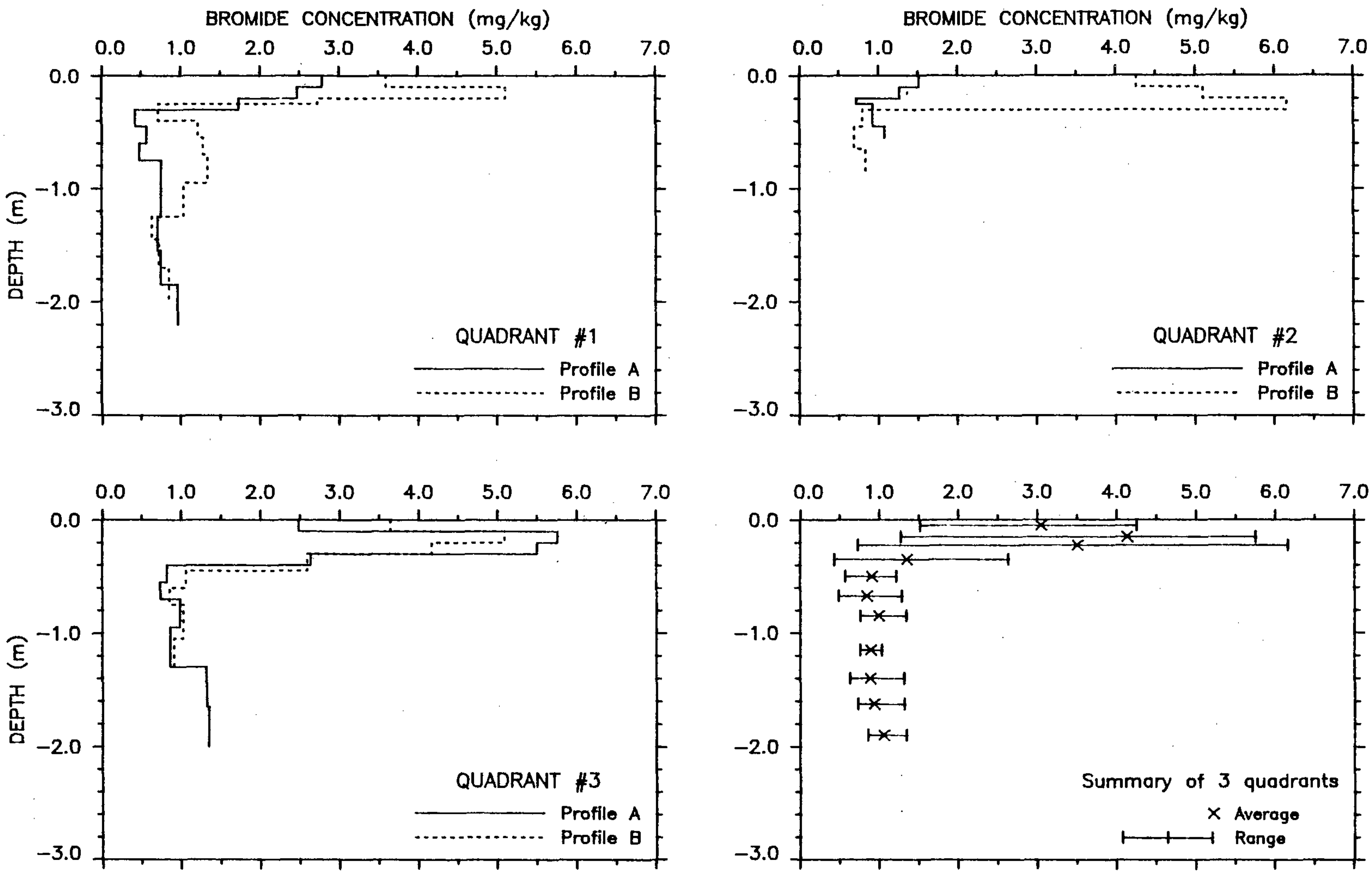


Appendix Figure A.6. Bromide concentration profiles at Waiawa plot, second sampling (1 Aug. 1988), 38 days post-application



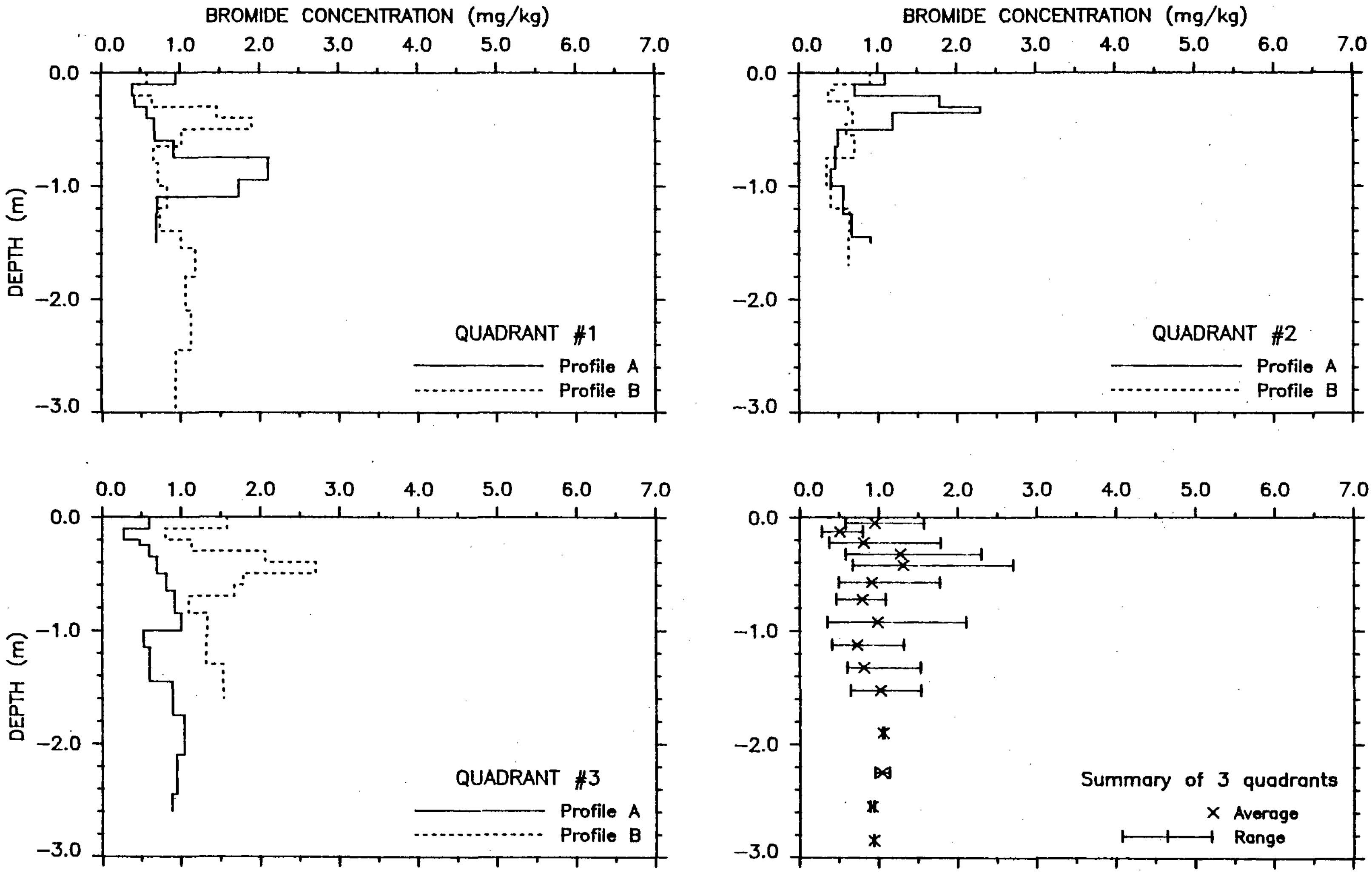
Appendix Figure A.7. Bromide concentration profiles at Waiawa plot, third sampling (26 Oct. 1988), 124 days post-application

Sampled on January 23, 1989; 213 & 17 days post-application



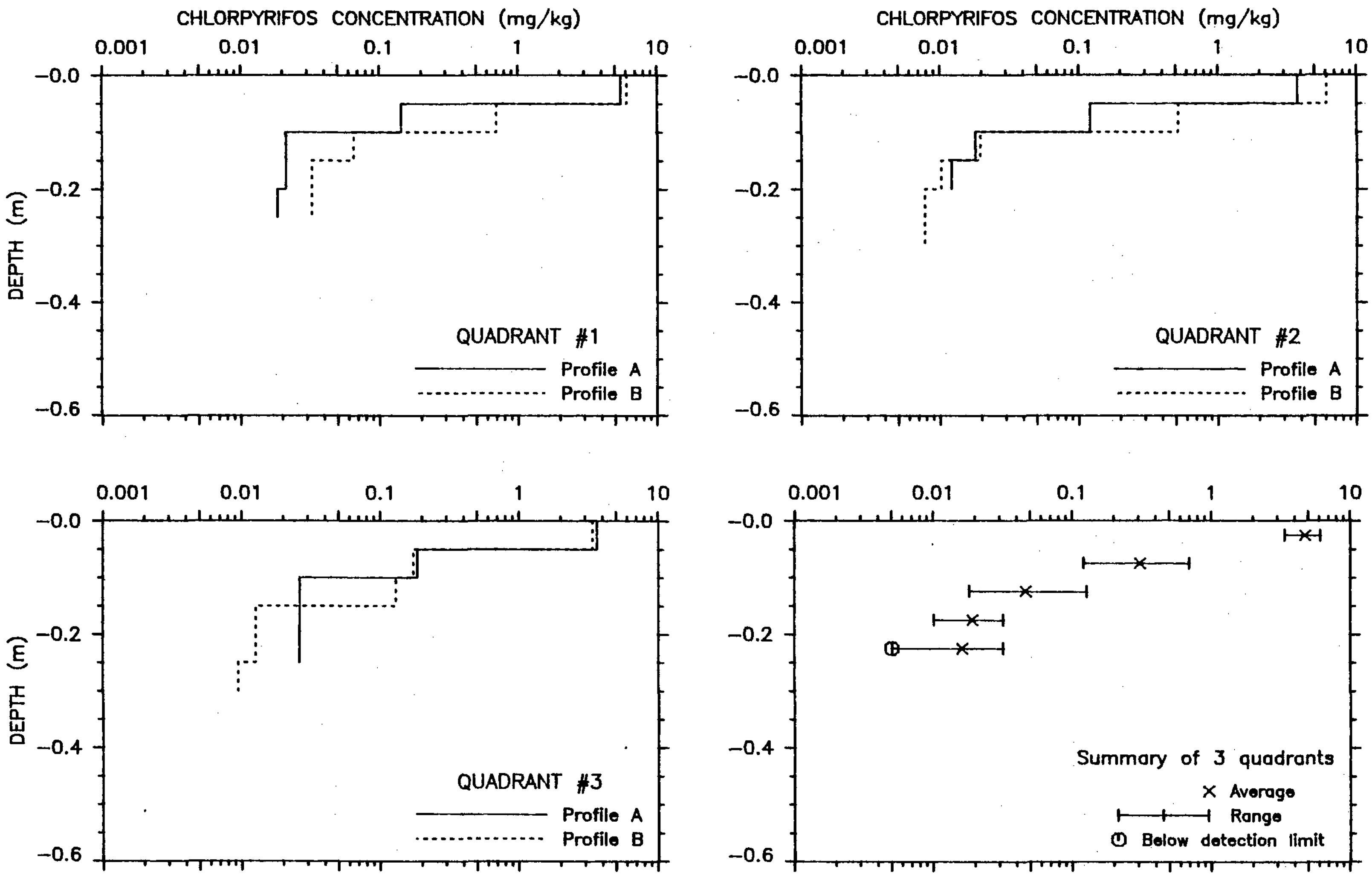
Appendix Figure A.8. Bromide concentration profiles at Waiawa plot, fourth sampling (23 Jan. 1989), 213 and 17 days post-application

Sampled on May 8, 1989; 318 & 122 days post-application



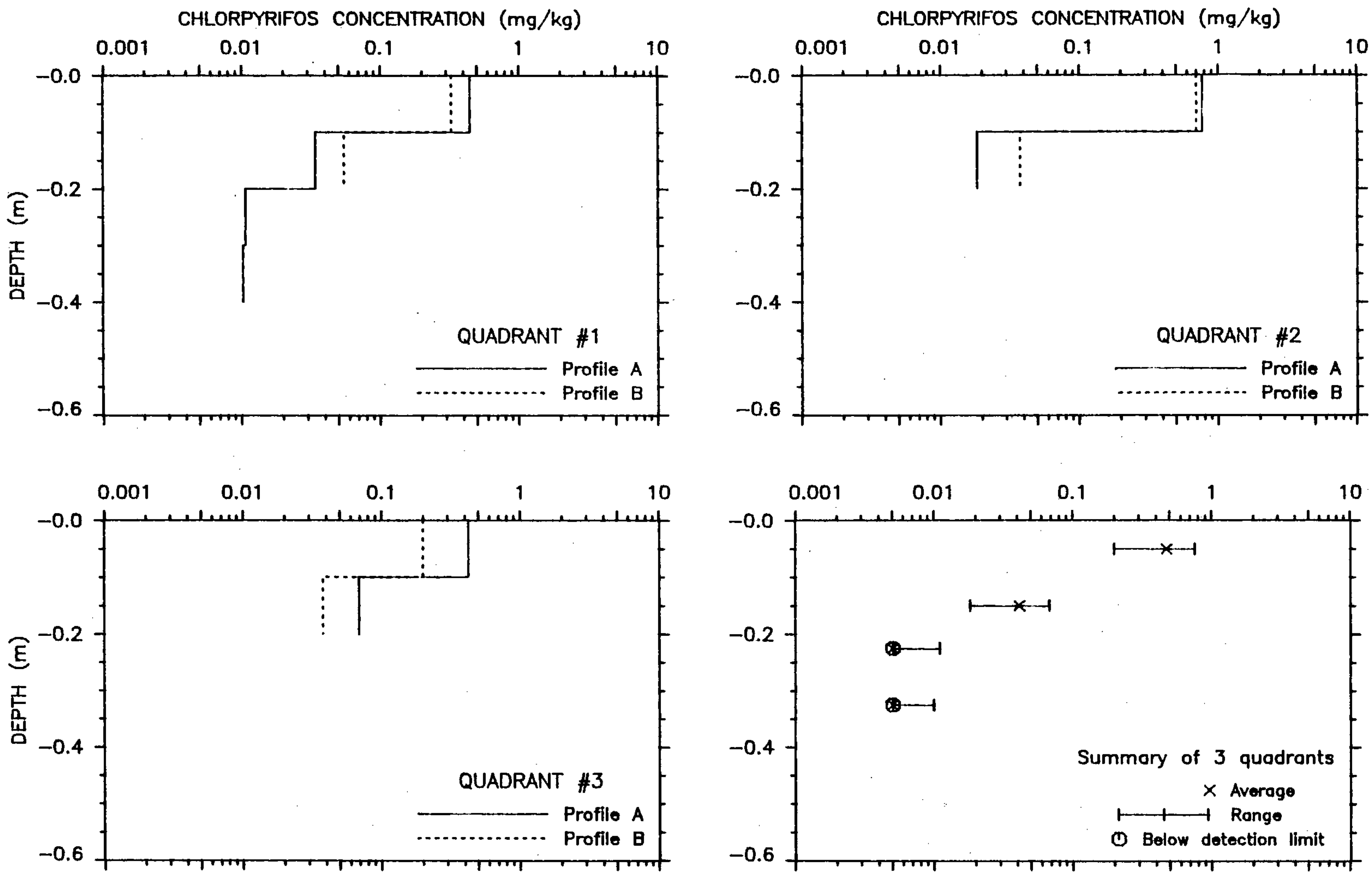
Appendix Figure A.9. Bromide concentration profiles at Waiawa plot, fifth sampling (8 May 1989), 318 and 122 days post-application

Sampled on June 28, 1988: 4 days post-application

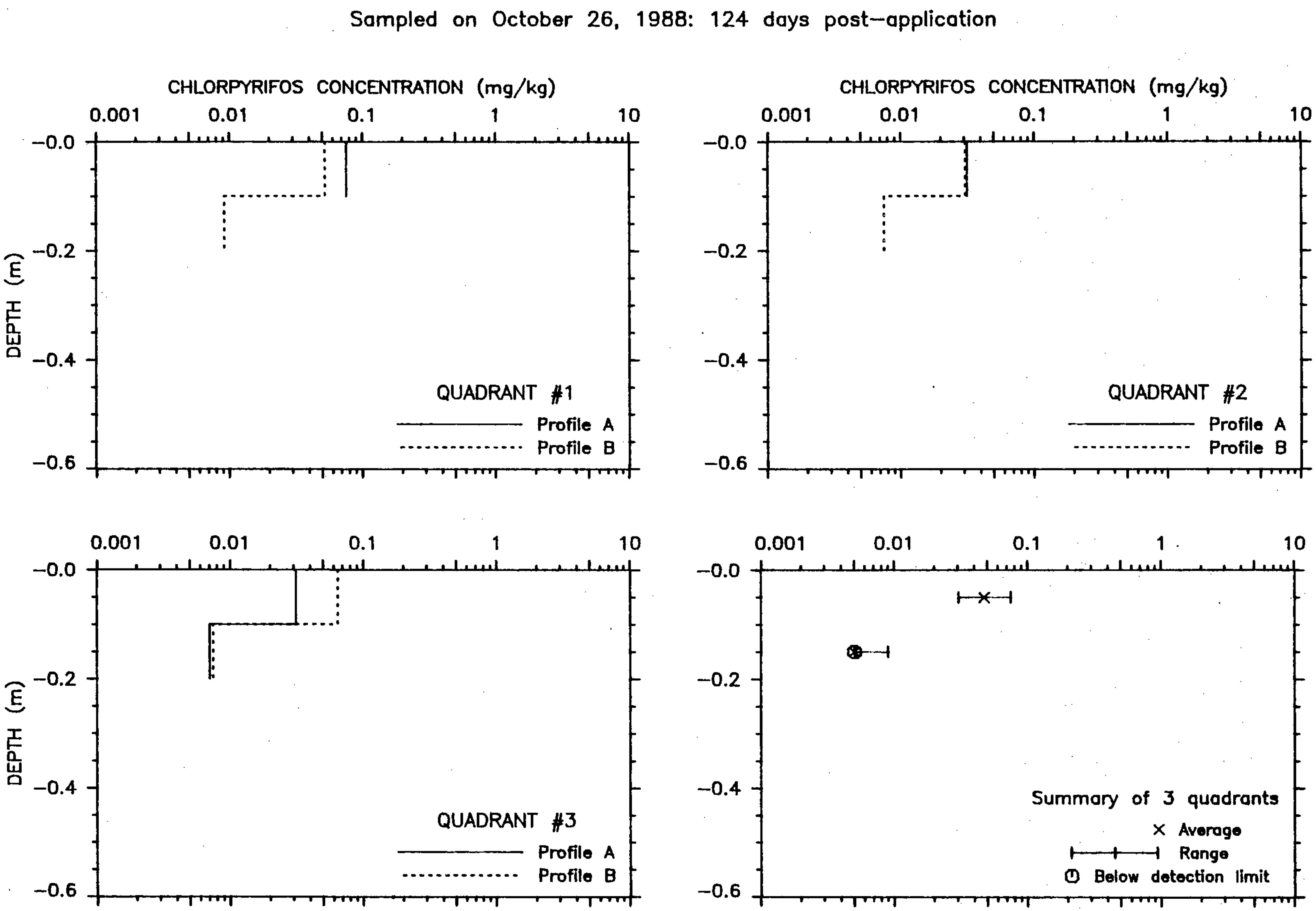


Appendix Figure A.10. Chlorpyrifos concentration profiles at Waiawa plot, first sampling (28 June 1988), 4 days post-application

Sampled on August 1, 1988: 38 days post-application

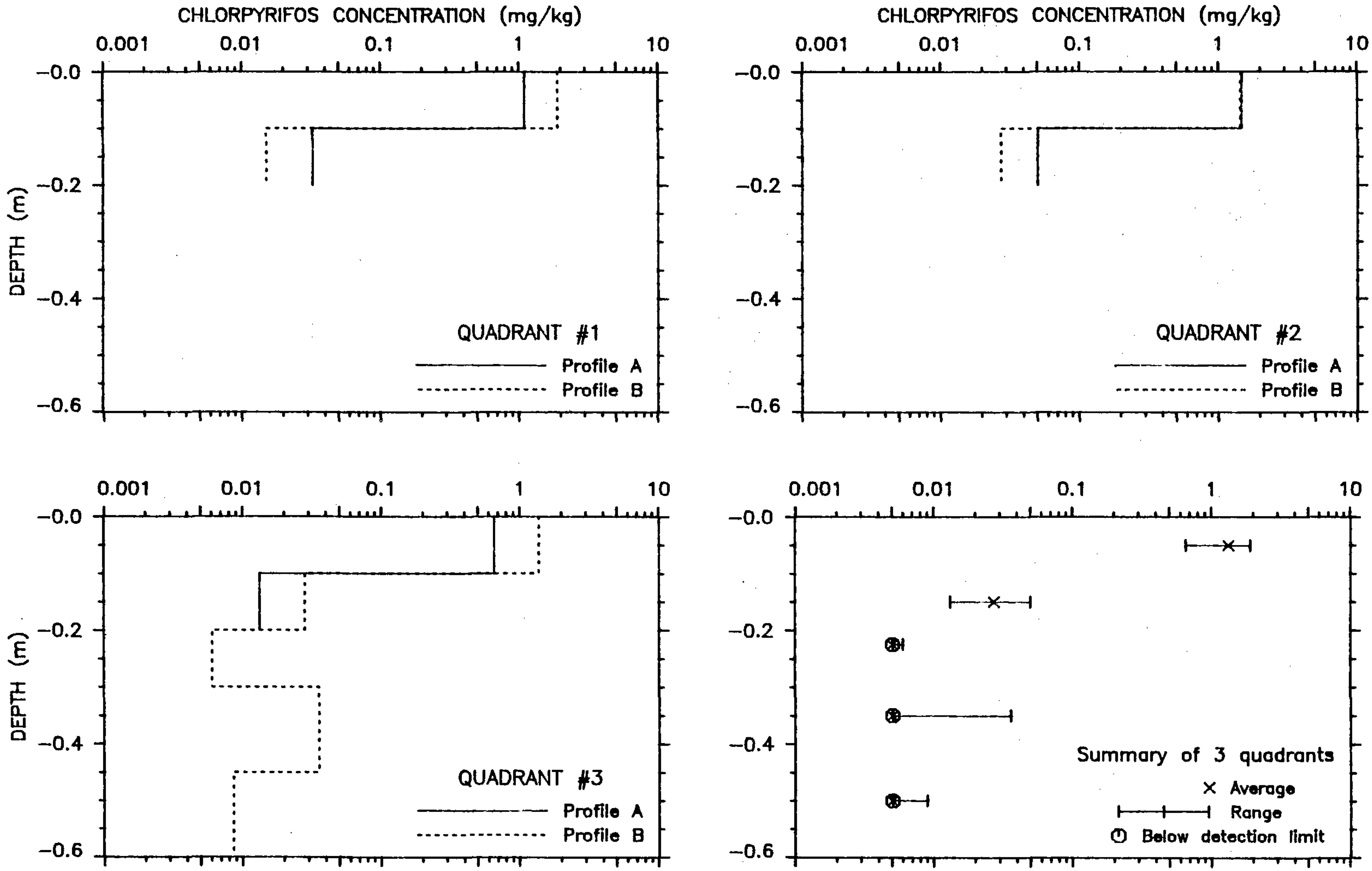


Appendix Figure A.11. Chlorpyrifos concentration profiles at Waiawa plot, second sampling (1 Aug. 1988), 38 days post-application



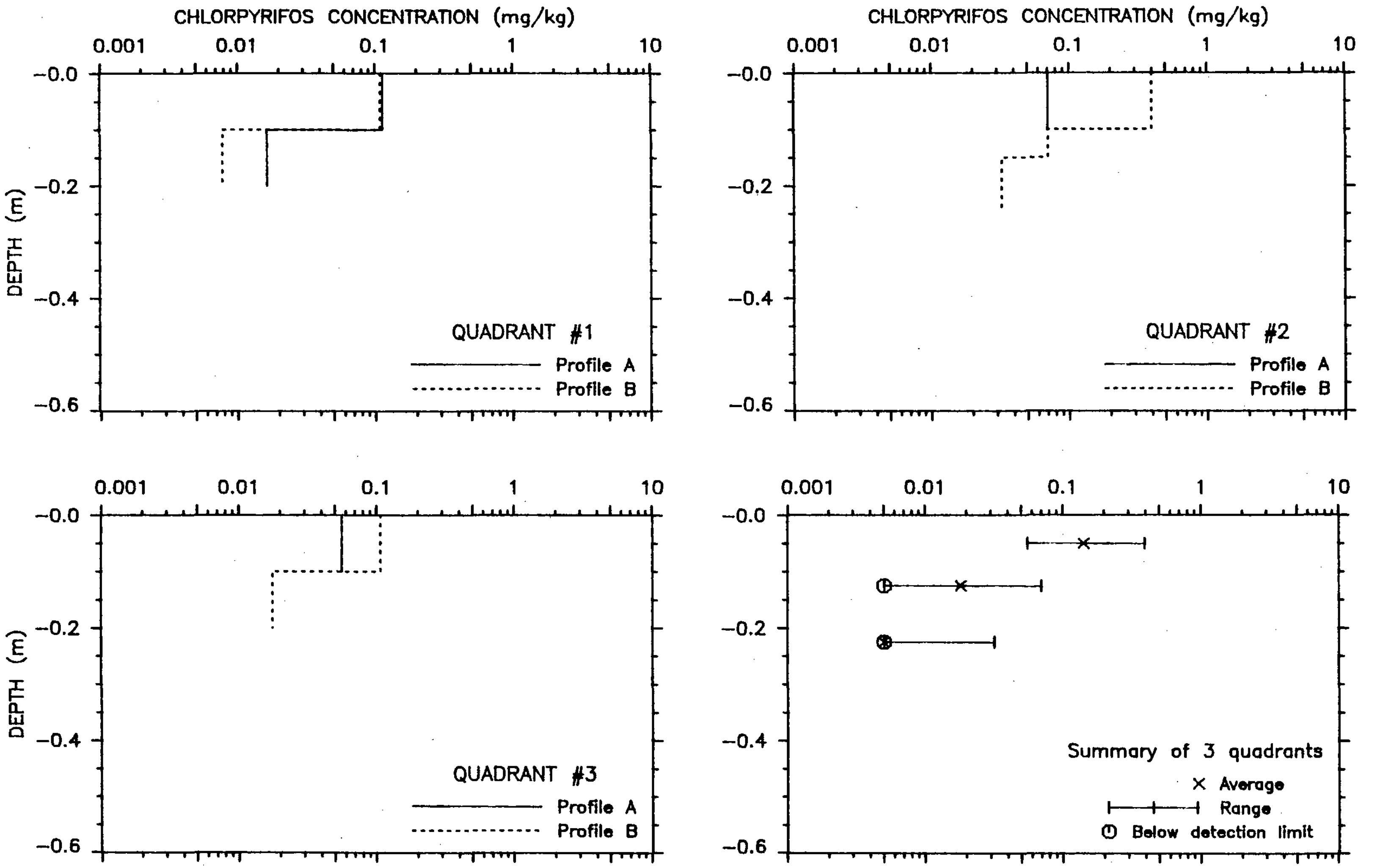
Appendix Figure A.12. Chlorpyrifos concentration profiles at Waiawa plot, third sampling (26 Oct. 1988), 124 days post-application

Sampled on January 23, 1989: 17 days post-application



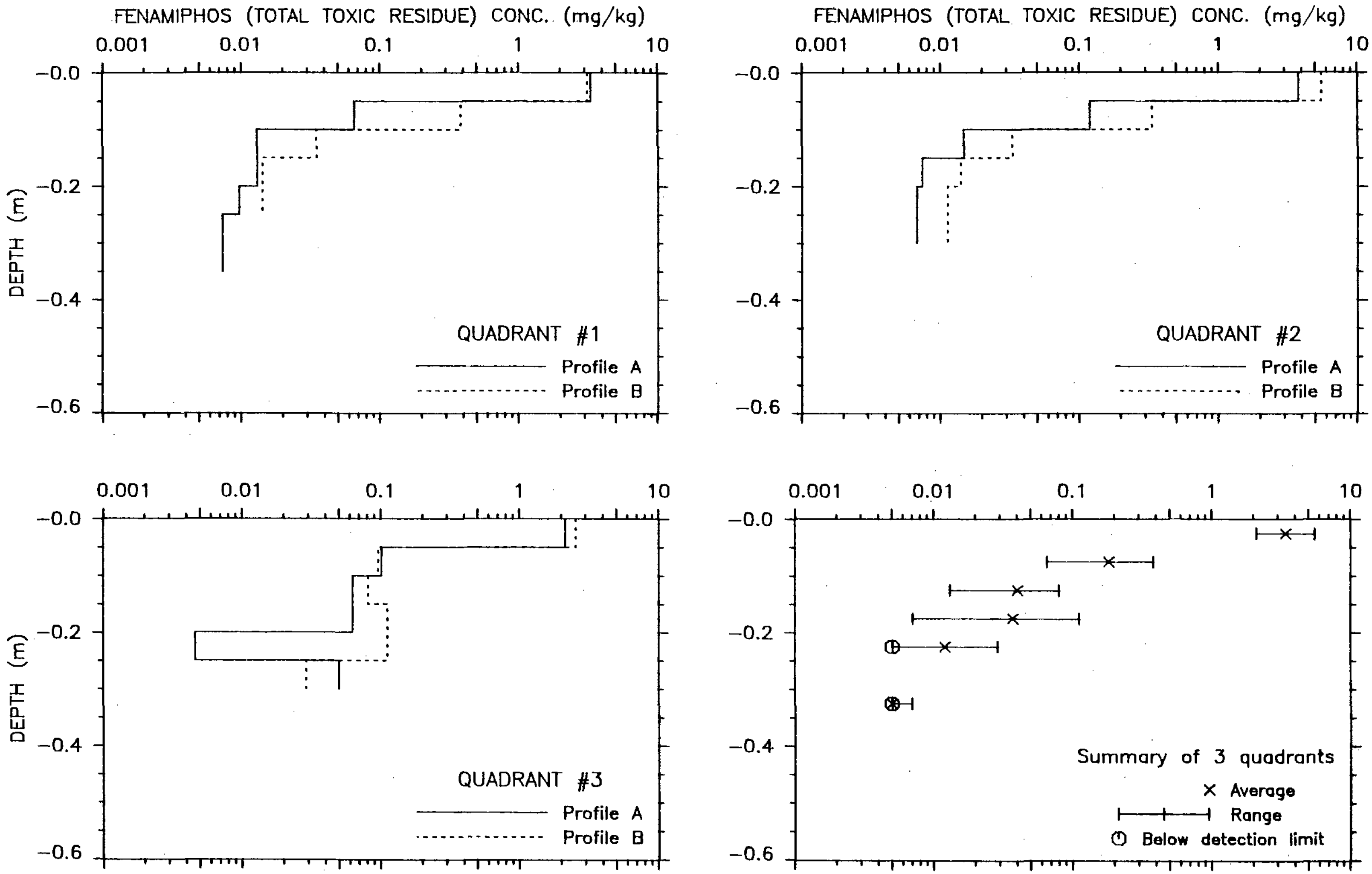
Appendix Figure A.13. Chlorpyrifos concentration profiles at Waiawa plot, fourth sampling (23 Jan. 1989), 213 and 17 days post-application

Sampled on May 8, 1989: 122 days post-application

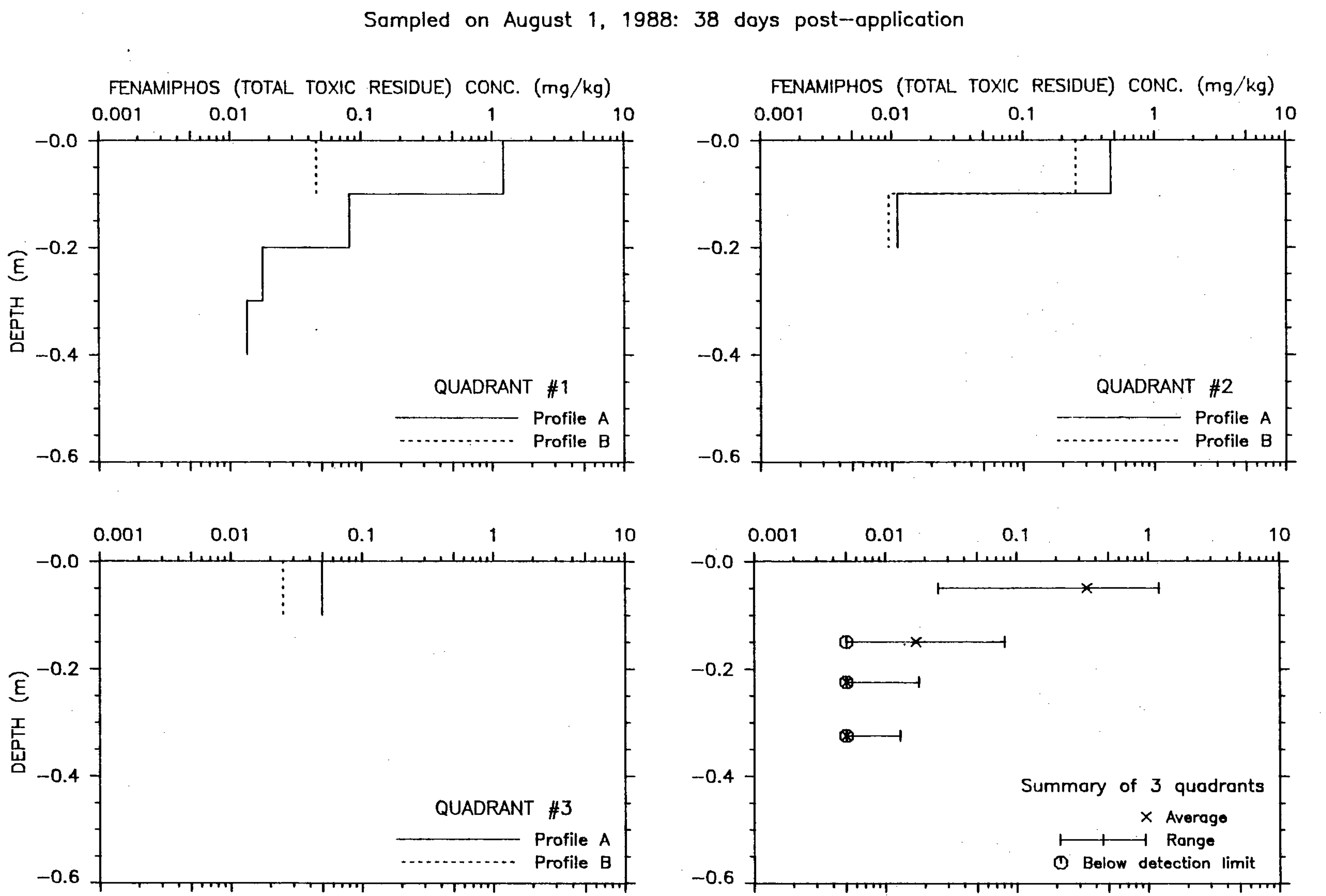


Appendix Figure A.14. Chlorpyrifos concentration profiles at Waiawa plot, fifth sampling (8 May 1989), 318 and 122 days post-application

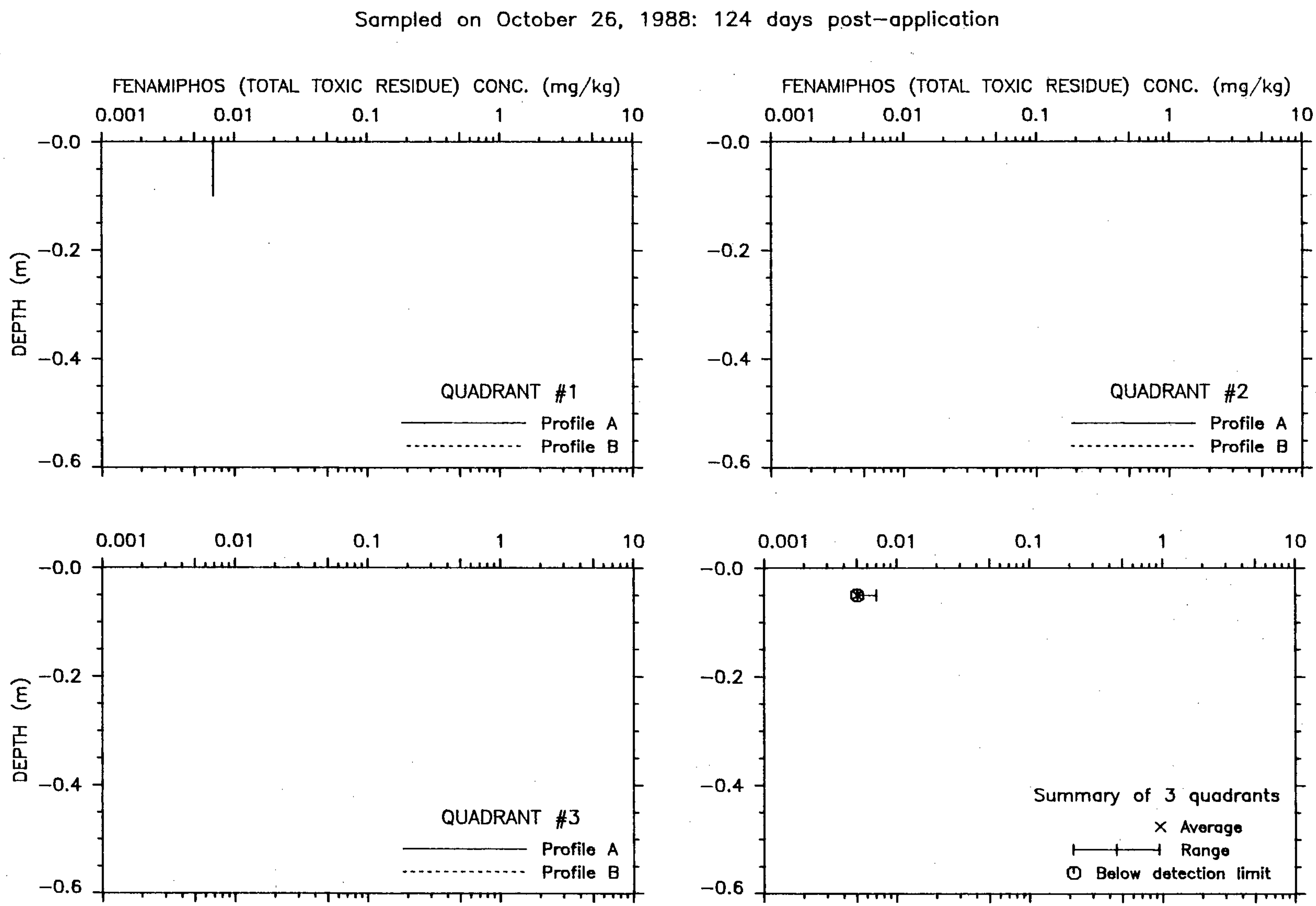
Sampled on June 28, 1988: 4 days post-application



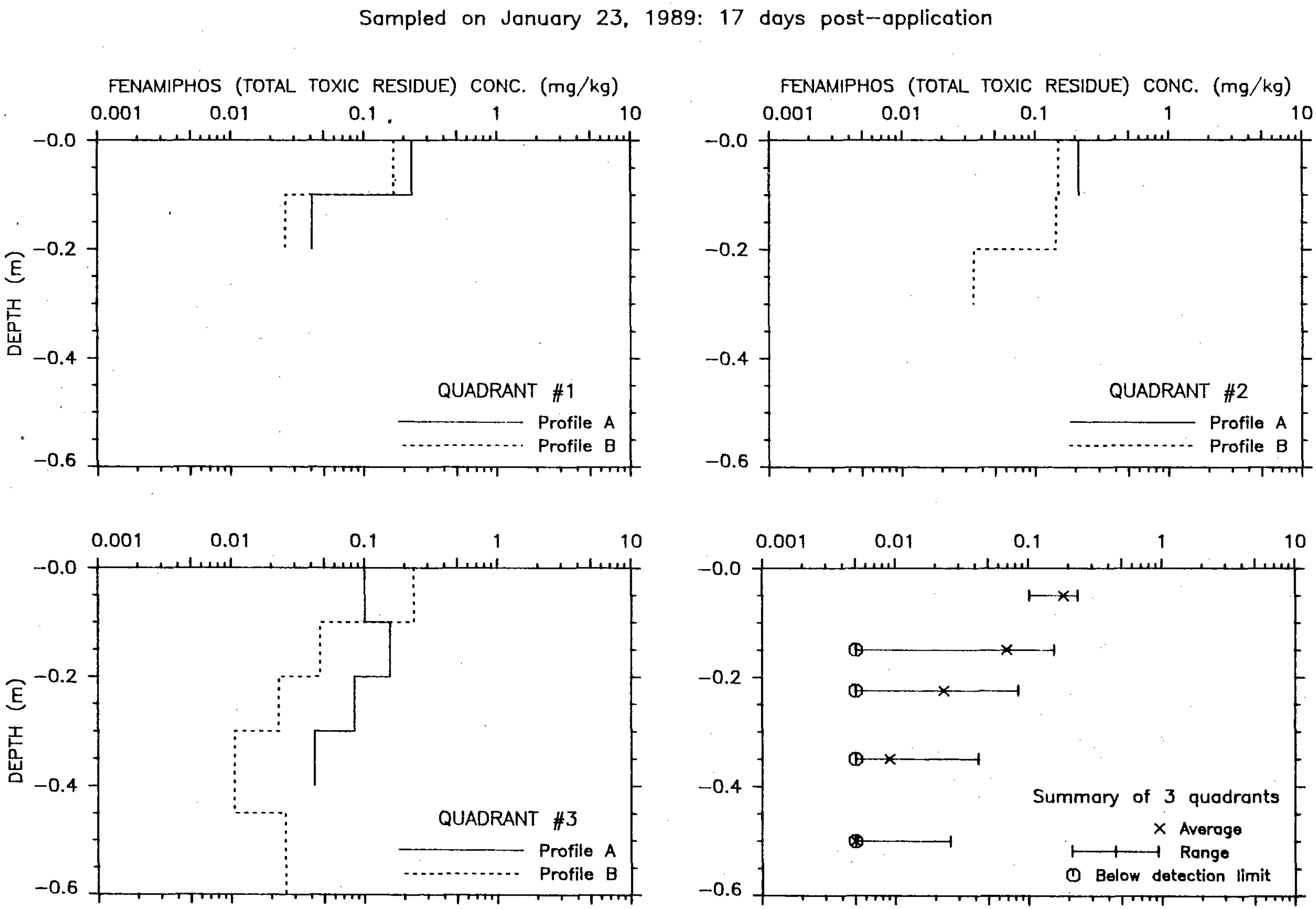
Appendix Figure A.15. Fenamiphos concentration profiles at Waiawa plot, first sampling (28 June 1988), 4 days post-application



Appendix Figure A.16. Fenamiphos concentration profiles at Waiawa plot, second sampling (1 Aug. 1988), 38 days post-application

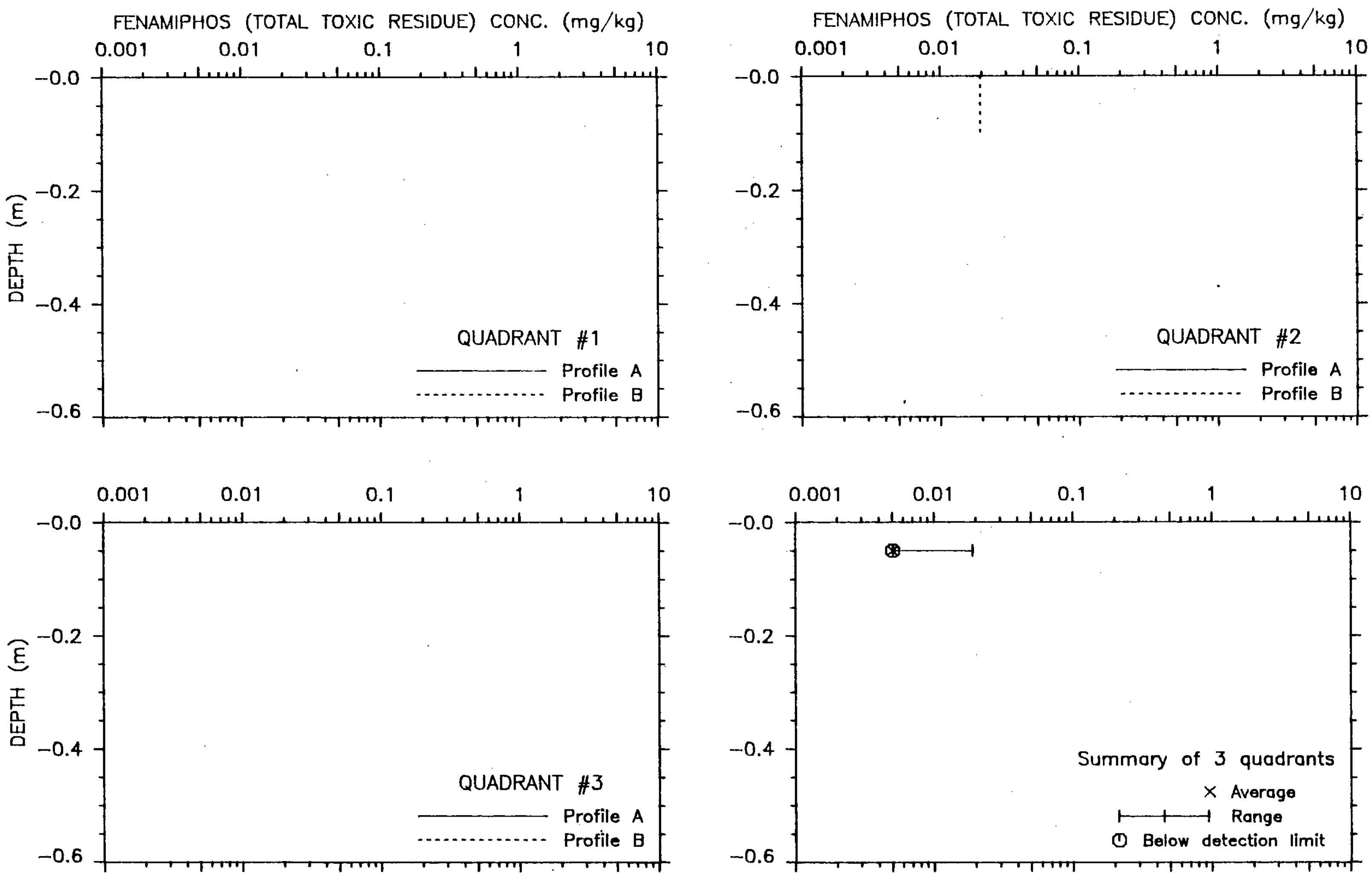


Appendix Figure A.17. Fenamiphos concentration profiles at Waiawa plot, third sampling (26 Oct. 1988), 124 days post-application



Appendix Figure A.18. Fenamiphos concentration profiles at Waiawa plot, fourth sampling (23 Jan. 1989), 213 and 17 days post-application

Sampled on May 8, 1989: 122 days post-application



Appendix Figure A.19. Fenamiphos concentration profiles at Waiawa plot, fifth sampling (8 May 1989), 318 and 122 days post-application on each sampling date are presented, with maximum and minimum concentrations for representative sampling depths also depicted. Concentrataions shown are on a dry-weight soil basis and do not reflect laboratory recovery rates, which were found to be about 90 and 95% for chlorpyrifos and fenamiphos, respectively.

POAMOHO CHEMICAL LEACHING STUDY

Throughout the first year of the project, an attempt was made to obtain access to Waiawa Ridge land, which is owned by Bishop Estate and leased by OSC (Amfac), and which is the site of the proposed Gentry Waiawa Master Plan community. It was hoped that three experimental test plots could be established on Waiawa Ridge to provide calibration and validation data for computer modeling. However, due to perceived liability problems with the chemical leaching experiments, OSC could grant access to WRRC only under conditions which were totally unacceptable to the Contracts and Grants Management office of the University of Hawaii.

During January 1989, a Right-of-Entry agreement between The Gentry Companies and OSC was eventually signed which also recognized WRRC's need to enter the Waiawa Ridge area to collect soil samples. In addition to the agreement between The Gentry Companies and OSC, WRRC was required to sign a Right-of-Entry agreement with The Gentry Companies. Although the agreements granted WRRC access to Waiawa Ridge, the application of any chemicals to the ground was strictly prohibited. Thus, experimental test plots could not be established on Waiawa Ridge for the purpose of testing chemical movement in the soil.

Since the application of any chemicals to the ground on Waiawa Ridge was strictly prohibited by the Right-of-Entry agreement with OSC and The Gentry Companies, an alternate experimental test site was selected at the University of Hawaii College of Tropical Agriculture and Human Resources experimental station at Poamoho. Soil at the Poamoho site is of the Wahiawa series which is also found on Waiawa Ridge. Two of the other main soils found on the ridge are the Lahaina and the Molokai series. All three soils belong to the Oxisols order.

A number of double-ring infiltration tests were conducted on the Wahiawa soil series on Waiawa Ridge and at the Poamoho site to determine if the soils had similar infiltration characteristics. Six tests, ranging in duration from 40 to 80 minutes, conducted on the Wahiawa soil series on Waiawa Ridge yielded steady-state infiltration rates of 9 to 170 mm/hr. These rates are similar to the infiltration rates obtained from tests conducted by Green et al. (1982) near the alternate experimental plot site at Poamoho. The results of Green et al. (1982) were further confirmed for this study at the actual plot site.

The field experiments conducted at Poamoho and Waiawa Valley provide an extreme range of soil types for model calibration. This range of soil conditions precluded the need to develop additional field plots on the Lahaina and Molokai soils found on Waiawa Ridge. Exact correspondence of soil properties between field test sites and the proposed development site is not essential since the principal purpose of the field experiment is only to test model performance. Key parameters required by the model were measured at both the test site and on each of the main soil series in the development area so that the model could be applied to Waiawa Ridge.

Plot Preparation. The site selected for the experimental plot at Poamoho was most recently used for corn crops but was fallow for approximately 1.5 yrs. In the past, insecticides such as carbaryl (Sevin), diazinon, methomyl (Lannate), and naled (Dibrom) and herbicides such as glyphosate (Roundup) and paraquat may have been applied at or near the test site.*

Remains of the previous corn crop planted in the experimental plot were raked into piles and burned by Poamoho station personnel. (Unfortunately, Poamoho station personnel burned the corn trash at locations which were impossible to completely avoid. Thus, small portions of the northern and eastern quadrants of the plot contain ash residues. These areas were noted and were avoided in all sampling efforts.) The field was then tilled to a depth of approximately 0.2 to 0.25 m on 19 January 1989 to obtain uniform soil conditions near the surface. The tilling process loosened hard and compacted surface soil and also facilitated manual levelling of the soil. The plot measures approximately 10.6 m x 10.6 m which is identical to the dimensions of the Waiawa Valley test plot. The diagonals of the plot are oriented approximately north-south and east-west.

*R.Y. Nakano (Hawaii Institute of Tropical Agriculture and Human Resources) 1989: personal communication.

To prevent unquantifiable amounts of runoff from entering the plot, an earthen berm approximately 0.15 to 0.2 m high was built around the perimeter of the plot. In addition, an interception ditch approximately 0.15 to 0.2 m deep and 0.2 to 0.25 m wide was dug just outside the berm along the northeast, southeast, and southwest edges of the plot. The land appears to slope at a grade of approximately 1 to 2% from southeast to northwest so that runoff will not likely enter the plot along the northwest edge. Thus, an interception ditch was unnecessary along the northwest edge of the plot.

After defining the boundaries of the plot, levelling the soil, and constructing the berm and interception ditch system, the plot was irrigated with 47.5 mm (1.87 in.) of water to slightly compact the tilled surface soil in a uniform manner. (Subsequent rainfall events also tended to uniformly compact the loose surface soil which made it possible to walk on the plot during the chemical application process without creating large surface depressions.) Weeds and grass were allowed to grow on the plot to enhance infiltration.

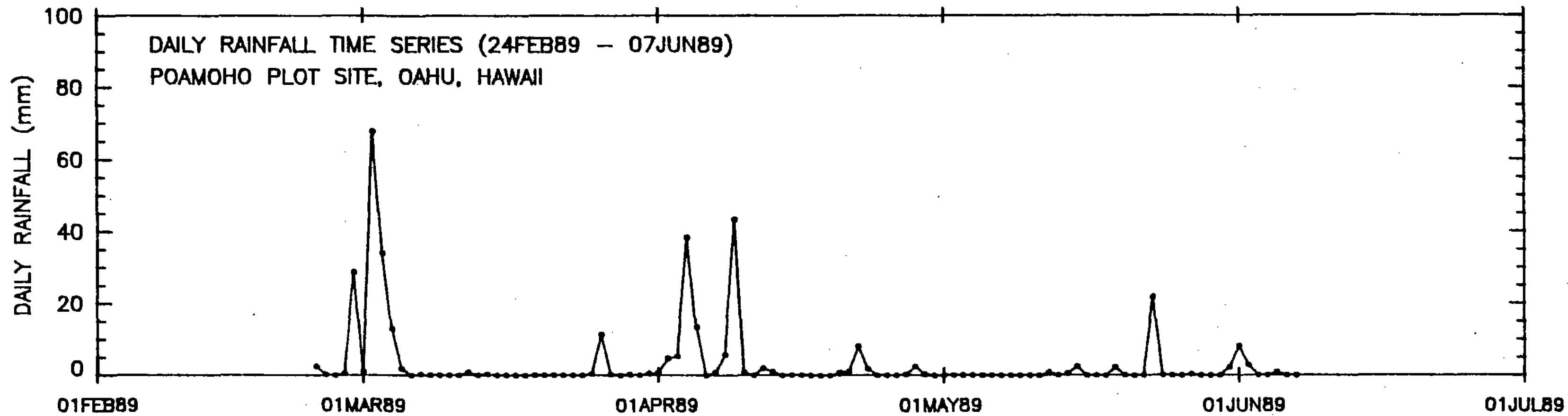
Selection of Test Chemicals. The chemicals selected for application on the Poamoho test site were bromide, chlorpyrifos, and fenamiphos. The three chemicals are the same as those applied on the Waiawa Valley plot. The rationale for selecting these chemicals was presented in the section above on the the Waiawa Valley leaching experiments and will not be repeated here.

Background Soil Samples. Prior to applying the pesticides and chemical tracer bromide to the plot, soil samples were collected to determine the background concentrations of fenamiphos, chlorpyrifos, and bromide. Holes were augered along the southwest, northwest, and northeast edges of the plot and soil samples were collected to a depth of approximately 1.2 m in each hole. Fenamiphos and chlorpyrifos were not detected in background sample analyses. Bromide was detected at concentrations slightly lower than the background levels found in Waiawa Valley.

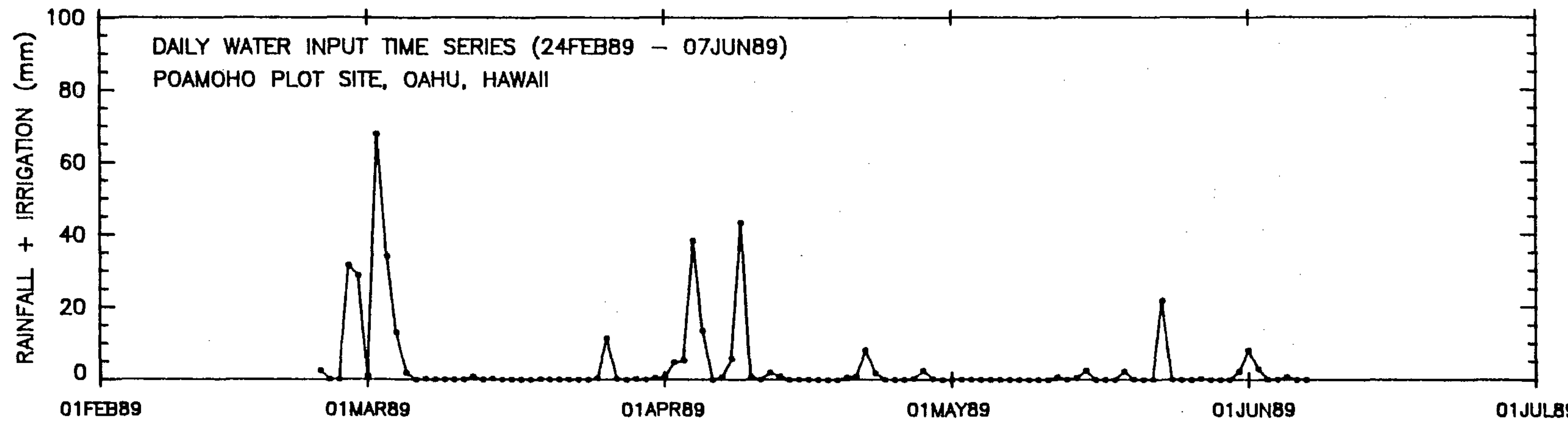
Chemical Application. The methodology used for the chemical application at Poamoho was essentially the same as that used for the two applications at the Waiawa Valley plot. During the week preceeding the application date, a total of 34 mm of rainfall occurred at Poamoho which made a pre-application irrigation of the plot unnecessary. The 27 February 1989 application of chemicals on the Poamoho plot was carried out by certified pesticide applicator D.N. Little. A total of 27 ml of Nemacur 3E containing 0.36 kg/l (3 lb/gal) fenamiphos, 114 ml of Dursban 2E containing 0.24 kg/l (2 lb/gal) chlorpyrifos, and 164 g of NaBr were mixed into 7.6 l (2 gal) of water in a CO_2-pressurized backpack tank and applied to one quadrant of the plot. Chemicals were applied only in the west, east, and south quadrants of the plot. The north quadrant was used for soil hydraulic experiments. By dividing the plot into quadrants, greater replication of results was possible. Final pesticide loading rates were 3.5 kg/ha (3 lb/acre) fenamiphos and 9.8 kg/ha (8.7 lb/acre) chlorpyrifos. These pesticide loading rates used at Poamoho were identical to the rates used in Waiawa Valley. The bromide dosage was identical to the dosage used for the second application at Waiawa Valley. Immediately following the application, the entire plot was irrigated with a depth of 31 mm of water to incorporate the chemicals into the soil.

Weather Station. Rainfall at the Poamoho experimental station was read on a daily basis by Richard Y. Nakano of the Hawaii Institute of Tropical Agriculture and Human Resources (HITAHR). A backup manual rain gage was also installed just outside the northwest edge of the plot site. A summary of the daily rainfall occurring at the plot site for the duration of the field test is presented in Appendix Figure A.20. A standard Class A pan equipped with a hook gage in a stilling well was also installed at the Poamoho station to measure daily pan evaporation.

Plot Maintenance. Plot maintenance at the Poamoho experimental site involved occassionally cutting down weeds by hand. Weed growth remained relatively sparse throughout the entire experiment. Aside from the irrigation immediately following the chemical application, the Poamoho experimental site did not receive water inputs other than rainfall. During the period soon after the chemical application, rainfall was sufficient to promote leaching. Thus, irrigation was felt to be unnecessary. A summary of the total water input to the plot during the experimental study period is presented in Appendix Figure A.21.



Appendix Figure A.20. Daily rainfall, 24 Feb.-7 June 1989, at Poamoho plot, Oahu, Hawaii

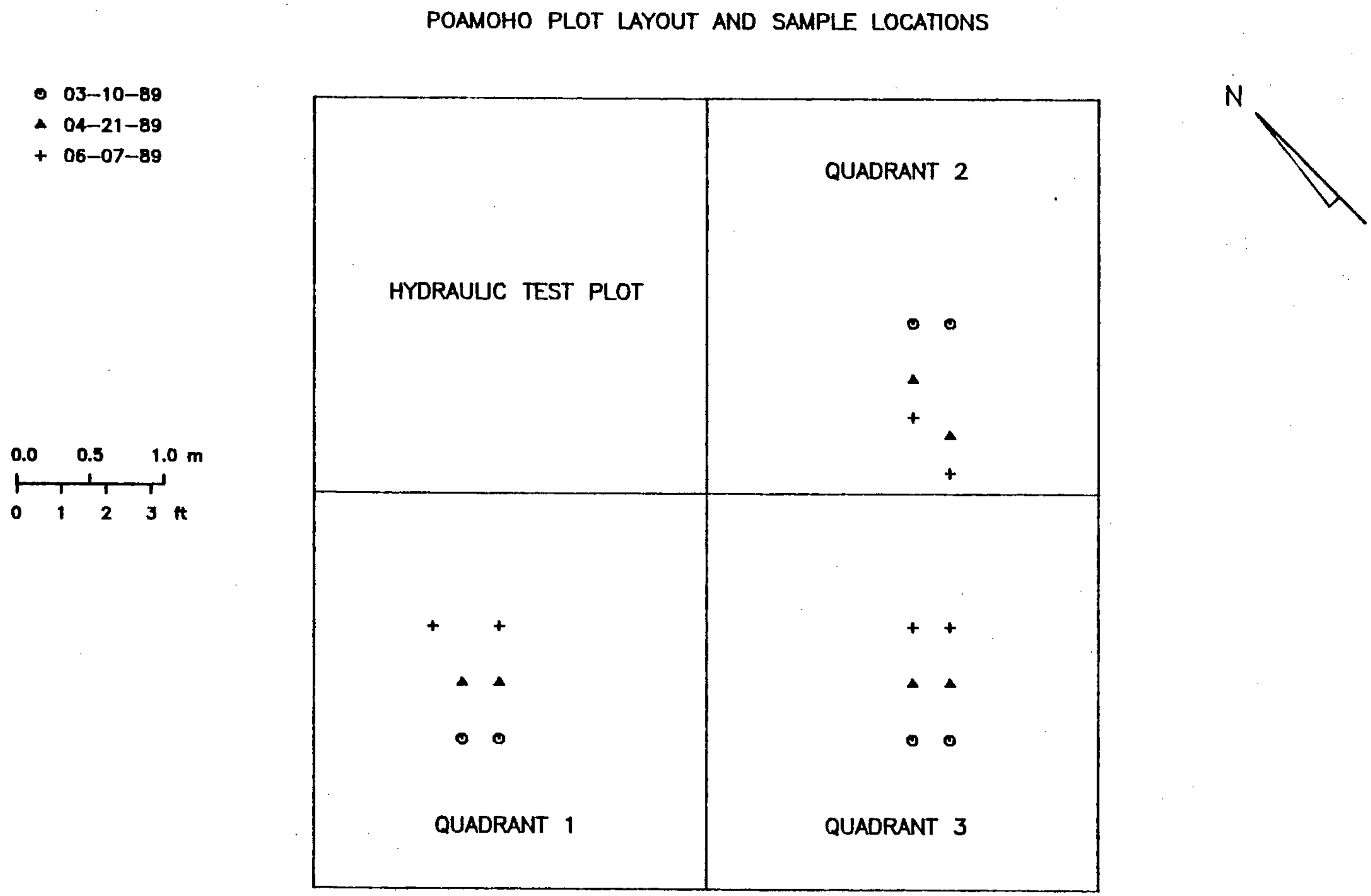


Appendix Figure A.21. Daily rainfall and irrigation, 24 Feb.-7 June 1989, at Poamoho plot, Oahu, Hawaii

Pesticide and Bromide Sampling. Due to rainy conditions following the chemical application, sampling for bromide and pesticide residues at the Poamoho plot could not be scheduled until 10 March 1989, 11 days after the application. Between the application and sampling dates, 147 mm of rainfall occurred at the Poamoho site. To account for this relatively heavy rainfall, sampling holes were augered to a minimum depth of 0.9 m so that the bottom of the solute profile would not be missed. For the initial sampling effort at Poamoho, two holes were augered in each of the three treated quadrants of the plot. The west, east, and south quadrants which were treated are labeled quadrants 1, 2, and 3, respectively, in Appendix Figure A.22. Sampling holes in each quadrant were spaced approximately 0.5 m apart and were located between 2 and 3 m from the plot edges. Maximum sampling depths were 0.94 and 1.47 m in quadrant 1, 1.13 and 1.49 m in quadrant 2, and 0.92 and 1.43 m in quadrant 3.

A sampling interval of 0.05 m was used for the first 0.1 m in order to obtain optimum resolution. A 0.04 m (1.5 in.) tube auger allowed accurate collection of 0.05 m soil samples. The tube auger penetrated the soil with a minimal amount of effort. Due to the small diameter of the tube auger, it was necessary to collect approximately 12 small 0.05-m cores at each sample location to provide enough soil for the laboratory analyses. All of the cores for a particular sample location and depth were augered within a 0.3 m diameter area and were mixed in a plastic ziplock bag. The sample bag was labeled and stored in an ice chest. The augered area was then cleared with a small hand-held garden spade to form a 0.05 m deep pit. Care was taken to remove all of the top 0.05 m of soil from the pit to avoid surface contamination in the next sampling increment. Prior to sampling for the 0.05 to 0.1 m depth range, the tube auger was cleaned beyond the plot boundaries with a scrubbing brush and water. Sampling for the 0.05- to 0.1-m increment was carried out using the same procedure described for the top 0.05 m. After collecting enough soil for the 0.05 to 0.1 m sample, the augered area was cleared with the garden tool to form a 0.1 m deep pit.

A 0.1 m (4 in.) bucket auger was used to collect the next two samples using a 0.1 m sampling increment down to a depth of 0.3 m. The top of each sample was discarded to minimize the potential for surface



Appendix Figure A.22. Poamoho experimental field plot layout and sample locations contamination. In addition, prior to augering, the bottom of the hole was carefully cleaned of any loose material which might represent soil from an overlying layer. The hole was then cased with a short length of 0.1 m (4 in.) PVC pipe prior to employing a 0.08 m (3.25 in.) bucket auger for sampling. The 0.08 m bucket auger was used to collect 0.1 m increment samples down to a depth of approximately 0.7 m. Once the hole had been augered to 0.7 m, a second casing of 0.08 m (3 in.) diameter PVC pipe was lowered into the hole. Beyond a depth of 0.7 m, a 0.05-m (2-in.) auger was used to collect samples in an uncased hole.

Care was taken to wash and scrub the augers after each sampling increment in each hole to avoid contamination of deeper soils layers by upper soil. Augered holes were subsequently backfilled with soil obtained from outside the plot and marked with flags attached to heavy-gage wire to prevent future sampling at the same locations.

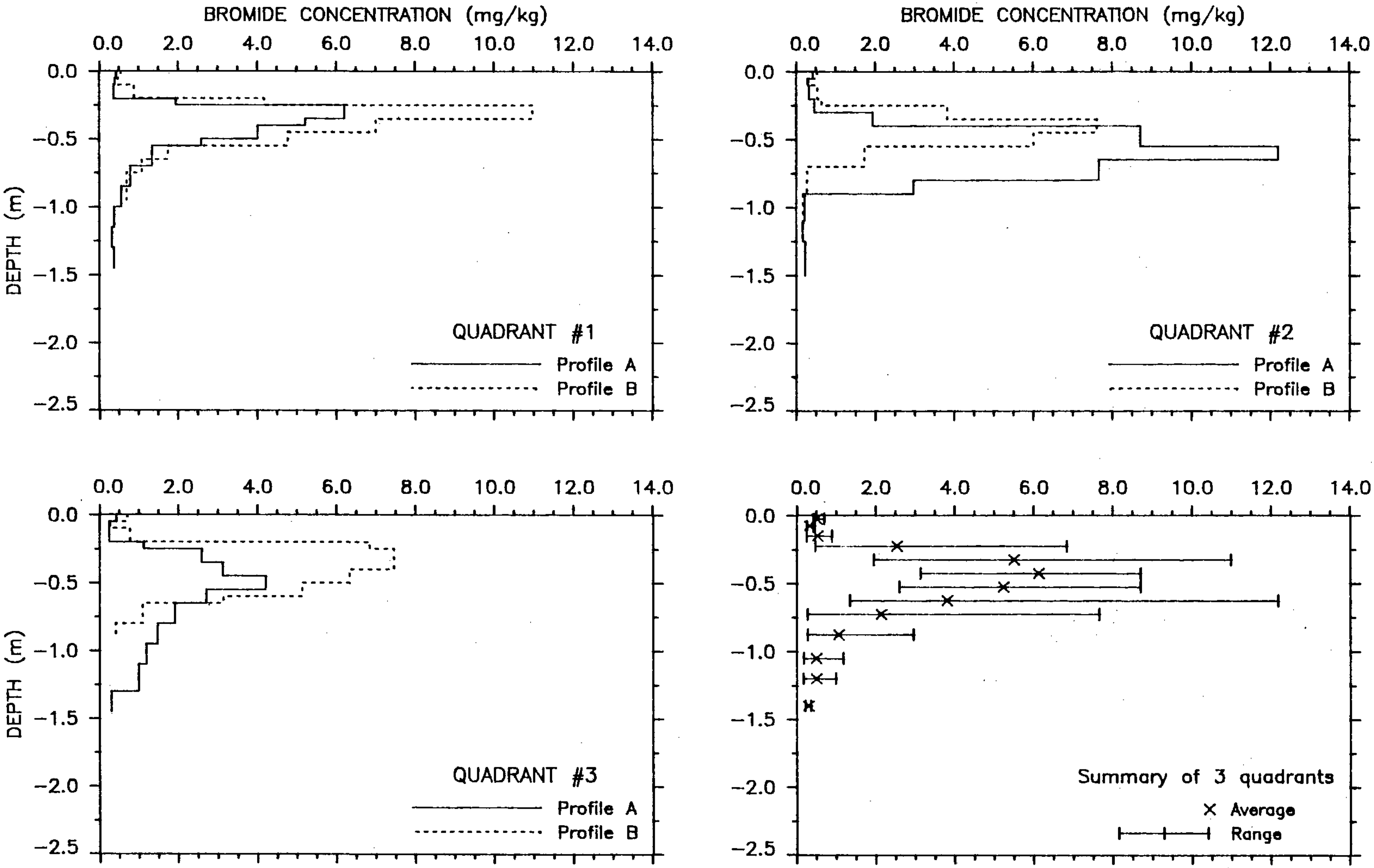
The second and third samplings at Poamoho occurred on 21 April 1989 and 7 June 1989. The sampling techniques used on these two dates are similar to the techniques used at Waiawa Valley (see description above for the 26 October 1988 sampling at Waiawa Valley). For the second sampling of 21 April 1989, maximum sampling depths were 1.50 and 2.43 m in quadrant 1, 1.58 and 2.52 m in quadrant 2, and 1.49 and 2.42 m in quadrant 3. For the final sampling of 7 June 1989, maximum sampling depths were 2.11 and 2.14 m in quadrant 1, 2.01 and 2.14 m in quadrant 2, and 2.02 and 2.50 m in quadrant 3. All sample locations are presented in Appendix Figure A.22.

All samples collected at Poamoho were transported to the University of Hawaii, Agronomy and Soil Science laboratory for analysis. Results of the bromide, chlorpyrifos, and fenamiphos analyses are presented in Appendix Figures A.23 to A.31.

ORGANIC CARBON TRANSECTS

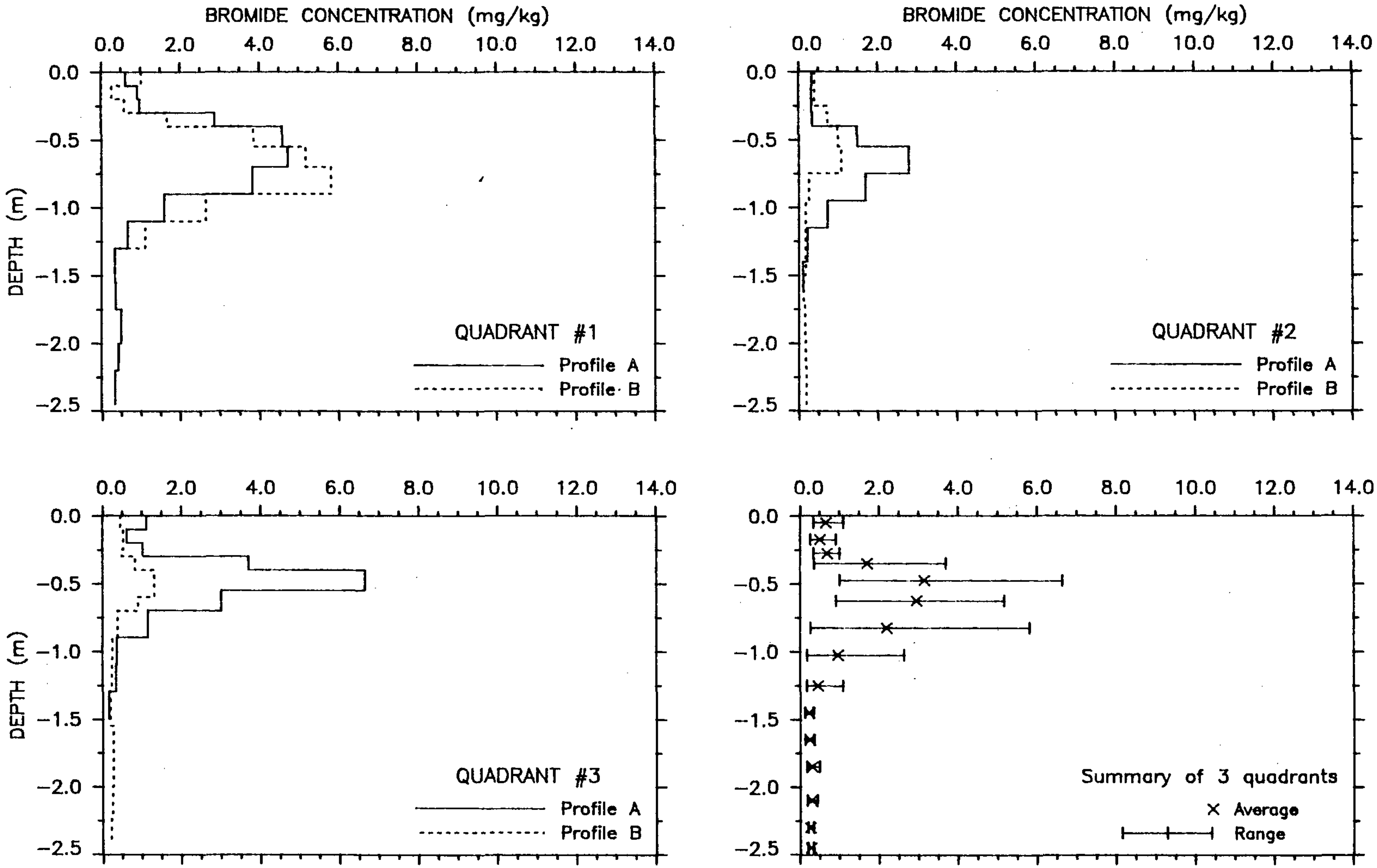
Organic matter is probably the most important factor affecting adsorption of pesticides in soil. Although adsorption of organic compounds by soil organic matter varies from soil to soil, it is generally recognized that greater organic contents in soil lead to greater adsorption of pesticides. For this study, it was necessary to characterize the spatial

Sampled on March 10, 1989; 11 days post-application

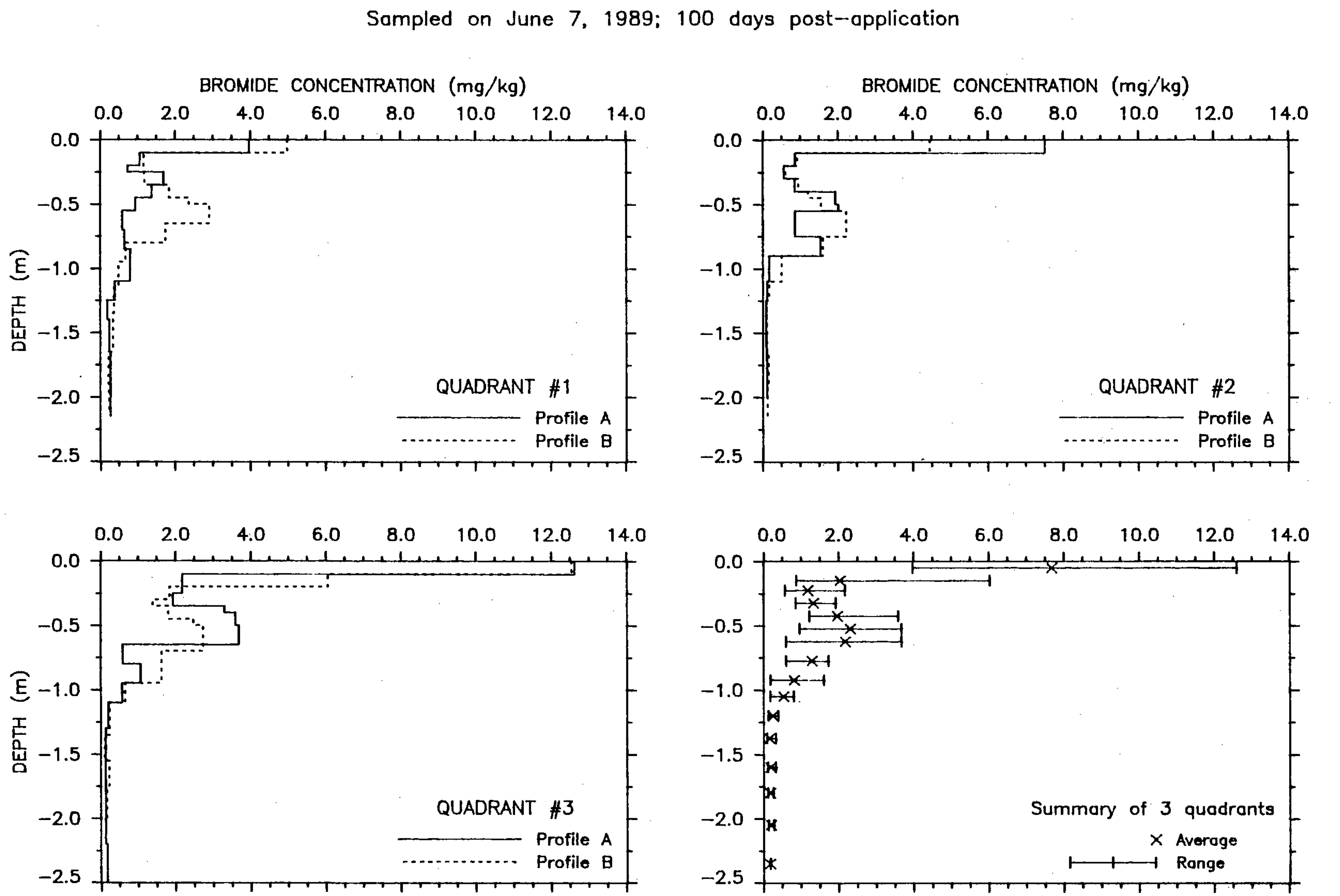


Appendix Figure A.23. Bromide concentration profiles at Poamoho plot, first sampling (10 Mar. 1989), 11 days post-application

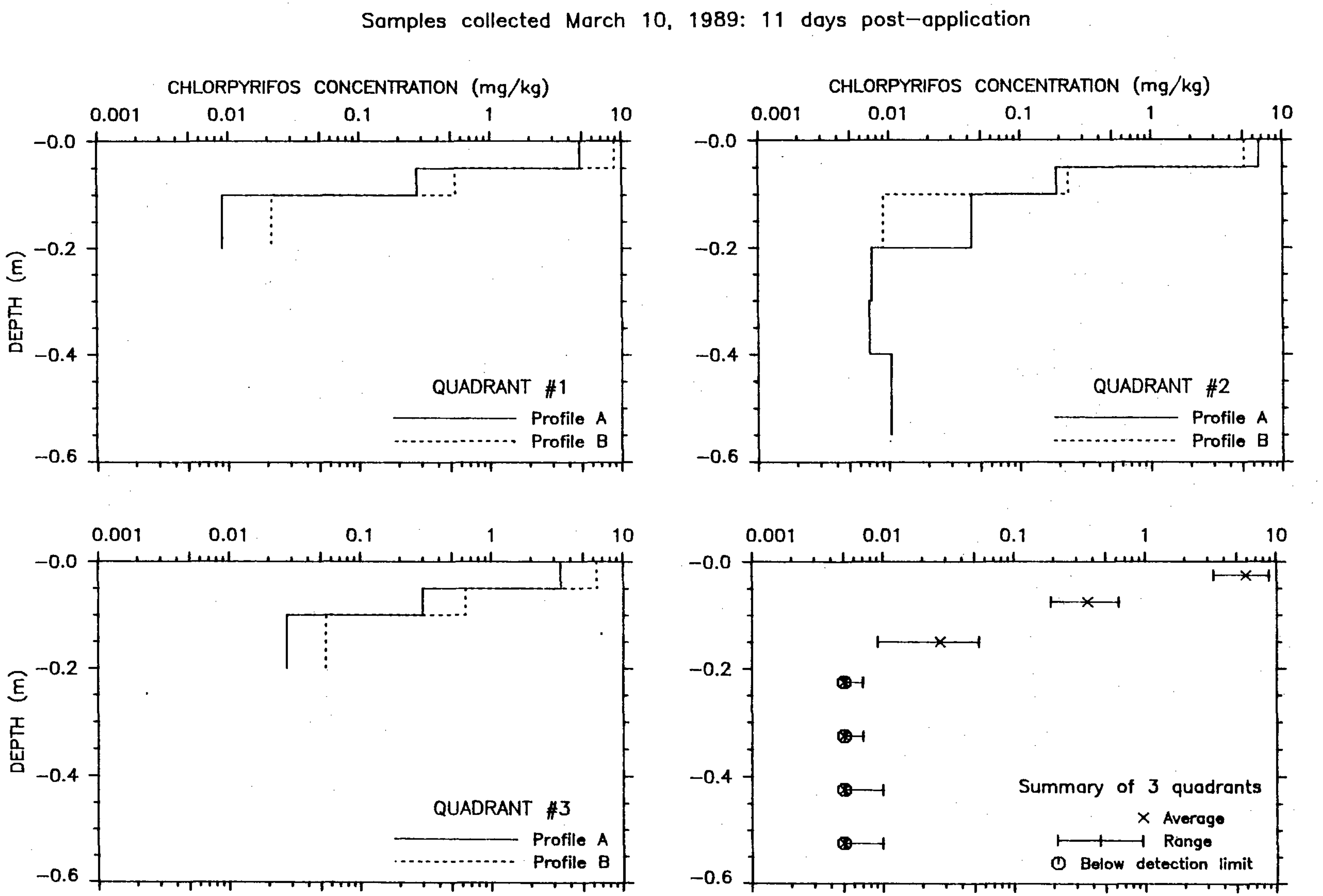
Sampled on April 21, 1989; 53 days post-application



Appendix Figure A.24. Bromide concentration profiles at Poamoho plot, second sampling (21 Apr. 1989), 53 days post-application

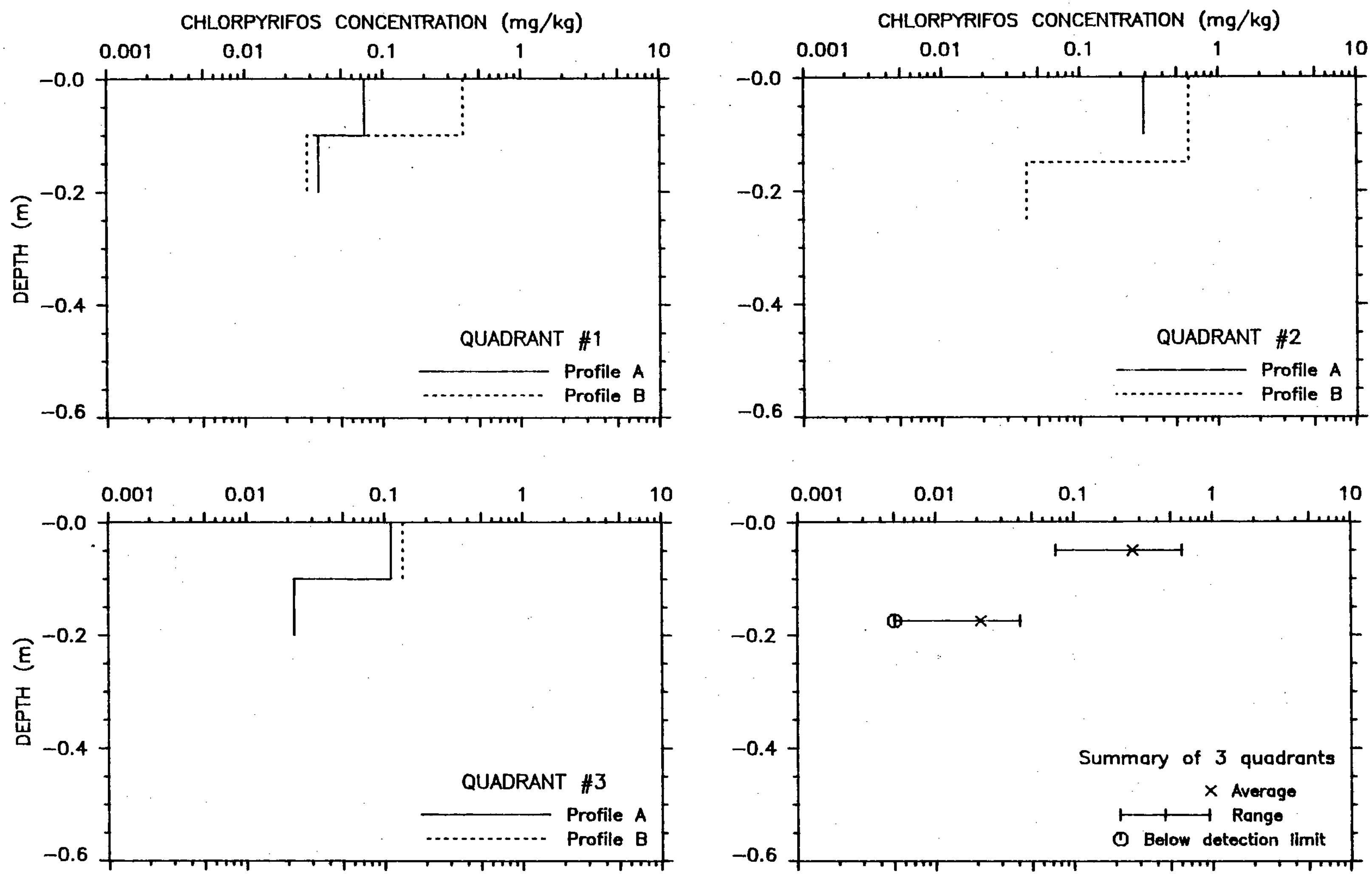


Appendix Figure A.25. Bromide concentration profiles at Poamoho plot, third sampling (7 June 1989), 100 days post-application

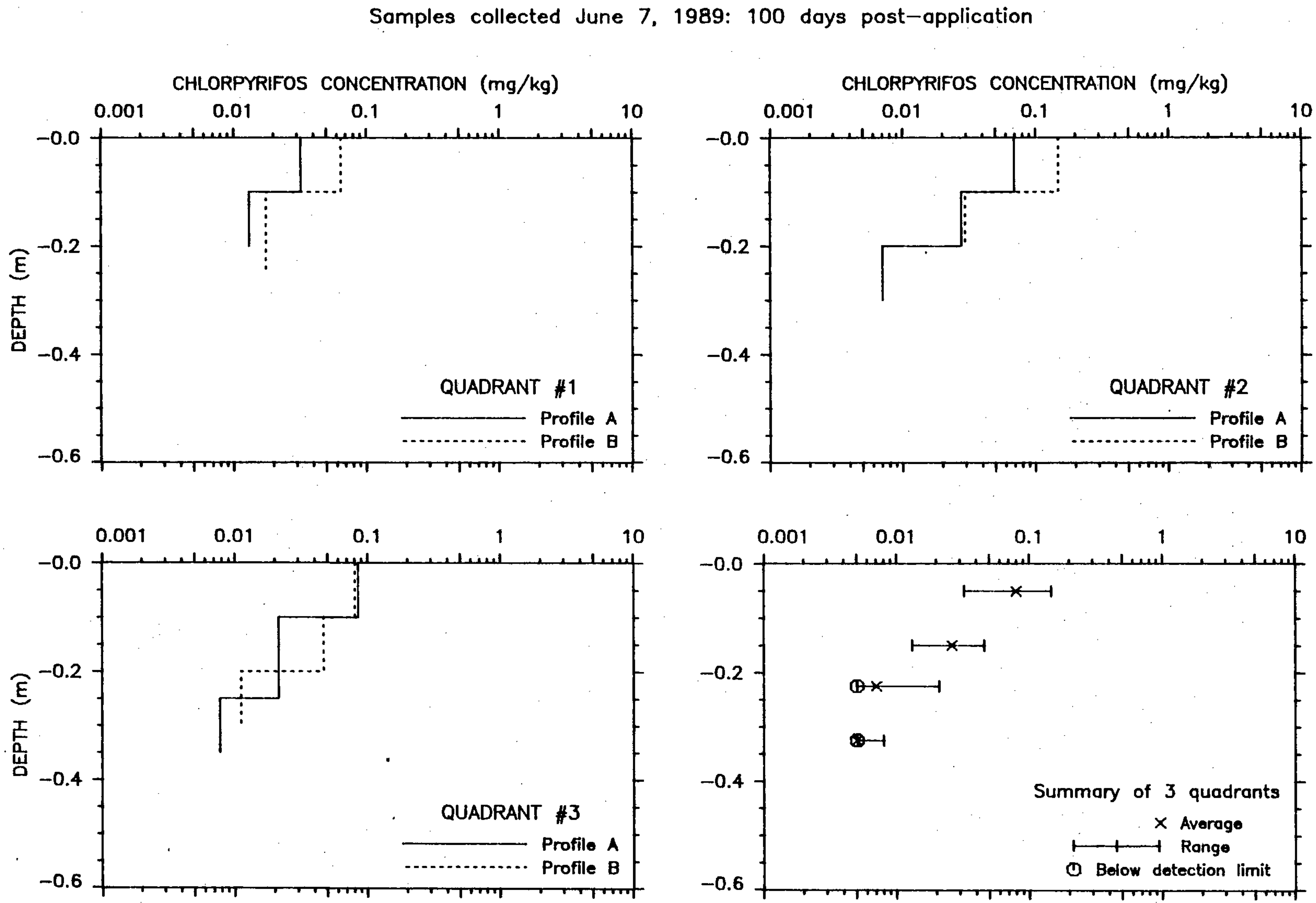


Appendix Figure A.26. Chlorpyrifos concentration profiles at Poamoho plot, first sampling (10 Mar. 1989), 11 days post-application

