ASSESSING NON-POINT POLLUTANT DISCHARGE TO THE COASTAL WATERS OF WEST MAUI, HAWAII

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By

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

THESIS COMMITTEE

Chairperson

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Mahalo to the 'aina, to the waves, to the mauka showers, for the aloha... and to Jerry.

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CHAPTER I. INTRODUCTION

BACKGROUND

Human manipulation of natural environments often leads to a state of disequilibrium in which natural systems are altered to less desirable (and less healthy) states. Such behavior may link land based practices with nuisance algae blooms in the coastal waters of West Maui. While the historical occurrence of such blooms is not well documented, severe blooms in 1989 and 1991 prompted public concern and a subsequent search for the factors contributing to algae growth. This study examines the terrestrial component of natural and externally supplied nutrients from their points of origin on land to the sea. Nutrient and sediment sources considered in this analysis include fertilizer applications on golf courses, sugarcane and pineapple fields, and subsurface wastewater injection. Quantification of nutrient discharge to the ocean aids in estimating individual contributions from each of the aforementioned sources. Our results allow oceanographers and coastal water ecologists to assess the significance of land based nutrients and sediment contributed from the land with respect to algae blooms specifically, and coastal water pollution in general. Regulators and land users may then devise more environmentally sound land use designation and management alternatives.

The objective of this study is to quantify natural and human enhanced nutrient and sediment discharge to the coastal waters of the Lahaina District. Estimates are made individually for each of the above mentioned land uses, yielding comparative figures which assess their role in total loading. Separate consideration for surface and groundwater discharge to the ocean further reveals the spatial and temporal distribution of each load. The following course of action (described in further detail in subsequent chapters) has been undertaken to meet the study objectives:

1.) Collection and analysis of groundwater samples throughout the study area for estimating spatial and temporal distributions of subsurface nutrients

2.) Collection and analysis of streamwater samples in three streams
3.) Extrapolation of surface water analysis to estimate total coastal loading
4.) Development of numerical groundwater models to simulate subsurface nutrient discharge to the coastal waters.

STUDY AREA

The bounds of the study area were chosen using the criteria of algae bloom extent, land use patterns, and hydrologic boundaries. While the most significant algae blooms have occurred off the coast of Kaanapali, floating algal mats have been documented between Kahana Stream to the north and Kahoma Stream (Lahaina) to the south (Tetra Tech, 1993). The entire portion of the island shown in Figure 1 is considered the Lahaina District. Sugarcane is grown within this area, generally south of Honokowai Stream and pineapple is grown north of Honokowai Stream. Finally, hydrologic connection of the groundwater bodies appears to extend at least to the topographic divide north of Honokohau Stream and south to the topographic and geologic divide just north of Olowalu. Since algae bloom occurrence falls centrally within these hydrologic boundaries, and because smaller areas allow finer descritization and more accurate numerical calculations, these natural boundaries delineate the extent of the modeling area.

Geology and Hydrogeology

Figure 2 shows the geology of the deeply dissected volcano of West Maui. Two episodes of volcanic eruptions, separated by a short quiet period, were followed by a long inactivity during which extensive erosion and sea level fluctuations shaped the present landscape. The first episode produced a regionally extensive series of lava flows, the Wailuku Volcanic Series, and the associated upland dike complex (Stearns, 1942). This series of thin flows is comprised of alternating, highly vesicular pahoehoe, a'a, and clinker beds. Significant portions of the area north of Honokowai Stream are overlain by the Honolua Volcanic Series, a more dense and massive unit with flows

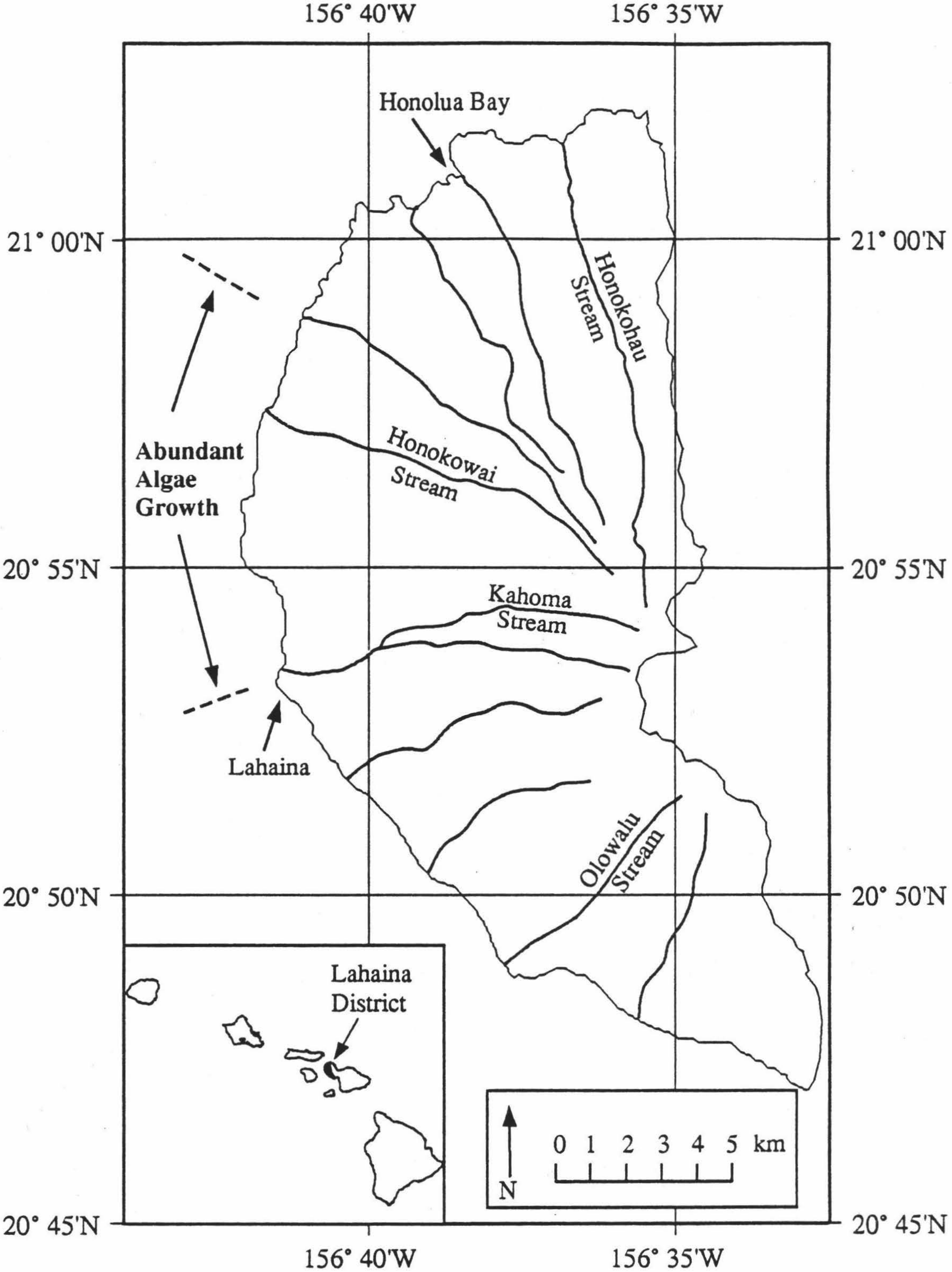


Figure 1. Study Area: Lahaina District of West Maui.

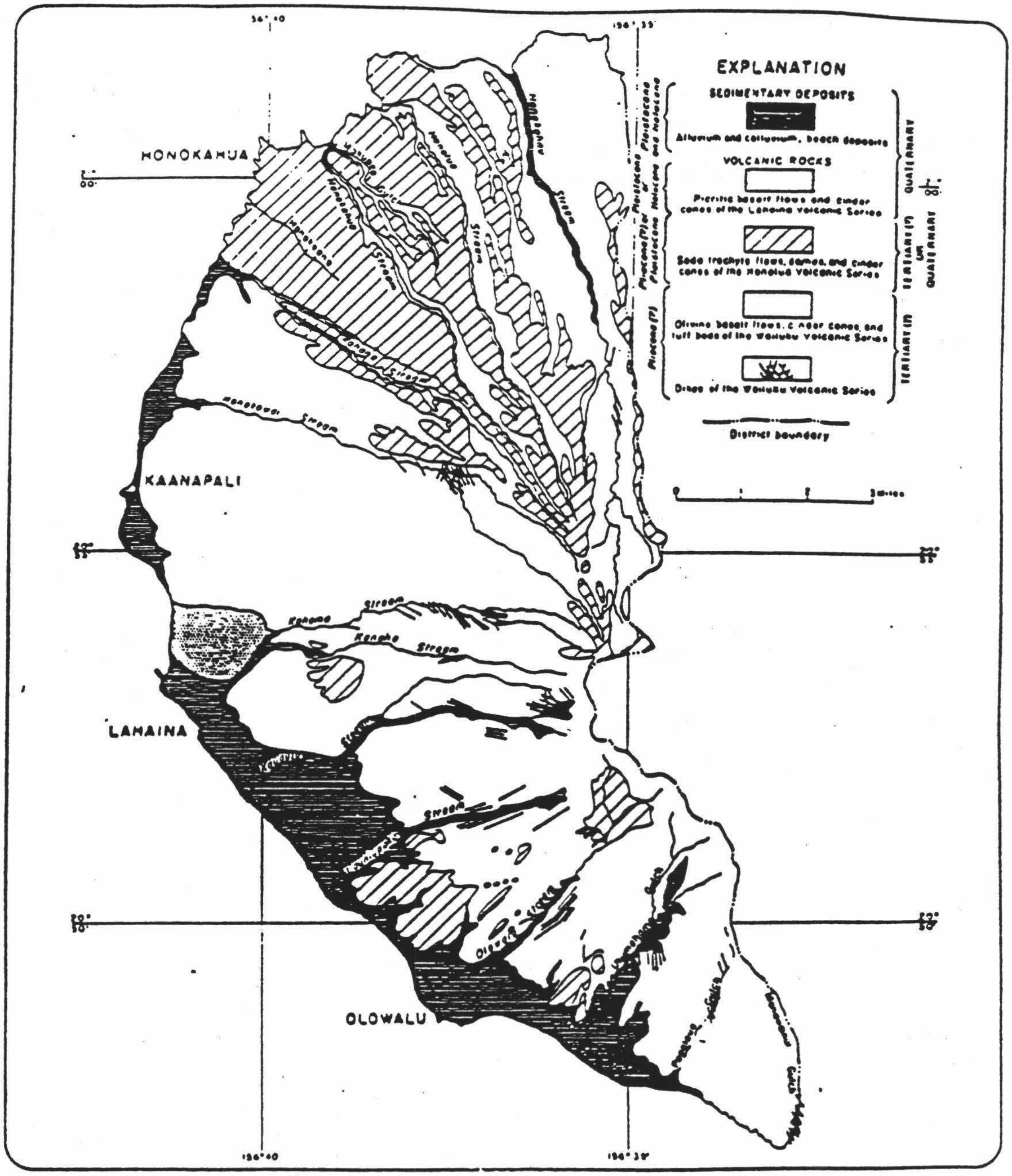


Figure 2. Geology of West Maui (from Yamanaga and Huxel, 1969).

averaging 25 meters in thickness. Near the town of Lahaina, the most recent eruption, that of the Lahaina Volcanic Series, produced localized fire-fountain deposits and lava flows. Thick sedimentary sequences separate the younger Lahaina Series from the Wailuku Series. Variably thick sedimentary deposits (up to 60 meters) unconformably overlie the coastal plain and fill valley floors.

Groundwater on West Maui occurs as a basal freshwater lens which extends three to six kilometers inland, beyond which dike impounded and perched systems exist (Figure 3). Localized weak confining conditions exist in the basal lens due to a sedimentary caprock near the coast, though generally considered insufficient to impede freshwater discharge to the ocean (Souza, 1981). The Wailuku Series (wherein lies the freshwater lens) is more permeable than most Hawaiian basalt due to its thin beds, heavy jointing, and frothy nature (Stearns, 1942). The Honolua Series, much more massive and less jointed in nature, is considerably less permeable. The Lahaina Series and sedimentary deposits are not thought to contain significant freshwater due to their limited extent and proximity to the coast. Mink and Lau (1990) subdivide the Lahaina Groundwater Sector into six aquifer sectors (Figure 4), all with spatial variations on the aforementioned groundwater reservoirs.

Groundwater heads generally increase inland and to the north, where rainfall (and thus groundwater recharge) is greatest. Maximum heads of nearly three meters have been measured in the northern mauka portion of the area. The Lahaina District has a history of groundwater contamination from agricultural pesticides and fertilizers, sufficient in one instance to close a drinking water well due to high DBCP (1,2-dibromo-3-chloroprophane, a pesticide used by Maui Pineapple Company) levels (Scott Rickard, personal communication). Contamination from seawater intrusion has also occurred as a result of overdraft from the basal freshwater lens.