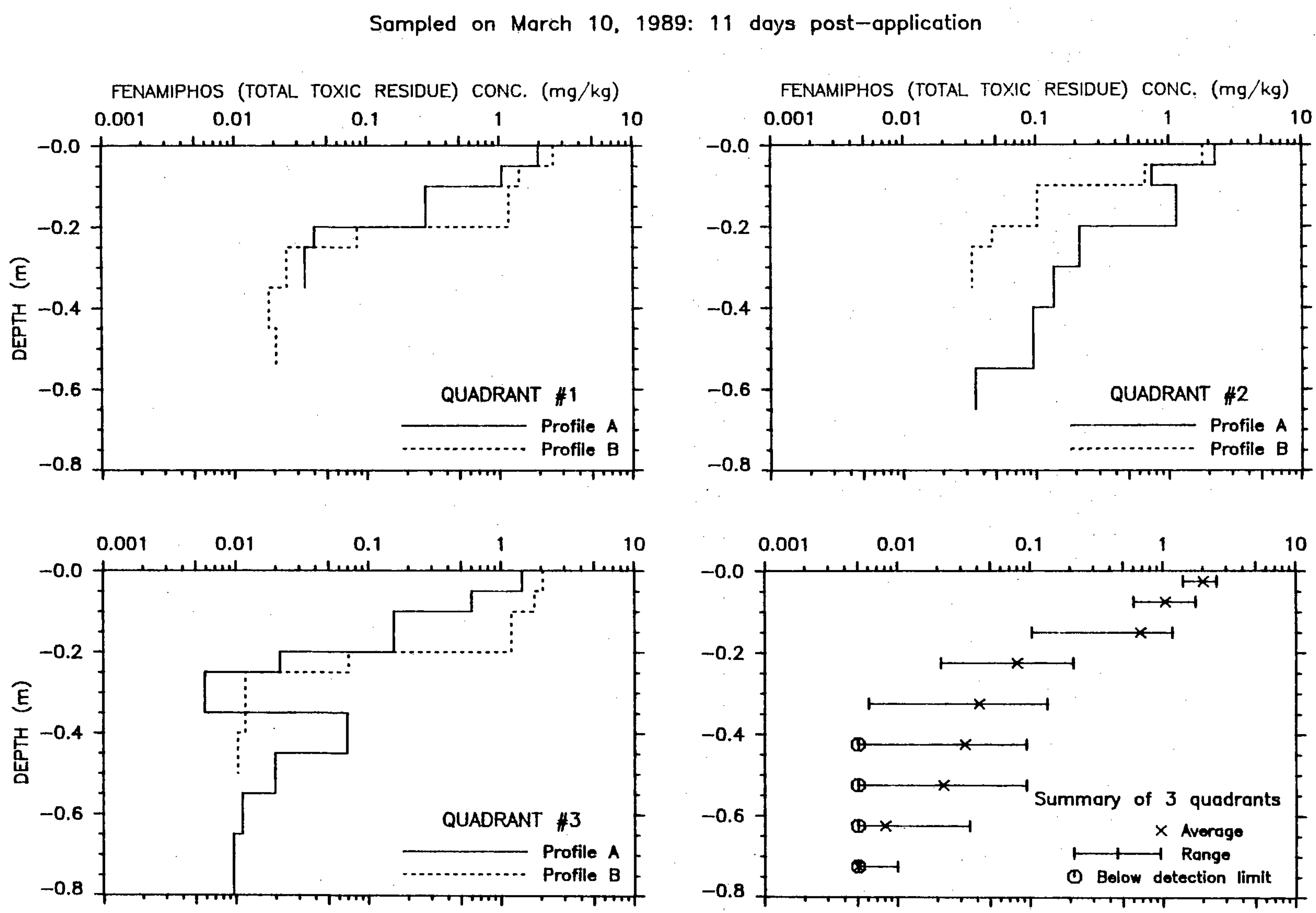
Samples collected April 21, 1989: 53 days post-application



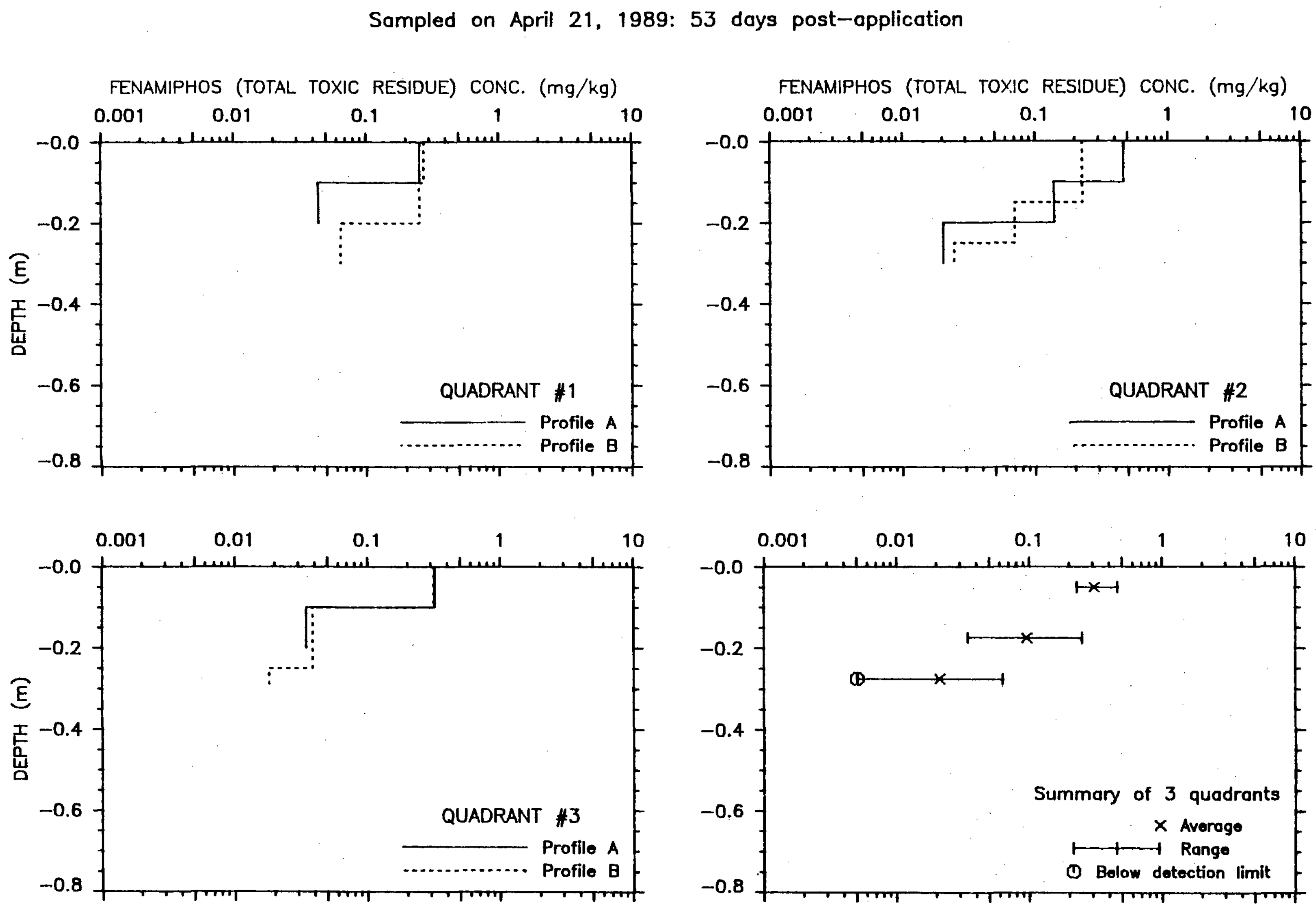
Appendix Figure A.27. Chlorpyrifos concentration profiles at Poamoho plot, second sampling (21 Apr. 1989), 53 days post-application



Appendix Figure A.28. Chlorpyrifos concentration profiles at Poamoho plot, third sampling (7 June 1989), 100 days post-application

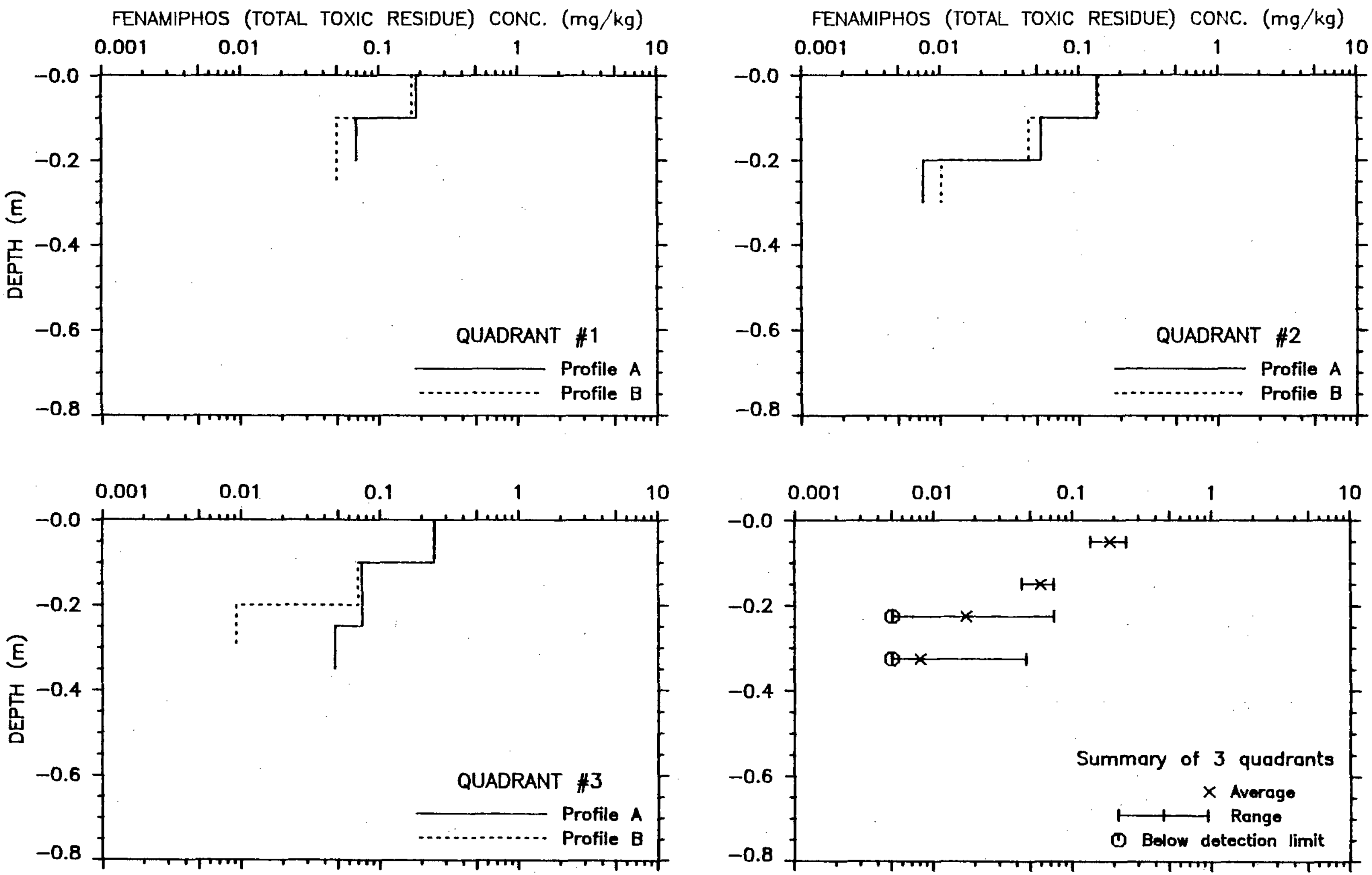


Appendix Figure A.29. Fenamiphos concentration profiles at Poamoho plot, first sampling (10 Mar. 1989), 11 days post-application



Appendix Figure A.30. Fenamiphos concentration profiles at Poamoho plot, second sampling (21 Apr. 1989), 53 days post-application

Sampled on June 7, 1989: 100 days post-application



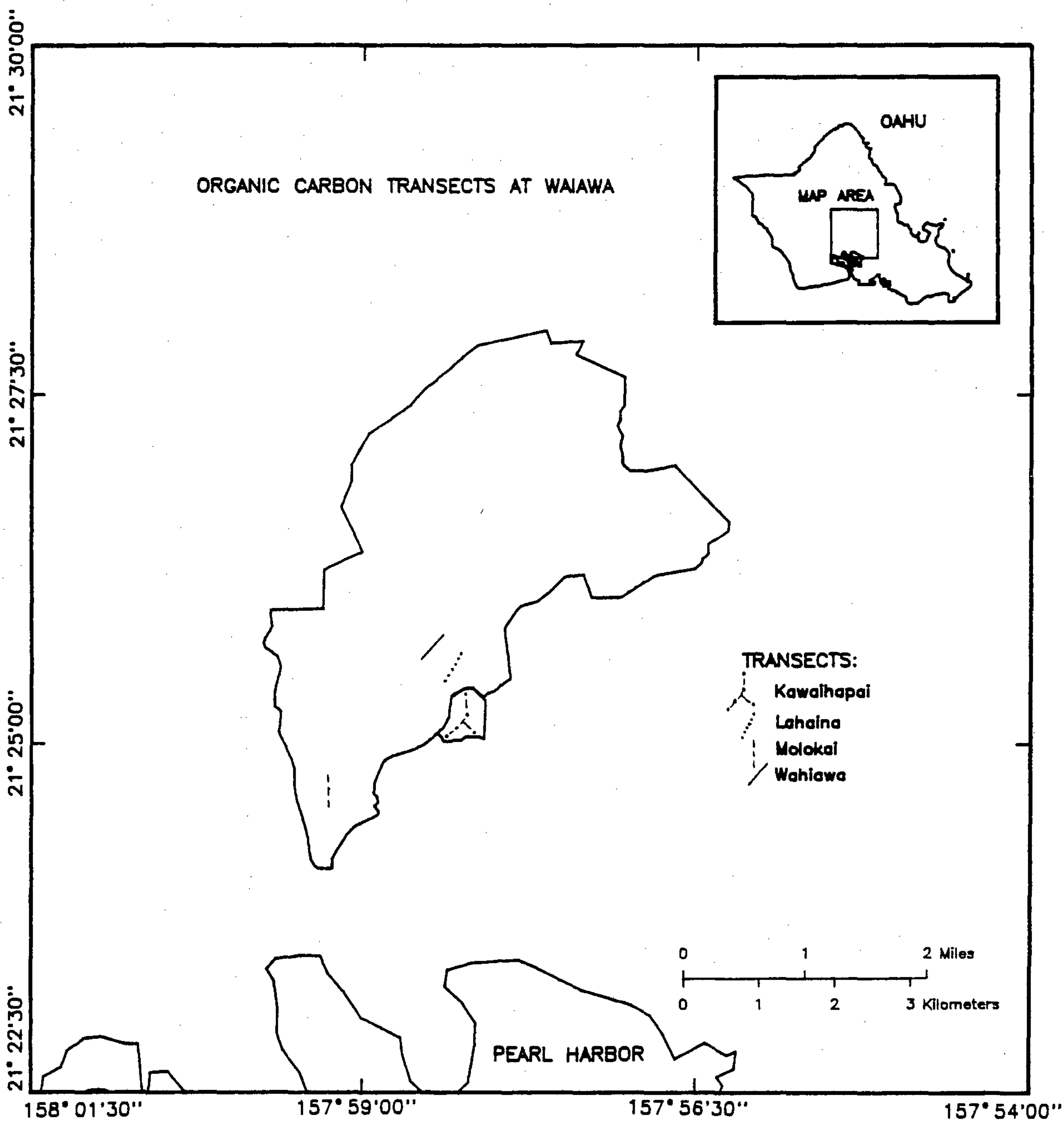
Appendix Figure A.31. Fenamiphos concentration profiles at Poamoho plot, third sampling (7 June 1989), 100 days post-application distributions of organic carbon throughout the proposed development areas on Waiawa Ridge and in Waiawa Valley.

In the USN Waiawa Valley property, sampling for organic carbon was conducted at the nodes of a 60-m^2 grid. Only those grid point locations occurring within the proposed development area were sampled. The general shape of the sampling network in Waiawa Valley is presented in Appendix Figure A.32. Sampling was conducted with a 0.08 m (3.25 in.) bucket auger in 0.3-m increments down to a minimum depth of 0.9 m. At certain grid point locations, however, the presence of rocks prevented augering to the desired 0.9-m depth. At such locations, at least three attempts were made to auger down to 0.9 m. Distances between sampling locations were measured with a steel tape after paths between adjacent sampling locations were established by clearing existing vegetation.

In addition to the 60-m grid point samples in Waiawa Valley, surface soil samples were collected for organic carbon analysis every 10 m along a straight transect running parallel to the existing road. The transect was offset 15 m to the east of the road centerline, and started near the southern extent of the USN property where a bridge currently exists over Waiawa Stream.

After obtaining access to Waiawa Ridge in January 1989, an effort was made to characterize the spatial distribution of organic carbon within the proposed development area. Straight transects through soils of the Lahaina, Molokai, and Wahiawa series (App. Fig. A.32) were established by erecting PVC pipes taller than the existing vegetation at each end of the line. PVC pipes were also erected at intermediate points to ensure that sampling was done on a line. Existing vegetation on the transect line was cleared to enhance visibility. An attempt was made to locate all transects with the same relative orientation to the prevailing grade. This was done to minimize inter-transect biases which might result if, for instance, one transect was oriented perpendicular and another parallel to the grade.

Surface soil samples on Waiawa Ridge were collected every 10 m for a distance of 400 m in each of the three main soil series. In addition, deeper holes were augered every 50 m along the transects to a depth of 1.2 m, with soil samples being collected at 0.3-, 0.6-, 0.9-, and 1.2-m

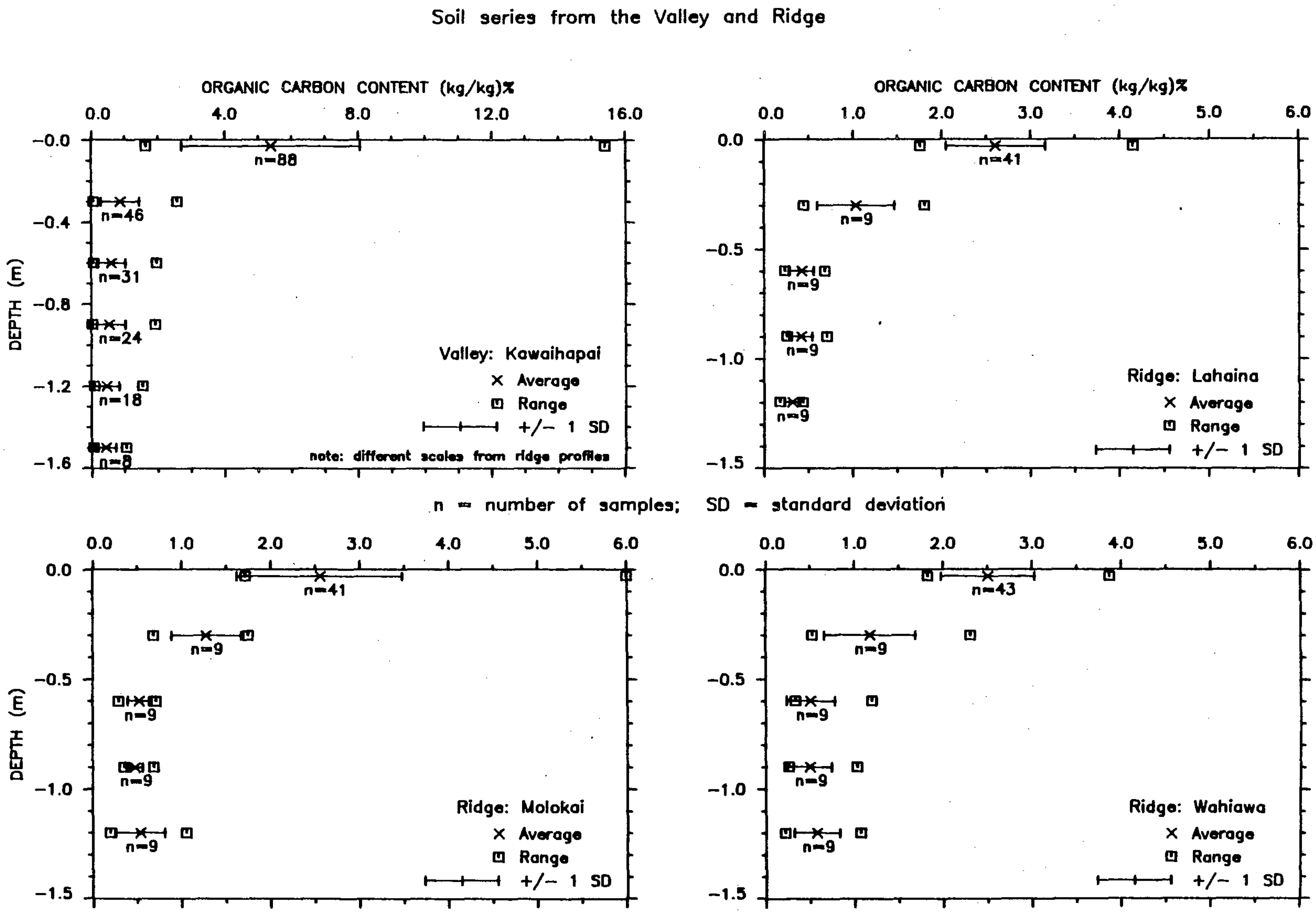


Appendix Figure A.32. Organic carbon transect sites at Waiawa, Oahu, Hawaii depths. A maximum sampling depth of 1.2 m was chosen since the bulk of the organic carbon content found in agricultural soils generally occurs within the plow layer which may extend to a depth of approximately 0.5 m. Organic carbon below a depth of 1 m is generally considerably lower.

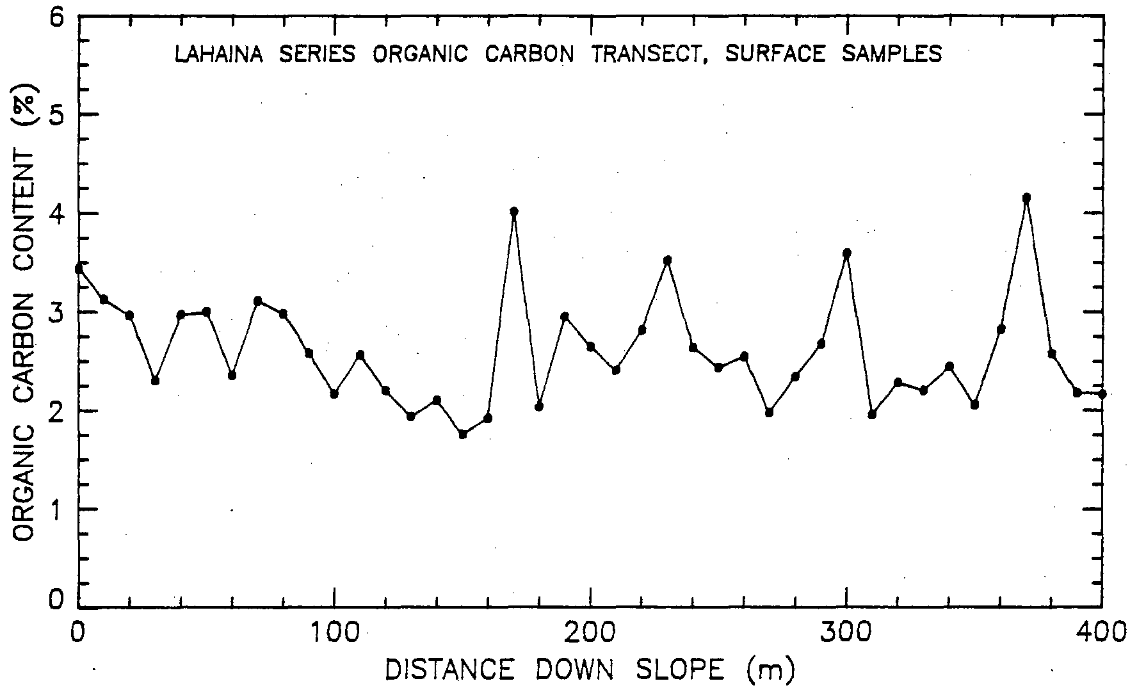
All soil samples collected in Waiawa Valley and on Waiawa Ridge were stored in plastic bags for transport to the University of Hawaii, Agronomy and Soil Science laboratory for analysis. The analytical methodology for the organic carbon analysis is presented in Appendix B. A summary of the organic carbon results is presented in Appendix Figure A.33. The spatial distributions of organic carbon within the Waiawa Ridge transects are presented in Appendix Figures A.34 to A.39.

The results presented in Appendix Figures A.34 to A.39 for Waiawa Ridge indicate very little variability in organic carbon content, especially in the subsoil. In the surface soil, organic carbon is generally greater than 2% in all three soil series. To characterize the spatial structure of variances, Bresler and Green (1982) suggest a minimum sample size of 30 measurement sites. For the surface soil, more than 30 samples were collected in each of the primary soil series and no structure was apparent. This is consistent with the findings of Abouna (1981) who determined that the variance of organic carbon in a 6-ha area of Lahaina soil had no clear structure.

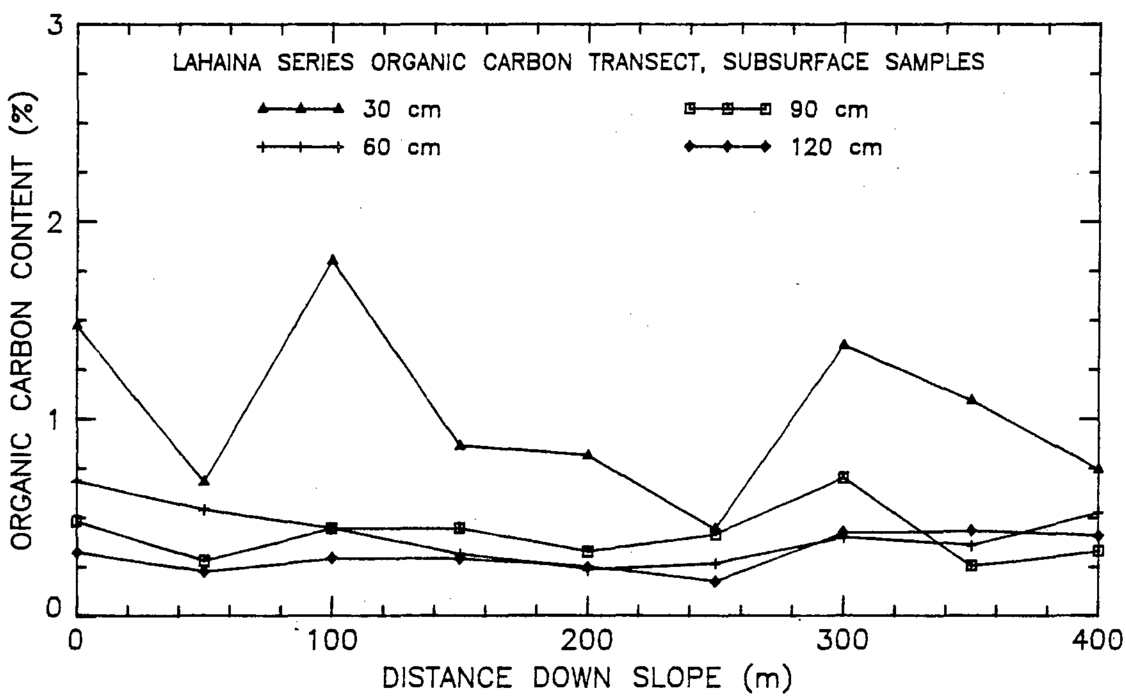
Sampling for organic carbon on Waiawa Ridge was limited by the access agreement with OSC, which holds the lease to the land. Thus, the areal extent of the transects could not be expanded throughout the proposed development area. While a more extensive organic carbon monitoring program on Waiawa Ridge may reveal local heterogeneities, additional sampling may not reveal any clear spatial structure.



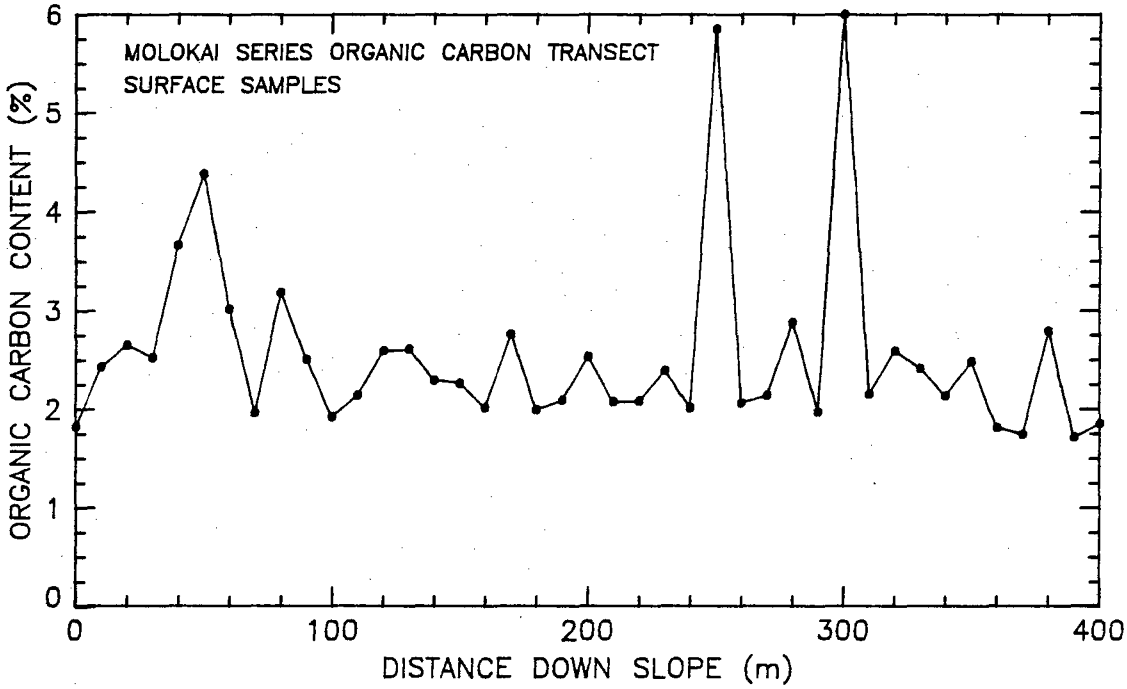
Appendix Figure A.33. Organic carbon profiles at Waiawa, Oahu, Hawaii



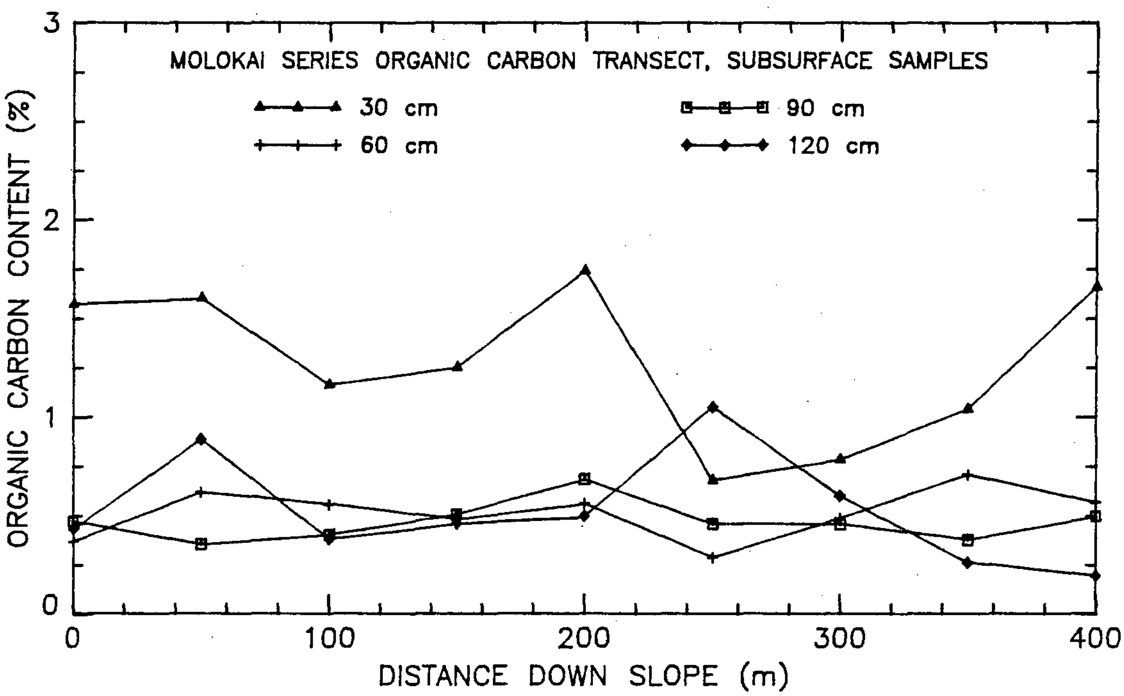
Appendix Figure A.34. Spatial distribution of organic carbon in surface samples of Lahaina series transect



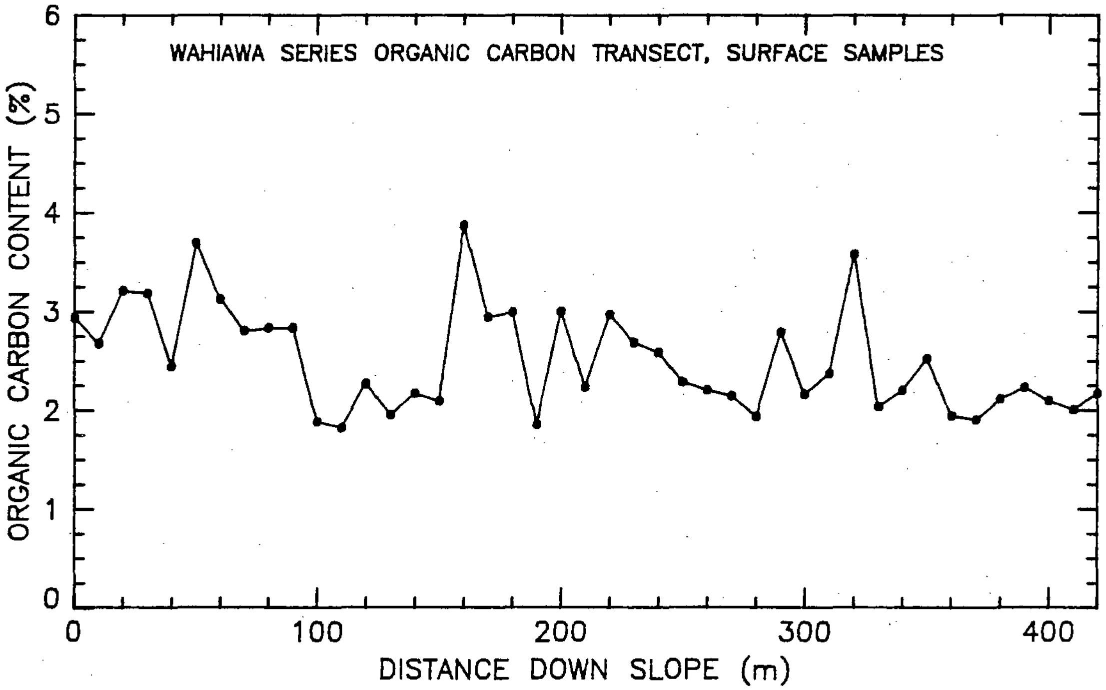
Appendix Figure A.35. Spatial distribution of organic carbon in subsurface samples of Lahaina series transect



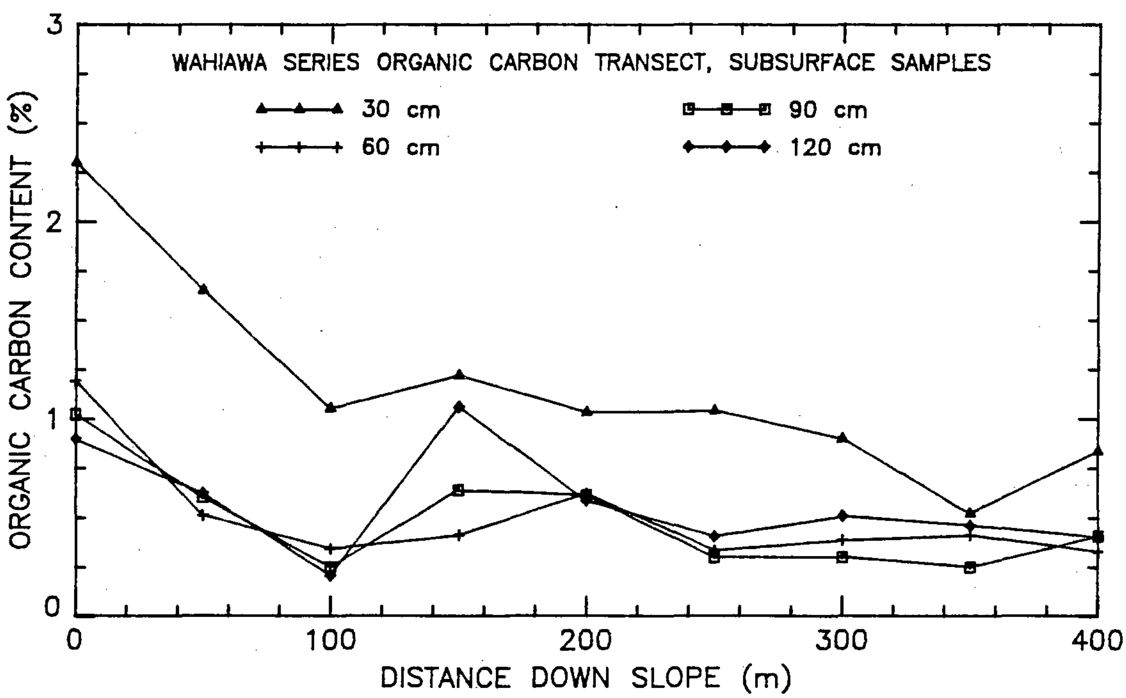
Appendix Figure A.36. Spatial distribution of organic carbon in surface samples of Molokai series transect



Appendix Figure A.37. Spatial distribution of organic carbon in subsurface samples of Molokai series transect



Appendix Figure A.38. Spatial distribution of organic carbon in surface samples of Wahiawa series transect



Appendix Figure A.39. Spatial distribution of organic carbon in subsurface samples of Wahiawa series transect

Kawaihapai Inclusion

Soil Classification: Fine, mixed, ishohyperthermic Typic Troporthents

Location: Island of Oahu, Hawaii. University of Hawaii Water Resources Research Center study plot in Waiawa Valley on Navy land

Elevation: 40 m (130 feet)

Annual Rainfall: 102 cm (40 inches)

Vegetation: Guineagrass, koa haole

Parent Material: Colluvium or possibly fill, consisting of highly weathered basaltic rock fragments

Physiography: Nearly level gulch bottom and at the base of the gulch side

Slope: 2 percent (0 to 3 percent)

Drainage: Well drained

Ground water: Deep

Erosion: None

Permeability: Moderate

Stoniness: Nonstony (few rock fragments in places)

Described by: S. Nakamura, 2/16/89

Sampled by: S. Nakamura, Delwyn Oki, Robert Miyahira, Ed Murabayashi

Remarks: This soil is mapped as an inclusion with Kawaihapai stony clay loam, 2 to 6 percent slopes. It lacks stratified alluvial layers typical of the Kawaihapai soils. This soil is along the bottom of the gulch but at a higher level than the existing stream. The site was probably filled by material cut from the base of the gulch side.

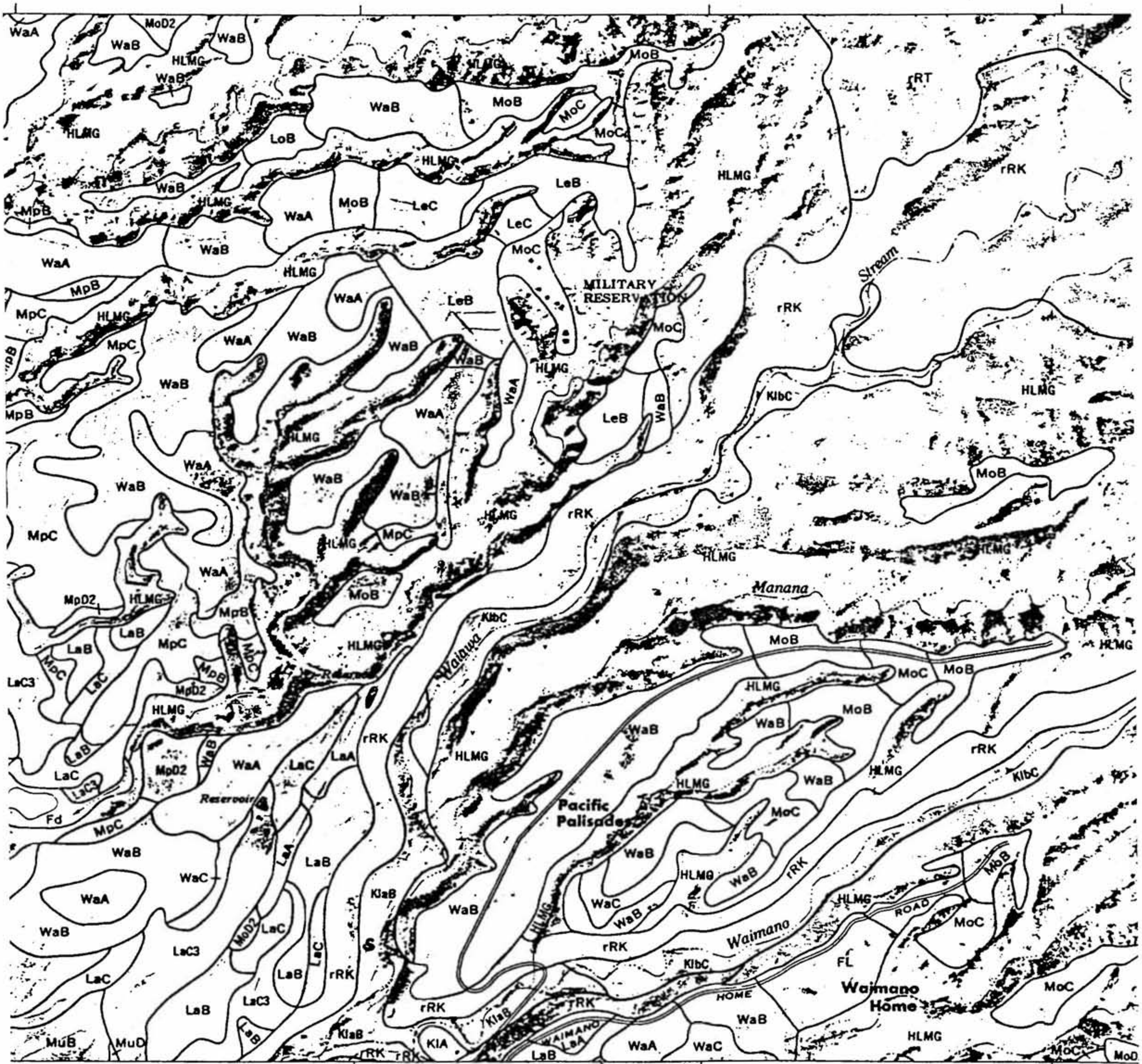
A1 -- 0 to 10 cm (0-4"); fill layer of oyster shells and coral rock fragments; common fine and very fine roots; abrupt smooth boundary.

A2 -- 10 to 18 cm (4-7"); dark brown (10YR 3/3) clay loam; weak fine and medium subangular blocky structure; firm, sticky, and plastic; common fine and very fine roots; common very fine pores; clear smooth boundary.

C1 -- 18 to 75 cm (7-30"); variegated dark yellowish brown (10YR 4/4) yellowish brown (10YR 5/6) and dark brown (10YR 3/3) clay loam; weak fine and medium subangular blocky structure; friable, very sticky, and plastic; common very fine roots; common very fine pores; 10 percent weathered gravel and 3% weathered cobbles; gradual smooth boundary.

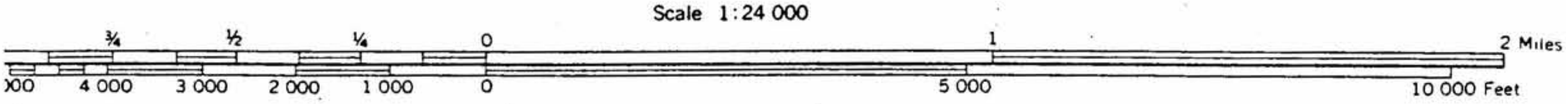
C2 -- 75-126 cm (30-50"); variegated yellowish brown (10YR 5/6), dark brown (10YR 4/4), and dark yellowish brown (10YR 4/6) gravelly clay loam; weak fine and medium subangular blocky structure; friable, very sticky, and plastic; few very fine roots; common very fine pores; 15% weathered gravel and 5% weathered cobbles; gradual smooth boundary.

C3 -- 126-190 cm (50-75"); variegated yellowish brown (10YR 5/6), dark brown (10YR 4/4), and dark yellowish brown (10YR 4/6) very gravelly clay loam; weak fine and medium subangular blocky structure; friable, very sticky, and plastic; few very fine roots; common very fine pores; 25% weathered gravel and 10% weathered cobbles.



↑ Pesticide Study Plot

Scale 1:24 000



APPENDIX B. LABORATORY TESTS

LABORATORY PROCEDURES

The laboratory analyses conducted for this study involve the quantification of chlorpyrifos, fenamiphos, and bromide concentrations in soil. In addition, analyses for soil organic carbon and soil moisture were conducted. All analyses were performed at the University of Hawaii, Agronomy and Soil Science laboratory. Each of the analytical methodologies utilized in this study is presented below. (The pesticide and bromide methodologies were provided by project chemist D.N. Little.)

Extraction Method for Pesticide Residues.

1. Homogenize the sample by sieving through a 4 mm sieve.
2. Remove a portion of the soil sample for soil moisture analysis.
3. Transfer 50 g (wet weight basis) of the homogenized sample into a 250 ml capped erlenmeyer flask. Add 200 ml of pesticide-grade ethyl acetate and extract the sample by shaking on a wrist-action shaker for 30 min.
4. Use a Whatman 2V filter paper to filter the extract into a 500 ml boiling flask. Add a second 200 ml of ethyl acetate to the soil in the erlenmeyer flask. Shake the sample for another 30 min and filter the extract into the 500 ml boiling flask.
5. Add 3 spoonfuls of anhydrous sodium sulfate to the extract to remove water. Use a Whatman #1 filter paper to filter the extract into a clean 500 ml boiling flask.
6. Place the extract in a rotary evaporator at 60°C and 533 mm Hg vacuum until dry.
7. Transfer the dry extract into a 15 ml graduated tube by rinsing with pesticide-grade acetone for gas chromatograph analysis (final volume should be about 5-10 ml).

Gas Chromatography Method for Pesticides. This method was developed to separate chlorpyrifos, fenamiphos, fenamiphos sulfoxide, and fenamiphos sulfone.

Equipment:

A Hewlett-Packard (HP) 5890A gas chromatograph equipped with a 7673A auto sampler, a 3392A integrator, and a nitrogen-phosphorus detector (NPD) was used for all pesticide analyses. A DB-1701, 7 m x 0.25 mm I.D. (25 µm film thickness) bonded fused silica capillary column manufactured by J & W Scientific was used in the gas chromatograph. The split/splitless injector was used in the split mode at a ratio of 1:20.

Temperature Program:

The initial oven temperature was 180°C which was held for 0.5 min. The temperature was then increased at a rate of 35°C/min to a temperature of 240°C which was maintained for 1.84 min. The injector and detector were set at respectively 270°C and 275°C.

The optimum injector volume was 2 µl for the sample concentration range of 0.01 to 2.0 µg/ml. Other settings on the auto sampler included two sample washes, three solvent washes, and four pumps of the sample before loading the syringe for the injection.

Using the above method and pesticide-grade acetone as the solvent, retention times for chlorpyrifos, fenamiphos, fenamiphos sulfoxide, and fenamiphos sulfone were respectively 1.41, 2.07, 3.53, and 3.76 min.

Bromide Analysis.

1. Homogenize the soil sample by sieving.
2. Place 100 g of field moist soil into a 250 ml centrifuge bottle.
3. Add 50 ml of distilled-deionized water to the centrifuge bottle.
4. Place the bottle on an orbital shaker for 60 min at 350 rpm.
5. Place the bottle in a centrifuge rotor and spin the bottles in the centrifuge for 20 min at 12,000 rpm.
6. Decant off the supernatant into 80-ml beakers.
7. Add an ionic strength adjuster (I.S.A.) at a rate of 1 ml per 50 ml of sample (I.S.A. = 4.25 g $NaNO_3$ in 100 ml deionized water).
8. Agitate the sample with a magnetic stirrer during measurement.
9. Measure bromide content with an Orion Bromide (model 94-35) electrode connected to a Fisher 815mp pH meter.
10. Compare samples to a standard curve consisting of the following standards: 100, 10, 1.0, 0.1, 0.01 µg/ml. The log of the standard's concentration is plotted against the millivolt reading

from the pH meter. Sample concentrations can be obtained from the regression equation. Note that the electrode and meter are not linear at concentrations below 0.4 μg/ml.

11. The concentration values obtained from the step above are normalized to a dry soil weight basis using the following equations:

    Br(μg/ml) x ml H_2O = total μg bromide in the sample

    (total μg bromide)/(g dry soil) = μg/g dry soil

Organic Carbon Analysis.

1. Oven dry approximately 50 g of soil in a seamless soil moiture can for 24 hours at 100°C.
2. Using a Spex ball mill grind the oven-dried soil for 2 min.
3. Weigh 0.25 g of the powderized soil sample into a crucible.
4. Add 0.5 g of Cu and 0.5 g of Fe chips to the sample.
5. Enter the sample, along with ID codes and weights, into a Leco Carbon Determinator (WR-112).

Soil Moisture Analysis.

1. Obtain the weight of a dry, seamless soil moisture can.
2. Add approximately 50 g of soil sample into the moisture can and weigh.
3. Place the moisture can containing the sample into an oven at 105°C for at least 24 hours.
4. Remove the moisture can from the oven and allow to cool before weighing.
5. Obtain the gravimetric soil moisture with the following equation:

$$\text{gravimetric soil moisture (g/g)} = (A-B)/C$$

where A is the weight of can and wet soil (g), B is the weight of can and dry soil (g), and C is the weight of dry soil and can - weight of can (g).

PESTICIDE DEGRADATION EXPERIMENTS

To quantify the effects of degradation of pesticides in soil, soil samples from the vicinity of the Waiawa Valley and Poamoho plots as well as soils of the Lahaina, Molokai, and Wahiawa series on Waiawa Ridge were collected.

Waiawa Valley Plot Degradation Study. Soil samples from three locations near the plot which were not subjected to any chemical application were collected in September 1988 and transported to the University of Hawaii, Agronomy and Soil Science laboratory. Holes were augered beyond the northern and eastern borders of the plot and near the southern border within the southeast quadrant of the plot. Soil samples collected between depths of 0 and 0.1 m and between 0.2 and 0.3 m from each hole were used in the degradation study.

The methodology used for the degradation study was developed by Lee (1986). Homogenized soil samples from each location and depth were obtained by passing the soil through a 4-mm sieve. All samples were brought to an initial gravimetric moisture content of approximately 0.37. The degradation study was designed to run for a period of approximately six weeks with eight different analysis dates. A total of sixteen 16 g (dry weight) soil samples from each location and depth were weighed on individual sheets of aluminum foil. Since duplicate samples were planned for each analysis date, a total of 16 samples for each location and depth were required. Each of the 96 weighed soil samples was then spiked with 1 ml of a solution containing 80 mg/l of both fenamiphos and chlorpyrifos (equivalent to 5 μg/g dry soil). After incorporating the two pesticides into the soil, spiked samples were placed in 20 ml glass tubes which were then covered with Kimble semi-permeable membranes. The membranes were employed to allow oxygen transfer into the tubes while maintaining a constant soil moisture content. The glass tubes were then placed on their sides in a dark incubator at a simulated field temperature of 30°C, which was determined from numerous field measurements at the Waiawa Valley plot site.

On each scheduled analysis date, two glass tubes containing soil from each location and depth were removed from the incubator and extracted by a wrist-action shaker (refer to above section on extraction method for pesticide residues). Duplicate samples for each location and depth were extracted 0, 4, 7, 14, 20, 28, and 39 days after the initial spiking. The final analysis date scheduled for 42 days after spiking was deemed to be unnecessary due to the low concentrations from the previous date. The day zero samples were extracted within one hour of spiking and were used to determine pesticide recovery rates. All extracted samples were run on a temperature programmed gas chromatograph (see section above on gas chromatography method for pesticides).

Poamoho Plot Degradation Study. Soil samples from the vicinity of the Poamoho experimental plot were collected for a degradation study similar to the Waiawa Valley study described above. Soil samples collected between depths of 0.05 and 0.2 m and between 0.35 and 0.55 m from three augered holes were used in the degradation tests. Soil moisture of each sample was standardized to 0.35.

Emulsifiable concentrates of chlorpyrifos and fenamiphos sulfoxide were added to 16 g (dry weight) of each soil sample. Note that for the Poamoho degradation study, fenamiphos sulfoxide, the persistent oxidation product of fenamiphos, was used instead of the parent compound. Both chlorpyrifos and fenamiphos sulfoxide were added at a rate of 5 μg/g dry soil. The spiked soil samples were mixed, placed in test tubes with permeable membrane caps, and then incubated at 30°C in the dark.

Time zero samples were extracted immediately after spiking and mixing to provide data on extraction recovery. Duplicate samples were extracted at 3, 14, and 28 days following the spiking and analyzed by gas chromatography.

Waiawa Ridge Degradation Study. Soils from the Lahaina, Molokai, and Wahiawa series on Waiawa Ridge were collected for a degradation study similar to the ones described above. Soils were collected at two locations and two depths (surface soil and subsoil) for each of the three series. The Waiawa Ridge degradation study was conducted using the same methodology described above for the Poamoho study. Soil samples were extracted 0, 2, 15, and 32 days following the spiking with chlorpyrifos and fenamiphos sulfoxide.

Assuming a first-order decay process for fenamiphos and chlorpyrifos of the form

$$C = C_0 e^{-kt} \qquad (B.1)$$

where C is the pesticide concentration at time t, C_0 is the initial pesticide concentration, k is the decay rate (day^{-1}), and t is time (days), decay rates of the two pesticides at each sampling location and depth can be computed using linear regression techniques on the laboratory data.

Pesticide half-lives may be determined from the estimated decay rates as

$$t_{1/2} = -\ln(0.5)/k \qquad \text{(B.2)}$$

A summary of the resulting pesticide half-lives computed from the decay rates is presented in Appendix Table B.1.

PESTICIDE SORPTION EXPERIMENTS

To quantify the effects of sorption of pesticides on soil, laboratory experiments were conducted using soil samples from the Waiawa Valley and Poamoho plots as well as from Waiawa Ridge. The soils from the two field plots were used to determine the shape of the sorption isotherms. Soils from the Lahaina, Molokai, and Wahiawa series on Waiawa Ridge were used to determine the relationship between adsorption and organic carbon content.

Waiawa Valley and Poamoho Sorption Studies. Sorption isotherms are often used to represent the equilibrium condition between the amount of material sorbed on a solid and the amount of material remaining in solution at a constant temperature. Various equations may be used to describe such isotherms. For this study, experiments were conducted with chlorpyrifos and fenamiphos sulfoxide on surface soil and subsoil samples from the Waiawa Valley and Poamoho field plots to determine the shape of the sorption isotherms.

One surface soil and one subsoil sample from each of the two experimental field plots was selected for the sorption studies using ^{14}C-labelled chlorpyrifos and fenamiphos sulfoxide. Separate experiments were conduted for each pesticide.

The methodology used in the batch equilibration experiments is similar to the method described by Lee (1986). ^{14}C-labelled chlorpyrifos and fenamiphos sulfoxide solutions were made to yield an activity of 2×10^4 DPM/ml. Emulsifiable concentrates of chlorpyrifos and fenamiphos sulfoxide were added to their respective solutions to bring the concentrations up to the desired level. Fenamiphos sulfoxide concentrations of 0.154, 0.441, 3.312, and 6.502 mg/l and chlorpyrifos concentrations of 0.176, 1.0, and 2.5 mg/l were tested.

Moist soil equivalent to one gram oven-dried soil was used at a soil:solution ratio of 1:5. The soil was weighed out into 50 ml teflon centrifuge bottles and 5 ml of pesticide solution was added. Fenamiphos

APPENDIX TABLE B.1. LABORATORY SOIL DEGRADATION RESULTS

Sample Location	Soil Series	Sample Depth (m)	----- Half-Life (days) ----- Chlorpyrifos	F. Sulfoxide or Fenamiphos
Waiawa Valley Plot	Kawaihapai	0-0.1	8.4	3.7*
	Kawaihapai	0.2-0.3	10.4	8.1*
Poamoho Plot	Wahiawa	0.05-0.2	7.6	28.1+
	Wahiawa	0.35-0.55	6.7	22.7+
Waiawa Ridge	Lahaina	0.05-0.2	10.8	23.0
	Lahaina	0.7-0.85	7.0	18.7
	Molokai	0.05-0.25	10.6	26.6
	Molokai	0.75-0.9	7.1	23.9
	Wahiawa	0.05-0.2	13.7	28.9
	Wahiawa	0.65-0.8	6.8	26.1

NOTE: Half-lives determined assuming first-order decay process.

*Fenamiphos used instead of fenamiphos sulfoxide for Waiawa Valley degradation study.

+Fenamiphos sulfoxide results include results from only one sample hole.

sulfoxide samples were rotated for 24 hrs at 20°C on a rotary shaker. Due to the fairly rapid hydrolysis of chlorpyrifos, a 4 hr equilibration time was used for all chlorpyrifos samples. At the end of the equilibration period, the samples were centrifuged at 12,000 rpm in a refrigerated Sorval Centrifuge. Duplicate samples (0.5 ml) of the supernatant were then counted in a Packard Tricarb Liquid Scintillation Counter.

Results of the sorption experiments are presented in Appendix Figures B.1 to B.8. The relationship between the sorbed and solution phases appears to be linear and of the form

$$C_s = K_d C \qquad (B.3)$$

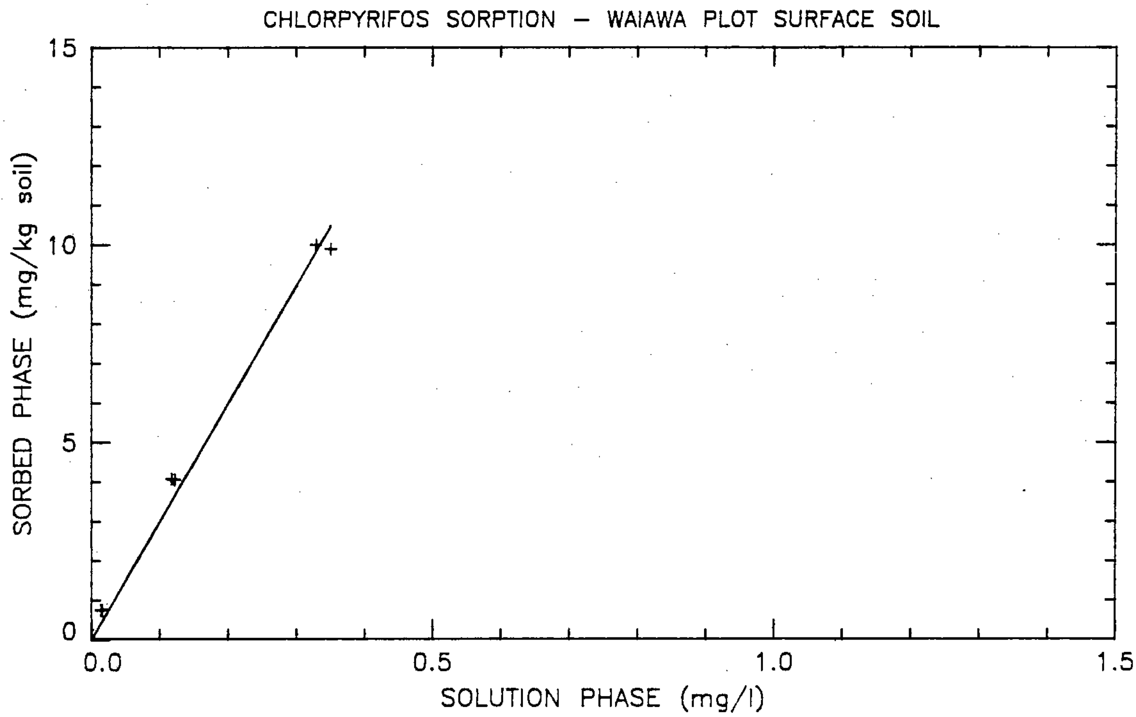
where C_s is the sorbed concentration, K_d is the sorption partition coefficient, and C is the the solution concentration. Estimated K_d values using linear regression techniques are presented in Appendix Table B.2.

Waiawa Ridge Sorption Study. To determine the relationship between sorption of chlorpyrifos and organic carbon content, soils with different amounts of organic carbon from the Lahaina, Molokai, and Wahiawa series on Waiawa Ridge were used. The methodology described in the section above was also used for the sorption experiments with the Waiawa Ridge soils. All soil samples from Waiawa Ridge were tested using a single concentration of chlorpyrifos (1.0 mg/l).

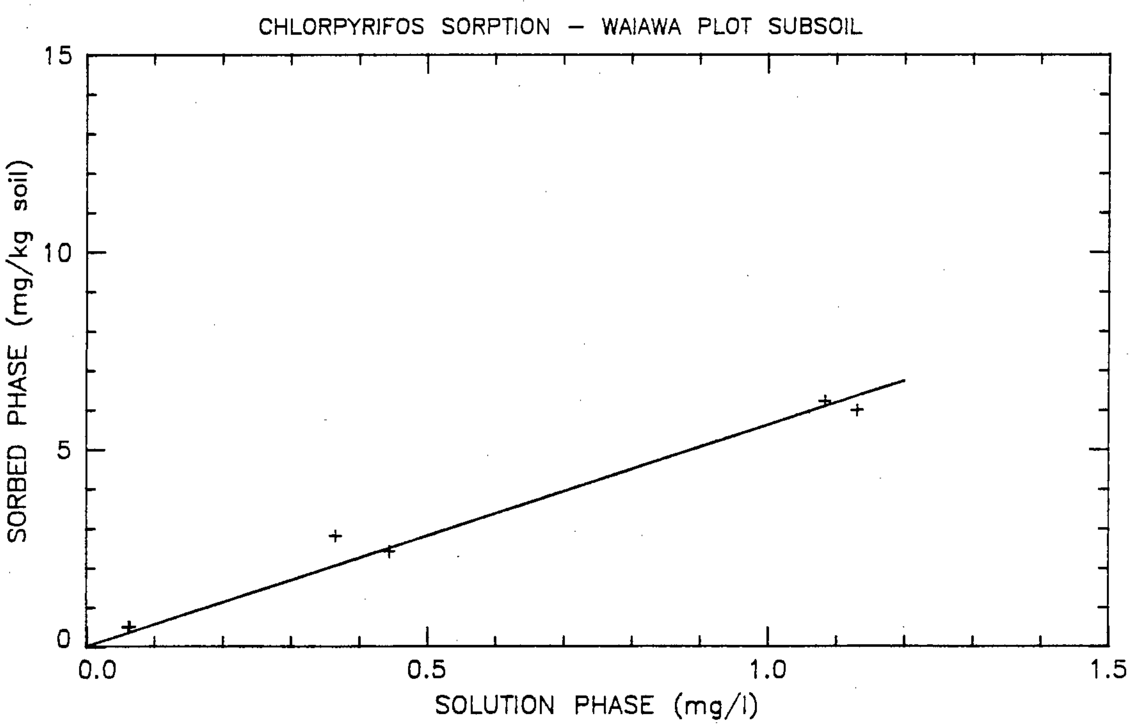
For each soil sample, the sorption partition coefficient, K_d, was computed assuming a linear sorption isotherm. The computed K_d values were then plotted against the known organic carbon fractions for each sample. The relationship between K_d and organic carbon is generally linear of the form

$$K_d = K_{oc} \cdot f_{oc} \qquad (B.4)$$

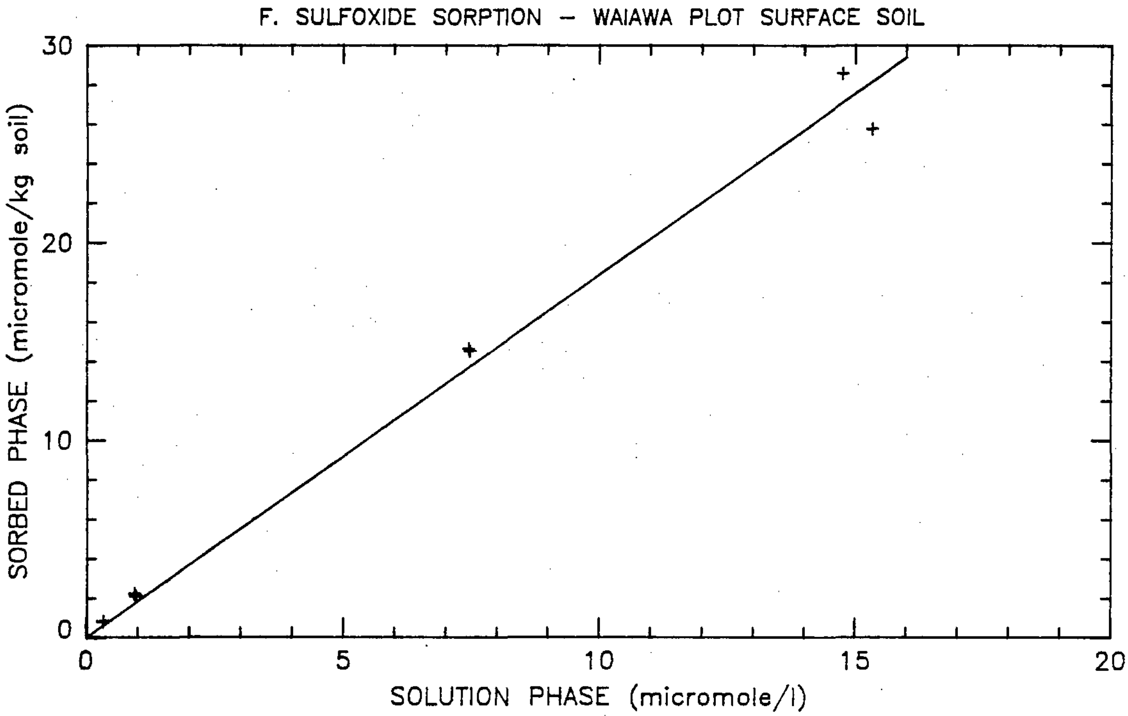
where K_{oc} is the the sorption partition coefficient expressed on a soil organic carbon basis, and f_{oc} is the the mass fraction of organic carbon to dry soil. Using linear regression techniques, the K_{oc} values for chlorpyrifos for each of the three Waiawa Ridge soils were computed and are presented in Appendix Table B.3. Also presented in Appendix Table B.3 are K_{oc} values for fenamiphos sulfoxide obtained using Lahaina and Wahiawa soils from pineapple fields on Oahu.



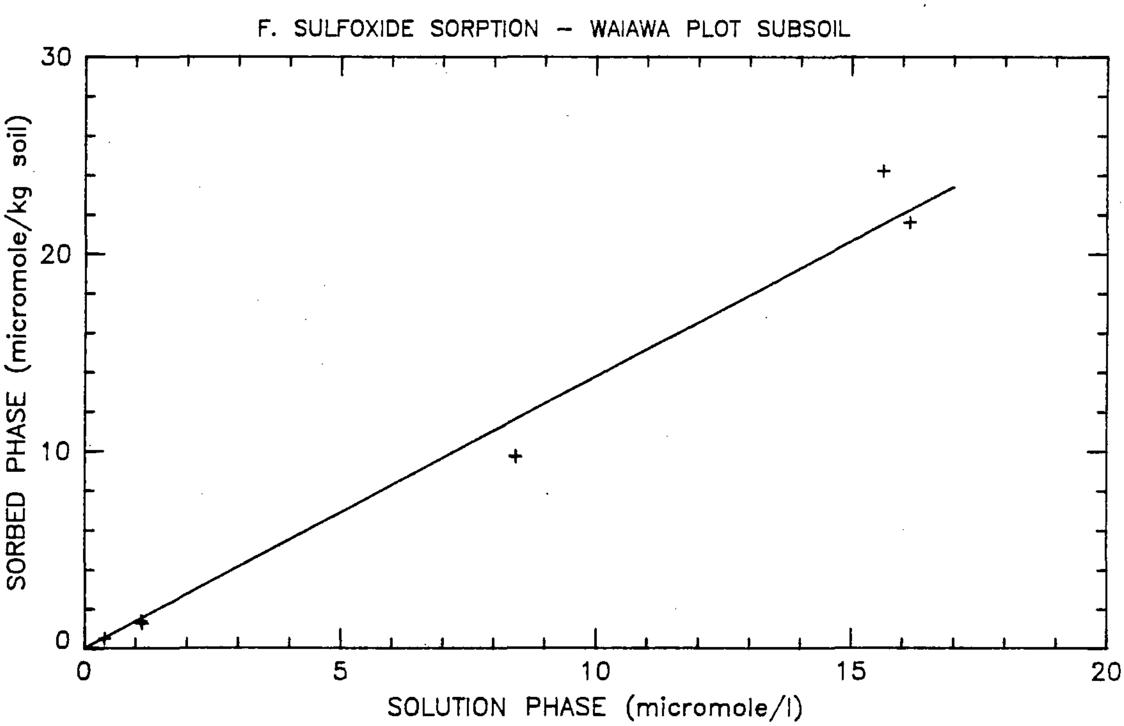
Appendix Figure B.1. Chlorpyrifos sorption isotherm for Waiawa plot surface soil



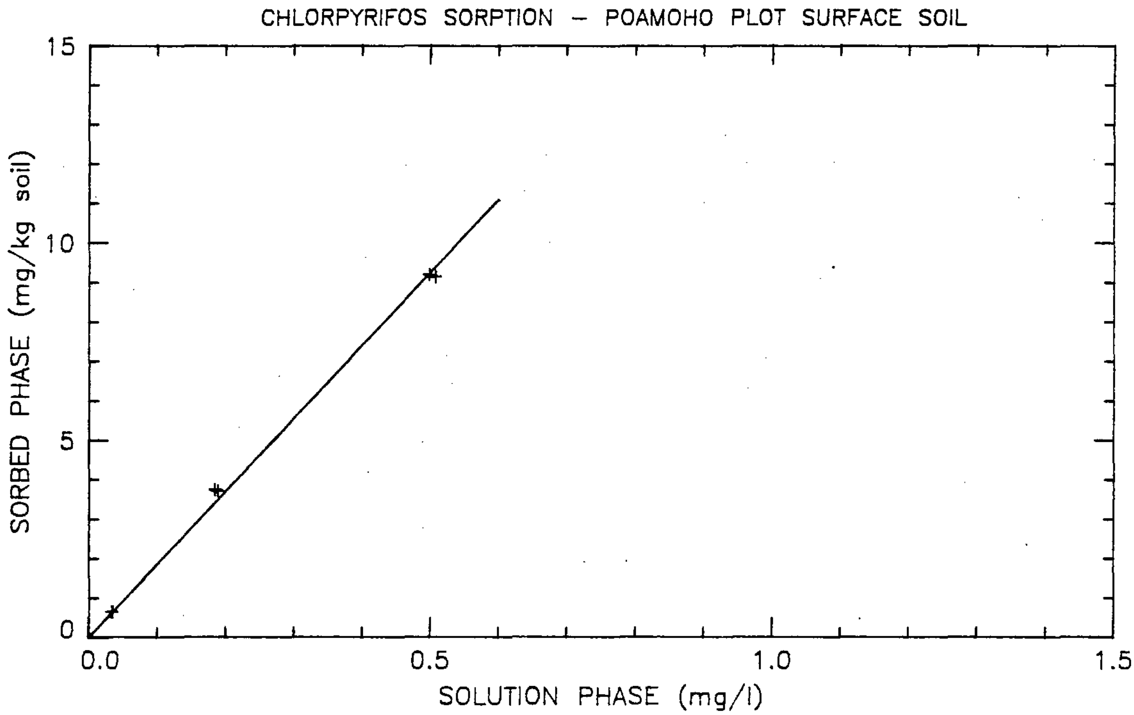
Appendix Figure B.2. Chlorpyrifos sorption isotherm for Waiawa plot subsoil



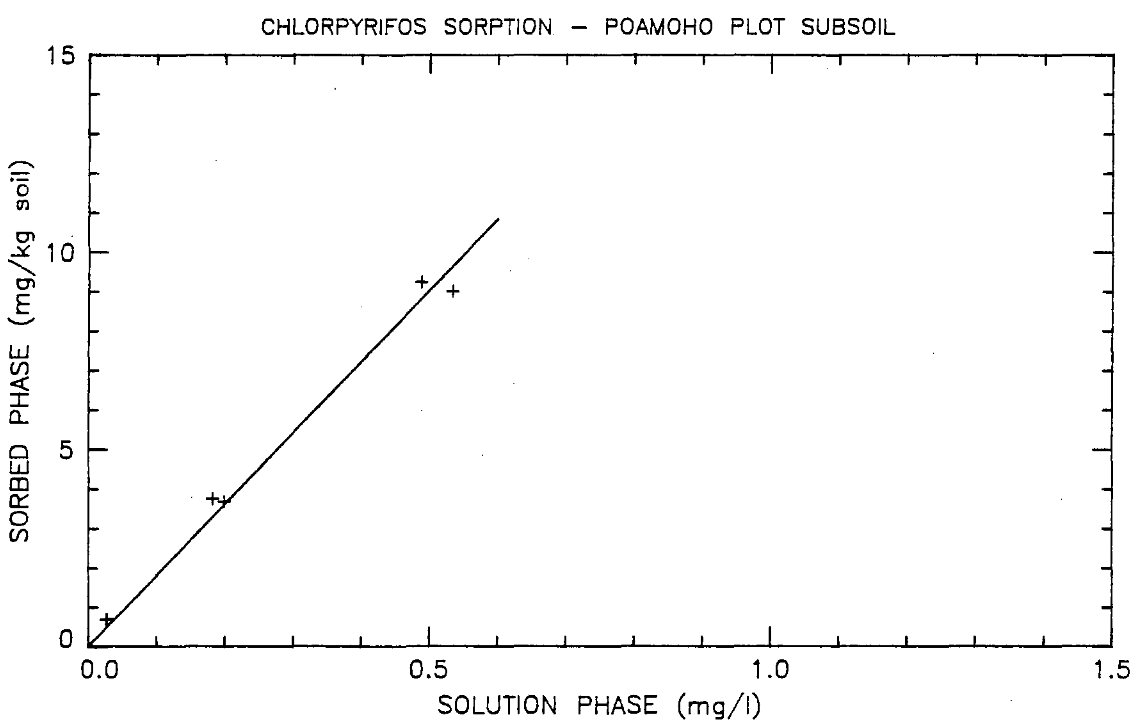
Appendix Figure B.3. Fenamiphos sulfoxide sorption isotherm for Waiawa plot surface soil



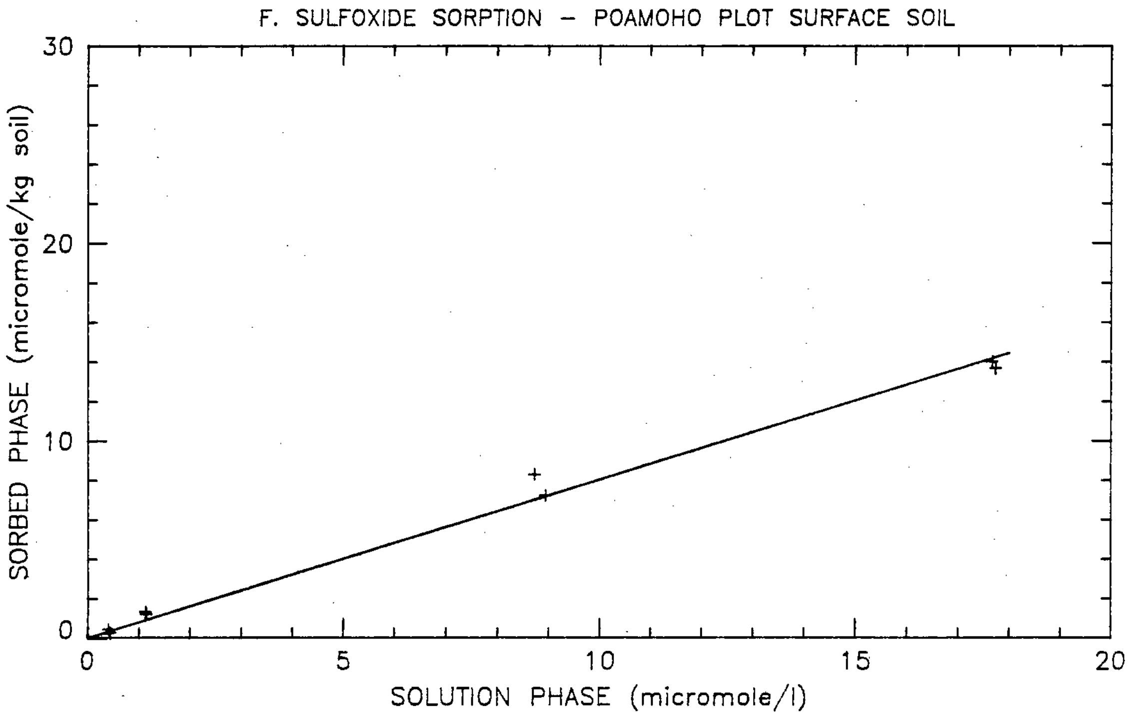
Appendix Figure B.4. Fenamiphos sulfoxide sorption isotherm for Waiawa plot subsoil



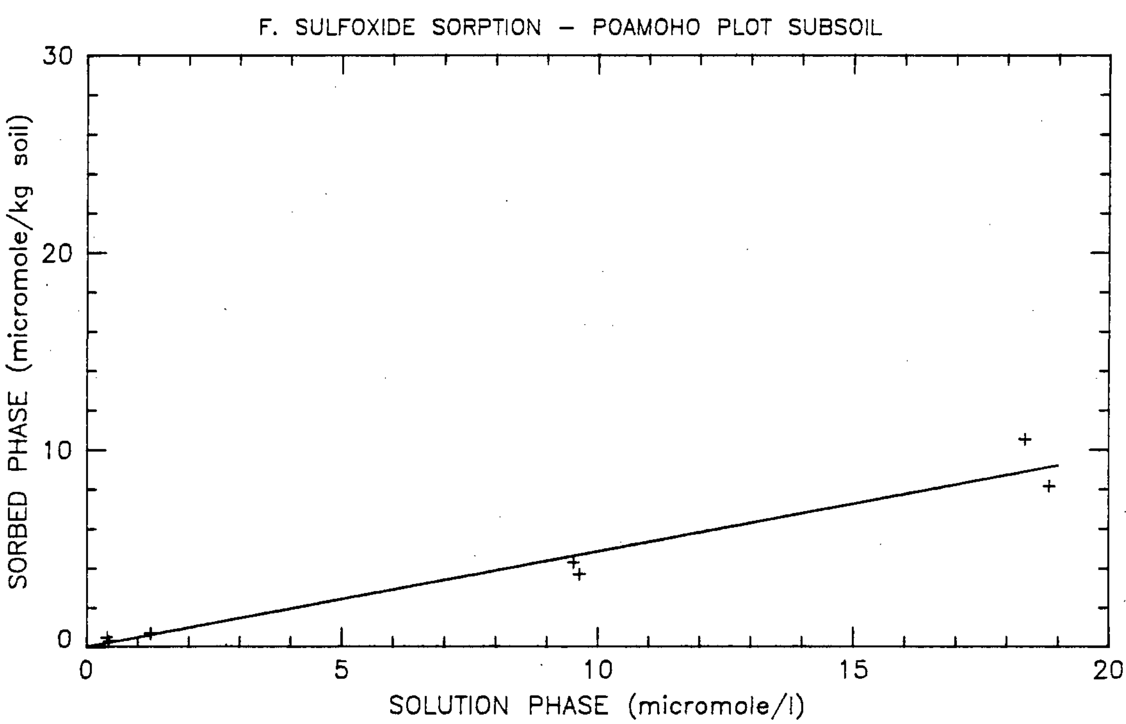
Appendix Figure B.5. Chlorpyrifos sorption isotherm for Poamoho plot surface soil



Appendix Figure B.6. Chlorpyrifos sorption isotherm for Poamoho plot subsoil



Appendix Figure B.7. Fenamiphos sulfoxide sorption isotherm for Poamoho plot surface soil



Appendix Figure B.8. Fenamiphos sulfoxide sorption isotherm for Poamoho plot subsoil

APPENDIX TABLE B.2. LABORATORY SORPTION ISOTHERM RESULTS USING FIELD PLOT SOILS

Sample Location	Soil Series	Sample Depth	f_{oc}*	--Chlorpyrifos-- K_d (ml/g)	r^2+	--F. Sulfoxide-- K_d (ml/g)	r^2+
Waiawa Valley Plot	Kawaihapai	surface	0.0253	29.9	0.988	1.8	0.989
	Kawaihapai	subsoil	0.0037	5.6	0.975	1.4	0.977
Poamoho Plot	Wahiawa	surface	0.0111	18.5	0.997	0.8	0.990
	Wahiawa	subsoil	0.0142	18.0	0.988	0.5	0.956

*Mass fraction of organic carbon to dry soil.
+Coefficient of determination.

APPENDIX TABLE B.3. LABORATORY K_{oc} SORPTION RESULTS

Soil Series	-- Chlorpyrifos -- K_{oc} (ml/g)	r^2+	-- F. Sulfoxide -- K_{oc} (ml/g)	r^2+
Lahaina	1220	0.958	33.3	0.927
Molokai	1270	0.967	-	-
Wahiawa	1410	0.981	27.0	0.974

NOTE: K_{oc} values for fenamiphos sulfoxide obtained from R.E. Green and C.C. Lee, University of Hawaii, Department of Agronomy and Soil Science (unpublished data).

+Coefficient of determination.

APPENDIX C. WATER BALANCE MODEL

A water balance is an application of the continuity equation based on the principle of conservation of mass. The general water balance equation over a specified time interval may be represented by

$$M_{in} - M_{out} = dM \qquad (C.1)$$

where M_{in} is the mass of water entering the control volume, M_{out} is the mass of water exiting the control volume, and dM is the change in mass of water in the volume during the given interval. Thus, for a given time interval, the net flux of water into a control volume is equal to the change in water storage within that volume.

Water balance techniques can be used to solve many practical hydrological problems. A water balance can be used as an engineering tool in the development and management of the water resources of a region and can provide an evaluation of the impact of man's activity on the local hydrologic cycle. The concept of a water balance based on mass conservation began early in the twentieth century when hydrologists recognized annual runoff to be a residual determined from the difference between annual precipitation and annual evapotranspiration (Eagleson 1978).

The development of the moisture balance as a tool in climatological and hydrological investigations has generally been attributed to C.W. Thornthwaite. Climatic water balance procedures were developed in the 1940s by Thornthwaite (1944, 1948) and later revised by Thornthwaite and Mather (1955). Climatic water balance models are essentially bookkeeping procedures which account for the income of water from precipitation (and possibly snowmelt), the outflow of water by evapotranspiration, runoff, and groundwater recharge, and the changes in soil moisture storage.

WATER BALANCE EFFORTS IN HAWAII

In Hawaii, a number of water balance efforts have been undertaken to evaluate the water resources. Kanehiro and Peterson (1977) estimated the groundwater recharge and coastal discharge for the northwest coast of the island of Hawaii using a computerized daily water budget approach.

Average annual hydrologic budgets for the southern Oahu area were estimated by Wentworth (1951), Mink (1980), and the Hawaii State Department of Land and Natural Resources (1980). Todd and Meyer (1971) proposed a mean monthly hydrologic budget for the Honolulu area. Ekern (in Cox et al. 1971) provided more realistic estimates of evapotranspiration and monthly rainfall in revising the water budget of Todd and Meyer. Dale (1967), Tenorio and Young (1971), Broadbent (1980), and Mink (1980) provide water budgets under development conditions for different areas on Oahu. Giambelluca (1983) used a monthly interval to compute the water balance of 258 discrete zones in the Pearl Harbor-Honolulu basin from 1946 to 1975. Giambelluca (1986) also evaluated the land use effects on the water balance of southern Oahu. Most recently, Giambelluca and Oki (in Lau 1987) estimated recharge from pineapple fields near Mililani, Oahu, using a daily time step. Water balance computations play an important role in groundwater modeling studies (Eyre, Ewart, and Shade 1986; Or and Lau 1987; Liu, Dale, and Ewart 1989) in which estimates of recharge rates are necessary.

WATER BALANCE MODEL

The water balance model used for this study to estimate groundwater recharge is a variant of the Thornthwaite and Mather (1955) bookkeeping procedure. At a given location, the model accounts for moisture exchanges that occur within the soil-plant system during each specified time interval. Water fluxes through the system are balanced for each time interval with the following equation:

$$dS = (P_i - R_i)G^{-1} + I_i - E_i - Q_i \qquad \text{(C.2)}$$

where dS is the change in available soil moisture storage for the unpaved portion of the area during time interval i, and P, I, R, E, and Q represent precipitation, irrigation, runoff, evapotranspiration, and groundwater recharge, respectively, for time interval i. (All variables are expressed as equivalent water depths [L].) The parameter G represents the fraction of the total area which is unpaved. Available moisture is defined as the difference between the total soil moisture and the wilting point, which is commonly assumed to be the soil moisture content at a tension of 1.5 MPa. The available soil moisture capacity of a soil can be defined as the amount of water available between the wilting point and field capacity, the maximum soil moisture content existing after the effects of gravity drainage.

Water input to the soil-plant system consists of rainfall and irrigation. Outputs from the system include surface runoff, evapotranspiration, and groundwater recharge. Groundwater recharge and end-of-interval soil moisture storage are assigned after estimates of P_i, R_i, E_i, and I_i have been obtained. Detailed descriptions of the techniques used to estimate the components of the water balance are provided below.

For this study, the water balance was computed on a daily basis over portions of a 9 x 10 rectangular grid encompassing the proposed development area as well as the zone of contribution of Waiawa Shaft (Fig. 23). The grid spacing and positioning were designed to provide good approximations of land use and soil types within cells as well as to minimize climate variations within a cell. Each cell of the grid measures 40" of latitude by 37.5" of longitude. The discretization of the development area was necessary to reduce the number of long-term pesticide leaching simulations which proved to be extremely computer intensive. Recharge estimates from the water balance model are used as input to PRZM to simulate leaching of urban related chemicals through the vadose zone.

EFFECT OF THE COMPUTATIONAL TIME INTERVAL

Models similar to those of Thornthwaite and Mather (1955) rely on the threshold concept that recharge does not occur until the soil moisture capacity is reached. One of the problems associated with such models is the effect of the computational time step between successive soil moisture balances on recharge estimates. Howard and Lloyd (1979) found total annual recharge estimated with a monthly time step to be significantly less than those totals determined on ten-day and daily bases. The monthly estimate was over 20% lower than the daily recharge total. Ten-day estimates were much closer to the daily estimates. However, both the monthly and ten-day balances failed to detect a major recharge event during the summer months. Rushton and Ward (1979) found that weekly and monthly balances underestimate daily recharge totals by 10% and 25%, respectively. Giambelluca and Oki (1987) also used a water balance model to determine the time-interval effect on the prediction of recharge events. Using an hourly interval as a standard for comparison, it was evident that the daily interval accurately predicted the occurrence of recharge events and only slightly underestimated their magnitude. The use of a monthly interval, however, resulted in a consistent and substantial underestimation of the magnitude of the recharge as well as failure to recognize many recharge events.

In general, there is a tendency for all Thornthwaite-type models to overestimate E_i and underestimate Q_i due to their inability to account for within-interval variability in soil moisture input. The importance of this bias increases with longer time intervals (Giambelluca and Oki 1987). Use of a monthly interval is inappropriate for this study since recharge would be consistently underestimated. Although use of a time step shorter than a day would be ideal, data are not available to estimate model parameters. Thus, for the purposes of this study, a daily time step was selected.

PRECIPITATION

The goal of this study is to assess the impact of proposed urban developments on groundwater quality, therefore some estimates of rainfall are necessary. Since rainfall records for future time periods are obviously not available, rainfall data must be generated. Historical rainfall records were used as the basis for the estimation of future rainfall. Thus, historical rainfall characteristics of the Waiawa area were assumed to be representative of future rainfall in the area.

Monthly Rainfall Interpolation. Water balance models based on a daily time step require daily rainfall as input. Accurate and continuous daily rainfall records, however, are scarce relative to monthly records. Thus, daily rainfall sequences must be constructed from monthly records with a rainfall disaggregation model. Although an extensive network of rain gages exists in central Oahu, there are few rain gage stations with complete monthly records for the entire period of interest. In order to determine monthly rainfall in ungaged areas, the 9 x 10 grid system covering the proposed Waiawa development areas in central Oahu and encompassing the zone of contribution of Waiawa Shaft was used. Based on usable monthly records at existing and discontinued rain gage stations in central Oahu (Fig. 25), a computer interpolation routine was used to calculate monthly rainfall at the centers of the 90 cells of the rectangular grid for each of the 444 months from January 1946 through December 1982. The 37-yr period was sufficient to assess the long-term impact of the proposed developments on groundwater quality in the Waiawa area. In addition, monthly rainfall records during this period were adequate to perform the computer interpolation routine. Note that after approximately 1982 when sugarcane fields on Waiawa Ridge were abandoned by Oahu Sugar Company, rainfall records in the area are relatively scarce. The ZGRID subroutine of the PLOT88 Software Library (Young and Van Woert 1987), based on a combination of Laplacian and spline interpolation, was utilized to estimate monthly rainfall in each of the cells of the water balance grid.

Rainfall Disaggregation Model Description. Interpolated monthly rainfall values for each pertinent cell of the water balance grid for the 37-yr study period were disaggregated into daily values with a simulated fragments (SF) disaggregation model (Oki and Giambelluca 1989). In the SF model, daily rainfall is simulated by first generating a sequence of wet and dry days and then apportioning the monthly rainfall total to the wet days. The model requires daily rainfall as input in order to identify the parameters of the wet-dry sequencing model and the rainfall distribution functions. For this study, a first-order binary Markov chain model was used to generate wet- and dry-day sequences and the beta distribution was selected for apportioning the monthly rainfall total to the wet days. The statistical characteristics of daily rainfall were estimated on the basis of data from Station 863 (Wahiawa Dam). The rainfall disaggregation model used in this study simulates daily rainfall sequences which sum to a known monthly total so that the monthly rainfall time series for a water balance cell is preserved.

To simulate daily rainfall at a particular location, values of the non-dimensionalized parameter Y, expressed as,

$$Y = P_d P_m^{-1} \tag{C.3}$$

where P_d is daily rainfall (mm) and P_m is monthly rainfall (mm), were first simulated. The chain of dimensionless Y values was subsequently multiplied by the known monthly rainfall total to obtain a simulated daily rainfall chain.

Using available historical data transformed according to equation C.3, Markov transitional probability matrices for a particular site can be formed. The matrix elements, $p_{i,j}$, represent the probabilities of a transition of Y from state i to state j on successive days (i=1,n; j=1,n). With n states defined, an n x n transitional probability matrix, PM, can be expressed as,

$$PM = [p_{i,j}] \qquad \text{for } i,j = 1,2,\ldots,n. \qquad (C.4)$$

For n = 2, the model is reduced to the consideration of sequences of wet and dry days.