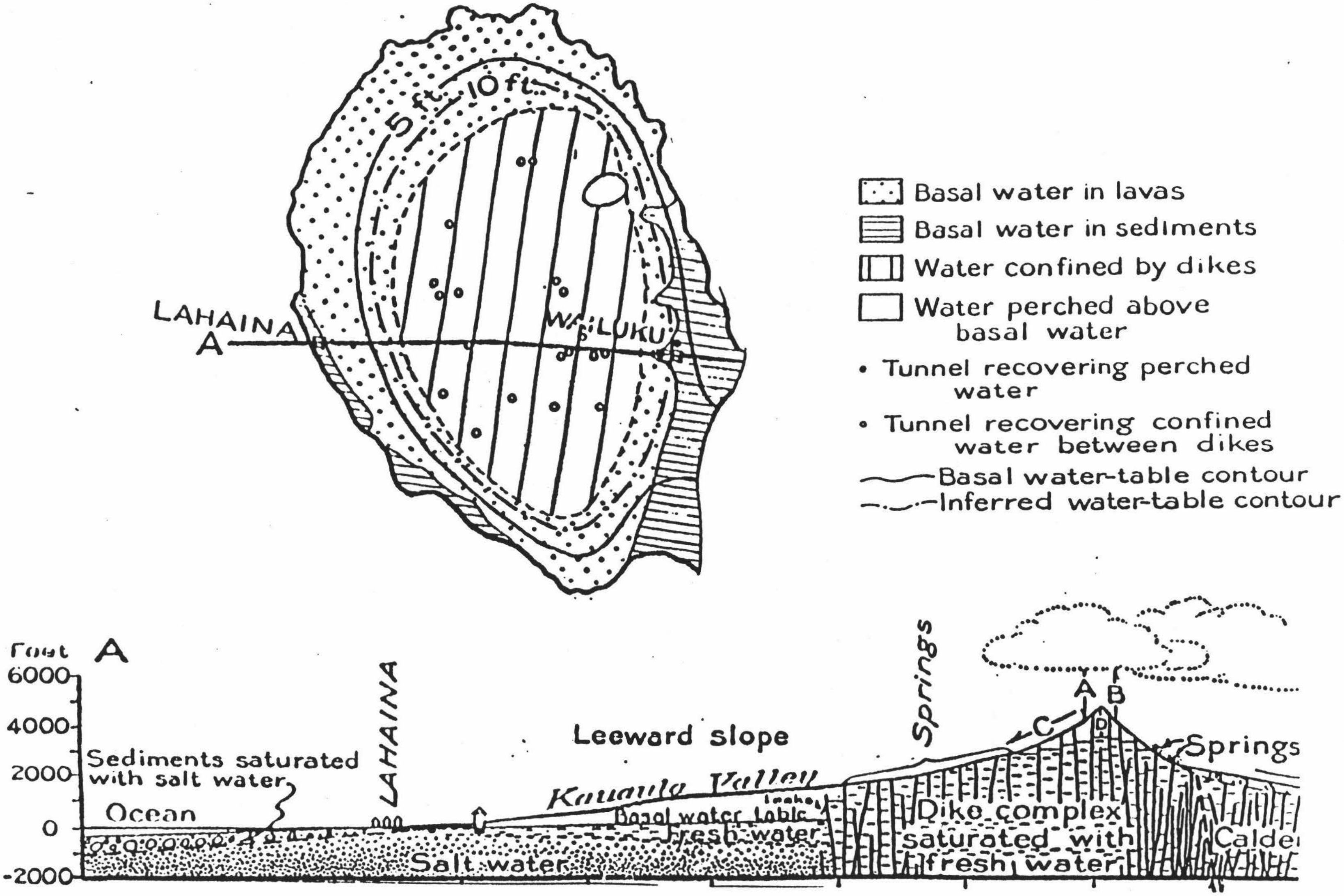


Figure 3. Hydrogeology of West Maui (from Stearns and MacDonald, 1945).

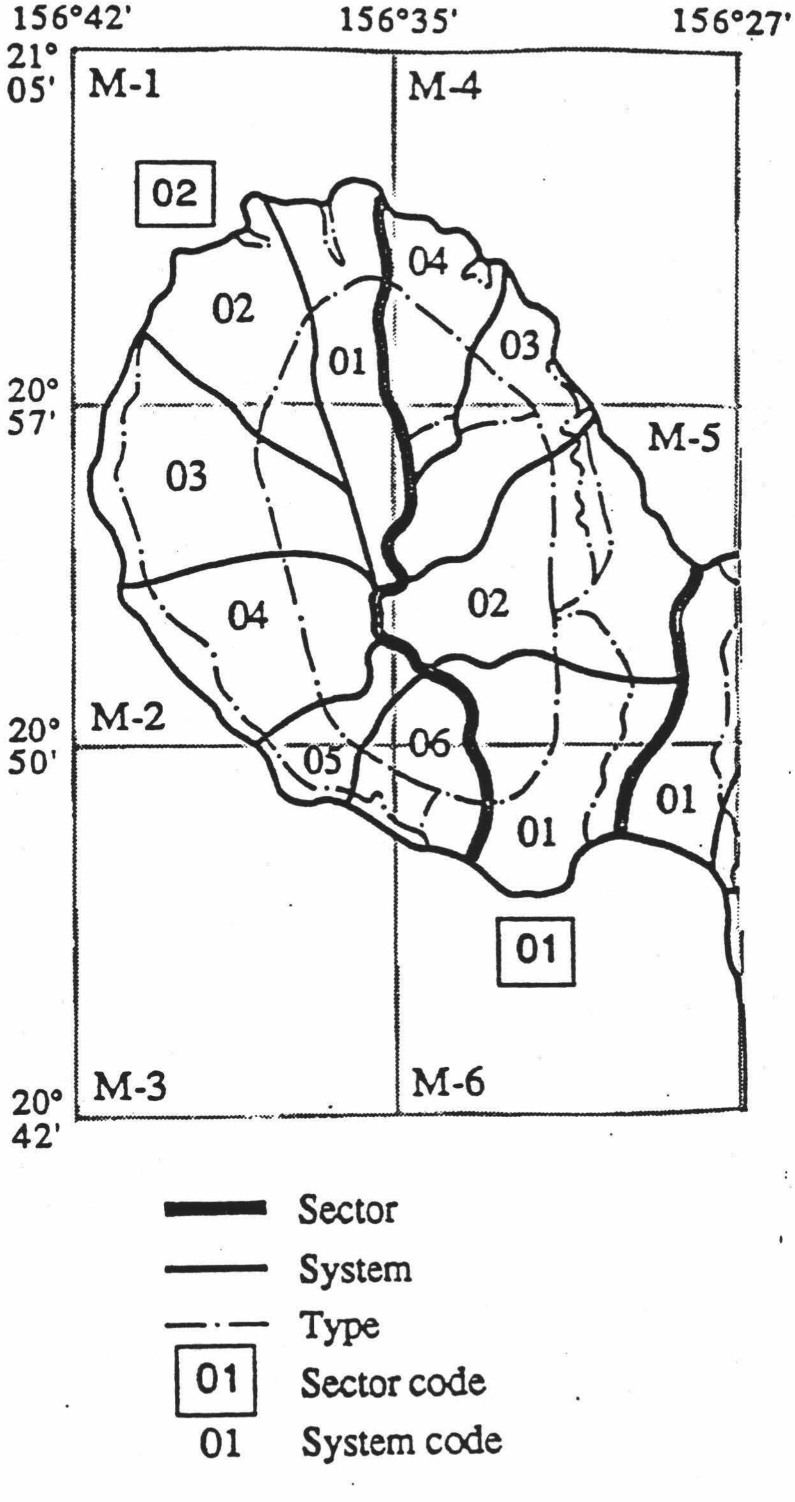


Figure 4. West Maui Aquifer Classification (from Mink and Lau, 1990).

Surface Water

Base streamflow on West Maui originates as spring discharge from the upland dike complex. Figure 5 shows the main streams in the Lahaina District. All streams in the region are perennial at higher elevations, though all but Honokohau Stream are completely diverted for irrigation purposes (most flow from Honokohau Stream is diverted to the south, while roughly 2.6 cubic meters per minute (m^3/min) is released into the streambed for taro and other small scale farming in Honokohau Valley (Wes Nohara, personal communication)). This leaves the streams dry during most of the year with flow at the lower elevations occurring only during periods of broad, heavy rainfall. As most rainfall occurs at higher elevations (Figure 6), some upland rain events do not cause water to overflow the diversion systems.

LAND USE

Figure 7 shows the present land use distribution in the Lahaina District. In years past, the area was dominated by sugarcane and pineapple cultivation. More recently, the district has seen a large influx of tourism and subsequent urbanization/development. County of Maui Land Use Maps (in M&E Pacific, 1991) delineate zoning in the Lahaina District as follows: Conservation (51%), Agricultural (42%), Urban/other (7%).

Sugarcane in the district is grown exclusively by the Pioneer Mill Company on roughly 2,520 hectares (Falconer, personal communication). Although acreage has declined in the recent past (from 3,782 ha in the 1970s (M&E Pacific, 1991)), it is still the dominant agricultural crop on West Maui. Excluding higher elevation fields and a parcel near the processing mill, most irrigation has been converted to the drip method. Sugarcane is now grown as far north as Honokowai Stream and extends inland up to five kilometers from the coast.

Pineapple is grown by Maui Pineapple Company in the northern part of the

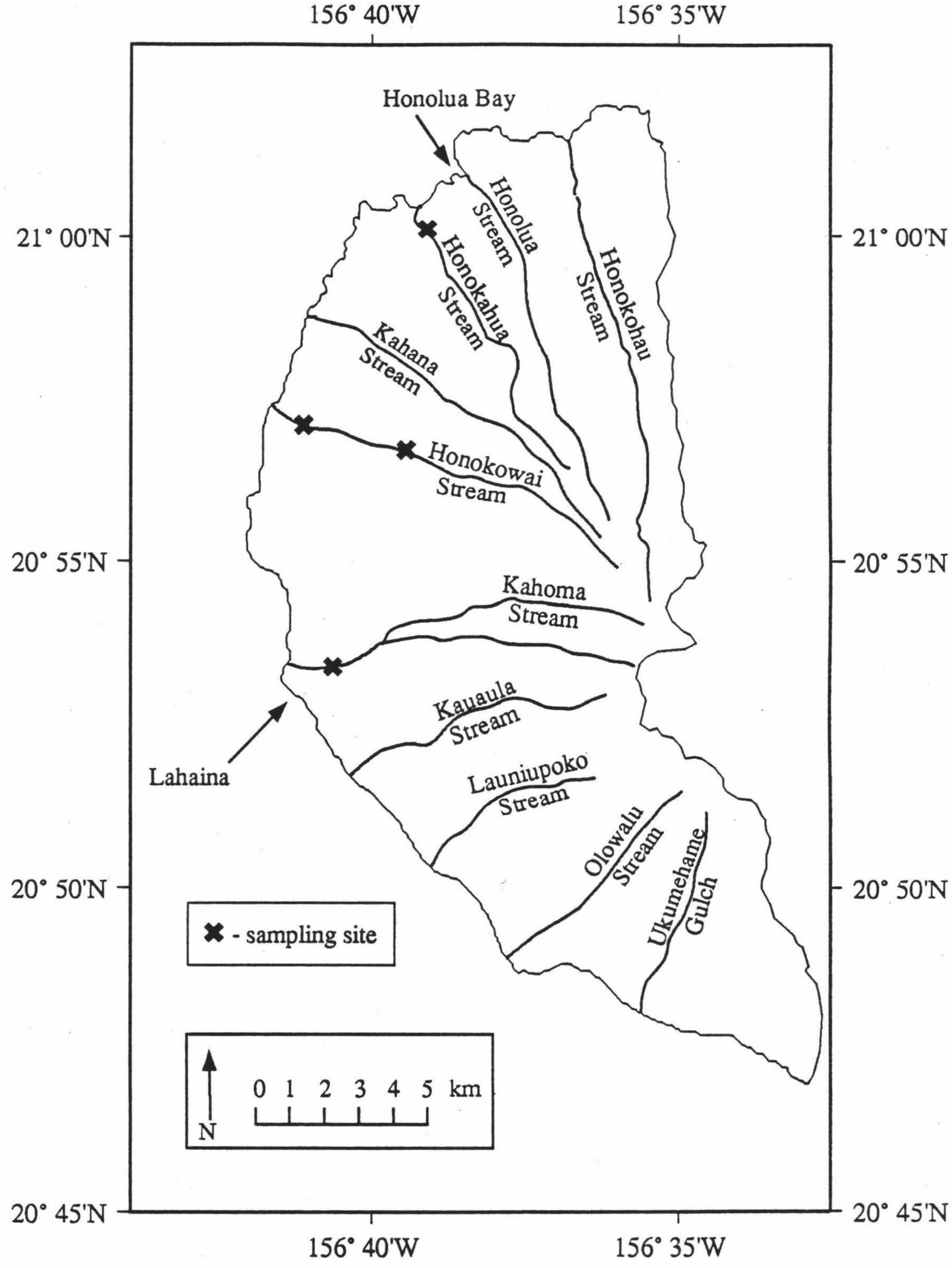


Figure 5. Streams of West Maui.

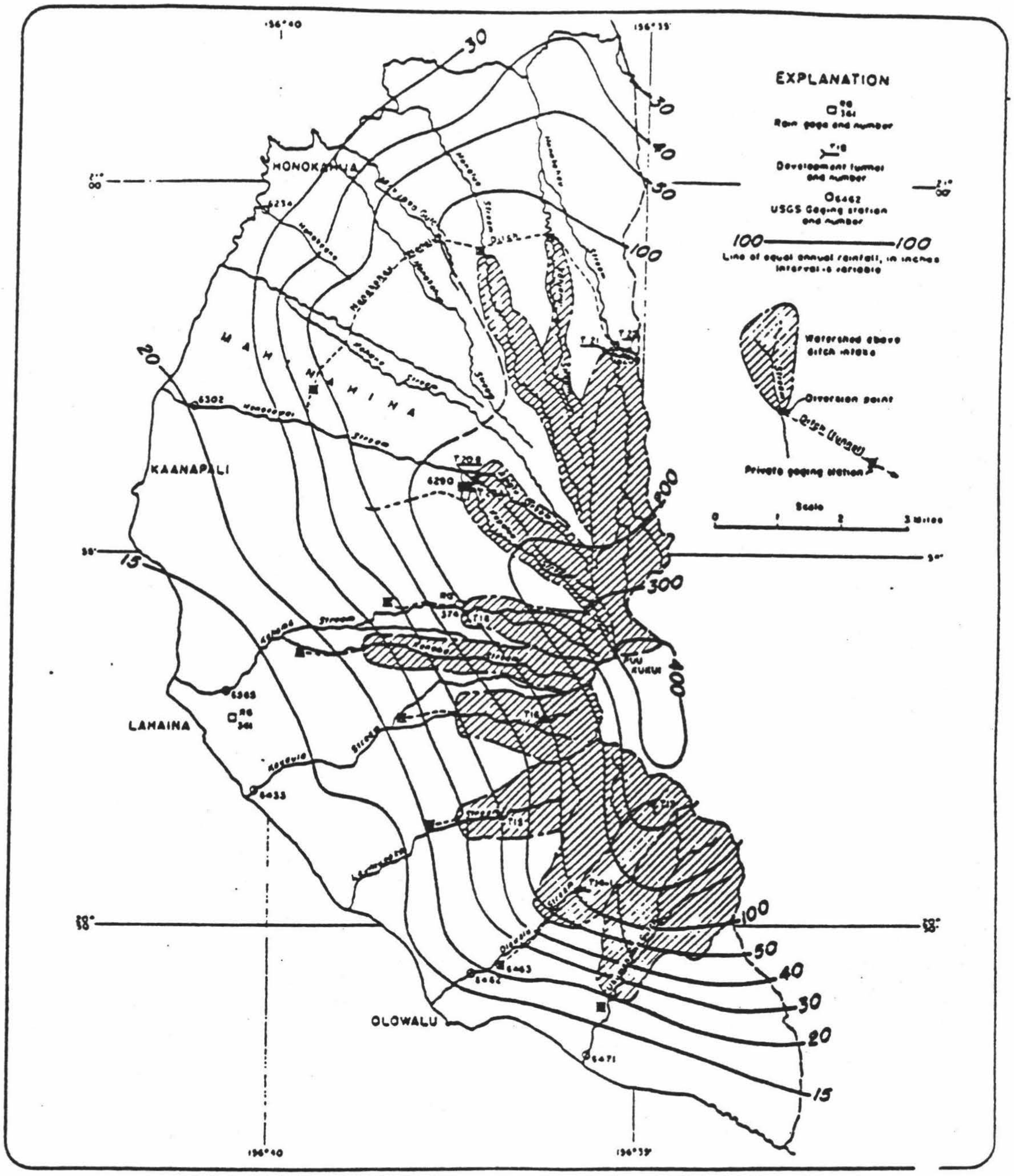


Figure 6. Average Annual Rainfall over the Lahaina District (from Yamanaga and Huxel, 1969).

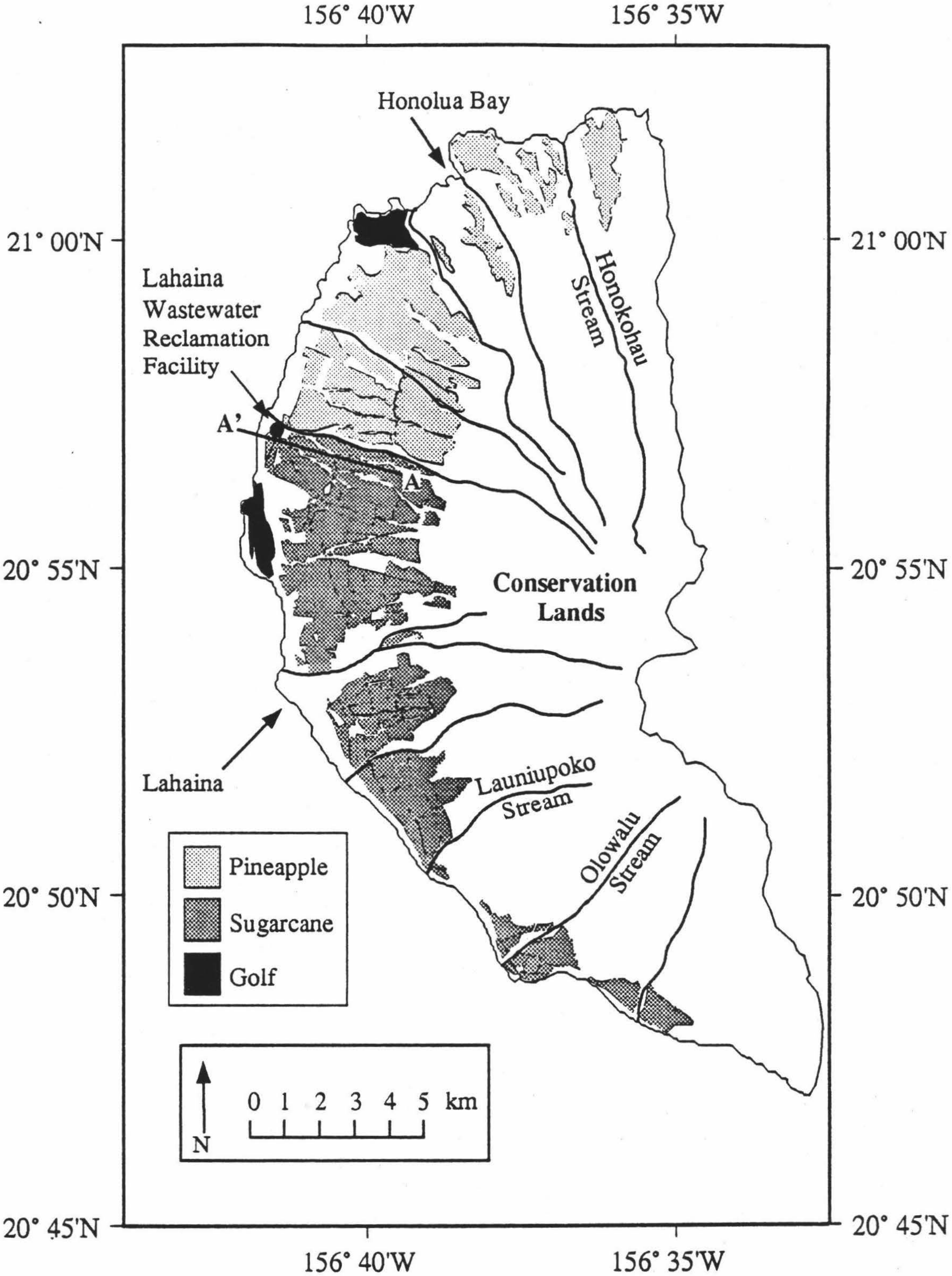


Figure 7. Major Land Uses in the Lahaina District.

study area, beginning near Honokowai Stream. It currently covers roughly 2,181 hectares (Wes Nohara, personal communication) and extends up to five kilometers inland. In the past, the wetter nature of the area made it unnecessary to irrigate this water conservative crop. More recently, however, Maui Pineapple Company has begun to irrigate their fields in an attempt to increase productivity (M&E Pacific, 1991).

Amfac has developed a large resort at Kaanapali including two golf courses with an area of 138 hectares. A similar resort complex has been developed at Kapalua to the north, with three golf courses totaling approximately 205 hectares. A rapidly expanding series of hotels, resorts, and residences are found along the coast of the area. Except for a small number of cesspools, all of these facilities are connected to regional sewer lines which flow into the Lahaina Wastewater Reclamation Facility near Honokowai Point.

PREVIOUS WORK

The geology and hydrology of the Lahaina District was originally described by Stearns and Macdonald (1942). Since then, numerous engineering consultant and USGS reports have expanded on that work and have attempted to estimate water availability in the district. Yamanaga (1969) documented surface water availability and Broadbent (1969) estimated a rough water budget over a portion of the Lahaina District (roughly Sectors three and four of Mink and Lau, Figure 4) with a half year, seasonal time step. Wilson, Okamoto and Associates (1977) computed water budgets over Sectors one through four (of Mink and Lau) in order to estimate sustainable yields for the region. Yuen and Associates (1990) estimated specific yield for the entire Lahaina District by computing an average water budget over each aquifer system with an annual time step. Austin, Tsutsumi and Associates (1991), in the West Maui Water Master Plan, and M&E Pacific (1991), in the Maui County Water Use and Development Plan, describe present and future water availability and demands in the district. Finally, Mink

(1990) provides a comprehensive review and further contributes to the general geology and hydrology of the area.

Nitrate contamination of groundwater has been observed in many regions of the world, often associated with areas of agricultural fertilization (Fetter, 1992). Leaching of agricultural fertilizers has been extensively studied, often with the aid of numerical models such as LEACHM (Wagenet, 1992), to analyze nitrogen movement through the vadose zone. Such analyses have aided in the development of best management practices (BMPs) for reducing nitrate fluxes to groundwater from agricultural lands (e.g. Storm, 1995). Numerical groundwater flow and transport models have been employed to simulate the distribution of nitrate species over time. Discharge of nitrate contaminated groundwater to coastal waters has been estimated using various numerical, deterministic, and geostatistical methods (e.g. Andres, 1993). Estimates of groundwater nitrate discharge to coastal waters has not been previously attempted for Hawaiian aquifers.

Only a few attempts at regional scale groundwater flow modeling of Hawaiian aquifers have been undertaken. Liu et al. (1983) and Eyre (1985) developed two-dimensional areal models to assess groundwater development scenerios on Oahu (neglecting the effects of density on flow). Wheatcraft (1979) modeled the fate of water discharged through injection wells in the context of two-dimensional, vertical, density dependent (freshwater/saltwater) flow dynamics. Souza and Voss (1987) used the two-dimensional, cross-sectional model SUTRA (Voss, 1984) to investigate groundwater flow in the aquifers of southern Oahu. Their work was the first in Hawaii to describe site specific flow dynamics for an entire freshwater/saltwater transition zone system.

Regional contaminant transport modeling efforts are limited to two studies in Hawaii. Orr and Lau (1987, 1988) use a mixing cell model and the two-dimensional, areal model MOC (Konikow and Bredehoeft, 1978) to simulate pesticide transport in the

Pearl Harbor aquifer on Oahu. Tetra Tech (1993) developed the two dimensional, areal flow and transport model SWIFT (Reeves et al., 1986) to investigate nutrient transport in West Maui groundwater. The Tetra Tech modeling area is part of the study area of this report. Their modeling effort uses a no flow boundary at the mauka end of the aquifer, and does not use current field measured concentrations to calibrate the model.

Sediment production and yield was estimated for the Lahaina Watershed (Lahaina town south to Puamana) by the Soil Conservation Service (USSCS, 1992) as part of a flood protection analysis. Water quality data for the Lahaina District (excluding salinity) is limited to two studies, one performed by Tenorio (1970) and the other by Souza (1981). These works each involve groundwater sampling in areas generally in or downgradient of sugarcane production.

AGRICULTURAL AND FERTILIZATION PRACTICES

Fertilizers are currently applied to most sugarcane fields in the Lahaina District through a drip irrigation system. 283 hectares of sugarcane are still in furrow irrigation, using process water from the sugar mill (a sugar milling by-product) to supply the fields. Falconer (1991) reports that most Pioneer Mill sugarcane receives 363 kilograms of nitrogen per hectare (kg-N/ha), with Olowalu and reef rock fields near the coast receiving up to 477 kg-N/ha. Nitrogen is applied as a urea (10.7-0-0) solution through drip irrigation lines, with rates of 33.6-56 kg-N/ha/month for nine months. According to Falconer (personal communication), the solution is distributed during the last 10-20 minutes of a full day of irrigation (approximately 2.5 cm of water). Phosphorus is applied through the drip irrigation system in the green acid form (10-34-0), with rates varying from 0 to 112 kg-P_2O_5/ha, depending on local conditions (Falconer, 1991). Potassium is applied as muriate of potash (0-0-14.8) to upland fields which are not irrigated with saline water (which contains naturally occurring potassium). Where applied, potassium is injected through the drip system beginning three months after germination and continuing every second month at 90 kg/ha/application.

Fertilization of Maui Pineapple Company pineapple fields occurs in various forms (Wes Nohara, personal communication). After the final harvest of a crop, the pineapple plants are shredded and left for two months to decay on the soil surface. The decomposing organic matter is then plowed into the top 76 centimeters of soil and the field is left fallow for the next eight to ten months. During this time, rock phosphate is incorporated into the soil at a rate of up to 2.5 metric tons/ha. Before planting, black plastic is laid over up to 80% of the exposed field area (not including the extensive road network). At planting, 103 m^3 of water is provided to the plants by slow driving boom-spray irrigators. Fertilizers are applied through the boom spray once to twice a month for the period from two to thirteen months after planting. Total nitrogen applied over this period is estimated at 616 kg-N/ha as UAN32 (Urea-Ammonium-Nitrate). Fertilization is then discontinued until the first harvest (20-24 months after planting), then restarted for six months after the first harvest at a rate of 392 kg-N/ha. Fertilization is again halted until harvest of the second crop, which marks the end of the pineapple growing cycle. This process begins on roughly 364-384 hectares each year with fields continually in each stage of the growing cycle.

The five golf courses in the Lahaina District all add nitrogen and phosphorus to their fairways, greens and tees. Tetra Tech (1993) reports nitrogen application rates of 1.1 kg-N/ha/month on greens and tees, and half that quantity applied to fairways. Phosphorus applications are estimated at one tenth that of nitrogen. Thus, on the approximately 344 hectares of golf courses, total loads of 2,404 kg-N/yr and 240 kg-P/yr are applied. Fertilization and irrigation practices for urban and resort landscaping are extremely variable and nearly impossible to quantify in this study (though likely orders of magnitude lower than the aforementioned agricultural practices).

POTENTIAL LAND BASED SOURCES OF COASTAL NUTRIENTS

Free nutrients applied to land can arrive at the coast either through surface or subsurface pathways. Surface transport generally involves nutrient collection in surface waters (overland runoff, soil erosion) and subsequent outflow to the sea. These nutrients can be in either a dissolved or solid (sorbed) state. Subsurface transport involves either leaching of nutrients applied on the surface or direct injection of nutrients into the subsurface, with eventual discharge to the sea.

Nitrogen is the primary nutrient transported in the subsurface. On West Maui, sources of dissolved nitrogen in groundwater include leachate of fertilizers from sugarcane, pineapple, golf courses, and resort/residential based landscaping, and the direct injection of wastewater effluent. Leaching of applied phosphorus is unlikely due to both its low solubility and high reactivity (sorption) in soils (Green, 1991).

Pioneer Mill sugarcane is grown with a urea solution distributed through irrigation water. Urea ($CO(NH_2)_2$) is a widely used chemical fertilizer which readily transforms to produce the ammonium ion (NH_4^+); the decomposition half life is on the order of one day (Green, 1981). Ammonium is then oxidized by nitrifying bacteria to the nitrate anion (NO_3^-). This process may take anywhere from a few days to a few weeks, with an average ammonium ion half life of ten days (Green, 1981). Adsorption plays an important role in the distribution of these chemicals in a typical soil column. Urea is a neutral molecule and is not attracted to the negatively-charged particles of the soil. It thus travels with the water unimpeded. Upon conversion, however, the ammonium cation bonds with the soil particles until it is either taken up by the plants or converted to the nitrate anion. Nitrates are repelled by the charged soil particles and migrate in solution with the flowing water.

Lysimeter studies conducted by Ekern (1977) show that when applying 78-90 kg-N/ha through a drip system, concentrations (even three months after fertilizing) in leachate ranged from 10.3 to 19.4 mg/L. Applying urea in much lower quantities (11 kg/ha/week) produced a maximum concentration of 1.47 mg/L with most concentrations below 0.1 mg/L. Stanley et al. (1990), while only analyzing waters less than one meter deep, found nitrate accumulations deep in the soil column with concentrations up to 50-60 mg/L after a period of moderate rainfall (3.3 centimeters over five days).