The year can be divided into a finite number of seasons provided that the transitional probabilities for each season are valid throughout that season. For this study, a two-state first-order Markov chain model using 12 seasons was employed to generate sequences of wet and dry days.

With the states and transitional probability matrices for each season defined, wet and dry sequences can be simulated by invoking a random number generator. The random number, RN1, distributed uniformly between 0 and 1, is used in conjunction with the appropriate transitional probability matrix to determine the next day's rainfall state. For Y currently in state i, the succeeding day's state, k, can be determined from the following condition:

$$\sum_{j=1}^{k-1} p_{i,j} \le RN1 < \sum_{j=1}^{k} p_{i,j} \qquad (C.5)$$

The sum of the transitional probabilities within a given row of the transitional probability matrix must be equal to 1. Random number RN1 lies between the cumulative probabilities of state k-1 and state k in row i of the transitional probability matrix. In all simulation runs, it was assumed that the initial state was the zero rainfall state. The model was run for a one month warm-up period prior to the starting day of simulation.

Once the sequences of wet and dry days have been generated, rainfall amount sequences within the wet spells can be simulated. For this study, values of Y were assigned to each of the wet days in a month using an appropriate beta distribution. No persistence between the rainfall amounts on the wet days was assumed to exist.

The beta distribution has both an upper and lower bound which makes it ideally suited to the parameter Y since, by definition, $0 \leq Y \leq 1$. The beta distribution function is given by

$$P(Y \leq y) = \frac{1}{B(a,b)} \cdot \int_0^y t^{a-1}(1-t)^{b-1}dt \qquad 0<y<1;\ a,b>0 \qquad (C.6)$$

where the function $B(a,b) = \int_0^1 t^{a-1}(1-t)^{b-1}dt$ is called the beta function. The moment estimators of the beta distribution parameters, a and b, can be computed from the first and second moments of Y. By definition, the mean of the non-zero Y values for a given month is equal to the reciprocal of the number of wet days, w, in that month.

Using an available historical daily rainfall record, months with the same number of rainy days can be grouped and a different probability distribution can be fitted to the observed values of Y within each group of months. Separate beta distributions for each number of rainy days in a month are used to assign values of Y to the wet days output from the Markov chain model. Thus, full advantage is taken of the information regarding the number of rainy days output from the Markov chain model.

For a given month, w values of Y are generated one at a time with the use of a random number distributed uniformly between 0 and 1. Simulated values of Y must be greater than some minimum threshhold value, Y_{min}. The value of Y_{min} varies with the monthly rainfall and is given by

$$Y_{min} = P_{min}/P_m \qquad (C.7)$$

where P_{min} is the minimum measureable rainfall. Simulated values of Y are restricted to the range between Y_{min} and Y_{max}, which have corresponding probabilities on the cumulative distribution function (CDF) plot of CDF_{min} and CDF_{max}, respectively. For the initial simulated value of Y in a given month, Y_{max} and CDF_{max} are both 1. However, as values of Y are simulated, Y_{max}, and consequently CDF_{max}, must also be reduced to account for the reduction in available rainfall in the month.

The applicable range on the CDF (CDF_{min} to CDF_{max}) for each simulated value of Y must be scaled between 0 and 1. The actual value of each simulated Y can then be obtained with the random number RN2, distributed uniformly between 0 and 1. By normalizing the probabilities between CDF_{min} and CDF_{max} to the range between 0 and 1, RN2 defines a probability and corresponding simulated value of Y on the cumulative distribution plot. Thus, the simulated value of Y is determined from the inverse of the cumulative distribution function at a probability corresponding to RN2. A daily rainfall amount (mm) can be obtained by multiplying the simulated Y value by the known monthly rainfall total (mm).

During the actual simulation process, w-1 values of Y are determined from the collapsing beta distribution function for each month with w≥2. The wth value of Y is determined as the residual,

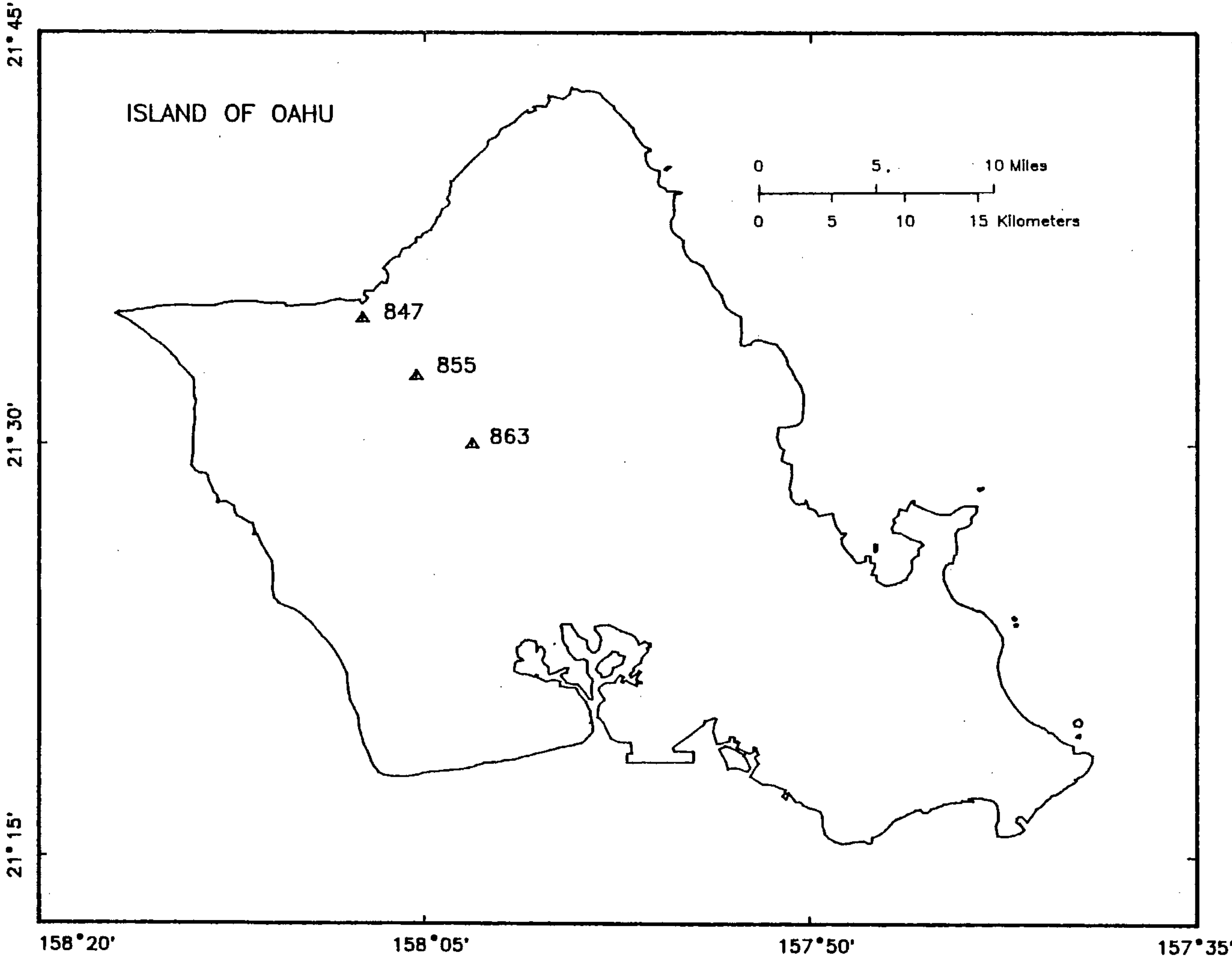
$$Y_w = 1 - \sum_{i=1}^{w-1} Y_i \qquad (C.8)$$

If the sum of the simulated Y values in a given month exceeds 1 prior to assigning all w values of Y, the simulation of Y values for that particular month is repeated.

Rainfall Disaggregation Model Calibration and Validation. To test the disaggregation model, a base station was selected whose record was used to determine parameters for the simulated fragments model. With these parameters, the model was used to simulate daily rainfall at the same station as well as at two other sites with known daily rainfall. Comparison with the base station amounts to a calibration check. Use of the model to simulate rainfall at the other sites is a means of validating the model in the mode in which it is to be applied.

Records of daily rainfall during the period 1949 to 1983 (obtained from the National Climatic Data Center, NOAA) from three stations on Oahu, Hawaii were selected (App. Fig. C.1). Numerous gaps occur in the historical records at each station. Daily rainfall data are recorded to the nearest 0.25 mm (0.01 in.). Station 863 (Wahiawa Dam) was used as the base station. With parameters derived from Station 863, rainfall was simulated at Stations 855 (Kemoo 9) and 847 (Waialua), located respectively 6 and 11 km away from the base station.

Transitional probabilites derived from Station 863 data are given by month in Appendix Table C.1. Based on the historical record of Station 863, months with the same number of rainy days were grouped, and the



Appendix Figure C.1. Locations of rain-gage Stations 847, 855, and 863, Oahu, Hawaii

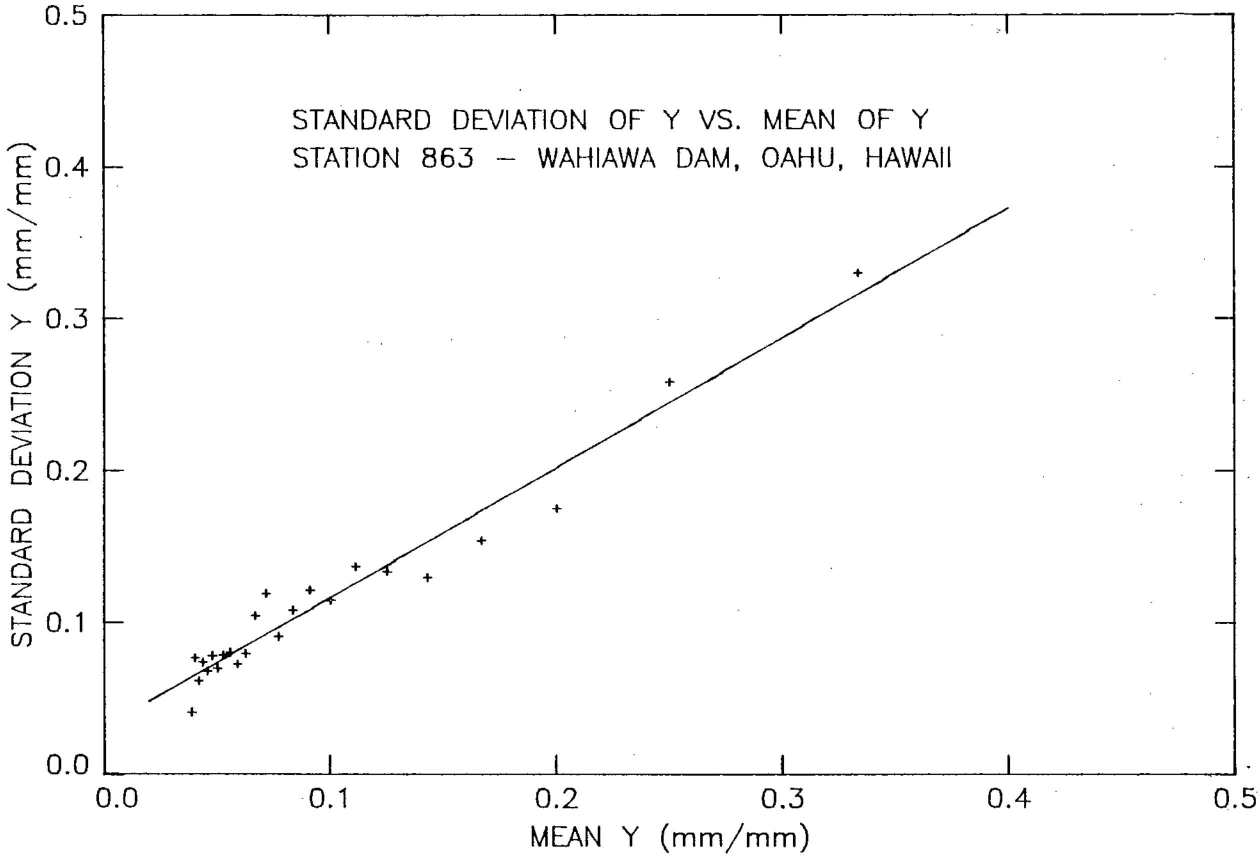
APPENDIX TABLE C.1. MARKOV TRANSITIONAL PROBABILITIES AT STATION 863, WAHIAWA DAM, OAHU, HAWAII

Month	Daily Rainfall State-to-State Transitional Probabilities dry -> dry	dry -> wet	wet -> dry	wet -> wet
1	0.679	0.321	0.338	0.662
2	0.673	0.327	0.346	0.654
3	0.693	0.307	0.379	0.621
4	0.694	0.306	0.351	0.649
5	0.696	0.304	0.407	0.593
6	0.678	0.322	0.389	0.611
7	0.670	0.330	0.409	0.591
8	0.716	0.284	0.396	0.604
9	0.678	0.322	0.492	0.508
10	0.699	0.301	0.409	0.591
11	0.677	0.323	0.364	0.636
12	0.679	0.321	0.332	0.668

standard deviation of the non-zero Y values for each group of months was then computed. The mean of the non-zero Y values for each group of months is necessarily equal to 1/w. Using the historical data, the standard deviation of Y for each available value of w was plotted against the mean of Y (App. Fig. C.2). Since not all possible values of w are adequately represented in the historical data set, and since the standard deviation and mean of Y are linearly correlated (correlation cofficient = 0.98) (App. Fig. C.2), the second moment of Y for each possible value of w between 2 and 31 can be computed as a function of the mean of Y. Note that for one rainy day in the month, computation of the first and second moments is trivial. For Station 863, the regression equation relating the standard deviation and mean of Y for a given month can be expressed as,

$$\sigma = 0.855\mu + 0.0308 \qquad (C.9)$$

where σ is the standard deviation of non-zero Y values (mm/mm), $\mu = 1/w$ is mean of non-zero Y values (mm/mm).



Appendix Figure C.2. Scattergram and regression line of standard deviation of Y versus mean of Y at Station 863, Wahiawa Dam, Oahu, Hawaii

The means of the non-zero Y values for 2 to 31 rainy days per month were used in conjunction with equation C.9 to obtain estimates of the second moments of the non-zero Y values. The moment estimators of the beta distribution parameters were then computed for each possible value of w between 2 and 31. The estimated beta distribution parameters for Station 863 are listed in Appendix Table C.2. The resulting cumulative frequency distribution curves are shown in Appendix Figure C.3. To illustrate the goodness-of-fit of the beta distribution, historical and fitted cumulative distributions for 16 rain days in a month are shown in Appendix Figure C.4.

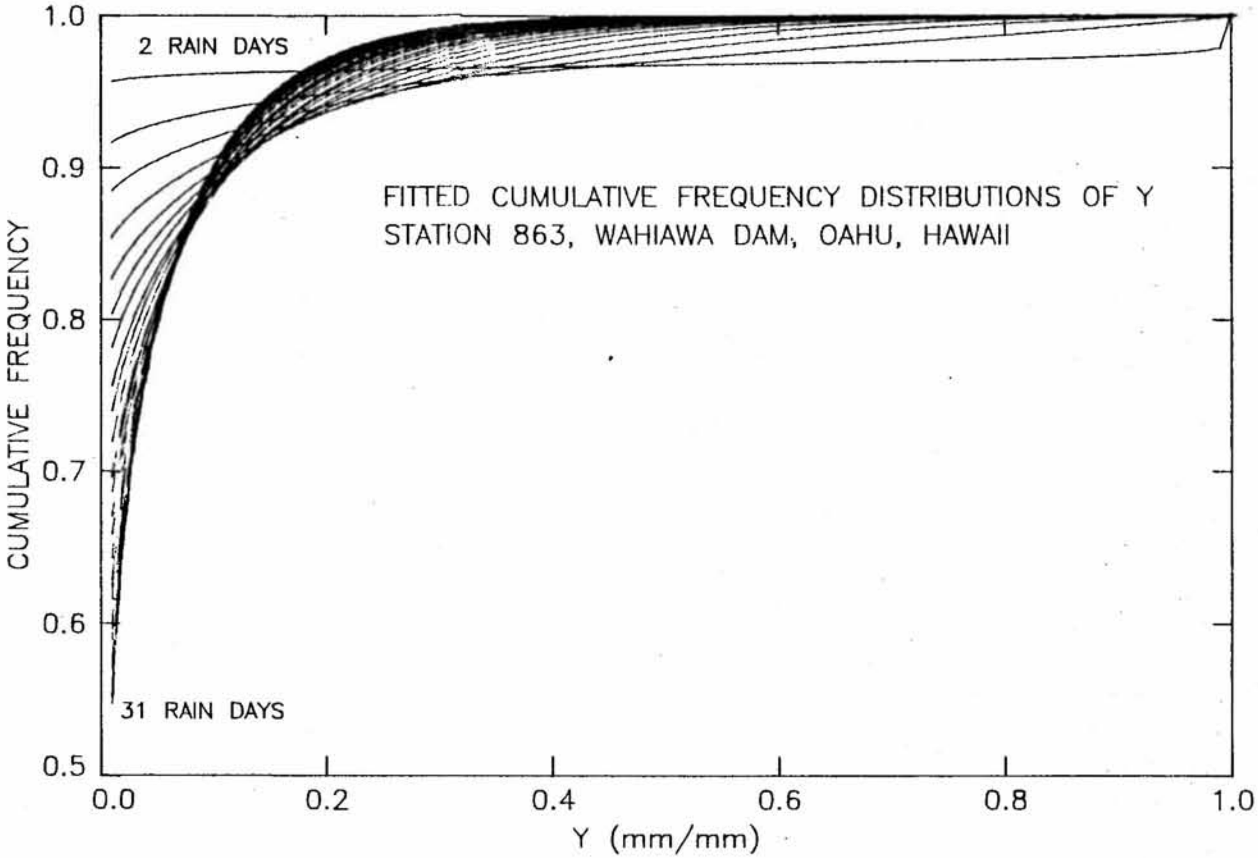
Using Markov-beta parameters from Station 863, twenty simulations of daily rainfall there and at each of the validation stations were made with the SF model by disaggregating the appropriate monthly rainfall totals. Model performance was tested by comparing the cumulative frequency distributions, variance and skewness, monthly maxima and wet- and dry-day run frequencies of the simulated rainfall with those of the observed rainfall.

In Appendix Figures C.5 through C.7, the cumulative frequency distributions of a representative simulation and the observed rainfall are shown for each station. In each case, it was impossible to clearly present more than one simulation because of the nearly identical shapes of their CDFs. As expected, the cumulative distributions of simulated daily rainfall are very similar to that of the observed rainfall at the base station. Simulated distributions also appear very similar to the observed distributions at the two validation stations.

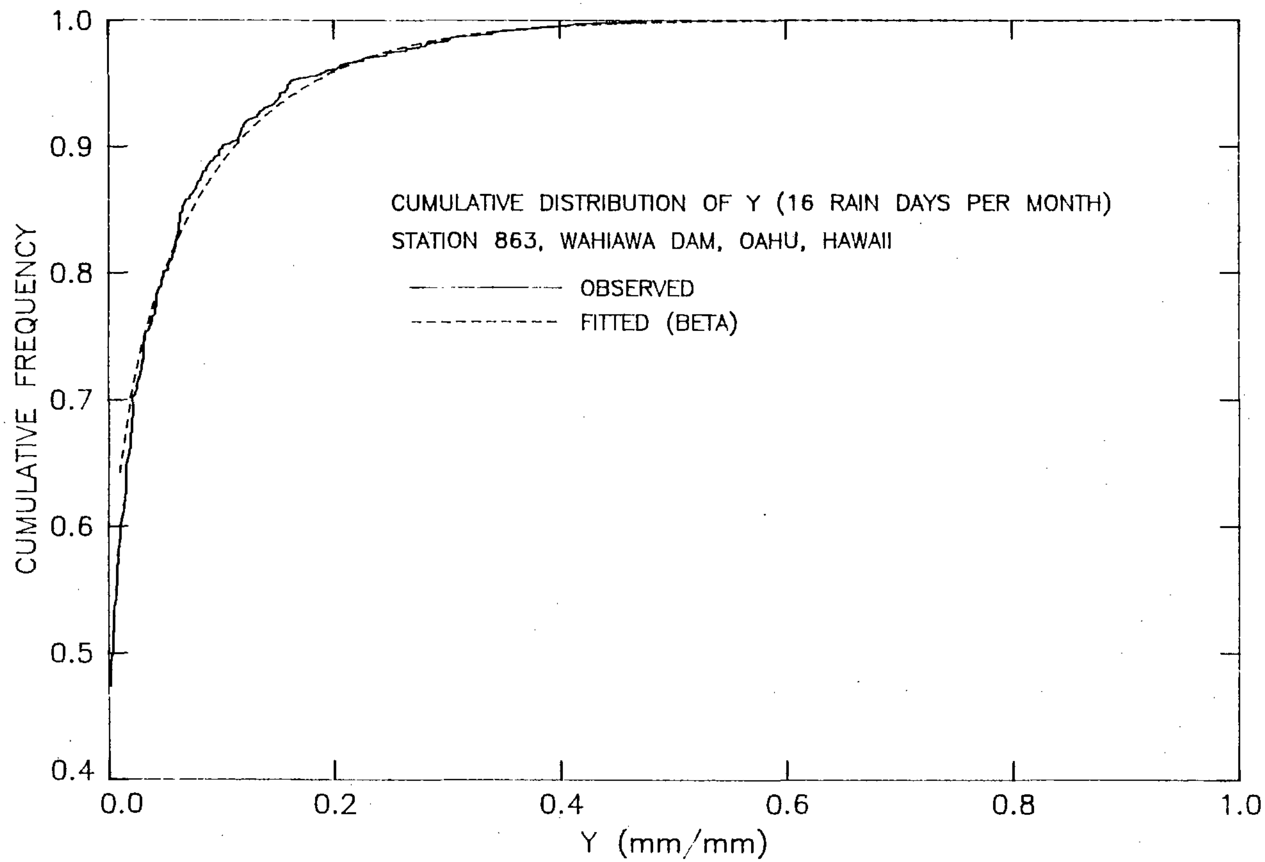
To better analyze model performance, the moments of the distributions can be examined. Appendix Tables C.3 through C.5 summarize, for each station, moments of observed rainfall and moments of three representative simulations. Recall that the disaggregation model reproduces monthly means exactly. Second and third moments of the simulated rainfall differ somewhat from the observed moments. Model performance was expected to degrade with distance. In general, the variances of the simulated distributions diverge from those of the observed distributions as distance from the base station increases (App. Tables C.4, C.5). The spatial pattern for skewness is less straightforward. Observed variance and

APPENDIX TABLE C.2. BETA DISTRIBUTION PARAMETERS BY NUMBER OF RAINY DAYS PER MONTH AT STATION 863, WAHIAWA DAM, OAHU, HAWAII

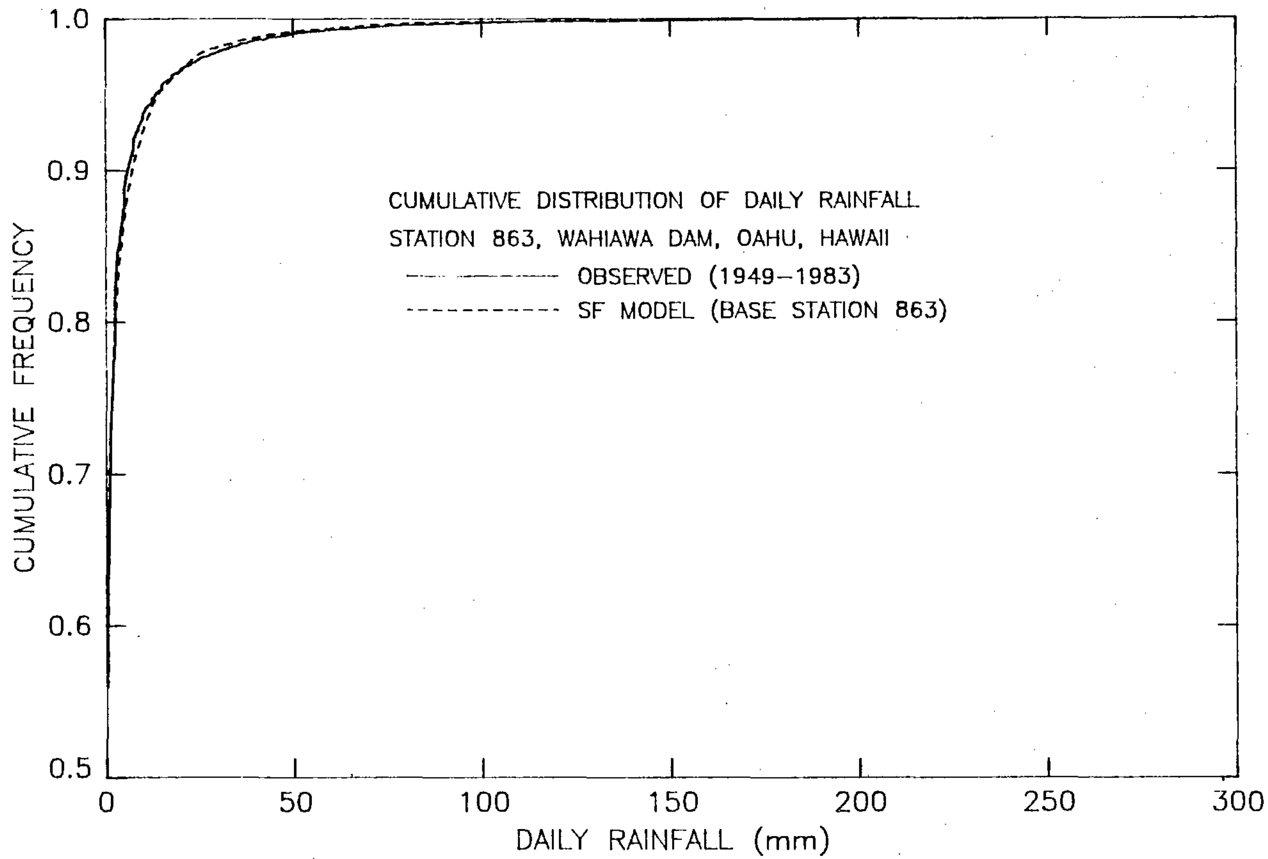
No. Rain Days	Mean Y (mm/mm)	Std. Dev. Y (mm/mm)	Beta Dist. Parameters a	b
2	0.5000	0.4585	0.0947	0.0947
3	0.3333	0.3159	0.4089	0.8179
4	0.2500	0.2446	0.5334	1.6001
5	0.2000	0.2018	0.5854	2.3417
6	0.1667	0.1733	0.6038	3.0191
7	0.1429	0.1530	0.6048	3.6285
8	0.1250	0.1377	0.5962	4.1731
9	0.1111	0.1258	0.5822	4.6578
10	0.1000	0.1163	0.5654	5.0883
11	0.0909	0.1085	0.5470	5.4699
12	0.0833	0.1020	0.5280	5.8077
13	0.0769	0.0966	0.5089	6.1063
14	0.0714	0.0919	0.4900	6.3699
15	0.0667	0.0878	0.4716	6.6021
16	0.0625	0.0842	0.4537	6.8062
17	0.0588	0.0811	0.4366	6.9852
18	0.0556	0.0783	0.4201	7.1416
19	0.0526	0.0758	0.4043	7.2778
20	0.0500	0.0735	0.3893	7.3958
21	0.0476	0.0715	0.3749	7.4976
22	0.0455	0.0696	0.3612	7.5846
23	0.0435	0.0680	0.3481	7.6584
24	0.0417	0.0664	0.3357	7.7202
25	0.0400	0.0650	0.3238	7.7713
26	0.0385	0.0637	0.3125	7.8127
27	0.0370	0.0624	0.3017	7.8454
28	0.0357	0.0613	0.2915	7.8701
29	0.0345	0.0603	0.2817	7.8876
30	0.0333	0.0593	0.2724	7.8987
31	0.0323	0.0584	0.2635	7.9040



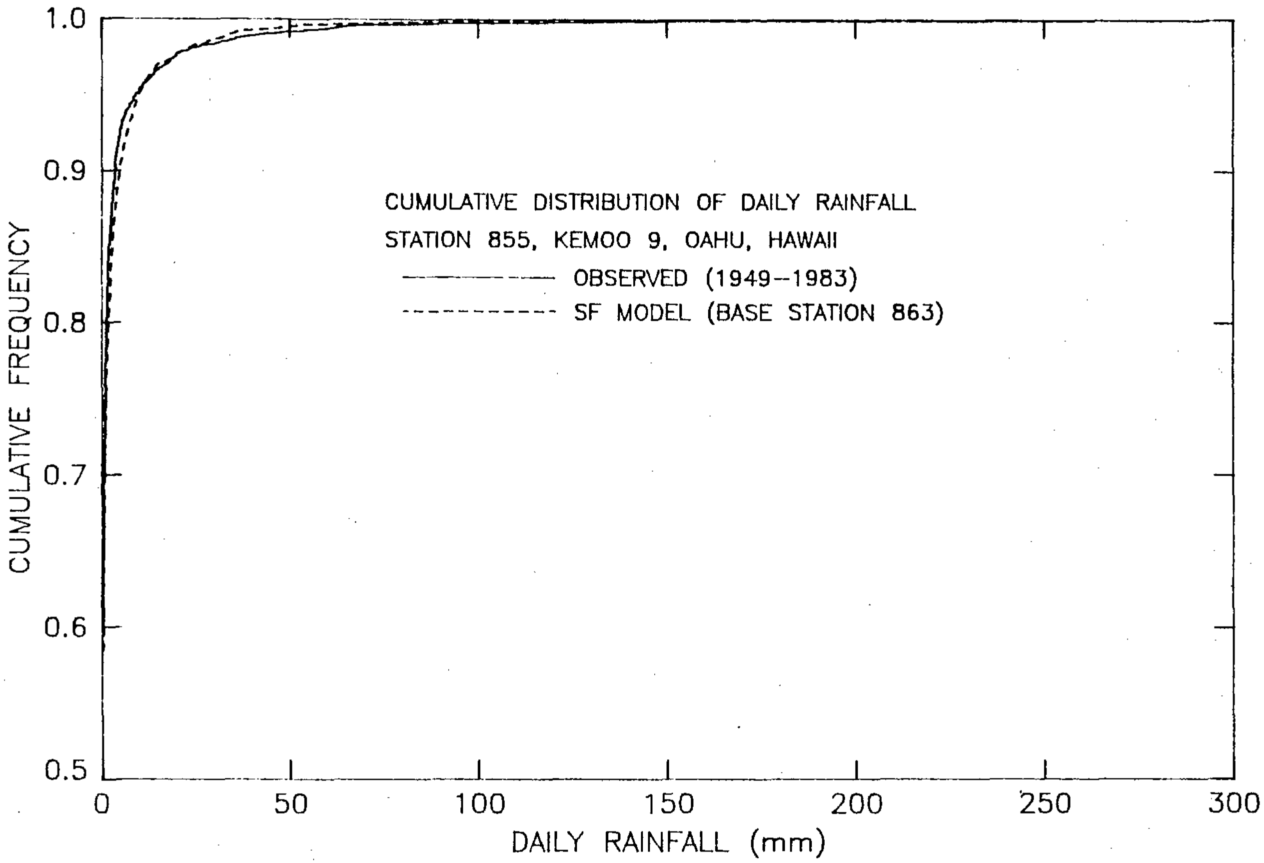
Appendix Figure C.3. Fitted beta cumulative frequency distributions of Y at Station 863, Wahiawa Dam, Oahu, Hawaii



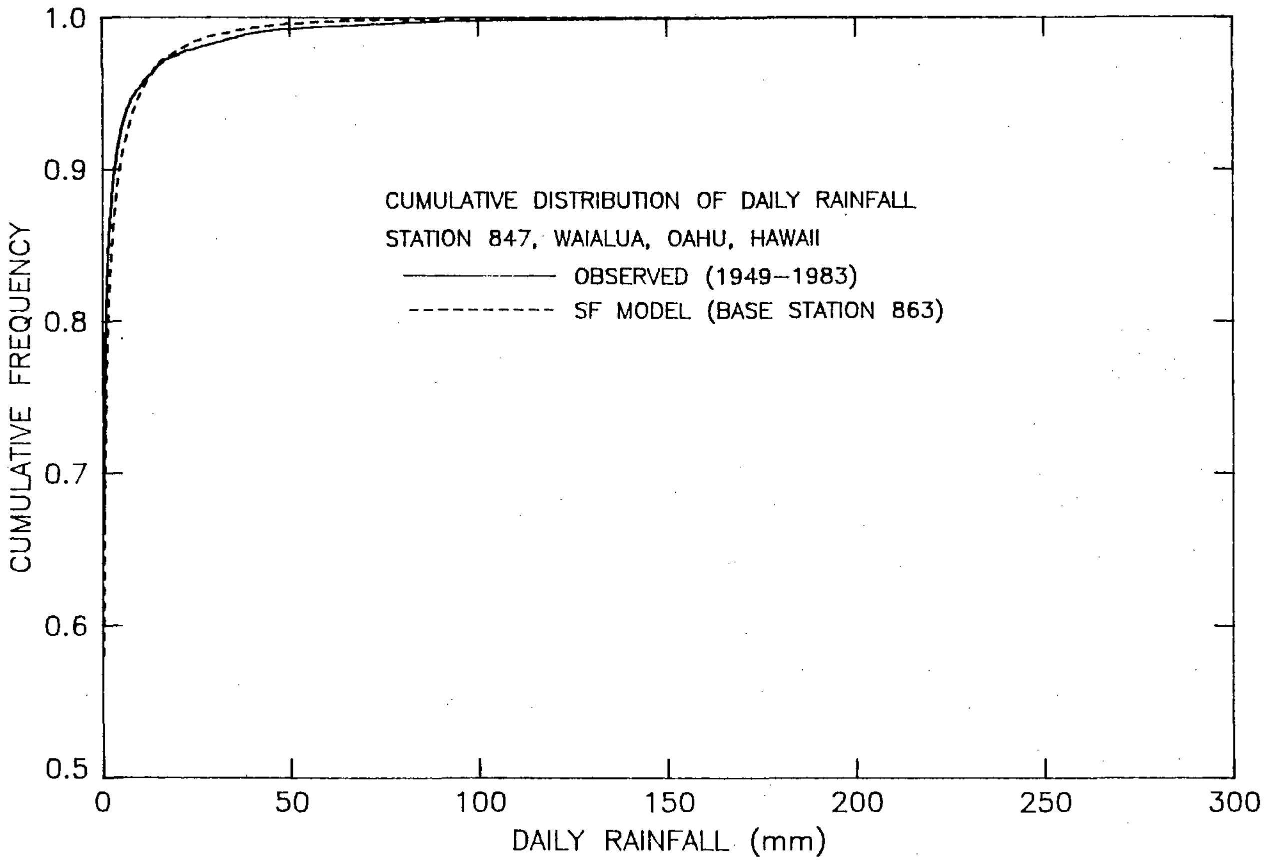
Appendix Figure C.4. Observed and fitted cumulative distributions of Y for 16 rain days per month at Station 863, Wahiawa Dam, Oahu, Hawaii



Appendix Figure C.5. Observed and simulated cumulative distributions of daily rainfall at Station 863, Wahiawa Dam, Oahu, Hawaii



Appendix Figure C.6. Observed and simulated cumulative distributions of daily rainfall at Station 855, Kemoo 9, Oahu, Hawaii



Appendix Figure C.7. Observed and simulated cumulative distributions of daily rainfall at Station 847, Waialua, Oahu, Hawaii

APPENDIX TABLE C.3. OBSERVED AND SIMULATED MOMENTS AT STATION 863, WAHIAWA DAM, OAHU, HAWAII

MONTH	NO.	MEAN (mm)	VARIANCE (mm^2) Obs.	Sim 1	Sim 2	Sim 3	SKEWNESS (mm^3) Obs.	Sim 1	Sim 2	Sim 3
1	806	6.7	490	495	401	392	69163	72270	53118	53585
2	791	4.8	184	228	146	180	12006	24217	9282	13648
3	837	4.0	155	155	151	168	11551	10979	11894	14590
4	840	2.6	73	39	49	49	7345	1174	2054	2099
5	961	1.9	32	29	34	34	1001	885	1510	1380
6	930	1.2	12	7	9	7	290	95	176	80
7	899	1.4	14	10	11	14	489	139	222	328
8	992	1.8	47	27	24	26	3168	829	693	975
9	900	1.5	26	21	20	16	1125	714	963	364
10	868	3.2	149	94	93	111	13107	5117	6845	8558
11	690	4.2	255	156	123	123	44891	12321	8518	8329
12	744	4.3	179	95	127	135	17699	3452	6673	8409
all	10258	3.0	129	109	96	101	14441	10856	8443	9272

APPENDIX TABLE C.4. OBSERVED AND SIMULATED MOMENTS AT STATION 855, KEMOO 9, OAHU, HAWAII

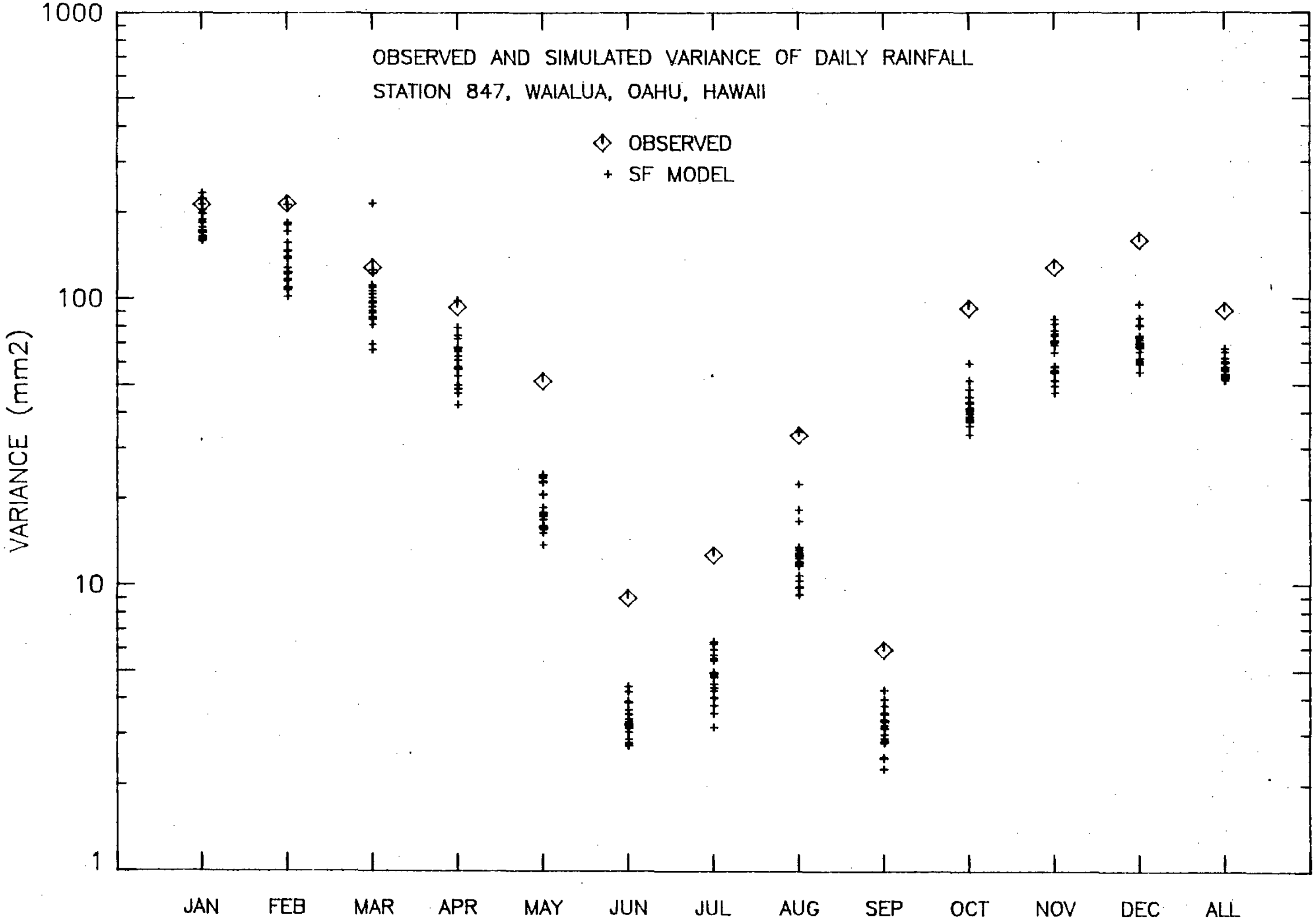
MONTH	NO.	MEAN (mm)	VARIANCE (mm^2) Obs.	Sim 1	Sim 2	Sim 3	SKEWNESS (mm^3) Obs.	Sim 1	Sim 2	Sim 3
1	186	6.1	316	462	1791	55	31137	95870	8132	5604
2	170	3.1	55	52	393	9	1404	1794	904	740
3	155	5.0	211	409	3282	86	11696	83935	35256	30542
4	180	2.3	39	54	353	5	1124	3173	975	978
5	310	1.2	11	6	8	7	179	53	112	71
6	390	.5	2	1	2	1	15	5	11	4
7	310	.8	5	3	5	4	77	23	77	35
8	372	1.6	71	25	27	26	6989	664	1026	833
9	390	1.0	16	10	7	6	456	169	98	68
10	310	2.4	74	62	54	91	3628	3254	2156	7033
11	180	4.6	658	198	148	128	159128	13164	8171	6604
12	93	5.8	327	151	190	195	27126	5930	9415	8915
all	3046	2.2	107	86	60	59	14639	12256	3873	3788

APPENDIX TABLE C.5. OBSERVED AND SIMULATED MOMENTS AT STATION 847, WAIALUA, OAHU, HAWAII

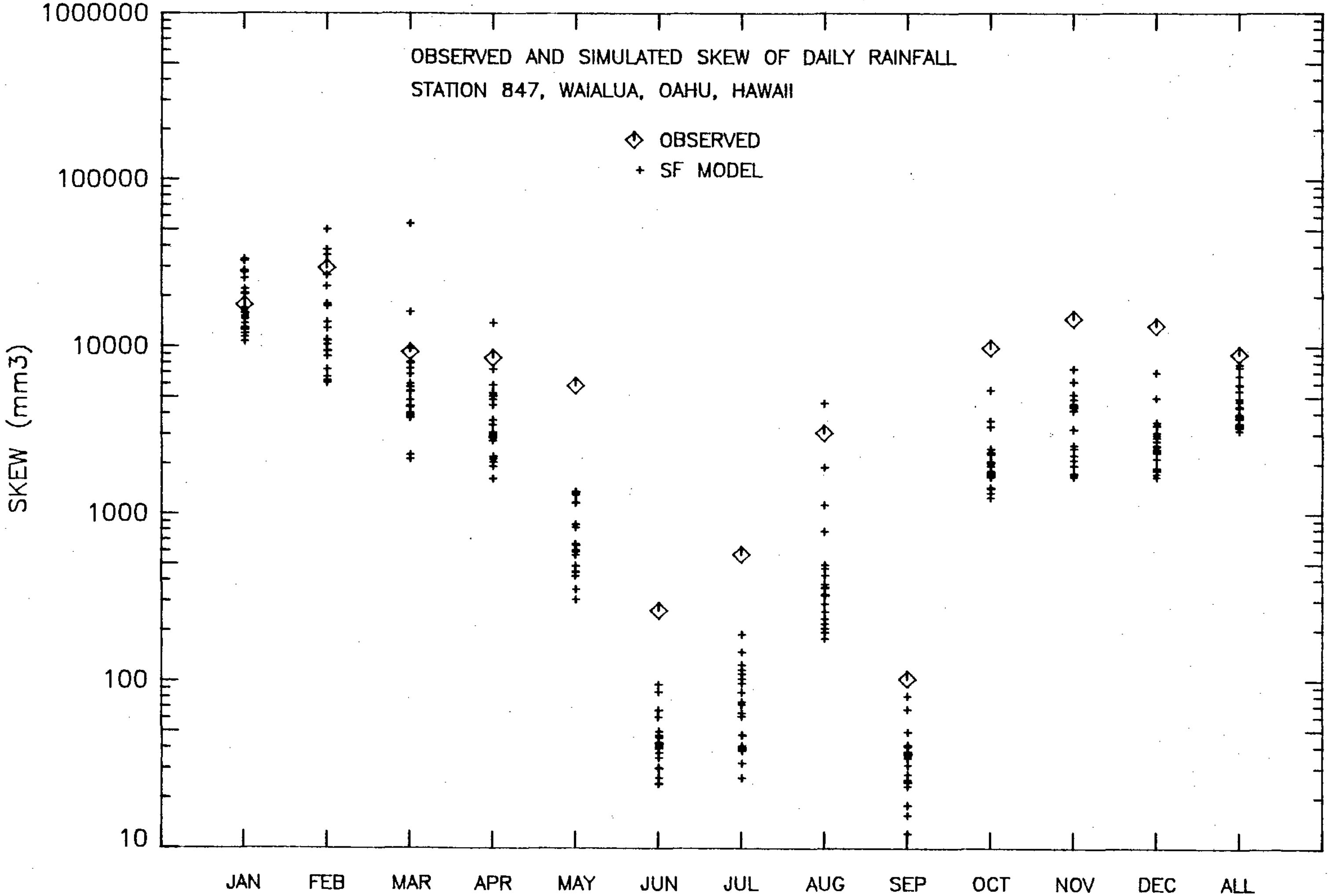
MONTH	NO.	MEAN (mm)	VARIANCE (mm^2) Obs.	Sim 1	Sim 2	Sim 3	SKEWNESS (mm^3) Obs.	Sim 1	Sim 2	Sim 3
1	775	4.4	212	203	234	169	17617	25351	33180	14501
2	736	3.7	214	146	212	140	29492	17954	50157	13962
3	806	3.4	128	126	69	91	9235	15998	2259	4419
4	780	2.3	93	48	57	54	8554	1927	2918	2748
5	899	1.2	51	16	16	24	5842	423	448	1348
6	960	.6	9	3	4	4	263	41	61	47
7	961	.7	13	5	5	3	571	85	103	26
8	868	1.0	33	12	18	10	3066	289	1136	195
9	810	.7	6	4	4	3	103	41	81	26
10	961	1.9	92	38	41	41	9847	1691	1824	2303
11	720	2.8	128	52	56	55	14720	1968	2483	3250
12	651	3.4	159	59	61	73	13285	1735	1895	3392
all	9927	2.1	91	57	62	53	9001	5464	7582	3752

skewness exhibit large differences from month to month reflecting the highly seasonal nature of rainfall in the region. The variance and skewness values by month for each of the 20 simulations at Station 847 are compared with the observed values in Appendix Figures C.8 and C.9, respectively. The simulated moments, while sometimes differing substantially from the observed values, reproduced month-to-month differences very well.

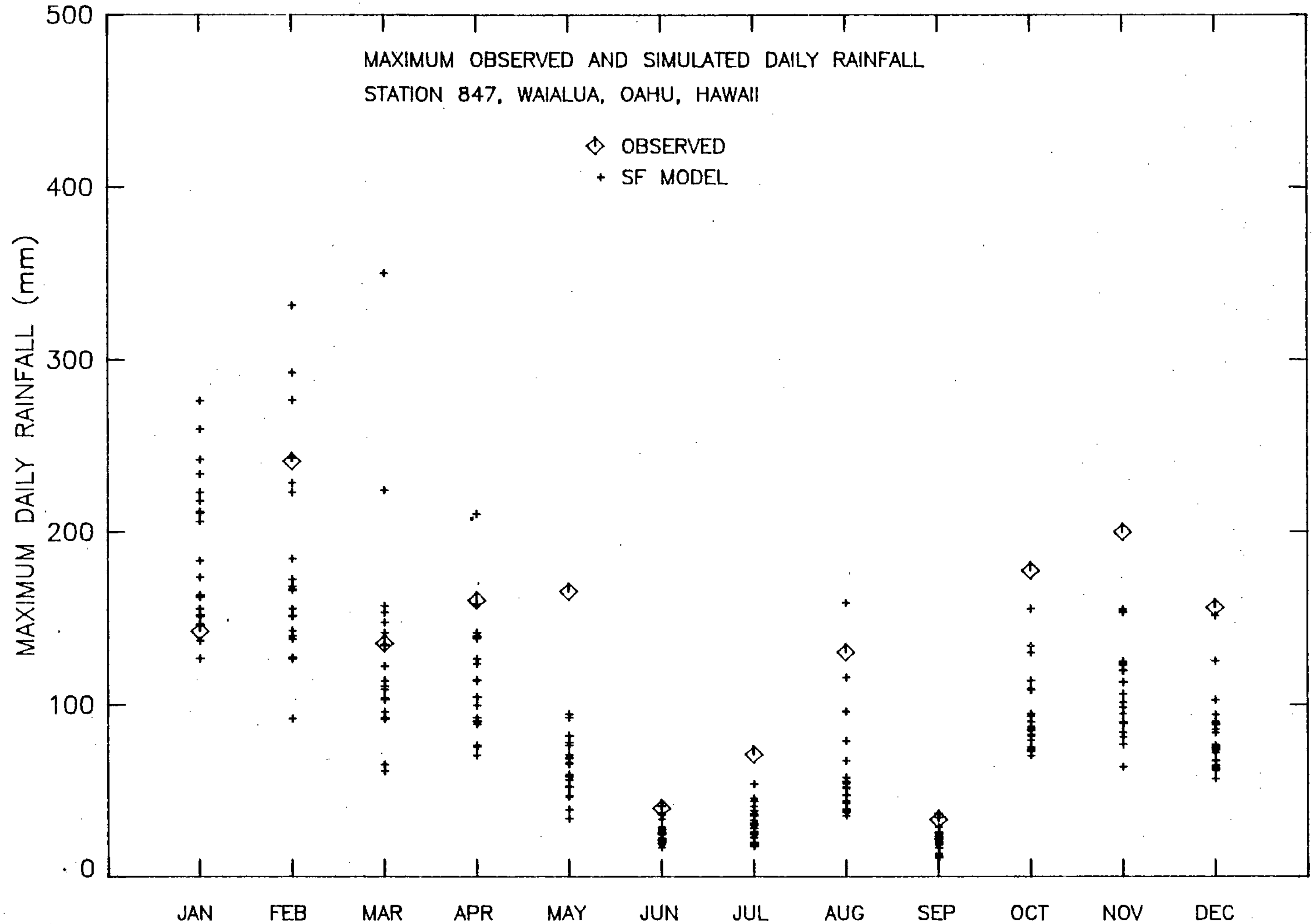
In most modeling applications, extreme rainfall events assume great importance. Thus, a disaggregation model should exhibit skill in reproducing observed frequencies at the high end of the distribution. The variance and skewness give some indication of model performance in this regard. As an additional check, the maximum values for each month and each simulation were compared with observed maxima. At all three stations, the model overestimated observed maxima for some months and underestimated observed maxima for others. In general, however, the disaggregation model is capable of reproducing extreme events (App. Fig. C.10).



Appendix Figure C.8. Observed and simulated variance of daily rainfall at Station 847, Waialua, Oahu, Hawaii



Appendix Figure C.9. Observed and simulated skew of daily rainfall at Station 847, Waialua, Oahu, Hawaii



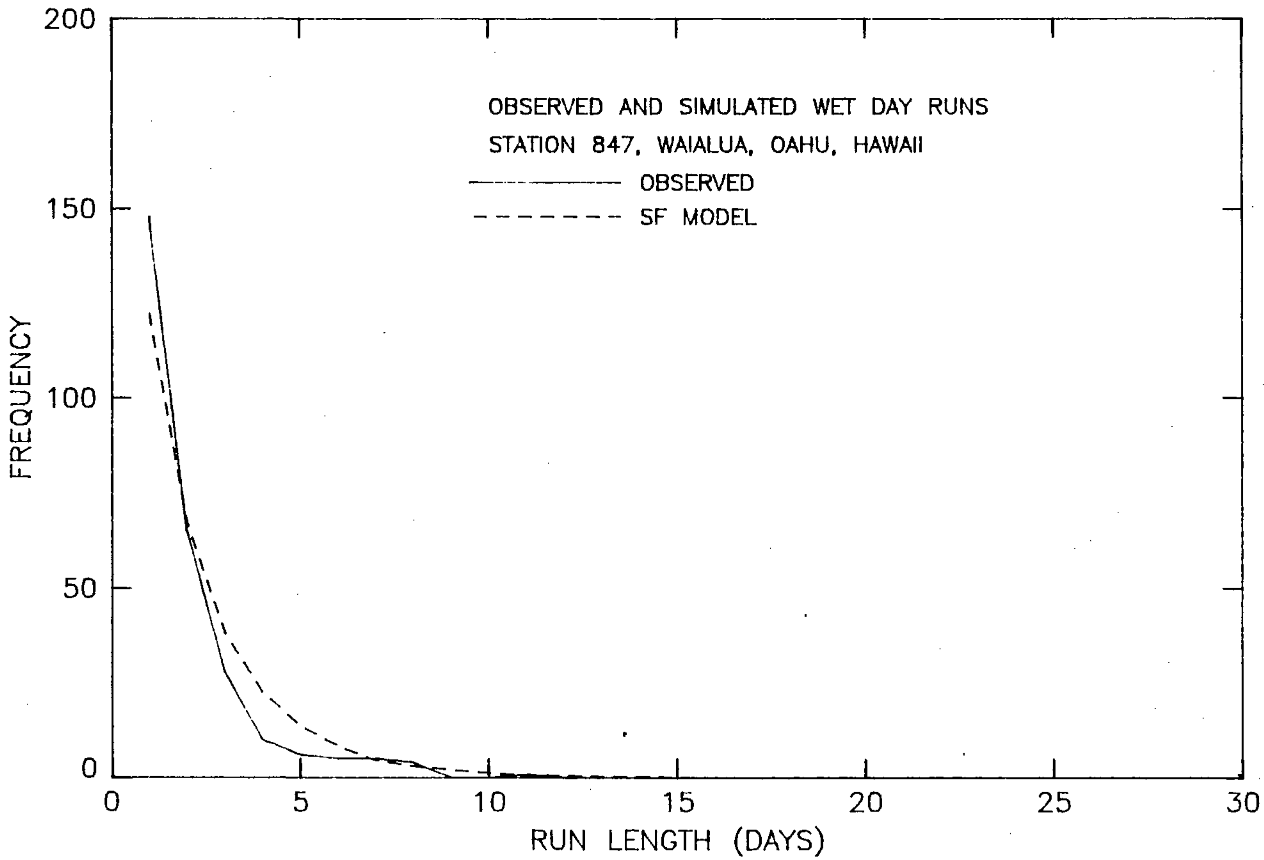
Appendix Figure C.10. Maximum observed and simulated daily rainfall at Station 847, Waialua, Oahu, Hawaii

Periods of consecutive wet or dry days may play an important role in determining the fate of chemicals in the soil. Average wet- and dry-day frequencies for 20 simulations at Station 847 are shown in comparison with observed runs in Appendix Figures C.11 and C.12, respectively. Temporal autocorrelation was incorporated in the SF model in the form of a two-state first-order Markov chain. The model was tested by examining the frequencies of wet- and dry-day runs. Appendix Figures C.11 and C.12 indicate that the model is capable of reproducing consecutive wet- and dry-day sequences at Station 847. As expected, run frequencies of simulated rainfall show greater deviation in comparison with observed values, as distance from the base station increases (run frequencies for St. 863 and 855 are not shown).

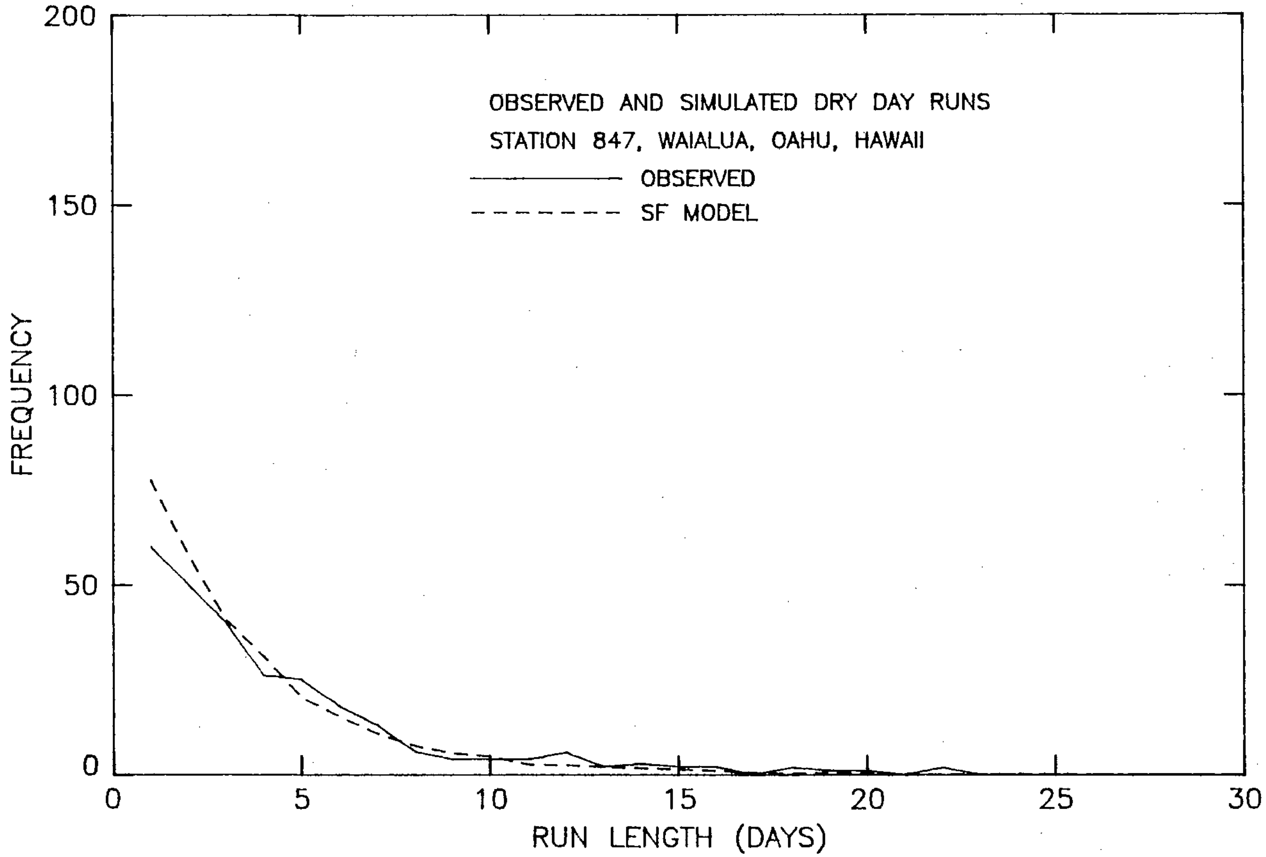
Rainfall Disaggregation Model Application. For this investigation, the SF model described above was used to disaggregate interpolated monthly rainfall for each of the water balance cells. A single Markov sequence of wet and dry days was generated for the 37-yr study period and was assumed to be applicable for all cells. Although an infinite number of different sequences can be generated with the model, a single sequence was used for all cells to maintain the spatial integrity of rainfall throughout the grid. This assumption probably underestimates the number of wet days near the wetter northeastern portion of the grid. However, because these areas are generally undeveloped, chemical leaching is not impacted. Values of the dimensionless parameter Y were assigned to each of the wet days in a month using the appropriate beta distribution. Simulated daily rainfall values were then obtained by multiplying the Y values by the proper monthly rainfall total.

IRRIGATION

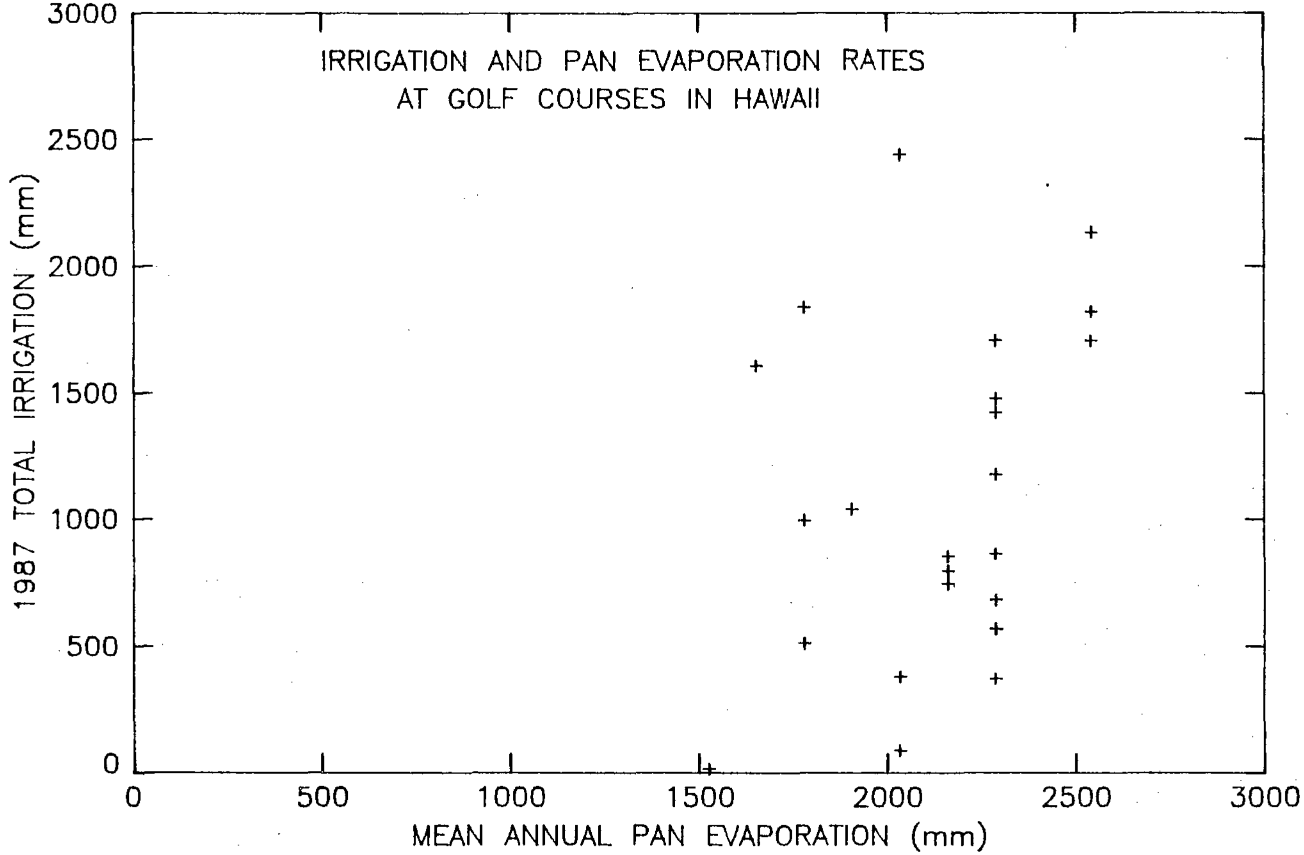
Golf course irrigation rates for 1987 throughout Hawaii were obtained from a survey conducted by Hollyer and Cox (1988). Estimates of mean annual pan evaporation rates at each golf course were based on the pan evaporation maps of Ekern and Chang (1985). Mean annual rainfall at each site was estimated from isohyet maps developed by Giambelluca, Nullet, and Schroeder (1986). A scattergram of annual irrigation versus mean annual pan evaporation (App. Fig. C.13) reveals no apparent relationship between the two parameters. Similarly, a scattergram of annual irrigation versus



Appendix Figure C.11. Observed and simulated wet day runs at Station 847, Waialua, Oahu, Hawaii



Appendix Figure C.12. Observed and simulated dry day runs at Station 847, Waialua, Oahu, Hawaii



Appendix Figure C.13. Irrigation and pan evaporation rates at golf courses in Hawaii mean annual rainfall at each golf course site reveals no apparent relationship (App. Fig. C.14). The scatter in the data reflects the unique conditions related to climate, soils, water availability, and management practices at each golf course. The scatter is also consistent with the wide range of golf course irrigation rates (790-3 750 mm/yr) recently determined by Murabayashi (1989).

Although there is scatter in the data, an upper envelope line was plotted (App. Fig. C.14) which was assumed to reflect golf course irrigation practices in Hawaii. The upper envelope line suggests irrigation rates which increase with decreasing rainfall. The data of Murabayashi (1989) were not available at the time of the analysis. However, a comparison of common golf courses surveyed indicates that the irrigation rates determined by Hollyer and Cox (1988) are generally lower than those obtained by Murabayashi (1989). Thus, the upper envelope line is generally representative of the data of Murabayashi (1989).

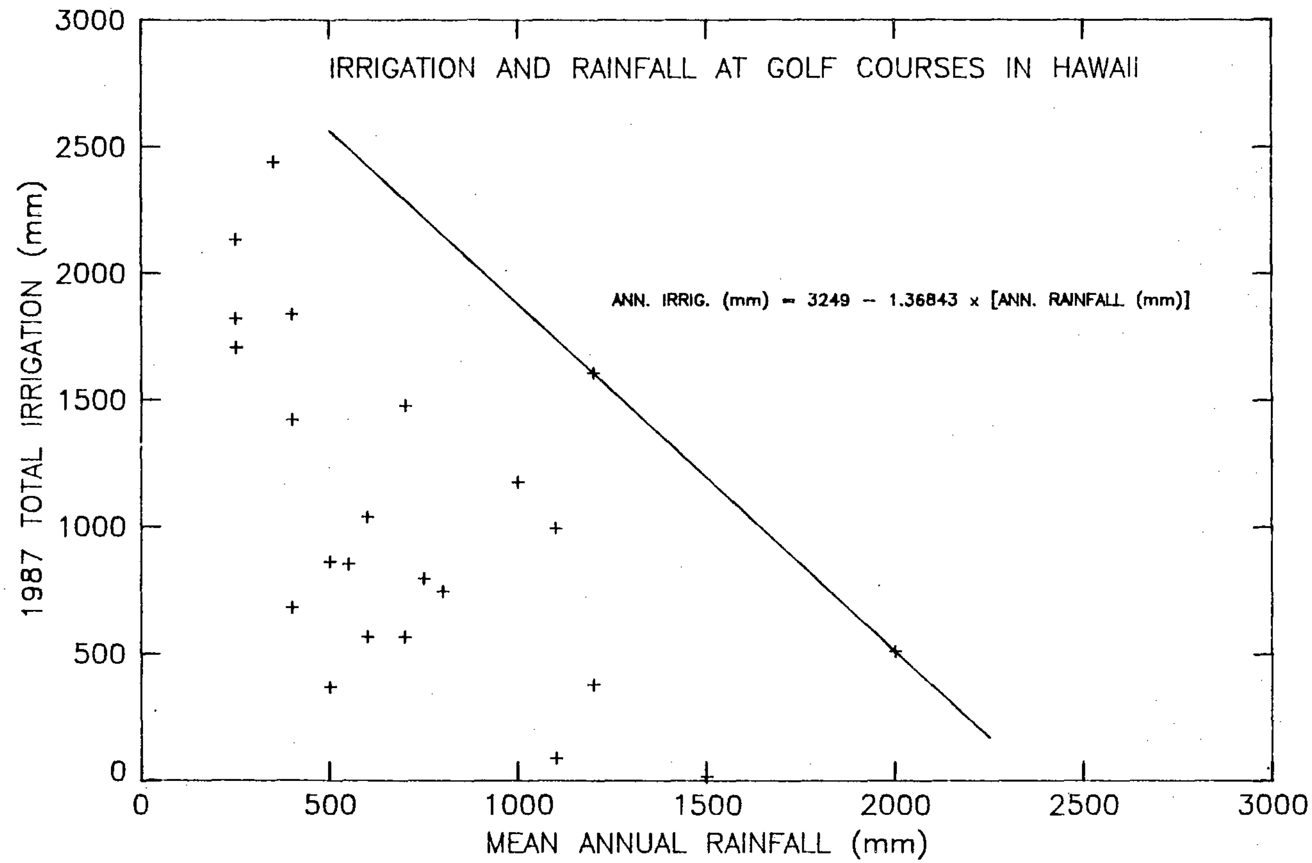
Based on the upper envelope line of Appendix Figure C.14, annual irrigation is related to annual rainfall by the following model,

$$I_a = 3249 - 1.36843P_a \qquad (C.10)$$

where I_a and P_a represent annual irrigation (mm) and rainfall (mm), respectively. Annual irrigation in each of the affected water balance cells was obtained using equation C.10 in conjunction with the appropriate average annual rainfall.

The annual irrigation totals for the relevant water balance cells were disaggregated into monthly values by first assuming total water input, given by the sum of annual irrigation and annual rainfall, to be uniformly distributed throughout the 12 months of the year. An unadjusted monthly irrigation value was obtained as the difference between the total monthly water input and the appropriate average monthly rainfall. When monthly rainfall exceeded the average total water input, irrigation was set equal to zero. The monthly irrigation totals were then adjusted to reflect the annual irrigation total. Daily irrigation was assumed to be uniformly distributed throughout the month.

The irrigation model described above was used for all water balance cells associated with a golf course land use. The model was also extrapolated to other unpaved portions of urban areas.



Appendix Figure C.14. Golf course irrigation-rainfall model for Hawaii

RUNOFF

Rainfall occurring over land surfaces may reach stream channels by a number of different paths. Some of the water may flow over the land surface as direct runoff, and contribute to streamflow soon after its occurrence as precipitation. According to the Hortonian concept of overland flow, surface runoff occurs when and where the rainfall intensity exceeds the rate at which water can infiltrate into the soil. A distinction should be made between infiltration, the passage of water through the soil surface, and percolation, the downward flow of water within the soil. Hortonian overland flow is just one of several mechanisms whereby precipitation appears as streamflow. Rainfall may also infiltrate the soil surface, and move laterally as interflow through the upper soil layers prior to reaching the stream channel (Linsley, Kohler, and Paulhaus 1982). A third possible route of entry is as groundwater or base flow. Additional mechanisms include saturation overland flow from "partial source areas" (Dunne and Black 1970) and overland flow from "variable source areas" during storms (Hewlett and Hibbert 1967).

The amount of runoff produced by a storm is dependent on the physical characteristics (including the antecedent moisture condition and vegetative cover) of the catchment and the quantity, intensity, and duration of the storm. A vast number of models have been proposed to account for the relationship between rainfall and runoff. These models range in complexity from simple estimates of runoff as a fixed percentage of rainfall, to complex, physically based computer techniques. A number of formulas, including the rational formula, have been proposed to estimate peak rates of runoff from urban and small watersheds. Hydrograph analyses can also yield estimates of direct surface runoff. Infiltration indexes, which generally assume that infiltration occurs at a constant rate throughout a storm, can be used to estimate runoff by determining when rainfall intensity exceeds the index value. Computer simulation models, such as the Stanford Watershed Model, provide continuous estimates of runoff using relatively detailed analyses.

<u>Soil Conservation Service Runoff Curve Number Model</u>. For this study, runoff was estimated with the SCS runoff curve number model (U.S. Department of Agriculture 1972). The SCS method of estimating

runoff from daily rainfall measurements involves the use of the following empirical relationship (U.S. Department of Agriculture 1972):

$$R = 0 \qquad \text{for } P \leq 0.2Z$$

$$R = \frac{(P - 0.2Z)^2}{P + 0.8Z} \qquad \text{for } P > 0.2Z \qquad (C.11)$$

where R is the daily runoff (mm), P is storm precipitation (mm), and Z is the retention parameter (mm). Equation C.11 states that 20% of the maximum retention, Z, is the initial abstraction (interception, infiltration, and surface storage) occurring prior to the onset of runoff. The runoff curve number, CN, is a transformation of Z represented by

$$CN = \frac{1000}{10 + Z/25.4} \qquad (C.12)$$

Curve numbers range from zero (no runoff) to 100 (all rainfall results in runoff).

The SCS empirically determined curve numbers for various hydrologic soil-cover complexes. Curve numbers reflect land use, treatment of vegetative cover, and soil type. Soils are classified according to runoff potential. Four hydrologic soil groups are used (A, B, C, D), varying from low runoff potential (A) to high runoff potential (D). Recommended curve numbers are valid for an average antecedent moisture condition (AMC). Three different antecedent moisture conditions are proposed based on seasonal, 5-day antecedent rainfall totals. AMC II represents the average condition. Drier antecedent moisture conditions (AMC I) and wetter antecedent moisture conditions (AMC III) require downward and upward adjustment of the recommended curve numbers, respectively.

For this study, curve numbers were assigned to each of the cells of the water balance grid based on the guidelines presented by the SCS (U.S. Department of Agriculture 1972; U.S. Department of Agriculture 1975). The majority of soils found in the Waiawa area belong to hydrologic soil groups B and C. The discretized soil designations for each of the pertinent cells of the water balance grid are presented in Figure 24. Pre-urban curve numbers of 60 and 73 for hydrologic soil groups B and C, respectively, were used as the basis for curve number estimates under urbanized conditions (U.S. Department of Agriculture 1972,). The pre-urban curve numbers are valid for antecedent moisture condition II and are based on a grazed and unprotected woods land use.

Curve numbers for urban conditions were computed based on the following model (U.S. Department of Agriculture 1975, Fig. 2-2):

$$CN_u = CN_p + (98 - CN_p)(1-G) \qquad (C.13)$$

where CN_u represents the curve number for urban conditions, CN_p is the pre-urban curve number, and G is the fraction of the urban area which is unpaved or pervious.

Murabayashi and Fok (1979) used large-scale aerial photographs to carefully determine the percentage of permeable and impermeable surfaces in various urban areas on Oahu. About 57% of the residential areas and 64% of the apartment areas in the proposed Waiawa development may be paved if Waiawa's development schemes are similar to those studied by Murabayashi and Fok (1979). The proposed commercial and industrial areas in the Waiawa development were assigned a paved area of 85% which is less than the value of 98% determined by Murabayashi and Fok (1979) for the dense Kakaako area of Honolulu. Using the paved area estimates described above, urban curve numbers were computed to be 82, 84, and 92, for residential, apartment, and commercial/industrial areas, respectively. A curve number of 60 was used for golf course areas. The curve numbers determined above are valid for antecedent moisture condition II. Curve numbers for antecedent moisture conditions I and III were based on Table 10.1 of the SCS National Engineering Handbook (U.S. Department of Agriculture 1972).

EVAPOTRANSPIRATION

Evaporation can be defined as the net rate of vapor transport to the atmosphere from all surfaces. At 20°C, approximately 2.45 MJ/kg are required to evaporate one gram of water. The energy required for evaporation is supplied by radiation and advection from overlying air or occurs at the expense of energy stored below the surface. Evaporation of rainfall can occur from free-water surfaces, from soil, and through the process of transpiration by plants. Rates of evaporation are dependent on the nature of the evaporating surface and various meteorological factors, including solar radiation, air temperature, vapor pressure, wind, and atmospheric pressure (Linsley, Kohler, and Paulhaus 1982).

Evapotranspiration from a plant-soil system includes evaporation of intercepted rainfall, soil evaporation, and transpiration. Precipitation, which is intercepted by vegetation and subsequently evaporated, uses some of the energy otherwise available for transpiration. Water entering the soil and moving through the root membrane into root cells by osmotic pressure is transferred through the plant to the intercellular space within the leaves. Chloroplasts within the leaf use a portion of the water, along with sunlight and carbon dioxide from the air, to manufacture carbohydrates necessary for plant growth through the process of photosynthesis. As air enters the leaf through open stomata, water escapes from the plant system in the process of transpiration.

To separate the influence of environmental factors (energy, wind, and humidity) from the influence of soil moisture availability on evapotranspiration, the concept of potential evapotranspiration was developed. Thornthwaite (1944, p. 687) defined potential evapotranspiration (PE) as "the water loss which will occur if at no time there is a deficiency of water in the soil for the use of vegetation." Because evapotranspiration is dependent on the density of cover and the developmental stage of the vegetation, Penman (1956, p. 20) defined PE as being "the amount of water transpired in unit time by a short green crop, completely shading the ground, of uniform height and never short of water." Penman's definition, however, fails to specify a particular crop and neglects the effects of advected energy (Chang 1965).

Actual evapotranspiration (AE) can be estimated on a basin-wide scale with a water budget. On a smaller scale, evapotranspiration can be determined by maintaining a water budget in a field lysimeter. For this study, actual evapotranspiration was estimated through an empirical relationship between AE, PE, and soil moisture. Soil moisture is an important factor affecting evapotranspiration. Reduced evapotranspiration with soil drying is related to the increasing resistances to the flows of energy, water vapor, and liquid water (Giambelluca 1983). As soil moisture decreases, transport of water to the earth-atmosphere interface is insufficient to meet the atmospheric demand. Thus, AE falls short of PE.

The exact nature of the relationship involving AE, PE, and soil moisture, however, is not precisely understood.

Potential Evapotranspiration Model. For this study, potential evapotranspiration is defined as the maximum amount of evapotranspiration possible under prevailing atmospheric conditions (radiation intensity, air temperature, humidity, and wind) and surface characteristics (reflectance, roughness, and stomatal resistance), given that soil moisture stress is non-limiting (Giambelluca 1983). Estimates of mean monthly potential evapotranspiration for the study period were based on PE maps developed by Giambelluca (1983). Monthly PE values for each relevant cell of the water balance grid were then adjusted by an appropriate crop coefficient to reflect the assumed surface characteristics within the cell.

Actual Evapotranspiration Model. Actual evapotranspiration is determined as a function of environmental demand, potential evapotranspiration, and soil moisture availability during a given time interval. Soil moisture availability at the beginning of an interval (Z_i) is determined as,

$$Z_i = S_{i-1} + P_i + I_i - R_i \qquad (C.14)$$

The instantaneous rate of evapotranspiration (E) is assumed to vary as a function of instantaneous soil moisture (S) according to the following rules:

$$E = PE_i \qquad \text{for } S \geq C_i$$

$$E = SC^{-1}PE_i \qquad \text{for } S < C_i \qquad (C.15)$$

The quantity C_i, sometimes called the root constant (Penman 1949), may be interpreted as the available soil moisture content below which $\dot{E}$ is less than the potential rate. A model was developed to estimate C_i (Giambelluca 1983) having the form:

$$C_i = \min[a + b(RD) + c(PE_i), 1] \cdot \Phi \qquad (C.16)$$

where a, b, and c are calibration coefficients, RD is the plant root depth (mm), Φ is the available soil moisture capacity (mm), defined between field capacity and the wilting point, and where PE_i is in units of mm day^{-1}. Data from lysimeter studies by Ekern (1966b) were used to calibrate the model for conditions in Hawaii: a = 1.25, b = -1.87×10^{-3}, and c = 5.20×10^{-2} for PE $\leq$ 6 mm day^{-1}; a = 1.41, b = -1.87×10^{-3}, and c = 2.20×10^{-2} for PE > 6 mm day^{-1}.

Based on this model E_i is determined as,

$$E_i = PE_iT_i + C_i\{1 - \exp[-\alpha(1-T_i)]\} \qquad \text{for } Z_i > C_i$$

$$E_i = Z_i[1 - \exp(-\alpha)] \qquad \text{for } Z_i \le C_i \qquad (C.17)$$

where T_i is the fraction of the current time interval during which soil moisture is above C_i,

$$T_i = \min[(Z_i - C_i)PE_i^{-1}, 1] \qquad (C.18)$$

and where

$$\alpha_i = PE_iC_i^{-1}. \qquad (C.19)$$

For this study, an available moisture capacity of 0.12 mm/mm was representative of the soils occurring in the Waiawa area. An initial soil moisture content corresponding to 90% of the available moisture capacity and a root depth of 300 mm was assumed for all cells in the water balance grid. In the computation of evapotranspiration, the crop coefficient was set equal to unity for all water balance cells.

RECHARGE

Knowing the available soil moisture at the beginning of a time interval, and after obtaining estimates of precipitation, runoff, evapotranspiration, and irrigation, a soil state variable (X_i) may be computed as,

$$X_i = S_{i-1} + (P_i - R_i)G^{-1} + I_i - E_i \qquad (C.20)$$

where G represents the fraction of the total area which is unpaved. On the basis of X_i, groundwater recharge and end-of-interval soil moisture were determined according to the following drainage rules:

$$S_i = 0 \qquad \text{for } X_i \le 0$$
$$Q_i = 0$$
$$E_i = S_{i-1} + (P_i - R_i)G^{-1} + I_i$$

$$S_i = X_i \qquad \text{for } 0 < X_i \le \Phi$$
$$Q_i = 0$$

$$S_i = \Phi \qquad \text{for } X_i > \Phi$$
$$Q_i = (X_i - \Phi)G \qquad (C.21)$$

ASSUMPTIONS OF THE WATER BALANCE MODEL

A number of simplifying assumptions were made to each of the components of the water balance model. These assumptions are discussed below.

Soil Moisture. Soil moisture within the root zone is assumed to be uniformly distributed.

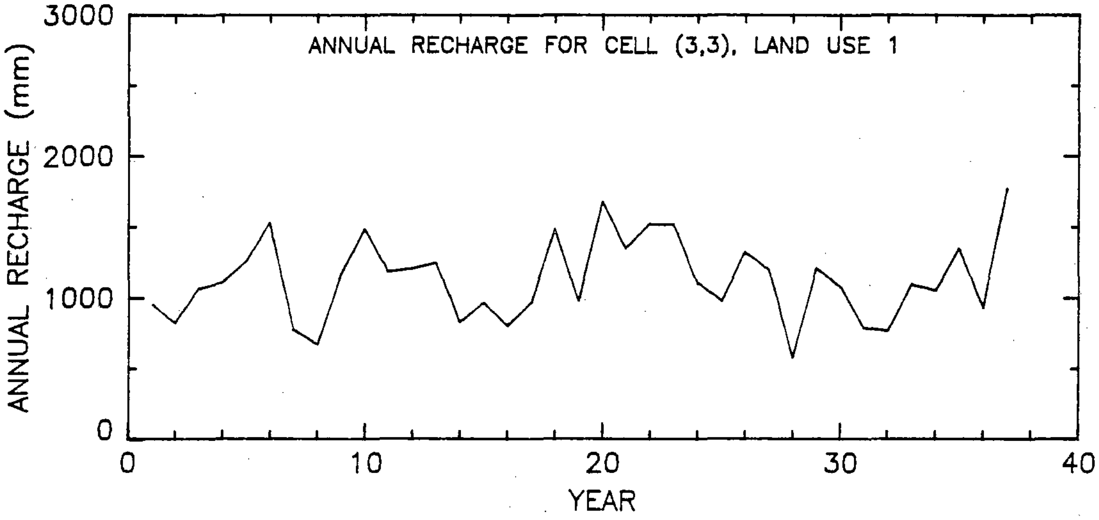
Runoff. Runoff is assumed to be an instantaneous response to rainfall, and receives first priority in the apportionment of precipitation. Thus, runoff is allowed to occur prior to the soil reaching its moisture capacity.

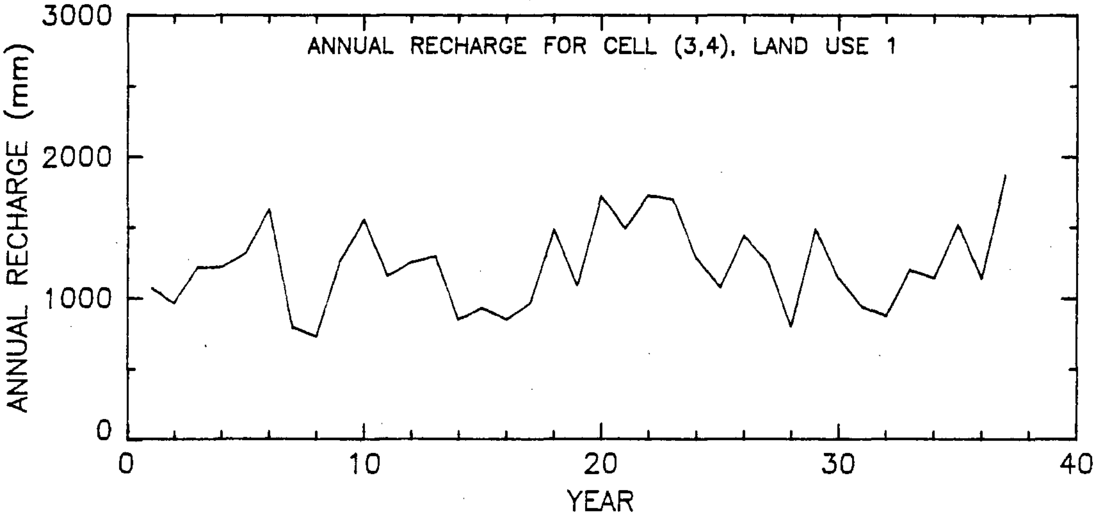
Evapotranspiration. Monthly potential evapotranspiration is assumed to be uniformly distributed throughout the month. Actual evapotranspiration is dependent on the available water at the beginning of an interval, after accounting for runoff. Declining soil moisture over a day due to drying is taken into account. The critical soil moisture content at which AE is depressed below the potential rate is assumed to be directly related to the potential evapotranspiration rate and inversely related to root depth. Below the critical point, available soil moisture is assumed to decay exponentially. No upward movement of water into the crop root zone is assumed to take place.

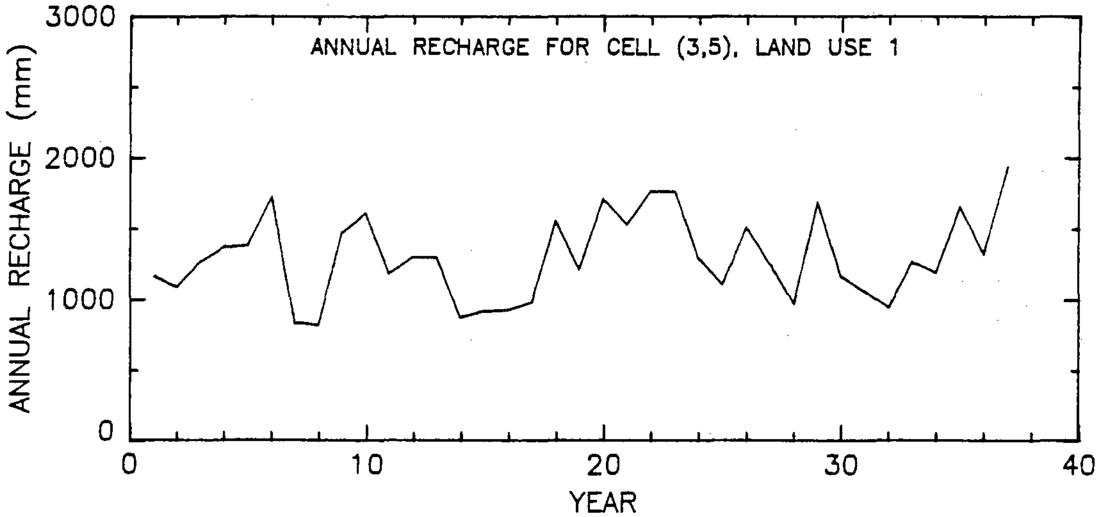
Recharge. Recharge is given third priority for apportionment of water and is assumed to occur only if the soil in the root zone reaches its water holding capacity. Soil water in excess of the available moisture capacity is assumed to drain instaneously at the end of each time interval.

LONG-TERM RECHARGE ESTIMATES

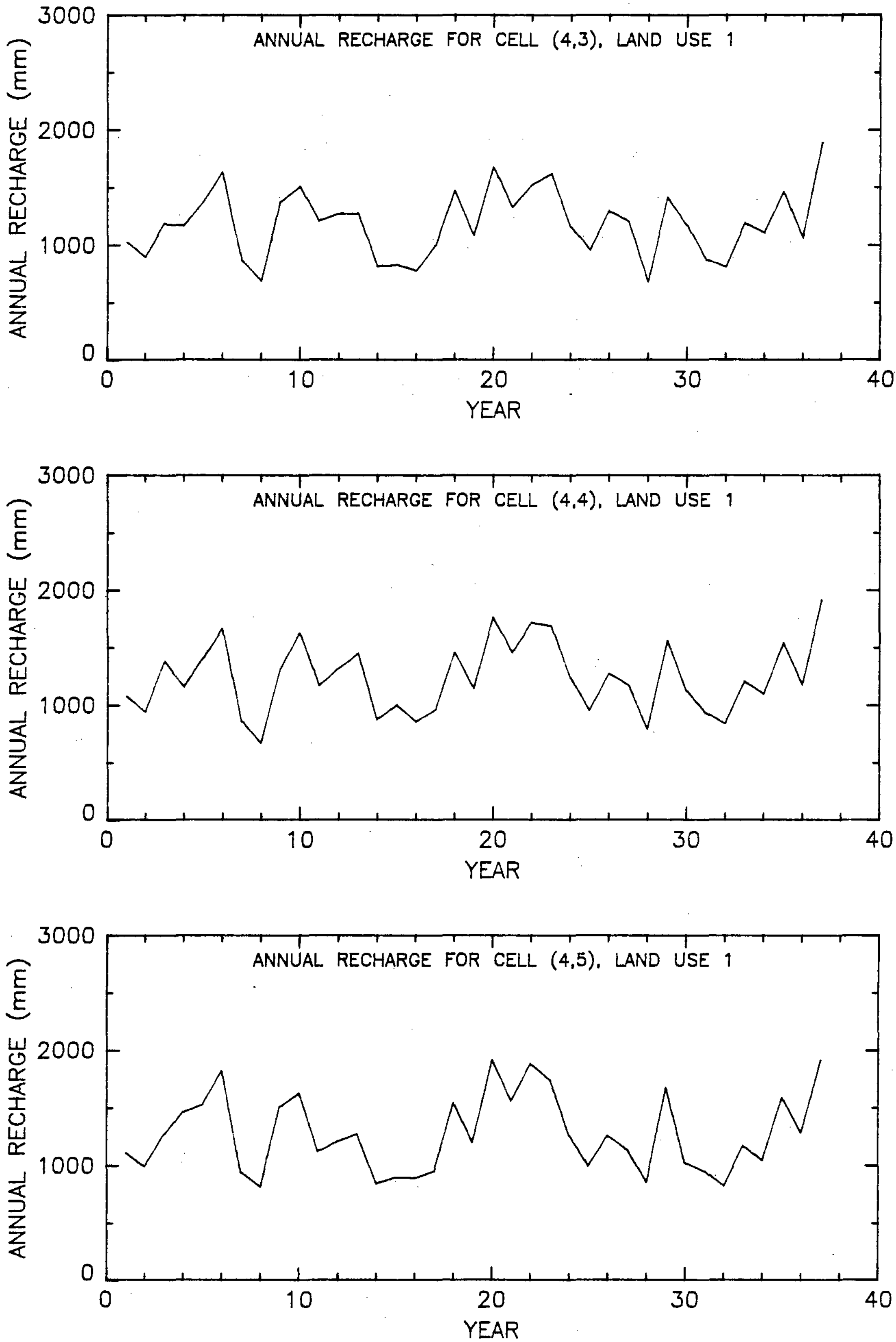
For this study, recharge estimates were obtained over portions of a 9 x 10 rectangular grid encompassing the study area. The water balance model was run for different land use scenarios using a daily time step for a period covering 37 yrs. The land use patterns for scenarios 1, 2, 3, and 4 are presented in Figures 27, 29, 31, and 33, respectively. (Each of the scenarios was described in detail in chapter 5 of this report.) Annual recharge time series for modeled cells of the water balance grid are presented in Appendix Figures C.15 to C.20.