Leaching from golf courses is extremely variable with respect to the percentages of leachate (0-84%); mean leakage equal to 10% of the applied nitrogen is typical (Petrovic, 1990). Fertilizer leachate estimates from urban/residential/resort sources in Hawaii are currently unavailable.

The final potential source of nutrients in groundwater is through the direct injection of secondary treated wastewater effluent below the basal freshwater lens. Table 1 summarizes the historical effluent concentrations of the Lahaina Wastewater Reclamation Facility (LWRF), which treats most of the wastewater generated in the Lahaina District. This effluent supplies both nitrogen and phosphorus to the subsurface, a portion of which ultimately reaches the sea. Although the County of Maui intended to use the injection wells as backup only with the predominant mode of disposal through agricultural application, all of the effluent is now injected. The fate of the injected nutrients is generally not known and is discussed in Chapter III.

TABLE 1

Lahaina Wastewater Reclamation Facility Effluent Concentrations

Time Period	Facility	Mean Effluent Concentration (mg/L)	
		Total Nitrogen	Total Phosphorus
1989-1991	1975 Plant	12.1	10.2
1989-1991	1985 Plant	11.9	10.2
1995	Total Combined	5.7	1.7

The dynamic combination of many physical and chemical variables governs the role of each of the aforementioned transport mechanisms in nutrifying the coastal waters. Natural parameters include soil type, topography, precipitation, geology and vegetative cover. Anthropogenic factors include land use, wastewater injection, and the distribution (in space and time) of nutrient loading from agricultural and urban sources. In this study, each parameter is considered in a comprehensive examination of nutrient discharge from land.

DATABASE

Previously Collected Chemical and Hydrologic Data

Two major groundwater sampling programs have been undertaken in the past 25 years, generally within or downgradient of sugarcane production in the Lahaina District. Tenorio (1971) collected groundwater samples in 11 wells over a two year period (sampling each well six times). Maximum nitrate concentrations of 22 ppm (~mg/L) were measured with extreme temporal variations in concentrations (as shown in Figure 8). Souza (1981) performed one round of groundwater sampling in many of the same wells as Tenorio (Figure 9). While nitrate concentrations were generally lower than those measured by Tenorio, there is no data on temporal variations. Other groundwater samples have been taken sporadically by various investigators.

Historical groundwater head data is sparse and has generally been collected following well drilling. The United States Geological Survey (USGS), together with the Commission on Water Resource Management (CWRM) has measured heads in a few wells in the area over time, and recently initiated a monitoring program in conjunction with groundwater flow modeling (Steve Anthony, unpublished). Prior to this study, there is only one record (Grigg, 1983) of chemical analysis of any Lahaina District stream water.

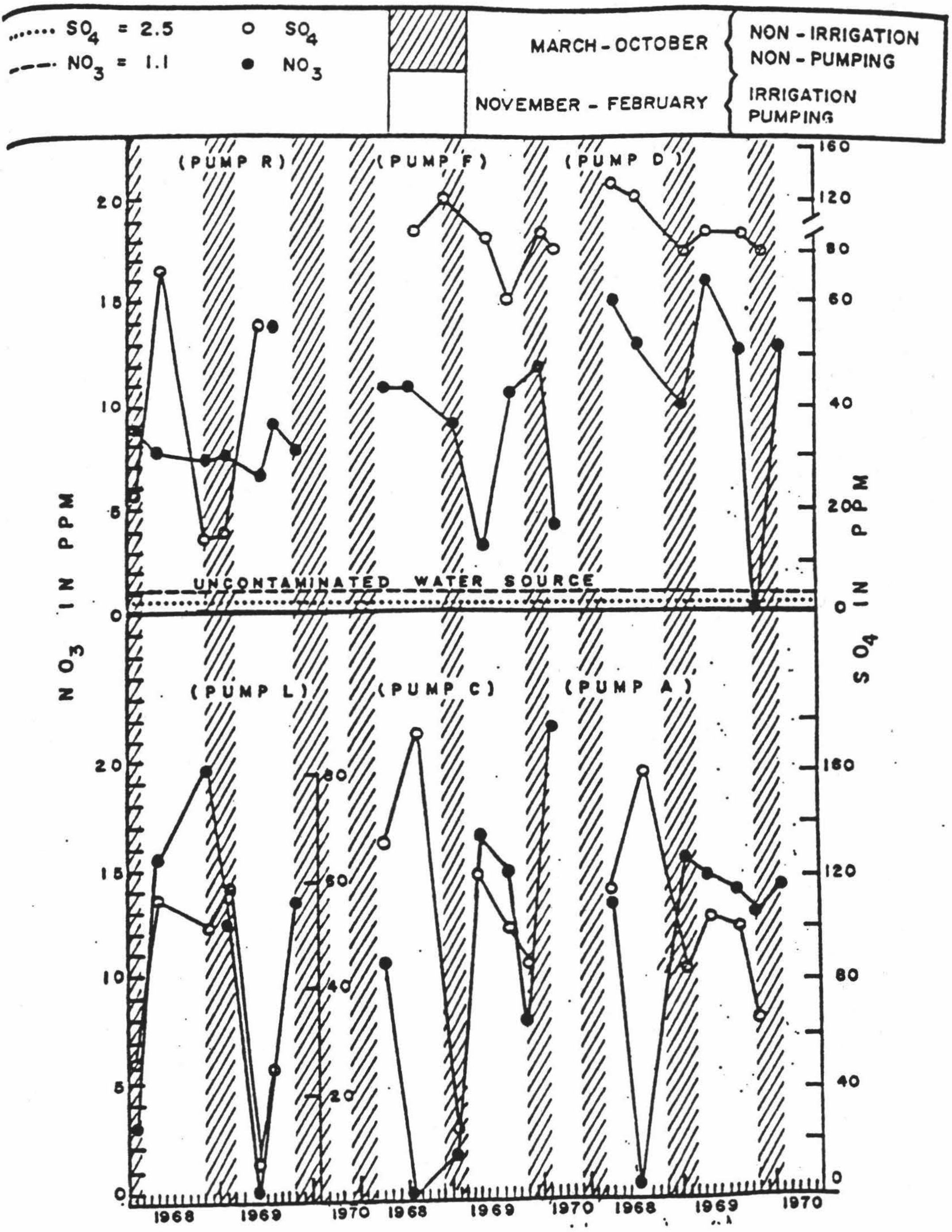


Figure 8. 1970 Nitrate Concentrations in Pioneer Mill Wells (from Tenorio, 1970).

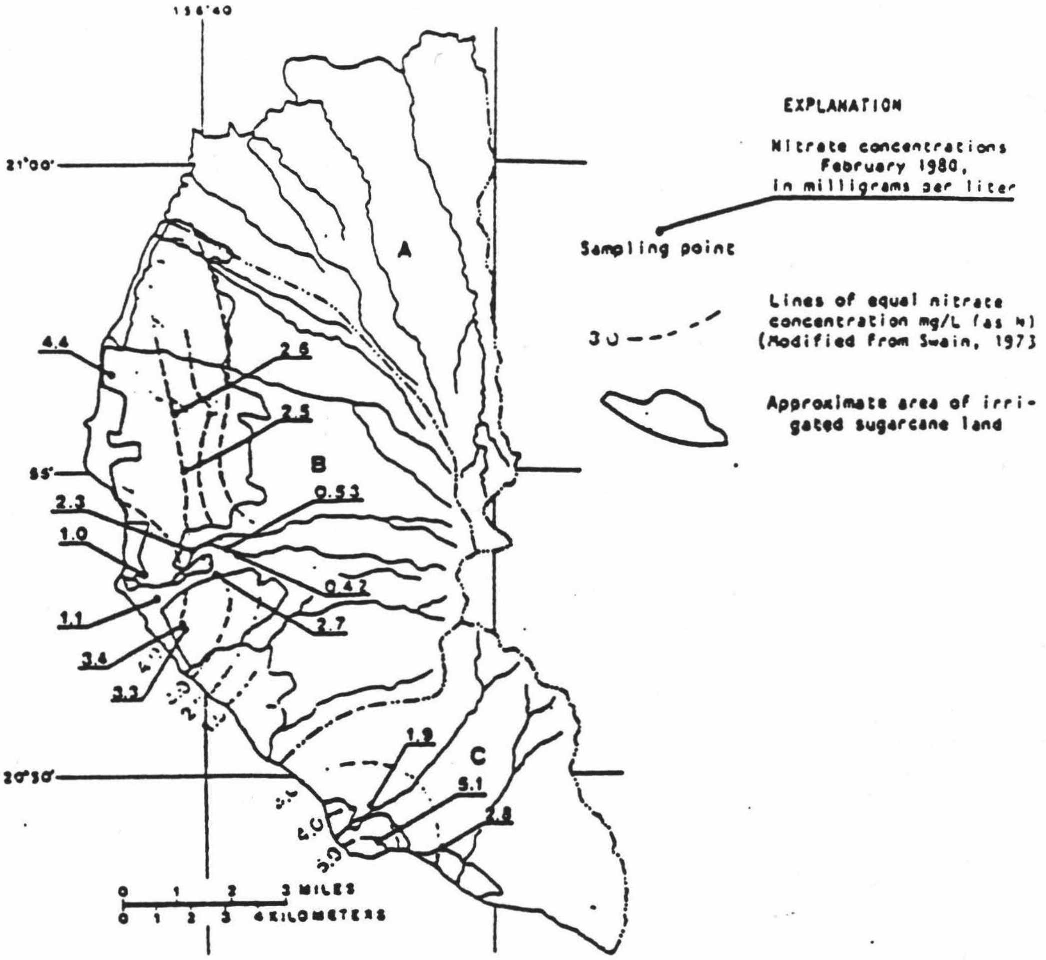


Figure 9. 1980 Nitrate Concentrations in Pioneer Mill Wells (from Souza, 1981).

Current Field Methods

Two methods of land based field studies were here utilized to quantify nutrient input to the hydrologic system. A semi-annual groundwater sampling program was undertaken in an array of wells distributed throughout the study area (shown in Figure 10). Chemical constituents including nitrate, nitrite, ammonium, organic nitrogen, total dissolved nitrogen, phosphate, organic phosphate, total dissolved phosphorus, chloride, and silica were monitored. Table 2 shows the results of all chemical analyses performed on West Maui groundwater.

Stream sampling was conducted using automatic stream samplers, installed to gage streamflow and collect water samples. Analysis was for total suspended solids, turbidity, particulate nitrogen and phosphorus, and the same dissolved constituents as for groundwater. Sampling methodology and results are discussed further in Chapter II.

Geographic Information System

The Geographic Information System (GIS) Mapinfo Version 2.0 was used to organize the various hydrologic, physical, and chemical data in this analysis. The GIS is useful in clearly displaying the spatial/temporal distribution of the data, facilitating computations of nutrient loading, and providing both the input and a shell (El-Kadi et al., 1994) in which to develop the groundwater and solute transport models.

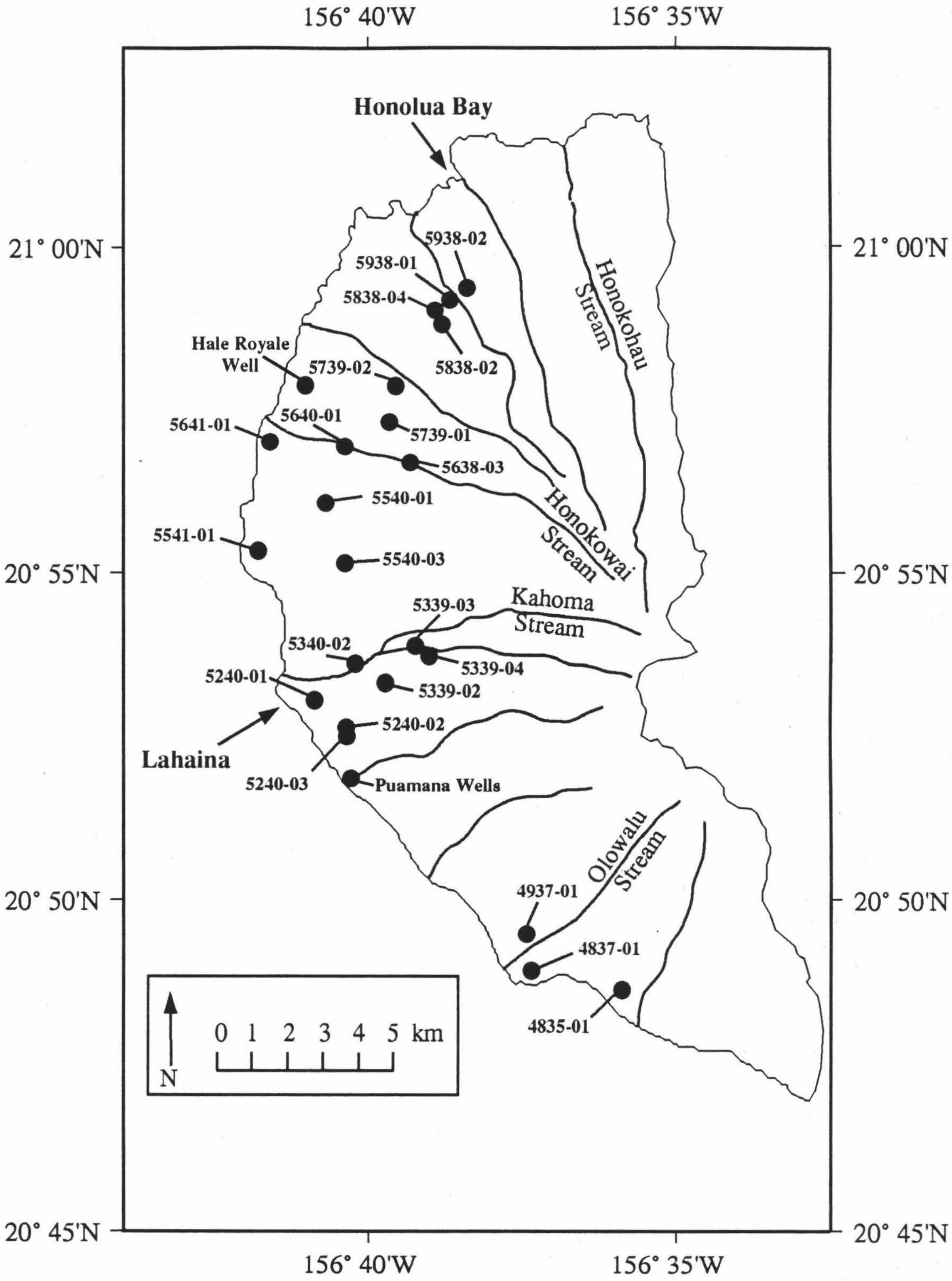


Figure 10. Wells Sampled During the Present Study.

TABLE 2

Maui Groundwater Nutrient Analyses (mg/L as N, P, Si). Note: 2/80 data from Souza, 1981; pre-1980 data from uncited USGS sources; all other data from this study.

WELL	NAME	OWNER	DATE	NO3	NH4	DON	TDN	PO4	DOP	TDP	SI	SALINITY (o/oo)
4835-01	Ukumehame-P	Pioneer	2/80	2.8	---	---	---	---	---	---	---	---
4837-01	Olowalu-O	Pioneer	2/80	5.1	---	---	---	---	---	---	---	---
			6/1/93	.07	.01	---	---	.02	---	---	15.3	---
			10/21/93	.12	.004	.04	.17	.02	.007	.02	15.2	---
			12/2/94	.10	.005	.20	.31	.02	.010	.04	14.8	.22
4937-01	Olowalu-N	Pioneer	12/79	1.9	---	---	---	---	---	---	---	---
			10/21/93	1.65	0	.02	1.68	.06	.002	.06	23.2	---
			12/2/94	1.20	.005	.31	1.51	.06	.008	.06	20.8	.61
5240-01	Mill-C	Pioneer	2/80	1.1	---	---	---	---	---	---	---	---
5240-02	Lahaina-A	Pioneer	2/80	3.4	---	---	---	---	---	---	---	---
			6/1/93	2.30	.002	---	---	.05	---	---	19.9	---
			10/21/93	3.61	.001	.001	3.65	.06	.001	.06	24.6	---
			4/14/94	3.65	.001	.03	3.68	.05	.002	.05	26.4	---
			12/2/94	.59	.004	.15	.75	.07	.015	.08	15.0	.58
			10/20/95	2.8	.004	.10	2.91	.07	0	.07	22.1	1.28
5240-03	Lahaina-B	Pioneer	2/80	3.3	---	---	---	---	---	---	---	---
			4/14/94	3.50	.002	.008	5.50	.07	.001	.07	28.0	---
	Lahaina-N		10/20/95	1.22	.005	.01	1.24	.06	.002	.06	21.7	.69
5339-02	Waipuka	County	1963	8.8	---	---	---	---	---	---	---	---
			1967	6.2	---	---	---	---	---	---	---	---
			1972	5.2	---	---	---	---	---	---	---	---
			1974	1.4	---	---	---	---	---	---	---	---
			2/80	2.7	---	---	---	---	---	---	---	---
			10/21/93	2.90	.001	.03	2.93	.20	.001	.20	29.9	---
			4/14/94	1.94	.001	.03	1.97	.19	0	.19	29.3	---
			12/1/94	1.67	.001	.004	1.67	.19	.001	.19	24.3	.46
			10/20/95	2.13	.004	.03	2.16	.19	.009	.20	25.8	.42
5339-03	Kanaha-1	County	1971	3.2	---	---	---	---	---	---	---	---
			1977	.01	---	---	---	---	---	---	---	---
			2/80	.53	---	---	---	---	---	---	---	---

TABLE 2. (Continued) Maui Groundwater Nutrient Analyses (mg/L as N, P, Si).

WELL	NAME	OWNER	DATE	NO3	NH4	DON	TDN	PO4	DOP	TDP	SI	SALINITY (o/oo)
5339-04	Kanaha-2	County	1973	.33	---	---	---	---	---	---	---	---
			1974	.58	---	---	---	---	---	---	---	---
			2/80	.4	---	---	---	---	---	---	---	---
			10/21/93	.59	.001	.006	.61	.07	.002	.07	22.1	---
			4/14/94	.57	.001	.001	.57	.06	.003	.07	23.5	---
			12/1/94	.34	.003	.05	.39	.06	.002	.06	18.1	1.34
			10/20/95	.41	.003	.01	.42	.06	.007	.07	19.7	.99
5340-02	Kahoma-M	Pioneer	2/80	2.3	---	---	---	---	---	---	---	---
			6/1/93	2.2	.002	---	---	.13	---	.13	22.7	---
			10/21/93	2.13	0	.03	2.17	.13	.001	.13	27.0	---
			12/2/94	1.70	.004	.13	1.84	.14	.015	.15	23.1	.69
			10/20/95	1.72	.003	.03	1.75	.12	.005	.13	23.6	1.09
5540-01	Puukoli	Kaanapali	2/80	2.6	---	---	---	---	---	---	---	---
			6/1/93	2.2	.001	---	---	.20	---	---	23.1	---
			10/21/93	2.39	0	.04	2.43	.19	.003	.19	25.7	---
			4/14/94	2.35	.001	.02	2.37	.19	.002	.19	22.8	---
			12/2/94	2.04	.007	.08	2.12	.18	.004	.19	22.3	.74
			10/20/95	2.35	.004	.06	2.41	.19	.007	.20	23.5	.81
5540-03	Hahakea-2	Kaanapali	2/80	2.5	---	---	---	---	---	---	--- ---	
			6/1/93	2.30	.001	---	---	.21	---	---	21.6	---
			10/21/93	2.49	0	.04	2.53	.20	.002	.20	24.3	---
			4/14/94	2.52	.001	.09	2.61	.20	.001	.20	26.2	---
			12/2/94	2.12	.006	.07	2.19	.21	.019	.23	21.1	.70
			10/20/95	2.35	.003	.01	2.26	.20	.002	.21	22.3	.74
5541-01	Kaanapali-G	Kaanapali	6/1/93	3.40	.005	---	---	.19	---	---	24.1	---
			10/21/93	3.69	0	.07	3.76	.18	.001	.18	27.1	---
			12/2/94	3.14	.006	.08	3.23	.19	.012	.20	24.7	1.62

TABLE 2. (Continued) Maui Groundwater Nutrient Analyses (mg/L as N, P, Si).

WELL	NAME	OWNER	DATE	NO3	NH4	DON	TDN	PO4	DOP	TDP	SI	SALINITY (o/oo)
5638-03	Honokawai-B	Kaanapali	6/1/93	.30	.001	---	---	.06	---	---	17.8	---
			10/21/93	.26	0	.06	.33	.05	.002	.05	19.6	---
			4/14/94	.28	.001	.07	.36	.04	.004	.04	19.6	---
			12/2/94	.29	.01	.10	.40	.06	.007	.06	17.5	.49
			10/20/95	.29	.003	.06	.35	.05	.013	.07	18.2	.42
5640-01	Honokawai-R	Pioneer	1974	1.9	---	---	---	---	---	---	--- ---	
			6/1/93	2.10	.008	---	---	.22	---	---	20.3	---
			10/21/93	2.34	0	.02	2.36	.21	.001	.21	23.0	---
			10/20/95	1.73	.004	.04	1.76	.20	.01	.22	21.1	.54
5641-01	Kaanapali-D	Pioneer	2/80	4.4	---	---	---	---	---	---	---	---
			6/1/93	1.8	.005	---	---	.96	---	---	24.1	---
5739-01	Kaanapali-P4	Kaanapali	4/14/94	1.85	.001	.03	1.88	.07	0	.07	21.4	---
			12/2/94	1.69	.007	.09	1.79	.06	.01	.07	17.3	.45
5739-02	Kaanapali-P6	Kaanapali	4/14/94	2.0	.001	.04	2.04	.07	.002	.07	21.1	---
			12/2/94	1.89	.007	.10	2.00	.08	.013	.09	17.4	.20
5838-02	Napili-B	County	4/14/94	.21	0	.06	.27	.07	.001	.07	21.6	---
			12/1/94	.17	.003	.02	.39	.07	.006	.08	17.4	.26
			10/20/95	.20	.003	.01	.21	.07	.005	.08	18.4	.26
5838-04	Napili-C	County	4/14/94	.28	.001	.05	.33	.08	.001	.08	22.0	---
			12/1/94	.25	.001	.07	.19	.08	.005	.08	17.5	.49
5938-01	Honokahua-B	County	10/21/93	.35	0	.02	.37	.06	0	.06	18.7	---
5938-02	Kapalua-1	Kapalua	10/21/93	.25	0	.06	.31	.05	.001	.05	18.7	---
			12/1/94	.20	.001	.002	.30	.05	.002	.05	15.9	.17
			10/20/95	.33	.002	.02	.35	.05	.006	.06	17.1	.17
5938-03	Kapalua-2	Kapalua	4/14/94	.36	0	.07	.43	.05	.003	.05	19.8	---
			12/1/94	.31	.004	.004	.39	.05	.004	.05	16.1	.17
			10/20/95	.23	.002	.03	.26	.05	.010	.06	17.2	.18
	Puamana 1	Puamana	12/1/94	3.21	.001	.06	3.28	.02	.002	.02	22.8	2.18
			10/20/95	3.58	.003	.08	3.66	.02	.001	.02	23.7	1.84
	Puamana 2	Puamana	12/1/94	2.69	0	.15	2.85	.02	.006	.02	21.8	1.85
			10/20/95	3.27	.003	.05	3.33	.02	.002	.02	22.0	2.01
	Hale Royale	Hale Royale	10/20/95	2.59	.003	.02	2.62	.19	.008	.20	22.4	1.68

CHAPTER II. SURFACE WATER

METHODOLOGY

Three streams in the Lahaina sector were monitored during the study period (sampling sites are shown in Figure 5). Sites were chosen based on accessibility and the land use practices affecting their drainage areas. Kahoma Stream drains sugarcane and forest reserve lands while Honokahua Stream drains both pineapple lands and the Kapalua golf courses; lower Honokowai Stream drains lands in sugarcane to the south and pineapple to the north. In an attempt to estimate natural loading from forested lands, a site was maintained above agricultural fields in upper Honokowai Stream. All of the monitored streams are diverted upgradient for irrigation purposes, leaving flow in them only during periods of heavy rainfall.

Flow meters and samplers were installed at three of the sites at the start of the 1994-95 rainy season (8/5/94 for upper Honokowai and Kahoma Streams, 9/9/94 for Honokahua Stream). Difficulties with access to the lower Honokowai site prevented installation until October 15, 1994. Sampling continued through April 28, 1995, was discontinued through the summer months, and resumed on September 22, 1995 at the lower Honokowai and Honokahua sites. Upper Honokowai sampling resumed on December 1, 1995, and the equipment in Kahoma Stream was vandalized beyond repair in October, 1995. This unfortunate occurrence prevented the use of Kahoma Stream in loading analyses, as the data collected prior to the vandalism was insufficient to make accurate estimations. Sampling was terminated at all other sites in Honokahua Stream on March 15, 1996 and in Honokowai Stream on April 23, 1996. Water levels in the streams were determined with an air bubbling sensor, with measurements recorded every fifteen minutes. Exceeding a preset threshold value triggered the samplers to pump water from the stream at twenty to forty minute intervals. A maximum of twenty four samples were collected per storm from each stream. Of those, five to ten samples from each site were retrieved as soon as possible after the event (generally 1-4 days). Samples were analyzed for a host of constituents including nitrate (NO_3^-), ammonium (NH_4^+), dissolved organic nitrogen (DON), total dissolved nitrogen (TDN), particulate nitrogen (PN), phosphate (PO_4^-), dissolved organic phosphorus (DOP), total dissolved phosphorus (TDP), particulate phosphorus (PP), total suspended solids (TSS), silica (SI), and salinity, at the School of Ocean and Earth Science and Technology (SOEST) Analytical Services Laboratory of the University of Hawaii. Analyses were performed using the standards of the Technicon Methods for Seawater Analysis. Results from these analyses are shown in Table 3.

Flow rates were calculated using the Manning Equation (Dunne, 1978):

$$Q = \frac{1.49 \cdot A \cdot R^{\frac{2}{3}} \cdot S^{\frac{1}{2}}}{m} \tag{2.1}$$

where:

A = cross sectional area of the stream [L^2]
R = hydraulic radius (ratio of A to the wetted perimeter) [L]
S = energy gradient, roughly equal to the stream surface slope [L/L]
m = Manning resistance coefficient.

A relationship between water level and area was established by fitting a polynomial function to the measured stream cross section and integrating to obtain the area corresponding with a given stage (Figure 11). The results of this integration were plotted against water level to yield stage-to-area rating curves. A linear function was generated to describe the relationship between hydraulic radius and area. The energy gradient was assumed equal to the slope of the streambed, which was estimated from topographic maps. Finally, estimates of the Manning coefficient were derived on the basis of matching coefficients from published stream conditions to those in the streams sampled.