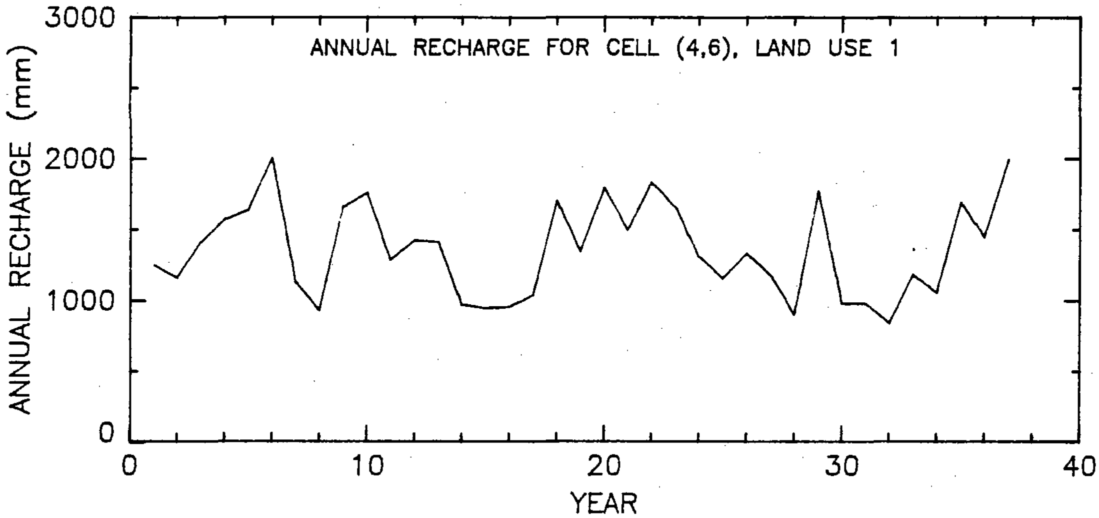


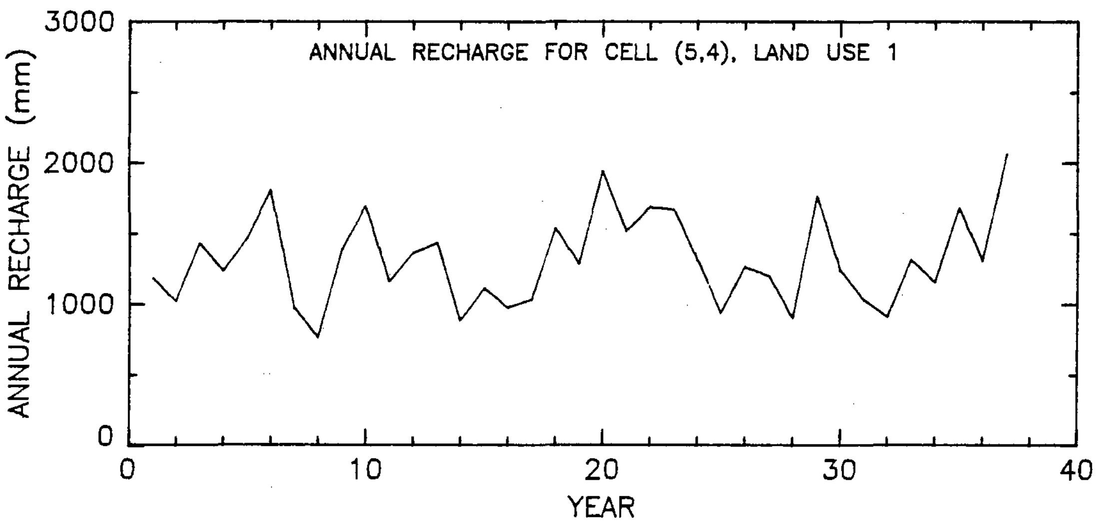


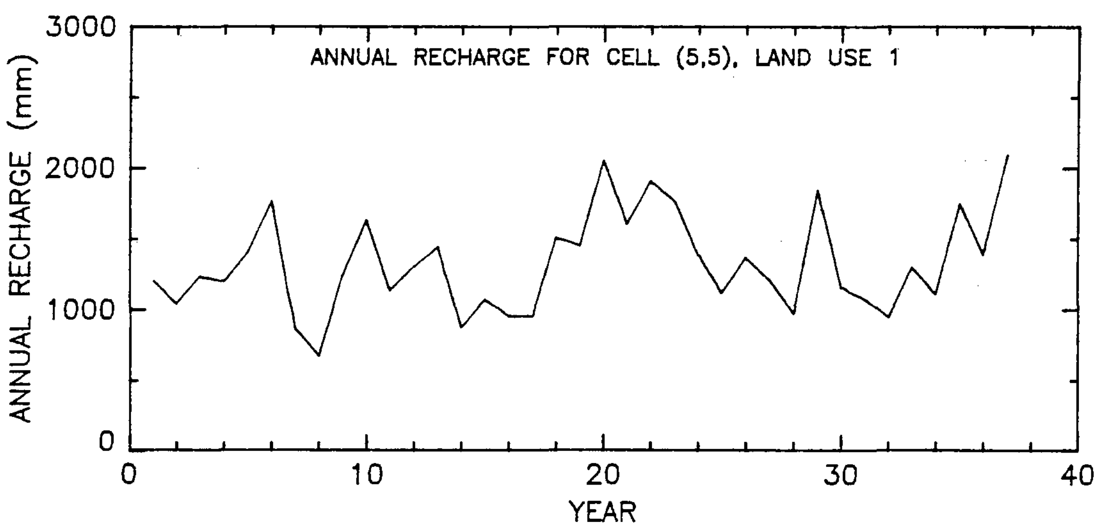
Appendix Figure C.15. Annual recharge time series for irrigated lawn without runoff (land use 1) water balance cells



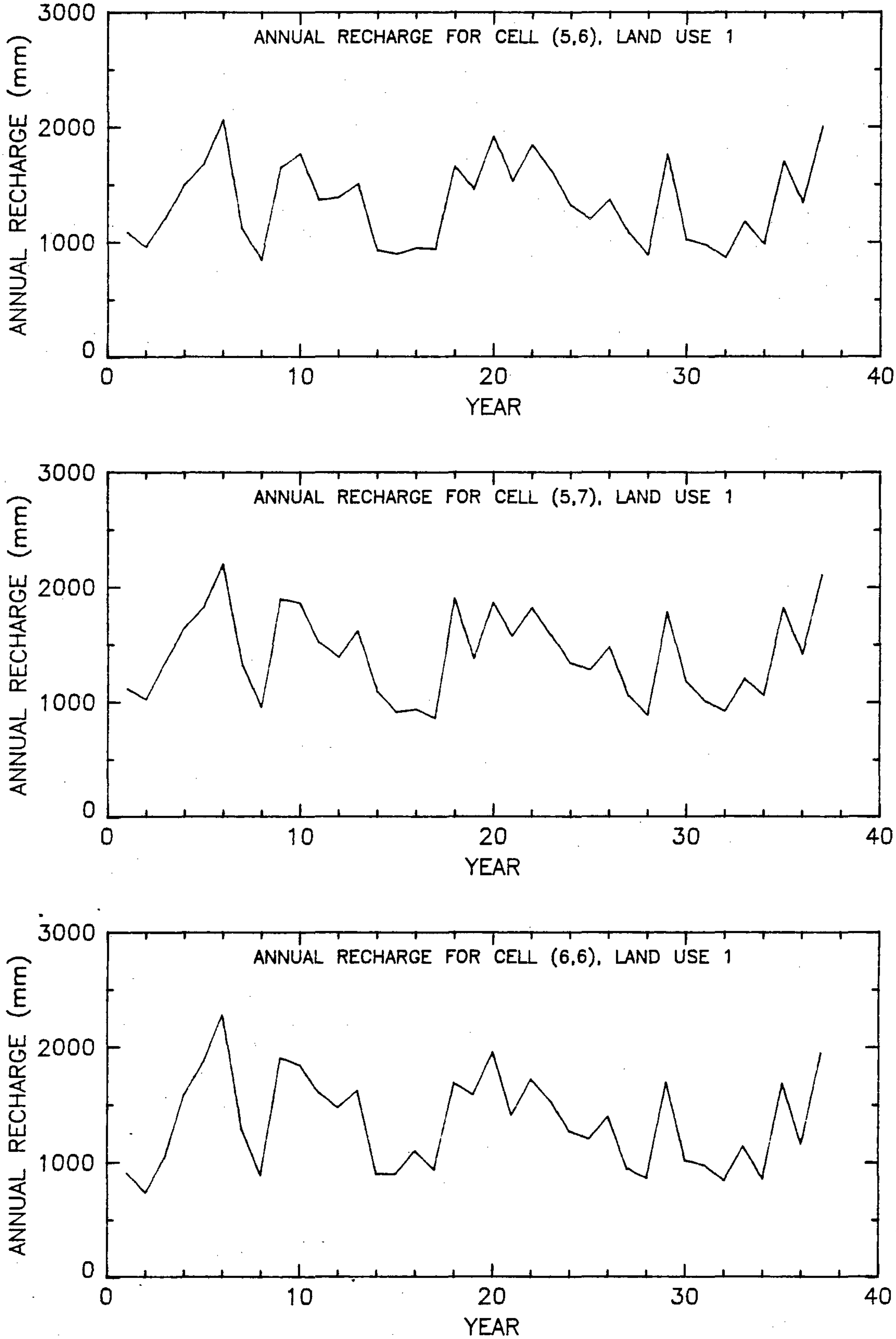
Appendix Figure C.15--Continued



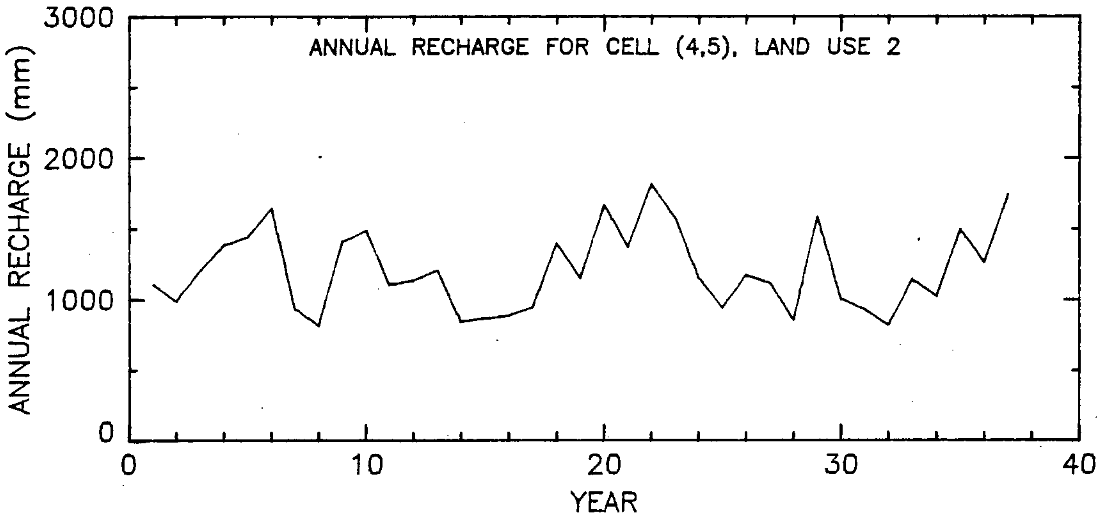


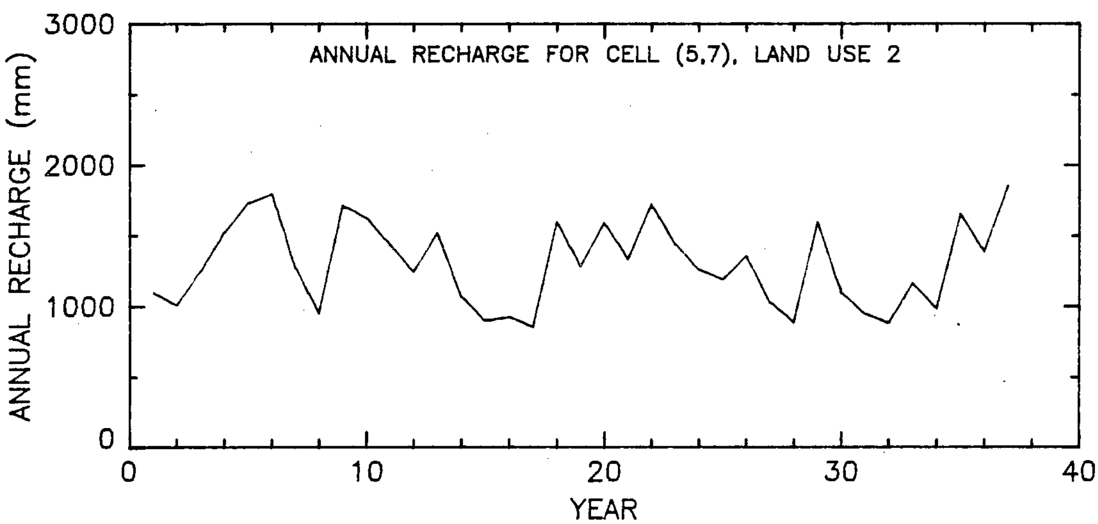


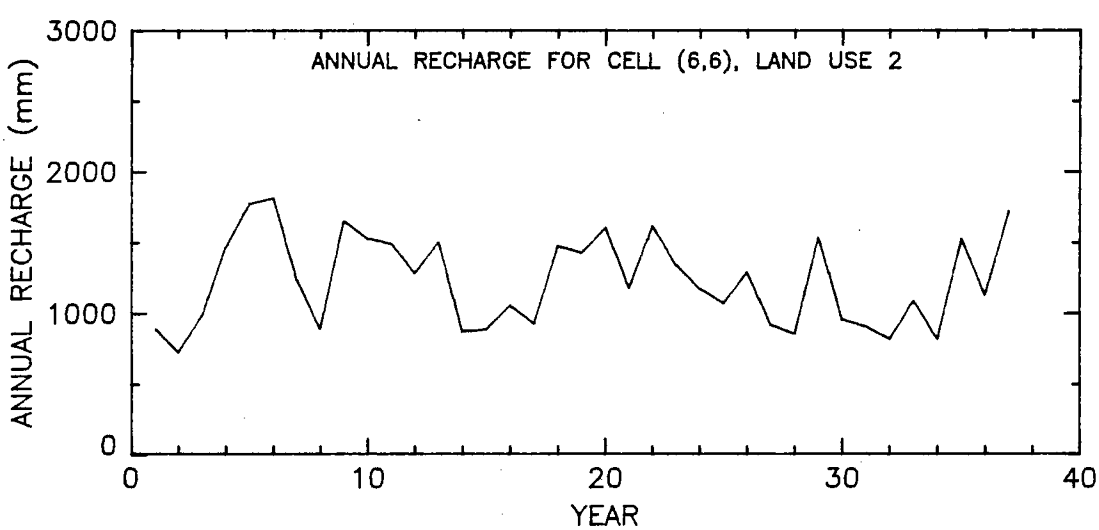
Appendix Figure C.15--Continued



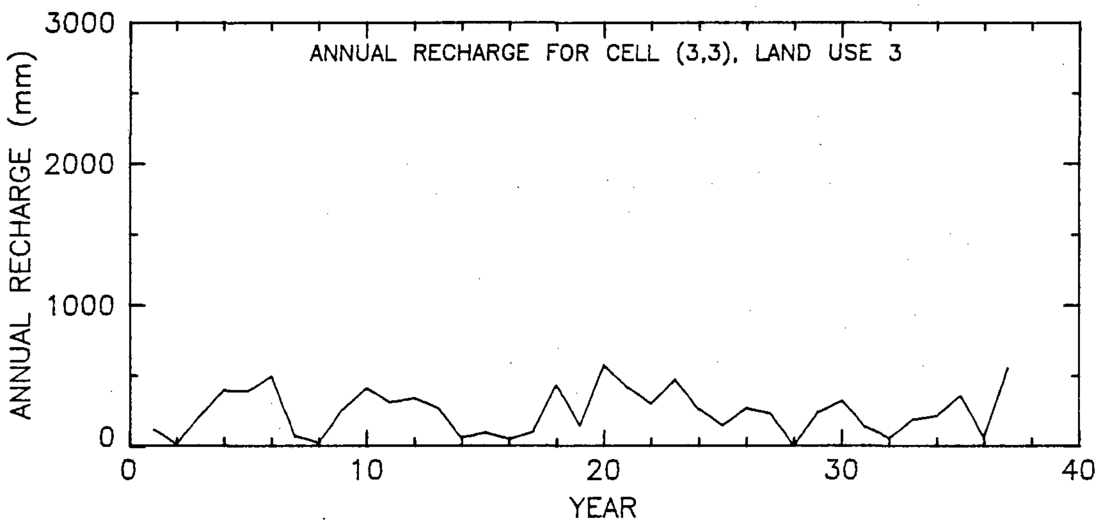
Appendix Figure C.15--Continued

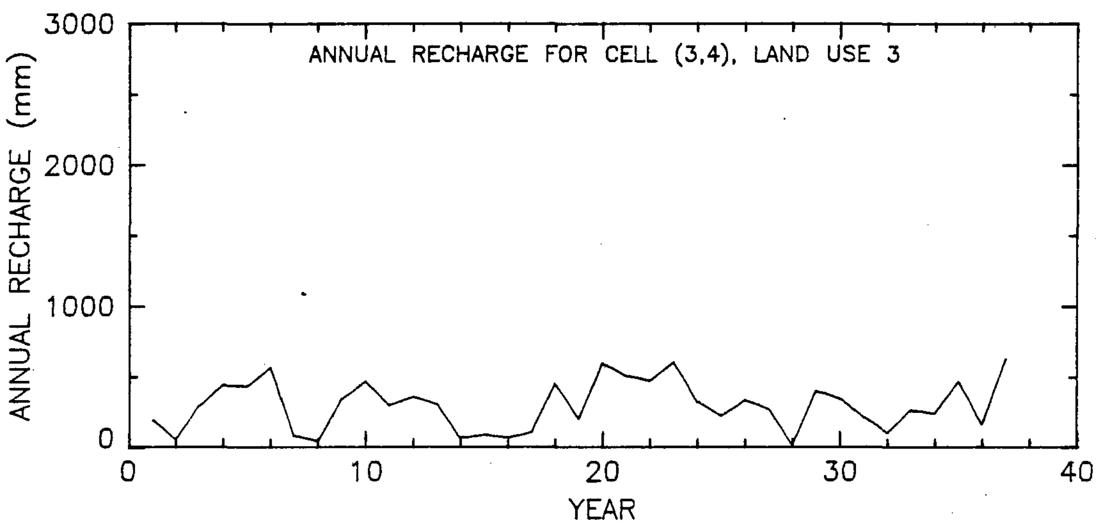


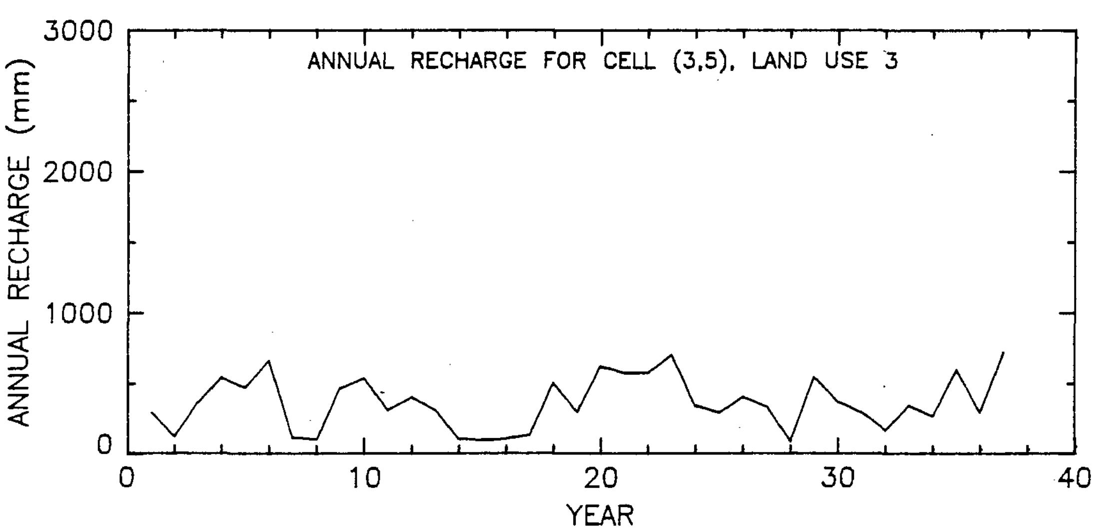




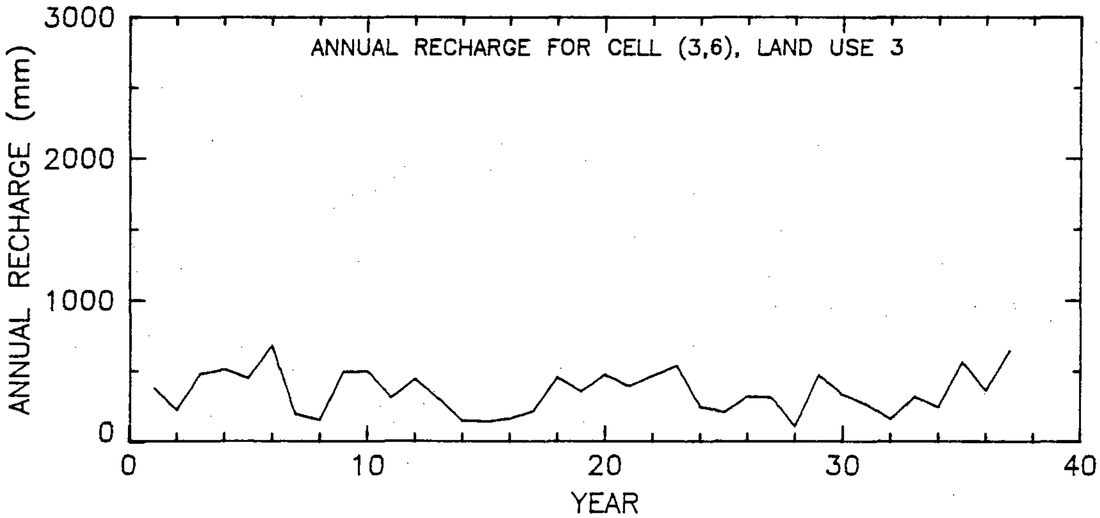
Appendix Figure C.16. Annual recharge time series for golf course (land use 2) water balance cells

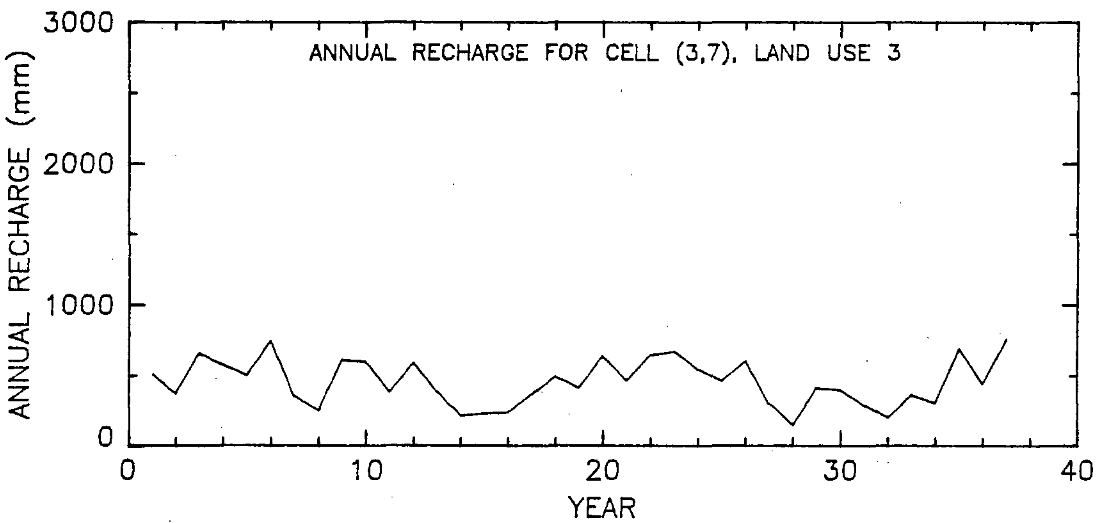


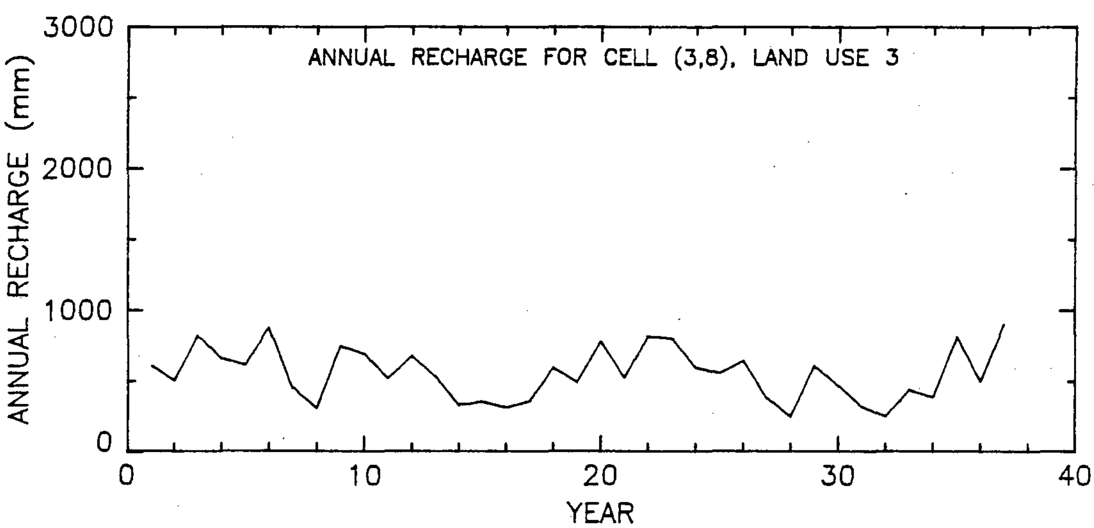




Appendix Figure C.17. Annual recharge time series for open/vacant (land use 3) water balance cells







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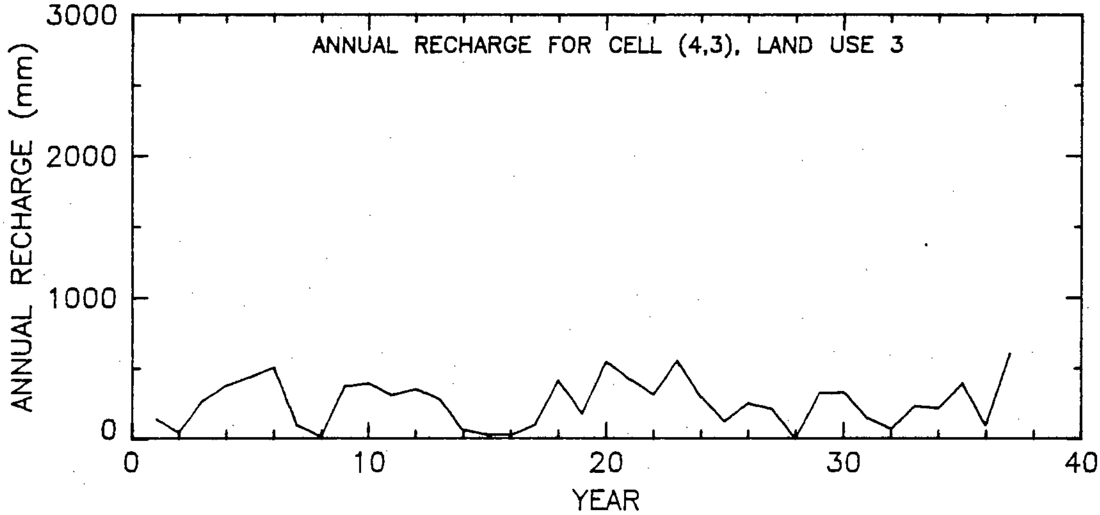

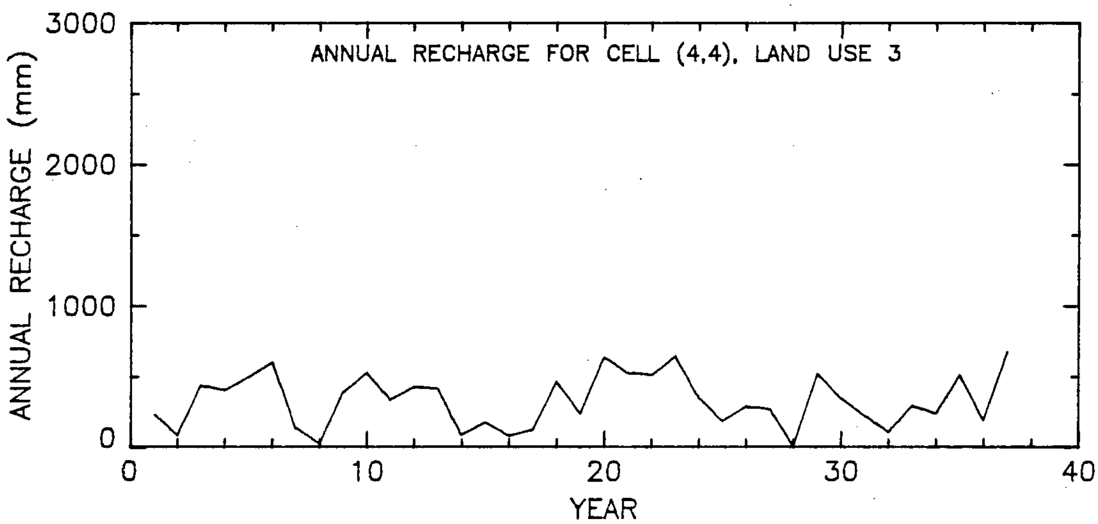

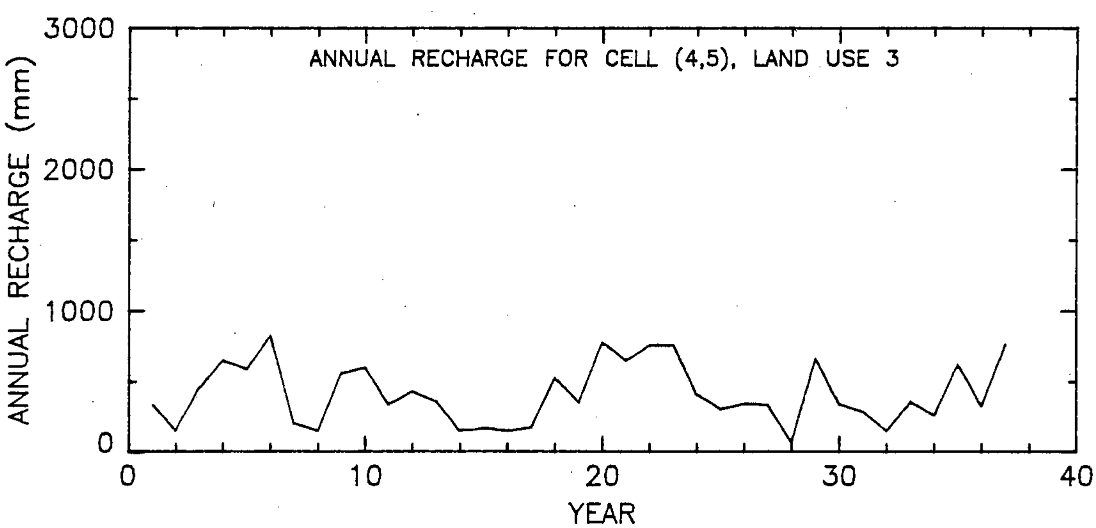

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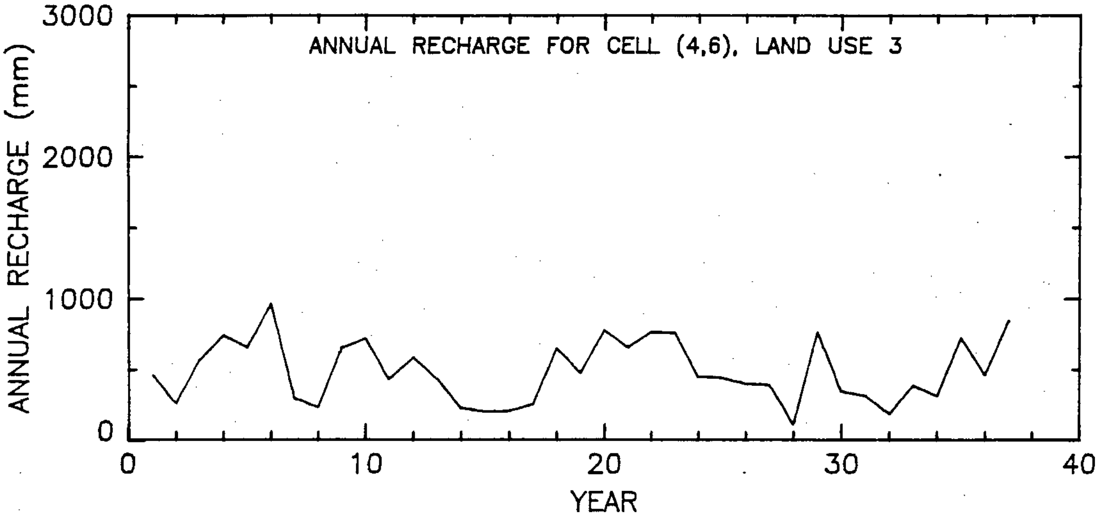

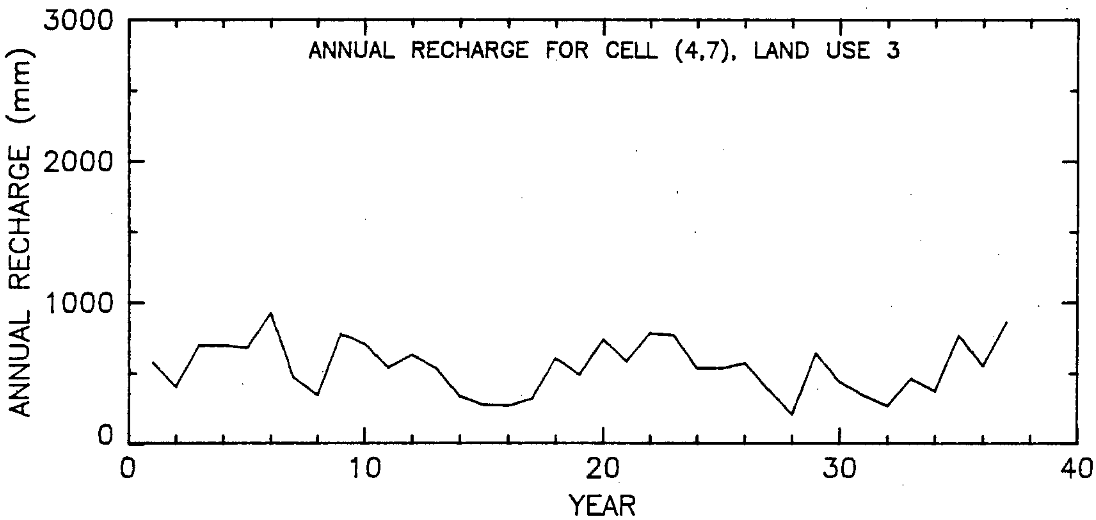

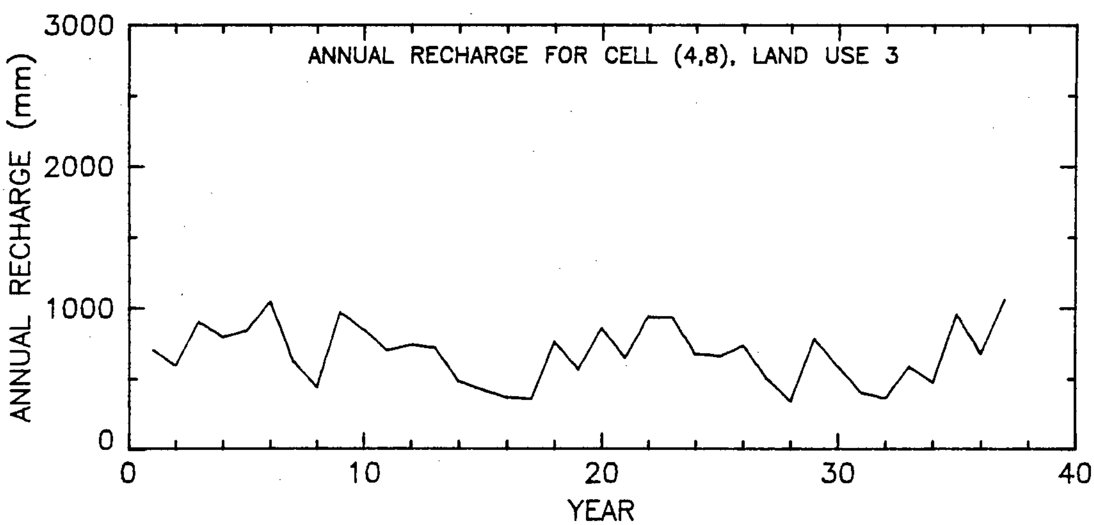

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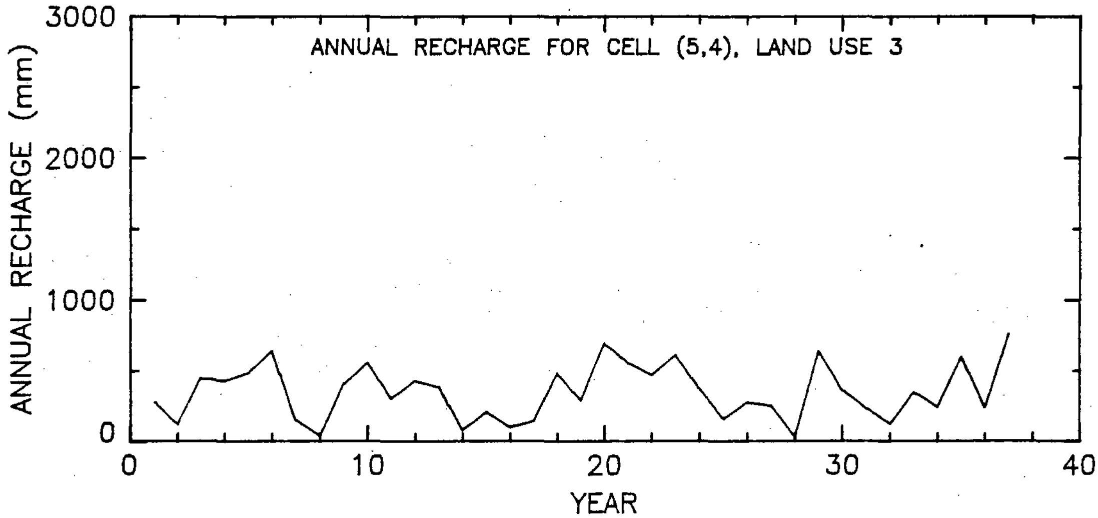

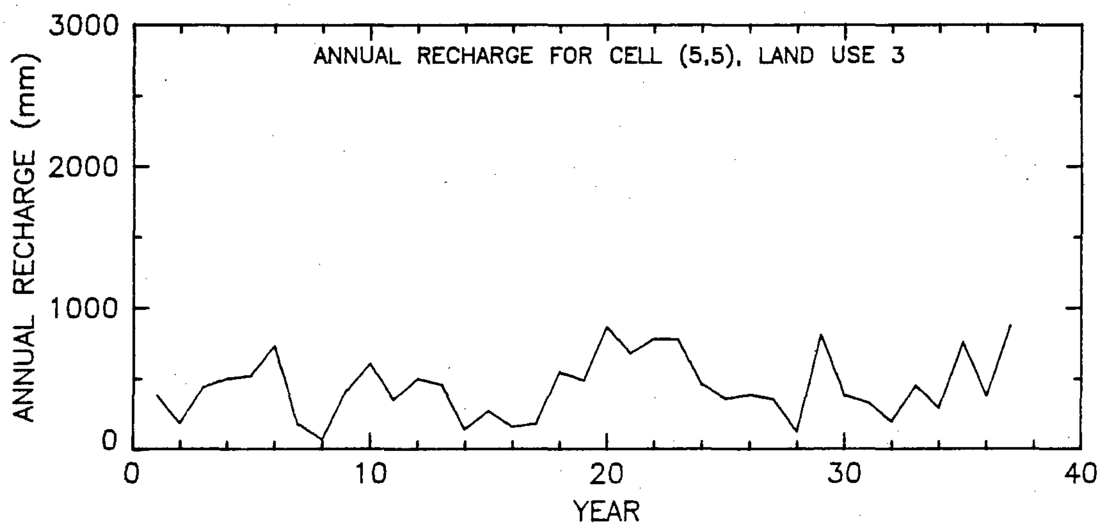

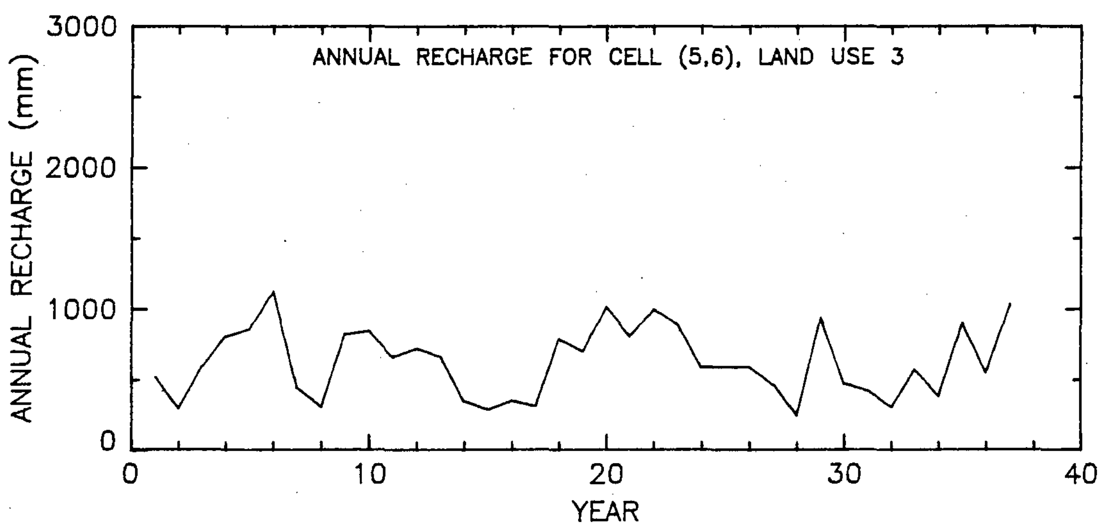

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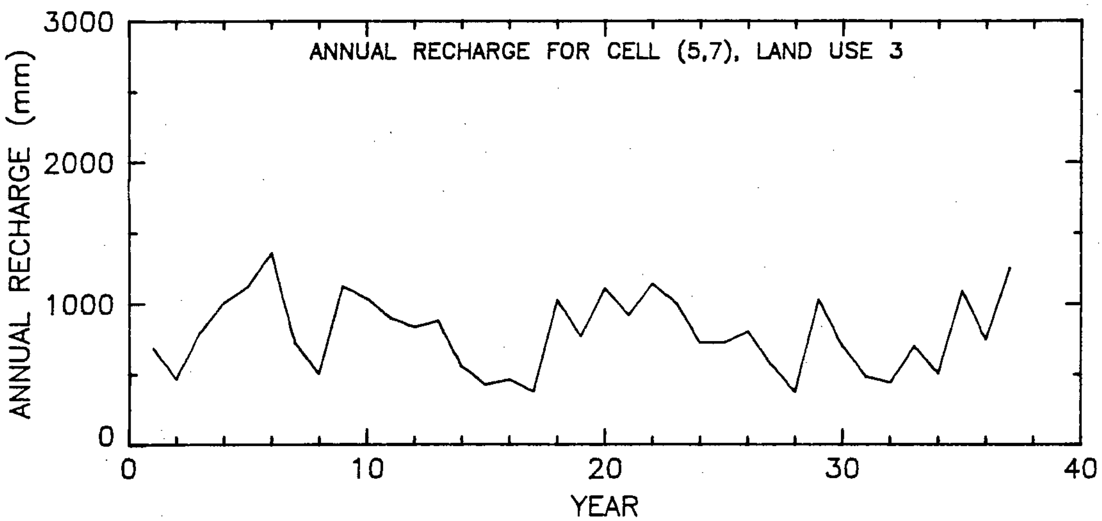

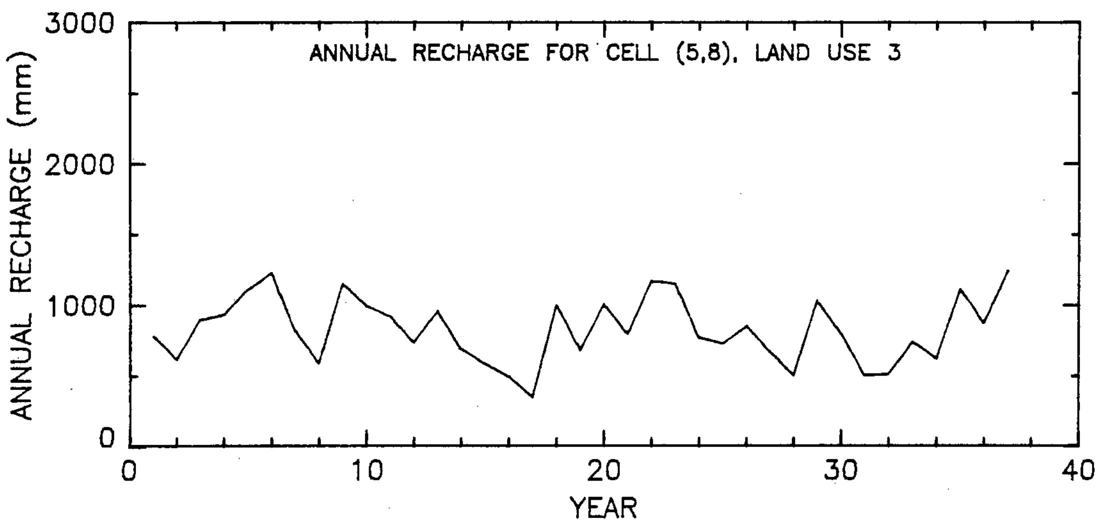

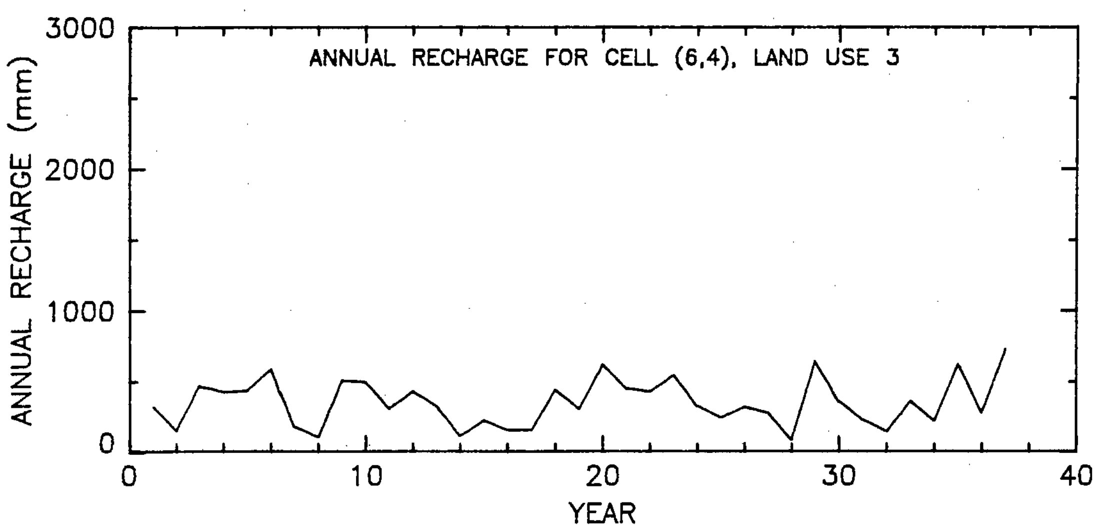

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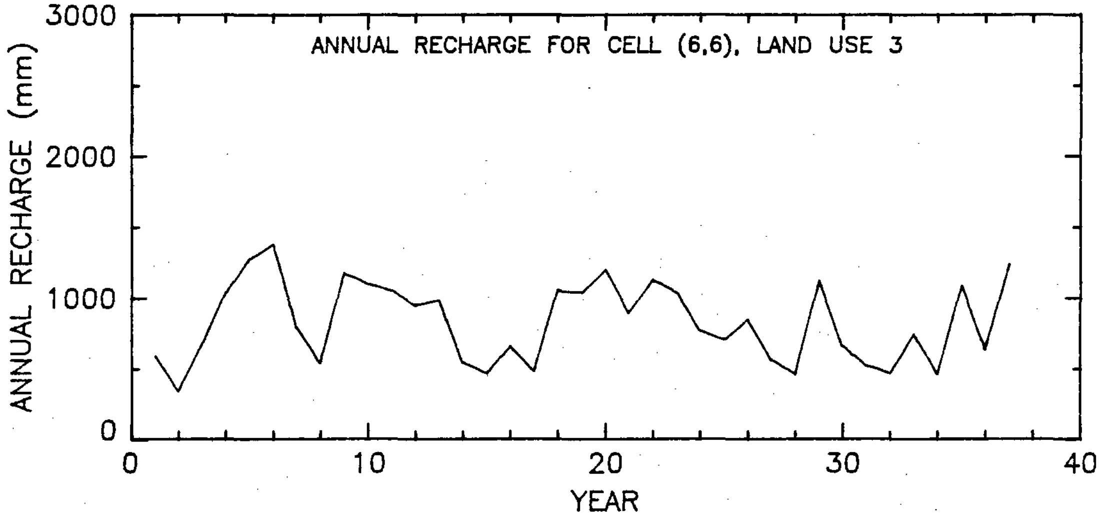
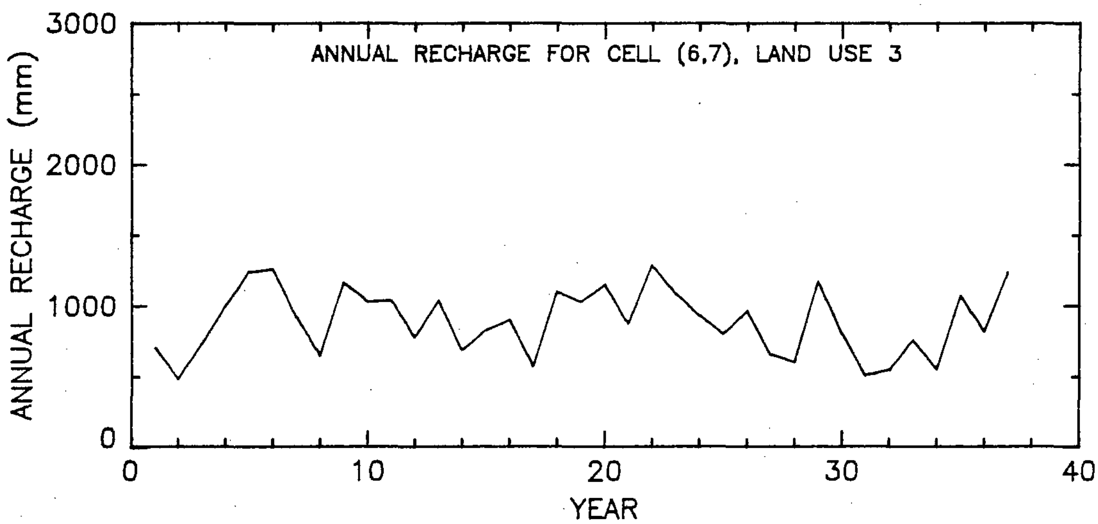
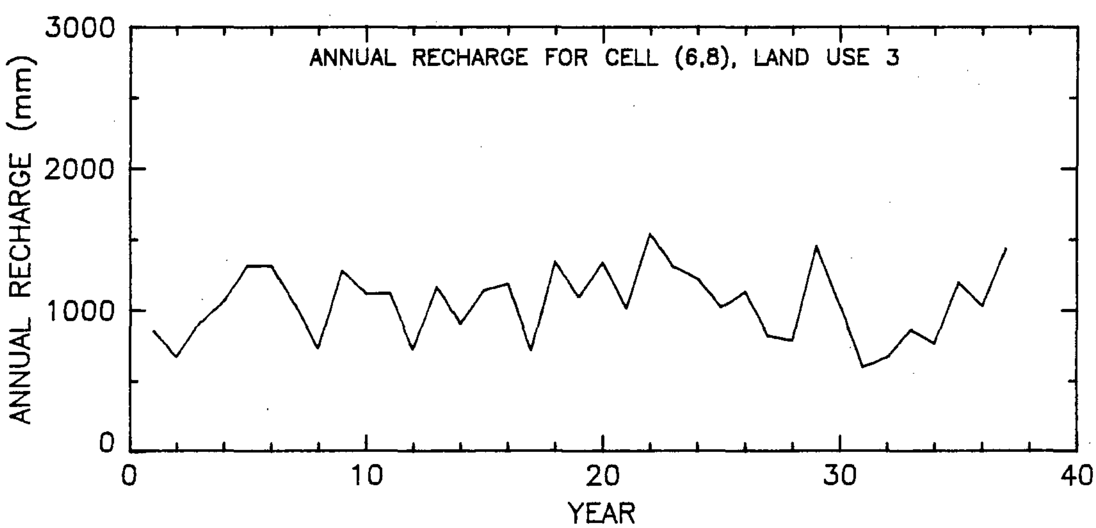
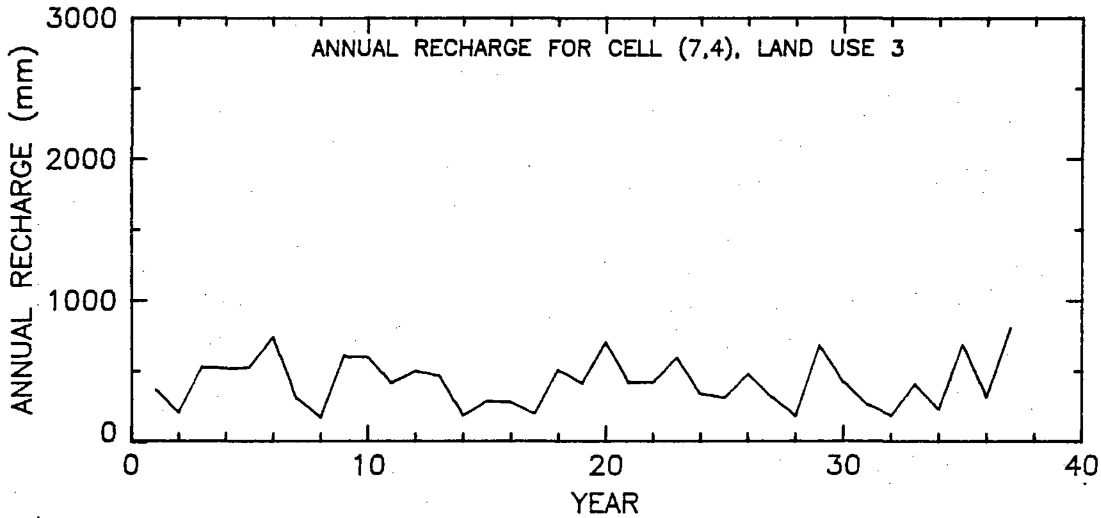
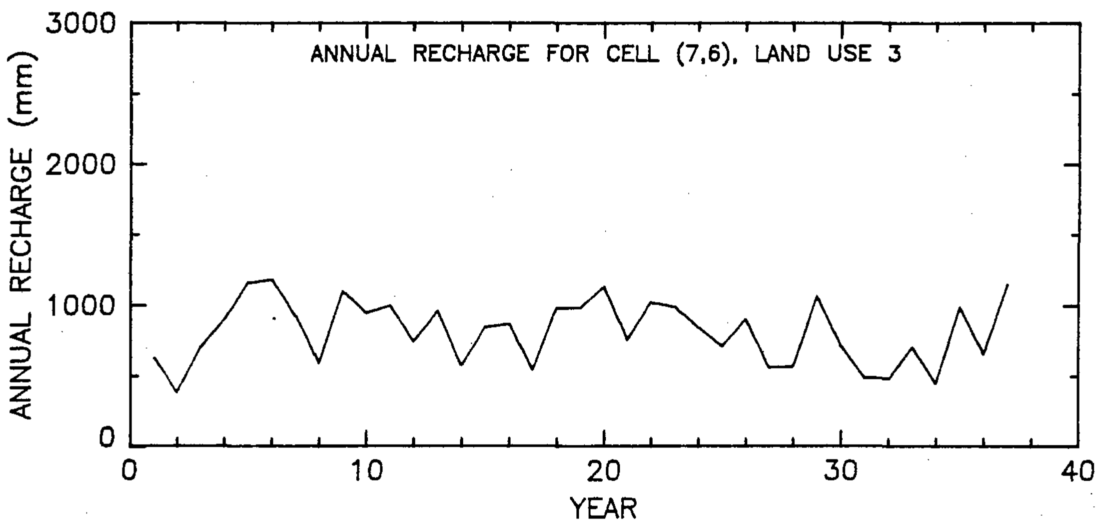


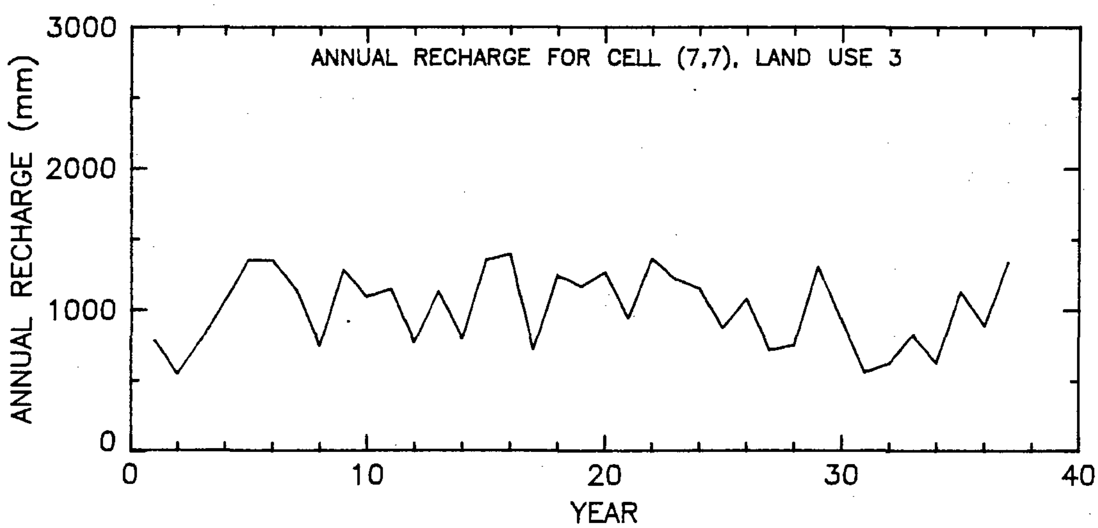




Appendix Figure C.17--Continued







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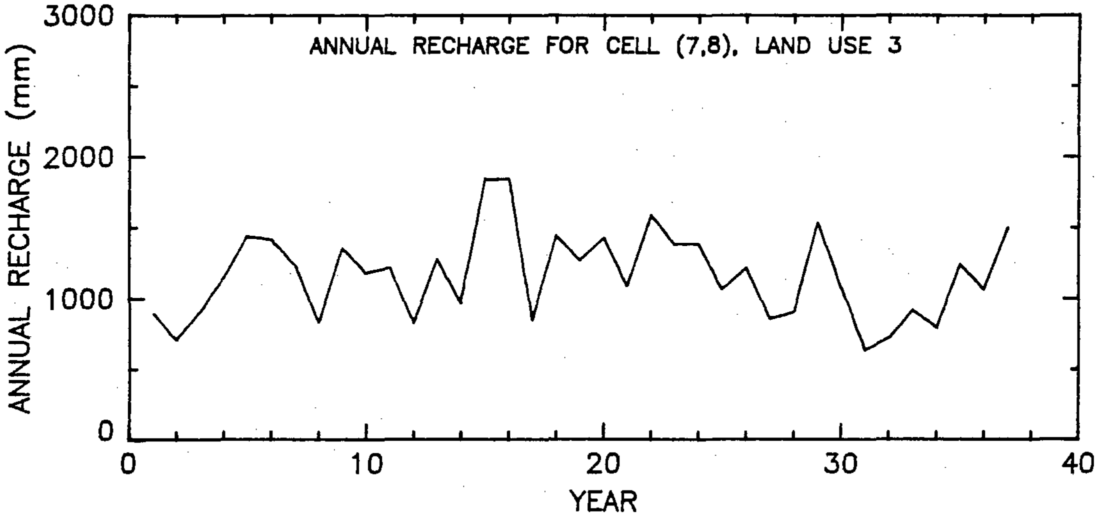
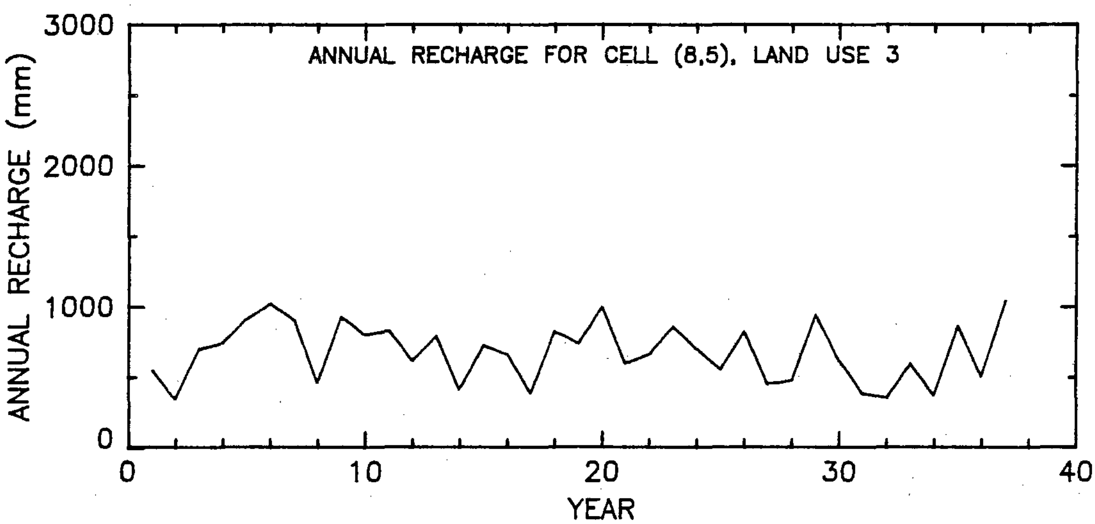
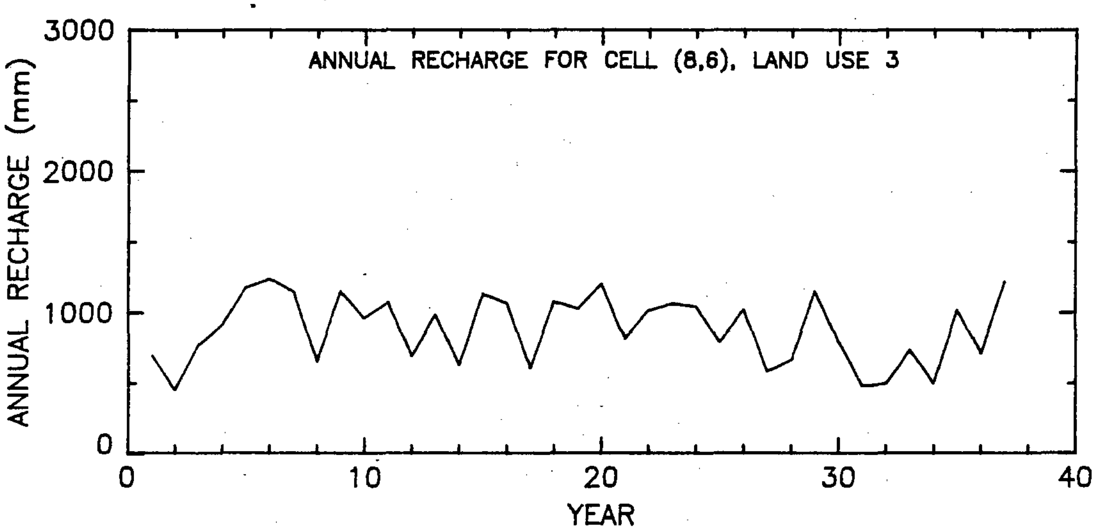
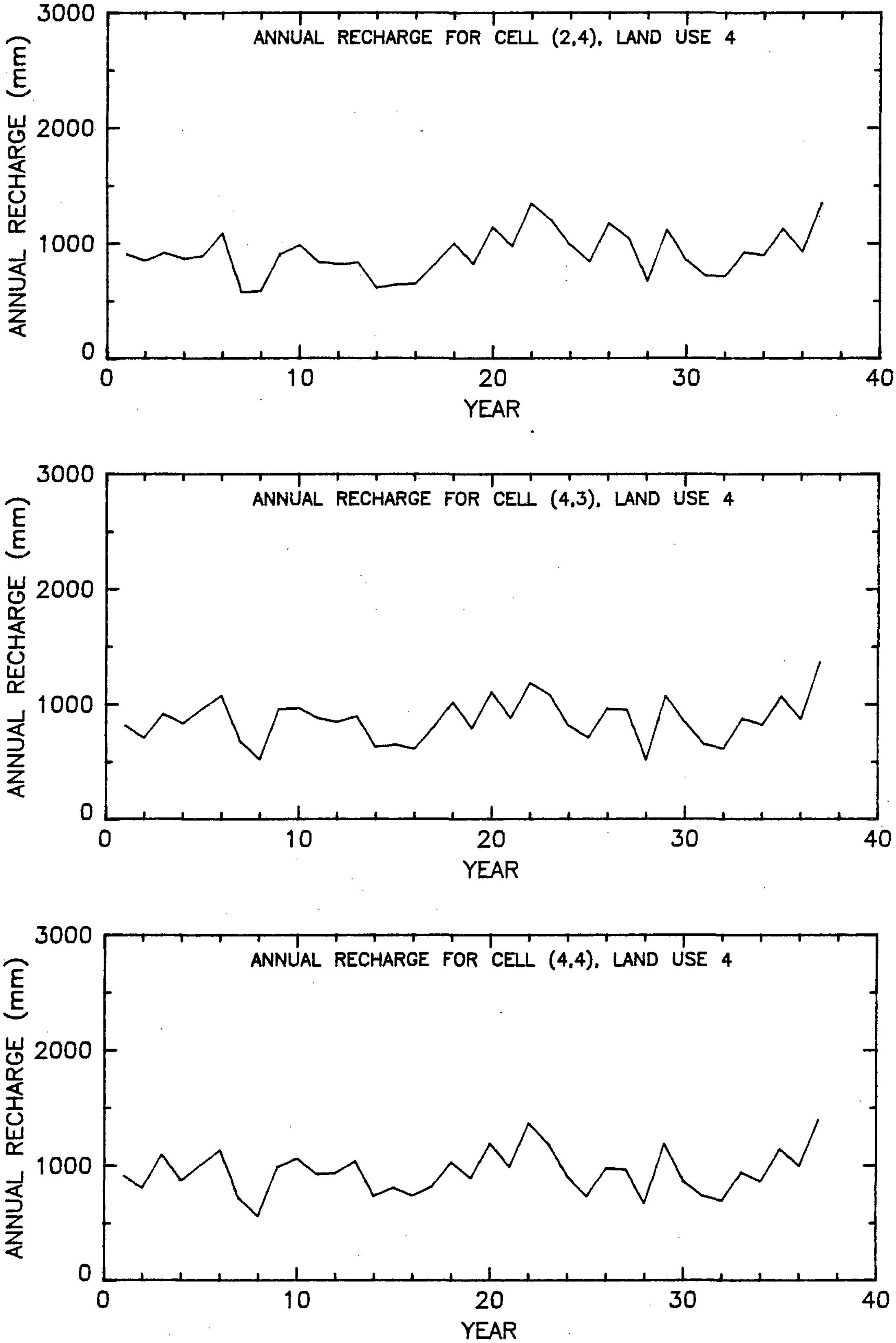


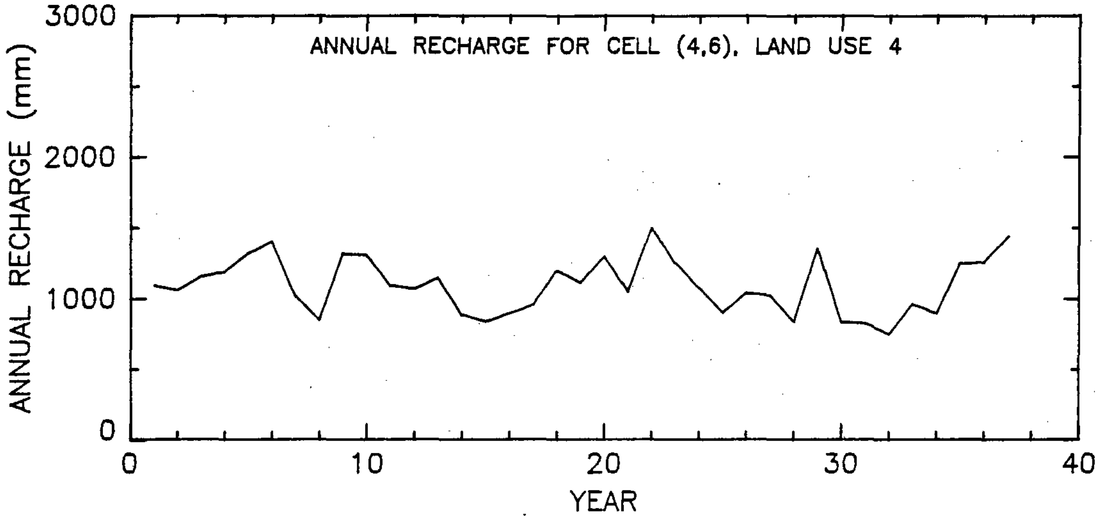


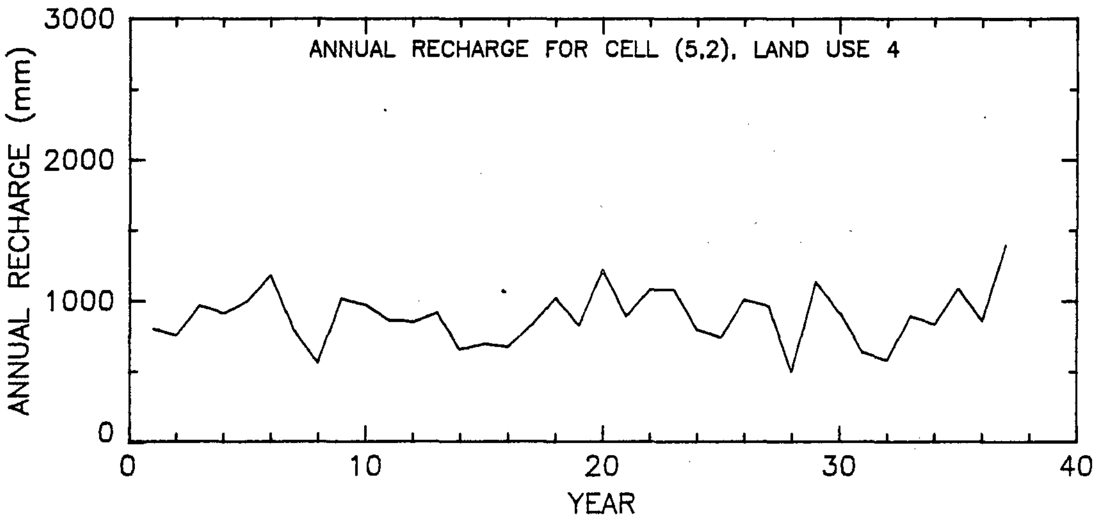


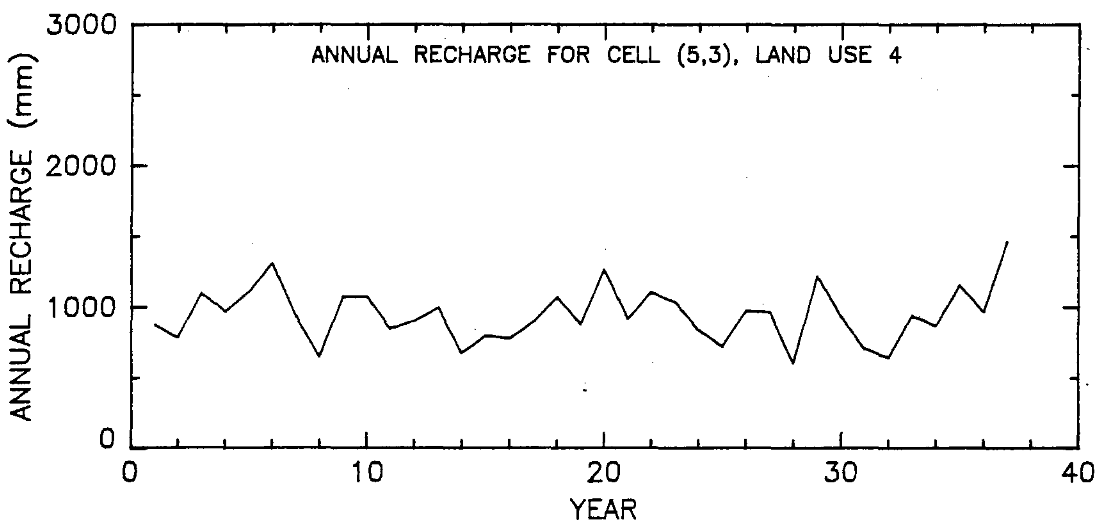
Appendix Figure C.17--Continued



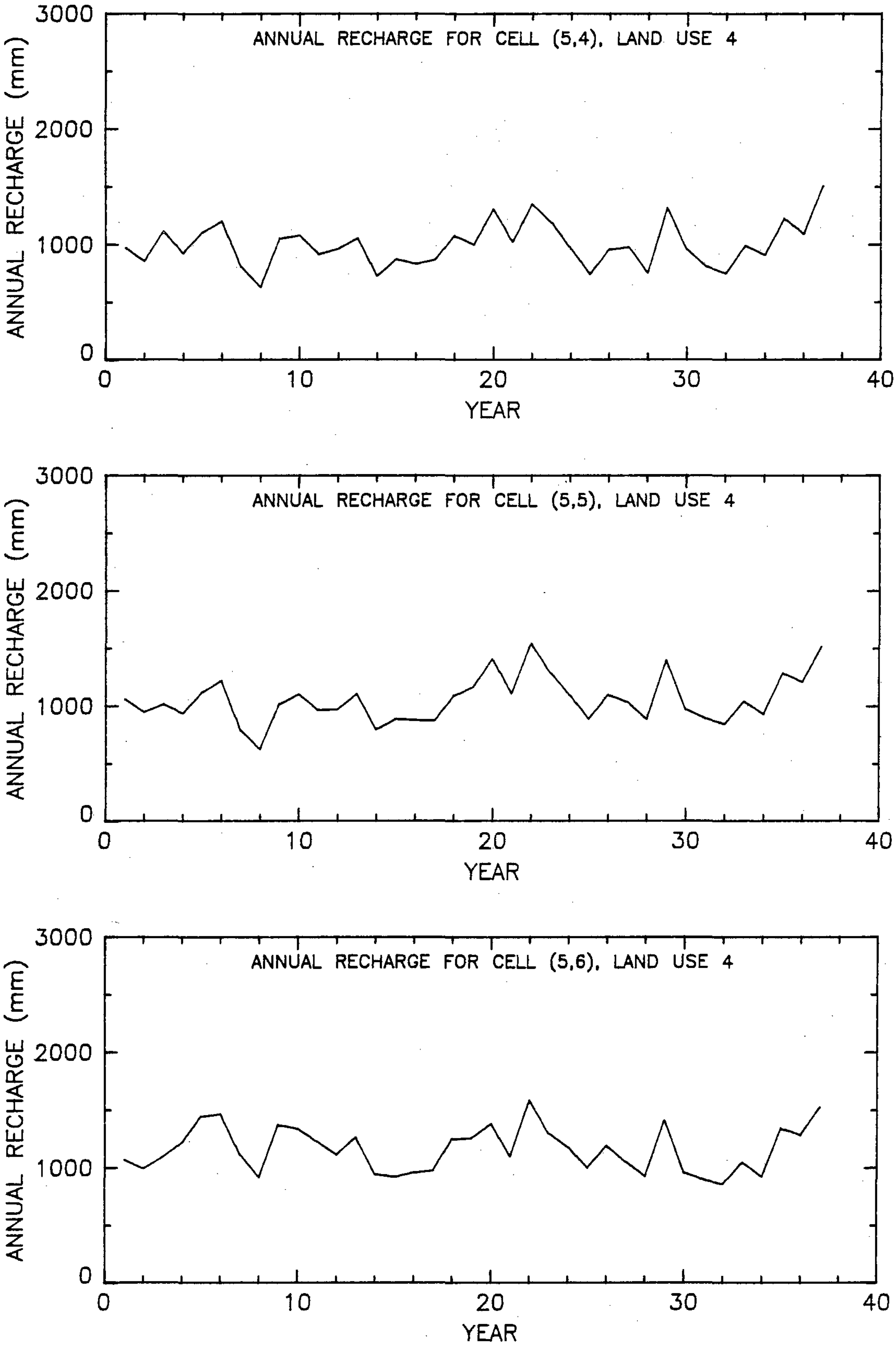
Appendix Figure C.18. Annual recharge time series for residential (land use 4) water balance cells



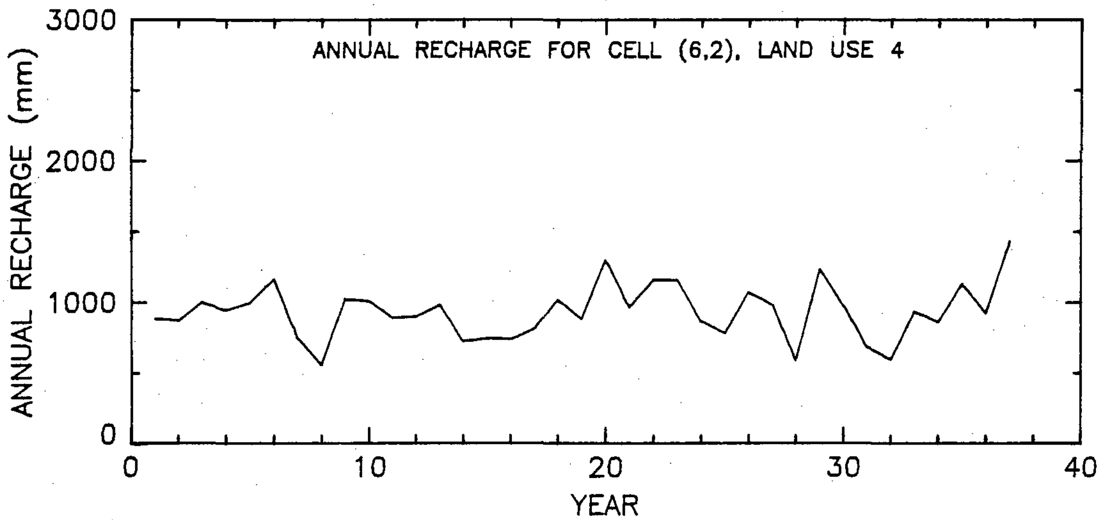


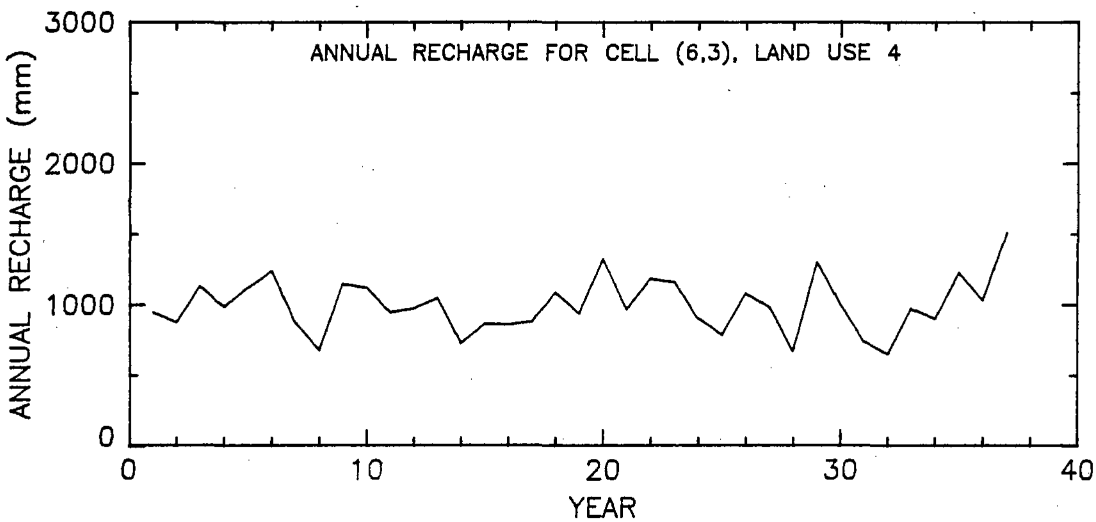


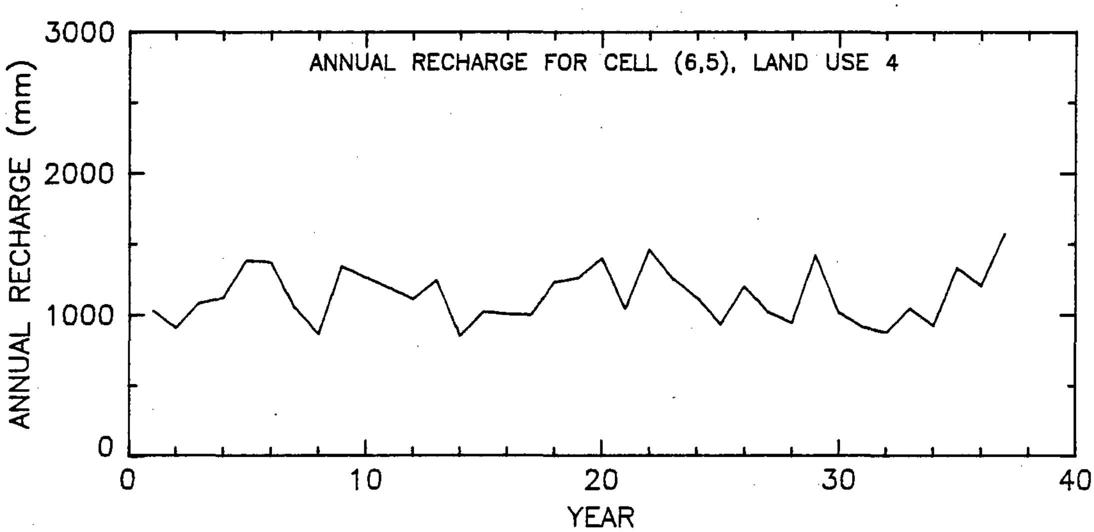
Appendix Figure C.18--Continued



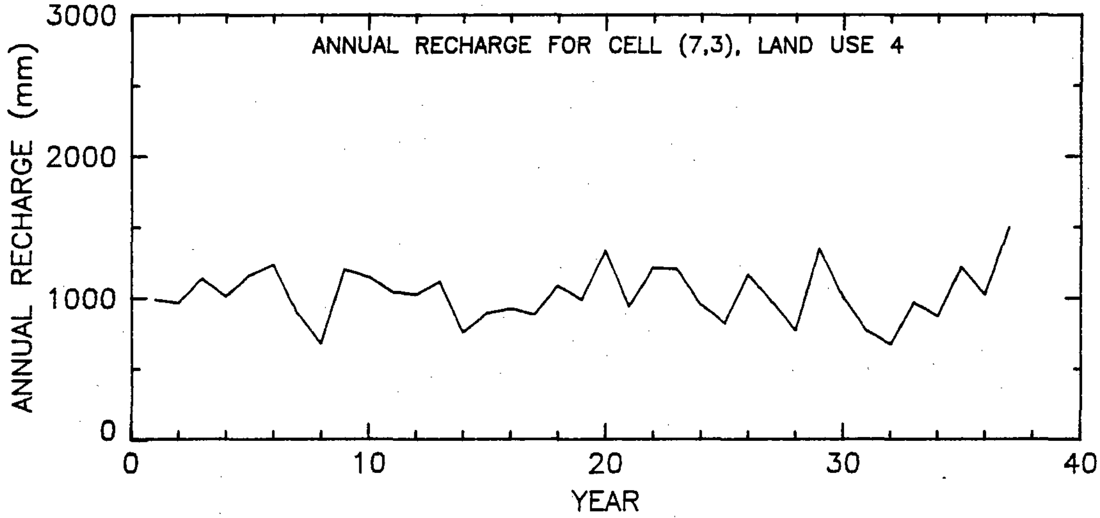
Appendix Figure C.18--Continued

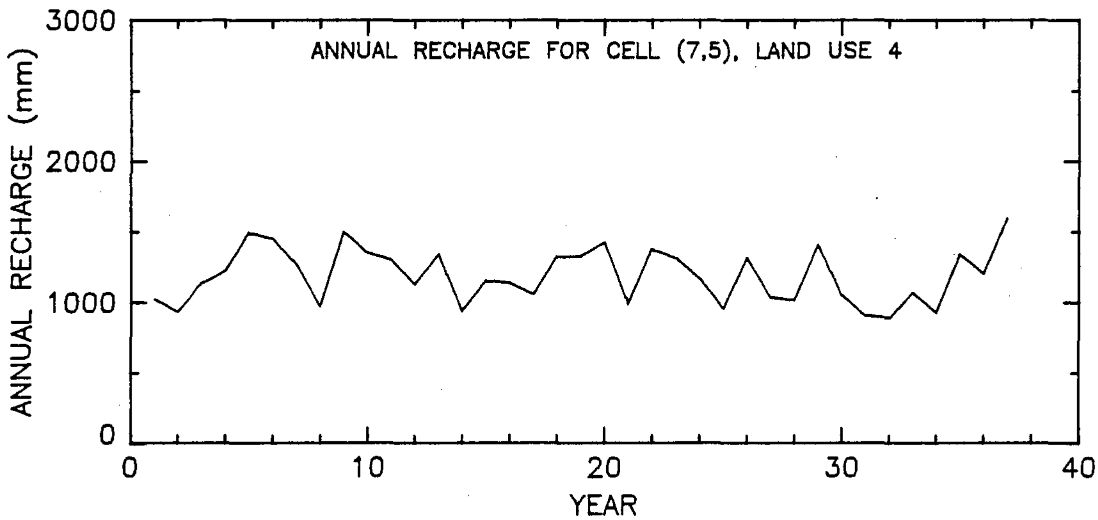




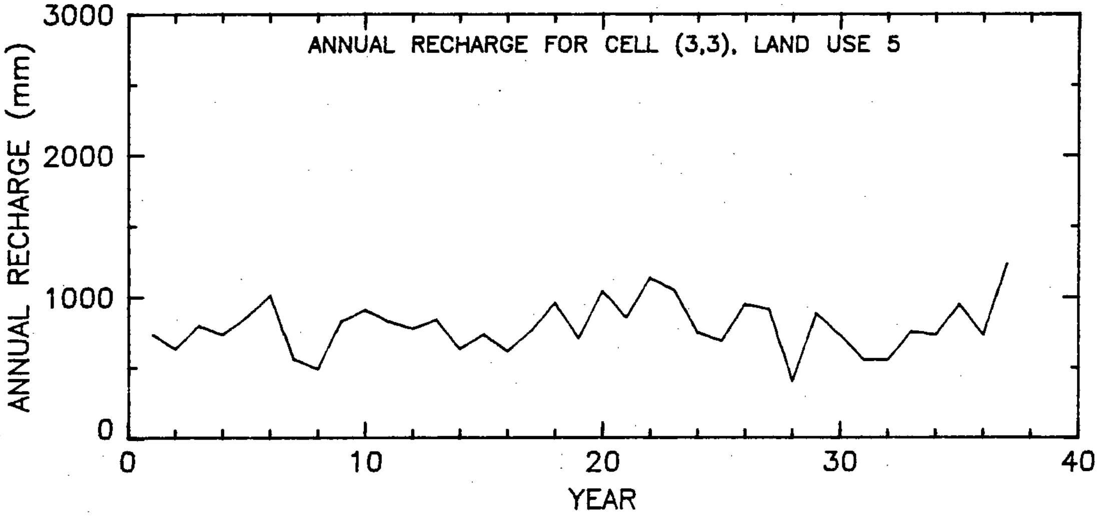


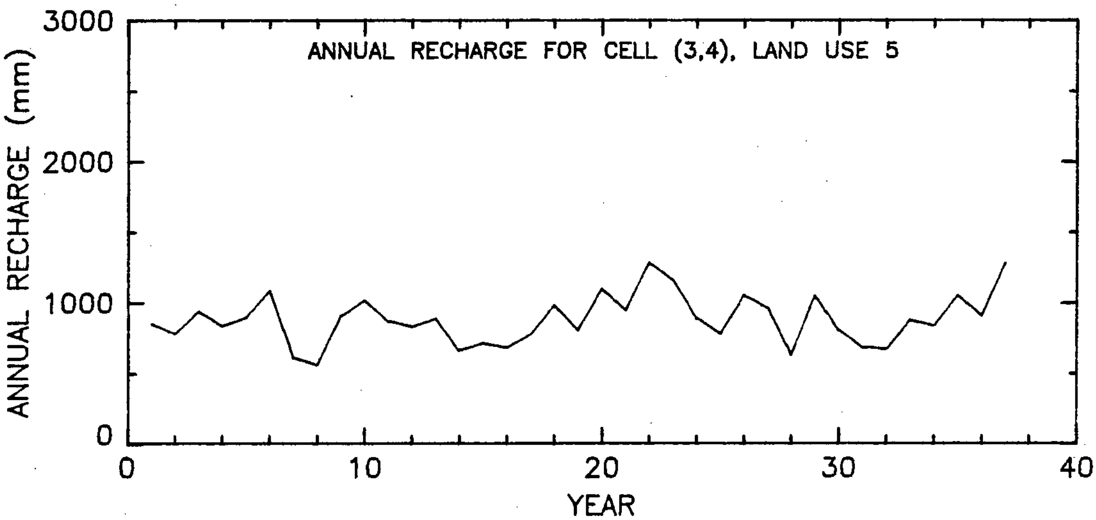
Appendix Figure C.18--Continued



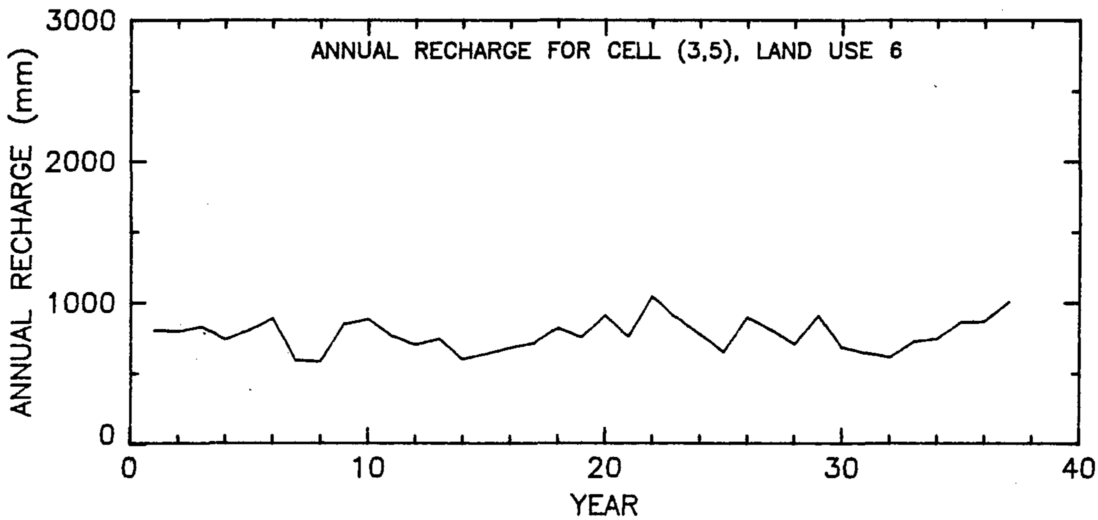


Appendix Figure C.18--Continued





Appendix Figure C.19. Annual recharge time series for apartment (land use 5) water balance cells



Appendix Figure C.20. Annual recharge time series for commercial/industrial (land use 6) water balance cells

APPENDIX D. PESTICIDE ROOT ZONE MODEL

DESCRIPTION OF PRZM

General. PRZM (acronym for Pesticide Root Zone Model) was developed by the U.S. Environmental Protection Agency to predict near surface pesticide movement to evaluate the potential for groundwater contamination. PRZM is a one-dimensional, deterministic-empirical, field-scale solute transport model which simulates soil water movement with an empirical drainage algorithm and chemical transport with the advection-dispersion equation.

The hydrologic component simulates runoff, erosion, evapotranspiration, and soil water movement. The chemical transport component simulates the effects of runoff, erosion, foliar loss (washoff), plant uptake, decay, sorption, advection, and dispersion. The PRZM structure can be represented by the compartmental soil profile shown in Appendix Figure D.1. A comprehensive description of PRZM is found in the user's manual by Carsel et al. (1984). A summary of the parameters and variables used for PRZM simulations is shown in Appendix Table D.1.

Hydrology. The water balance equation solved by PRZM is expressed as

$$\theta_c = \theta_0 + R_f - I + I_a - R_o - E_v - T \qquad \text{(D.1)}$$

where, θ_c = current θ, θ = soil-water content

θ_0 = initial θ

R_f = rainfall + irrigation + snowmelt

I = percolation out of layer

I_a = percolation in from layer above

R_o = surface runoff

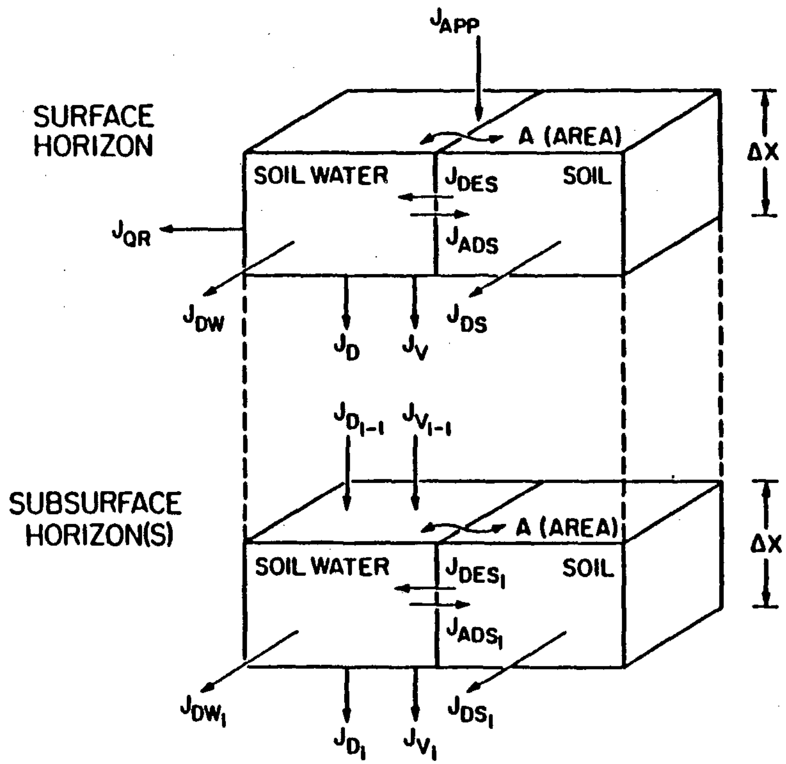
E_v = evaporation

T = transpiration

with the following conditions:

I_a and T = 0 at the surface

R_f, E_v, and R_o = 0 below the surface



ΔX = COMPARTMENT SIZE

J_{ADS} = ADSORPTION

J_{APP} = APPLICATION

J_D = DISPERSION

J_{DES} = DESORPTION

J_{DS} = DECAY-SOIL

J_{DW} = DECAY-WATER

J_{QR} = RUNOFF

J_V = ADVECTION

1. Mass flow due to advection and dispersion-diffusion, $J_{D,V}$ and J_{D_I,V_I}

    $J_{D,V}$ = Flow across upper boundary of compartment

    J_{D_I,V_I} = Flux across lower boundary of compartment

    Assume: Dispersive-diffusive term is constant

2. Reversible Sorption, J_{ADS}, J_{DES} and J_{ADS_I}, J_{DES_I}

    J_{ADS} = Adsorption of chemical to soil

    J_{DES} = Desorption of chemical from soil

    Assume: Equilibrium between phases is reached instantaneously

3. Chemical Decomposition, J_{DW}, J_{DS} and J_{DW_I}, J_{DS_I}

    J_{DW} = Decay in the soil water phase

    J_{DS} = Decay in the soil phase

    Assume: One first order decomposition rate represents the sum of all processes in both soil water and soil phases

Appendix Figure D.1. PRZM's structure, compartmental model (Loague et al. 1989c, after Carsel et al. 1984)

APPENDIX TABLE D.1. SUMMARY OF PRZM INPUT PARAMETERS AND VARIABLES

PARAMETER/VARIABLE (units)	PARAMETER/VARIABLE (units)
HYDROLOGY	CROP
daily rainfall (mm)	max. areal coverage (m^2/m^2)
daily pan evaporation (mm)	max.intercept. storage (m)
pan factor (*)	max. root depth (m)
runoff curve numbers (*)	cropping dates (M-D-Y)
PESTICIDES	SOIL
application date (M-D-Y)	organic carbon (kg/kg)
application rate (kg/ha)	hydrodynamic dispersion (m^2/day)
incorporation depth (m)	bulk density (kg/m^3)
degradation rate (day^{-1})	water content (m^3/m^3)
distribution coef. (m^3/kg)	@ wilting point
	@ initial conditions
	@ field capacity

*Dimensionless

T = 0 below the root zone

percolation occurs when $\theta > \theta_{fc}$

evapotranspiration occurs when $\theta > \theta_{wp}$

where θ_{fc} is field capacity and θ_{wp} is the wilting point.

PRZM has two different drainage algorithms which govern soil-water movement. The first assumes a freely draining soil which will drain all water in excess of the field capacity within one day. The second option, for poorly permeable soils, requires the input of an empirical drainage parameter. The velocity of water movement, v, is calculated by dividing the amount of percolating water by the soil-water content, θ , and then averaging over the time step of one day.

PRZM calculates surface runoff according to the SCS curve number method (U.S. Department of Agriculture 1972) which incorporates the effects of soil type, land use, and management practices. Evapotranspiration is estimated by PRZM from pan evaporation data or air temperatures, and crop information.

Chemical transport. The simplified chemical mass balance equation solved by PRZM may be expressed as

$$\frac{\partial[C(\theta + \rho K_d)]}{\partial t} = D\frac{\partial^2(C\theta)}{\partial z^2} - \frac{\partial(C\theta v)}{\partial z} \tag{D.2}$$

$$+ A - P_i + P_w - C[k(\theta + \rho K_d) + P_u + R_o + E_r]$$

where, C = dissolved concentration of solute
θ = volumetric soil-water content
K_d = sorption partition coefficient
ρ = soil bulk density
t = time
D = diffusion-dispersion coefficient
z = depth
v = velocity of water movement
A = applied solute
P_i = plant interception
P_w = plant washoff
k = solute transformation rate
P_u = plant uptake
R_o = surface runoff
E_r = erosion.

The assumptions of a reversible and instantaneous equilibrium condition and a linear relation of the form,

$$C_s = K_d C \tag{D.3}$$

where C_s is the sorbed concentration, allows (D.2) to be expressed solely in terms of C, the solution concentration.

The pesticide transformation rate, k, is assumed to be a first-order constant which collectively represents the effects of biological, photochemical, and chemical degradation. It is assumed to apply to both the sorbed and dissolved phases. The diffusion-dispersion coefficient, D, is assumed to be constant and to include the effects of both diffusion and mechanical dispersion.

The amount of applied pesticide, A, is partitioned between the soil surface and the plant canopy. Solute intercepted by the plant canopy, P_i, is allowed to be washed off, P_w, to the soil surface by R_f. Plant uptake of the solute, P_u, is assumed to be directly related to the transpiration rate.

APPENDIX TABLE D.2. MODELING ASSUMPTIONS USING PRZM

Transport
advection-dispersion equation applies
no preferential flow
one-dimensional flow
daily timestep
drainage algorithm based on θ_{fc}
D is constant
Transformation
first-order decay rates
constant decay rates
$k_{sorbed} = k_{dissolved}$
no volatilization
Retention
linear sorption isotherms
linear relationship between K_d and f_{oc}
constant K_d
singularity of sorption-desorption
instantaneous equilibrium (daily timestep)

The erosion of surface sediments along with its sorbed solute, E_r, is calculated by the Modified Universal Soil Loss Equation (MUSLE) which incorporates surface runoff and other estimated factors relating to the slope, land use, and soil erodibility and cover (described by Williams and Berndt 1977).

Assuming low solute concentrations such that flow is not influenced by concentration gradients, the dispersion and advection terms (i.e., D and v) are assumed to be independent of each other, as shown in (D.2). This allows the solution of v and θ by (D.1) followed by the solution of (D.2) by an implicit finite difference scheme which employs the Thomas algorithm. Appendix Table D.2 summarizes the assumptions made in the modeling effort.

PRIOR USE OF PRZM

PRZM outside of Hawaii. Performance tests in Florida, Georgia, New York, and Wisconsin have shown that PRZM is useful in assessing the threat to groundwater from pesticides (Carsel et al. 1984). PRZM was successfully calibrated with observed data through a depth of 2.5 m for the insecticide aldicarb at a site in New York (Carsel et al. 1985). Hedden (1986) reports on the PRZM calibration with aldicarb and the herbicide metolachlor as used on a peanut crop in Georgia. Lorber and Offutt (1986) describe the calibration of PRZM with aldicarb data from tobacco grown in North Carolina and potatoes in Wisconsin. They suggest modifying PRZM's decay rate, k, to make it a function of temperature or time.

Carsel et al. (1988a) used PRZM in a Monte-Carlo simulation procedure to assess the leaching potential of aldicarb applied to corn grown in Ohio. PRZM has also been linked to a groundwater solute transport model to assess leaching of aldicarb applied to peanuts in North Carolina and its movement in groundwater (Carsel et al. 1988b).

Long-term PRZM simulations were used by Dean, Jowise, and Donigan (1984) to develop the Leaching Evaluation of Agricultural Chemicals (LEACH) methodology. They performed sensitivity analyses with PRZM and observed that pesticide properties and climatic factors are more important than soil properties in determining the losses of pesticides by leaching. They also noted that the sorption partition coefficient, K_{oc}, is the most important parameter affecting pesticide mobility.

Villeneuve et al. (1988) performed sensitivity analyses of PRZM with respect to the sorption partition coefficient, K_d, and the decay rate, k, for aldicarb. Their results show that these two parameters are very sensitive, and therefore they emphasize the need for accurate field data to obtain reliable predictions with PRZM.

<u>PRZM in Hawaii</u>. Khan and Green (1988) found that PRZM performed reasonably well in simulating the general shape and peak location of actual DBCP concentration profiles from two pineapple fields on the island of Maui. PRZM did not accurately simulate the DBCP concentrations with depth, but this was at least partly attributed to three factors: (1) PRZM was not calibrated, (2) volatilization was not considered, and (3) the estimated water balance data input to PRZM were crude.

Loague et al. (1989c,d) also used PRZM in an uncalibrated mode to simulate EDB, DBCP, and TCP leaching at two pineapple fields in central Oahu. They simulated volatilization by incorporating a separate model developed by Green, Liu, and Tamrakar (1986). PRZM failed to simulate the shape of EDB concentration profiles but was fairly successful with the depth and time for peak concentrations (Loague et al. 1989c). In general, PRZM performed reasonably well in predicting the deep leaching (up to 20 m) of these three pesticides. Loague et al. (1989c) suggest that with modification, extension, and further testing, PRZM may be a useful tool for making pesticide leaching assessments in Hawaii.

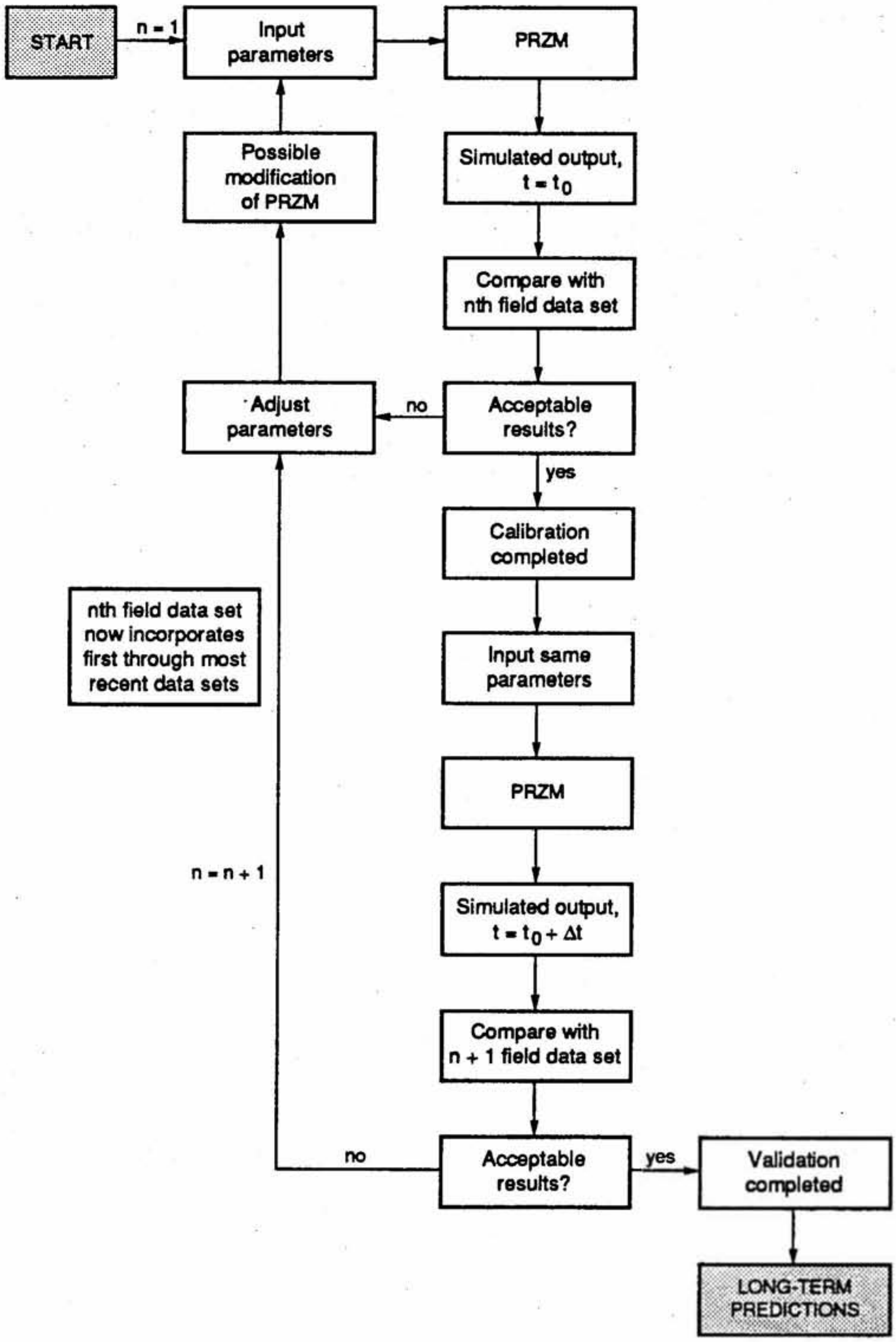
Loague and Green (1989b) added to the results of Loague et al. (1989c,d) with a series of 75 PRZM calibration simulations for the deep EDB profiles. Their results show that the parameters which yielded the best model calibration with the first observed data set (1983) gave poor model validation with the second set (1985). Unfortunately, this has been the only attempt at calibrating and validating PRZM with deep profiles in Hawaii. Thus, the use of PRZM for predictive purposes through the typically deep unsaturated profiles of Hawaii must be done with caution.

PRZM EVALUATION

The modeling strategy for the unsaturated zone is outlined in Appendix Figure D.2. Before long-term predictions were made with PRZM, the model was evaluated with field observations. Field data were obtained from experiments, described in Appendix A, which were conducted in Waiawa Valley and at Poamoho. The ideal goal of evaluating any model is to calibrate and validate it with the use of at least two sets of field data from each evaluation site.

The calibration process involves the adjustment of selected model parameters within their accepted ranges until the simulated results adequately describe the field data for a given time. Once the calibration is completed, another simulation for a different time is compared with a second, independent set of field data. If the second simulation adequately describes the second data set without further adjustment to the calibrated parameters, then the model is validated. If not, then the calibration process must be repeated with further adjustments before another attempt at validation is made. The validation process provides an independent check of model simulations versus field observations.

Donigian (1983) summarizes the model validation process and describes the need for calibration of empirical models to account for the various factors which are not sufficiently described by the model. These factors



Appendix Figure D.2. PRZM calibration/validation strategy may include the effects of: spatial variation on parameter values; unrepresented, unquantifiable, or unknown functional relationships of parameters; errors associated with the extrapolation of lab measured parameters to actual field conditions.

Parameter and variable estimation. Rainfall at the Waiawa plot was recorded digitally on an hourly basis and summed to provide daily values. There were several gaps in the rainfall record due to data logger malfunctions. These gaps were filled using data from a manually read back-up rain gage installed at the plot. When necessary, the back-up data were disaggregated to a daily basis by comparison with data, provided by the U.S. National Weather Service, from a rain gage in the Pacific Palisades area (see App. A). The rainfall record at Poamoho was read manually on a daily basis so there were no data gaps.

Potential evapotranspiration at Waiawa was estimated by the Priestly-Taylor equation (Priestley and Taylor 1972) using net radiation data recorded at the plot. Data gaps in the net radiation were either interpolated or filled with monthly average values.

Data from a Class A pan evaporimeter and a pan factor of 0.33 (Ekern 1966a) were used to estimate potential evapotranspiration at Poamoho. There were 15 days of missing pan data from the months of February, March and April. These gaps were filled in by assuming a pan evaporation rate of 1.78 m/yr (from Ekern and Chang 1985). This annual rate was then disaggregated into monthly rates by using historical data from the two nearest sources. The stations selected have six yrs of continuous data between them (Ekern and Chang 1985). Stations 851.00 and 856.10 are located approximately 2.4 and 4.3 km from the test plot at respective elevations of 87 and 213 m. The two data sets were then normalized and averaged to obtain the monthly variation. Pan evaporation for each month was then equally distributed to each of its days to provide daily values.

The organic carbon content of soils from each plot were determined in the laboratory. Soil bulk densities and field capacities were determined from soil cores and taken from Green et al. (1982). Appendix Table D.3 summarizes the soil and hydrologic data used to evaluate PRZM. Reference values for the chemical properties of chlorpyrifos and fenamiphos were

APPENDIX TABLE D.3. SOIL AND HYDROLOGIC PARAMETERS USED TO EVALUATE PRZM FOR WAIAWA AND POAMOHO PLOTS, OAHU, HAWAII

Depth (m)	ρ_b (kg/m³)	f_{oc} (kg/kg)	θ_{fc} (m³/m³)	D (m²/day)
		WAIAWA PLOT		
0.0 - 0.05	1100	0.040	0.45	0.002
0.05 - 0.1	1100	0.015	0.45	0.002
0.1 - 0.2	1200	0.005	0.45	0.002
0.2 - 0.3	1200	0.004	0.45	0.002
0.3 - 0.5	1250	0.004	0.50	0.002
0.5 - 0.6	1250	0.003	0.50	0.002
0.6 - 0.8	1300	0.003	0.50	0.002
0.8 - 1.0	1350	0.003	0.50	0.002
1.0 - 3.0	1350	0.001	0.50	0.002
		POAMOHO PLOT		
0.0 - 0.1	950	0.017	0.35	0.001
1.0 - 0.2	1050	0.015	0.37	0.001
0.2 - 0.3	1150	0.010	0.37	0.001
0.3 - 0.4	1200	0.010	0.40	0.001
0.4 - 0.5	1200	0.008	0.40	0.001
0.5 - 0.7	1250	0.008	0.40	0.001
0.7 - 2.5	1300	0.005	0.42	0.001

NOTE: ρ_b = bulk density
f_{oc} = mass fraction of organic carbon to dry soil
θ_{fc} = water content at field capacity
D = hydrodynamic dispersion coefficient
θ_{wp} = water content at wilting point = 0.25 m³/m³
pan factor = 1.0 for Waiawa plot since potential evapotranspiration is input
pan factor = 0.33 for Poamoho plot

obtained from laboratory experiments and the literature (chlorpyrifos [Wauchope 1988]; fenamiphos [Lee 1987] and [Lee, Green, and Apt 1986]). The chemical properties used to evaluate PRZM are presented in Appendix Table D.4.

Simulated and observed concentration profiles for bromide, chlorpyrifos, and fenamiphos are shown in Appendix Figures D.3 to D.5, and a summary of the statistical evaluation is presented in Appendix Table D.5.

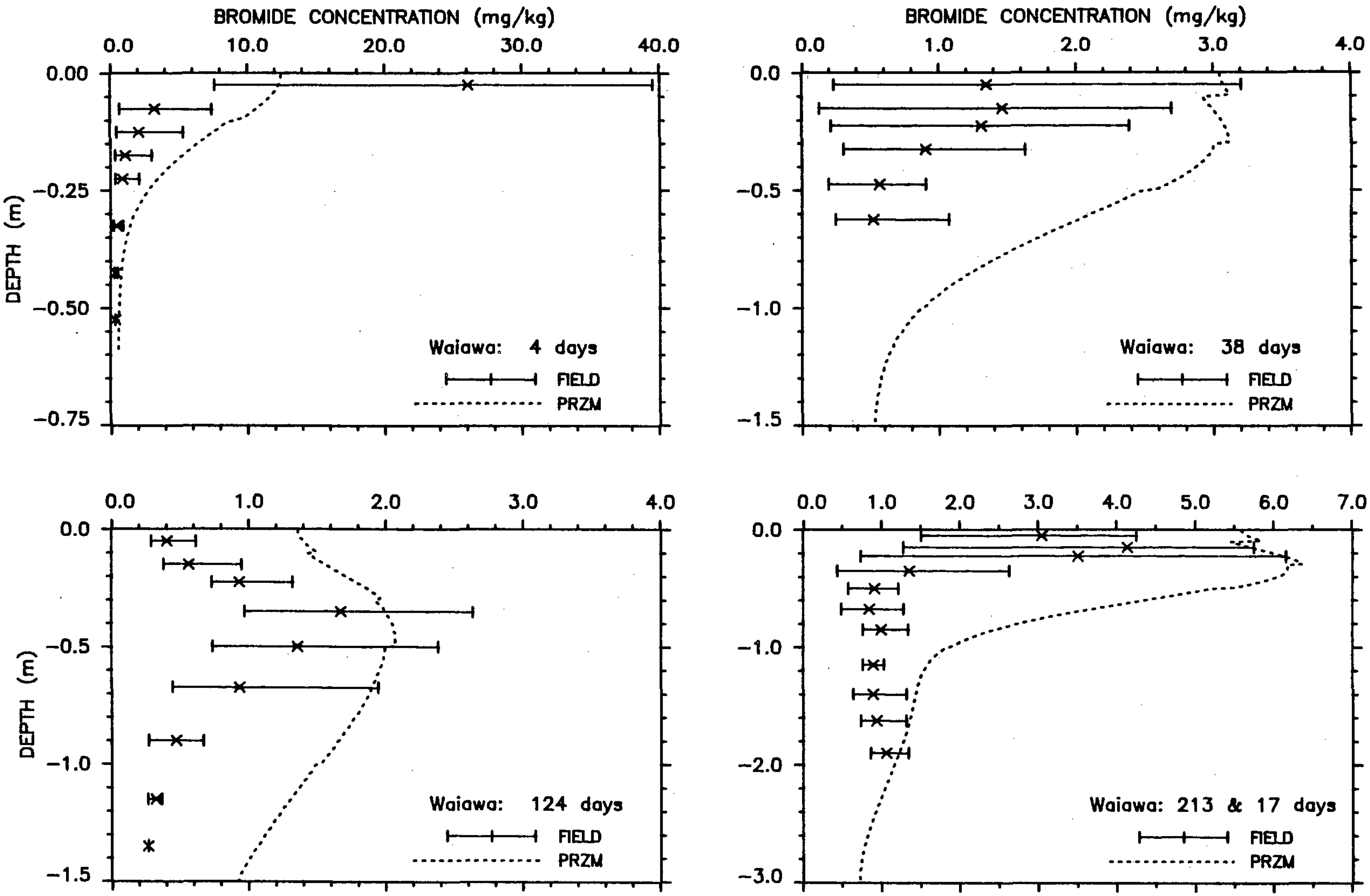
APPENDIX TABLE D.4. CHEMICAL PROPERTIES USED TO EVALUATE PRZM FOR WAIAWA AND POAMOHO PLOTS, OAHU, HAWAII

Depth (m)	BROMIDE		CHLORPYRIFOS		FENAMIPHOS	
	K_{oc} m^3/day	k day^{-1}	K_{oc} m^3/day	k day^{-1}	K_{oc} m^3/day	k day^{-1}
			WAIAWA PLOT			
0.0 - 0.05	0.0	0.0	0.60	0.055	0.20	0.060
0.05 - 0.1	0.0	0.0	0.60	0.050	0.20	0.055
0.1 - 0.6	0.0	0.0	0.60	0.040	0.20	0.050
0.6 - 3.0	0.0	0.0	---	---	---	---
APPLICATION RATE (kg/ha)	22.85 & 45.7		8.82*		3.31*	
			POAMOHO PLOT			
0.0 - 0.1	0.0	0.0	0.65	0.055	0.20	0.040
0.1 - 0.6	0.0	0.0	0.65	0.040	0.20	0.035
0.6 - 0.8	0.0	0.0	0.65	---	0.20	0.035
0.8 - 2.5	0.0	0.0	---	---	---	---
APPLICATION RATE (kg/ha)	45.7		8.82*		3.31*	

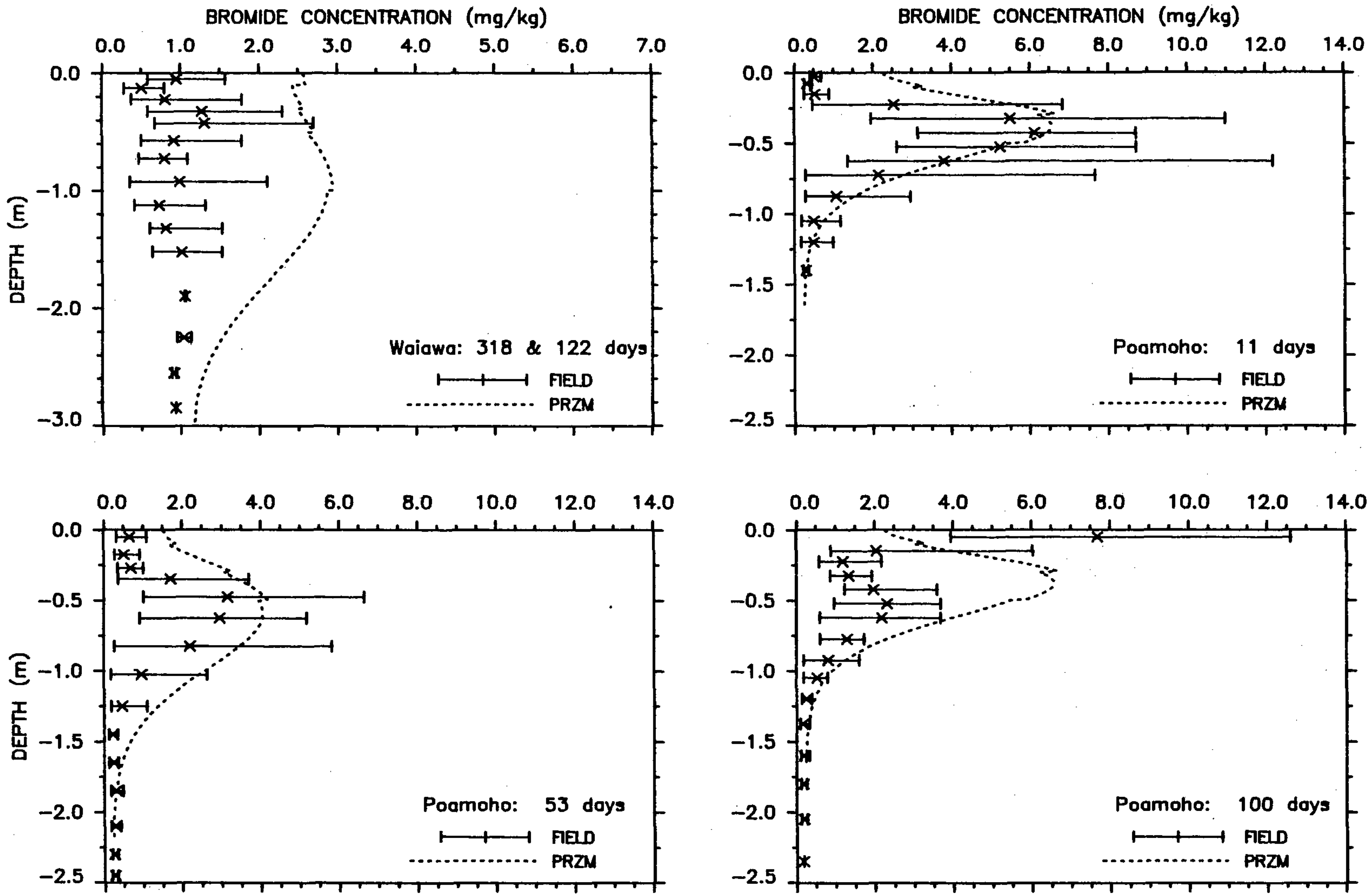
* Values reduced to account for laboratory recoveries of 0.90 and 0.95 for chlorpyrifos and fenamiphos, respectively.

LONG-TERM PRZM SIMULATIONS

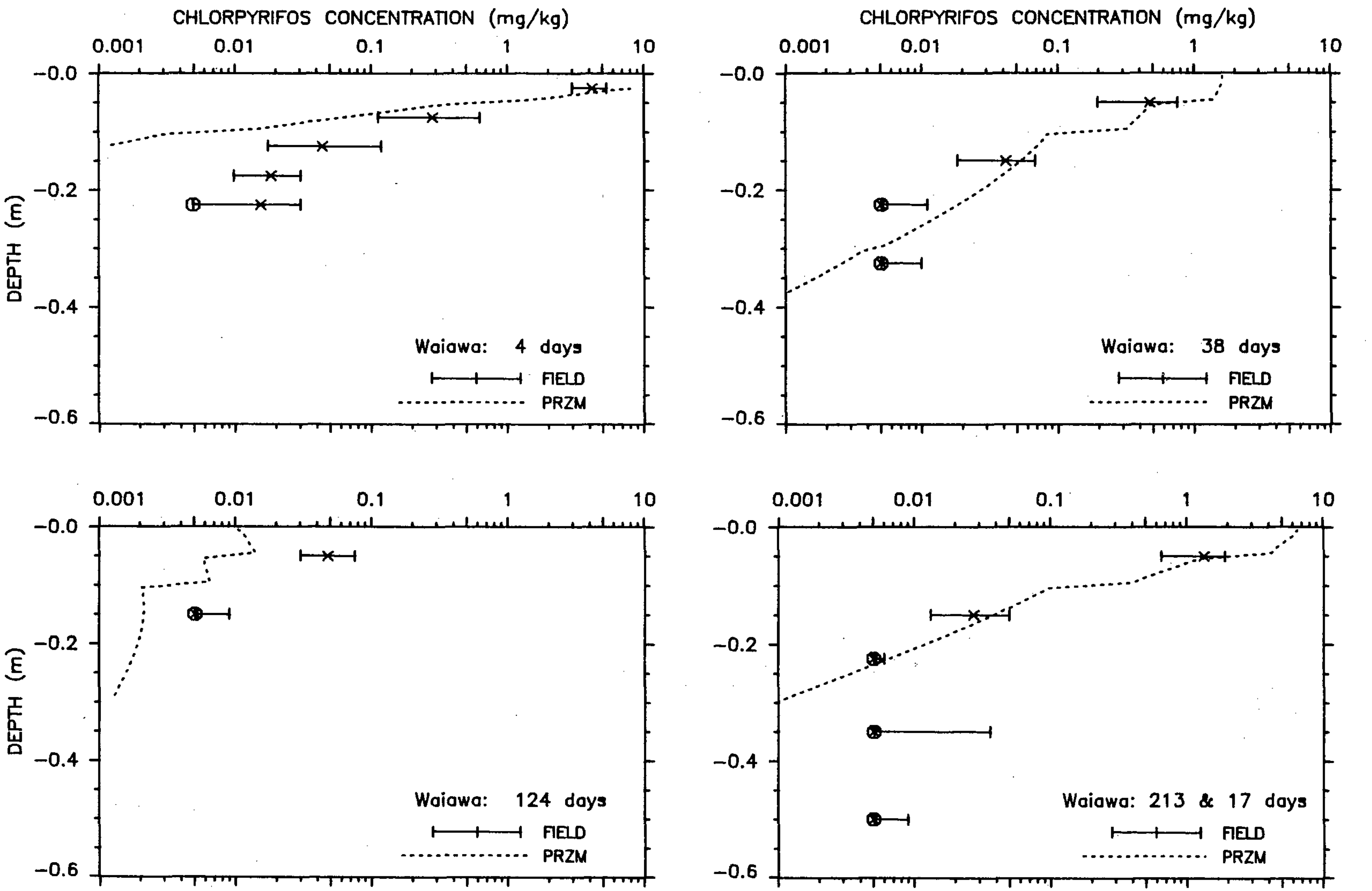
The annual output from PRZM to the water table for the various scenarios is listed in Appendix Tables D.6 to D.9. A legend describing the identification system used for the simulations is presented in Appendix Figure D.6. The daily time series for case 454.n2 on selected years is compared with the average annual recharge and loading rates in Appendix Figure D.7.



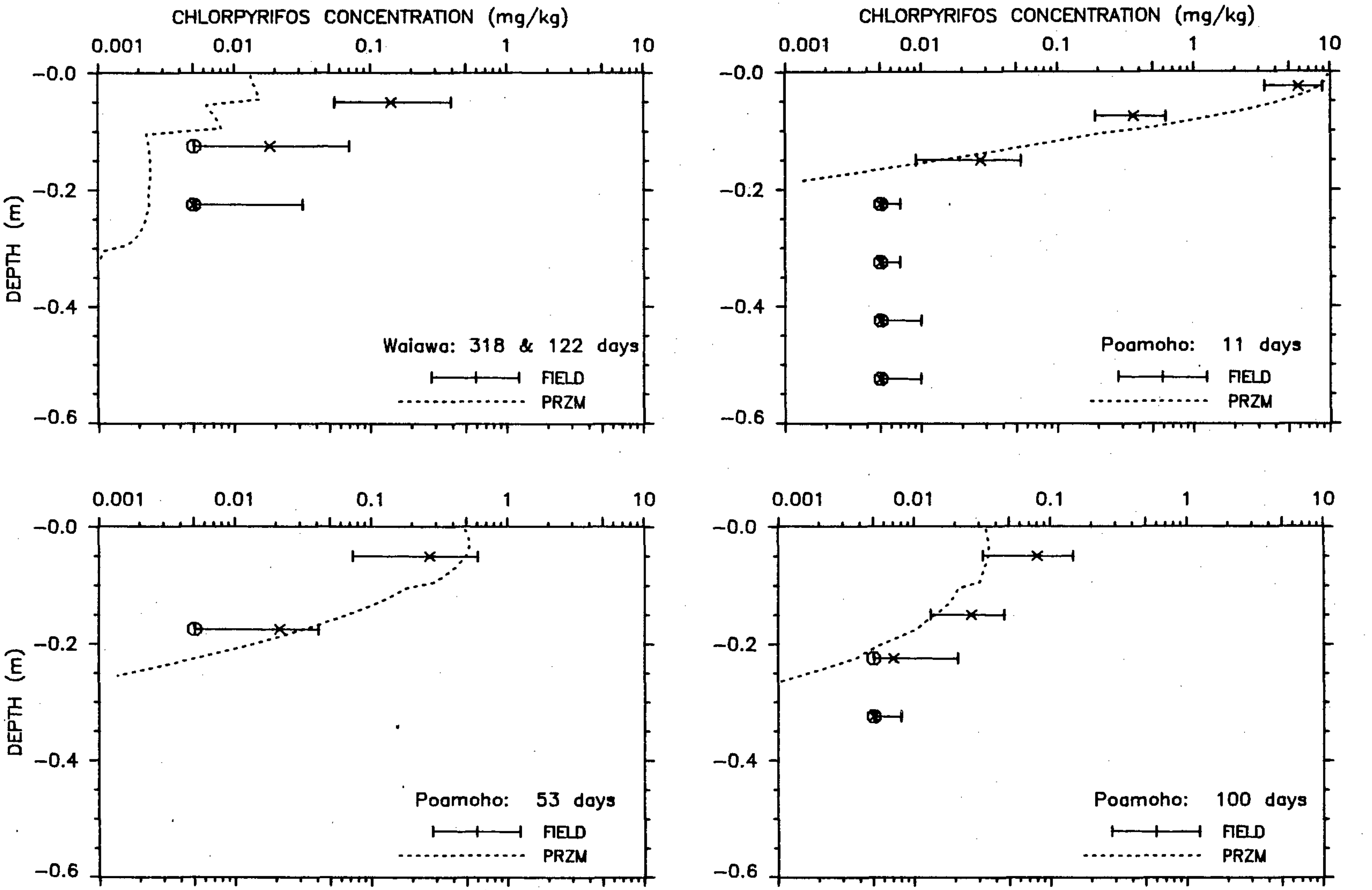
Appendix Figure D.3. PRZM vs. field data for bromide



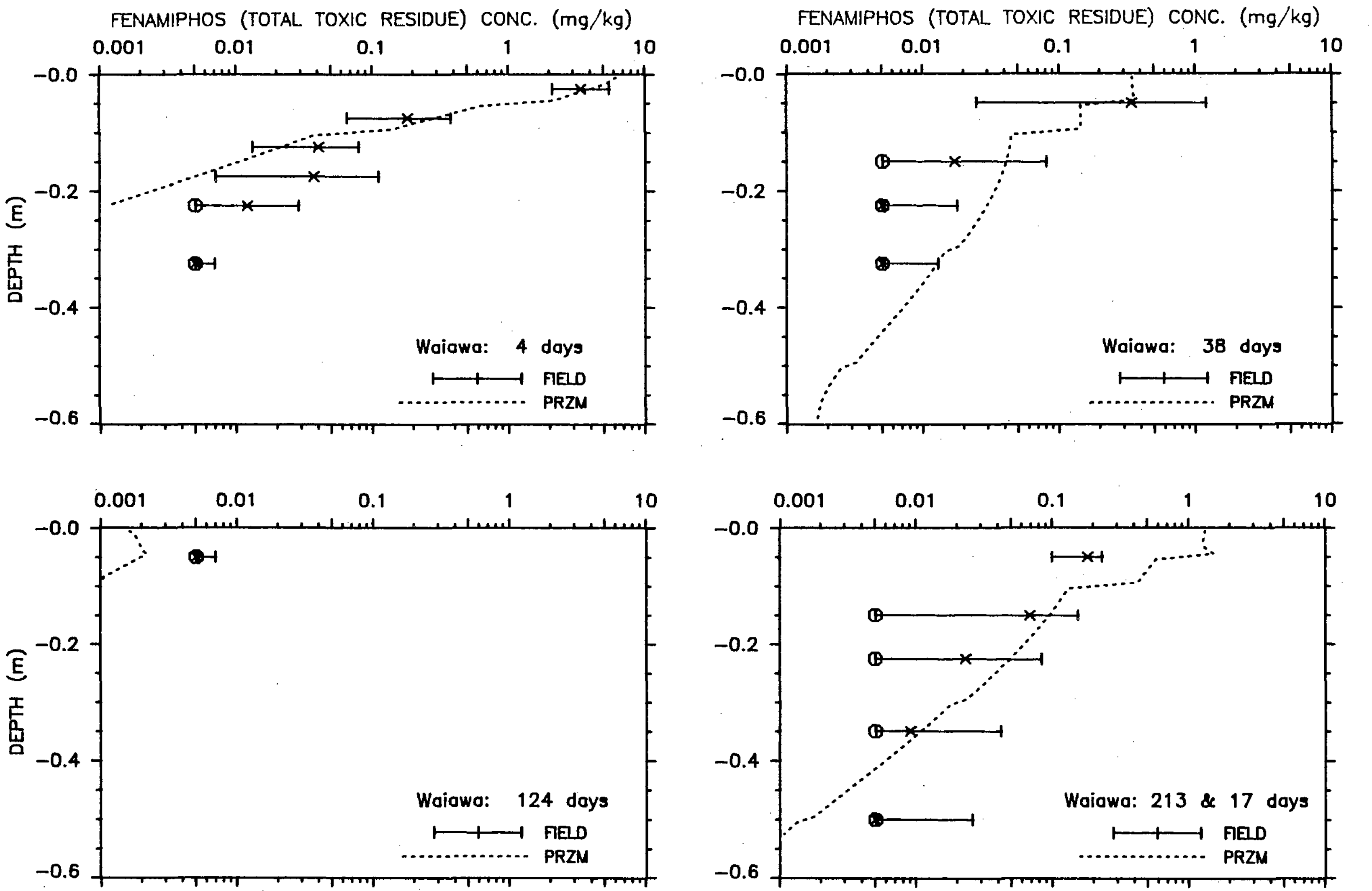
Appendix Figure D.3--Continued



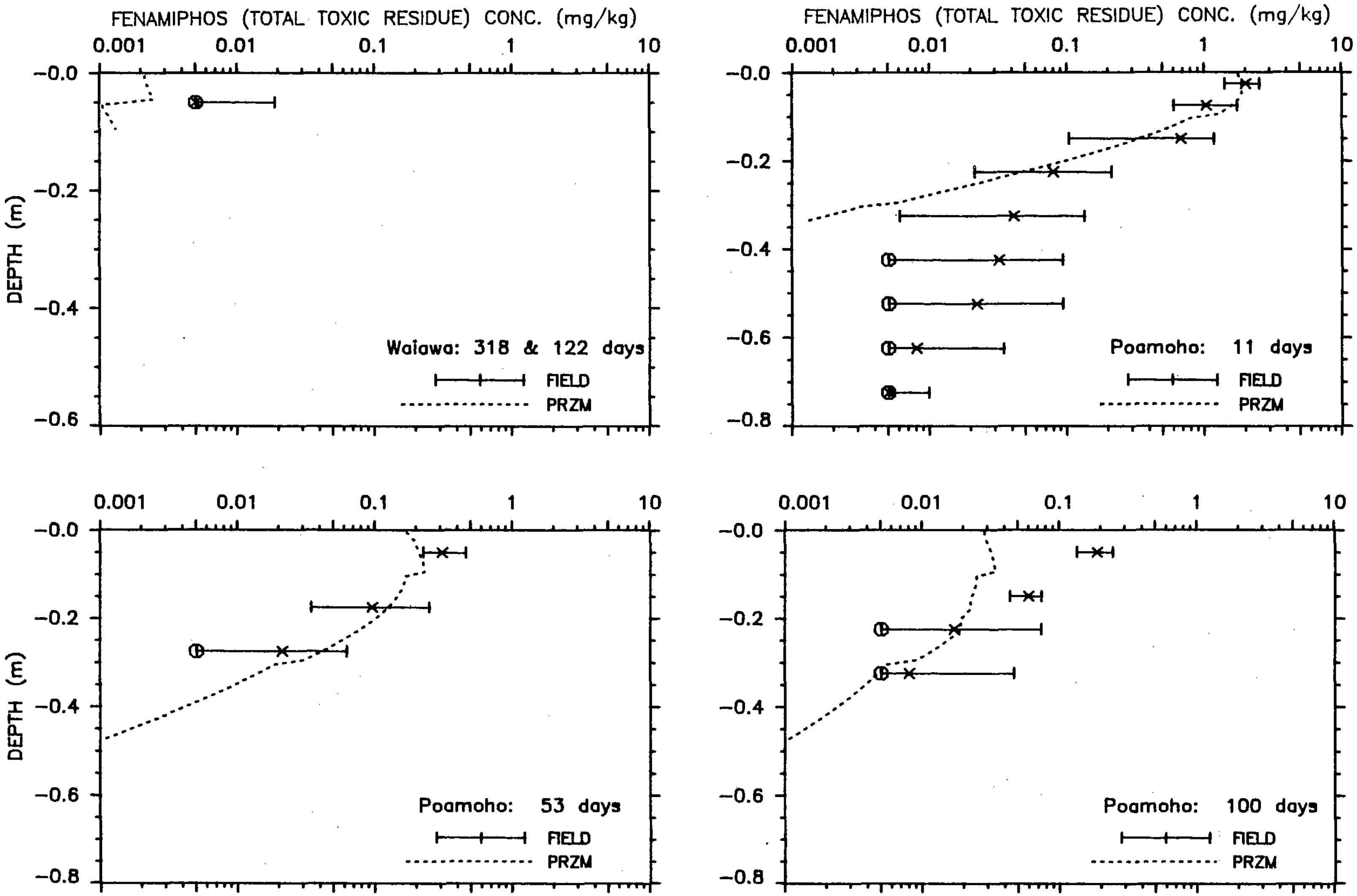
Appendix Figure D.4. PRZM vs. field data for chlorpyrifos



Appendix Figure D.4--Continued



Appendix Figure D.5. PRZM vs. field data for fenamiphos



Appendix Figure D.5--Continued

APPENDIX TABLE D.5. STATISTICAL SUMMARY OF PRZM EVALUATION

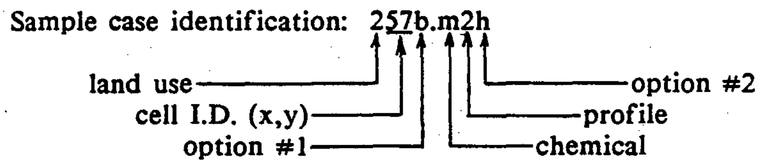
Sample*	ME	RMSE	CD	EF	CRM	N
wb1	13.79	143.16	3.63	0.45	-0.22	8
wb2	2.10	178.14	0.04	-21.74	-1.77	6
wb3	1.18	116.95	0.25	-2.73	-1.13	9
wb4	4.82	150.33	0.17	-3.59	-1.20	11
wb5	2.11	163.91	0.02	-60.16	-1.50	15
wc1	4.47	195.44	0.24	-0.16	-0.81	5
wc2	0.44	170.37	0.24	-0.25	-0.90	4^{**2}
wc3	0.04	134.86	3.11	0.05	0.74	4^{**3}
wc4	1.36	223.57	0.23	-0.34	-1.00	5^{**3}
wc5	0.13	156.14	2.27	-0.30	0.90	4^{**1}
wf1	0.66	44.65	0.69	0.95	-0.19	6^{**1}
wf2	0.09	52.63	2.18	0.89	0.09	4^{**2}
wf3	0.00	169.39	3.20	-0.60	0.22	4^{**4}
wf4	0.87	671.97	0.02	-33.84	-3.17	5^{**1}
wf5	0.00	84.22	4.97	-0.63	0.18	4^{**4}
pb1	3.41	70.88	0.82	0.44	-0.47	13
pb2	2.38	116.03	0.34	-0.35	-0.89	15
pb3	4.84	124.74	1.78	0.07	-0.54	16
pc1	2.51	116.00	0.48	0.74	-0.57	7^{**4}
pc2	0.22	152.17	0.27	0.03	-0.79	4^{**2}
pc3	0.04	79.97	2.13	0.41	0.55	4^{**1}
pf1	0.56	51.63	0.86	0.88	0.01	9^{**1}
pf2	0.10	48.32	2.37	0.82	0.10	4^{**1}
pf3	0.15	116.31	2.02	-0.27	0.71	4

NOTE: ME = maximum error; RMSE = root mean square error
CD = coefficient of determination; EF = modeling efficiency
CRM = coefficient of residual mass; N = number of samples

*w = Waiawa, p = Poamoho, b = bromide, c = chlorpyrifos, f = fenamiphos; numbers refer to sampling dates.

**One or more average concentrations were below limit of detection (LD), thus, an estimated field value equal to one-half LD was used for first sample below LD and a field value of zero was used for any deeper average concentrations. Numeral superscript after the asterisk indicates number of samples below LD.

A perfect match between observed and predicted concentration profiles would yield ME, RMSE, and CRM values of zero; and CD and EF values of one (see statistical criteria described by Loague and Green [1989a,b]).



land use	
1	irrigated lawn, no runoff
2	golf course
4	residential
5	apartment
6	commercial/industrial

chemical	
d	diazinon
m	metribuzin
n	nitrate (as N)

cell I.D.	
X	Y
3	3
4	4
5	5
6	6
7	7

profile	
1	no loss of surface f_{oc}
2	0.2 m loss of surface f_{oc}
3	0.5 m loss of f_{oc}, lower θ_{fc}, thinner saprolite

option #1	
b	chemical application dates are offset
v	valley profile (default = ridge)

option #2	
d	distributed at top of saprolite (default = at top of water table)
h	includes hydrolysis rate for metribuzin (default = no metribuzin hydrolysis rate)

Appendix Figure D.6. Legend for long-term PRZM simulations (App. Tables D.6-D.9)

APPENDIX TABLE D.6. LONG-TERM PRZM SIMULATIONS FOR DIAZINON

YEAR	Case: 533.d3 LOAD (kg/ha)	Case: 533.d3 CONC. (µg/l)	Case: 534.d3 LOAD (kg/ha)	Case: 534.d3 CONC. (µg/l)	Case: 635.d3 LOAD (kg/ha)	Case: 635.d3 CONC. (µg/l)	Case: 443.d3 LOAD (kg/ha)	Case: 443.d3 CONC. (µg/l)	Case: 444.d3 LOAD (kg/ha)	Case: 444.d3 CONC. (µg/l)	Case: 446.d3 LOAD (kg/ha)	Case: 446.d3 CONC. (µg/l)	Case: 453.d3 LOAD (kg/ha)	Case: 453.d3 CONC. (µg/l)	Case: 454.d3 LOAD (kg/ha)	Case: 454.d3 CONC. (µg/l)
1	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
2	LL	LC	LL	LC	0.00293	0.371	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
3	LL	LC	0.00001	0.001	0.04344	5.247	0.00005	0.005	LL	LC	LL	LC	0.00023	0.021	LL	LC
4	0.00031	0.043	0.00114	0.137	0.04618	6.314	0.00185	0.223	0.00027	0.031	LL	LC	0.00530	0.548	0.00017	0.019
5	0.00288	0.338	0.00516	0.577	0.04710	5.879	0.00769	0.803	0.00270	0.269	0.00082	0.062	0.01682	1.521	0.00269	0.244
6	0.00761	0.756	0.00999	0.924	0.05290	5.995	0.01396	1.301	0.00641	0.566	0.00376	0.268	0.02869	2.196	0.00645	0.538
7	0.00383	0.697	0.00456	0.762	0.03532	6.108	0.00782	1.182	0.00365	0.519	0.00317	0.318	0.02168	2.356	0.00440	0.553
8	0.00209	0.427	0.00257	0.458	0.02043	3.502	0.00429	0.811	0.00186	0.327	0.00199	0.231	0.01190	1.813	0.00224	0.350
9	0.00294	0.356	0.00348	0.386	0.02638	3.125	0.00547	0.570	0.00227	0.230	0.00244	0.186	0.01195	1.112	0.00277	0.264
10	0.00318	0.350	0.00424	0.419	0.05743	6.504	0.00547	0.564	0.00294	0.278	0.00291	0.223	0.01179	1.099	0.00324	0.300
11	0.00335	0.407	0.00442	0.510	0.05901	7.764	0.00709	0.808	0.00237	0.256	0.00196	0.180	0.01071	1.268	0.00228	0.249
12	0.00583	0.753	0.00702	0.849	0.03438	4.935	0.01097	1.302	0.00370	0.395	0.00194	0.182	0.01372	1.519	0.00305	0.316
13	0.00653	0.779	0.00716	0.808	0.03103	4.187	0.00923	1.029	0.00578	0.558	0.00256	0.224	0.01130	1.139	0.00475	0.450
14	0.00363	0.575	0.00361	0.549	0.02644	4.444	0.00494	0.787	0.00310	0.423	0.00186	0.210	0.00576	0.856	0.00258	0.355
15	0.00317	0.433	0.00265	0.373	0.02056	3.235	0.00363	0.560	0.00230	0.285	0.00092	0.111	0.00584	0.736	0.00196	0.225
16	0.00253	0.413	0.00240	0.355	0.02307	3.396	0.00263	0.433	0.00202	0.274	0.00064	0.072	0.00503	0.649	0.00192	0.232
17	0.00274	0.361	0.00244	0.316	0.03138	4.400	0.00294	0.368	0.00194	0.237	0.00071	0.074	0.00547	0.613	0.00193	0.222
18	0.00459	0.481	0.00373	0.382	0.04647	5.688	0.00476	0.468	0.00237	0.231	0.00091	0.076	0.00900	0.844	0.00240	0.223
19	0.00352	0.497	0.00352	0.439	0.03816	5.097	0.00482	0.608	0.00217	0.244	0.00080	0.072	0.00875	0.998	0.00260	0.261
20	0.00664	0.640	0.00661	0.603	0.05115	5.654	0.01012	0.918	0.00394	0.331	0.00123	0.095	0.01661	1.317	0.00486	0.373
21	0.00763	0.896	0.00834	0.883	0.05131	6.791	0.01031	1.172	0.00502	0.508	0.00160	0.153	0.01462	1.596	0.00571	0.559
22	0.01488	1.313	0.01829	1.428	0.08068	7.750	0.01923	1.626	0.01073	0.786	0.00340	0.228	0.02164	1.961	0.01039	0.771
23	0.01984	1.908	0.02521	2.188	0.07545	8.507	0.02337	2.172	0.01475	1.246	0.00380	0.306	0.02101	2.043	0.01238	1.046
24	0.01366	1.824	0.01995	2.237	0.05751	7.421	0.01726	2.114	0.01210	1.333	0.00407	0.377	0.01444	1.719	0.01021	1.055
25	0.00691	1.010	0.00963	1.244	0.03204	4.955	0.00890	1.263	0.00534	0.731	0.00216	0.240	0.00750	1.043	0.00449	0.605
26	0.00881	0.932	0.01205	1.148	0.04573	5.125	0.01081	1.125	0.00588	0.604	0.00236	0.228	0.00952	0.979	0.00473	0.495
27	0.00735	0.819	0.00929	0.979	0.06768	8.493	0.00912	0.973	0.00408	0.428	0.00155	0.154	0.00832	0.877	0.00328	0.339
28	0.00218	0.529	0.00473	0.742	0.03748	5.292	0.00413	0.788	0.00189	0.277	0.00082	0.097	0.00479	0.783	0.00182	0.238
29	0.00548	0.623	0.01013	0.967	0.05407	5.985	0.00989	0.924	0.00459	0.387	0.00135	0.100	0.01284	1.054	0.00435	0.331
30	0.00388	0.534	0.00616	0.769	0.04866	7.143	0.00757	0.896	0.00382	0.443	0.00102	0.123	0.01099	1.182	0.00422	0.442
31	0.00222	0.402	0.00455	0.670	0.03586	5.619	0.00578	0.892	0.00299	0.407	0.00088	0.107	0.00916	1.303	0.00370	0.458
32	0.00136	0.246	0.00318	0.478	0.02052	3.363	0.00411	0.673	0.00197	0.285	0.00046	0.062	0.00593	0.932	0.00253	0.338
33	0.00183	0.242	0.00347	0.396	0.01983	2.750	0.00449	0.514	0.00232	0.248	0.00045	0.047	0.00600	0.640	0.00285	0.288
34	0.00218	0.298	0.00359	0.431	0.03157	4.243	0.00427	0.523	0.00229	0.266	0.00051	0.057	0.00531	0.612	0.00255	0.282
35	0.00280	0.297	0.00494	0.471	0.05146	5.985	0.00694	0.652	0.00285	0.250	0.00065	0.052	0.00934	0.810	0.00310	0.253
36	0.00323	0.442	0.00669	0.737	0.05232	6.027	0.00919	1.055	0.00357	0.359	0.00074	0.059	0.01295	1.343	0.00401	0.367
37	0.01230	1.001	0.01692	1.325	0.08286	8.274	0.02364	1.736	0.01134	0.816	0.00240	0.168	0.03114	2.132	0.01256	0.835

NOTE: LL = less than 0.00001 kg/ha; LC = less than 0.001 µg/l.

APPENDIX TABLE D.6--Continued

YEAR	Case: 455.d3		Case: 456.d3		Case: 463.d3		Case: 465.d3		Case: 473.d3		Case: 475.d3		Case: 533.d2		Case: 534.d2	
	LOAD (kg/ha)	CONC. (μg/l)	LOAD (kg/ha)	CONC. (μg/l)	LOAD (kg/ha)	CONC. (μg/l)	LOAD (kg/ha)	CONC. (μg/l)	LOAD (kg/ha)	CONC. (μg/l)	LOAD (kg/ha)	CONC. (μg/l)	LOAD (kg/ha)	CONC. (μg/l)	LOAD (kg/ha)	CONC. (μg/l)
1	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
2	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
3	LL	LC	LL	LC	0.00002	0.002	LL	LC	0.00007	0.007	LL	LC	LL	LC	LL	LC
4	0.00028	0.030	LL	LC	0.00198	0.202	0.00069	0.062	0.00345	0.343	0.00006	0.005	LL	LC	LL	LC
5	0.00325	0.291	0.00029	0.020	0.00911	0.814	0.00796	0.575	0.01179	1.017	0.00353	0.236	LL	LC	LL	LC
6	0.00655	0.538	0.00257	0.176	0.01509	1.221	0.01560	1.141	0.01672	1.355	0.01028	0.710	0.00001	0.001	0.00005	0.004
7	0.00401	0.518	0.00303	0.275	0.00963	1.126	0.01255	1.214	0.01052	1.197	0.01092	0.880	0.00003	0.005	0.00008	0.013
8	0.00222	0.351	0.00220	0.236	0.00535	0.780	0.00868	0.989	0.00594	0.857	0.00784	0.787	0.00003	0.007	0.00007	0.013
9	0.00263	0.260	0.00269	0.197	0.00711	0.621	0.00952	0.710	0.00805	0.671	0.00906	0.605	0.00006	0.008	0.00010	0.012
10	0.00314	0.285	0.00298	0.223	0.00711	0.636	0.00982	0.777	0.00832	0.725	0.00890	0.659	0.00010	0.011	0.00016	0.016
11	0.00232	0.241	0.00224	0.183	0.00709	0.752	0.01090	0.917	0.00988	0.947	0.00899	0.693	0.00010	0.012	0.00014	0.016
12	0.00325	0.335	0.00208	0.187	0.00969	0.995	0.01386	1.250	0.01361	1.334	0.00950	0.844	0.00009	0.011	0.00012	0.014
13	0.00547	0.496	0.00284	0.225	0.00931	0.890	0.01205	0.970	0.01208	1.083	0.00958	0.716	0.00008	0.010	0.00011	0.013
14	0.00328	0.415	0.00203	0.216	0.00459	0.634	0.00631	0.745	0.00642	0.847	0.00492	0.525	0.00008	0.012	0.00011	0.016
15	0.00246	0.278	0.00108	0.118	0.00403	0.469	0.00559	0.548	0.00553	0.620	0.00410	0.357	0.00009	0.013	0.00010	0.015
16	0.00254	0.291	0.00078	0.082	0.00397	0.464	0.00534	0.534	0.00542	0.585	0.00425	0.375	0.00007	0.012	0.00008	0.012
17	0.00230	0.265	0.00076	0.078	0.00367	0.417	0.00475	0.478	0.00462	0.525	0.00390	0.371	0.00007	0.010	0.00007	0.010
18	0.00300	0.276	0.00096	0.077	0.00534	0.493	0.00666	0.541	0.00651	0.599	0.00508	0.384	0.00010	0.011	0.00009	0.010
19	0.00389	0.334	0.00095	0.076	0.00511	0.546	0.00825	0.654	0.00646	0.652	0.00615	0.463	0.00006	0.009	0.00007	0.009
20	0.00742	0.527	0.00141	0.102	0.00990	0.749	0.01232	0.881	0.01114	0.837	0.00784	0.550	0.00011	0.010	0.00010	0.010
21	0.00924	0.836	0.00168	0.154	0.00981	1.014	0.01130	1.086	0.01018	1.083	0.00602	0.607	0.00014	0.016	0.00016	0.017
22	0.01961	1.273	0.00380	0.240	0.01426	1.206	0.01811	1.242	0.01501	1.238	0.00872	0.634	0.00034	0.030	0.00045	0.035
23	0.02148	1.675	0.00418	0.324	0.01692	1.472	0.01759	1.411	0.01834	1.533	0.00911	0.697	0.00047	0.045	0.00070	0.061
24	0.01791	1.631	0.00438	0.371	0.01190	1.317	0.01597	1.421	0.01391	1.453	0.00817	0.698	0.00046	0.061	0.00081	0.091
25	0.00843	0.952	0.00245	0.246	0.00639	0.817	0.00860	0.924	0.00800	0.974	0.00467	0.490	0.00032	0.047	0.00057	0.073
26	0.00877	0.802	0.00293	0.247	0.00847	0.787	0.01020	0.851	0.01126	0.968	0.00673	0.513	0.00049	0.052	0.00083	0.079
27	0.00572	0.560	0.00181	0.174	0.00618	0.638	0.00645	0.642	0.00752	0.781	0.00423	0.415	0.00038	0.042	0.00060	0.063
28	0.00373	0.418	0.00102	0.109	0.00321	0.475	0.00497	0.523	0.00500	0.641	0.00301	0.295	0.00009	0.023	0.00023	0.036
29	0.00905	0.649	0.00160	0.114	0.00948	0.731	0.01128	0.796	0.01297	0.965	0.00614	0.437	0.00015	0.017	0.00032	0.031
30	0.00652	0.674	0.00137	0.144	0.00802	0.804	0.00785	0.777	0.00994	0.991	0.00485	0.462	0.00010	0.014	0.00022	0.027
31	0.00612	0.688	0.00109	0.122	0.00593	0.808	0.00740	0.813	0.00776	1.014	0.00358	0.397	0.00007	0.012	0.00019	0.028
32	0.00440	0.524	0.00062	0.072	0.00345	0.535	0.00548	0.628	0.00445	0.662	0.00249	0.283	0.00004	0.008	0.00011	0.017
33	0.00406	0.392	0.00061	0.059	0.00432	0.444	0.00467	0.449	0.00466	0.482	0.00244	0.229	0.00004	0.005	0.00010	0.011
34	0.00343	0.369	0.00066	0.072	0.00363	0.404	0.00375	0.407	0.00371	0.426	0.00209	0.225	0.00004	0.005	0.00011	0.013
35	0.00467	0.364	0.00085	0.064	0.00523	0.427	0.00539	0.405	0.00519	0.427	0.00251	0.187	0.00006	0.006	0.00015	0.015
36	0.00658	0.545	0.00083	0.065	0.00769	0.747	0.00710	0.590	0.00719	0.702	0.00276	0.230	0.00005	0.006	0.00012	0.014
37	0.01647	1.089	0.00240	0.158	0.02129	1.414	0.01843	1.175	0.01997	1.337	0.00842	0.529	0.00014	0.011	0.00032	0.025

NOTE: LL = less than 0.00001 kg/ha; LC = less than 0.001 μg/l.

APPENDIX TABLE D.6--Continued

YEAR	Case: 635.d2 LOAD (kg/ha)	CONC. (µg/l)	Case: 443.d2 LOAD (kg/ha)	CONC. (µg/l)	Case: 444.d2 LOAD (kg/ha)	CONC. (µg/l)	Case: 446.d2 LOAD (kg/ha)	CONC. (µg/l)	Case: 453.d2 LOAD (kg/ha)	CONC. (µg/l)	Case: 454.d2 LOAD (kg/ha)	CONC. (µg/l)	Case: 455.d2 LOAD (kg/ha)	CONC. (µg/l)	Case: 456.d2 LOAD (kg/ha)	CONC. (µg/l)
1	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
2	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
3	0.00024	0.029	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
4	0.00506	0.691	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
5	0.00794	0.990	LL	LC	LL	LC	LL	LC	0.00002	0.001	LL	LC	LL	LC	LL	LC
6	0.00943	1.068	0.00005	0.005	0.00001	0.001	0.00000	0.000	0.00033	0.025	0.00001	0.001	0.00001	0.001	LL	LC
7	0.00493	0.852	0.00010	0.015	0.00002	0.003	0.00001	0.001	0.00062	0.067	0.00003	0.004	0.00004	0.005	0.00001	0.001
8	0.00370	0.634	0.00008	0.016	0.00003	0.005	0.00003	0.003	0.00041	0.062	0.00004	0.006	0.00004	0.006	0.00002	0.002
9	0.00445	0.527	0.00014	0.014	0.00005	0.005	0.00006	0.005	0.00053	0.049	0.00006	0.006	0.00006	0.006	0.00005	0.004
10	0.00524	0.594	0.00018	0.018	0.00008	0.007	0.00010	0.007	0.00062	0.058	0.00010	0.009	0.00009	0.008	0.00010	0.007
11	0.00717	0.944	0.00016	0.019	0.00007	0.007	0.00008	0.007	0.00040	0.048	0.00008	0.008	0.00008	0.008	0.00010	0.008
12	0.00833	1.196	0.00013	0.016	0.00006	0.007	0.00007	0.006	0.00030	0.034	0.00007	0.007	0.00008	0.008	0.00008	0.007
13	0.00572	0.771	0.00014	0.016	0.00006	0.006	0.00005	0.005	0.00030	0.031	0.00006	0.006	0.00007	0.006	0.00007	0.005
14	0.00350	0.588	0.00012	0.019	0.00005	0.007	0.00003	0.004	0.00021	0.032	0.00004	0.006	0.00005	0.007	0.00004	0.004
15	0.00287	0.452	0.00010	0.016	0.00005	0.007	0.00002	0.003	0.00020	0.025	0.00005	0.005	0.00006	0.007	0.00003	0.003
16	0.00290	0.428	0.00007	0.011	0.00005	0.007	0.00002	0.002	0.00014	0.017	0.00005	0.006	0.00007	0.008	0.00003	0.003
17	0.00344	0.483	0.00007	0.009	0.00005	0.006	0.00002	0.002	0.00014	0.016	0.00004	0.005	0.00006	0.007	0.00003	0.003
18	0.00507	0.621	0.00009	0.009	0.00005	0.005	0.00002	0.002	0.00019	0.018	0.00005	0.005	0.00007	0.007	0.00003	0.002
19	0.00548	0.731	0.00007	0.008	0.00004	0.005	0.00002	0.002	0.00015	0.017	0.00005	0.005	0.00008	0.007	0.00002	0.002
20	0.00732	0.809	0.00010	0.009	0.00005	0.005	0.00002	0.002	0.00028	0.022	0.00007	0.005	0.00012	0.009	0.00003	0.002
21	0.00749	0.992	0.00014	0.016	0.00006	0.007	0.00002	0.002	0.00033	0.036	0.00008	0.008	0.00016	0.015	0.00002	0.002
22	0.01395	1.340	0.00036	0.031	0.00017	0.013	0.00004	0.003	0.00056	0.050	0.00019	0.014	0.00044	0.028	0.00005	0.003
23	0.01512	1.706	0.00052	0.049	0.00027	0.023	0.00007	0.005	0.00062	0.060	0.00027	0.023	0.00065	0.051	0.00008	0.006
24	0.01313	1.695	0.00049	0.059	0.00029	0.032	0.00008	0.008	0.00055	0.065	0.00029	0.030	0.00076	0.070	0.00011	0.009
25	0.00670	1.036	0.00035	0.049	0.00017	0.023	0.00005	0.006	0.00034	0.048	0.00016	0.021	0.00045	0.051	0.00007	0.007
26	0.00817	0.915	0.00047	0.049	0.00026	0.027	0.00007	0.006	0.00043	0.044	0.00021	0.022	0.00054	0.050	0.00010	0.008
27	0.00735	0.923	0.00038	0.041	0.00020	0.021	0.00006	0.005	0.00032	0.034	0.00016	0.016	0.00036	0.035	0.00007	0.007
28	0.00726	1.024	0.00013	0.025	0.00009	0.013	0.00003	0.004	0.00014	0.022	0.00008	0.011	0.00021	0.023	0.00005	0.005
29	0.01014	1.123	0.00022	0.020	0.00013	0.011	0.00005	0.004	0.00026	0.021	0.00013	0.010	0.00028	0.020	0.00006	0.005
30	0.00672	0.986	0.00017	0.020	0.00008	0.009	0.00002	0.003	0.00025	0.026	0.00008	0.009	0.00018	0.018	0.00003	0.004
31	0.00623	0.976	0.00014	0.021	0.00006	0.008	0.00002	0.002	0.00022	0.031	0.00006	0.008	0.00016	0.018	0.00002	0.003
32	0.00403	0.660	0.00008	0.014	0.00004	0.005	0.00001	0.001	0.00012	0.019	0.00004	0.006	0.00011	0.013	0.00001	0.002
33	0.00319	0.443	0.00008	0.010	0.00004	0.004	0.00001	0.001	0.00014	0.015	0.00005	0.005	0.00011	0.010	0.00001	0.001
34	0.00350	0.471	0.00010	0.012	0.00005	0.005	0.00001	0.001	0.00017	0.020	0.00006	0.007	0.00012	0.013	0.00001	0.001
35	0.00506	0.588	0.00015	0.014	0.00007	0.006	0.00001	0.001	0.00025	0.022	0.00010	0.008	0.00017	0.013	0.00002	0.001
36	0.00813	0.937	0.00012	0.013	0.00006	0.006	0.00001	0.001	0.00019	0.020	0.00009	0.008	0.00015	0.012	0.00002	0.002
37	0.01436	1.434	0.00034	0.025	0.00013	0.010	0.00003	0.002	0.00058	0.040	0.00018	0.012	0.00030	0.020	0.00004	0.002

NOTE: LL = less than 0.00001 kg/ha; LC = less than 0.001 µg/l.

APPENDIX TABLE D.6--Continued

YEAR	Case: 463.d2 LOAD (kg/ha)	Case: 463.d2 CONC. (µg/l)	Case: 465.d2 LOAD (kg/ha)	Case: 465.d2 CONC. (µg/l)	Case: 473.d2 LOAD (kg/ha)	Case: 473.d2 CONC. (µg/l)	Case: 475.d2 LOAD (kg/ha)	Case: 475.d2 CONC. (µg/l)	Case: 533.d3d LOAD (kg/ha)	Case: 533.d3d CONC. (µg/l)	Case: 534.d3d LOAD (kg/ha)	Case: 534.d3d CONC. (µg/l)	Case: 635.d3d LOAD (kg/ha)	Case: 635.d3d CONC. (µg/l)	Case: 443.d3d LOAD (kg/ha)	Case: 443.d3d CONC. (µg/l)
1	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
2	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
3	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
4	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
5	LL	LC	LL	LC	0.00001	0.001	LL	LC	LL	LC	LL	LC	LL	LC	0.00001	0.001
6	0.00009	0.007	0.00008	0.006	0.00015	0.012	0.00002	0.001	LL	LC	LL	LC	LL	LC	0.00015	0.014
7	0.00020	0.023	0.00025	0.024	0.00028	0.032	0.00015	0.012	LL	LC	LL	LC	LL	LC	0.00016	0.024
8	0.00016	0.023	0.00026	0.030	0.00020	0.029	0.00021	0.021	LL	LC	LL	LC	LL	LC	0.00011	0.021
9	0.00025	0.022	0.00042	0.031	0.00031	0.026	0.00039	0.026	0.00001	0.001	0.00001	0.001	LL	LC	0.00019	0.020
10	0.00030	0.026	0.00057	0.045	0.00037	0.032	0.00053	0.039	0.00001	0.001	0.00001	0.001	LL	LC	0.00029	0.030
11	0.00024	0.025	0.00047	0.039	0.00032	0.031	0.00046	0.036	0.00002	0.002	0.00002	0.002	LL	LC	0.00020	0.023
12	0.00019	0.020	0.00036	0.033	0.00026	0.026	0.00033	0.029	0.00002	0.002	0.00002	0.002	LL	LC	0.00019	0.022
13	0.00019	0.019	0.00040	0.032	0.00031	0.028	0.00033	0.025	0.00001	0.002	0.00001	0.001	LL	LC	0.00022	0.024
14	0.00015	0.021	0.00032	0.038	0.00026	0.034	0.00024	0.026	0.00001	0.001	0.00001	0.001	LL	LC	0.00020	0.031
15	0.00015	0.017	0.00029	0.029	0.00023	0.026	0.00025	0.022	0.00001	0.001	0.00001	0.001	LL	LC	0.00013	0.020
16	0.00012	0.014	0.00022	0.022	0.00019	0.020	0.00019	0.017	0.00001	0.002	0.00001	0.001	LL	LC	0.00009	0.015
17	0.00010	0.012	0.00018	0.018	0.00015	0.017	0.00014	0.014	0.00001	0.002	0.00001	0.001	LL	LC	0.00011	0.014
18	0.00013	0.012	0.00022	0.018	0.00018	0.017	0.00017	0.013	0.00002	0.002	0.00001	0.001	LL	LC	0.00015	0.015
19	0.00010	0.010	0.00022	0.017	0.00014	0.014	0.00018	0.013	0.00001	0.002	0.00001	0.001	LL	LC	0.00010	0.013
20	0.00017	0.013	0.00030	0.022	0.00023	0.017	0.00022	0.015	0.00002	0.002	0.00001	0.001	LL	LC	0.00017	0.016
21	0.00019	0.020	0.00030	0.029	0.00023	0.024	0.00017	0.017	0.00002	0.002	0.00001	0.001	LL	LC	0.00024	0.027
22	0.00034	0.028	0.00059	0.041	0.00038	0.032	0.00027	0.020	0.00005	0.004	0.00004	0.003	LL	LC	0.00054	0.045
23	0.00044	0.038	0.00071	0.057	0.00052	0.043	0.00034	0.026	0.00007	0.007	0.00006	0.005	LL	LC	0.00064	0.059
24	0.00042	0.046	0.00074	0.066	0.00052	0.054	0.00035	0.030	0.00006	0.008	0.00007	0.008	LL	LC	0.00064	0.078
25	0.00026	0.033	0.00042	0.045	0.00033	0.040	0.00020	0.021	0.00004	0.006	0.00005	0.006	LL	LC	0.00036	0.052
26	0.00038	0.036	0.00056	0.046	0.00050	0.043	0.00027	0.021	0.00007	0.007	0.00008	0.008	LL	LC	0.00060	0.063
27	0.00026	0.027	0.00037	0.037	0.00035	0.036	0.00019	0.019	0.00007	0.008	0.00008	0.008	LL	LC	0.00044	0.047
28	0.00012	0.018	0.00024	0.026	0.00019	0.025	0.00014	0.014	0.00002	0.005	0.00004	0.006	LL	LC	0.00017	0.032
29	0.00022	0.017	0.00034	0.024	0.00033	0.025	0.00019	0.014	0.00003	0.003	0.00005	0.005	LL	LC	0.00030	0.028
30	0.00018	0.018	0.00024	0.024	0.00028	0.028	0.00013	0.013	0.00002	0.003	0.00003	0.004	LL	LC	0.00026	0.031
31	0.00015	0.020	0.00023	0.026	0.00023	0.031	0.00011	0.012	0.00001	0.002	0.00002	0.003	LL	LC	0.00019	0.029
32	0.00008	0.013	0.00015	0.018	0.00012	0.018	0.00008	0.009	0.00001	0.001	0.00001	0.002	LL	LC	0.00011	0.018
33	0.00009	0.010	0.00014	0.013	0.00012	0.013	0.00007	0.006	0.00001	0.001	0.00001	0.001	LL	LC	0.00013	0.014
34	0.00011	0.012	0.00015	0.016	0.00013	0.015	0.00006	0.007	0.00001	0.001	0.00001	0.001	LL	LC	0.00018	0.022
35	0.00017	0.014	0.00022	0.016	0.00019	0.016	0.00009	0.007	0.00001	0.001	0.00002	0.002	LL	LC	0.00022	0.020
36	0.00013	0.012	0.00017	0.014	0.00013	0.013	0.00008	0.007	0.00001	0.001	0.00002	0.002	LL	LC	0.00016	0.018
37	0.00032	0.021	0.00036	0.023	0.00031	0.020	0.00014	0.009	0.00002	0.002	0.00003	0.002	LL	LC	0.00056	0.041

NOTE: LL = less than 0.00001 kg/ha; LC = less than 0.001 µg/l.

APPENDIX TABLE D.6--Continued

YEAR	Case: 444.d3d LOAD (kg/ha)	Case: 444.d3d CONC. (µg/l)	Case: 446.d3d LOAD (kg/ha)	Case: 446.d3d CONC. (µg/l)	Case: 453.d3d LOAD (kg/ha)	Case: 453.d3d CONC. (µg/l)	Case: 454.d3d LOAD (kg/ha)	Case: 454.d3d CONC. (µg/l)	Case: 455.d3d LOAD (kg/ha)	Case: 455.d3d CONC. (µg/l)	Case: 456.d3d LOAD (kg/ha)	Case: 456.d3d CONC. (µg/l)	Case: 463.d3d LOAD (kg/ha)	Case: 463.d3d CONC. (µg/l)	Case: 465.d3d LOAD (kg/ha)	Case: 465.d3d CONC. (µg/l)
1	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
2	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
3	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
4	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
5	LL	LC	LL	LC	0.00004	0.004	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
6	LL	LC	LL	LC	0.00045	0.034	LL	LC	LL	LC	LL	LC	0.00003	0.002	0.00001	0.000
7	LL	LC	LL	LC	0.00065	0.071	LL	LC	LL	LC	LL	LC	0.00008	0.009	0.00003	0.003
8	0.00001	0.001	LL	LC	0.00038	0.058	0.00000	0.001	0.00001	0.001	LL	LC	0.00007	0.010	0.00005	0.005
9	0.00001	0.001	LL	LC	0.00054	0.050	0.00001	0.001	0.00001	0.001	LL	LC	0.00012	0.010	0.00010	0.007
10	0.00003	0.002	LL	LC	0.00071	0.066	0.00002	0.002	0.00002	0.002	LL	LC	0.00017	0.015	0.00016	0.012
11	0.00003	0.003	LL	LC	0.00039	0.046	0.00002	0.002	0.00002	0.002	LL	LC	0.00015	0.015	0.00016	0.014
12	0.00003	0.003	LL	LC	0.00033	0.036	0.00002	0.002	0.00002	0.002	LL	LC	0.00011	0.011	0.00013	0.012
13	0.00003	0.002	LL	LC	0.00036	0.036	0.00002	0.002	0.00002	0.002	LL	LC	0.00010	0.010	0.00011	0.009
14	0.00002	0.002	LL	LC	0.00026	0.039	0.00001	0.002	0.00001	0.002	LL	LC	0.00007	0.010	0.00007	0.009
15	0.00002	0.002	LL	LC	0.00020	0.025	0.00001	0.001	0.00001	0.001	LL	LC	0.00008	0.009	0.00008	0.008
16	0.00002	0.002	LL	LC	0.00016	0.021	0.00001	0.001	0.00001	0.002	LL	LC	0.00006	0.008	0.00007	0.007
17	0.00002	0.002	LL	LC	0.00018	0.021	0.00001	0.001	0.00002	0.002	LL	LC	0.00006	0.007	0.00006	0.006
18	0.00002	0.002	LL	LC	0.00024	0.023	0.00001	0.001	0.00002	0.002	LL	LC	0.00008	0.007	0.00007	0.005
19	0.00002	0.002	LL	LC	0.00018	0.020	0.00001	0.001	0.00002	0.002	LL	LC	0.00006	0.006	0.00007	0.005
20	0.00002	0.002	LL	LC	0.00036	0.029	0.00002	0.002	0.00004	0.002	LL	LC	0.00009	0.007	0.00009	0.006
21	0.00002	0.002	LL	LC	0.00041	0.045	0.00002	0.002	0.00004	0.004	LL	LC	0.00011	0.011	0.00008	0.007
22	0.00006	0.005	LL	LC	0.00061	0.056	0.00005	0.003	0.00011	0.007	LL	LC	0.00018	0.015	0.00016	0.011
23	0.00009	0.008	LL	LC	0.00064	0.062	0.00007	0.006	0.00016	0.012	LL	LC	0.00022	0.020	0.00019	0.015
24	0.00010	0.011	LL	LC	0.00059	0.070	0.00007	0.008	0.00020	0.018	LL	LC	0.00021	0.023	0.00022	0.020
25	0.00006	0.008	LL	LC	0.00034	0.047	0.00004	0.005	0.00012	0.013	LL	LC	0.00013	0.017	0.00013	0.014
26	0.00008	0.009	LL	LC	0.00047	0.048	0.00005	0.005	0.00015	0.014	LL	LC	0.00019	0.018	0.00017	0.014
27	0.00007	0.008	LL	LC	0.00034	0.036	0.00004	0.005	0.00011	0.011	LL	LC	0.00015	0.016	0.00011	0.011
28	0.00004	0.006	LL	LC	0.00016	0.026	0.00002	0.003	0.00007	0.008	LL	LC	0.00007	0.011	0.00008	0.009
29	0.00006	0.005	LL	LC	0.00032	0.026	0.00004	0.003	0.00010	0.007	LL	LC	0.00012	0.010	0.00012	0.008
30	0.00003	0.004	LL	LC	0.00032	0.034	0.00003	0.003	0.00006	0.006	LL	LC	0.00011	0.011	0.00008	0.008
31	0.00002	0.003	LL	LC	0.00024	0.034	0.00002	0.002	0.00005	0.005	LL	LC	0.00008	0.011	0.00007	0.007
32	0.00001	0.002	LL	LC	0.00014	0.021	0.00001	0.002	0.00003	0.004	LL	LC	0.00004	0.007	0.00004	0.005
33	0.00001	0.002	LL	LC	0.00017	0.018	0.00001	0.001	0.00003	0.003	LL	LC	0.00005	0.005	0.00004	0.004
34	0.00002	0.002	LL	LC	0.00025	0.029	0.00001	0.002	0.00003	0.003	LL	LC	0.00006	0.006	0.00004	0.004
35	0.00003	0.002	LL	LC	0.00029	0.025	0.00002	0.002	0.00005	0.004	LL	LC	0.00011	0.009	0.00006	0.005
36	0.00003	0.003	LL	LC	0.00022	0.023	0.00003	0.003	0.00005	0.004	LL	LC	0.00008	0.007	0.00006	0.005
37	0.00005	0.004	LL	LC	0.00075	0.051	0.00005	0.004	0.00009	0.006	LL	LC	0.00017	0.011	0.00010	0.007

NOTE: LL = less than 0.00001 kg/ha; LC = less than 0.001 µg/l.

APPENDIX TABLE D.6--Continued

YEAR	Case: 473.d3d LOAD (kg/ha)	Case: 473.d3d CONC. (µg/l)	Case: 475.d3d LOAD (kg/ha)	Case: 475.d3d CONC. (µg/l)	Case: 533.d2d LOAD (kg/ha)	Case: 533.d2d CONC. (µg/l)	Case: 534.d2d LOAD (kg/ha)	Case: 534.d2d CONC. (µg/l)	Case: 635.d2d LOAD (kg/ha)	Case: 635.d2d CONC. (µg/l)	Case: 443.d2d LOAD (kg/ha)	Case: 443.d2d CONC. (µg/l)	Case: 444.d2d LOAD (kg/ha)	Case: 444.d2d CONC. (µg/l)	Case: 446.d2d LOAD (kg/ha)	Case: 446.d2d CONC. (µg/l)
1	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
2	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
3	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
4	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
5	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
6	0.00005	0.004	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
7	0.00011	0.013	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
8	0.00009	0.013	0.00001	0.001	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
9	0.00015	0.012	0.00003	0.002	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
10	0.00021	0.018	0.00006	0.005	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
11	0.00019	0.019	0.00008	0.006	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
12	0.00015	0.015	0.00007	0.006	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
13	0.00016	0.014	0.00006	0.004	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
14	0.00012	0.016	0.00003	0.003	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
15	0.00012	0.014	0.00003	0.003	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
16	0.00010	0.011	0.00003	0.003	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
17	0.00009	0.010	0.00003	0.003	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
18	0.00011	0.010	0.00003	0.002	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
19	0.00008	0.008	0.00003	0.002	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
20	0.00012	0.009	0.00003	0.002	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
21	0.00013	0.013	0.00002	0.002	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
22	0.00020	0.017	0.00003	0.002	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
23	0.00027	0.022	0.00004	0.003	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
24	0.00026	0.028	0.00005	0.004	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
25	0.00017	0.020	0.00003	0.003	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
26	0.00026	0.022	0.00004	0.003	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
27	0.00020	0.021	0.00003	0.003	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
28	0.00011	0.014	0.00002	0.002	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
29	0.00019	0.014	0.00003	0.002	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
30	0.00016	0.016	0.00002	0.002	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
31	0.00012	0.016	0.00002	0.002	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
32	0.00006	0.009	0.00001	0.001	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
33	0.00006	0.007	0.00001	0.001	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
34	0.00007	0.008	0.00001	0.001	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
35	0.00012	0.010	0.00001	0.001	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
36	0.00008	0.008	0.00001	0.001	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
37	0.00017	0.011	0.00002	0.001	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC

NOTE: LL = less than 0.00001 kg/ha; LC = less than 0.001 µg/l.

APPENDIX TABLE D.6--Continued

YEAR	Case: 453.d2d		Case: 454.d2d		Case: 455.d2d		Case: 456.d2d		Case: 463.d2d		Case: 465.d2d		Case: 473.d2d		Case: 475.d2d	
	LOAD (kg/ha)	CONC. (µg/l)	LOAD (kg/ha)	CONC. (µg/l)	LOAD (kg/ha)	CONC. (µg/l)	LOAD (kg/ha)	CONC. (µg/l)	LOAD (kg/ha)	CONC. (µg/l)	LOAD (kg/ha)	CONC. (µg/l)	LOAD (kg/ha)	CONC. (µg/l)	LOAD (kg/ha)	CONC. (µg/l)
1	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
2	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
3	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
4	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
5	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
6	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
7	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
8	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
9	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
10	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
11	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
12	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
13	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
14	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
15	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
16	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
17	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
18	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
19	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
20	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
21	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
22	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
23	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
24	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
25	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
26	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
27	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
28	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
29	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
30	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
31	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
32	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
33	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
34	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
35	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
36	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
37	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC

NOTE: LL = less than 0.00001 kg/ha; LC = less than 0.001 µg/l.

APPENDIX TABLE D.6--Continued

YEAR	Case: 533.dld LOAD (kg/ha)	Case: 533.dld CONC. (µg/l)	Case: 534.dld LOAD (kg/ha)	Case: 534.dld CONC. (µg/l)	Case: 635.dld LOAD (kg/ha)	Case: 635.dld CONC. (µg/l)	Case: 443.dld LOAD (kg/ha)	Case: 443.dld CONC. (µg/l)	Case: 444.dld LOAD (kg/ha)	Case: 444.dld CONC. (µg/l)	Case: 446.dld LOAD (kg/ha)	Case: 446.dld CONC. (µg/l)	Case: 453.dld LOAD (kg/ha)	Case: 453.dld CONC. (µg/l)	Case: 454.dld LOAD (kg/ha)	Case: 454.dld CONC. (µg/l)
1	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
2	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
3	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
4	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
5	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
6	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
7	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
8	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
9	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
10	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
11	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
12	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
13	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
14	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
15	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
16	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
17	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
18	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
19	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
20	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
21	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
22	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
23	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
24	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
25	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
26	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
27	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
28	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
29	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
30	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
31	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
32	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
33	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
34	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
35	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
36	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
37	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC

NOTE: LL = less than 0.00001 kg/ha; LC = less than 0.001 µg/l.

APPENDIX TABLE D.6--Continued

YEAR	Case: 455.dld LOAD (kg/ha)	Case: 455.dld CONC. (μg/l)	Case: 456.dld LOAD (kg/ha)	Case: 456.dld CONC. (μg/l)	Case: 463.dld LOAD (kg/ha)	Case: 463.dld CONC. (μg/l)	Case: 465.dld LOAD (kg/ha)	Case: 465.dld CONC. (μg/l)	Case: 473.dld LOAD (kg/ha)	Case: 473.dld CONC. (μg/l)	Case: 475.dld LOAD (kg/ha)	Case: 475.dld CONC. (μg/l)
1	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
2	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
3	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
4	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
5	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
6	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
7	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
8	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
9	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
10	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
11	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
12	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
13	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
14	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
15	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
16	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
17	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
18	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
19	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
20	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
21	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
22	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
23	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
24	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
25	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
26	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
27	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
28	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
29	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
30	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
31	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
32	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
33	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
34	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
35	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
36	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
37	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC

NOTE: LL = less than 0.00001 kg/ha; LC = less than 0.001 μg/l.