TABLE 3

Maui Stream Nutrient and Sediment Analyses (mg/l, except salinity in ppt)

STREAM	DATE	TIME	NO3	NH4	DON	TDN	PN	PO4	DOP	TDP	PP	TSS	SI	SALINITY
Kahoma	3/94	grab	.06	.002	.07	.13	–	.007	.005	.011	.006	28.8	4.45	--
"	3/94	grab	.055	.003	.07	.13	–	.009	.006	.015	–	–	4.47	--
Kahoma	4/22/94	grab	.02	.001	.06	.08	–	.009	.002	.011	.002	1.0	6.3	.16
"	4/22/94	grab	.02	.001	.06	.08	–	.009	.002	.011	.001	1.3	6.3	.14
"	4/22/94	grab	.03	.001	.06	.09	–	.01	.003	.013	.003	1.5	6.3	.14
Kahoma	11/4/94	1040	.03	.16	.12	.32	.65	.06	.013	.069	2.63	31.0	5.62	.13
"	11/4/94	1058	0	.004	.19	.19	.72	.004	.014	.018	1.60	33.8	5.66	.13
"	11/4/94	1146	.001	.04	.15	.19	.65	.003	.009	.013	1.01	37.1	5.27	.13
"	11/4/94	1315	0	.01	.27	.28	1.48	.008	.022	.031	2.94	128.8	3.87	.14
"	11/4/94	1415	.002	.03	.17	.21	.92	.002	.009	.012	3.07	103.2	2.85	.13
"	11/4/94	1515	.001	.05	.14	.19	.65	.004	.007	.011	1.89	47.2	2.92	.13
"	11/4/94	1615	.002	.10	.15	.25	.54	.007	.012	.018	1.51	57.6	3.28	.13
"	11/4/94	1720	.001	.07	.16	.23	.54	.006	.014	.020	1.26	27.8	3.69	.13
Kahoma	11/10/94	323	.02	.09	.10	.21	.33	.04	.004	.018	.78	25.5	5.41	.14
"	11/10/94	443	.02	.10	.10	.22	.35	.007	.006	.013	1.28	34.9	3.82	.13
"	11/10/94	603	.03	.09	.10	.22	.19	.005	.006	.011	.76	19.6	4.08	.14
"	11/10/94	703	.04	.12	.08	.24	.09	.004	.006	.010	.29	5.2	4.21	.13
Kahoma	1/29/95	139	.18	.002	.14	.33	.66	.002	.01	.01	3.07	143	6.99	.15
"	1/29/95	209	.31	.03	.13	.47	.79	.03	.003	.03	2.80	113	5.23	.17
"	1/29/95	239	.20	.02	.15	.37	.93	.03	.001	.03	4.86	163	4.47	.14
Honokahua	3/94	grab	.03	0	.12	.16	–	.004	.006	.01	.008	19.0	2.17	–
"	3/94	grab	.03	.002	.11	.14	–	.004	.006	.01	–	–	2.23	–

TABLE 3. (Continued) Maui Stream Nutrient and Sediment Analyses (mg/l, except salinity in ppt)

STREAM	DATE	TIME	NO3	NH4	DON	TDN	PN	PO4	DOP	TDP	PP	TSS	SI	SALINITY
Honokahua	11/17/94	1340	.02	.09	.27	.39	8.85	.06	.015	.073	4.29	214.5	2.87	.15
"	11/17/94	1510	.05	.05	.23	.39	4.83	.02	.003	.022	4.82	219.3	1.19	.15
"	11/17/94	1640	.06	.05	.21	.32	3.96	.02	.003	.021	6.47	346.0	1.14	.15
"	11/17/94	1810	.07	.03	.21	.30	2.72	.01	.004	.018	4.54	199.6	1.24	.13
"	11/17/94	1940	.06	.02	.22	.30	1.20	.01	.004	.016	2.44	115.6	1.37	.13
"	11/17/94	2110	.07	.03	.19	.29	.78	.01	.005	.016	1.68	59.8	1.51	.13
"	11/17/94	2240	.08	.02	.19	.29	.46	.01	.005	.015	.63	26.4	1.66	.13
"	11/18/94	0010	.09	.02	.19	.29	.41	.01	.005	.016	.38	16.0	1.83	.13
Honokahua	1/29/95	452-522	.09	.004	.24	.33	1.58	.005	.016	.02	2.05	45.9	2.71	.13
"	1/29/95	622-652	.10	.004	.23	.33	.28	.004	.011	.01	1.84	17.5	1.76	.14
"	1/29/95	752-822	.07	.005	.24	.31	.22	.003	.009	.01	1.47	11.3	1.68	.14
"	1/29/95	1552-1622	.04	.006	.26	.30	.12	.004	.010	.01	1.76	2.8	2.25	.14
Honokahua	12/30/95	1949	.21	.03	.53	.77	1.07	.04	.03	.07	0.60	1602	2.91	.13
“	12/30/95	2019	.28	.01	.40	.69	1.83	.02	.02	.04	0.35	570	1.45	.12
“	12/30/95	2049	.29	.01	.40	.70	1.71	.01	.02	.03	0.28	467	1.29	.11
“	12/30/95	2119	.27	.01	.39	.67	1.52	.01	.02	.02	0.25	370	1.16	.12
“	12/31/95	0719	.18	.01	.39	.58	2.25	.03	.02	.05	0.40	991	1.75	.12
Honokahua	3/3/96	0923	.16	.04	.32	.53	3.57	.08	0	.08	.29	2704	1.83	.12
“	3/3/96	1003	.03	.02	.28	.32	1.67	.02	.01	.03	.19	730	1.19	.11
“	3/3/96	1923	.03	.01	.31	.36	3.02	.02	.02	.04	.35	6042	1.28	.11
“	3/3/96	2003	.03	.01	.27	.31	3.13	.02	.01	.03	.31	8649	1.32	.11
Honokowai-L	3/94	grab	.04	.001	.08	.12	–	0	.004	.004	.007	25.5	2.94	--
"	3/94	grab	.04	.001	.09	.13	–	.001	.004	.004	–	–	2.98	--

TABLE 3. (Continued) Maui Stream Nutrient and Sediment Analyses (mg/l, except salinity in ppt)

STREAM	DATE	TIME	NO3	NH4	DON	TDN	PN	PO4	DOP	TDP	PP	TSS	SI	SALINITY
Honokowai-L	4/28/94	grab	.03	.001	.06	.09	–	.007	.003	.01	.001	1.7	6.6	.13
"	4/28/94	grab	.03	.001	.05	.08	–	.007	.003	.01	.001	1.7	6.6	.14
"	4/28/94	grab	.04	.004	.11	.15	–	.01	.007	.017	.01	2.9	4.7	.20
"	4/28/94	grab	.04	.004	.11	.15	–	.01	.009	.019	.008	3.0	4.7	.16
"	4/28/94	grab	.04	.004	.11	.15	–	.01	.005	.015	.011	3.4	4.7	.15
"	4/28/94	grab	.04	.004	.11	.15	–	.01	.005	.015	.011	3.7	4.7	.14
"	4/28/94	grab	.04	.004	.11	.15	–	.01	.005	.015	.01	3.7	4.7	.13
Honokowai-L	11/4/94	1141	.001	.02	.24	.26	.58	.004	.023	.022	1.01	16.2	3.4	.13
"	11/4/94	1301	0	.004	.20	.20	.50	.004	.015	.019	.42	8.2	3.3	.13
"	11/4/94	1421	.02	.08	.11	.21	.02	.006	.006	.012	.82	49.9	2.4	.13
"	11/4/94	1541	.06	.04	.12	.22	.50	.003	.007	.009	.53	26.9	2.4	.13
"	11/4/94	1703	.07	.04	.11	.23	.02	.002	.007	.009	.19	13.5	2.5	.13
"	11/4/94	1823	.05	.04	.11	.20	.02	.002	.006	.007	.08	15.9	2.8	.13
"	11/4/94	1943	.03	.03	.11	.18	.02	.002	.006	.008	.21	2.4	3.3	.13
"	11/4/94	2103	.10	.06	.17	.32	.02	.003	.012	.015	.34	15.9	2.8	.13
Honokowai-L	11/17/94	1120	.002	.004	.35	.36	1.72	.005	.003	.037	6.22	162.4	4.08	.15
"	11/17/94	1220	.06	.08	.09	.24	.18	.005	.007	.012	.31	10.1	3.37	.13
"	11/17/94	1320	.06	.08	.09	.22	.16	.006	.003	.090	.28	7.5	2.83	.13
"	11/17/94	1420	.05	.07	.09	.20	.14	.003	.004	.081	.25	6.5	2.86	.13
"	11/17/94	1520	.04	.06	.08	.18	.07	.003	.004	.068	.04	2.4	2.97	.13
"	11/17/94	1620	.03	.07	.09	.18	.06	.003	.004	.068	.03	.6	3.14	.13
"	11/17/94	1720	.03	.06	.10	.19	.12	.004	.005	.087	.20	4.3	3.35	.13
"	11/17/94	1820	.06	.06	.10	.16	.04	.004	.006	.068	.11	.5	3.55	.14
Honokowai-L	1/29/95	354-424	.02	.03	.23	.28	6.44	.03	.001	.03	22.28	2496	6.15	.16
"	1/29/95	654-724	.20	.004	.14	.34	.27	.002	.005	.007	.50	24.9	2.31	.14
"	1/29/95	1054-1124	.13	.004	.13	.26	.15	.001	.007	.007	.46	7.9	2.46	.14
"	1/29/95	1454-1524	.07	.004	.13	.21	.18	.001	.005	.006	.77	19.2	2.21	.13

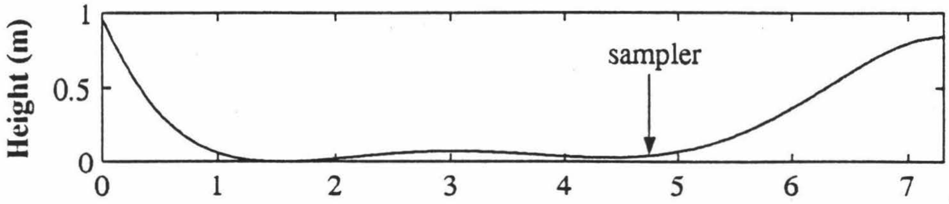
TABLE 3. (Continued) Maui Stream Nutrient and Sediment Analyses (mg/l, except salinity in ppt)

STREAM	DATE	TIME	NO3	NH4	DON	TDN	PN	PO4	DOP	TDP	PP	TSS	SI	SALINITY
Honokowai-L	12/30/95	1925	.01	.01	1.24	1.27	6.00	.01	.11	.13	1.85	2910	3.63	.16
"	12/30/95	1955	.23	.01	.44	.67	2.55	0	.02	.02	.42	971	1.53	.14
"	12/30/95	2025	.42	.01	.35	.78	1.27	0	.02	.02	.22	624	1.19	.12
"	12/31/95	0625	.07	.02	.59	.67	1.80	.02	.03	.05	.72	3736	3.16	.13
"	12/31/95	0655	.29	.03	.46	.77	5.33	.02	.03	.05	.62	3020	1.48	.12
Honokowai-L	3/3/96	0914	1.48	.10	.43	2.02	2.43	.05	.03	.08	.16	2981	2.82	.11
"	3/3/96	0954	.34	.02	.29	.65	2.16	.02	.02	.04	.13	1979	1.97	.12
"	3/3/96	1956	.08	.02	.20	.30	1.16	.01	.01	.02	.10	771	2.17	.11
"	3/4/96	0436	.16	.08	.25	.50	.29	.03	.02	.05	.03	122	3.33	.12
Honokowai-L	3/30/96	2107	.92	.39	.30	1.60	2.58	.02	.02	.04	.18	2545	2.24	.12
"	3/30/96	2147	.39	.09	.23	.71	4.11	.03	.02	.05	.25	2765	1.14	.10
"	3/31/96	307	.78	.14	.25	1.17	4.10	.06	.03	.09	.27	4345	.52	.10
"	3/31/96	347	.62	.06	.31	.99	5.74	.05	.02	.07	.33	6677	1.48	.10
"	3/31/96	427	.86	.08	.22	1.16	2.96	.04	.02	.06	.21	2155	1.32	.10
Honokowai-U	11/4/94	1203	.13	.18	.06	.37	.21	.03	.007	.033	.19	11.7	2.42	.14
"	11/4/94	1224	.13	.005	.11	.25	.51	.008	.004	.012	1.07	72.8	2.28	.13
"	11/4/94	1303	.15	.002	.11	.27	.51	.003	.006	.009	.88	55.4	1.71	.13
"	11/4/94	1343	.15	.01	.10	.27	.54	.004	.005	.008	.80	34.8	1.75	.13
"	11/4/94	1423	.16	.01	.10	.27	.02	.008	.006	.014	.36	21.4	1.90	.13
"	11/4/94	2027	.13	.008	.09	.24	.02	.004	.007	.011	.44	19.9	2.64	.13
"	11/4/94	2107	.15	.03	.09	.27	.02	.006	.005	.011	.29	18.8	1.96	.13
"	11/4/94	2127	.13	.002	.08	.22	.02	.002	.009	.011	.25	13.7	1.91	.14

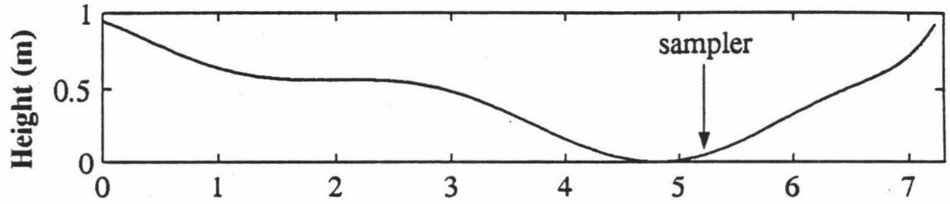
TABLE 3. (Continued) Maui Stream Nutrient and Sediment Analyses (mg/l, except salinity in ppt)

STREAM	DATE	TIME	NO3	NH4	DON	TDN	PN	PO4	DOP	TDP	PP	TSS	SI	SALINITY
Honokowai-U	11/17/94	929	.02	0	.13	.15	.47	.002	.001	.012	.95	26.9	4.11	.14
"	11/17/94	1009	.10	.02	.09	.21	.09	.003	.001	.009	.31	6.1	2.43	.13
"	11/17/94	1049	.09	.03	.09	.21	.11	.003	.006	.009	.42	8.3	2.16	.13
"	11/17/94	1129	.09	.03	.08	.20	.07	.002	.005	.007	.34	3.9	2.14	.13
"	11/17/94	1209	.09	.02	.08	.20	.15	.001	.006	.007	.32	6.5	2.15	.13
"	11/17/94	1249	.09	.02	.09	.19	.08	.001	.004	.006	.11	2.8	2.32	.14
"	11/17/94	1329	.08	.02	.09	.19	.65	.003	.005	.007	.10	0.9	2.51	.13
"	11/17/94	1409	.08	.02	.08	.19	.05	.002	.004	.005	.14	0.3	2.66	.13
Honokowai-U	1/29/95	227-257	.14	.001	.13	.28	1.12	0	.007	.007	3.63	112	4.20	.25
"	1/29/95	527-557	.22	.002	.12	.35	.34	.001	.006	.008	.96	21.0	1.63	.14
"	1/29/95	827-857	.21	.002	.11	.33	.15	0	.006	.006	.36	6.4	2.49	.14
"	1/29/95	1127-1157	.16	.002	.10	.27	.12	0	.005	.005	.28	4.4	2.03	.13
Honokowai-U	12/30/95	1836	.08	.19	.45	.72	1.45	.06	.03	.09	.96	1614	4.31	.14
“	12/30/95	1906	.42	.05	.29	.77	2.21	.01	.01	.02	.36	767	1.49	.12
“	12/30/95	1936	.48	.02	.34	.84	1.35	.01	.02	.03	.17	666	1.08	.12
“	12/30/95	2006	.47	.07	.33	.87	1.03	.02	.02	.04	.15	287	1.10	.12
“	12/31/95	0606	.24	.05	.41	.69	6.04	.02	.03	.05	.58	582	1.53	.12
Honokowai-U	3/30/96	2113	.06	.03	.28	.37	2.06	.009	.06	.07	.17	749	1.12	.10
“	3/30/96	2153	.09	.02	.20	.31	1.08	.009	.03	.04	.14	1313	.83	.10
“	3/30/96	2233	.06	.01	.19	.26	1.76	.004	.02	.03	.13	527	.78	.10
“	3/31/96	233	.02	.04	.41	.48	2.85	.06	.04	.10	.21	643	1.07	.10
“	3/31/96	313	.04	.01	.21	.26	1.79	.01	.02	.03	.14	814	.85	.10