APPENDIX TABLE D.7. LONG-TERM PRZM SIMULATIONS FOR METRIBUZIN

YEAR	Case: 145.m3 LOAD (kg/ha)	Case: 145.m3 CONC. (µg/l)	Case: 157.m3 LOAD (kg/ha)	Case: 157.m3 CONC. (µg/l)	Case: 166.m3 LOAD (kg/ha)	Case: 166.m3 CONC. (µg/l)	Case: 245.m3 LOAD (kg/ha)	Case: 245.m3 CONC. (µg/l)	Case: 257.m3 LOAD (kg/ha)	Case: 257.m3 CONC. (µg/l)	Case: 266.m3 LOAD (kg/ha)	Case: 266.m3 CONC. (µg/l)	Case: 245.m2 LOAD (kg/ha)	Case: 245.m2 CONC. (µg/l)	Case: 257.m2 LOAD (kg/ha)	Case: 257.m2 CONC. (µg/l)
1	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
2	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
3	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
4	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
5	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
6	0.00079	0.043	LL	LC	LL	LC	0.00016	0.010	LL	LC	LL	LC	LL	LC	LL	LC
7	0.00812	0.879	0.00001	0.001	0.00003	0.003	0.00280	0.306	LL	LC	LL	LC	LL	LC	LL	LC
8	0.0308	3.74	0.00025	0.026	0.00046	0.051	0.0161	1.96	0.00001	0.001	0.00002	0.002	LL	LC	LL	LC
9	0.1903	12.64	0.0193	1.02	0.0255	1.34	0.1212	8.62	0.00225	0.132	0.00301	0.182	LL	LC	LL	LC
10	0.4345	26.75	0.1730	9.31	0.1937	10.51	0.3132	21.10	0.0456	2.80	0.0439	2.88	0.00012	0.008	LL	LC
11	0.4175	37.35	0.3491	23.03	0.4157	25.93	0.3531	32.06	0.1768	12.34	0.1866	12.55	0.00150	0.136	LL	LC
12	0.4866	40.28	0.4607	33.18	0.5628	38.20	0.4282	37.78	0.2894	23.31	0.3272	25.52	0.0101	0.891	0.00004	0.003
13	0.4849	38.14	0.6528	40.45	0.6634	41.01	0.4565	37.87	0.4983	32.90	0.5523	36.90	0.0364	3.02	0.00102	0.067
14	0.3222	38.36	0.4424	40.64	0.3257	36.25	0.3303	39.38	0.4210	39.46	0.3487	40.24	0.0494	5.89	0.00528	0.495
15	0.3109	34.77	0.3322	36.57	0.2976	33.24	0.3254	37.61	0.3555	39.87	0.3404	38.35	0.0856	9.89	0.0148	1.66
16	0.2909	32.83	0.3129	33.52	0.3403	31.08	0.3138	35.45	0.3498	37.92	0.3896	37.03	0.1287	14.54	0.0355	3.85
17	0.3055	32.24	0.2703	31.65	0.2807	30.01	0.3186	33.70	0.3116	36.74	0.3249	35.18	0.1841	19.47	0.0575	6.78
18	0.4887	31.74	0.5817	30.64	0.5335	31.64	0.4541	32.65	0.5482	34.38	0.4932	33.47	0.3409	24.51	0.1940	12.16
19	0.3943	32.96	0.4379	31.83	0.5080	32.02	0.3904	34.01	0.4243	33.15	0.4728	33.17	0.3301	28.75	0.2521	19.69
20	0.6646	34.75	0.5891	31.63	0.6382	32.72	0.5721	34.37	0.5185	32.66	0.5341	33.37	0.4982	29.94	0.4165	26.24
21	0.5681	36.41	0.5282	33.61	0.4902	34.84	0.4869	35.58	0.4472	33.57	0.4131	35.10	0.3855	28.17	0.3962	29.74
22	0.6998	37.19	0.6575	36.22	0.6433	37.47	0.6796	37.60	0.6052	35.22	0.5798	35.97	0.4963	27.46	0.5209	30.32
23	0.6087	35.10	0.5840	36.97	0.5977	39.04	0.5505	35.10	0.5238	36.46	0.5046	37.70	0.4249	27.09	0.4247	29.57
24	0.4518	35.65	0.5117	38.28	0.4923	38.85	0.4174	36.19	0.4669	37.16	0.4612	39.42	0.3133	27.17	0.3484	27.73
25	0.3526	35.49	0.4685	36.75	0.4580	38.13	0.3297	35.11	0.4542	38.33	0.4177	39.10	0.2684	28.58	0.3162	26.68
26	0.4208	33.40	0.5364	36.42	0.5357	38.47	0.4153	35.56	0.4955	36.67	0.4920	38.23	0.3355	28.73	0.3727	27.58
27	0.3359	29.83	0.3764	36.22	0.3544	38.03	0.3790	34.43	0.3697	36.51	0.3477	38.52	0.3206	29.12	0.2836	28.01
28	0.2248	25.99	0.3149	35.08	0.3257	37.48	0.2642	30.56	0.3266	36.49	0.3292	38.23	0.2552	29.51	0.2519	28.14
29	0.4164	24.85	0.5810	32.67	0.5838	34.48	0.4578	29.00	0.5735	36.00	0.5810	37.94	0.4665	29.56	0.4676	29.35
30	0.2636	25.87	0.3329	28.41	0.2990	29.47	0.2665	26.68	0.3768	34.51	0.3488	36.61	0.2826	28.29	0.3288	30.12
31	0.2720	28.79	0.2588	25.86	0.2571	26.48	0.2624	28.40	0.2992	31.72	0.3072	34.05	0.2585	27.98	0.2866	30.39
32	0.2563	31.22	0.2244	24.53	0.2054	24.49	0.2435	29.90	0.2611	29.85	0.2561	31.44	0.2275	27.93	0.2665	30.47
33	0.3825	32.65	0.2968	24.77	0.2932	25.80	0.3518	30.89	0.3201	27.64	0.3119	28.71	0.3020	26.52	0.3510	30.31
34	0.3910	37.45	0.2950	27.85	0.2495	29.16	0.3590	35.16	0.2739	27.86	0.2374	29.16	0.2462	24.11	0.2937	29.87
35	0.6300	39.70	0.5773	31.78	0.5447	32.44	0.5699	38.23	0.4946	29.98	0.4704	30.88	0.3609	24.21	0.4753	28.81
36	0.5086	39.66	0.5070	35.83	0.4164	35.93	0.4921	39.07	0.4523	32.67	0.3738	33.16	0.3018	23.96	0.3910	28.24
37	0.7011	36.75	0.8037	38.23	0.7297	37.54	0.6189	35.73	0.6725	36.38	0.6253	36.46	0.4205	24.28	0.4690	25.38

NOTE: LL = less than 0.00001 kg/ha; LC = less than 0.001 µg/l.

APPENDIX TABLE D.7--Continued

YEAR	Case: 266.m2 LOAD (kg/ha)	Case: 266.m2 CONC. (µg/l)	Case: 245.ml LOAD (kg/ha)	Case: 245.ml CONC. (µg/l)	Case: 257.ml LOAD (kg/ha)	Case: 257.ml CONC. (µg/l)	Case: 266.ml LOAD (kg/ha)	Case: 266.ml CONC. (µg/l)	Case: 145.m3h LOAD (kg/ha)	Case: 145.m3h CONC. (µg/l)	Case: 157.m3h LOAD (kg/ha)	Case: 157.m3h CONC. (µg/l)	Case: 166.m3h LOAD (kg/ha)	Case: 166.m3h CONC. (µg/l)	Case: 245.m3h LOAD (kg/ha)	Case: 245.m3h CONC. (µg/l)
1	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
2	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
3	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
4	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
5	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
6	LL	LC	LL	LC	LL	LC	LL	LC	0.00001	0.001	LL	LC	LL	LC	LL	LC
7	LL	LC	LL	LC	LL	LC	LL	LC	0.00009	0.010	LL	LC	LL	LC	0.00003	0.003
8	LL	LC	LL	LC	LL	LC	LL	LC	0.00021	0.025	LL	LC	LL	LC	0.00010	0.012
9	LL	LC	LL	LC	LL	LC	LL	LC	0.00081	0.054	0.00005	0.003	0.00008	0.004	0.00045	0.032
10	LL	LC	0.00006	0.004	LL	LC	LL	LC	0.00201	0.124	0.00041	0.022	0.00063	0.034	0.00111	0.075
11	LL	LC	0.00078	0.071	LL	LC	LL	LC	0.00180	0.161	0.00073	0.048	0.00134	0.084	0.00115	0.104
12	0.00009	0.007	0.00570	0.503	0.00002	0.001	0.00004	0.003	0.00178	0.147	0.00086	0.062	0.00171	0.116	0.00121	0.107
13	0.00191	0.128	0.0217	1.80	0.00053	0.035	0.00100	0.067	0.00133	0.105	0.00105	0.065	0.00160	0.099	0.00101	0.084
14	0.00610	0.703	0.0305	3.64	0.00292	0.274	0.00335	0.387	0.00066	0.079	0.00059	0.054	0.00062	0.069	0.00055	0.065
15	0.0173	1.94	0.0543	6.28	0.00860	0.965	0.00985	1.11	0.00048	0.053	0.00030	0.032	0.00036	0.040	0.00038	0.044
16	0.0454	4.32	0.0839	9.48	0.0213	2.31	0.0270	2.56	0.00041	0.046	0.00019	0.020	0.00032	0.030	0.00032	0.036
17	0.0735	7.96	0.1235	13.06	0.0357	4.21	0.0452	4.90	0.00045	0.047	0.00013	0.015	0.00025	0.026	0.00034	0.036
18	0.2128	14.44	0.2365	17.01	0.1253	7.86	0.1373	9.32	0.00076	0.050	0.00032	0.017	0.00051	0.030	0.00054	0.039
19	0.3196	22.42	0.2360	20.56	0.1699	13.27	0.2173	15.25	0.00055	0.046	0.00023	0.017	0.00043	0.027	0.00043	0.037
20	0.4497	28.09	0.3635	21.84	0.2928	18.45	0.3205	20.03	0.00098	0.051	0.00028	0.015	0.00050	0.026	0.00064	0.038
21	0.3518	29.89	0.2820	20.61	0.2886	21.67	0.2586	21.97	0.00106	0.068	0.00027	0.017	0.00041	0.029	0.00064	0.047
22	0.4845	30.06	0.3599	19.92	0.3877	22.57	0.3602	22.35	0.00210	0.112	0.00038	0.021	0.00056	0.033	0.00125	0.069
23	0.3745	27.98	0.3065	19.54	0.3170	22.07	0.2772	20.71	0.00339	0.195	0.00037	0.023	0.00061	0.040	0.00168	0.107
24	0.3178	27.16	0.2255	19.56	0.2578	20.51	0.2337	19.98	0.00341	0.269	0.00037	0.027	0.00063	0.050	0.00178	0.154
25	0.2913	27.27	0.1927	20.52	0.2328	19.65	0.2143	20.06	0.00207	0.209	0.00034	0.027	0.00055	0.046	0.00116	0.124
26	0.3610	28.05	0.2398	20.54	0.2750	20.35	0.2666	20.72	0.00265	0.210	0.00056	0.038	0.00081	0.058	0.00157	0.134
27	0.2566	28.43	0.2276	20.67	0.2098	20.72	0.1900	21.05	0.00176	0.157	0.00037	0.035	0.00048	0.051	0.00126	0.114
28	0.2521	29.27	0.1797	20.79	0.1863	20.81	0.1867	21.68	0.00090	0.104	0.00023	0.026	0.00032	0.037	0.00070	0.081
29	0.4673	30.52	0.3256	20.63	0.3447	21.63	0.3450	22.53	0.00170	0.101	0.00044	0.025	0.00055	0.033	0.00129	0.082
30	0.2963	31.10	0.1966	19.69	0.2410	22.08	0.2174	22.82	0.00090	0.089	0.00024	0.020	0.00024	0.024	0.00068	0.068
31	0.2846	31.55	0.1804	19.52	0.2089	22.15	0.2073	22.98	0.00073	0.077	0.00018	0.018	0.00019	0.019	0.00055	0.059
32	0.2582	31.70	0.1594	19.57	0.1928	22.05	0.1864	22.89	0.00045	0.055	0.00011	0.012	0.00011	0.013	0.00034	0.042
33	0.3452	31.77	0.2128	18.68	0.2517	21.73	0.2468	22.72	0.00049	0.042	0.00010	0.008	0.00011	0.009	0.00037	0.032
34	0.2518	30.93	0.1746	17.10	0.2090	21.26	0.1787	21.95	0.00051	0.049	0.00009	0.009	0.00009	0.010	0.00039	0.038
35	0.4642	30.47	0.2579	17.30	0.3374	20.46	0.3284	21.56	0.00084	0.053	0.00018	0.010	0.00016	0.010	0.00062	0.042
36	0.3381	30.00	0.2172	17.25	0.2784	20.11	0.2398	21.28	0.00073	0.057	0.00014	0.010	0.00010	0.009	0.00057	0.045
37	0.4702	27.42	0.3027	17.47	0.3354	18.15	0.3353	19.55	0.00144	0.076	0.00028	0.013	0.00022	0.011	0.00104	0.060

NOTE: LL = less than 0.00001 kg/ha; LC = less than 0.001 µg/l.

APPENDIX TABLE D.7--Continued

YEAR	Case: 257.m3h LOAD (kg/ha)	Case: 257.m3h CONC. (µg/l)	Case: 266.m3h LOAD (kg/ha)	Case: 266.m3h CONC. (µg/l)	Case: 245.m2h LOAD (kg/ha)	Case: 245.m2h CONC. (µg/l)	Case: 257.m2h LOAD (kg/ha)	Case: 257.m2h CONC. (µg/l)	Case: 266.m2h LOAD (kg/ha)	Case: 266.m2h CONC. (µg/l)	Case: 245.m1h LOAD (kg/ha)	Case: 245.m1h CONC. (µg/l)	Case: 257.m1h LOAD (kg/ha)	Case: 257.m1h CONC. (µg/l)	Case: 266.m1h LOAD (kg/ha)	Case: 266.m1h CONC. (µg/l)
1	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
2	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
3	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
4	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
5	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
6	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
7	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
8	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
9	0.00001	LC	0.00001	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
10	0.00008	0.005	0.00009	0.006	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
11	0.00023	0.016	0.00032	0.022	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
12	0.00031	0.025	0.00052	0.041	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
13	0.00047	0.031	0.00075	0.050	0.00001	0.001	LL	LC	LL	LC	0.00001	0.001	LL	LC	LL	LC
14	0.00036	0.033	0.00039	0.045	0.00001	0.001	LL	LC	LL	LC	0.00001	0.001	LL	LC	LL	LC
15	0.00021	0.023	0.00025	0.028	0.00001	0.001	LL	LC	LL	LC	0.00001	0.001	LL	LC	LL	LC
16	0.00014	0.015	0.00021	0.020	0.00001	0.001	LL	LC	LL	LC	0.00001	0.001	LL	LC	LL	LC
17	0.00010	0.011	0.00014	0.015	0.00001	0.001	LL	LC	LL	LC	0.00001	0.001	LL	LC	LL	LC
18	0.00016	0.010	0.00022	0.015	0.00002	0.001	LL	LC	0.00001	LC	0.00001	0.001	LL	LC	LL	LC
19	0.00012	0.009	0.00022	0.015	0.00001	0.001	LL	LC	0.00001	LC	0.00001	0.001	LL	LC	LL	LC
20	0.00015	0.009	0.00025	0.015	0.00002	0.001	LL	LC	0.00001	LC	0.00001	0.001	LL	LC	0.00001	LC
21	0.00013	0.010	0.00019	0.016	0.00002	0.001	LL	LC	LL	LC	0.00001	0.001	LL	LC	LL	LC
22	0.00019	0.011	0.00027	0.017	0.00003	0.002	LL	LC	0.00001	LC	0.00002	0.001	LL	LC	LL	LC
23	0.00018	0.013	0.00025	0.019	0.00003	0.002	LL	LC	0.00001	LC	0.00002	0.001	LL	LC	LL	LC
24	0.00016	0.013	0.00024	0.020	0.00003	0.002	LL	LC	0.00001	LC	0.00002	0.002	LL	LC	LL	LC
25	0.00014	0.012	0.00019	0.018	0.00002	0.002	LL	LC	LL	LC	0.00001	0.001	LL	LC	LL	LC
26	0.00020	0.015	0.00028	0.022	0.00002	0.002	LL	LC	LL	LC	0.00002	0.001	LL	LC	LL	LC
27	0.00016	0.016	0.00020	0.022	0.00002	0.002	LL	LC	LL	LC	0.00001	0.001	LL	LC	LL	LC
28	0.00012	0.013	0.00015	0.018	0.00002	0.002	LL	LC	LL	LC	0.00001	0.001	LL	LC	LL	LC
29	0.00022	0.014	0.00028	0.018	0.00004	0.003	LL	LC	LL	LC	0.00003	0.002	LL	LC	LL	LC
30	0.00015	0.013	0.00015	0.016	0.00003	0.003	LL	LC	LL	LC	0.00002	0.002	LL	LC	LL	LC
31	0.00011	0.012	0.00012	0.013	0.00002	0.003	LL	LC	LL	LC	0.00002	0.002	LL	LC	LL	LC
32	0.00007	0.008	0.00007	0.009	0.00002	0.002	LL	LC	LL	LC	0.00001	0.001	LL	LC	LL	LC
33	0.00007	0.006	0.00006	0.006	0.00002	0.001	LL	LC	LL	LC	0.00001	0.001	LL	LC	LL	LC
34	0.00005	0.006	0.00005	0.006	0.00001	0.001	LL	LC	LL	LC	0.00001	0.001	LL	LC	LL	LC
35	0.00009	0.006	0.00009	0.006	0.00002	0.001	LL	LC	LL	LC	0.00001	0.001	LL	LC	LL	LC
36	0.00008	0.006	0.00006	0.005	0.00001	0.001	LL	LC	LL	LC	0.00001	0.001	LL	LC	LL	LC
37	0.00014	0.008	0.00012	0.007	0.00002	0.001	LL	LC	LL	LC	0.00002	0.001	LL	LC	LL	LC

NOTE: LL = less than 0.00001 kg/ha; LC = less than 0.001 µg/l.

APPENDIX TABLE D.7--Continued

YEAR	Case: 245b.m2 LOAD (kg/ha)	Case: 245b.m2 CONC. (µg/l)	Case: 257b.m2 LOAD (kg/ha)	Case: 257b.m2 CONC. (µg/l)	Case: 266b.m2 LOAD (kg/ha)	Case: 266b.m2 CONC. (µg/l)	Case: 245b.m2h LOAD (kg/ha)	Case: 245b.m2h CONC. (µg/l)	Case: 257b.m2h LOAD (kg/ha)	Case: 257b.m2h CONC. (µg/l)	Case: 266b.m2h LOAD (kg/ha)	Case: 266b.m2h CONC. (µg/l)
1	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
2	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
3	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
4	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
5	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
6	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
7	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
8	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
9	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
10	0.00004	0.002	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
11	0.00067	0.061	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
12	0.00601	0.530	0.00001	0.001	0.00004	0.003	LL	LC	LL	LC	LL	LC
13	0.0262	2.17	0.00047	0.031	0.00114	0.076	0.00001	0.001	LL	LC	LL	LC
14	0.0392	4.68	0.00307	0.287	0.00426	0.492	0.00001	0.001	LL	LC	LL	LC
15	0.0712	8.23	0.0101	1.14	0.0133	1.50	0.00001	0.001	LL	LC	LL	LC
16	0.1083	12.23	0.0271	2.94	0.0372	3.53	0.00001	0.001	LL	LC	LL	LC
17	0.1518	16.06	0.0473	5.58	0.0612	6.63	0.00001	0.001	LL	LC	LL	LC
18	0.2688	19.33	0.1664	10.44	0.1725	11.71	0.00001	0.001	LL	LC	0.00001	LC
19	0.2541	22.13	0.2107	16.46	0.2455	17.23	0.00001	0.001	LL	LC	0.00001	LC
20	0.4027	24.20	0.3257	20.52	0.3367	21.04	0.00002	0.001	LL	LC	0.00001	LC
21	0.3477	25.41	0.2986	22.42	0.2723	23.13	0.00002	0.001	LL	LC	LL	LC
22	0.4857	26.87	0.4090	23.80	0.4091	25.38	0.00003	0.002	LL	LC	0.00001	LC
23	0.4158	26.51	0.3708	25.81	0.3501	26.16	0.00003	0.002	LL	LC	0.00001	LC
24	0.2914	25.27	0.3312	26.36	0.3105	26.54	0.00002	0.002	LL	LC	0.00001	LC
25	0.2388	25.42	0.3091	26.08	0.2831	26.50	0.00001	0.002	LL	LC	LL	LC
26	0.2896	24.80	0.3570	26.42	0.3371	26.19	0.00002	0.002	LL	LC	LL	LC
27	0.2769	25.15	0.2599	25.67	0.2273	25.19	0.00002	0.002	LL	LC	LL	LC
28	0.2263	26.18	0.2213	24.72	0.2137	24.81	0.00002	0.002	LL	LC	LL	LC
29	0.4362	27.64	0.3905	24.51	0.3768	24.61	0.00004	0.003	LL	LC	LL	LC
30	0.2794	27.97	0.2652	24.29	0.2327	24.43	0.00003	0.003	LL	LC	LL	LC
31	0.2672	28.92	0.2316	24.56	0.2248	24.92	0.00003	0.003	LL	LC	LL	LC
32	0.2464	30.26	0.2209	25.26	0.2084	25.59	0.00002	0.002	LL	LC	LL	LC
33	0.3476	30.52	0.3048	26.31	0.2884	26.54	0.00002	0.002	LL	LC	LL	LC
34	0.3009	29.46	0.2694	27.41	0.2180	26.78	0.00002	0.002	LL	LC	LL	LC
35	0.4577	30.70	0.4674	28.34	0.4213	27.66	0.00002	0.002	LL	LC	LL	LC
36	0.3778	30.00	0.4204	30.36	0.3274	29.05	0.00002	0.001	LL	LC	LL	LC
37	0.4897	28.27	0.5585	30.22	0.5003	29.17	0.00002	0.001	LL	LC	LL	LC

NOTE: LL = less than 0.00001 kg/ha; LC = less than 0.001 µg/l.

APPENDIX TABLE D.8. LONG-TERM PRZM SIMULATIONS FOR NITRATE

YEAR	Case: 133.n3 LOAD (kg/ha)	Case: 133.n3 CONC. (mg/l)	Case: 134.n3 LOAD (kg/ha)	Case: 134.n3 CONC. (mg/l)	Case: 135.n3 LOAD (kg/ha)	Case: 135.n3 CONC. (mg/l)	Case: 143.n3 LOAD (kg/ha)	Case: 143.n3 CONC. (mg/l)	Case: 144.n3 LOAD (kg/ha)	Case: 144.n3 CONC. (mg/l)	Case: 145.n3 LOAD (kg/ha)	Case: 145.n3 CONC. (mg/l)	Case: 146.n3 LOAD (kg/ha)	Case: 146.n3 CONC. (mg/l)	Case: 153.n3 LOAD (kg/ha)	Case: 153.n3 CONC. (mg/l)
1	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
2	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
3	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
4	LL	LC	LL	LC	LL	LC	0.0026	LC	LL	LC	LL	LC	LL	LC	0.0119	0.001
5	0.0005	LC	0.0004	LC	LL	LC	0.355	0.026	0.0012	LC	LL	LC	LL	LC	0.944	0.062
6	0.233	0.015	0.232	0.014	0.0224	0.001	5.05	0.310	0.376	0.023	0.0268	0.002	0.0007	LC	10.07	0.508
7	0.972	0.128	0.926	0.119	0.202	0.025	6.35	0.745	1.41	0.167	0.283	0.031	0.0261	0.002	10.73	0.921
8	2.16	0.320	2.40	0.329	0.963	0.117	6.81	0.974	2.79	0.412	1.13	0.137	0.249	0.026	8.22	0.978
9	7.83	0.672	8.19	0.648	6.28	0.427	15.26	1.111	9.61	0.728	7.20	0.478	3.59	0.217	14.09	0.980
10	16.10	1.084	15.81	1.019	13.64	0.849	14.47	0.960	16.65	1.024	14.72	0.906	11.93	0.679	14.24	0.838
11	12.46	1.055	11.71	1.016	11.87	1.007	12.39	1.027	11.39	0.975	11.28	1.009	11.67	0.909	9.95	0.848
12	13.06	1.082	11.92	0.953	12.04	0.929	13.64	1.070	12.13	0.920	11.11	0.920	12.75	0.897	12.11	0.900
13	13.85	1.110	13.20	1.020	11.61	0.896	16.46	1.290	14.51	1.003	10.51	0.827	11.60	0.825	15.30	1.098
14	10.08	1.216	9.51	1.126	8.31	0.955	10.12	1.244	9.89	1.136	7.39	0.879	7.34	0.760	9.13	1.052
15	13.42	1.396	12.04	1.300	9.63	1.050	9.62	1.163	13.09	1.314	8.31	0.930	7.36	0.783	10.28	0.983
16	10.82	1.347	10.92	1.291	10.97	1.182	8.35	1.079	10.48	1.226	9.54	1.076	8.03	0.843	8.74	0.905
17	12.26	1.269	11.78	1.228	12.24	1.245	9.90	0.993	10.87	1.141	11.33	1.196	10.12	0.979	10.37	0.934
18	16.03	1.083	15.84	1.070	16.78	1.081	14.40	0.981	14.56	1.000	16.89	1.097	18.08	1.066	15.09	0.971
19	10.20	1.044	10.97	1.013	11.57	0.954	10.90	1.008	11.28	0.988	11.53	0.964	12.23	0.910	11.68	0.998
20	18.09	1.078	17.44	1.014	16.44	0.962	20.72	1.236	17.16	0.975	18.51	0.968	15.19	0.849	22.35	1.197
21	16.96	1.257	18.07	1.211	15.65	1.023	17.84	1.346	16.70	1.147	16.41	1.052	13.35	0.894	16.66	1.204
22	19.83	1.304	22.12	1.281	21.65	1.228	20.84	1.370	21.05	1.227	23.67	1.258	17.34	0.949	16.54	1.176
23	19.74	1.309	21.94	1.298	22.64	1.288	19.49	1.209	21.35	1.270	22.91	1.321	18.93	1.148	16.07	1.093
24	13.74	1.242	15.53	1.210	15.48	1.192	13.63	1.168	14.87	1.197	15.58	1.230	16.12	1.229	13.04	1.074
25	12.07	1.237	12.57	1.173	12.51	1.131	10.21	1.067	10.96	1.153	11.46	1.154	13.88	1.205	8.91	0.934
26	14.56	1.103	14.68	1.020	16.51	1.095	11.99	0.925	13.26	1.044	13.90	1.104	14.21	1.071	11.86	0.896
27	11.53	0.975	11.33	0.917	11.81	0.956	10.34	0.867	11.11	0.956	11.18	0.993	12.02	1.034	10.13	0.834
28	4.80	0.814	6.03	0.746	8.90	0.907	5.71	0.824	6.45	0.806	7.35	0.850	9.22	1.014	6.87	0.862
29	10.62	0.878	11.39	0.766	12.59	0.747	12.62	0.895	11.96	0.768	12.99	0.775	16.13	0.915	15.24	0.925
30	9.73	0.904	9.03	0.795	8.62	0.742	11.18	0.954	8.78	0.782	7.18	0.704	8.14	0.834	12.83	1.006
31	7.37	0.940	7.94	0.850	8.24	0.783	9.37	1.078	7.63	0.821	6.75	0.714	7.16	0.737	10.29	1.092
32	7.53	0.985	8.13	0.937	7.95	0.843	8.43	1.043	7.78	0.931	6.17	0.752	6.25	0.746	8.99	1.064
33	11.67	1.066	12.00	1.001	11.94	0.943	14.40	1.210	12.69	1.054	9.62	0.821	8.99	0.762	15.50	1.204
34	11.86	1.130	11.59	1.019	11.68	0.981	12.75	1.152	12.14	1.108	10.33	0.990	8.62	0.817	12.73	1.096
35	15.69	1.167	16.86	1.111	17.10	1.035	17.36	1.188	18.31	1.189	17.24	1.086	15.49	0.919	16.73	1.057
36	11.39	1.225	12.17	1.069	13.68	1.036	12.41	1.164	12.89	1.094	15.24	1.188	14.68	1.016	12.52	1.043
37	23.22	1.314	20.97	1.123	19.03	0.982	24.16	1.281	21.47	1.124	20.55	1.077	21.96	1.104	24.41	1.216

NOTE: LL = less than 0.0001 kg/ha; LC = less than 0.001 mg/l.

APPENDIX TABLE D.8--Continued

YEAR	Case: 154.n3 LOAD (kg/ha)	Case: 154.n3 CONC. (mg/l)	Case: 155.n3 LOAD (kg/ha)	Case: 155.n3 CONC. (mg/l)	Case: 156.n3 LOAD (kg/ha)	Case: 156.n3 CONC. (mg/l)	Case: 157.n3 LOAD (kg/ha)	Case: 157.n3 CONC. (mg/l)	Case: 163.n3 LOAD (kg/ha)	Case: 163.n3 CONC. (mg/l)	Case: 165.n3 LOAD (kg/ha)	Case: 165.n3 CONC. (mg/l)	Case: 166.n3 LOAD (kg/ha)	Case: 166.n3 CONC. (mg/l)	Case: 173.n3 LOAD (kg/ha)	Case: 173.n3 CONC. (mg/l)
1	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
2	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
3	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
4	LL	LC	LL	LC	LL	LC	LL	LC	0.0001	LC	LL	LC	LL	LC	0.0001	LC
5	0.0003	LC	0.0001	LC	LL	LC	LL	LC	0.0748	0.005	0.0004	LC	LL	LC	0.0564	0.004
6	0.271	0.015	0.148	0.008	LL	LC	LL	LC	3.65	0.192	0.360	0.018	LL	LC	3.09	0.166
7	1.40	0.146	0.764	0.090	0.0006	LC	0.0003	LC	6.71	0.630	1.82	0.174	0.0014	LC	5.79	0.576
8	2.99	0.388	1.69	0.248	0.0114	0.001	0.0090	LC	7.26	0.843	3.77	0.460	0.0208	0.002	6.19	0.789
9	9.87	0.712	6.68	0.539	0.629	0.038	0.722	0.038	14.52	0.951	13.68	0.843	1.23	0.065	14.73	0.954
10	16.54	0.978	15.05	0.925	6.01	0.341	6.57	0.354	15.65	0.911	18.37	1.046	9.15	0.496	16.18	0.935
11	11.21	0.969	11.86	1.047	10.84	0.796	12.20	0.805	10.04	0.825	12.39	0.918	15.87	0.990	10.66	0.845
12	11.85	0.870	12.20	0.937	13.84	0.998	13.00	0.936	12.23	0.871	11.54	0.816	15.13	1.027	12.52	0.898
13	13.17	0.918	13.76	0.958	14.26	0.950	13.91	0.862	14.17	0.991	12.98	0.870	13.68	0.846	14.96	1.031
14	8.90	1.011	8.82	1.012	7.65	0.829	8.35	0.768	10.59	1.151	8.80	1.036	6.39	0.711	10.54	1.193
15	12.80	1.153	12.37	1.158	6.87	0.770	6.40	0.705	11.91	1.052	11.79	1.129	6.18	0.690	11.87	1.083
16	11.52	1.182	12.09	1.270	7.45	0.788	6.51	0.698	9.78	0.936	10.95	1.063	8.13	0.743	9.88	0.941
17	11.02	1.068	11.32	1.194	7.90	0.847	6.36	0.745	9.53	0.878	8.68	0.894	8.04	0.860	8.85	0.884
18	14.70	0.958	16.14	1.072	17.02	1.029	17.10	0.901	14.40	0.922	13.44	0.852	16.83	0.998	13.34	0.900
19	12.38	0.964	14.73	1.013	15.10	1.035	13.42	0.976	11.88	0.956	12.99	0.878	13.65	0.860	11.66	0.948
20	18.86	0.972	20.61	1.007	16.60	0.867	14.72	0.790	20.47	1.051	18.37	0.933	14.48	0.742	19.54	1.026
21	17.15	1.132	18.50	1.153	13.13	0.859	11.97	0.762	16.60	1.158	15.84	1.118	10.98	0.780	15.22	1.159
22	19.98	1.186	23.16	1.217	16.65	0.906	15.25	0.840	16.98	1.151	20.03	1.204	14.54	0.847	17.00	1.175
23	19.78	1.191	20.90	1.189	16.88	1.049	13.90	0.880	17.24	1.087	19.13	1.192	14.92	0.975	18.40	1.158
24	14.18	1.077	15.05	1.083	15.94	1.207	13.70	1.025	13.12	1.051	13.67	1.066	14.53	1.146	13.03	1.096
25	9.98	1.065	11.00	0.986	15.01	1.256	14.87	1.166	10.74	1.035	11.06	1.011	14.58	1.214	11.13	1.090
26	12.72	1.005	11.67	0.856	16.21	1.190	17.90	1.215	12.72	0.886	13.06	0.939	16.33	1.173	13.97	0.945
27	10.09	0.852	9.22	0.773	11.48	1.076	11.68	1.124	10.05	0.816	8.99	0.841	9.95	1.067	9.96	0.865
28	7.60	0.835	7.10	0.724	9.21	1.030	9.31	1.037	6.86	0.798	7.72	0.820	8.76	1.008	7.42	0.828
29	13.24	0.751	12.58	0.684	16.47	0.936	17.69	0.995	15.51	0.851	13.69	0.763	15.83	0.935	16.00	0.878
30	9.49	0.768	8.32	0.719	8.43	0.827	10.61	0.906	12.14	0.902	8.96	0.791	8.64	0.852	11.84	0.913
31	8.36	0.815	8.51	0.796	7.53	0.776	8.28	0.827	9.65	0.998	8.55	0.842	7.97	0.821	9.38	1.005
32	8.25	0.903	8.43	0.893	6.16	0.716	7.01	0.767	8.58	1.018	8.17	0.915	6.48	0.772	8.24	1.030
33	13.82	1.049	12.83	0.990	8.62	0.734	8.68	0.725	13.81	1.039	12.54	1.016	8.63	0.759	12.81	1.040
34	12.82	1.106	11.37	1.025	7.53	0.768	7.99	0.754	13.61	1.161	10.28	1.035	6.73	0.787	12.27	1.164
35	19.71	1.172	19.17	1.100	14.43	0.850	14.95	0.823	16.37	0.991	19.40	1.134	14.14	0.842	16.36	1.034
36	13.05	0.995	13.16	0.947	12.94	0.966	12.79	0.904	12.29	0.968	12.95	1.015	10.97	0.947	11.73	0.985
37	20.74	1.005	20.61	0.989	21.17	1.059	20.44	0.972	22.68	1.091	20.54	1.005	19.98	1.028	21.16	1.051

NOTE: LL = less than 0.0001 kg/ha; LC = less than 0.001 mg/l.

APPENDIX TABLE D.8--Continued

YEAR	Case: 175.n3 LOAD (kg/ha)	Case: 175.n3 CONC. (mg/l)	Case: 533.n2 LOAD (kg/ha)	Case: 533.n2 CONC. (mg/l)	Case: 534.n2 LOAD (kg/ha)	Case: 534.n2 CONC. (mg/l)	Case: 635.n2 LOAD (kg/ha)	Case: 635.n2 CONC. (mg/l)	Case: 443.n2 LOAD (kg/ha)	Case: 443.n2 CONC. (mg/l)	Case: 444.n2 LOAD (kg/ha)	Case: 444.n2 CONC. (mg/l)	Case: 245.n2 LOAD (kg/ha)	Case: 245.n2 CONC. (mg/l)	Case: 446.n2 LOAD (kg/ha)	Case: 446.n2 CONC. (mg/l)
1	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
2	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
3	LL	LC	LL	LC	LL	LC	0.0907	0.011	LL	LC	LL	LC	LL	LC	LL	LC
4	LL	LC	LL	LC	LL	LC	1.37	0.188	LL	LC	LL	LC	LL	LC	LL	LC
5	LL	LC	0.0030	LC	0.0110	0.001	2.01	0.251	0.0351	0.004	0.0012	LC	LL	LC	LL	LC
6	0.0121	LC	0.396	0.039	0.841	0.078	2.13	0.242	1.11	0.103	0.246	0.022	LL	LC	0.0398	0.003
7	0.288	0.023	1.18	0.215	1.84	0.307	1.32	0.229	2.47	0.373	1.13	0.161	LL	LC	0.699	0.070
8	1.16	0.132	2.12	0.431	2.72	0.485	1.53	0.262	3.05	0.576	2.09	0.368	LL	LC	2.36	0.274
9	9.65	0.533	4.94	0.599	4.91	0.544	1.99	0.236	6.11	0.637	5.41	0.548	LL	LC	6.17	0.470
10	17.55	0.990	5.31	0.586	5.15	0.508	2.39	0.271	5.98	0.616	6.06	0.572	0.0081	0.001	6.42	0.492
11	14.60	0.994	4.87	0.591	4.55	0.526	2.61	0.344	5.43	0.620	5.08	0.549	0.0995	0.009	4.92	0.452
12	11.66	0.850	4.36	0.564	4.27	0.517	1.92	0.276	5.10	0.606	5.34	0.571	0.635	0.056	4.66	0.438
13	11.79	0.767	5.07	0.605	5.08	0.573	1.56	0.211	6.24	0.696	6.06	0.585	2.15	0.178	5.01	0.438
14	7.14	0.809	4.60	0.729	4.56	0.694	1.41	0.237	4.95	0.790	4.95	0.675	2.74	0.327	4.17	0.472
15	10.62	0.918	5.56	0.760	4.88	0.686	1.67	0.262	5.16	0.797	6.14	0.762	4.41	0.510	4.51	0.542
16	11.95	1.049	3.89	0.634	3.80	0.561	1.97	0.290	4.05	0.668	5.29	0.720	6.02	0.680	5.22	0.583
17	9.51	1.004	4.31	0.568	3.81	0.493	1.88	0.263	4.87	0.610	4.83	0.591	7.67	0.811	4.86	0.509
18	13.33	0.813	5.43	0.569	5.17	0.528	2.69	0.329	6.31	0.621	5.84	0.569	12.33	0.887	5.24	0.437
19	11.47	0.788	4.06	0.575	4.44	0.554	2.27	0.303	5.33	0.672	5.29	0.595	10.84	0.945	5.23	0.470
20	16.83	0.867	6.49	0.625	6.51	0.595	2.35	0.260	7.73	0.701	7.20	0.605	16.60	0.997	6.74	0.521
21	11.86	0.929	5.73	0.673	6.21	0.658	1.90	0.252	7.11	0.808	6.43	0.651	14.23	1.040	5.51	0.526
22	15.21	1.066	7.55	0.666	8.16	0.637	2.88	0.277	9.42	0.797	9.63	0.706	19.56	1.082	8.90	0.596
23	17.52	1.145	6.18	0.594	6.49	0.564	2.04	0.230	7.60	0.706	7.86	0.664	16.63	1.060	7.84	0.630
24	13.90	1.141	4.64	0.619	5.27	0.591	1.87	0.241	5.46	0.669	5.78	0.637	12.00	1.041	6.08	0.565
25	11.99	1.104	4.21	0.615	4.14	0.534	1.28	0.197	4.79	0.680	4.62	0.632	10.27	1.093	4.75	0.529
26	15.09	1.028	4.94	0.523	4.91	0.468	1.92	0.215	5.63	0.586	5.89	0.606	13.17	1.128	5.63	0.544
27	9.67	0.988	4.27	0.476	3.90	0.411	1.83	0.229	5.18	0.552	4.90	0.515	13.30	1.208	5.21	0.517
28	8.76	0.923	1.80	0.436	2.47	0.388	2.13	0.301	2.77	0.529	3.32	0.488	11.17	1.292	4.10	0.486
29	15.49	0.869	4.12	0.468	4.39	0.419	2.04	0.226	5.61	0.524	5.43	0.457	21.21	1.344	6.07	0.449
30	9.43	0.822	3.51	0.483	3.81	0.476	1.62	0.238	4.99	0.591	4.01	0.465	12.79	1.281	3.45	0.416
31	8.21	0.865	3.13	0.567	3.69	0.543	1.86	0.291	4.26	0.658	4.05	0.551	11.47	1.241	3.52	0.429
32	7.41	0.885	3.31	0.602	3.38	0.508	1.41	0.231	4.19	0.687	4.37	0.633	9.89	1.215	3.37	0.453
33	10.83	0.918	4.28	0.567	4.30	0.491	1.66	0.230	5.50	0.629	5.92	0.632	12.85	1.128	5.07	0.528
34	9.18	0.996	4.05	0.555	4.56	0.547	2.05	0.276	5.53	0.677	5.38	0.626	10.20	0.999	4.99	0.560
35	17.33	1.040	6.21	0.658	5.88	0.560	2.79	0.325	7.41	0.696	7.33	0.642	14.28	0.958	6.99	0.561
36	13.29	1.121	4.82	0.660	4.79	0.528	2.64	0.304	5.80	0.666	5.90	0.594	11.23	0.892	7.30	0.579
37	21.46	1.070	8.28	0.673	7.90	0.619	2.52	0.251	10.10	0.742	8.64	0.622	15.09	0.871	7.54	0.526

NOTE: LL = less than 0.0001 kg/ha; LC = less than 0.001 mg/l.

APPENDIX TABLE D.8--Continued

YEAR	Case: 453.n2 LOAD (kg/ha)	Case: 453.n2 CONC. (mg/l)	Case: 454.n2 LOAD (kg/ha)	Case: 454.n2 CONC. (mg/l)	Case: 455.n2 LOAD (kg/ha)	Case: 455.n2 CONC. (mg/l)	Case: 456.n2 LOAD (kg/ha)	Case: 456.n2 CONC. (mg/l)	Case: 257.n2 LOAD (kg/ha)	Case: 257.n2 CONC. (mg/l)	Case: 463.n2 LOAD (kg/ha)	Case: 463.n2 CONC. (mg/l)	Case: 465.n2 LOAD (kg/ha)	Case: 465.n2 CONC. (mg/l)	Case: 266.n2 LOAD (kg/ha)	Case: 266.n2 CONC. (mg/l)
1	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
2	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
3	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
4	0.0005	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
5	0.196	0.018	0.0010	LC	LL	LC	LL	LC	LL	LC	0.0416	0.004	0.0261	0.002	LL	LC
6	3.38	0.258	0.249	0.021	0.0191	0.002	0.0114	0.001	LL	LC	1.51	0.122	1.36	0.099	LL	LC
7	5.15	0.560	1.38	0.174	0.266	0.034	0.431	0.039	LL	LC	3.57	0.418	4.06	0.392	LL	LC
8	3.96	0.603	2.50	0.389	0.960	0.151	2.05	0.220	LL	LC	3.79	0.552	4.81	0.548	LL	LC
9	5.78	0.538	5.78	0.550	3.71	0.366	6.38	0.465	LL	LC	6.32	0.552	7.03	0.524	LL	LC
10	5.63	0.525	5.92	0.547	5.92	0.537	6.87	0.514	LL	LC	5.62	0.502	5.81	0.460	LL	LC
11	4.30	0.509	4.75	0.519	5.29	0.548	5.56	0.453	LL	LC	4.96	0.526	5.12	0.431	0.0003	LC
12	4.49	0.497	5.19	0.538	5.16	0.531	4.58	0.413	0.0029	LC	5.00	0.513	4.98	0.449	0.0088	0.001
13	5.90	0.595	5.61	0.532	5.87	0.532	5.17	0.410	0.0720	0.005	5.99	0.572	6.54	0.526	0.171	0.011
14	4.55	0.676	4.42	0.608	4.23	0.534	4.19	0.446	0.349	0.033	4.81	0.664	4.88	0.576	0.513	0.059
15	5.01	0.632	6.01	0.690	5.49	0.621	4.68	0.511	0.930	0.104	5.54	0.644	4.97	0.487	1.36	0.153
16	4.21	0.544	5.66	0.682	6.13	0.702	5.22	0.546	2.10	0.228	4.56	0.534	4.29	0.429	3.26	0.310
17	5.04	0.564	4.88	0.561	5.76	0.664	4.56	0.467	3.19	0.376	4.57	0.519	4.48	0.451	4.67	0.506
18	6.63	0.621	5.96	0.554	6.01	0.553	5.21	0.417	9.42	0.591	6.15	0.568	6.02	0.489	11.08	0.752
19	5.60	0.639	5.91	0.592	6.51	0.559	5.61	0.446	10.18	0.795	5.39	0.576	6.28	0.497	12.95	0.908
20	8.64	0.685	7.72	0.592	8.05	0.572	6.74	0.489	13.73	0.865	8.14	0.616	7.68	0.550	14.66	0.916
21	6.62	0.723	6.62	0.648	6.59	0.596	5.34	0.487	11.35	0.852	6.51	0.673	6.05	0.581	10.45	0.887
22	7.28	0.660	9.04	0.671	9.86	0.640	8.87	0.561	14.80	0.861	7.71	0.652	8.01	0.550	15.01	0.931
23	6.28	0.611	7.24	0.612	7.85	0.612	7.55	0.584	13.36	0.930	6.83	0.594	6.30	0.506	12.71	0.950
24	5.15	0.612	5.66	0.585	6.25	0.570	6.38	0.540	11.83	0.942	5.42	0.600	5.58	0.496	11.09	0.948
25	4.42	0.615	4.40	0.593	4.92	0.556	4.99	0.500	10.78	0.909	4.63	0.591	4.42	0.475	9.94	0.931
26	5.15	0.529	5.28	0.553	5.42	0.495	5.93	0.499	12.24	0.906	5.62	0.522	5.52	0.460	11.82	0.918
27	5.04	0.532	4.74	0.489	4.64	0.455	4.82	0.463	9.01	0.889	4.87	0.503	4.57	0.454	8.13	0.900
28	3.26	0.534	3.70	0.484	3.86	0.433	4.22	0.452	7.89	0.881	3.37	0.498	4.08	0.430	7.88	0.915
29	6.64	0.544	5.96	0.454	5.66	0.406	5.93	0.420	14.68	0.922	6.50	0.501	6.05	0.427	14.79	0.966
30	5.83	0.627	4.43	0.464	4.03	0.416	3.75	0.393	10.72	0.982	5.43	0.544	4.81	0.476	9.85	1.034
31	4.67	0.665	4.40	0.545	4.09	0.460	3.68	0.412	9.92	1.052	4.54	0.619	4.95	0.544	10.02	1.110
32	4.21	0.661	4.65	0.622	4.58	0.545	3.82	0.447	9.84	1.125	3.84	0.595	4.52	0.517	9.54	1.172
33	5.87	0.626	6.13	0.621	5.69	0.548	5.33	0.510	13.74	1.186	5.78	0.595	5.47	0.525	13.20	1.215
34	5.70	0.657	5.72	0.632	5.13	0.553	4.62	0.502	11.86	1.206	5.51	0.614	5.11	0.554	9.72	1.194
35	7.05	0.612	7.31	0.598	7.25	0.564	6.88	0.513	19.22	1.165	7.36	0.601	6.59	0.495	17.64	1.158
36	5.71	0.592	5.79	0.531	6.07	0.503	6.90	0.538	15.64	1.129	5.44	0.528	5.72	0.476	12.58	1.116
37	10.53	0.721	8.68	0.577	7.72	0.511	7.38	0.485	18.57	1.005	9.60	0.637	8.92	0.569	17.47	1.019

NOTE: LL = less than 0.0001 kg/ha; LC = less than 0.001 mg/l.

APPENDIX TABLE D.8--Continued

YEAR	Case: 473.n2 LOAD (kg/ha)	Case: 473.n2 CONC. (mg/l)	Case: 475.n2 LOAD (kg/ha)	Case: 475.n2 CONC. (mg/l)	Case: 533.n2d LOAD (kg/ha)	Case: 533.n2d CONC. (mg/l)	Case: 534.n2d LOAD (kg/ha)	Case: 534.n2d CONC. (mg/l)	Case: 635.n2d LOAD (kg/ha)	Case: 635.n2d CONC. (mg/l)	Case: 443.n2d LOAD (kg/ha)	Case: 443.n2d CONC. (mg/l)	Case: 444.n2d LOAD (kg/ha)	Case: 444.n2d CONC. (mg/l)	Case: 446.n2d LOAD (kg/ha)	Case: 446.n2d CONC. (mg/l)
1	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
2	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
3	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
4	0.0001	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
5	0.0943	0.008	0.0020	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
6	2.04	0.166	0.503	0.035	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
7	3.94	0.448	3.58	0.289	LL	LC	LL	LC	LL	LC	0.0002	LC	LL	LC	LL	LC
8	3.73	0.538	5.17	0.519	LL	LC	LL	LC	LL	LC	0.0019	LC	LL	LC	LL	LC
9	6.25	0.521	7.61	0.508	LL	LC	LL	LC	LL	LC	0.0492	0.005	LL	LC	LL	LC
10	5.62	0.490	5.87	0.435	0.0007	LC	0.0007	LC	LL	LC	0.254	0.026	0.0038	LC	LL	LC
11	5.32	0.510	5.13	0.395	0.0154	0.002	0.0139	0.002	LL	LC	0.617	0.070	0.0466	0.005	0.0001	LC
12	5.18	0.508	4.62	0.410	0.0760	0.010	0.0849	0.010	0.0001	LC	1.23	0.146	0.244	0.026	0.0050	0.001
13	6.67	0.598	6.01	0.449	0.241	0.029	0.275	0.031	0.0013	LC	2.11	0.235	0.717	0.069	0.0609	0.005
14	4.98	0.658	4.76	0.509	0.406	0.064	0.431	0.066	0.0064	0.001	2.00	0.319	1.02	0.139	0.224	0.025
15	5.21	0.584	5.31	0.462	0.819	0.112	0.811	0.114	0.0248	0.004	2.44	0.376	1.73	0.215	0.558	0.067
16	4.53	0.489	4.42	0.390	1.07	0.174	1.16	0.172	0.0678	0.010	2.85	0.470	2.13	0.290	1.14	0.128
17	4.42	0.502	4.30	0.409	1.79	0.236	1.84	0.238	0.149	0.021	4.04	0.506	2.90	0.355	1.90	0.199
18	5.92	0.545	5.92	0.448	3.15	0.330	3.03	0.310	0.334	0.041	5.50	0.541	4.48	0.437	3.52	0.294
19	5.35	0.541	6.36	0.478	2.78	0.393	3.14	0.391	0.511	0.068	4.43	0.559	4.47	0.502	4.13	0.372
20	7.92	0.595	6.92	0.486	4.70	0.452	4.77	0.436	0.911	0.101	7.23	0.656	6.47	0.544	5.36	0.415
21	6.08	0.648	5.32	0.537	4.26	0.501	4.53	0.479	1.02	0.135	5.50	0.626	5.74	0.581	4.58	0.437
22	7.49	0.618	6.94	0.504	6.51	0.574	6.79	0.530	1.74	0.167	7.69	0.650	8.52	0.624	7.04	0.471
23	6.88	0.575	6.36	0.487	5.84	0.561	6.19	0.537	1.70	0.192	7.10	0.660	7.11	0.601	5.98	0.481
24	5.62	0.587	5.44	0.464	4.46	0.596	4.88	0.547	1.65	0.213	5.66	0.694	5.60	0.617	5.23	0.485
25	4.69	0.571	4.45	0.466	4.05	0.593	4.23	0.546	1.49	0.231	4.78	0.679	4.41	0.603	4.41	0.490
26	5.87	0.505	5.90	0.449	5.80	0.613	5.94	0.566	2.13	0.238	7.36	0.766	6.04	0.621	5.12	0.494
27	4.90	0.509	4.70	0.460	5.57	0.621	5.52	0.581	1.94	0.243	6.56	0.700	6.06	0.637	4.89	0.485
28	3.85	0.494	4.68	0.458	2.76	0.670	3.90	0.612	1.76	0.249	3.78	0.721	4.51	0.664	4.20	0.498
29	6.52	0.484	6.08	0.432	5.49	0.624	6.38	0.609	2.32	0.257	8.03	0.750	7.95	0.669	6.94	0.514
30	5.50	0.549	4.56	0.436	4.50	0.619	4.70	0.586	1.82	0.267	5.59	0.661	5.60	0.649	4.50	0.543
31	4.55	0.594	4.46	0.494	3.50	0.634	4.06	0.597	1.77	0.277	4.25	0.656	4.82	0.656	4.62	0.563
32	3.67	0.548	4.60	0.521	3.63	0.660	4.04	0.608	1.71	0.280	4.05	0.663	4.46	0.647	4.29	0.576
33	5.48	0.568	5.11	0.479	4.63	0.614	4.90	0.561	1.96	0.271	5.83	0.666	5.55	0.593	5.64	0.587
34	5.18	0.595	4.71	0.509	4.25	0.583	4.44	0.533	2.04	0.275	4.91	0.602	5.07	0.590	5.04	0.564
35	6.80	0.559	6.98	0.521	5.59	0.593	5.47	0.521	2.38	0.277	6.17	0.580	6.52	0.571	6.96	0.559
36	5.15	0.503	5.61	0.466	4.17	0.570	4.57	0.504	2.30	0.265	5.11	0.587	5.45	0.548	6.70	0.532
37	9.24	0.618	7.90	0.497	6.33	0.515	5.81	0.455	2.66	0.265	8.20	0.602	7.21	0.519	7.13	0.497

NOTE: LL = less than 0.0001 kg/ha; LC = less than 0.001 mg/l.

APPENDIX TABLE D.8--Continued

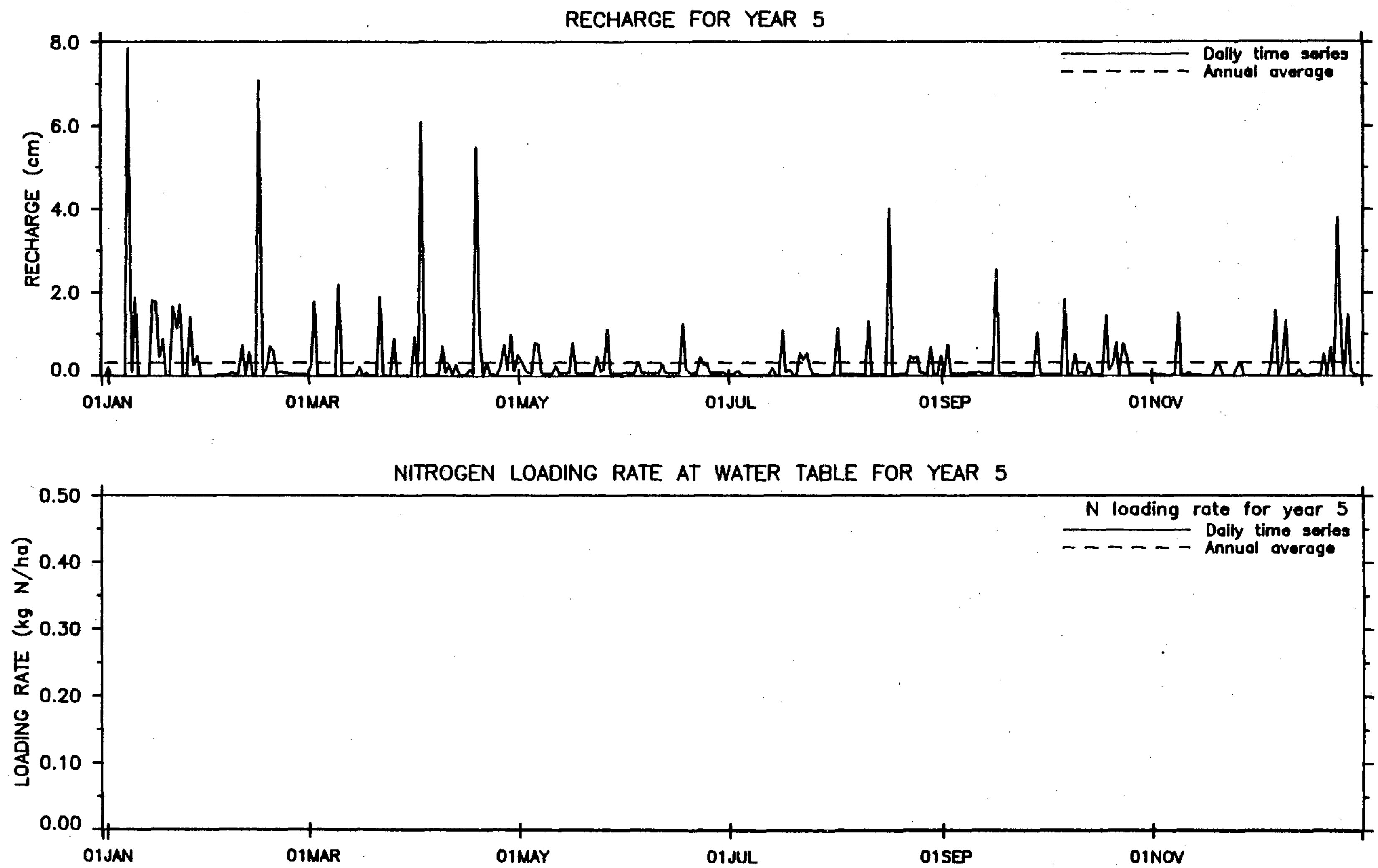
YEAR	Case: 453.n2d LOAD (kg/ha)	Case: 453.n2d CONC. (mg/l)	Case: 454.n2d LOAD (kg/ha)	Case: 454.n2d CONC. (mg/l)	Case: 455.n2d LOAD (kg/ha)	Case: 455.n2d CONC. (mg/l)	Case: 456.n2d LOAD (kg/ha)	Case: 456.n2d CONC. (mg/l)	Case: 463.n2d LOAD (kg/ha)	Case: 463.n2d CONC. (mg/l)	Case: 465.n2d LOAD (kg/ha)	Case: 465.n2d CONC. (mg/l)	Case: 473.n2d LOAD (kg/ha)	Case: 473.n2d CONC. (mg/l)	Case: 475.n2d LOAD (kg/ha)	Case: 475.n2d CONC. (mg/l)
1	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
2	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
3	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
4	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
5	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
6	0.0001	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
7	0.0030	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC	LL	LC
8	0.0170	0.003	LL	LC	LL	LC	LL	LC	0.0002	LC	LL	LC	0.0005	LC	LL	LC
9	0.202	0.019	LL	LC	LL	LC	LL	LC	0.0117	0.001	0.0045	LC	0.0224	0.002	0.0001	LC
10	0.773	0.072	0.0018	LC	LL	LC	LL	LC	0.141	0.013	0.0806	0.006	0.219	0.019	0.0082	0.001
11	1.19	0.140	0.0239	0.003	0.0001	LC	LL	LC	0.501	0.053	0.486	0.041	0.744	0.071	0.119	0.009
12	2.18	0.242	0.166	0.017	0.0027	LC	0.0017	LC	1.09	0.112	1.30	0.117	1.44	0.141	0.525	0.047
13	3.34	0.337	0.622	0.059	0.0431	0.004	0.0333	0.003	2.19	0.209	2.66	0.214	2.75	0.247	1.83	0.137
14	2.66	0.396	0.835	0.115	0.157	0.020	0.150	0.016	2.17	0.300	2.71	0.320	2.51	0.332	2.17	0.232
15	3.42	0.431	1.68	0.193	0.475	0.054	0.468	0.051	3.13	0.363	3.89	0.382	3.46	0.388	3.72	0.323
16	3.84	0.496	2.30	0.278	0.925	0.106	1.10	0.115	3.51	0.410	4.24	0.423	3.93	0.424	4.43	0.391
17	4.40	0.493	3.05	0.350	1.58	0.182	1.88	0.193	4.09	0.465	4.35	0.438	4.23	0.481	4.40	0.418
18	5.47	0.512	4.44	0.412	2.99	0.275	3.61	0.289	5.44	0.502	5.73	0.465	5.49	0.506	5.60	0.424
19	4.65	0.530	4.84	0.485	4.28	0.367	4.71	0.375	4.85	0.518	6.02	0.477	5.15	0.520	5.72	0.430
20	7.35	0.583	6.73	0.516	6.36	0.452	5.75	0.417	7.17	0.542	6.79	0.486	7.22	0.542	6.31	0.443
21	5.13	0.560	5.64	0.553	5.63	0.509	4.68	0.427	5.52	0.571	5.02	0.482	5.24	0.557	4.38	0.442
22	6.48	0.587	7.80	0.579	8.48	0.550	7.12	0.450	6.63	0.561	7.03	0.482	6.56	0.541	6.08	0.442
23	6.18	0.601	6.95	0.588	7.43	0.579	5.97	0.462	6.40	0.557	5.92	0.475	6.42	0.536	5.64	0.432
24	5.31	0.631	5.56	0.574	6.47	0.589	5.48	0.464	5.22	0.578	5.48	0.488	5.28	0.552	5.14	0.439
25	4.50	0.626	4.44	0.599	5.09	0.574	4.58	0.458	4.59	0.587	4.65	0.500	4.57	0.556	4.23	0.443
26	6.75	0.694	5.65	0.592	6.39	0.584	5.49	0.462	6.49	0.603	6.19	0.516	6.72	0.577	6.09	0.464
27	5.96	0.628	5.92	0.612	5.94	0.582	4.77	0.459	6.15	0.635	5.42	0.539	5.92	0.615	4.87	0.477
28	4.05	0.662	4.73	0.619	5.26	0.591	4.35	0.466	4.30	0.635	5.18	0.545	4.65	0.596	4.98	0.488
29	8.00	0.656	8.55	0.651	8.47	0.607	6.85	0.485	7.86	0.605	7.56	0.534	7.86	0.585	6.99	0.497
30	5.44	0.585	5.85	0.614	6.03	0.622	4.86	0.509	6.15	0.617	5.20	0.515	5.96	0.595	5.28	0.504
31	4.16	0.591	4.97	0.616	5.40	0.608	4.76	0.533	4.34	0.591	4.64	0.510	4.25	0.555	4.29	0.476
32	3.88	0.609	4.49	0.602	4.85	0.578	4.63	0.542	3.51	0.543	4.25	0.487	3.55	0.529	4.19	0.475
33	5.67	0.604	5.54	0.561	5.90	0.568	5.76	0.550	5.40	0.556	4.81	0.462	5.25	0.544	5.08	0.477
34	5.02	0.579	4.91	0.542	4.96	0.534	4.87	0.529	4.98	0.555	4.30	0.467	4.68	0.538	4.28	0.462
35	6.40	0.555	6.54	0.535	6.27	0.488	6.92	0.516	6.85	0.560	6.15	0.462	6.64	0.546	6.02	0.450
36	5.60	0.581	5.78	0.530	5.72	0.474	6.35	0.495	5.24	0.509	5.69	0.472	5.10	0.498	5.51	0.458
37	8.84	0.605	7.56	0.503	7.01	0.463	6.96	0.457	8.26	0.549	7.36	0.470	7.96	0.533	7.41	0.466

NOTE: LL = less than 0.0001 kg/ha; LC = less than 0.001 mg/l.

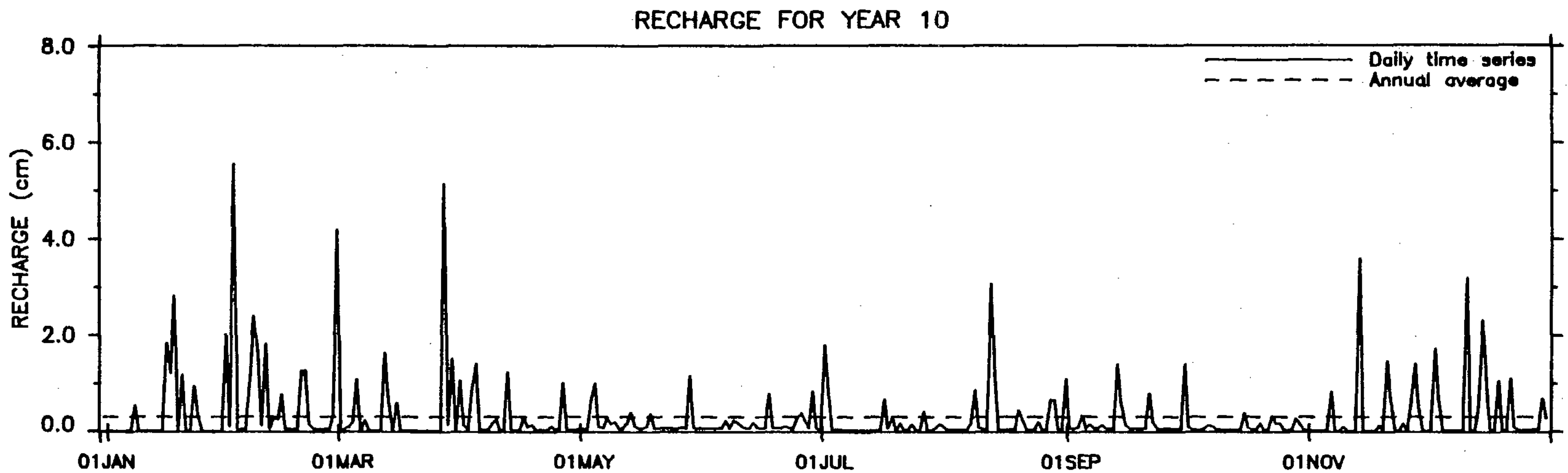
APPENDIX TABLE D.9. LONG-TERM PRZM SIMULATIONS FOR WAIAWA VALLEY

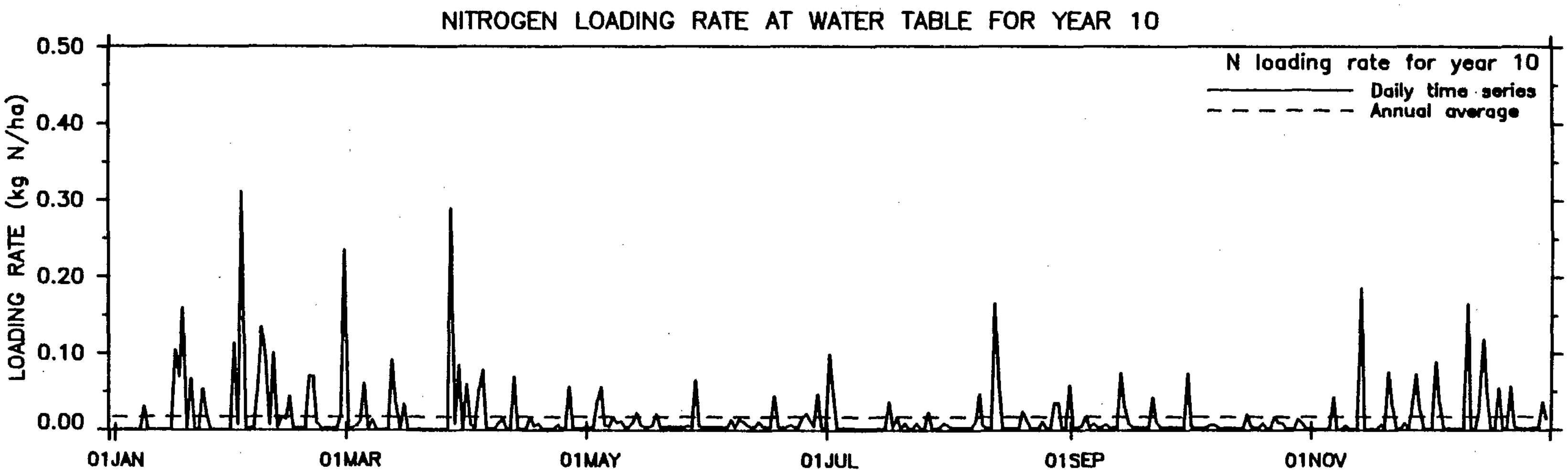
YEAR	Case: 454v.d3 LOAD (kg/ha)	CONC. (ug/l)	Case: 454v.d2 LOAD (kg/ha)	CONC. (ug/l)	Case: 454v.d3d LOAD (kg/ha)	CONC. (ug/l)	Case: 454v.d2d LOAD (kg/ha)	CONC. (ug/l)	Case: 454v.d1d LOAD (kg/ha)	CONC. (ug/l)	Case: 154v.n3 LOAD (kg/ha)	CONC. (mg/l)	Case: 454v.n2 LOAD (kg/ha)	CONC. (mg/l)	Case: 454v.n2d LOAD (kg/ha)	CONC. (mg/l)
1	LDL	LDC	LDL	LDC	LDL	LDC	LDL	LDC	LDL	LDC	LNL	LNC	LNL	LNC	LNL	LNC
2	0.00011	0.013	LDL	LDC	LDL	LDC	LDL	LDC	LDL	LDC	LNL	LNC	0.0060	0.001	LNL	LNC
3	0.01060	0.954	0.00186	0.167	0.00009	0.008	0.00001	0.001	LDL	LDC	0.0327	0.002	1.154	0.104	0.0138	0.001
4	0.03206	3.470	0.01023	1.107	0.00093	0.101	0.00017	0.019	0.00008	0.009	0.9082	0.074	4.395	0.476	0.2432	0.026
5	0.04769	4.319	0.01920	1.739	0.00309	0.280	0.00084	0.076	0.00043	0.039	6.091	0.417	6.592	0.597	1.465	0.133
6	0.05259	4.382	0.02382	1.985	0.00532	0.443	0.00179	0.149	0.00100	0.083	15.55	0.863	6.265	0.522	3.692	0.308
7	0.03643	4.578	0.01561	1.962	0.00371	0.466	0.00139	0.175	0.00082	0.103	9.218	0.963	4.290	0.539	3.393	0.427
8	0.01878	2.927	0.00887	1.383	0.00229	0.356	0.00088	0.138	0.00053	0.082	7.354	0.954	3.434	0.535	3.047	0.475
9	0.01818	1.729	0.00851	0.809	0.00257	0.245	0.00104	0.099	0.00063	0.060	13.02	0.939	5.444	0.518	5.266	0.501
10	0.02827	2.615	0.01066	0.986	0.00274	0.253	0.00110	0.101	0.00066	0.061	15.17	0.897	6.725	0.622	5.592	0.517
11	0.03794	4.146	0.01319	1.442	0.00244	0.267	0.00086	0.094	0.00050	0.054	11.75	1.015	6.970	0.762	4.979	0.544
12	0.03555	3.686	0.01632	1.692	0.00334	0.346	0.00109	0.113	0.00060	0.062	16.36	1.201	5.667	0.588	5.732	0.594
13	0.03108	2.946	0.01403	1.329	0.00378	0.358	0.00141	0.134	0.00081	0.077	15.72	1.096	5.530	0.524	6.562	0.622
14	0.02343	3.222	0.00925	1.271	0.00232	0.319	0.00091	0.125	0.00055	0.075	8.285	0.941	4.282	0.589	4.424	0.608
15	0.02084	2.393	0.00908	1.042	0.00218	0.251	0.00082	0.094	0.00049	0.056	10.40	0.937	5.306	0.610	5.173	0.594
16	0.01660	1.999	0.00704	0.848	0.00189	0.228	0.00072	0.086	0.00042	0.050	9.493	0.974	4.721	0.568	4.897	0.590
17	0.01979	2.277	0.00760	0.875	0.00185	0.213	0.00069	0.080	0.00040	0.047	10.19	0.987	5.465	0.629	5.108	0.588
18	0.03047	2.832	0.01165	1.082	0.00249	0.231	0.00087	0.081	0.00049	0.046	15.87	1.034	7.495	0.697	6.405	0.595
19	0.03193	3.200	0.01256	1.259	0.00266	0.267	0.00090	0.091	0.00050	0.050	14.93	1.163	6.467	0.648	6.211	0.623
20	0.05018	3.846	0.02080	1.595	0.00444	0.341	0.00152	0.116	0.00084	0.065	23.91	1.232	7.723	0.592	8.363	0.641
21	0.05100	4.999	0.02145	2.102	0.00482	0.472	0.00171	0.168	0.00098	0.096	17.01	1.123	6.067	0.594	6.459	0.633
22	0.08450	6.273	0.03788	2.812	0.00832	0.617	0.00299	0.222	0.00174	0.129	18.12	1.076	7.379	0.548	8.256	0.613
23	0.07469	6.310	0.03648	3.083	0.00931	0.787	0.00352	0.297	0.00207	0.175	15.90	0.957	5.758	0.487	6.957	0.588
24	0.05676	5.863	0.02871	2.966	0.00786	0.812	0.00320	0.331	0.00196	0.203	10.74	0.815	4.438	0.459	5.325	0.550
25	0.02510	3.382	0.01229	1.656	0.00382	0.515	0.00164	0.221	0.00103	0.139	7.242	0.773	3.268	0.440	3.847	0.518
26	0.02798	2.932	0.01330	1.393	0.00399	0.418	0.00171	0.179	0.00108	0.113	9.567	0.757	4.455	0.467	4.729	0.496
27	0.02542	2.625	0.01039	1.073	0.00295	0.304	0.00125	0.129	0.00078	0.080	8.995	0.759	5.358	0.553	4.638	0.479
28	0.02181	2.852	0.00832	1.088	0.00193	0.253	0.00074	0.097	0.00045	0.059	7.497	0.823	5.014	0.656	3.723	0.487
29	0.04494	3.417	0.01840	1.400	0.00413	0.314	0.00146	0.111	0.00084	0.064	17.12	0.971	8.024	0.610	6.917	0.526
30	0.04463	4.680	0.01762	1.848	0.00378	0.396	0.00134	0.140	0.00076	0.080	13.30	1.076	6.201	0.650	5.437	0.570
31	0.04035	4.999	0.01691	2.095	0.00353	0.438	0.00123	0.152	0.00069	0.085	11.75	1.144	4.764	0.590	4.805	0.595
32	0.02062	2.759	0.00996	1.334	0.00262	0.351	0.00096	0.129	0.00055	0.073	10.50	1.150	3.699	0.495	4.520	0.605
33	0.01818	1.841	0.00840	0.850	0.00252	0.255	0.00101	0.102	0.00060	0.060	13.96	1.060	5.216	0.528	5.832	0.591
34	0.02088	2.308	0.00837	0.926	0.00225	0.249	0.00091	0.100	0.00054	0.060	11.40	0.984	5.620	0.621	5.168	0.571
35	0.04481	3.666	0.01620	1.325	0.00311	0.254	0.00112	0.091	0.00065	0.053	17.75	1.056	9.004	0.737	7.037	0.576
36	0.04605	4.221	0.02010	1.843	0.00401	0.368	0.00133	0.122	0.00074	0.068	16.02	1.222	6.386	0.585	6.749	0.619
37	0.09297	6.181	0.04176	2.776	0.00938	0.624	0.00337	0.224	0.00195	0.130	23.45	1.137	8.166	0.543	9.509	0.632

NOTE: LDL = less than 0.00001 kg/ha; LDC = less than 0.001 μg/l; LNL = less than 0.0001 kg/ha; LNC = less than 0.001 mg/kg.

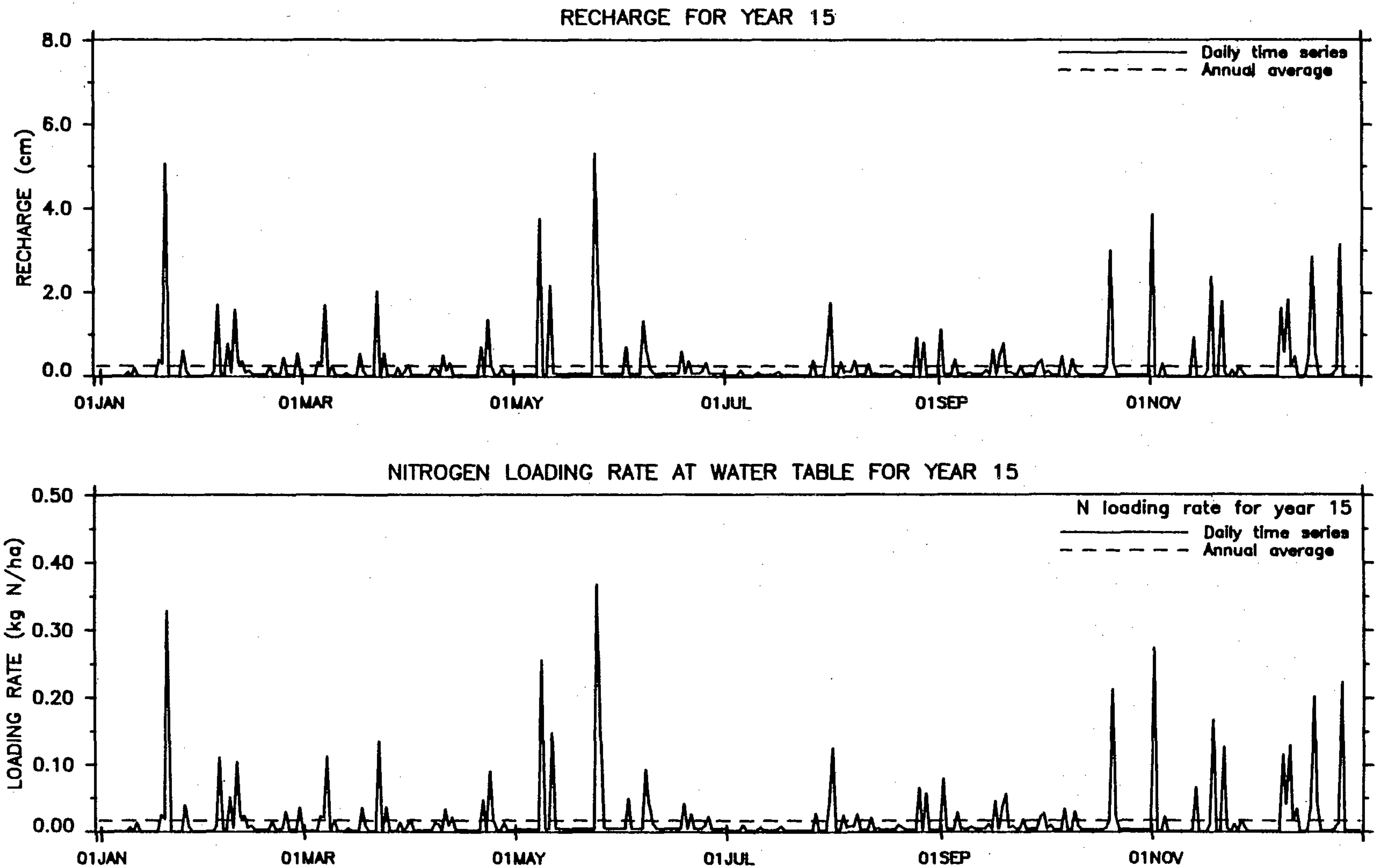


Appendix Figure D.7. Daily time series vs. annual mean for PRZM simulation 454.n2





Appendix Figure D.7--Continued



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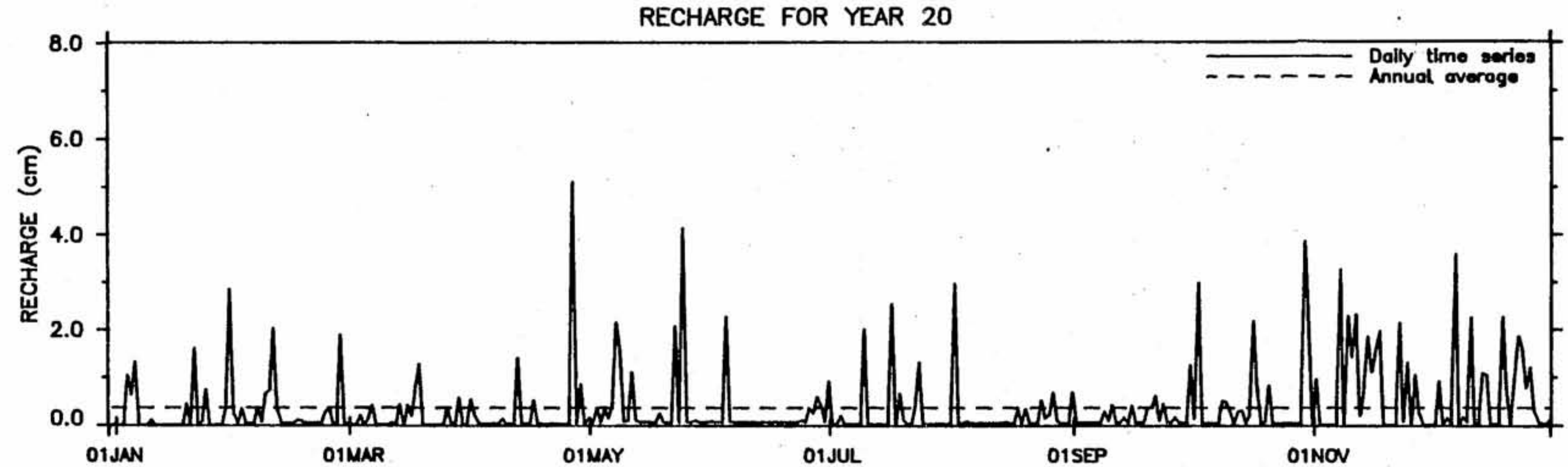

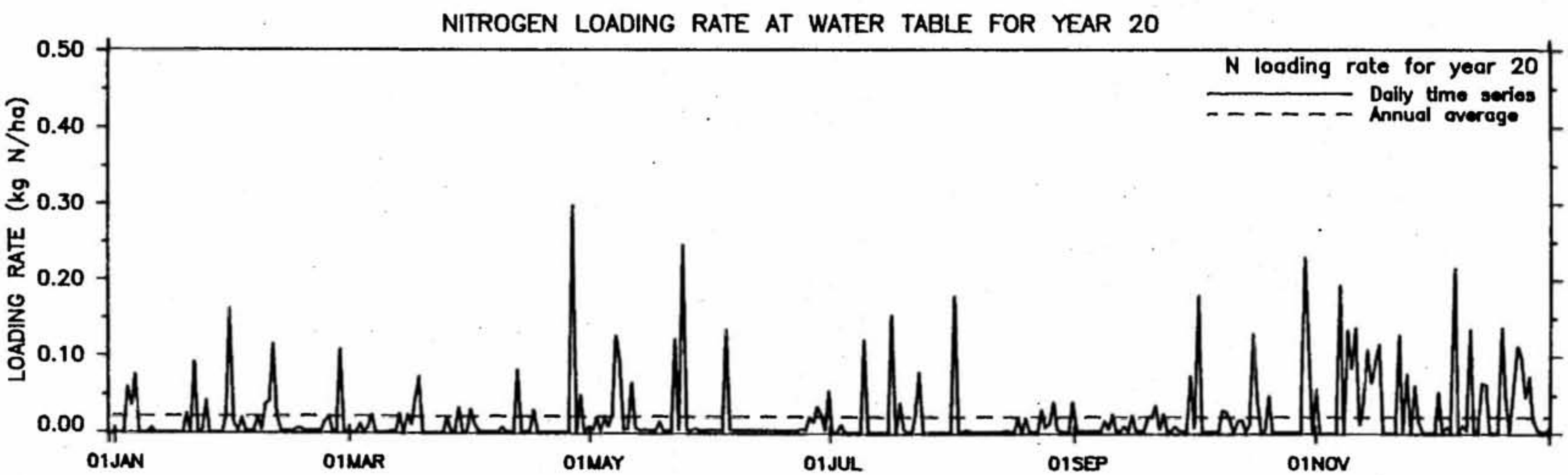

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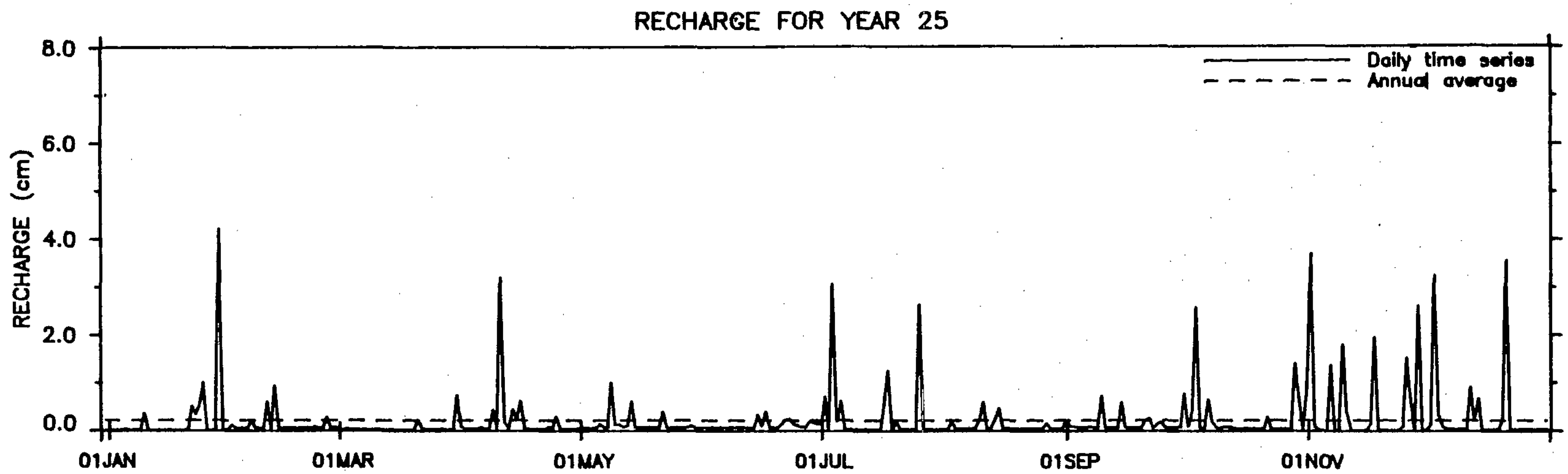

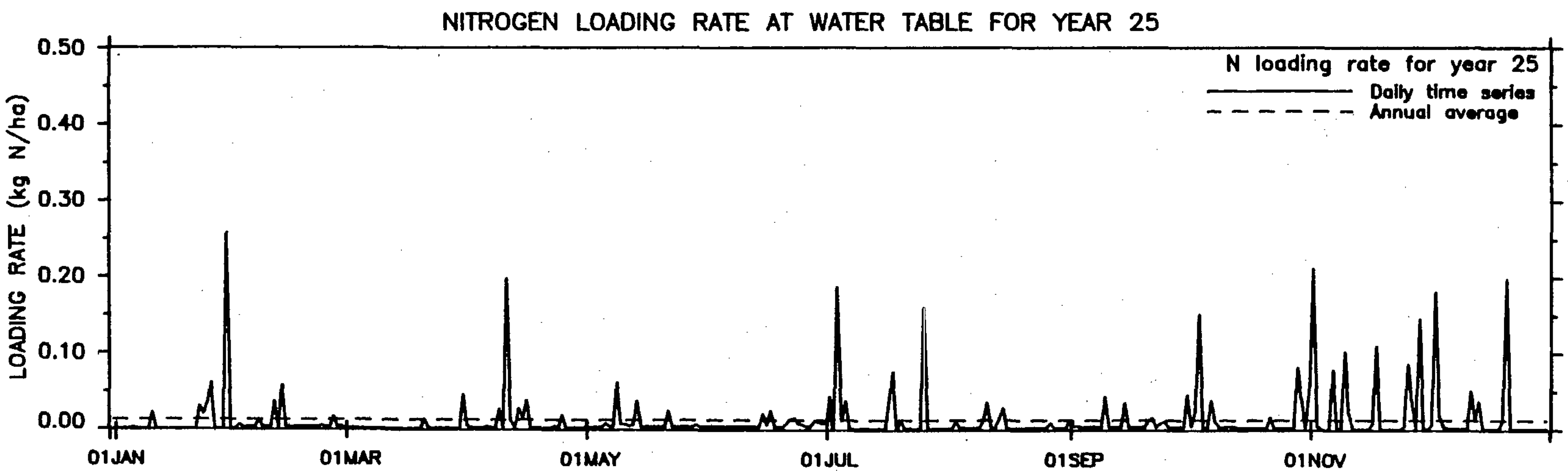

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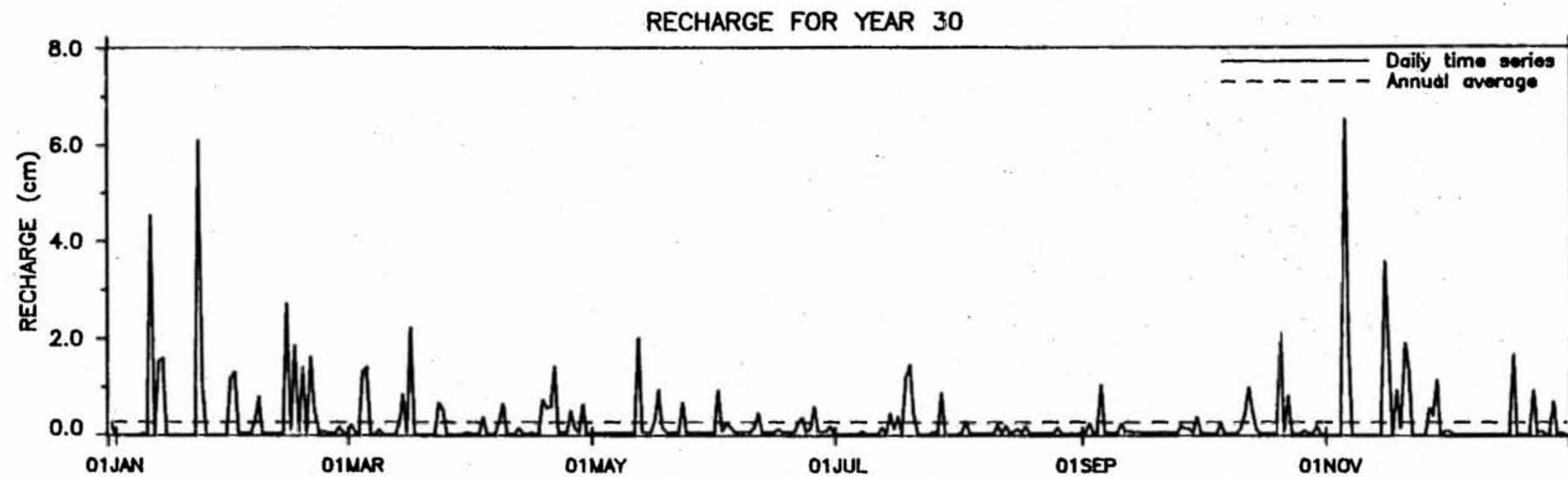
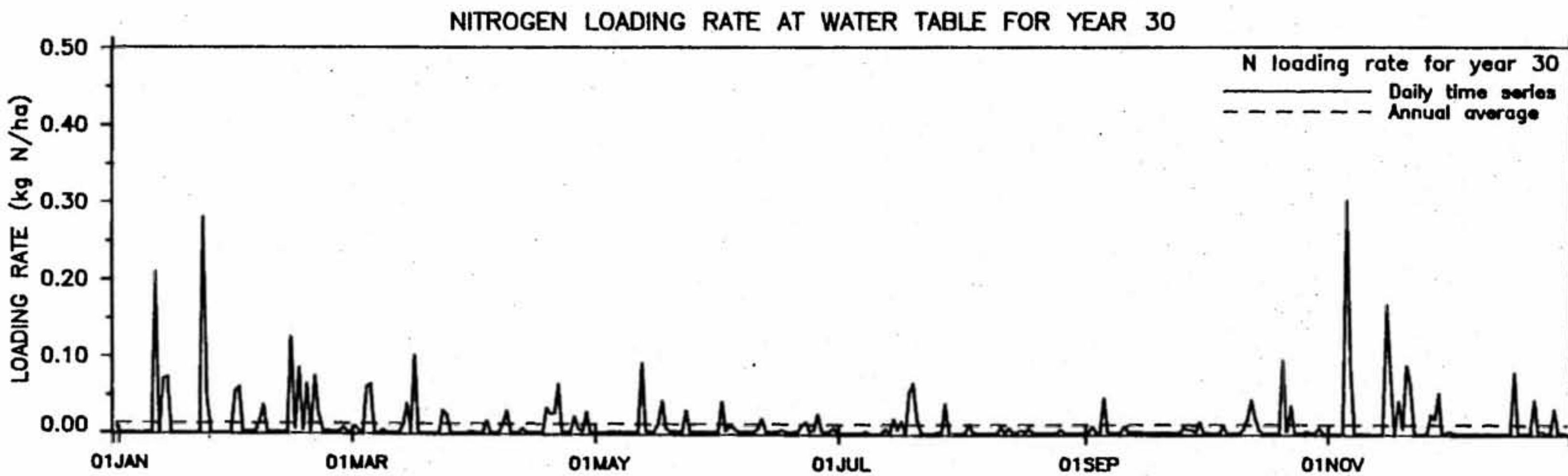
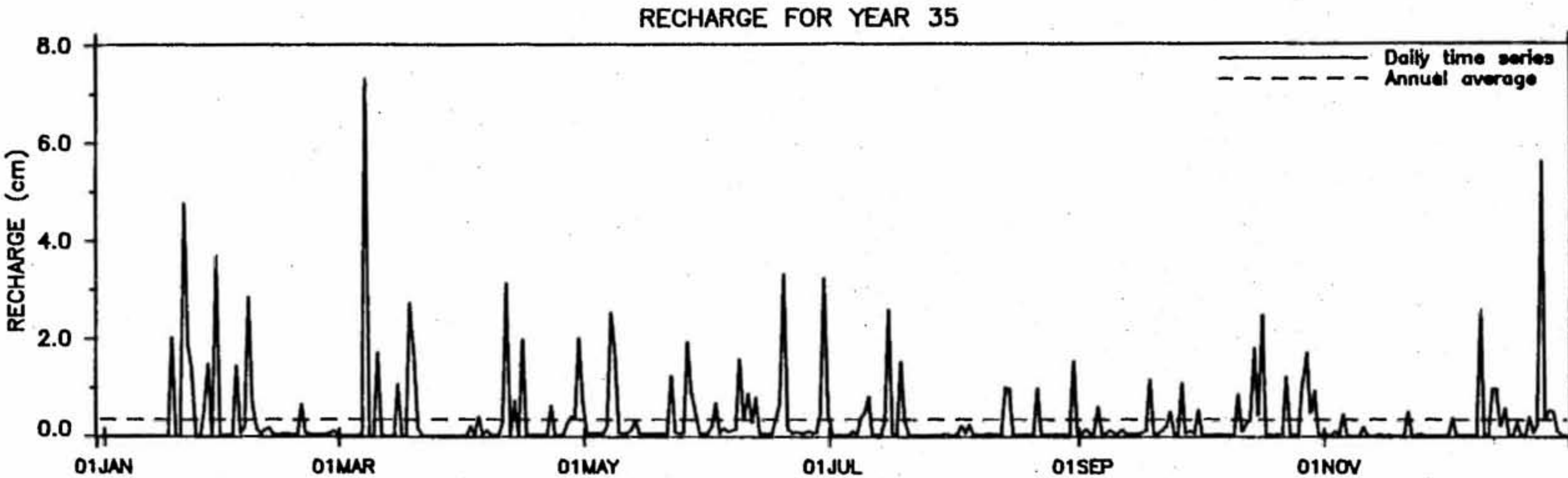
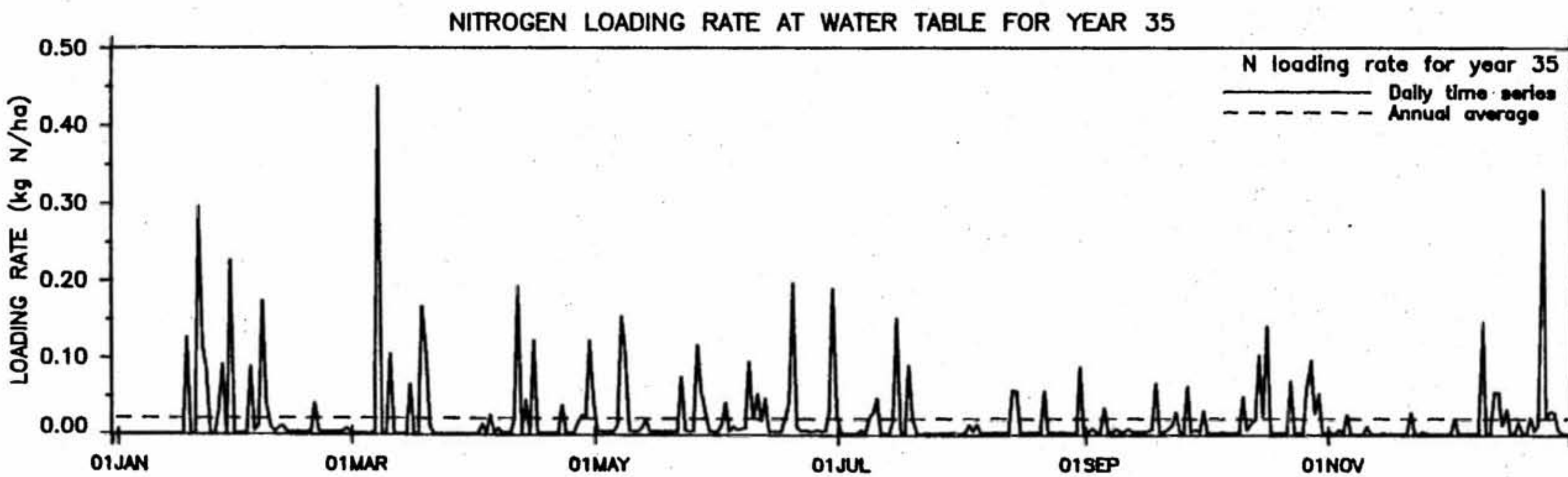




Appendix Figure D.7--Continued





Appendix Figure D.7--Continued

APPENDIX E. SATURATED ZONE MODELS

To verify that a given groundwater model is appropriate for long-term predictive simulations, the model must first demonstrate an ability to simulate observed data. For the current study, three groundwater models were calibrated and evaluated with the historical time series of chloride concentrations in water pumped by Waiawa Shaft. The three saturated zone models used in this study are (1) the method of characteristics model in an areal mode, (2) the method of characteristics model in a vertical section mode, and (3) a multiple mixing cell model. The calibrations of each model are presented below.

METHOD OF CHARACTERISTICS MODEL CALIBRATION--AREAL MODE

A numerical, deterministic, distributed parameter model that simulates two-dimensional solute transport in groundwater flow is used here to simulate groundwater flow supplying the USN Waiawa Shaft (well no. 2558-10). The model was documented by Konikow and Bredehoeft (1978) and later revised to include decay and equilibrium sorption-desorption reactions (see International Ground Water Modeling Center, 1987). The two-dimensional method of characteristics (MOC) model was recently applied by Or and Lau (1987) in an effort to simulate the transport of DBCP in the basal aquifer near and downgradient from the Mililani area of central Oahu. The model was used to predict potential contamination of downgradient wells from upgradient pesticide applications.

In order to use the MOC model to determine the long-term impact of urban developments in the Waiawa area of central Oahu, the model must first demonstrate an ability to simulate solute transport in the area. The applicability of the MOC model to the current research investigation is demonstrated here through a calibration procedure using the historical time series of chloride concentrations in water pumped by Waiawa Shaft.

Model Description. The following model description was obtained from Konikow and Bredehoeft (1978). A more complete development of the model is presented therein.

The MOC model computes spatial and temporal changes in solute concentration caused by the processes of advective transport, hydrodynamic dispersion, mixing with fluid sources, first-order decay, and adsorption. The model assumes that gradients of fluid density, viscosity, and temperature do not affect the velocity distribution. The aquifer may be heterogeneous and/or anisotropic and flow may be steady or transient.

The model couples the groundwater flow and solute transport equations. The model utilizes a rectangular, block centered, finite-difference grid with a constant node spacing and an iterative alternating-direction implicit (ADI) procedure to solve a finite difference approximation to the groundwater flow equation. After the head distribution has been computed for a given time step, the velocity of groundwater is computed at each node by using an explicit finite-difference form of Darcy's law. The computed velocities are then used to solve the transport equation during that time step for the concentration of the simulated water quality parameter (solute).

The mass balance equation for two-dimensional areal flow is:

$$\frac{\partial}{\partial x}\left(T_{xx}\cdot\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_{yy}\cdot\frac{\partial h}{\partial y}\right) = S\cdot\frac{\partial h}{\partial t} + W \qquad (E.1)$$

where h is the hydraulic head [L], t is time [T], x and y are the cartesian coordinates [L], $T_{ij} = K_{ij}b$ is the transmissivity $[L^2T^{-1}]$ for which K_{ij} is the hydraulic conductivity tensor $[LT^{-1}]$ and b the saturated thickness of the aquifer [L], assuming b >> h (for an unconfined aquifer), S is the storage coefficient (dimensionless), and W = W(x,y,t) is the flux per unit surface area $[LT^{-1}]$, which may represent a variety of source-sink flux terms.

The method of characteristics, which was developed to solve hyperbolic differential equations, is used in this model to solve the solute transport equation. When advection is the primary transport mechanism, the solute transport equation closely approximates a hyperbolic partial differential equation (Konikow and Bredehoeft 1978). By considering saturated thickness as a variable, the two dimensional transport of a nonreactive solute may be described by

$$\frac{\partial C}{\partial t} = \frac{1}{b}\cdot\frac{\partial}{\partial x_i}\left(bD_{ij}\cdot\frac{\partial C}{\partial x_j}\right) - V_x\cdot\frac{\partial C}{\partial x} - V_y\cdot\frac{\partial C}{\partial y} + F \qquad (E.2)$$

$$F = \frac{C}{nb}\left(S \cdot \frac{\partial h}{\partial t} + W - n \cdot \frac{\partial b}{\partial t}\right) - \frac{C'W}{nb} \tag{E.3}$$

where C is the solute concentration $[ML^{-3}]$ in the water, C' is the concentration of the solute in the source or sink fluid $[ML^{-3}]$, D_{ij} is the coefficient of hydrodynamic dispersion (a second-order tensor) $[L^2T^{-1}]$, x_i and x_j are the cartesian coordinates [L], V_x and V_y are the components of the average linear velocity $[LT^{-1}]$ (Freeze and Cherry 1979) in the x and y directions, respectively, and n is the effective porosity of the aquifer. The average linear velocity is related to the specific discharge, q, in Darcy's law by q = Vn, where n is the effective porosity of the aquifer.

The method of characteristics considers representative fluid particles that are advected with the flowing groundwater. Changes with time in properties of the fluid, such as concentration, may be described with respect to a fixed reference point within a stationary coordinate system or a moving reference particle. For changes in concentration with time, $\partial C/\partial t$ represents the change with respect to a fixed observation point whereas dC/dt, called the material derivative, represents the change with respect to a moving fluid particle. The material derivative of concentration may be defined as

$$\frac{dC}{dt} = \frac{\partial C}{\partial t} + \frac{\partial C}{\partial x} \cdot \frac{dx}{dt} + \frac{\partial C}{\partial y} \cdot \frac{dy}{dt} \tag{E.4}$$

with velocity components given by

$$\frac{dx}{dt} = V_x \tag{E.5}$$

$$\frac{dy}{dt} = V_y \tag{E.6}$$

If equations E.2, E.5, and E.6 are substituted into E.4, the following is obtained:

$$\frac{dC}{dt} = \frac{1}{b} \cdot \frac{\partial}{\partial x_i}\left(bD_{ij} \cdot \frac{\partial C}{\partial x_j}\right) + F \tag{E.7}$$

Solutions to equations E.5 to E.7 yield values of x, y, and C as a function of t and represent the characteristic curves of the fluid particles. Given the solutions to equations E.5 to E.7, a solution of the partial differential equation E.2 may be obtained by following these characteristic curves for each fluid particle. Numerically, a finite number of fluid particles is distributed within the rectangular grid. For a given time step, each particle is advected through the grid a distance proportional to the velocity at the particle's location and the length of the time step. After each particle has been moved, the concentration in each cell due to advection is computed as the average of the concentrations of all particles located in that cell. The changes in concentration caused by hydrodynamic dispersion and fluid sources are calculated using a two-step explicit finite-difference approximation to equation E.7 (a detailed procedure is given in Konikow and Bredehoeft 1978).

A number of stability criteria limit the size of the time step used to numerically solve the solute transport equation. To maintain a stable numerical solution, the solute transport equation is often solved with a much smaller time step than that used for the flow equation. Thus, after solving the flow equation, the time step used to compute the new head distribution must often be subdivided to solve for the new concentration distribution over the same time interval.

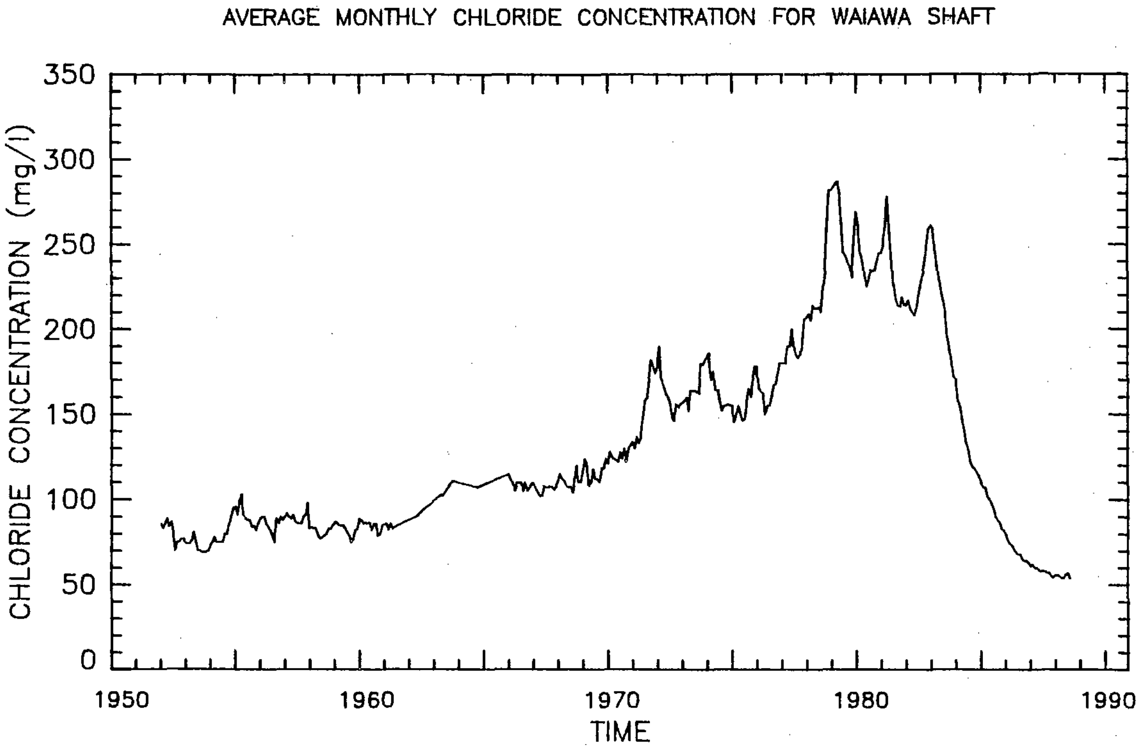
Different types of flow boundary conditions can be represented in the simulation model. A no-flow boundary can be created by specifying a transmissivity equal to zero in the desired cells. The numerical procedure requires that an artificial no-flow boundary be imposed around the modeled region. A prescribed head boundary can be employed which accounts for leakage into or out of the specified cells. This constant head boundary is created by setting the leakage factor, defined as the vertical hydraulic conductivity of the confining layer divided by the thickness of the confining layer, to a high enough value (e.g., 1 s^{-1}). A prescribed flux boundary is created by specifying the flux as a well discharge or injection rate at the appropriate cells.

The MOC model allows the specification of an injection or withdrawal well in each cell of the grid, and spatially varying diffuse recharge or discharge, saturated aquifer thickness, transmissivity, boundary conditions, and initial conditions. Note that the MOC model may be utilized directly to simulate two-dimensional solute transport in vertical cross sections. When the model is applied in this manner, the horizontal width of the cross section corresponds to the aquifer thickness in the areal case. In addition, if any diffuse recharge or discharge is specified, care must be taken to adjust the values so that proper dimensions are maintained by the program.

Model Application. Portions of the Waiawa infiltration tunnel, which was constructed between 1949 and 1951, lie directly beneath land previously used for sugarcane cultivation by Oahu Sugar Company (OSC). Water from OSC Waipahu Pump 6 (2459-01 to -14) was used for furrow irrigation of sugarcane fields on Waiawa Ridge until 1983. The Waipahu Pump 6 well field consists of 14 deep wells drilled to depths of 150 to 210 m (500-700 ft) below mean sea level. From 1902 until about 1951, the chloride concentration in Pump 6 water generally ranged from 200 to 400 mg/l (Eyre 1983b). Due to the shrinking of the basal lens of the Pearl Harbor aquifer (Soroos and Ewart 1979), Waipahu Pump 6 wells began to withdraw water from the rising transition zone which eventually resulted in chloride concentrations in Pump 6 water in excess of 1 000 mg/l during the 1970s. As a result of the irrigation of Waiawa Ridge sugarcane fields with water from Pump 6, chlorides applied at the surface eventually leached through the 90 to 150 m (300-500 ft) thick vadose zone to the groundwater table. This irrigation return flow caused a rise in chloride concentration of water pumped by Waiawa Shaft (App. Fig. E.1) until approximately 1983 when the overlying sugarcane fields were abandoned.

Chloride concentrations in Waiawa Shaft water have been shown to be inversely related to draft (Mink 1973; Eyre 1983b). It is generally felt that this phenomenon is caused by the extraction of deeper, fresher water from the core of the basal lens under increased drafts. Increased pumpage, however, also results in a wider zone of contribution so that a greater amount of fresh, upgradient water enters the shaft.

Grid Dimensions. The modeled area for this study is located in the Waiawa system (Mink and Lau 1987) of the Pearl Harbor aquifer of central Oahu, and extends south of Waiawa Shaft to include downgradient pumpage and north to include upgradient areas previously used for sugarcane



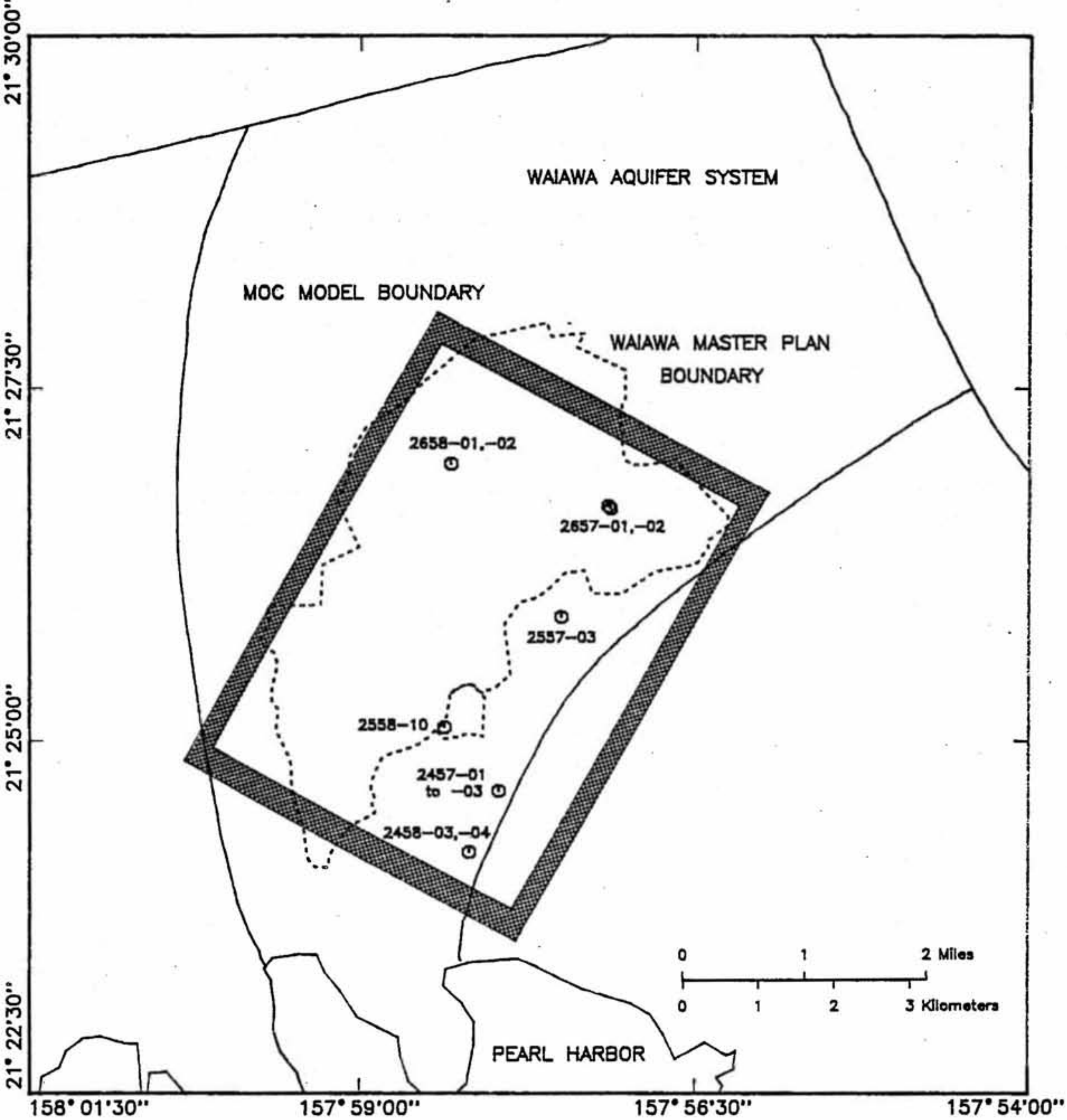
Appendix Figure E.1. Historical time series of chloride concentrations in water pumped by Waiawa Shaft

cultivation (App. Fig. E.2). The size of the grid was selected to include the proposed Waiawa developments and to adequately encompass the zone of contribution of Waiawa Shaft.

The orientation of the grid was chosen to coincide with the direction of groundwater flow in the Waiawa aquifer system. The dividing lines of the Waiawa aquifer system were chosen based on an analysis of water balance results for the entire Pearl Harbor aquifer and the known locations of principal spring discharges near Pearl Harbor (Mink, Yuen, and Chang 1988). Based on groundwater head contour maps of Visher and Mink (1964), Dale and Takasaki (1976), and Soroos and Ewart (1979) in conjunction with information from simultaneous head measurements at Waiawa Shaft and Mililani Wells II (2859-01) during 1982, Eyre* determined a central flow line for Waiawa Shaft (see Figure 68) which is oriented approximately 8 degrees further north-south than the direction of groundwater flow assumed in this study. Hufen, Eyre, and McConachie (1980) determined a groundwater flow direction which is oriented approximately 20 degrees toward the east of the groundwater flow direction assumed for this study. The orientation of the two-dimensional grid is essential to properly evaluate the water quality impact of recharge from the vadose zone to the basal aquifer. An improper grid orientation could result in simulations wherein too much or too little recharge water from a particular area enters Waiawa Shaft. By properly orienting the grid, the zone of contribution of Waiawa Shaft can be adequately described and the effects of lateral transfer of water into and out of the modeled area can be minimized.

The 20 x 20 grid utilizes a constant cell size of 244 m (800 ft) in the transverse direction by 335 m (1100 ft) in the longitudinal direction. Although the grid contains 20 cells in the longitudinal and transverse directions, the numerical scheme used in the model requires that the outermost rows and columns represent no-flow boundaries. Thus, the actual usable portion of the grid consists of 18 cells in the longitudinal and transverse directions. The depth of the grid was varied from 60 to 150 m (200-500 ft) to determine the approximate depth of extraction of the Waiawa water development complex.

*P.R. Eyre (USGS) 1989: personal communication.

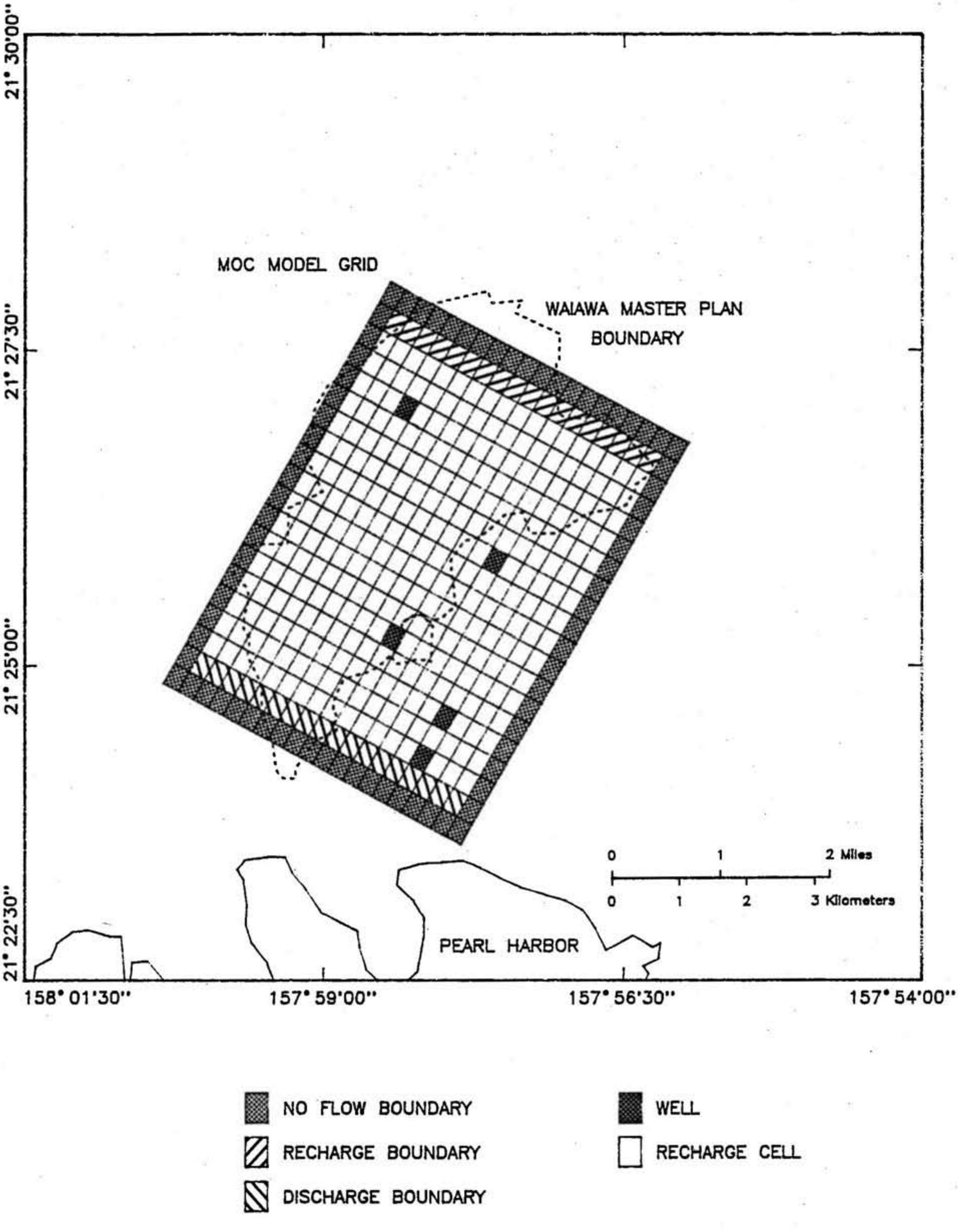


Appendix Figure E.2. Wells within areal MOC model boundaries

Boundary Conditions. As mentioned above, the numerical scheme of the MOC model requires that the outermost rows and columns of the grid represent no flow boundaries and cannot be utilized for other purposes. Thus, the usable portion of a 20 x 20 grid is actually an 18 x 18 subgrid. The upgradient boundary of this subgrid is a flux boundary condition represented by 18 recharge wells. The upgradient flux boundary represents groundwater input to the grid from the high recharge area near the crest of the Koolau Range. The upgradient influx to the grid is assumed to be uniformly distributed. The downgradient boundary is also a flux boundary which represents groundwater discharge from the grid toward the spring outlets near Pearl Harbor. Since the grid is oriented in the direction of groundwater flow, the sides of the grid are assumed to be no-flow boundaries. Note that the fluctuations in the water table are assumed to be relatively small so that the model can approximate an unconfined aquifer. The bottom boundary of the grid is a no-flow boundary which precludes inflow from deeper in the basal lens. The boundary conditions used in this modeling application are presented in Appendix Figure E.3. It should be noted that within each annual pumping period, changes in water storage are assumed to be negligible. Thus, the upgradient influx and unsaturated zone recharge are balanced by the downgradient discharge and pumpage for each year.

Waiawa, Waimano, and Panakauahi gulches are represented by cells of reduced conductivity. Boring logs from holes within nearby gulches (R.M. Towill 1978; Eyre 1983a) indicate that the alluvial fill and weathered basalt sections beneath these valley floors extend beneath the groundwater table. Because of the low permeability of the weathered sections, partial barriers to flow are created.

Based on the continuous occurrence of bedrock in Waiawa Stream between elevations of 90 m (300 ft) and 180 m (600 ft) where the valley gradient is approximately 3% (R.M. Towill 1978), the alluvium thicknesses in the gulches were estimated by extrapolation. The weathered basalt was assumed to extend 60 m (200 ft) beneath the alluvium (R.M. Towill 1978; Eyre 1983a). The hydraulic conductivities of the MOC cells within the gulches were then weighted by the depths of the alluvium/saprolite and unweathered sections. The average hydraulic conductivity of the



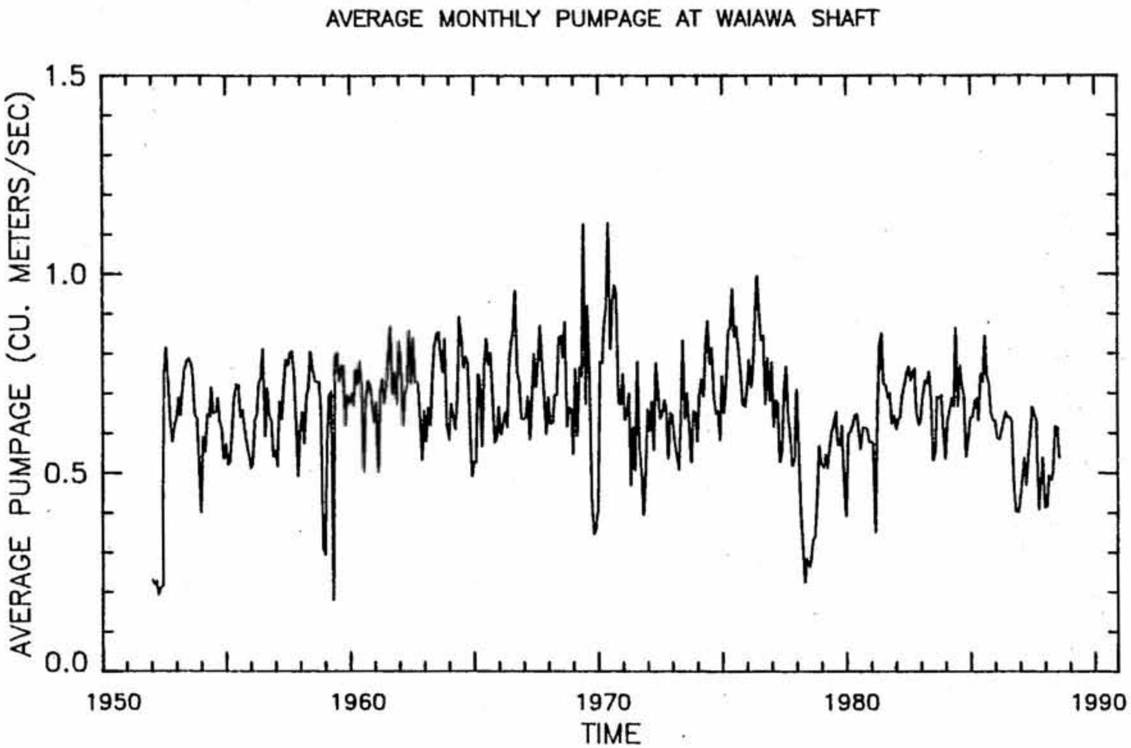
Appendix Figure E.3. Areal MOC model boundary conditions and well locations alluvium/saprolite material was assumed to be approximately 15 m/day (50 ft/day) (Eyre 1983a).

Water pumped from Waiawa Shaft is from the unlined sump as well as the 519 m (1,702 ft) long infiltration tunnel. A preliminary attempt to measure the flow velocity in the infiltration tunnel indicates that about 50% of the draft from Waiawa Shaft originates from the tunnel itself (App. F). This estimate is likely to be conservative. In any event, the Waiawa water development complex would probably be best represented by a combination of large partially penetrating dug well and a modified line sink which is influenced by drawdown created by heavy pumping in the cavity well. Due to program limitations, however, the relatively coarse mesh used cannot realistically represent the infiltration tunnel. With this limitation in mind, the Waiawa water development complex was simulated by a sink located in a single cell of the grid (App. Fig. E.3).

Initial Conditions. Waiawa Shaft was constructed between 1949 and 1951. During that period, the average head near the shaft was approximately 7 m (23 ft) above sea level. Using this head and a regional hydraulic gradient of about 0.19 m/km (1 ft/mile), initial heads were assigned to the upgradient and downgradient cells of the grid.

Records from test wells in the vicinity of Waiawa Shaft indicate that the top of the basal lens underlying sugarcane fields on Waiawa Ridge had a chloride concentration of about 250 mg/l during shaft construction. Upgradient of the sugarcane fields, the groundwater was assumed to have a background chloride level of 20 mg/l. This value is representative of chloride concentrations in water samples from upgradient wells (Swain 1973).

Input Data. For calibration purposes, annual pumpage data for Waiawa Shaft from 1950 to 1988 were obtained from USGS files and directly from the USN. A monthly time series of pumpage from Waiawa Shaft is given in Appendix Figure E.4. In addition to Waiawa Shaft, a number of other wells are located within the modeled area. These include the City and County of Honolulu Board of Water Supply's Pearl City Wells I (2458-03, -04), Pearl City Wells II (2457-01 to -03), and Pearl City Well III (2557-03), OSC Pump 17 (2658-01, -02), and Bishop Estate's wells in Waiawa Valley (2657-01, -02) (App. Fig. E.2). Annual pumpage data for



Appendix Figure E.4. Historical time series of pumpage at Waiawa Shaft, Oahu, Hawaii all wells except the Bishop Estate wells were available at the Honolulu Board of Water Supply (BWS). The Bishop Estate wells, however, were not used extensively during the calibration period.* The other wells were directly accounted for in this modeling investigation by assigning them to a single cell of the MOC grid from which pumpage was assumed to occur (App. Fig. E.3). Based on well logs and known casing depths, Pearl City Wells I, Pearl City Wells II, Pearl City Well III, and OSC Pump 17 are all assumed to extract water from within the modeled grid depths. It should be noted that OSC Pump 6 wells are also located within the study area. The depth of extraction of these wells, however, was assumed to be below the MOC grid. Note also that the MOC model cannot be expected to accurately simulate the time series of chloride concentrations in water pumped from wells which require a different grid depth than that used for Waiawa Shaft. Basically, the modeled depth determines the extent to which the irrigation return water is diluted since the selected depth controls how much dilution water enters the upgradient end of the grid.

In order to calibrate the MOC model using annual pumping periods, the annual time series of recharge and input chloride concentrations to the groundwater from the vadose zone were needed and determined. Estimates of recharge to each cell were based on the water balance results of Giambelluca (1983, 1986). To estimate recharge in each cell, the plan view of the MOC grid was superimposed over the water balance zones defined by Giambelluca (1983). The relative areas of the water balance zones occurring in each of the MOC model cells was first estimated. The annual recharge occurring in a particular cell was then determined by weighting the annual water balance zone recharge estimates (Giambelluca 1983; Giambelluca 1986) according to their areas in the cell and then dividing by the total cell area. Annual recharge estimates for each of the MOC grid cells for the 39-yr calibration period (1950-1988) were determined in this manner. Annual water balance zone estimates of recharge were computed by Giambelluca (1983) during the period 1946 to 1975. The annual recharge time series for each of the affected water balance zones was extended to 1988 using average annual estimates for the zones (Giambelluca 1986). The latter estimates required knowledge of the land use history of the water balance zones from 1976 to 1988.

*P.R. Eyre (USGS) 1989: personal communication.

The groundwater recharge estimates from Giambelluca (1983, 1986) are assumed to occur just below the plant root zone. Eyre (1987) suggests that infiltrated storm water can force pulses of water from the vadose zone to arrive at the groundwater table within a period of several months to a year. For the current study, the recharge occurring below the root zone is assumed to displace an equivalent amount of water from the bottom of the vadose zone which recharges the basal aquifer within the year.

The chloride concentrations associated with the recharge water near the ground surface are dependent on land use. For instance, vacant areas receiving only rainfall will have lower recharge water chloride concentrations than sugarcane cultivation areas receiving saline irrigation water. The primary land uses occurring in the study area during the calibration period and their associated recharge water chloride concentration time series are provided in Appendix Table E.1. Sugarcane cultivation in the Pearl City area of central Oahu is assigned a different recharge water chloride concentration than in the Waiawa area due to the different source of irrigation water. In the Waiawa area, OSC fields 420, 500, 501, 505, 510, 515, 520, 525, 530, and 531 received irrigation water from Pump 6 as well as Waiahole and Ahrens ditches (Eyre 1983).

The concentrations presented in Appendix Table E.1 are applicable to the recharge water occurring just below the plant root zone and not at the water table. Water balance zones beneath vacant and pineapple cultivation areas are assumed to have recharge chloride levels of 20 mg/l. The chloride level for vacant areas is based on chloride concentrations found in wells located in areas unaffected by anthropogenic surface activities. The chloride level in recharge water beneath pineapple growing areas is based on chloride concentrations found in Mililani wells which are located downgradient from pineapple cultivation areas.

The chloride concentration of recharge beneath urban and sugarcane cultivation areas requires knowledge of chloride levels in the irrigation water as well as the return fraction of applied water. Due to evapotranspiration and runoff, not all of the rainfall and irrigation occurring at the ground surface will result in recharge. Thus, chloride concentrations of the recharge water are dependent on the fraction of applied water that actually contributes to recharge. Return fractions can

APPENDIX TABLE E.1. ESTIMATED RECHARGE WATER CHLORIDE CONCENTRATIONS

	Chloride Concen. (mg/l) of Recharge Water by Land Use									
						Sugarcane				
			--Urban--		Pearl	Waiawa zone				
Year	Open	Pine	med.	m/h	City	149	161	162	163	164
1946	20	20	90	45	350	20	439	390	323	221
1947	20	20	90	45	350	20	490	436	367	145
1948	20	20	90	45	350	20	326	231	20	20
1949	20	20	90	45	350	20	297	265	222	56
1950	20	20	90	45	350	20	414	370	302	293
1951	20	20	90	45	350	20	398	347	314	20
1952	20	20	110	50	350	198	523	494	20	20
1953	20	20	110	50	350	674	810	776	20	20
1954	20	20	110	50	350	20	675	530	20	20
1955	20	20	110	50	350	20	477	304	20	20
1956	20	20	110	50	350	20	531	372	20	20
1957	20	20	110	50	350	20	595	505	20	20
1958	20	20	110	50	350	20	426	253	20	20
1959	20	20	110	50	350	20	701	593	20	20
1960	20	20	110	50	350	20	963	807	20	20
1961	20	20	110	50	350	282	1119	1060	20	20
1962	20	20	70	40	350	1023	1218	1156	1086	20
1963	20	20	70	40	350	20	807	681	20	20
1964	20	20	70	40	350	961	1204	1131	1017	20
1965	20	20	70	40	350	20	707	514	20	20
1966	20	20	70	40	350	20	674	603	20	20
1967	20	20	50	30	350	20	611	386	20	20
1968	20	20	50	30	350	567	679	645	606	171
1969	20	20	50	30	350	812	978	956	855	872
1970	20	20	50	30	350	1085	1357	1317	1147	1193
1971	20	20	50	30	350	1033	1167	1084	1090	992
1972	20	20	50	30	350	1248	1292	1183	1299	1175
1973	20	20	45	30	350	1449	1888	1819	1529	1506
1974	20	20	45	30	350	849	1043	907	573	21
1975	20	20	45	30	-	1292	1662	1547	1354	1492
1976	20	20	45	30	-	1168	1476	1366	1238	475
1977	20	20	45	30	-	1395	1763	1631	1478	1499
1978	20	20	45	30	-	1416	1789	1655	1500	1521
1979	20	20	45	30	-	1097	1386	1283	1163	153
1980	20	20	45	30	-	20	1325	958	20	20
1981	20	20	45	30	-	1407	1778	1645	1491	38
1982	20	20	45	30	-	20	1154	546	20	20
1983	20	20	45	30	-	-	-	-	-	-
1984	20	20	45	30	-	-	-	-	-	-
1985	20	20	45	30	-	-	-	-	-	-
1986	20	20	45	30	-	-	-	-	-	-
1987	20	20	45	30	-	-	-	-	-	-
1988	20	20	45	30	-	-	-	-	-	-

NOTE: Pine = pineapple land use
med. = medium density urban land use
m/h = mixed medium/high density urban land use.

NOTE: Waiawa sugarcance zones correspond in part or in whole to water balance zones defined by Giambelluca (1983).

be determined from water balance results of Giambelluca (1986). In areas receiving 1 000 mm (40 in.) of rainfall, typical return fractions, expressed as the ratio of water recharge to total water input, can be computed with average irrigation rates for medium density urban, medium-high density urban, and furrow irrigated sugarcane land uses to be respectively 0.27, 0.35, and 0.64.

Annual recharge water chloride concentration time series can be obtained using known or estimated irrigation, rainfall, runoff, and recharge time series in conjunction with estimated chloride concentrations in rainfall and irrigation water. The average chloride concentration in the recharge for a given time period can be computed as

$$Cl_{rc} = [P(Cl_p) + IR(Cl_{ir}) - RO(Cl_{ro})]/RC \qquad (E.8)$$

where Cl_{rc}, Cl_p, Cl_{ir}, and Cl_{ro} are the chloride concentrations $[ML^3]$ in the recharge water, precipitation, irrigation, and runoff, respectively; and RC, P, IR, and RO represent respectively recharge $[LT^{-1}]$, precipitation $[LT^{-1}]$, irrigation $[LT^{-1}]$, and runoff $[LT^{-1}]$. The chloride concentration in the runoff can be estimated as the weighted average of the rainfall and irrigation chloride concentrations

$$Cl_{ro} = [P(Cl_p) + IR(Cl_{ir})]/(P + IR) \qquad (E.9)$$

Using Giambelluca's (1983) water balance zone arrangement, all or portions of five different water balance zones (149, 161, 162, 163, and 164) were assumed to receive irrigation water from Pump 6. For convenience, Giambelluca's water balance zone configurations were used rather than the actual OSC field configurations to estimate recharge and chloride concentrations input to the MOC model. Roughly speaking, zone 161 corresponds to OSC field 420 and zone 162 corresponds to fields 500, 501, 505, 510, and 515. The portions of zones 149 and 163 which received irrigation water from Pump 6 roughly correspond to fields 530 and 531, respectively. Fields 520 and 525 make up the portion of water balance zone 164 which received irrigation water from Pump 6.

For the sugarcane fields in the Waiawa area, annual irrigation totals (Giambelluca 1983) were assumed to be comprised of water from OSC Pump 6 and possibly water from Waiahole and Ahrens ditches. Annual pumpage totals for Pump 6 were obtained from BWS records. Based on proximity to

Pump 6, the annual pumpage was assumed to be used for irrigation of water balance zone 161 first, followed by zones 162, 149, 163, and then 164. Thus, the Pump 6 annual pumpage total was assigned to the five water balance zones until exhausted. The remainder of the annual irrigation total for each zone (Giambelluca 1983) was assumed to be from Waiahole or Ahrens ditches. The chloride concentration in the ditch water was assumed to be about 12 mg/l (Visher and Mink 1964). For OSC Pump 6, annual chloride concentrations in pumped water were computed as the flow weighted average of chloride concentrations from Pumps 6A and 6B. The irrigation water chloride concentration for each year and each zone was then computed as the flow weighted average of the Pump 6 and ditch water chloride concentrations. Equations E.8 and E.9 were then employed to estimate the chloride concentration in the recharge water emanating from the crop root zone.

Each cell of the MOC model grid may be heterogeneous with regard to land use and elevation. Within each cell, chlorides applied at the ground surface are likely to reach the groundwater table at different times dependent on the vadose zone thickness, water contents in the vadose zone, amount of recharge water, and numerous other factors. To simplify the analysis, a piston-type displacement model is used to simulate the downward movement of chlorides in the vadose zone. Since chloride is nonreactive, it will move downward unretarded with the recharge water.

The vadose zone beneath Waiawa Ridge typically consists of a soil layer to a depth of 0.3 m (1 ft), a subsoil layer to a depth of 5 m (16 ft) and a saprolite layer to a depth of 23 m (75 ft). The remainder of the vadose zone extending beneath the saprolite to the water table consists of unweathered basalt. Assuming constant soil, subsoil, and saprolite thicknesses, the thickness of the unweathered basalt layer is thus dependent on the elevation at the particular location of interest. Average field capacities $[L^3L^{-3}]$ for the soil, subsoil, saprolite, and unweathered basalt layers, are assumed to be 0.40, 0.42, 0.50, and 0.05, respectively.

The travel time through a particular layer of the vadose zone can be determined as

$$t = (L \cdot FC)/RC \qquad (E.10)$$

where t is the travel time [T], FC is the field capacity of the layer $[L^3L^{-3}]$, and L is the layer thickness [L]. Chlorides applied to the land surface during a given year will move downward with the recharge water during that year and will be pushed downward in piston-like fashion by the recharge occurring during subsequent years. Thus, determining the recharge water chloride concentration at the groundwater table involves tracking the downward movement of each year's recharge events. Note that if an annual time step is used, and if the travel times through any of the vadose zone layers are less than a year, recharge water originating during a particular year may be spread throughout several layers of the vadose zone.

The chloride concentration reaching the groundwater table during a year can be estimated as the volume weighted chloride average of the recharge events purged from the bottom of the vadose zone column during that year. The water balance zones occurring within a MOC model cell represent different vadose zone columns contributing chlorides to that cell. In a given year, each water balance zone within a MOC cell produces a different amount of recharge with an associated chloride concentration. The chloride concentration emanating from the vadose zone above a particular cell in a given year is determined as the recharge weighted average of chloride concentrations from each individual water balance zone in the cell for that same year.

The elevation on Waiawa Ridge varies from about 60 to 180 m (200-600 ft). During the period of sugarcane cultivation, average annual recharge in the area was about 2 m (Giambelluca 1986). Using the vadose zone parameters and displacement model described above, at a typical elevation of 120 m (400 ft) on Waiawa Ridge it will take approximately 8 yrs for water applied at the surface to reach the water table. This is in good agreement with the travel times estimated by Eyre (1987).

Water input to the upgradient end of the MOC model grid represents recharge from the area near the crest of the Koolau Range. Using results of a water budget analysis performed by Giambelluca (in Mink, Yuen, and Chang 1988), and accounting for leeward rift zone loss of groundwater to the windward side of the Koolau Range, Mink, Yuen, and Chang (1988) estimate that natural recharge to the Waiawa aquifer system amounts to approximately 3.2 m^3/s (73 mgd). Based on the orientation and width of the MOC model grid, approximately 71% or 2.3 m^3/s (52 mgd) of this recharge should enter the upgradient end of the grid through the entire freshwater lens thickness. The upgradient end of the grid is 18 cells wide so that the intake length is 4.39 km (14,400 ft). The upgradient recharge to the grid is thus 0.52 m^3/s per kilometer width of aquifer (19 mgd/mile) which is in good agreement with the value of 0.54 m^3/s per kilometer (20 mgd/mile) suggested by Eyre.*

Model Parameters. The groundwater flow submodel of the MOC model was used to determine the average hydraulic conductivity of the aquifer in the Waiawa area. Although hydraulic conductivity of the aquifer in the horizontal plane may be higher in the direction of the lava flows, the grid was oriented in the direction of the groundwater flow rather than in the direction of the lava flows to better simulate the flow paths within the aquifer. In order to account for the anisotropy in the aquifer, the components of hydraulic conductivity should be transformed from the principal directions of the aquifer to the coordinate system of the grid. Due to the uncertainty in the anisotropy caused by local irregularities in the lava flows, a single average value of hydraulic conductivity was assumed to be representative of the aquifer within the plane of the MOC model grid.

During the pre-groundwater development era (ca. 1879) groundwater storage heads in the Pearl Harbor aquifer were generally between 10 and 12 m (33 and 40 ft) (Mink 1980). At a typical initial storage head of 11 m (36.5 ft) for the Waiawa area, the freshwater lens thickness estimated by the Ghyben-Herzberg principle is 41 times the storage head or 460 m (1,500 ft). To determine the best value of hydraulic conductivity, the MOC grid depth was set equal to the freshwater lens thickness. Recharge at the upgradient end of the grid was maintained at 2.3 m^3/s (52 mgd). Recharge from rainfall occurring directly over the modeled aquifer area was based on the natural open land use recharge estimates of Giambelluca (1986). Under steady state flow conditions, a hydraulic conductivity of 460 m (1,500 ft)/day yielded a reasonable hydraulic gradient of approximately 0.00019 to 0.00038 m/m (1 to 2 ft/mile). Hydraulic

*P.R. Eyre (USGS) 1989: personal communication.

conductivities of 760 m (2,500 ft)/day and 1 520 m (5,000 ft)/day yielded smaller hydraulic gradients.

During 1958, a labor strike by sugarcane workers led to a great reduction of groundwater withdrawals. The hydraulic conductivity value obtained above was validated for the 1958 quasi-equilibrium period when storage heads in the Pearl Harbor aquifer were estimated to be between 7.0 and 8.8 m (23 and 29 ft). Based on a typical storage head of 8.1 m (26.5 ft) for the Waiawa area, the freshwater lens thickness was approximately 330 m (1,100 ft). The MOC grid depth was set equal to the lens thickness. Recharge at the upgradient end of the grid was maintained at 2.3 m^3/s (52 mgd). Recharge from rainfall and irrigation occurring directly over the modeled aquifer for 1958 was based on the water balance results of Giambelluca (1983). As in the pre-development test, under steady state flow conditions, a hydraulic conductivity of 460 m (1,500 ft)/day produced a reasonable hydraulic gradient. Thus, a hydraulic conductivity of 460 m/day was used in all calibration runs. This value is in agreement with the "best model" value of hydraulic conductivity used by Souza and Voss (1987).

The impact of dispersion on solute transport in the Waiawa area was tested by varying the longitudinal and transverse dispersivities. A range of longitudinal and transverse dispersivity values were tested during the calibration procedure. The values for transverse dispersivity were selected to generally reflect the corresponding longitudinal dispersivity values. That is, lower longitudinal dispersivities were paired with lower values of transverse dispersivity.

Effective porosities of 0.05 and 0.1 were tested to determine the impact of groundwater velocities on the transport phenomenon.

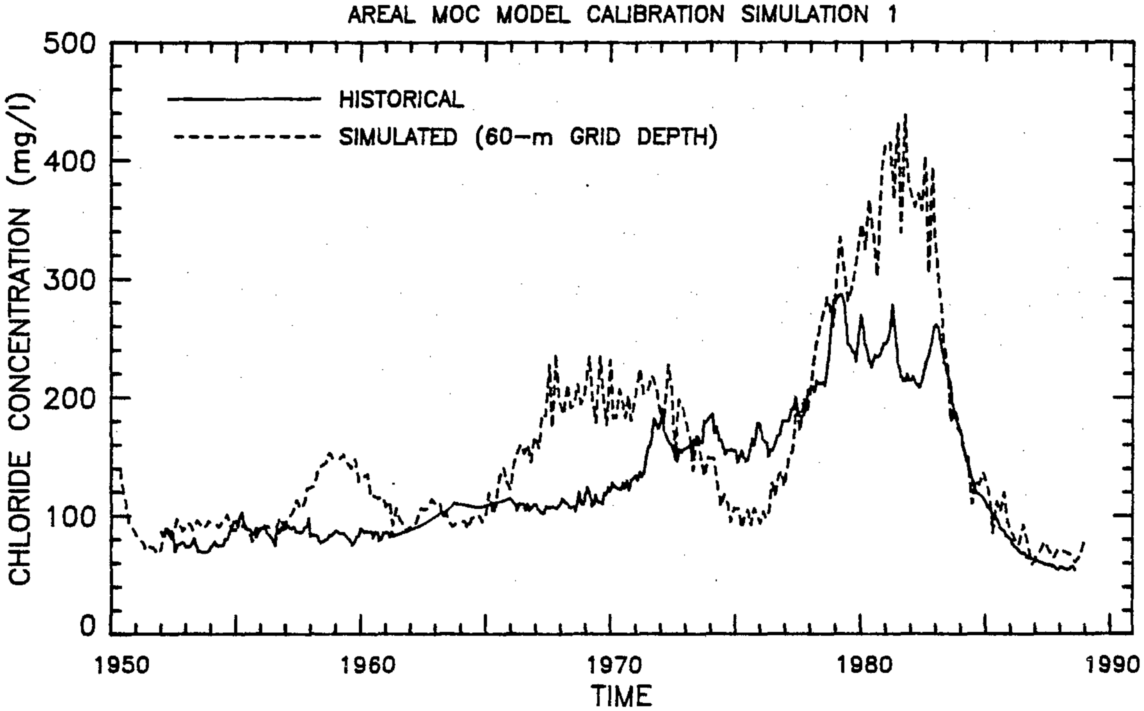
Numerous computer runs were made using the MOC model with the grid setup, boundary conditions, initial conditions, and input data discussed above. Each of the simulations covers the period 1950 to 1988. The recharge amounts and concentrations were changed on an annual basis. Steady state flow conditions were assumed to exist within each annual pumping period. Three different grid depths were tested to determine the approximate depth of groundwater extraction for the Waiawa water development complex. The upgradient groundwater influx rate was adjusted to reflect the depth of the grid. A summary of 30 representative computer runs is provided in Appendix Table E.2. All computer simulations were performed on a Sun 4/110 Workstation.

APPENDIX TABLE E.2. AREAL MOC MODEL PARAMTER SUMMARY

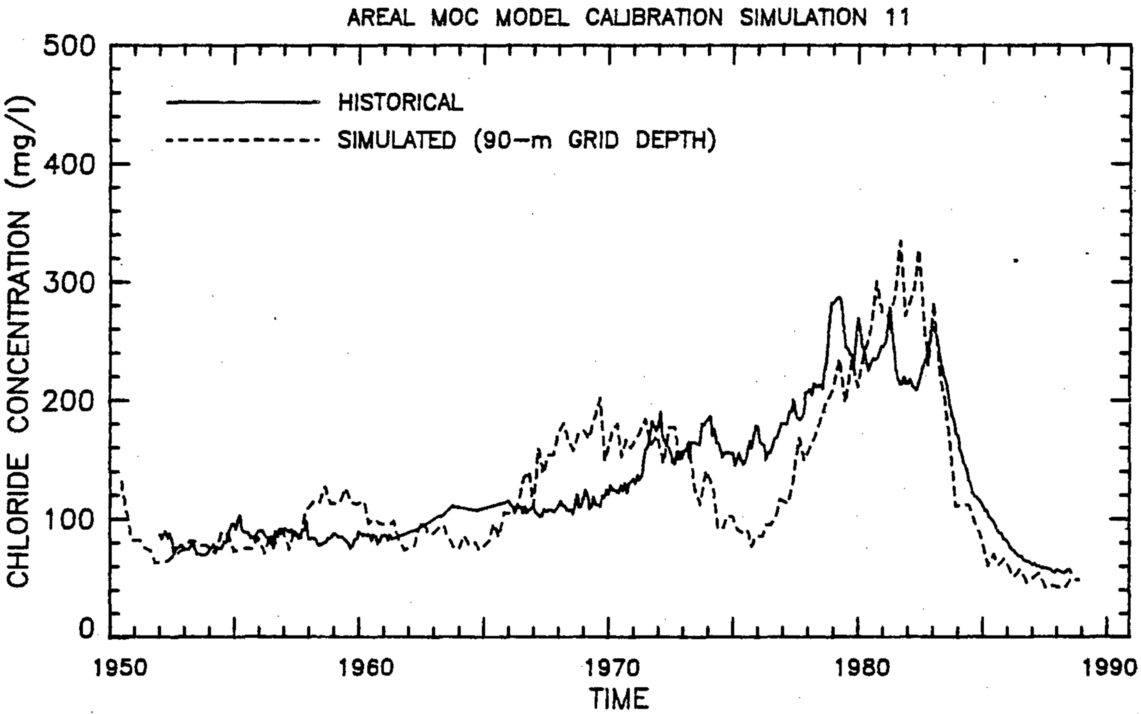
Run	Grid Depth (m)	Dispersivity (m) Long.	Trans.	Porosity
1	60	76	9.1	0.1
2		76	3.0	0.1
3		76	24	0.1
4		15	0.76	0.1
5		15	3.0	0.1
6		15	6.1	0.1
7		152	9.1	0.1
8		152	15	0.1
9		152	46	0.1
10		76	9.1	0.05
11	90	76	9.1	0.1
12		76	3.0	0.1
13		76	24	0.1
14		15	0.76	0.1
15		15	3.0	0.1
16		15	6.1	0.1
17		152	9.1	0.1
18		152	15	0.1
19		152	46	0.1
20		76	9.1	0.05
21	150	76	9.1	0.1
22		76	3.0	0.1
23		76	24	0.1
24		15	0.76	0.1
25		15	3.0	0.1
26		15	6.1	0.1
27		152	9.1	0.1
28		152	15	0.1
29		152	46	0.1
30		76	9.1	0.05

Results and Discussion. Results of the simulations in terms of chloride concentrations over time at Waiawa Shaft are presented in Appendix Figures E.5 to E.7. The results presented in Appendix Figures E.5 to E.7 represent one simulation for each of the three different grid depths tested. The simulations shown utilize the best parameter estimates as determined from the calibration effort. Based on the calibration computer runs, the following observations are offered.

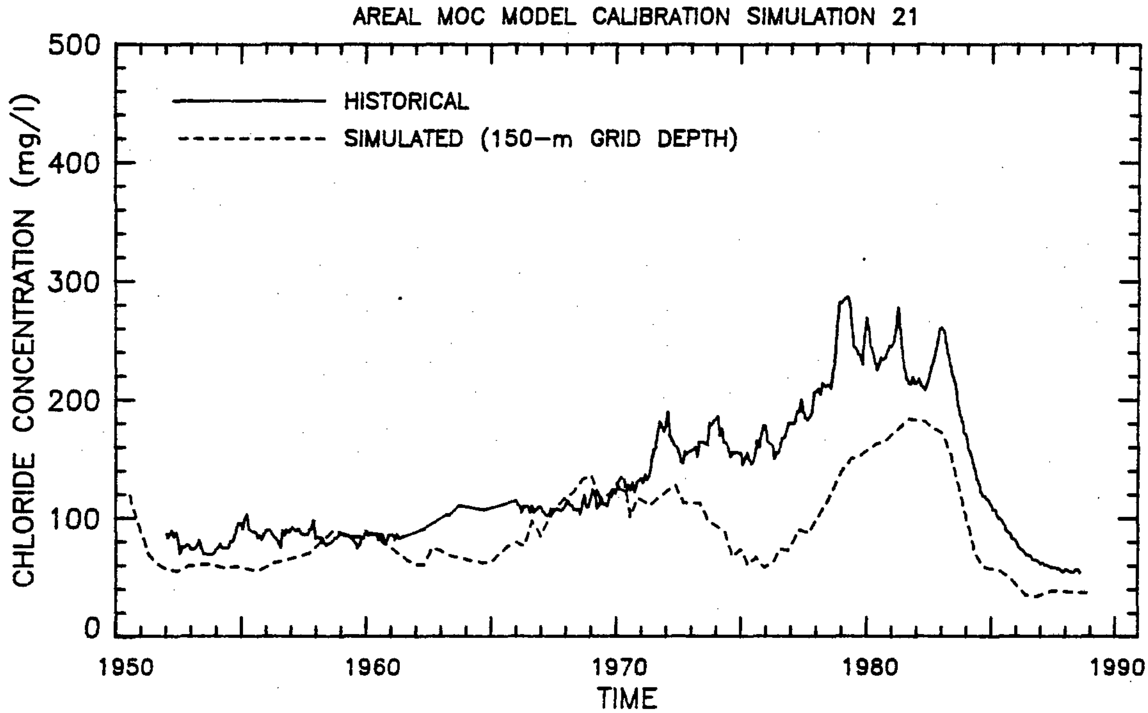
1. A comparison of Appendix Figures E.5 to E.7 indicates that the depth of contribution of Waiawa Shaft appears to be between 60 and 90 m (200 and 300 ft). Over the 39-yr calibration period, an average value of 90 m best represents the depth of contribution of Waiawa Shaft. The implication is that although the groundwater flow lines entering the Waiawa water development complex may not extend to a depth of 90 m immediately beneath the sump or infiltration tunnel, further upgradient the draft from Waiawa Shaft causes groundwater flowing at a depth of 90 m below the water table to eventually enter the sump or infiltration tunnel.
2. Within the range tested, the model appears to be insensitive to changes in the longitudinal dispersivity. Using different values of longitudinal dispersivity while holding the transverse dispersivity constant resulted in only small changes in the simulated chloride distributions within the modeled area. As expected, the simulated chloride time series at Waiawa Shaft for a particular grid depth are also quite similar to each other. The model's insensitivity to changes in dispersivity may indicate that flow due to pumpage from Waiawa Shaft is dominated by convective rather than dispersive processes. The longitudinal dispersivity value of 76 m suggested by Souza and Voss (1987) was also adopted for this study.
3. For each of the three longitudinal dispersivity values tested, three different transverse dispersivities were used. Within the range tested, the model was insensitive to the transverse dispersivity. For two-dimensional areal transport, transverse dispersivity values of one-twentieth to one-third of longitudinal



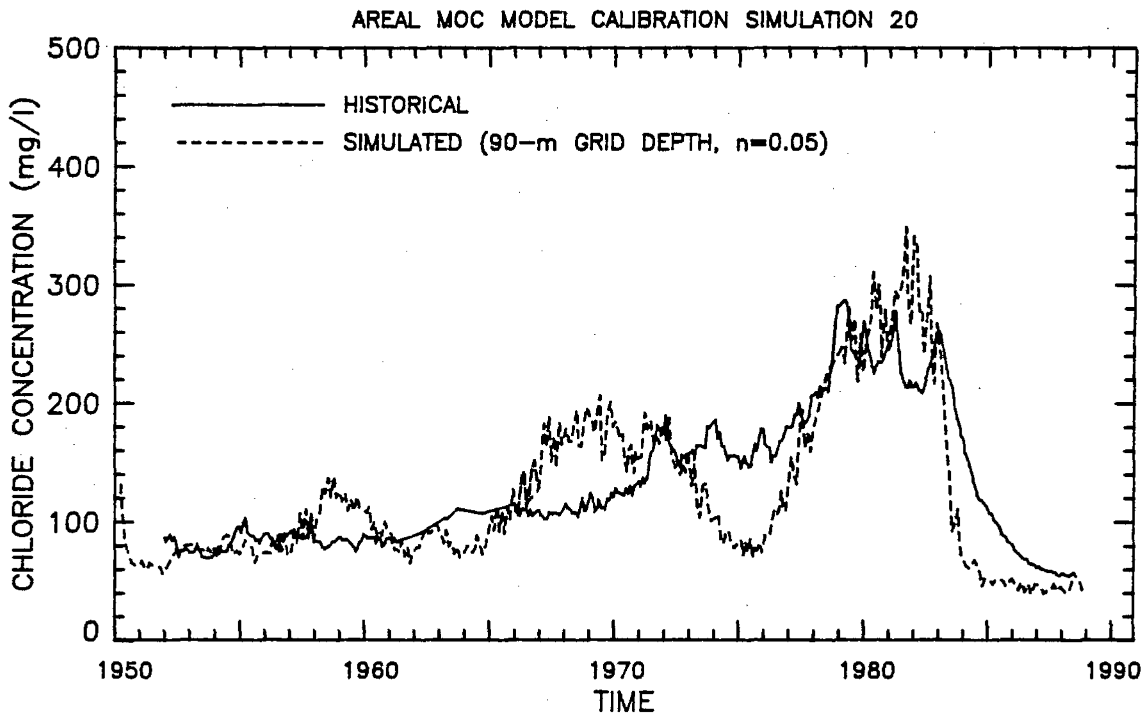
Appendix Figure E.5. Simulated chloride time series at Waiawa Shaft, areal MOC model simulation 1, 60-m aquifer depth



Appendix Figure E.6. Simulated chloride time series at Waiawa Shaft, areal MOC model simulation 11, 90-m aquifer depth



Appendix Figure E.7. Simulated chloride time series at Waiawa Shaft, areal MOC model simulation 21, 150-m aquifer depth



Appendix Figure E.8. Simulated chloride time series at Waiawa Shaft, areal MOC model simulation 20, 90-m aquifer depth dispersivity are often employed (Souza and Voss 1987). Due to the lack of field measurements to quantify transverse dispersivity and since the model was relatively insensitive to this parameter, a value of 9 m, which is within the acceptable range, was adopted.

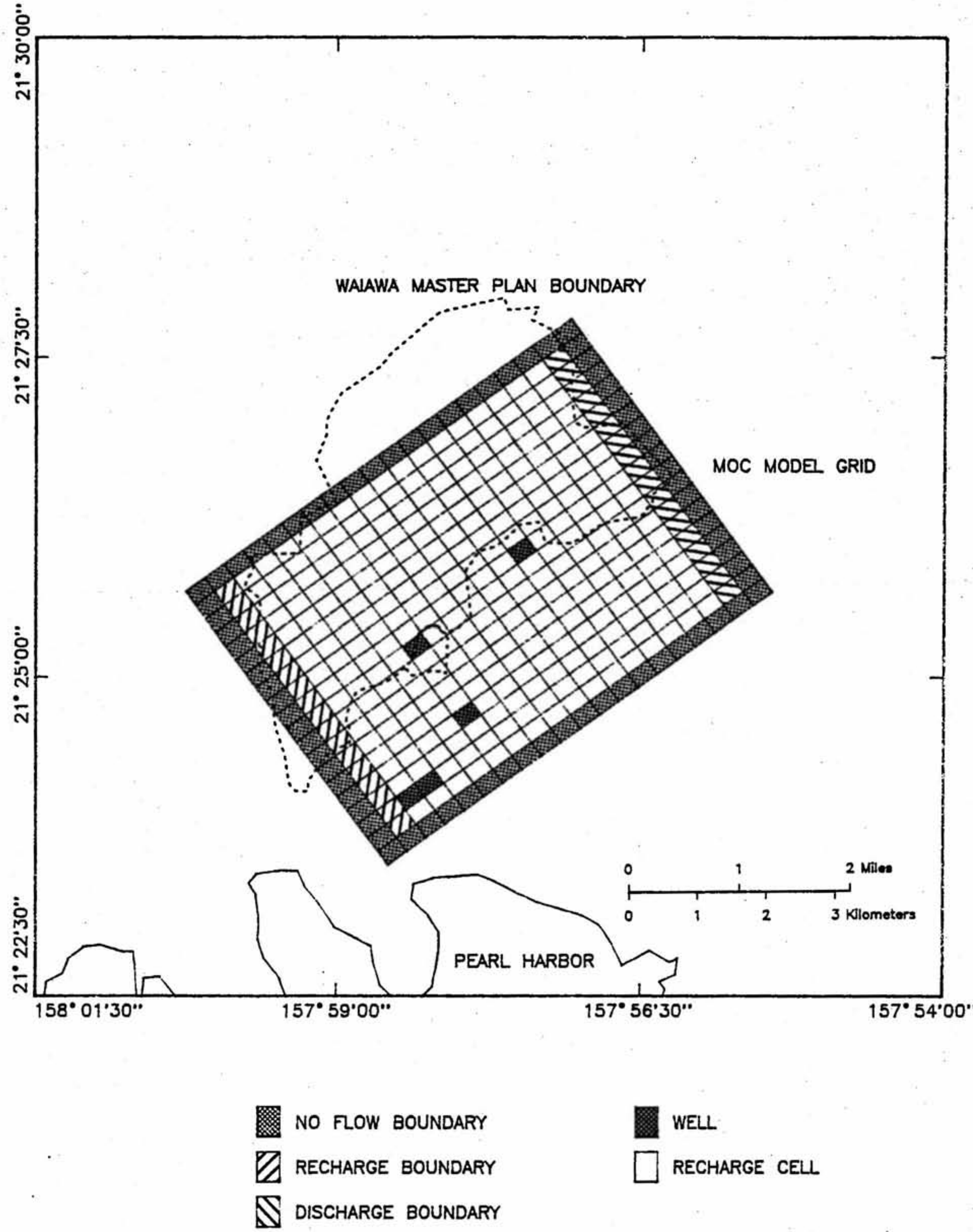
4. Using the best estimate hydraulic conductivity and dispersivity values mentioned above and a grid depth of 90 m, model sensitivity to the effective porosity of the aquifer was tested. Appendix Figures E.6 and E.8 are the simulated chloride time series for Waiawa Shaft using effective porosities of 0.1 and 0.05, respectively. A typical value of 0.05 for the specific yield of the Pearl Harbor aquifer was obtained by Mink (1980) in his analysis of groundwater head recovery data during the 1958 sugar worker strike. In the current study, however, an effective porosity of 0.05 caused groundwater flow velocities to increase so that toward the end of the calibration period when irrigation of sugarcane fields on Waiawa Ridge was stopped, the chlorides in the groundwater were too quickly flushed from the aquifer. This phenomenon manifests itself in the steep decline in simulated chloride concentrations after 1983 (App. Fig. E.8). Simulations employing an effective porosity of 0.1 more closely followed the historical decline in chlorides pumped by Waiawa Shaft (App. Fig. E.6).
5. Although the results are not presented here, the transport of chlorides was not sensitive to the hydraulic conductivity. If all fluxes and parameters remain unchanged except for the hydraulic conductivity, the flow model indicates that smaller conductivity values are balanced by larger hydraulic gradients. Thus, the resulting flow pattern and, consequently, the transport phenomenon, remains unchanged.

Differences between observed and simulated chloride concentration time series at Waiawa Shaft can be attributed to a number of different factors. Errors in the basic recharge and concentration inputs to the groundwater, which are computed on an annual basis, can greatly affect the simulated output. These errors can arise as a result of the inability of the piston displacement model to adequately account for preferential flow through soil macropores or exceptional vertical flow in the unweathered basalt. It should be mentioned, however, that the exact nature of flow in the unweathered basalt remains largely unknown. While preferred pathways may exist, they will be intersected frequently by many thin lava flows. Thus, the overall effect of these pathways is difficult to assess. Errors in the recharge and concentration inputs to the water table may also be attributed to the lack of detailed data regarding the spatial and temporal distributions of irrigation on Waiawa Ridge.

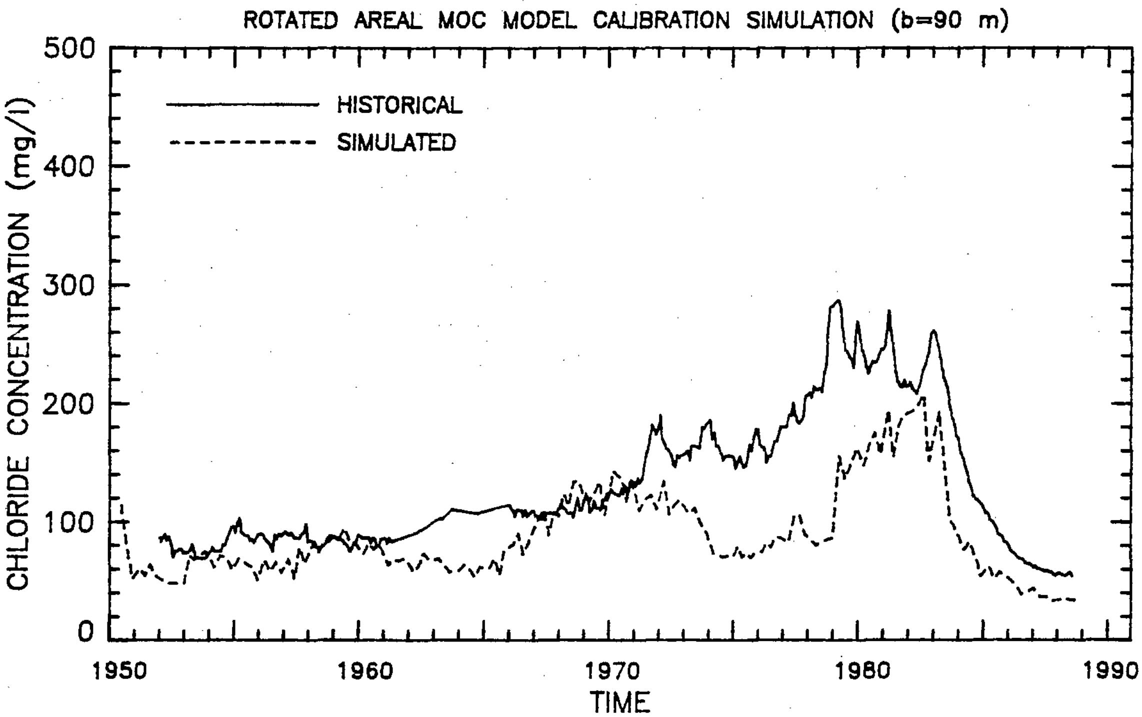
The generalized representation of the infiltration tunnel in the coarse finite difference grid may also contribute to the discrepancy between observed and simulated concentration time series. The Waiawa water development complex was assumed to withdraw water from a single cell measuring 335 m (1,100 ft) long, 244 m (800 ft) wide, and 90 m (300 ft) deep. In reality, the infiltration tunnel is 519 m (1,702 ft) long, and approximately 3 m (10 ft) wide and 3 m (10 ft) high with an invert 3 to 6 m (10-20 ft) below the water table.

The orientation of the grid in the direction of the assumed groundwater flow path also affects the model output. Model sensitivity to grid orientation was tested by rotating the upgradient end of the grid 20 degrees to the east about the shaft sump (App. Fig. E.9). This grid orientation corresponds roughly to the flow direction determined by Hufen, Eyre, and McConachie (1980). The simulated chloride time series using the calibrated parameters defined above is presented in Appendix Figure E.10. Clearly, this grid orientation did not allow an adequate amount of high chloride content recharge water from Waiawa Ridge to enter the shaft. In order to draw in more water from the west, the effective extraction depth of the shaft was reduced to 60 m (200 ft). However, the model was still unable to properly simulate the rise in chloride concentration experienced at Waiawa Shaft during the late 1970s and early 1980s (App. Fig. E.11).

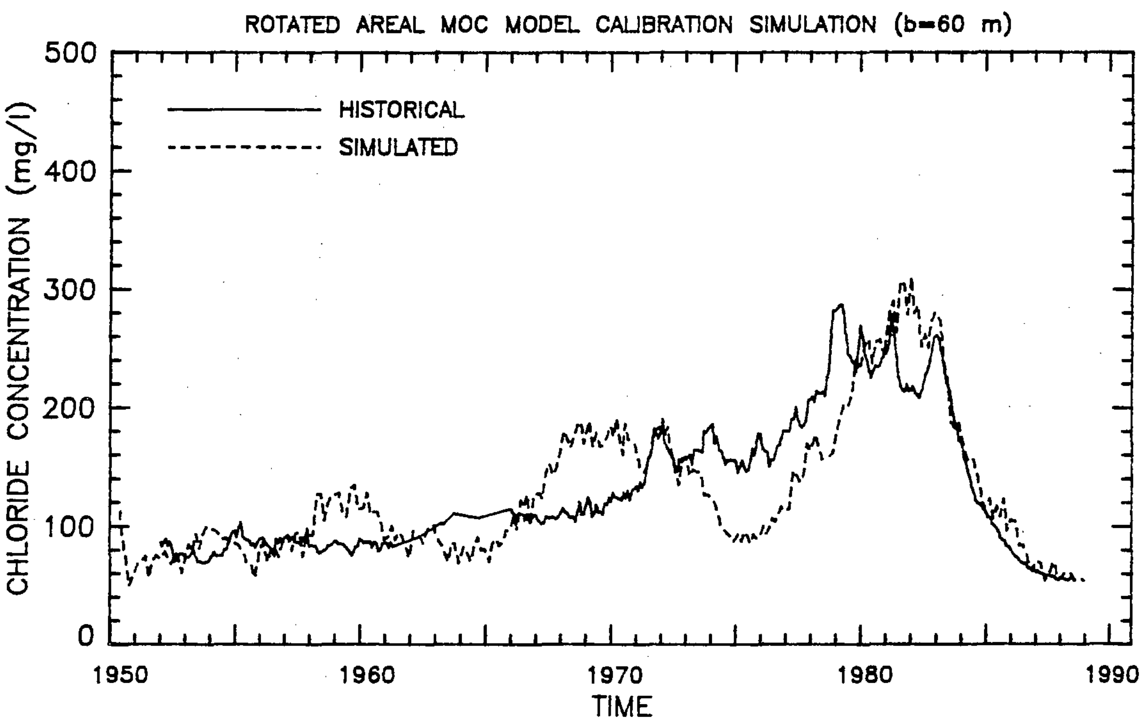
Although the vertical depth of contribution of a well changes in response to changes in pumping rates, for this investigation a single depth of contribution was assumed to be valid for the range of pumping rates encountered at Waiawa Shaft. During periods of low pumpage, the depth of contribution of Waiawa Shaft is likely reduced so that a greater portion



Appendix Figure E.9. Rotated areal MOC model grid



Appendix Figure E.10. Simulated chloride time series at Waiawa Shaft using the rotated areal MOC model grid and an aquifer depth of 90 m



Appendix Figure E.11. Simulated chloride time series at Waiawa Shaft using the rotated areal MOC model grid and an aquifer depth of 60 m of the pumped water originates from the upper irrigation return layer of the basal lens. The MOC model is clearly sensitive to the choice of aquifer mixing depth used. A three-dimensional model may be more appropriate to accurately simulate the flow pattern in the vicinity of Waiawa Shaft. It should be emphasized, however, that model performance can only be as good as the associated input data. With a lack of data no model can account for local heterogeneities in the aquifer caused by more or less permeable members which might play an important role in the flow pattern near the infiltration tunnel. Although a three-dimensional model could be employed to account for the changing depth of contribution of Waiawa Shaft, at the pumping rates commonly encountered, the MOC model was able to establish an average depth of contribution of about 90 m (300 ft). A 90-m depth provided the proper amount of dilution of the upper irrigation return layer with fresher, upgradient water.

Results of the calibration effort indicate that the MOC model is capable of simulating the general transport mechanisms in the aquifer and that the proper fluxes are being maintained. Although simulated heads are of a reasonable order of magnitude, because of its design the current model is not meant to simulate the historical trend of head decline within the aquifer. The historical head decline, caused by increased regional pumpage from the aquifer over time, can only be properly simulated under transient flow conditions leading to reduced groundwater storage. Within the modeled study area, however, pumpage is relatively constant over the simulation period which makes it difficult to readily reproduce the historical time series of heads. In addition, the upper layer of the aquifer was isolated to more accurately simulate the depth of contribution of Waiawa Shaft. Ideally, a region-wide, aquifer-deep, three-dimensional solute transport model incorporating the natural boundaries of the aquifer should be employed to simulate the historical trend of head decline while simultaneously simulating transport of a chemical species. Such an approach, which is beyond the scope of the current project, would be data intensive, time consuming, and costly, and would not necessarily produce accurate results.

METHOD OF CHARACTERISTICS MODEL CALIBRATION--VERTICAL MODE

The MOC model may be utilized directly to simulate two-dimensional solute transport in vertical cross sections. When the model is applied in this manner, the horizontal width of the cross section corresponds to the aquifer thickness in the areal case.

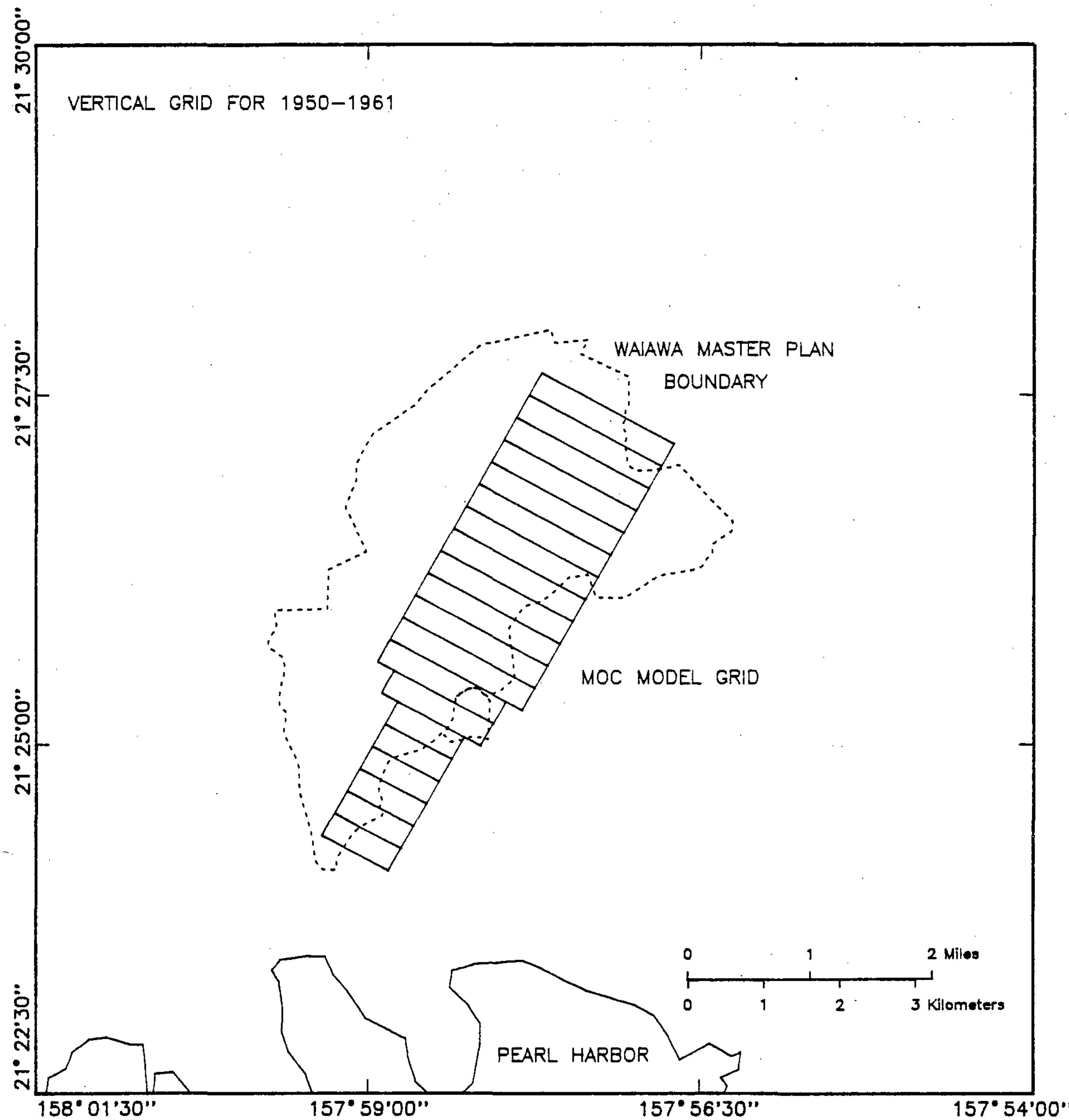
Chloride concentrations in Waiawa Shaft water have been shown to be inversely related to draft (Mink 1973; Eyre 1983b). It is generally felt that this phenomenon is caused by the extraction of deeper, fresher water from the core of the basal lens under increased drafts. To test this hypothesis, the MOC model is applied here in a vertical cross section mode, rather than an areal mode, to simulate solute transport in the vicinity of Waiawa Shaft. Since the MOC model is two dimensional, an areal grid orientation is unable to account for the layered nature of the basal lens which consists of a warmer irrigation return layer near the top, underlain by colder fresh water. The areal model essentially averages the effects of the layered lens. In a vertical mode, the model can account for vertical concentration gradients that existed in the Waiawa area during the period when sugarcane fields were furrow irrigated. It should be emphasized that the MOC model does not account for temperature gradients. However, the temperature gradient is probably a relatively minor factor affecting solute transport in the area. As with the areal MOC model, the historical chloride time series of water pumped from Waiawa Shaft (1950-1988) is used to calibrate and evaluate the MOC model in a vertical orientation.

Grid Dimensions. The modeled area for this study is located in the Waiawa system (Mink and Lau 1987) of the Pearl Harbor aquifer of central Oahu and extends south of Waiawa Shaft to include downgradient pumpage and north to include upgradient areas previously used for sugarcane cultivation. If groundwater flows in the direction of the cross section centerline, lateral transfer of water into the grid is minimized.

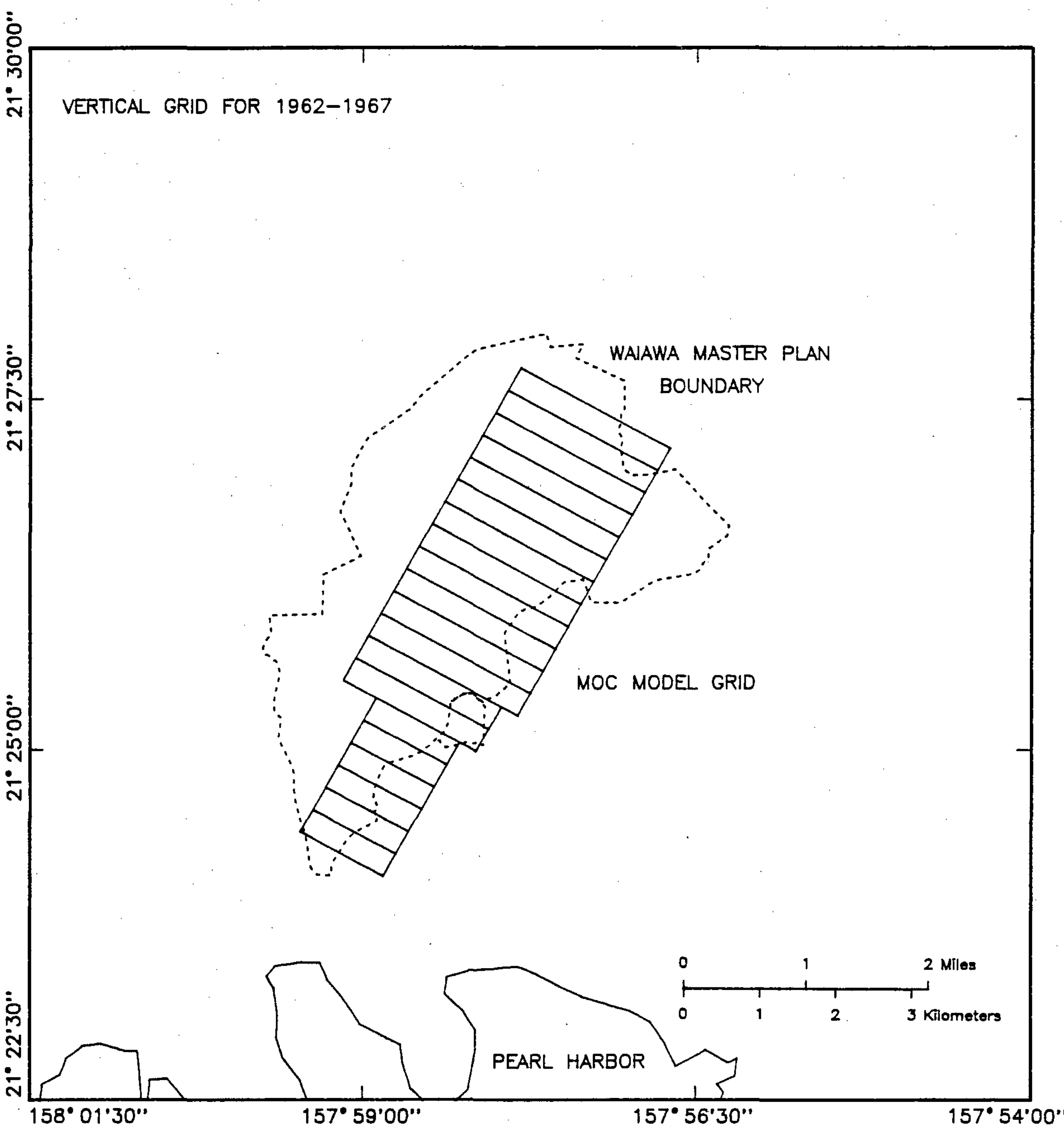
Since it was constructed in the early 1950s, the zone of contribution of Waiawa Shaft has continually changed in response to varying pumping rates at the shaft and at nearby wells. In addition, changes in recharge due to fluctuations in rainfall and changes in land use have had a profound impact on the zone of contribution of Waiawa Shaft. The calibrated areal model was used to evaluate the changes in the zone of contribution of Waiawa Shaft. Using the velocity vectors output from the groundwater flow submodel of the calibrated areal MOC model, the flow pattern in the vicinity of Waiawa Shaft was determined for each year of the calibration period. Although the velocity distribution in the aquifer varied from year to year, six different periods were identified during which the zone of contribution of Waiawa Shaft remained relatively stable. A summary of these six periods is presented in Appendix Table E.3. The corresponding zones of contribution for each of these six periods are presented in Appendix Figures E.12 to E.17. The shapes of the contribution zones presented in Appendix Figures E.12 to E.17 vary according to the prevailing recharge and pumping conditions. In each case, the length of the vertical section was increased to provide a downgradient buffer for Waiawa Shaft so that the large sink was not unnecessarily close to the downstream boundary. Although numerous wells exist in the vicinity of the modeled area, the MOC grid was designed to coincide with the zone of contribution of Waiawa Shaft. Thus, no other wells are included in the grid. Pumpage from other wells in the area, however, directly influenced the shape of the capture zone of Waiawa Shaft. In addition, the partial boundary of the Waiawa Valley fill causes more of the pumped water at Waiawa Shaft to originate from the west rather than equally from both sides of the central flow line.