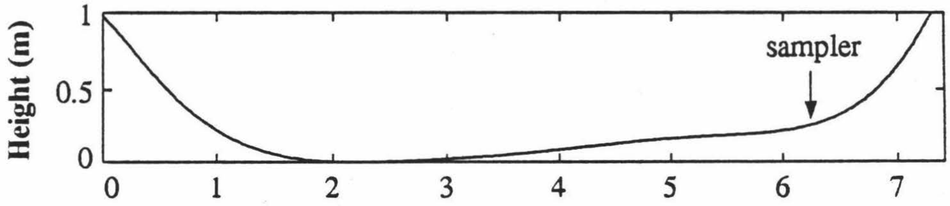
KAHOMA STREAM



HONOKAHUA STREAM



LOWER HONOKOWAI STREAM



UPPER HONOKOWAI STREAM

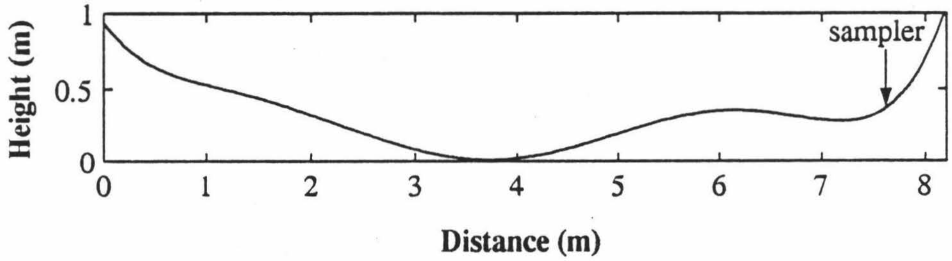


Figure 11. Stream Cross Sections at Monitoring Stations

There is significant uncertainty associated with all of the above measurements/parameters. While Figure 11 shows stream cross sections as smooth curves, the streambeds are, in fact, irregular surfaces made up of variably sized rocks ranging from pebbles to boulders (shapes of which may change with each storm, as the rushing water alters stream morphology). The energy gradient, which is truly a measure of the slope of the *water* surface in the stream, is approximated by the slope of the streambed, which is extremely variable both laterally and along the length of the stream. The gradient used in this analysis is only an average approximation of the true energy gradient of each stream. Finally, the Manning resistance coefficient is a scaling factor which is only a crude approximation for the studied streams, considering the enormous morphological irregularities.

STREAM LOADING ANALYSES

Figures 12 and 13 show the resulting flow hydrographs for Kahoma, Honokahua and upper and lower Honokowai Streams during the study period. Plots were generated of flow versus concentration of particulate and dissolved nitrogen and phosphorus, and total suspended solids (Figures 14 through 17). Where present, mathematical relationships were derived between flow and concentration parameters by fitting power functions to the data through regression analyses. The R value associated with these curve fits is a measure of how well the function represents the relationship (R=1 is a perfect fit). This curve permits the calculation of concentration at any flow rate, which is used, ultimately, to estimate total constituent loading over the entire period of study.

Total suspended solids shows the strongest positive correlation between flow and concentration. Particulate and dissolved nitrogen show similar relationships, with concentrations of the former roughly an order of magnitude greater than the latter.

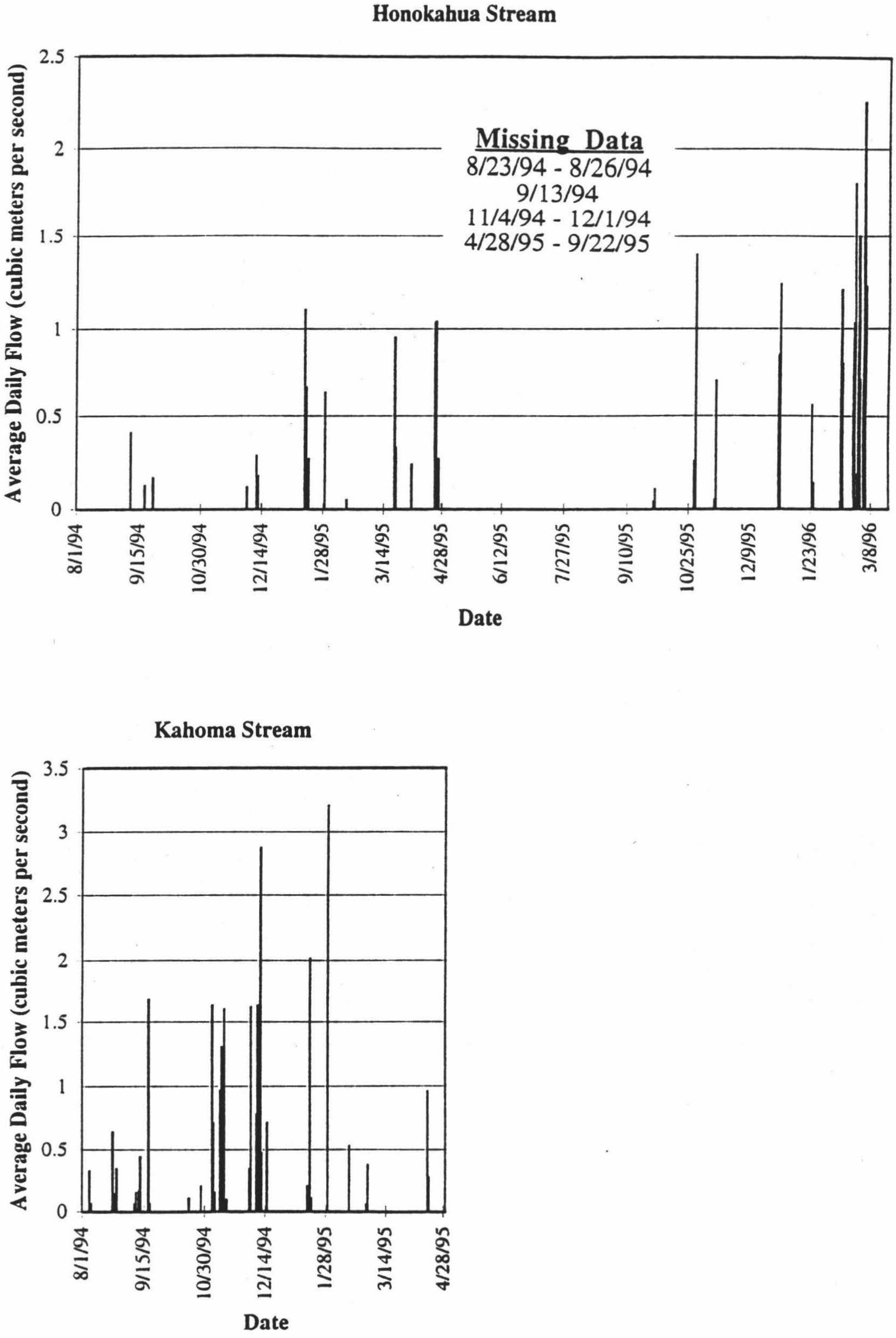
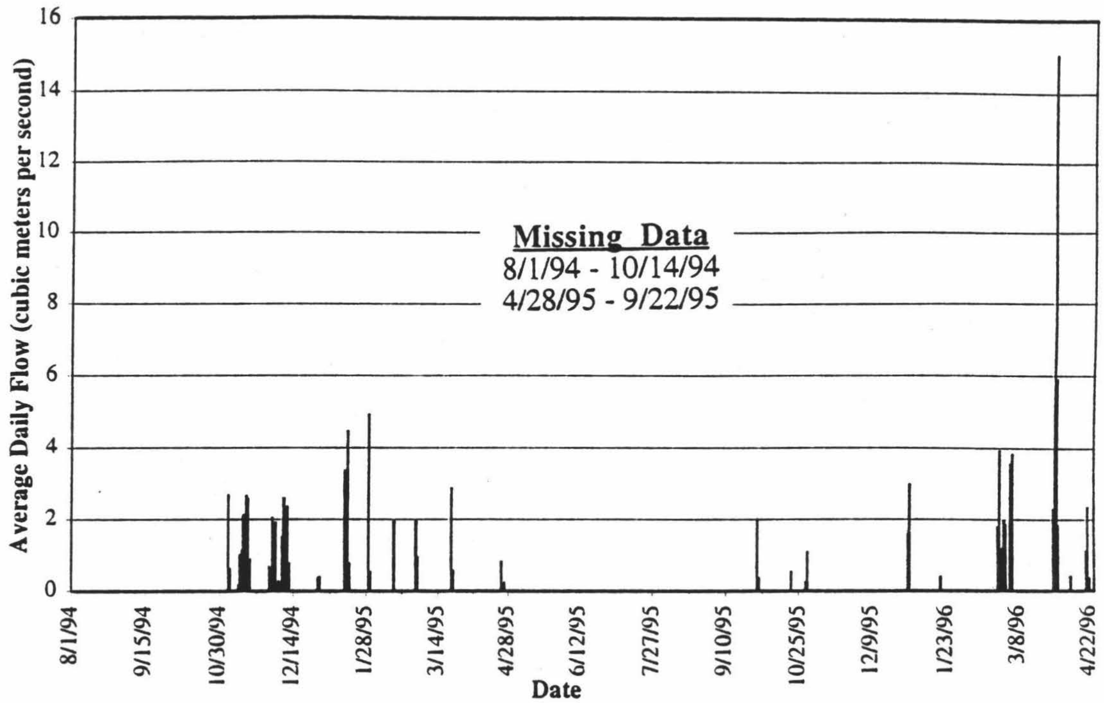