APPENDIX TABLE E.3. PERIOD DEFINITIONS FOR VERTICAL MOC MODEL GRIDS

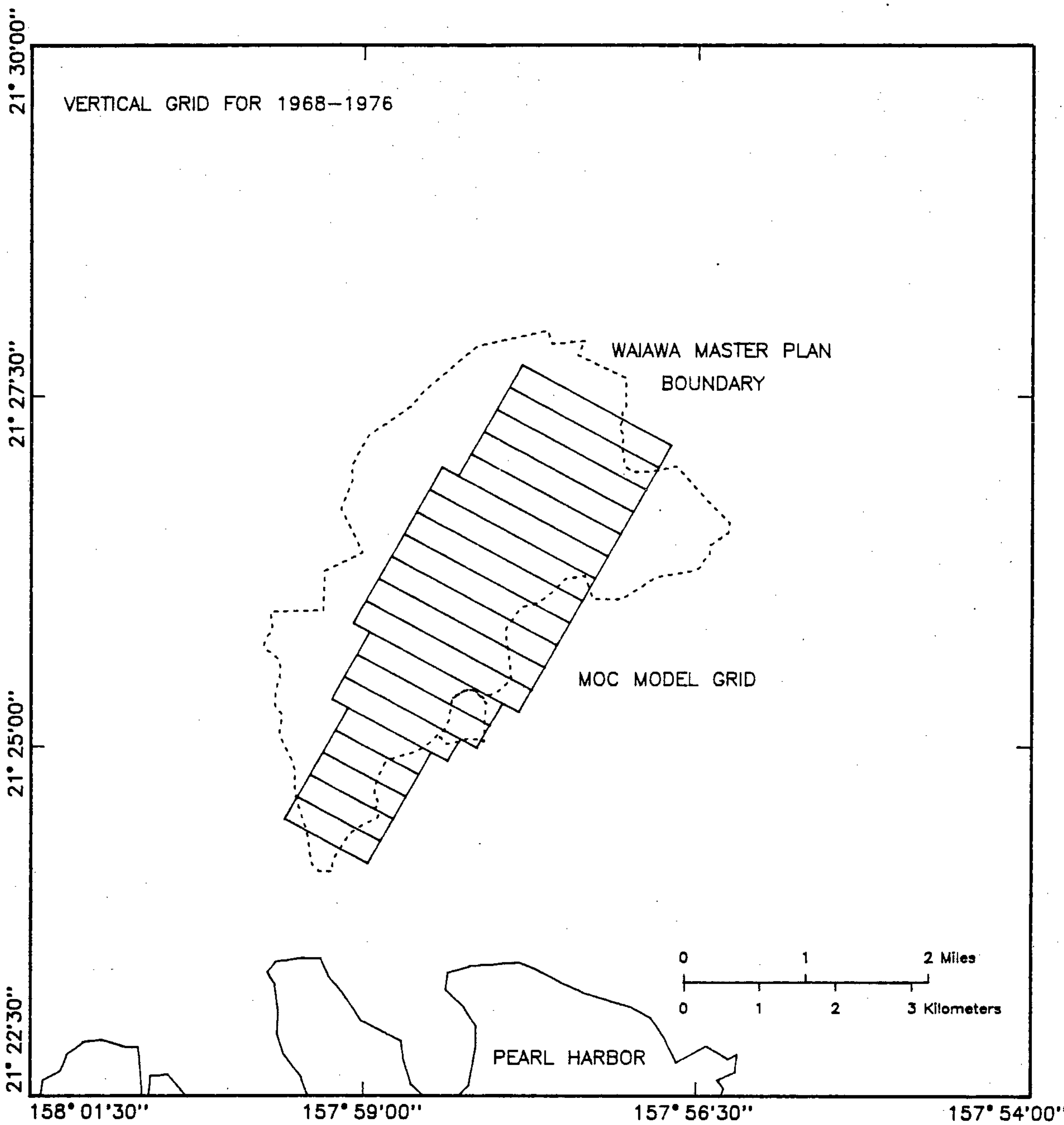
Grid No.	Period	General Characteristics of Period
1	1950-1961	no pumpage from upgradient OSC Pump 17
2	1962-1967	pumpage from OSC Pump 17 begins
3	1968-1976	sugarcane cultivation near Pearl City phased out
4	1977-1982	reduced pumpage at Waiawa Shaft
5	1983-1985	no sugarcane cultivation on Waiawa Ridge
6	1986-1988	reduced pumpage at Waiawa Shaft



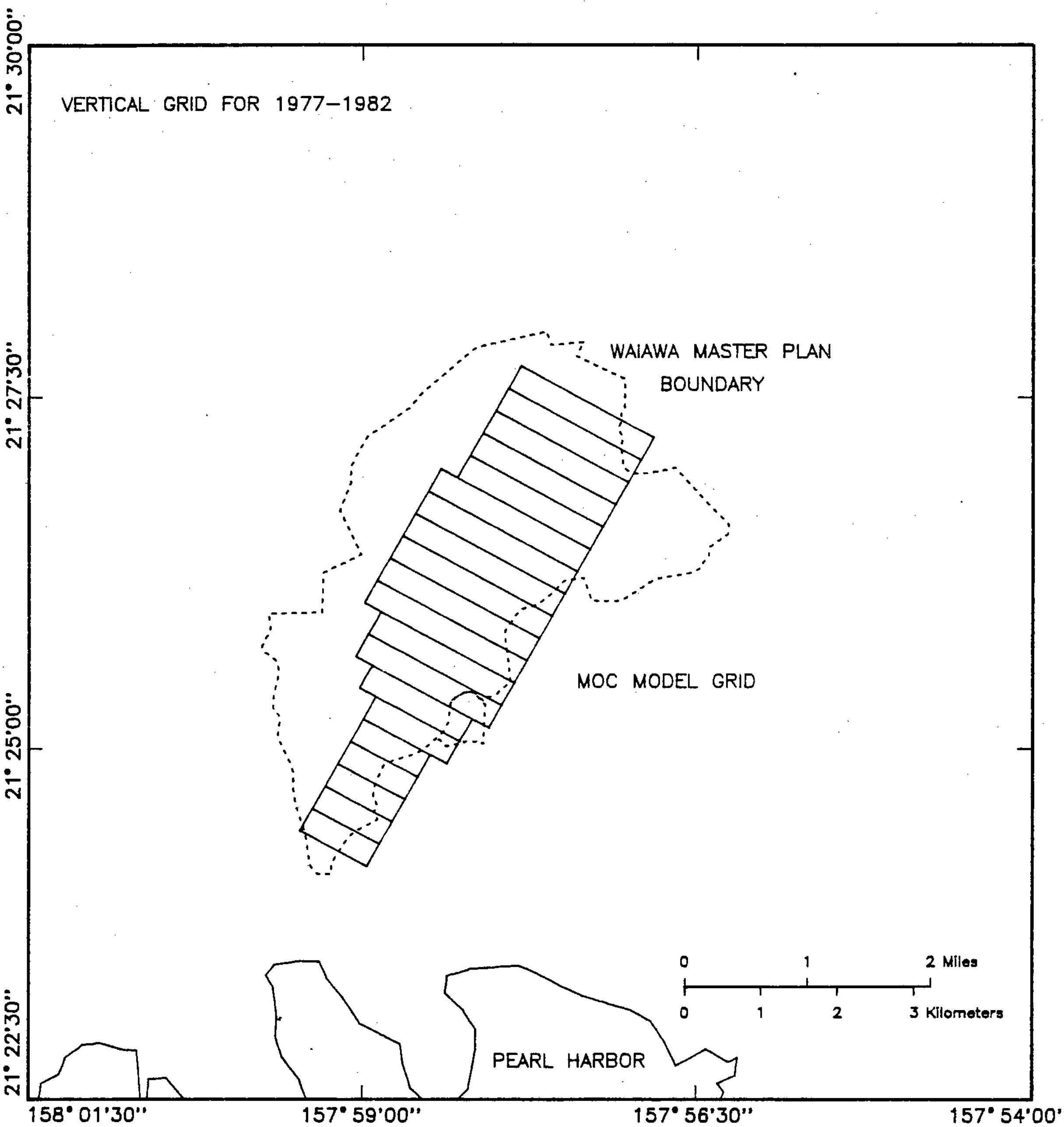
Appendix Figure E.12. Plan view of vertical MOC model grid for 1950-1961



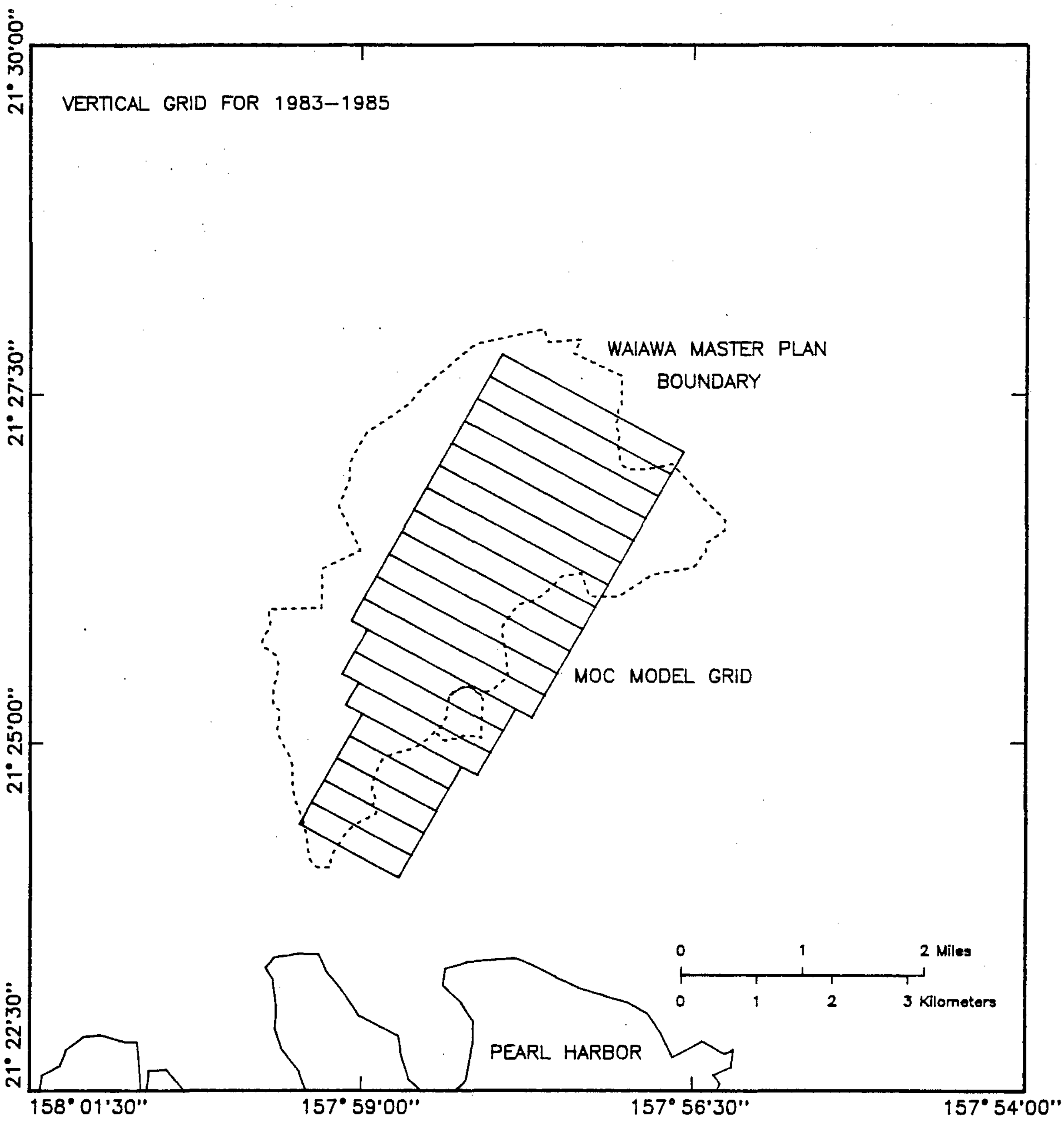
Appendix Figure E.13. Plan view of vertical MOC model grid for 1962-1967



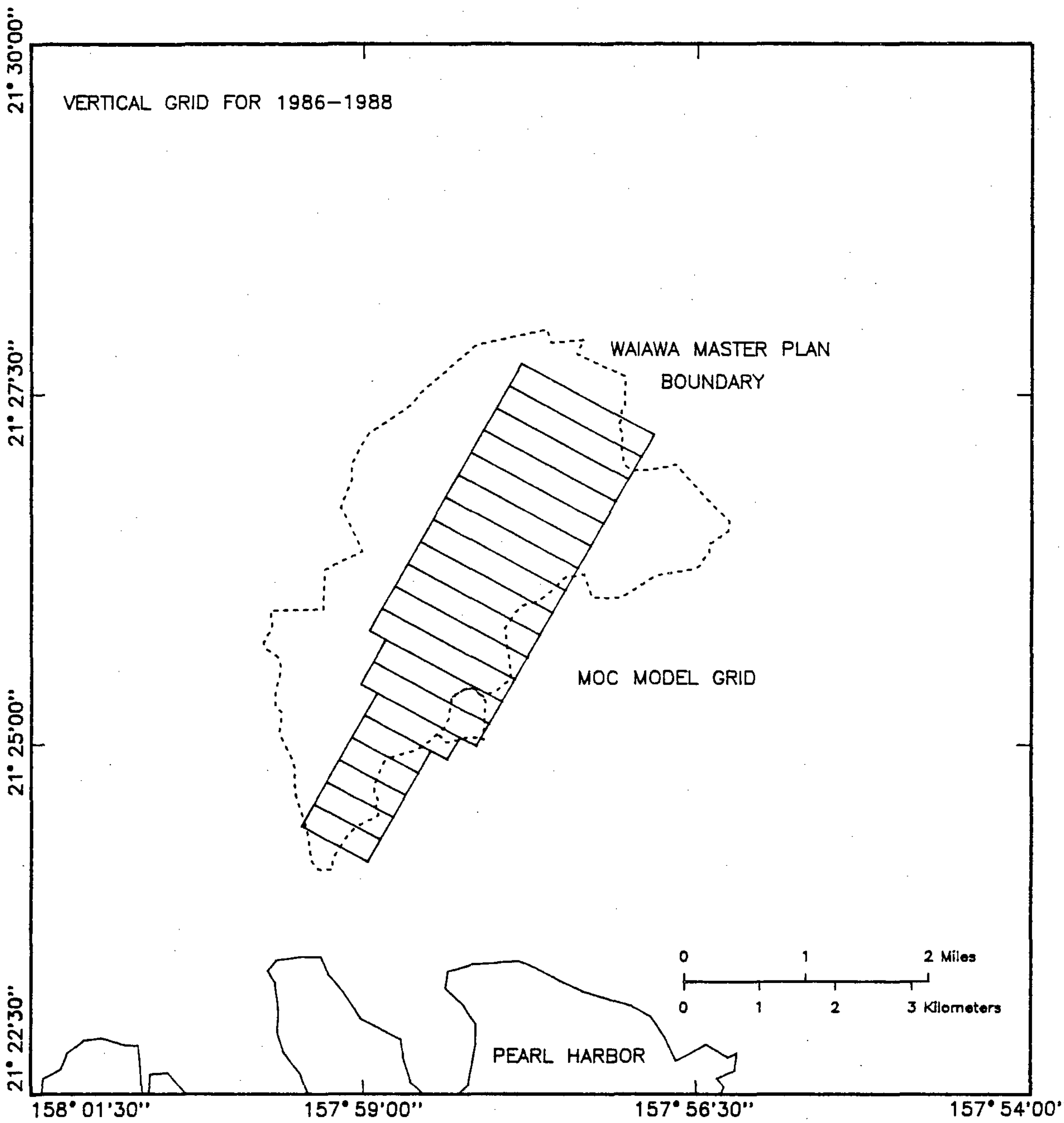
Appendix Figure E.14. Plan view of vertical MOC model grid for 1968-1976



Appendix Figure E.15. Plan view of vertical MOC model grid for 1977-1982



Appendix Figure E.16. Plan view of vertical MOC model grid for 1983-1985



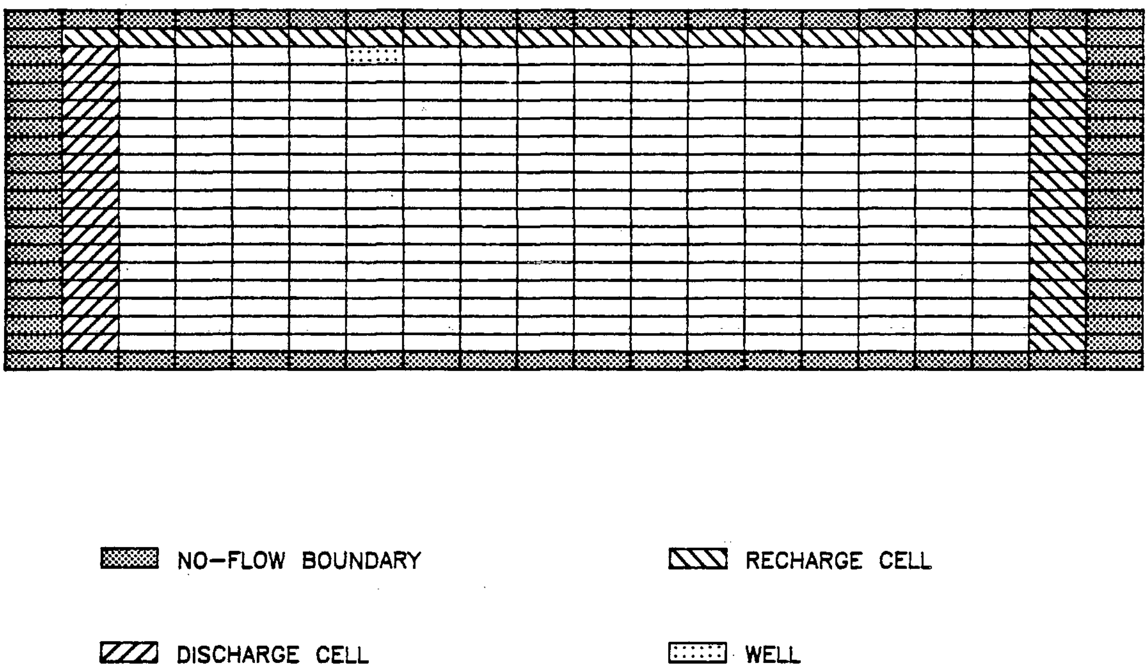
Appendix Figure E.17. Plan view of vertical MOC model grid for 1986-1988

The longitudinal and vertical dimensions of the grid cells are made constant at 335 m (1,100 ft) and 11 m (35 ft), respectively. The grid extends to a depth of 192 m (630 ft) below the water table. The bottom of the grid is maintained above the transition zone. Thus, water between the bottom of the irrigation return layer and the bottom boundary of the grid is assumed to consist of fresh water. The vertical section view of the grid is presented in Appendix Figure E.18.

Boundary Conditions. The top water table boundary of the grid is a flux boundary condition represented by 18 recharge wells. Because fluctuations in the water table are assumed to be relatively small, the top boundary remains stationary. The bottom boundary of the grid is a no-flow boundary which precludes inflow from deeper in the basal lens. The upgradient boundary is a flux boundary which represents groundwater input to the grid from the high recharge area near the crest of the Koolau Range. The downgradient boundary is also a flux boundary which represents groundwater discharge from the grid. The boundary conditions used in this modeling application are presented in Appendix Figure E.18. Within each annual pumping period, changes in water storage are assumed to be negligible. Thus, the upgradient influx and unsaturated zone recharge are balanced by the downgradient discharge and pumpage. Furthermore, the upgradient recharge and downgradient discharge are justified to be uniformly distributed in the vertical direction by the Dupuit assumption and the modeling results of Souza and Voss (1987). The Waiawa water development complex was simulated by a sink located in a single cell of the grid (App. Fig. E.18).

Initial Conditions. Initial heads were assigned in a manner similar to those in the areal MOC calibration. Applying the Dupuit assumption prior to pumping, flow is essentially horizontal and equipotential lines are vertical.

Records from test wells in the vicinity indicate that the top of the basal lens underlying sugarcane fields on Waiawa Ridge had a chloride concentration of about 250 mg/l during shaft construction. Upgradient of the sugarcane fields, the groundwater was assumed to have a background chloride level of 20 mg/l. The chloride concentration in the basal lens beneath the irrigation return layer was also assumed to be 20 mg/l. The



Appendix Figure E.18. Section view of vertical MOC model grid with boundary conditions and well location chloride level was gradually reduced from 250 mg/l at the top of the lens to 20 mg/l over a vertical distance of 90 m (300 ft) in the aquifer beneath the area of sugarcane cultivation.

Input Data. For calibration purposes, annual pumpage data for Waiawa Shaft from 1950 to 1988 were obtained from USGS files and directly from the USN. A monthly time series of pumpage from Waiawa Shaft is given in Appendix Figure E.4.

In order to calibrate the MOC model using annual pumping periods, the annual time series of recharge and input chloride concentrations to the groundwater from the vadose zone were needed for each of the six vertical sections defined in Appendix Table E.3. The procedure for determining the recharge at the top boundary of the vertical section is essentially identical to the procedure outlined in the areal MOC model calibration section.

Model Parameters. For each vertical section or zone of contribution, 13 different runs were made using the MOC model. The initial conditions for the first vertical section valid for the calibration period 1950 to 1961 were described above. Model output at the end of this first period was used to define the initial conditions for the second zone of contribution valid for 1962 to 1967. Similarily, output from the second, third, fourth, and fifth calibration periods was used to define the initial conditions for the third, fourth, fifth, and sixth vertical sections, respectively.

The recharge amounts and concentrations entering the top boundary of the grid were changed on an annual basis. Steady state flow conditions were assumed to exist within each annual pumping period. As defined in the areal model calibration section, a steady upgradient groundwater influx rate of 0.52 m^3/s per kilometer width of aquifer (19 mgd/mile) was assumed to be valid for the total depth of the basal lens. The actual amount of water entering the grid was adjusted to reflect the vertical extent of the grid.

The areal model calibrated values for the horizontal component of hydraulic conductivity (460 m/day), longitudinal dispersivity (76 m), and effective porosity (0.1) were used for all vertical model simulations. A total of 13 different parameter combinations of vertical hydraulic conductivity and transverse dispersivity were tested. A summary of the 13 different runs is provided in Appendix Table E.4.

APPENDIX TABLE E.4. VERTICAL MOC MODEL PARAMETER SUMMARY

Run	Conductivity (m/day) Horiz.	Conductivity (m/day) Vert.	Dispersivity (m) Long.	Dispersivity (m) Trans.
1	457	2.3	76	0.3
2	457	4.6	76	0.3
3	457	22.9	76	0.3
4	457	91.5	76	0.3
5	457	2.3	76	0.15
6	457	2.3	76	1.5
7	457	2.3	76	3.0
8	457	4.6	76	0.15
9	457	4.6	76	1.5
10	457	4.6	76	3.0
11	457	22.9	76	0.15
12	457	22.9	76	1.5
13	457	22.9	76	3.0

Results and Discussion. All computer simulations were run on a Sun 4/110 Workstation. Based on the results of the simulations, the following observations are offered.

1. In general, increasing the vertical hydraulic conductivity or transverse dispersivity causes the irrigation return layer to move downward in the aquifer. Within the ranges tested, the transverse dispersivity has a greater impact on the resulting chloride concentration distribution in the aquifer and on the chloride concentrations pumped at Waiawa Shaft.
2. Based on the velocity distribution output from the flow model, a vertical hydraulic conductivity value of 2.3 m (7.5 ft)/day suggested by Souza and Voss (1987) results in a depth of contribution of Waiawa Shaft of approximately 90 m (300 ft) which, is in agreement with the results of the areal model calibration. Higher values of vertical conductivity lead to unrealistic velocity distributions in the aquifer.
3. Solute transport in the vertical section is quite sensitive to changes in transverse dispersivity. Increasing the transverse

(vertical) dispersivity causes greater downward dispersion of the chlorides in the recharge water. This results in a dilution of the irrigation return layer over a greater depth so that water pumped from Waiawa Shaft will have lower chloride concentrations. A transverse dispersivity of 1.5 to 3 m (5-10 ft) best simulates the historical chloride time series at Waiawa Shaft. These values are larger than the transverse dispersivity values of 0.25 m (Souza and Voss 1987) and 0.76 m (Liu, Dale, and Ewart 1989) derived for the transition zone where flow is essentially horizontal. For the current investigation, however, significant flow components in the vertical direction may exist due to the pumpage from Waiawa Shaft and, to a lesser extent, as a result of recharge from the overlying vadose zone. In addition, the dispersion phenomenon in the MOC model is simplified by assuming an isotropic aquifer. Thus, the fourth rank dispersivity tensor is reduced to two constants (Konikow and Bredehoeft 1978). The effect of this assumption is difficult to assess. However, in the vicinity of Waiawa Shaft, significant anisotropy may exist in the vertical direction and this may not be adequately addressed by the model.

4. Whether or not the vertical MOC model adequately simulates the inverse relationship between chloride concentrations in water pumped by Waiawa Shaft and pumpage is difficult to assess. The spatial pattern of pumpage and recharge throughout the aquifer define the zone of contribution of Waiawa Shaft. Thus, it is difficult to single out the effects of varying pumpage at Waiawa Shaft with the two-dimensional vertical MOC model.

Differences between observed and simulated chloride concentration time series at Waiawa Shaft can be attributed to a number of different factors. In general, both the areal and vertical models do not simulate very well the historical time series of chloride concentrations at Waiawa Shaft from about 1965 to 1978. This may indicate that the basic recharge and concentration inputs may be in error for that period. The generalized representation of the infiltration tunnel in the coarse finite difference grid may also contribute to the discrepancy. The influence of the impermeable old alluvium and weathered basalt beneath Waiawa Valley cannot be accounted for with the two-dimensional MOC model in a vertical mode. By ignoring this partial flow boundary, the vertical model may actually simulate too much water extraction from the eastern portion of the zone of contribution.

The model calibration presented above is valid for the period dominated by furrow irrigation of sugarcane fields in the vicinity of Waiawa Shaft. Recharge under sugarcane crops is intense and thus probably reduces the zone of contribution as compared to that which would exist under urbanized conditions on Waiawa Ridge. If the vertical MOC model is to be used for the future urbanized scenario, an adjustment of the grid size may be necessary.

Due to the design of the grid which isolates the portion of the aquifer affected by pumpage from Waiawa Shaft, the historical trend of groundwater head decline in the aquifer cannot be simulated. Souza and Voss (1987) successfully simulated this phenomenon by selecting a typical vertical section which incorporated the trend of increased pumpage in the aquifer. The intent of this investigation, however, was to isolate the aquifer section which specifically included Waiawa Shaft so that solute transport in the area could be simulated. Since pumpage from the shaft does not exhibit any trend of increase over time, the regional decline of groundwater heads in the Pearl Harbor aquifer will not be simulated sucessfully with the selected vertical sections shown in Appendix Figures E.12 to E.17.

In general, isolating similar portions of the aquifer reveals that the vertical model produces slightly lower concentrations than the horizontal model. Whereas the areal MOC model assumes an average concentration distribution in the vertical direction, the vertical MOC model averages solute distributions in the horizontal plane. Although there is a tradeoff in using either model orientation, the horizontal model more accurately accounts for the spatial distribution of recharge inputs to the groundwater. In addition, the horizontal model is able to account for the partial flow barrier created by the Waiawa Valley fill. These factors may explain the differences in results obtained. Because the areal model better accounts for spatially varying inputs and major aquifer heterogeneities, it consequently produces superior calibration results.

MIXING CELL MODEL CALIBRATION

A simple analytical model which treats a portion of the aquifer as a mixing cell (Mercado 1976) can be employed to provide an initial estimate of the potential for groundwater contamination due to proposed urban development in the vicinity of the USN Waiawa Shaft. The ability of the mixing cell model to simulate solute transport in the Waiawa area of central Oahu is demonstrated here by calibrating the model with the historical time series of chloride concentrations in water pumped by Waiawa Shaft.

In Hawaii, the mixing cell concept was used by Mink and Kumagai (1970) to describe the effects of irrigation on groundwater quality in the Pearl Harbor region of central Oahu. The model developed by Mink and Kumagai (1970) ignored dispersion and only considered the effects of mechanical mixing. In addition, mixing in the vertical plane was assumed to be instantaneous. The model was used to successfully simulate steady state silica concentrations at various locations within the aquifer.

Eyre (1987) used a steady state mixing cell model to compute the chloride concentration of the irrigation return water for the period of furrow irrigation in the Waianae portion of the Pearl Harbor aquifer near the Barbers Point water tunnel. Eyre then used the same model to predict the effect of conversion to drip irrigation on the groundwater quality.

Most recently, Or (1987) used a single cell model and a multiple mixing cell model to simulate DBCP transport in the basaltic aquifer near the Mililani area of central Oahu. Or treated the top soil as a reservoir that releases adsorbed pesticide residues with the natural recharge, and paid special attention to the attenuation of DBCP during its downward transit through the approximately 240 m (800 ft) thick vadose zone. Despite its success in simulating the average temporal variations of DBCP concentrations, the mixing cell model could not fully describe the spatial distribution of the trace organics throughout the relevant aquifer portion due to inherent limitations with the complete mixing approach.

Mixing Cell Concept. Application of the model requires the division of the aquifer into a desired number of discrete mixing cells. The water balance equation for each cell in the aquifer can be expressed as

$$Q_{in} + Q_{un} - Q_p - Q_{out} = A \cdot S \cdot (dh/dt) \qquad \text{(E.11)}$$

where Q_{in} is the upgradient groundwater flow into the cell $[L^3T^{-1}]$, Q_{un} is the groundwater recharge entering the cell due to rainfall and irrigation return flow $[L^3T^{-1}]$, Q_p is the total water withdrawal from the cell due to pumpage $[L^3T^{-1}]$, Q_{out} is the groundwater flow exiting the cell $[L^3T^{-1}]$, A is the horizontal surface area of the cell $[L^2]$, S is the aquifer specific yield (volume of water released per unit surface area per unit decline in head), h is the piezometric head [L], and t represents time [T]. If the changes in aquifer piezometric head over time are small compared with the effective mixing depth, the above water balance equation can be reduced to

$$Q_{in} + Q_{un} - Q_p - Q_{out} = 0 \qquad \text{(E.12)}$$

The nonreactive solute mass balance equation associated with the water balance equation is given by:

$$V(dC/dt) = Q_{in}C_{in} + Q_{un}C_{un} - Q_pC - Q_{out}C \qquad \text{(E.13)}$$

where C is the solute concentration $[ML^{-3}]$ in the aquifer at time t, C_{in} is the concentration of the upgradient groundwater flow into the cell $[ML^{-3}]$, C_{un} is the concentration of the recharge water from the overlying vadose zone $[ML^{-3}]$, and V is the effective volume $[L^3]$ of water within the cell (Mercado 1976). The effective volume is given by

$$V = A{\bullet}b{\bullet}n \qquad \text{(E.14)}$$

where A is the surface area of the cell $[L^2]$, b is the effective mixing depth [L], and n is the aquifer effective porosity. Combining equations E.12 and E.13 yields:

$$V(dC/dt) + (Q_{in} + Q_{un}){\bullet}C = Q_{in}C_{in} + Q_{un}C_{un} \qquad \text{(E.15)}$$

or

$$V(dC/dt) + b'C = a' \qquad \text{(E.16)}$$

where, $a' = Q_{in}C_{in} + Q_{un}C_{un}$ and $b' = Q_{in} + Q_{un}$.

If the concentration in the cell at some initial time t_0 is C_0, the solution of equation E.16 for any time $t > t_0$ is given by

$$C(t) = a'/b' - [a'/b' - C_0]{\bullet}\exp\{-b'(t-t_0)/V\} \qquad \text{(E.17)}$$

Model Description. Prior to utilizing the multiple mixing cell model for predictive purposes, the model must be calibrated and evaluated with existing historical data. The calibration and evaluation phase of the modeling effort will be accomplished by checking model performance against the historical chloride time series of Waiawa Shaft (App. Fig. E.1). For this study, a multiple mixing cell model grid can be established with dimensions which account for the complete mixing assumption, the effective mixing depth of the irrigation return layer, and the zone of contribution of the Waiawa infiltration tunnel. The central axis of the grid can be aligned with the assumed direction of groundwater flow.

Because Waiawa Shaft appears to withdraw water from deeper in the basal lens as pumpage is increased, a two-layered mixing cell model is proposed for the current study. The top layer of the mixing cell model grid is used to represent the portion of the aquifer affected by the irrigation return flow. The bottom layer of the model is used to represent the fresher water from deeper in the basal lens which is unaffected by the irrigation return water.

If no mixing is assumed to occur between the top and bottom layers of the model, the modified water balance equations are given by

$$\text{top layer:} \quad Q_{in,1} + Q_{un} - Q_{p,1} - Q_{out,1} = 0$$

$$\text{bottom layer:} \quad Q_{in,2} - Q_{p,2} - Q_{out,2} = 0 \qquad \text{(E.18)}$$

where the top and bottom components of the various flows are designated with the symbols 1 and 2, respectively. The total pumpage from a particular cell is

$$Q_p = Q_{p,1} + Q_{p,2} \qquad \text{(E.19)}$$

The nonreactive solute mass balance equations associated with the water balance equations above are

top layer:

$$V_1(dC_1/dt) = Q_{in,1}C_{in,1} + Q_{un}C_{un} - Q_{p,1}C_1 - Q_{out,1}C_1 \qquad \text{(E.20)}$$

bottom layer:

$$V_2(dC_2/dt) = Q_{in,2}C_{in,2} - Q_{p,2}C_2 - Q_{out,2}C_2 \qquad \text{(E.21)}$$

The solution to equations E.20 and E.21 is given by E.17 with the coefficients a' and b' given by

top layer: $a' = Q_{in,1}C_{in,1} + Q_{un}C_{un}$; $b' = Q_{in,1} + Q_{un}$

bottom layer: $a' = Q_{in,2}C_{in,2}$; $b' = Q_{in,2}$

The appropriate volumes for each layer must also be used to properly solve E.17 for the upper and lower layer aquifer concentrations C_1 and C_2, respectively.

For a particular time step, the computational procedure for a multiple mixing cell model with cells aligned along a common flow line involves solving first for changes in concentration in the upgradient cell of the grid. With known steady input concentrations to the upgradient cell, the final aquifer concentration in that cell for the given time step is computed with E.17 using the appropriate coefficients for the top and bottom layers. Rather than using the final aquifer concentrations for the top and bottom layers computed by E.17 as input to the adjacent downgradient cell, an average concentration over the time step is used to better maintain mass conservation. Although a time varying input concentration should ideally be used, an average concentration is used for simplicity. The average output concentration is determined from the known initial mass in the cell, known mass input to the cell, and computed final mass as

top layer:

$$C_{av,1} = [(C_{0,1} - C_1)V_1 + a'dt]/(b'dt) \qquad (E.22)$$

bottom layer:

$$C_{av,2} = [(C_{0,2} - C_2)V_2 + a'dt]/(b'dt) \qquad (E.23)$$

where $C_{av,1}$ and $C_{av,2}$ are the average output concentrations for the top and bottom layers, respectively, over the time step of length dt.

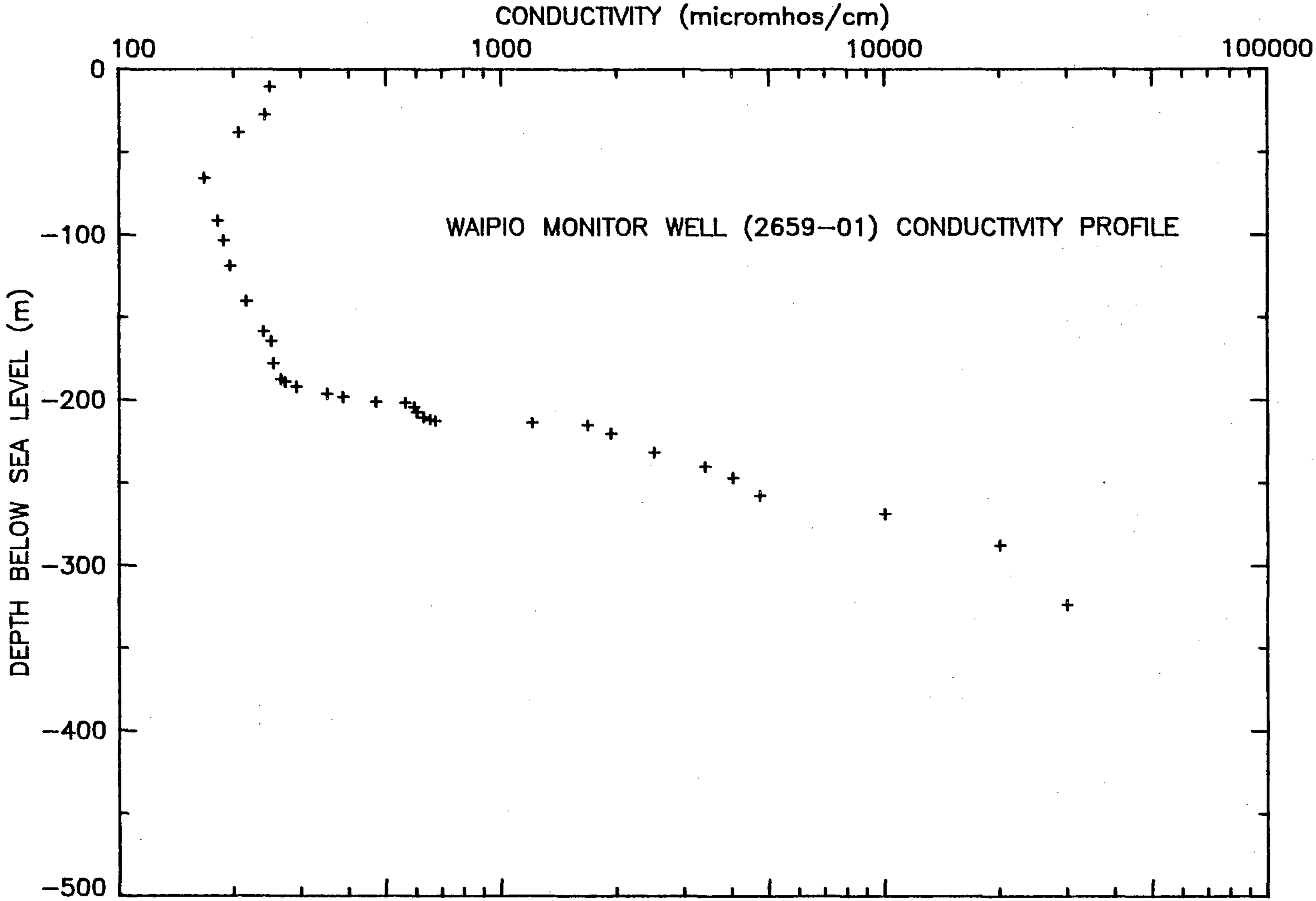
Once the aquifer concentrations in the top and bottom layers of a cell are determined for the desired time, the output concentration in a well pumping from that cell can be determined. Given a relationship between $Q_{p,1}$ and $Q_{p,2}$, the flow weighted concentration from each pumping well is easily calculated as

$$C_p = (Q_{p,1}C_{av,1} + Q_{p,2}C_{av,2})/Q_p \qquad (E.24)$$

Grid Dimensions. To account for the spatial variation of recharge and input concentration to the groundwater from the overlying vadose zone, a multiple mixing cell model was employed. The grid was aligned in the direction of the assumed groundwater flow path near Waiawa to minimize lateral flow into and out of each cell. Waiawa Shaft is located in the extreme downgradient cell. The upgradient extent of the grid was designed to include the most upgradient sugarcane fields formerly in the area. The dimensions of the multiple mixing cell model grid used for the current study were determined based on the rationale presented by Or (1987).

Mink (1964) reported that the basal lens of southern Oahu can be divided into three layers. The uppermost layer consists of a mixture of subsurface inflow and irrigation return water making it slightly warmer than the middle layer, which consists only of cooler subsurface inflow from mountain recharge areas. The lowest layer is also slightly warmer than the middle, reflecting the effect of the geothermal gradient. Work by Tenorio, Young, and Whitehead (1969) and Mink and Kumagai (1970) suggests an upper layer thickness of approximately 60 m (200 ft). Or (1987) assumed an effective mixing depth in the aquifer of 75 m (250 ft). Most recently, resistivity and temperature profiles were measured by the Honolulu Board of Water Supply on 23 April 1987 at the Waipio monitor well (2659-01) (Mink, Yuen, and Chang 1988). The conductivity (reciprocal of resistivity) profile (App. Fig. E.19) and temperature profile (Fig. 12) suggest an effective mixing depth of approximately 60 m (200 ft). Thus, an effective mixing depth of 60 m (200 ft) was used, which corresponds to the depth of the top layer of each cell. The thickness of the bottom layer of each cell was set at a sufficiently high value to adequately account for pumpage from Waiawa Shaft.

The lateral dimensions of the mixing cell grid were made to coincide with the zone of contribution of Waiawa Shaft as determined by the flow submodel of the calibrated areal MOC model. A summary of six periods during which the zone of contribution remained relatively stable is presented in Appendix Table E.3. Using the zones of contribution defined by the areal MOC model, six mixing cell model grids corresponding to the six zones of contribution were formed. As suggested by Or (1987), the



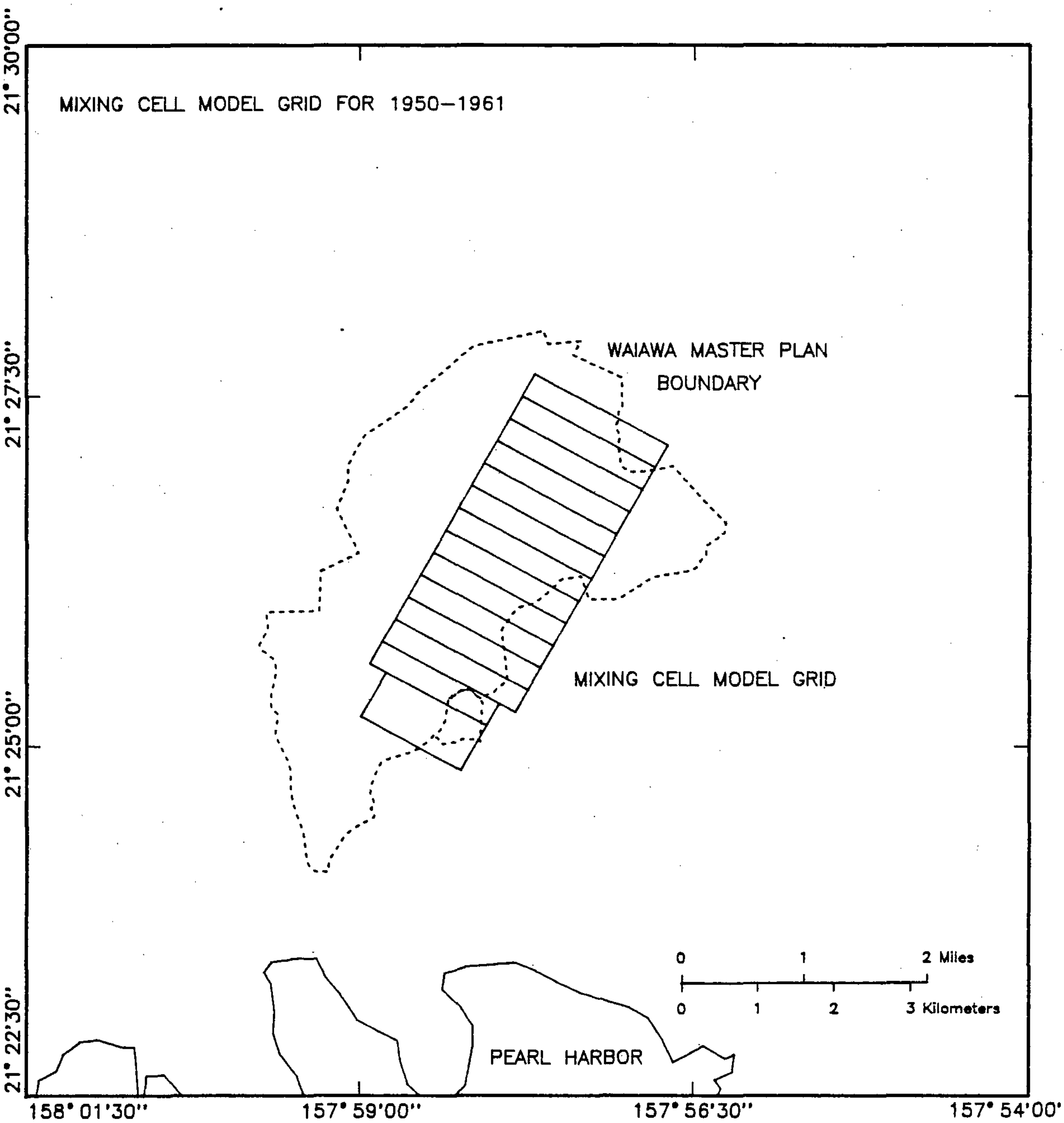
SOURCE: Data from Mink, Yuen, and Chang (1988).

Appendix Figure E.19. Conductivity profile for Waipio monitor well (2659-01), Oahu, Hawaii length of each cell of the multiple mixing cell model should be less than 300 to 600 m (1,000-2,000 ft). For this investigation, a cell length of 335 m (1,100 ft) was used for all cells except the most downgradient one. The length of the downgradient cell was increased to accommodate the downstream stagnation point of Waiawa Shaft. The multiple mixing cell grids corresponding to the six different zones of contribution each consist of 13 cells and are presented in Appendix Figures E.20 to E.25. The mixing cell model grids are similar to the grids defined for the MOC vertical section model except at the downgradient ends. The downgradient cell of the multiple mixing cell model was designed to terminate at the stagnation point of Waiawa Shaft whereas the corresponding MOC vertical model grid was extended to avoid boundary effects associated with the model.

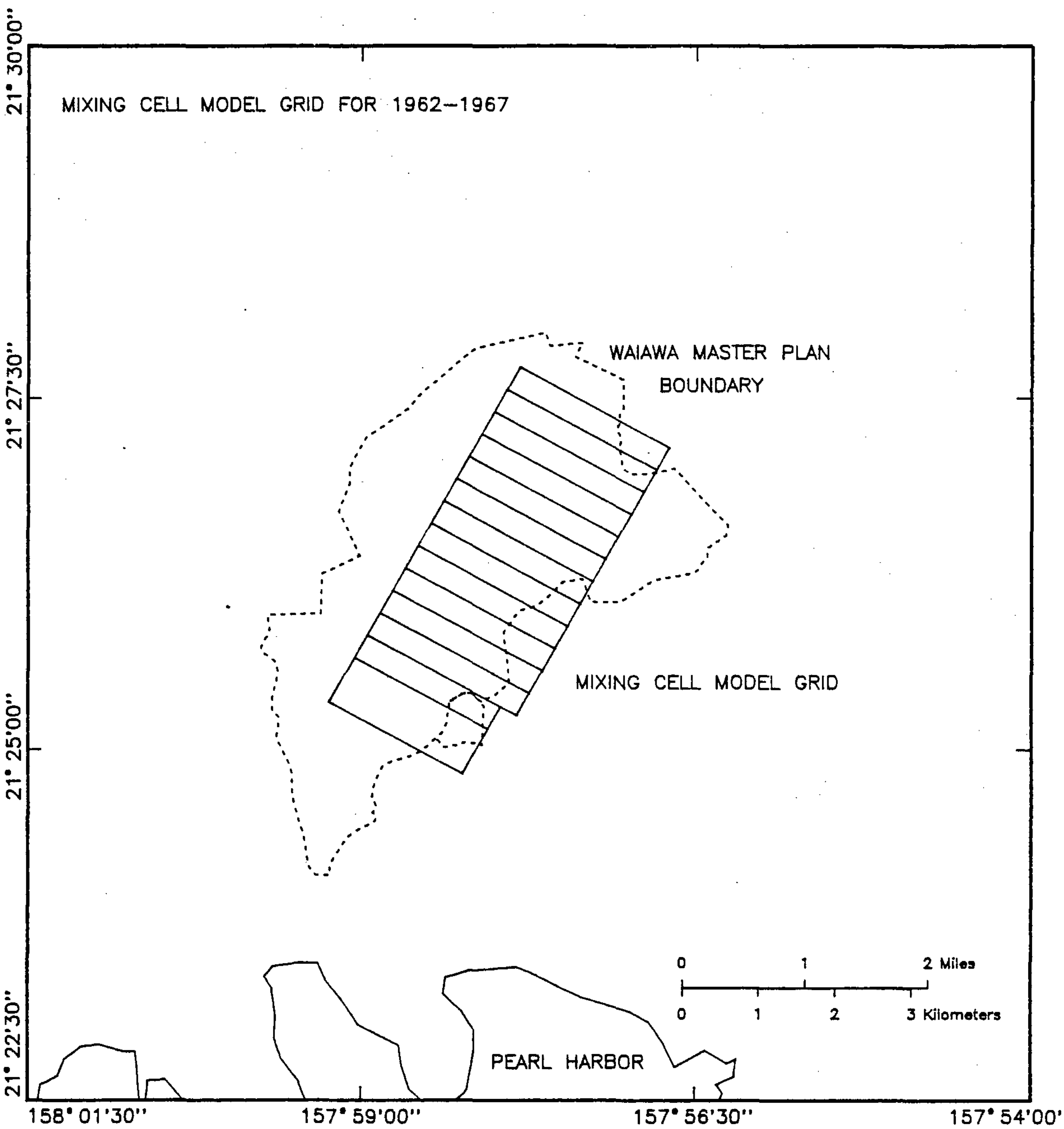
Input Data. In order to calibrate the mixing cell model using a yearly time step, annual time series of recharge and input chloride concentrations to the groundwater from the vadose zone must be obtained. The methodology used to estimate the recharge and associated chloride concentration input to the groundwater from the unsaturated zone was outlined in the section on the areal MOC model calibration and will not be repeated here.

Groundwater input to the upgradient cell of each mixing cell model grid was assumed to be steady. A groundwater influx rate of 0.52 m^3/s per kilometer width of aquifer (19 mgd/mile), defined in the areal MOC model calibration, was assumed to be valid for the total depth of the basal lens. The actual amount of water entering the grid was adjusted to reflect the intake area. The upgradient groundwater is assumed to have a chloride concentration of 20 mg/l (Swain 1973).

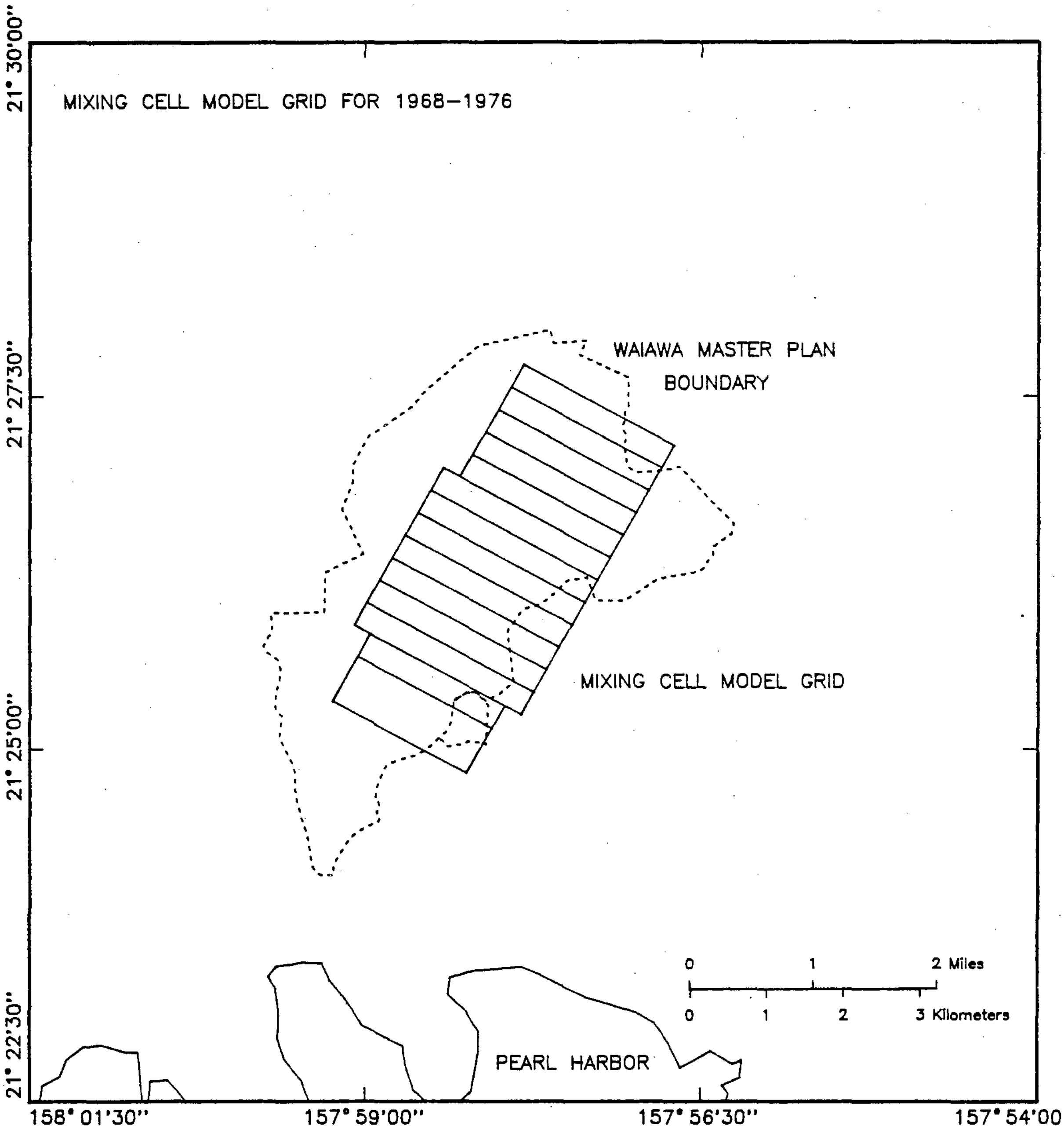
Initial Conditions. At the beginning of the calibration period, initial concentrations in cells were assumed to be 20 mg/l except in the top layer of cells 9, 10, 11, 12, and 13 which had initial concentrations of 50, 50, 200, 250, and 250 mg/l, respectively. (Note that cell 1 corresponds to the upgradient end of the grid and cell 13 represents the extreme downgradient end of the grid.) This distribution was based on records from test wells in the vicinity of Waiawa Shaft and on the locations of sugarcane fields receiving irrigation water from OSC Pump 6.



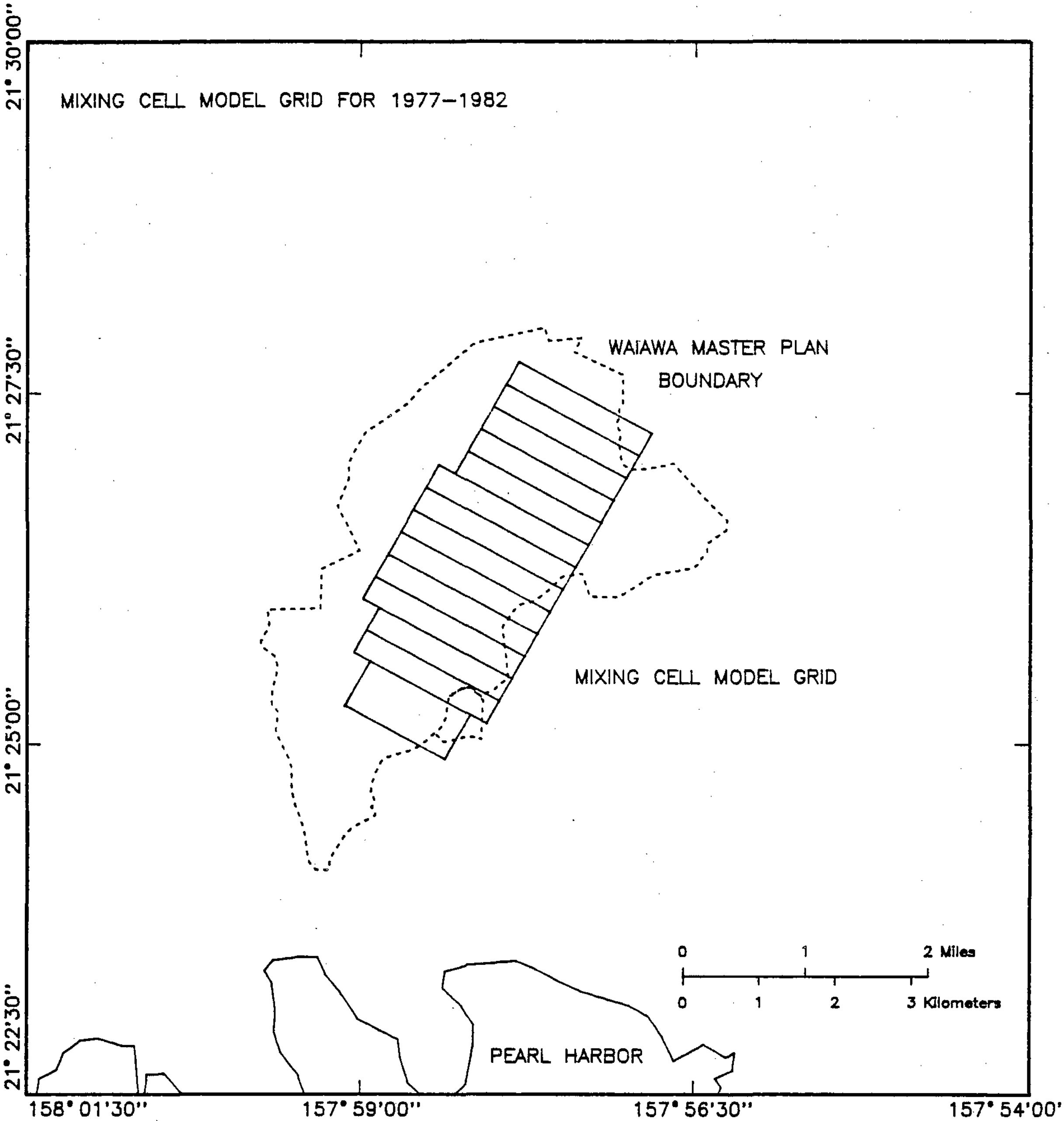
Appendix Figure E.20. Plan view of multiple mixing cell model grid for 1950-1961



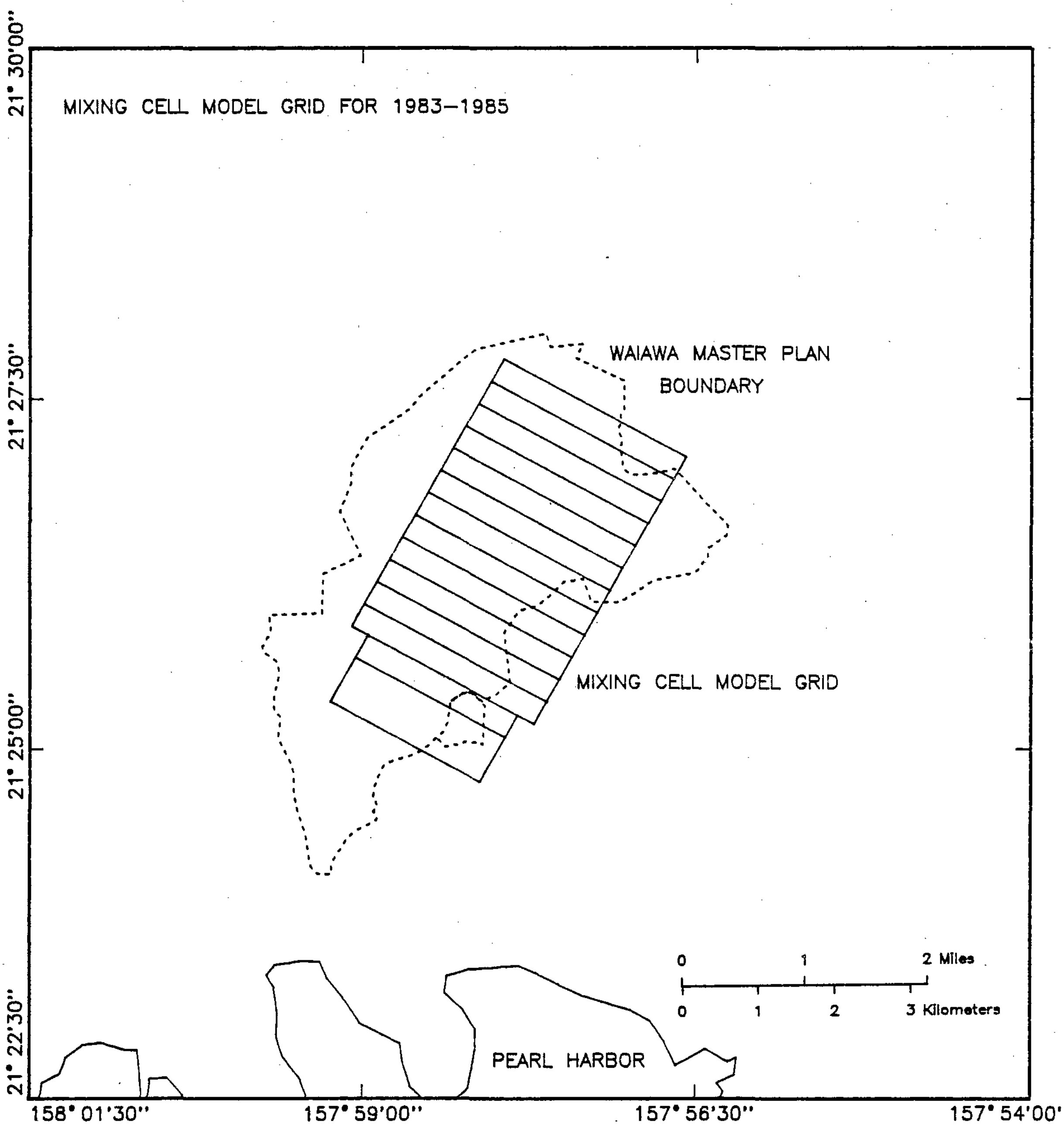
Appendix Figure E.21. Plan view of multiple mixing cell model grid for 1962-1967



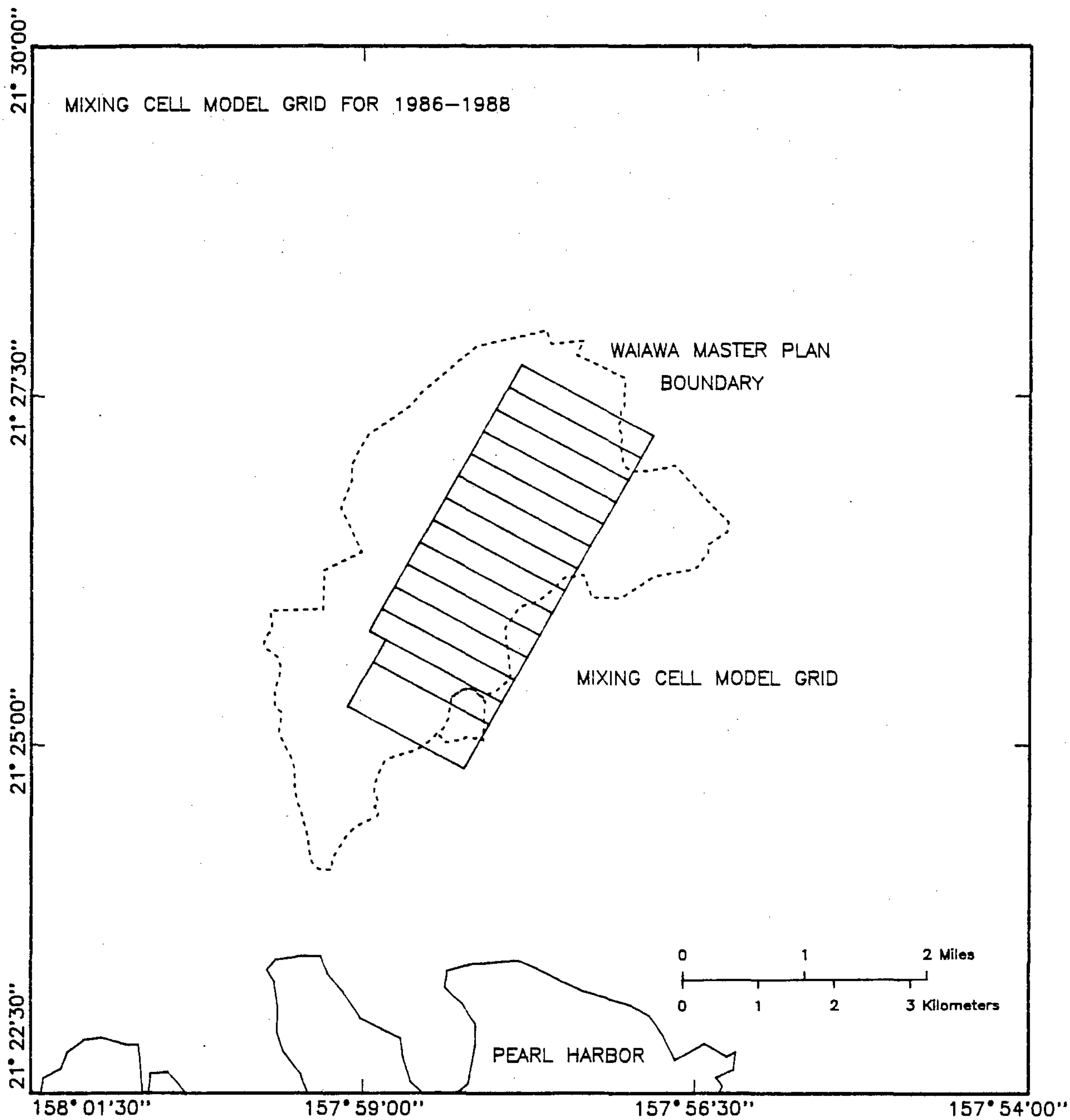
Appendix Figure E.22. Plan view of multiple mixing cell model grid for 1968-1976



Appendix Figure E.23. Plan view of multiple mixing cell model grid for 1977-1982



Appendix Figure E.24. Plan view of multiple mixing cell model grid for 1983-1985



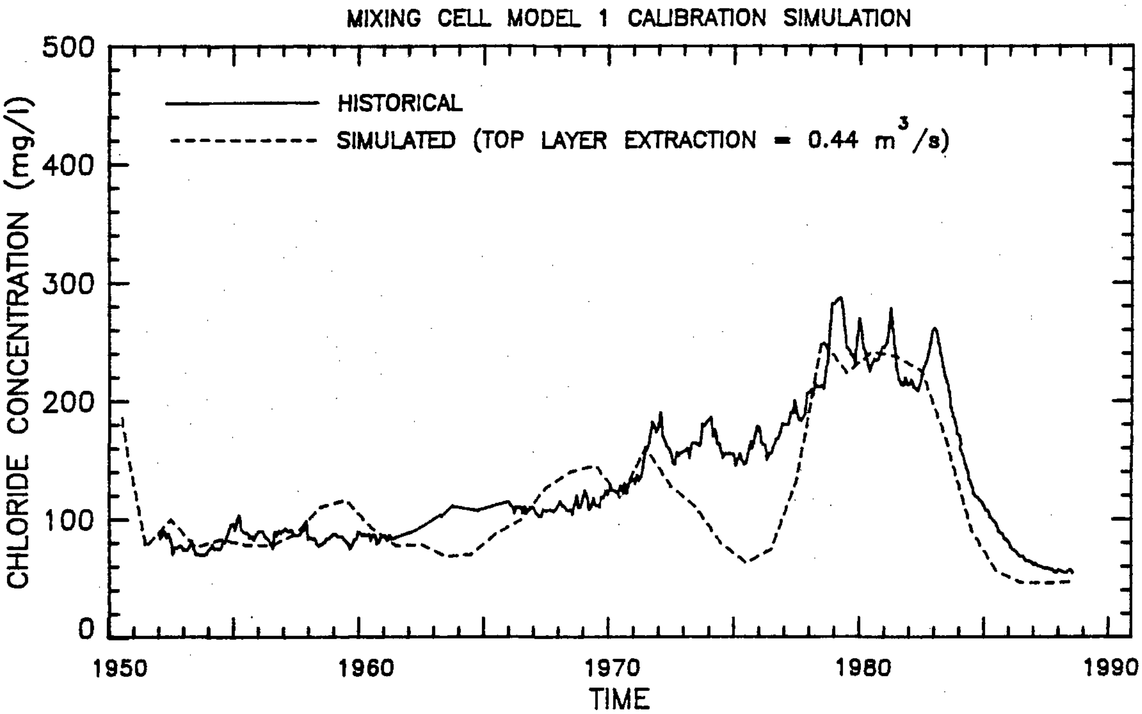
Appendix Figure E.25. Plan view of multiple mixing cell model grid for 1986-1988

Since six different zones of contribution were defined for the entire calibration period, initial conditions must be defined each time the zone of contribution changes. The initial conditions for the first zone of contribution valid until 1961 were defined above. Model output at the end of this first period was used to define the initial conditions for the second zone of contribution valid for 1962 to 1967. In a similar manner, output from the second, third, fourth, and fifth calibration periods was used to define the initial conditions for the third, fourth, fifth, and sixth zones of contribution, respectively.

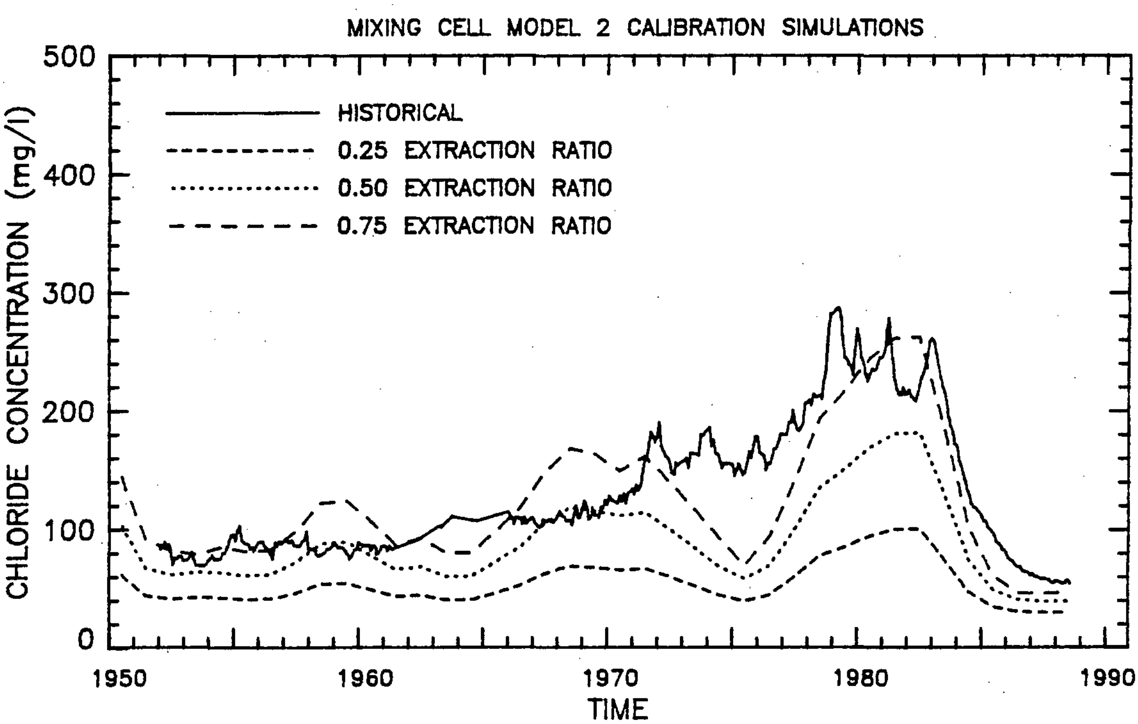
Model Parameters. Three different mixing cell models employing the same recharge and unsaturated zone input concentration time series were used to determine whether the historical time series (1950-1988) of chloride pumped from Waiawa Shaft could be reproduced. The three models differed only in the way pumpage from Waiawa Shaft was divided between the top and bottom layers of the model. The first model assumes that a constant minimum amount of water must be pumped from the top layer prior to extraction from the bottom layer. The second model assumes a constant ratio of top to bottom extraction. The final model tested assumes that the fraction of the total pumpage extracted from the top layer declines exponentially with total pumpage. In all models, the apportioning rules are allowed to be violated if insufficient water is available in the top layer. Water in the bottom layer is assumed to be unlimited by assigning a large bottom layer thickness. In all simulations, an effective aquifer porosity of 0.1 was used to determine the volume of water in each cell.

Results and Discussion. Results from each of the three mixing cell models are presented separately below.

Model 1--Constant Minimum Extraction from the Top Layer. Model 1 was run using constant minimum extraction amounts of 0.35, 0.39, 0.44, 0.48, and 0.53 m^3/s (8, 9, 10, 11, and 12 mgd, respectively). Increasing the top layer extraction resulted in greater chloride concentrations in water pumped by Waiawa Shaft. Results of the simulation using a constant minimum top layer extraction of 0.44 m^3/s (10 mgd) are presented in Appendix Figure E.26. At a constant minimum extraction rate of 0.44 m^3/s (10 mgd), model sensitivity to the top layer thickness, top layer groundwater flux, and effective aquifer porosity was tested. Reducing the



Appendix Figure E.26. Simulated chloride time series at Waiawa Shaft using multiple mixing cell model 1 with a constant top layer extraction of 0.44 m^3/s



Appendix Figure E.27. Simulated chloride time series at Waiawa Shaft using multiple mixing cell model 2 with top layer extraction to total pumpage ratios of 0.25, 0.50, and 0.75

thickness of the top layer from 60 m (200 ft) to 30 m (100 ft) resulted in a rise of chloride concentrations at Waiawa Shaft. Reducing the top layer thickness results in a smaller amount of upgradient fresh groundwater entering the grid. Decreasing the upgradient groundwater flux entering the top layer by approximately 20% resulted in an increase of chloride concentrations at Waiawa Shaft. Decreasing the effective aquifer porosity from 0.1 to 0.05 resulted in a quicker response to changes in vadose zone inputs at Waiawa Shaft. This phenomenon manifests itself toward the end of the calibration period when sugarcane cultivation was being phased out over Waiawa Ridge. Using a porosity of 0.05 results in a faster decline in chloride concentrations pumped by Waiawa Shaft after about 1983.

Model 2--Constant Ratio of Top to Bottom Layer Extraction. Model 2 was run using ratios of top layer extraction to total pumping of 0.25, 0.5, and 0.75 (App. Fig. E.27). It should be mentioned that the assumptions of this model are probably not valid for lower ratios in conjunction with low pumping rates. That is, it seems unlikely that Waiawa Shaft should be withdrawing only a small fraction of its total pumpage from the irrigation return layer under low pumping rates. Appendix Figure E.27 indicates that increasing the ratio of top layer extraction to total pumping results in a greater amount of water being extracted from the top degraded layer which in turn leads to higher simulated chloride concentrations.

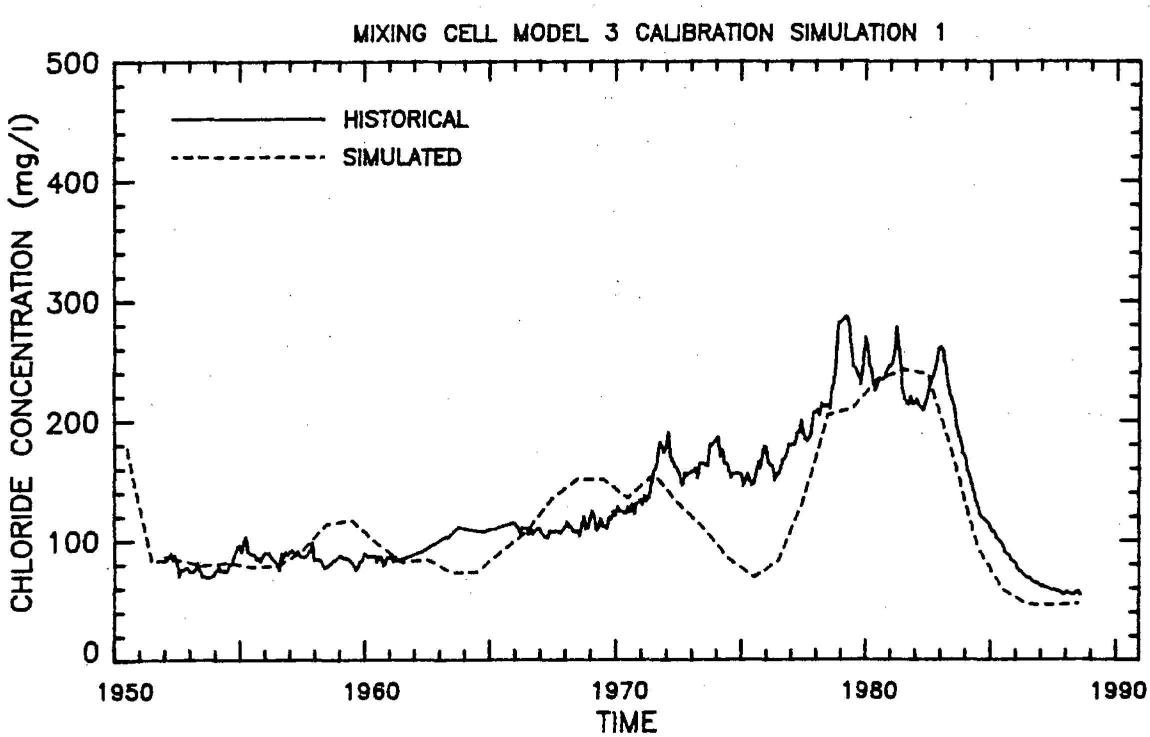
Model 3--Exponential Function of Describing Top Layer Extraction. Based on historical pumpage and chloride data from Waiawa Shaft and historical chloride data from test borings drilled near Waiawa Shaft which provide an indication of the existing chloride levels in the irrigation return layer of the aquifer, a steady state equation was derived to describe the relationship between the fraction of water pumped from the top degraded layer and the total pumpage. Under steady state conditions, and assuming that the irrigation return layer of the basal lens remains separate from the underlying fresh core of the lens, the following mass balance equation can be used to determine the amount of Waiawa Shaft pumpage derived from the upper return layer:

$$Q_{top} = Q(C - C_{bot})/(C_{top} - C_{bot}) \qquad (E.25)$$

where Q and Q_{top} represent the total Waiawa Shaft pumpage and the portion of pumpage derived from the irrigation return layer, respectively, C is the chloride concentration in water pumped by Waiawa Shaft, C_{top} is the concentration in the return layer, and C_{bot} is the concentration of the deeper, fresh core of the basal lens. Four periods were identified during which conditions were relatively steady and measurements of Q, C, and C_{top} were simultaneously available. Chloride measurements from test borings on Waiawa Ridge were assumed to be representative of C_{top}. The chloride concentration in the deeper, fresh portion of the basal lens was assumed to be constant at 20 mg/l. Using equation E.25, values for Q_{top} were thus obtained for different pumpage totals, Q, at Waiawa Shaft. Using regression techniques, an exponential function relating Q_{top} and Q was obtained:

$$Q_{top}/Q = \exp(-0.56671Q) \qquad \text{(E.26)}$$

where Q_{top}/Q is the fraction of total pumpage derived from the top layer and Q is the total pumpage from Waiawa Shaft (m^3/s). Results of the simulation using this model are presented in Appendix Figure E.28.



Appendix Figure E.28. Simulated chloride time series at Waiawa Shaft using multiple mixing cell model 3

Based on the results of mixing cell model 1 presented above, it appears that at extraction rates of up to approximately 0.53 m^3/s (12 mgd), water pumped by Waiawa Shaft originates from the upper irrigation return layer of the basal lens. At greater pumping rates, Waiawa Shaft begins to extract from deeper in the basal lens where water is relatively fresh. Model 2 indicates that at least 75% of the water pumped by Waiawa Shaft originates from the upper return layer of the basal lens. Assuming an average operating rate of 0.66 m^3/s (15 mgd), this result is consistent with the results of model 1. A model similar to model 3 probably best describes the steady state operating characteristics of Waiawa Shaft in terms of defining the source of water pumped. A limited amount of data, however, makes it difficult to derive a valid expression defining the relative quantities of water pumped from the top and bottom layers of the basal lens by Waiawa Shaft. Equation E.26 may not be the optimum model describing the characteristics of the shaft.

MODEL SELECTION FOR LONG-TERM PREDICTIVE SIMULATIONS

To predict the long-term effects of the proposed developments in the Waiawa area on groundwater quality in the vicinity of Waiawa Shaft, the areal MOC is probably the most appropriate model of those tested. The areal MOC model was successfully calibrated using the historical record of chloride concentrations in water pumped by Waiawa Shaft. In addition, the areal MOC model is able to account for the spatial variation of recharge and chemical inputs to the groundwater table. Both the vertical MOC model and the simple multiple mixing cell model require an estimate of the zone of contribution of Waiawa Shaft which can be provided by a groundwater flow model such as the the flow submodel of the areal MOC model. However, the changing zone of contribution as recharge and pumping conditions change makes it difficult to simulate with either the vertical MOC model or the mixing cell model. Thus, for all long-term predictive simulations, only the areal MOC model was employed.

APPENDIX F. WAIAWA SHAFT FLOW MEASUREMENT

The Navy's Waiawa water development complex consists of an unlined sump excavated to 6.1 m (20 ft) below sea level, and a 519 m (1,702 ft) long infiltration tunnel. The invert at the tunnel entrance to the sump is at an elevation of 1.2 m (4 ft) below sea level, rising gradually to 1.2 m (4 ft) above sea level at the terminus. A typical section at the tunnel entrance, which is lined with concrete, is presented in Appendix Figure F.1. The lined tunnel entrance is 3.30 m (10.83 ft) high and 2.95 m (9.67 ft) wide at its base. Operating heads at Waiawa Shaft are typically about 5 m (17 ft) so that the infiltration tunnel remains completely submersed and full flowing.

The sump is approximately 19 m (62 ft) long and 3.7 m (12 ft) wide. Four deep well turbine pumps are located toward one end of the sump. The infiltration tunnel enters the sump at the end opposite the pumps and is perpendicular to the length of the sump. An access ladder, which leads down from the pump room to the sump, is located approximately across the tunnel entrance.

On 20 July 1989 an attempt was made to measure the flow velocity of water near the tunnel entrance to the sump. Pumpage on 20 July 1989 was maintained between 0.745 and 0.789 m^3/s (17 and 18 mgd) for about three hours prior to any measurements and was approximately 0.745 m^3/s (17 mgd) during the time the velocity readings were taken. The two pumps furthest from the tunnel entrance were operating during this period. The groundwater level in the sump was approximately 5.0 m (16.5 ft) above sea level.

Velocity measurements were made with a calibrated Teledyne Gurley model 645 current meter connected to a Teledyne Gurley model 700 digital flow velocity indicator. The flow meter was attached to the horizontal end of an L-shaped extension consisting of a 6.1 m (20 ft) vertical length of aluminum pipe and a 2.4 m (8 ft) horizontal length of aluminum pipe. The L-shaped extension allowed us to lower the flow meter to the level of the infiltration tunnel and place the meter at various locations within the tunnel so as to avoid velocity fluctuations near the tunnel entance to the sump.

A total of 15 velocity readings were made at each of seven depths along the tunnel centerline, approximately 2.4 m (8 ft) in from the sump. Velocity measurements were taken at heights of 0.46, 0.76, 1.07, 1.37, 1.68, 1.98, and 2.13 m (1.5, 2.5, 3.5, 4.5, 5.5, 6.5, 7.0 ft) above the tunnel invert. The vertical profile velocity results obtained on 20 July 1989 are presented in Appendix Table F.1.

APPENDIX TABLE F.1. WAIAWA SHAFT FLOW MEASUREMENTS OF 20 JULY 1989 MEASURED ALONG THE TUNNEL CENTERLINE

	Height Above Invert (m)						
	0.46	0.76	1.07	1.37	1.68	1.98	2.13
Reading No.	Flow Velocity (m/sec)						
1	0.02	0.04	0.06	0.08	0.04	0.07	0.07
2	0.03	0.04	0.09	0.05	0.08	0.07	0.05
3	0.01	0.08	0.05	0.06	0.07	0.07	0.07
4	0.01	0.07	0.03	0.06	0.07	0.07	0.05
5	0.05	0.08	0.03	0.05	0.03	0.07	0.06
6	0.00	0.06	0.05	0.05	0.06	0.05	0.06
7	0.03	0.06	0.02	0.04	0.09	0.05	0.07
8	0.01	0.06	0.04	0.08	0.06	0.07	0.07
9	0.02	0.08	0.06	0.05	0.08	0.06	0.06
10	0.04	0.06	0.03	0.05	0.06	0.08	0.08
11	0.01	0.07	0.06	0.07	0.08	0.07	0.05
12	0.01	0.08	0.05	0.06	0.06	0.09	0.09
13	0.00	0.05	0.07	0.05	0.08	0.07	0.06
14	0.03	0.06	0.05	0.04	0.08	0.07	0.07
15	0.02	0.08	0.05	0.07	0.08	0.06	0.07
Average	0.019	0.065	0.049	0.057	0.068	0.068	0.065

NOTE: Readings at 1.68, 1.98, and 2.13 m above invert were taken every 15 s; measurements at other depths taken every 10 s.

To determine the lateral variation in flow velocity, measurements were made at three different lateral positions at the same depth. Velocity measurements were taken approximately 0.91 m (3 ft) from the left tunnel wall (as viewed from the sump toward the tunnel entrance), 0.53 m (1.75 ft) from the right tunnel wall, and near the tunnel centerline, all at a height of 0.76 m (2.5 ft) above the invert and at a distance of 2.4 m (8 ft) into the tunnel. A total of 15 readings, taken at 10-second intervals, were made at each of the three positions (App. Table F.2). The velocity appears to increase from right to left at a particular depth in the tunnel. This may be due to the location of the pumps in the sump, which are closest to the right side of the tunnel, or to the presence of a known bend in the infiltration tunnel occurring about 3.0 m (10 ft) upstream of the measuring point.

APPENDIX TABLE F.2. WAIAWA SHAFT FLOW MEASUREMENTS OF 20 JULY 1989 MEASURED OFF THE TUNNEL CENTERLINE

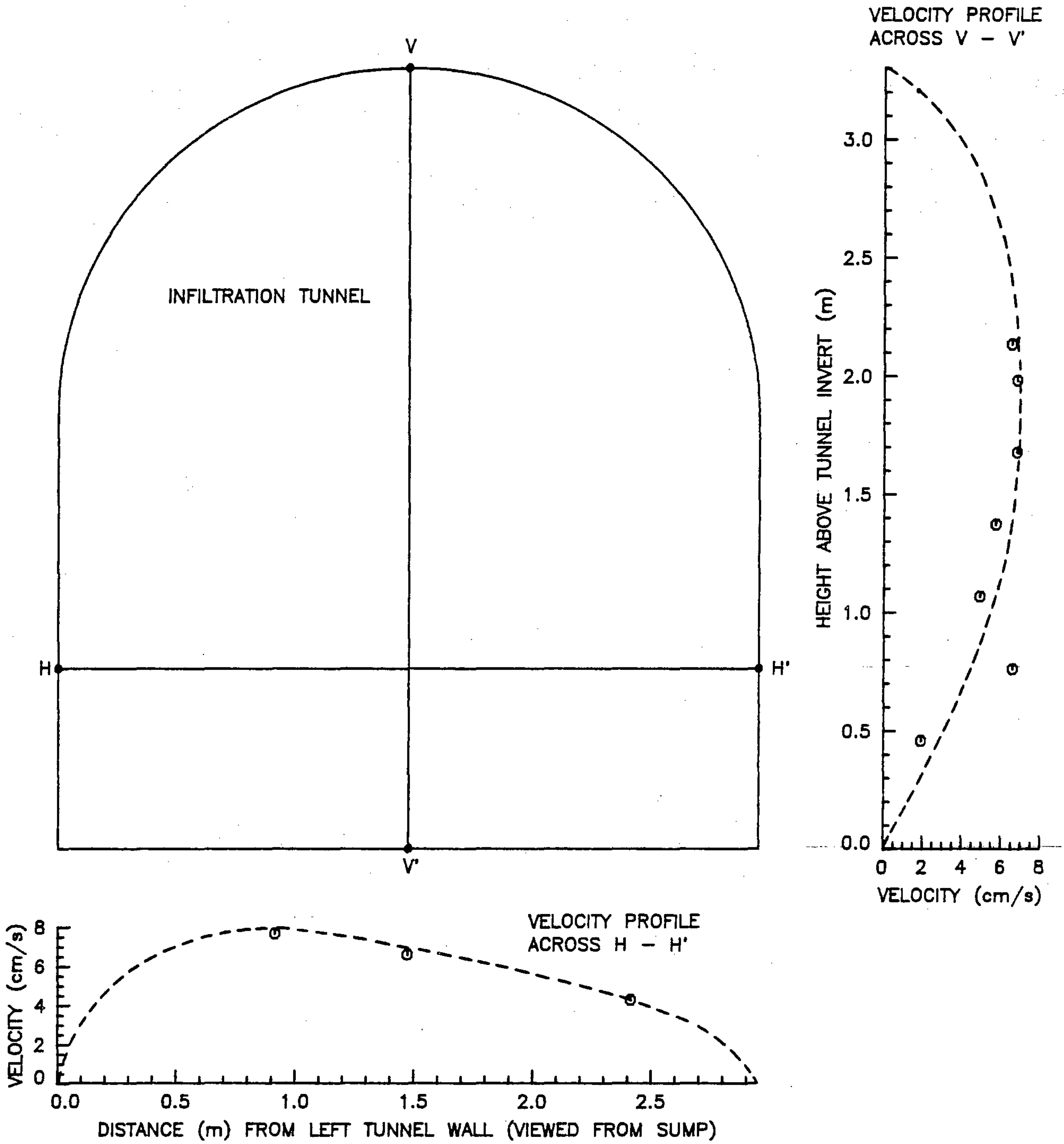
	Measurement Location		
	0.91 m from the Left Tunnel Wall	Centerline	0.53 m from the Right Tunnel Wall
Reading No.	Flow Velocity (m/sec)		
1	0.07	0.07	0.04
2	0.07	0.06	0.07
3	0.09	0.07	0.07
4	0.09	0.06	0.05
5	0.08	0.06	0.05
6	0.05	0.07	0.05
7	0.08	0.06	0.04
8	0.06	0.08	0.05
9	0.07	0.07	0.04
10	0.09	0.07	0.04
11	0.08	0.08	0.02
12	0.07	0.05	0.03
13	0.09	0.06	0.04
14	0.09	0.07	0.01
15	0.07	0.08	0.04
Average	0.077	0.067	0.043

NOTE: All measurements taken at a height of 0.76 m above tunnel invert; at each location, measurements taken every 10 s.

The vertical and horizontal velocity profiles are provided in Appendix Figure F.1. The average flow velocities across the vertical and horizontal traverses are respectively 0.048 and 0.057 m/s. The average velocity from the horizontal profile is about 86.4% of the 0.066 m/s velocity at the point which intersects the two profiles. Assuming that this is a representative percentage for all horizontal profiles, the average flow velocity across the entire area of the tunnel is estimated to be about 86.4% of 0.048 m/s, or 0.041 m/s. This average velocity corresponds to a discharge rate of 0.365 m^3/s from the infiltration tunnel. At the time the velocity measurements were taken, the total discharge from Waiawa Shaft was 0.745 m^3/s. Thus, the velocity measurements indicate that approximately 49% of the total discharge from Waiawa Shaft originates from the infiltration tunnel, with the remainder of the water being extracted from the unlined sump.

Although our calibration showed that the current meter can detect velocities as low as those measured at Waiawa Shaft, it should be kept in mind that the meter is only sensitive to 0.01 m/s (0.03 ft/s) so that all flow measurements obtained approach the meter's capability limit. The velocity readings at a height of 0.46 m (1.5 ft) above the invert may be influenced by the uneven rocky surface at the bottom of the tunnel since the concrete lining may not extend to the location where the current meter was inserted.

Possible future efforts to measure the flow velocity at Waiawa Shaft might include readings under different draft conditions which may better reveal the role of the unlined sump in terms of its contribution to the overall draft from the shaft. In any event, it appears that under typical operating conditions, a significant portion of the total draft from Waiawa Shaft originates from the infiltration tunnel. The draft from the infiltration tunnel is dependent on the drawdown created by heavy pumping from the sump.



Appendix Figure F.1. Waiawa infiltration tunnel cross section and vertical and horizontal velocity profiles near sump