Figure 12. Hydrographs for Honokahua and Kahoma Streams

Lower Honokowai Stream



Upper Honokowai Stream

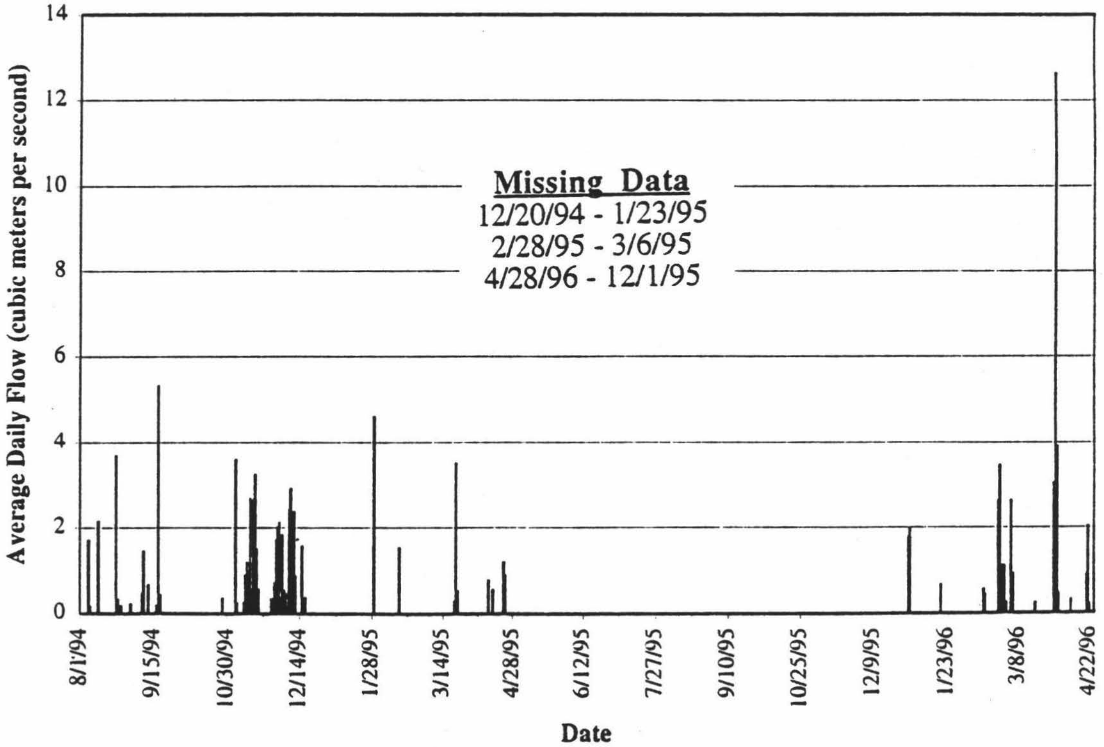


Figure 13. Hydrographs for Honokowai Stream

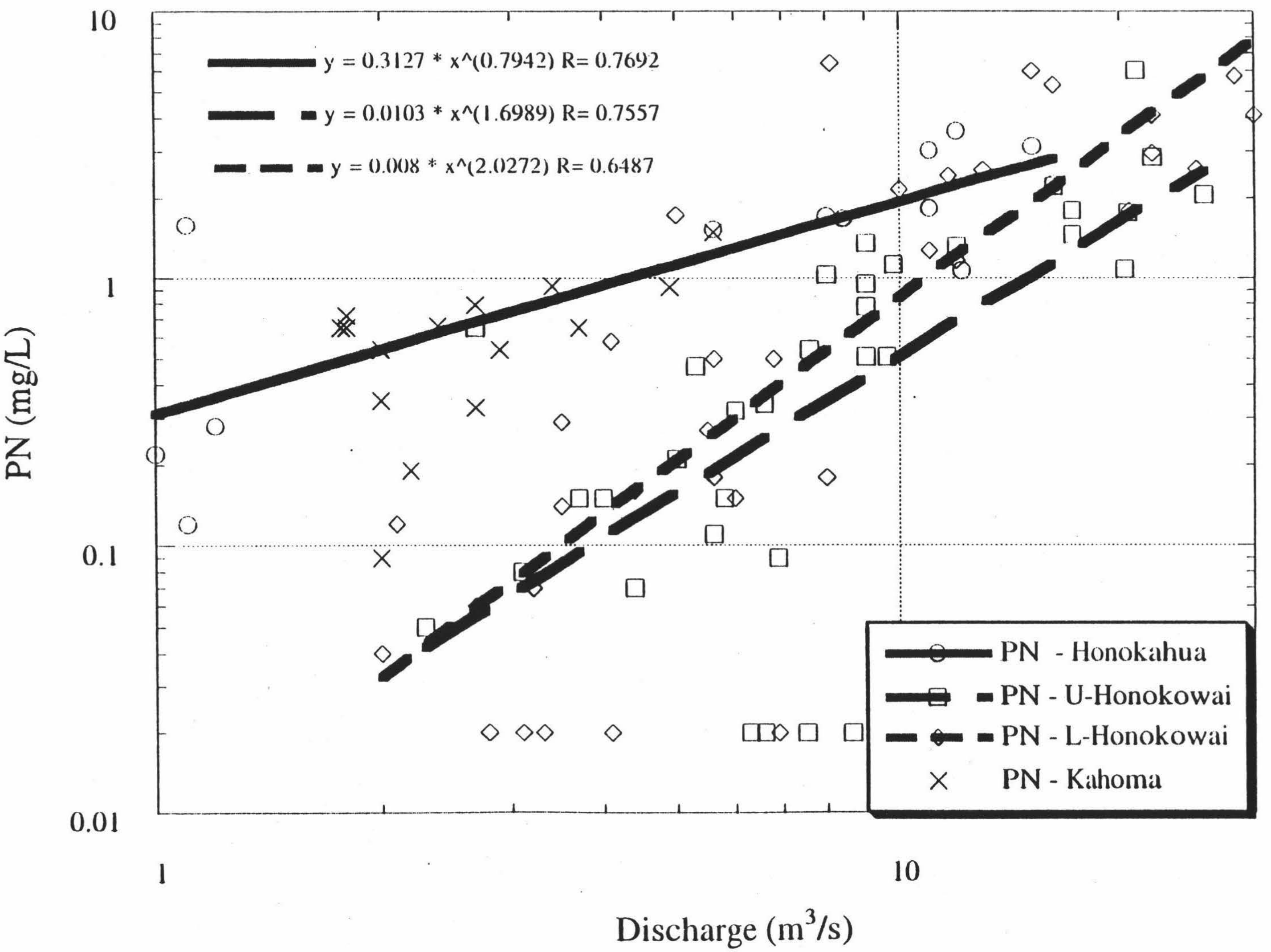


Figure 14. Particulate Nitrogen versus Flow in Streams.

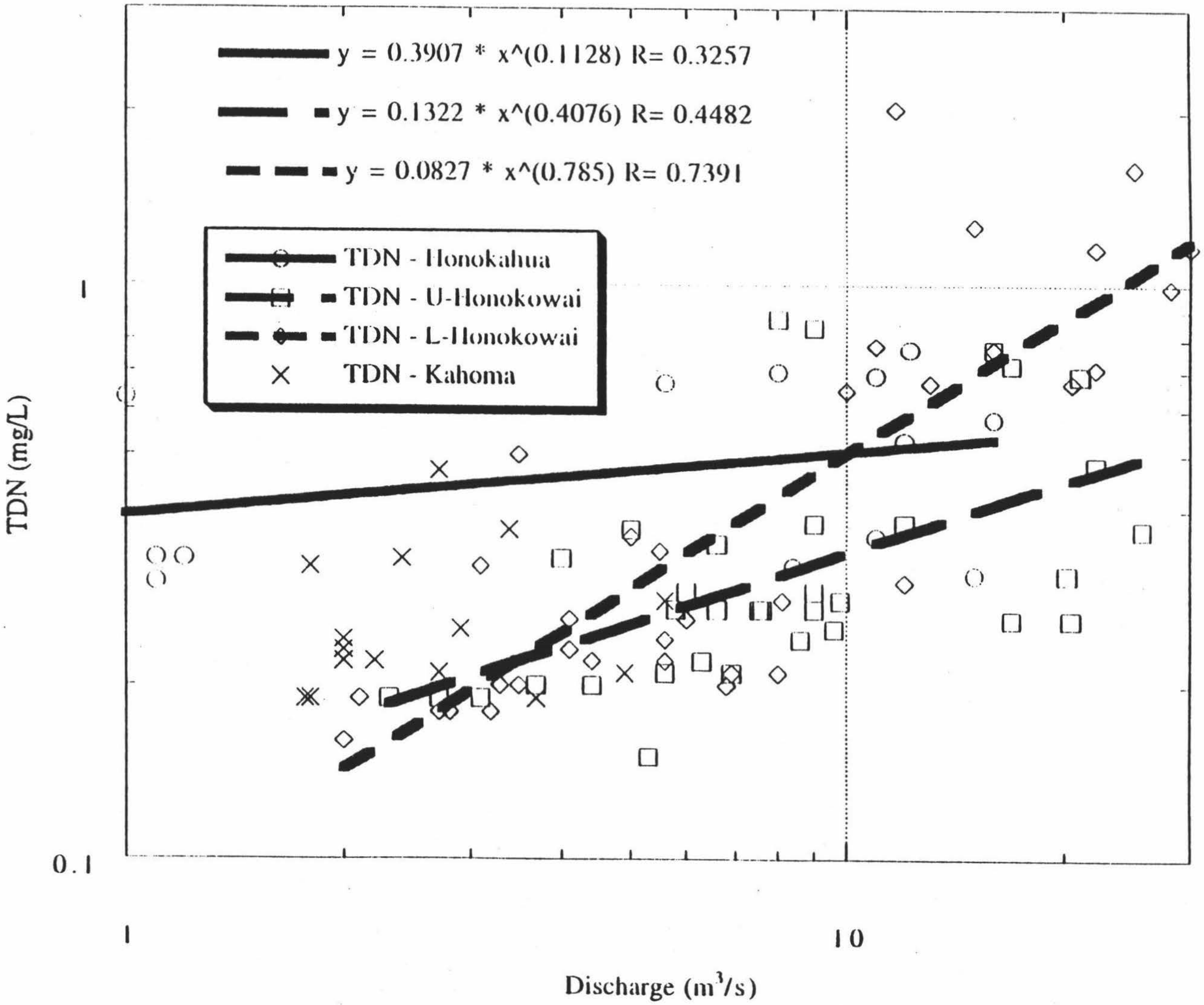


Figure 15. Total Dissolved Nitrogen versus Flow in Streams.

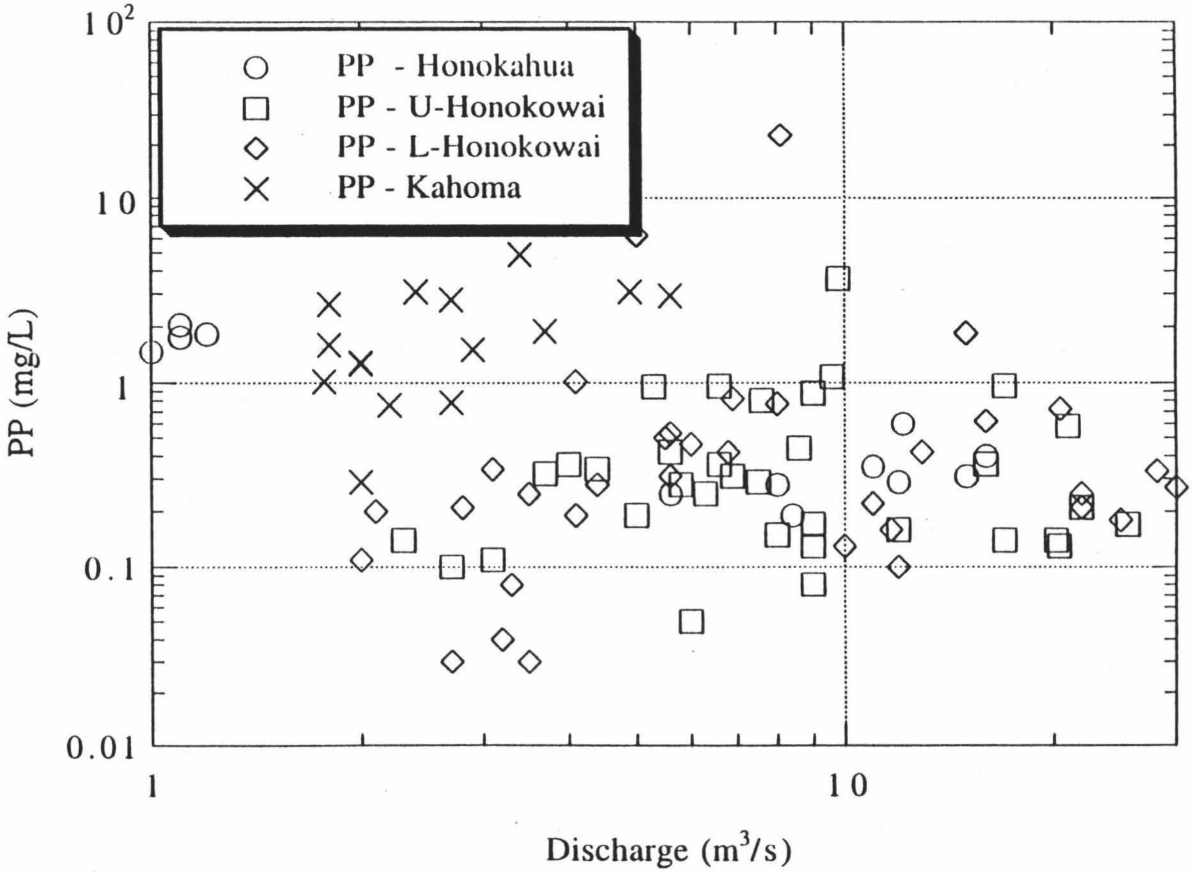


Figure 16. Particulate Phosphorus versus Flow in Streams.

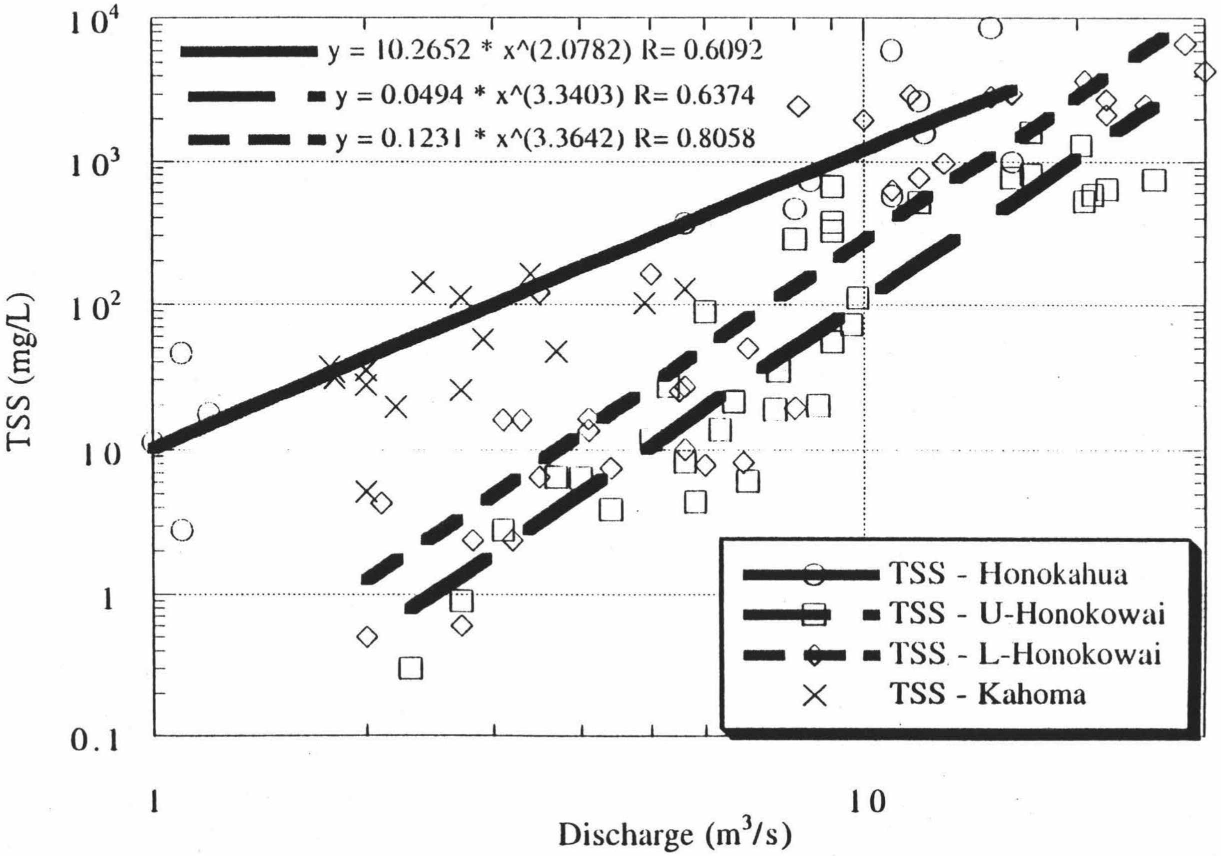


Figure 17. Total Suspended Solids versus Flow in Streams.

Particulate and dissolved phosphorus show little correlation of flow and concentration. Dissolved phosphorus concentrations are very low (generally <0.1mg/L), and particulate phosphorus concentrations are generally lower than those of particulate nitrogen. Total loading analyses were performed for TSS, PN, and TDN. These deduced relationships are similar to those observed by Devito (1990) who found no correlation between flow and dissolved constituents, and positive correlation between PN, PP and TSS, and flow in Oahu streams. Indeed weak positive correlation exists between PP and flow (Figure 16) though not sufficiently defined by the existing data.

The "first flush" phenomenon occurs as sediment previously deposited in the streambed joins with other loose material and swiftly remobilizes into the waters of a current storm. Its effects are short-lived and highly variable. From Table 3, it is clear that even for low flow events (1-29-95, for example) the first flush provides a significant quantity of nutrients and sediment (with respect to the rest of the storm's flow). The first flush effect may be even more extreme than the data suggests, as the samplers are only triggered by exceeding a threshold water level and the initial flow in the stream at the onset of a storm may be missed. While discharge in the streams is observed to be highest at the onset of flow, the "first flush" may add to the already higher nutrient and sediment concentrations in the water, elevating them even more dramatically. This may help explain the high PP concentration measured in lower Honokowai Stream on 1-29-95, as well as other high levels in first samples taken.

As concentration alone does not reveal the magnitude of loading from each site, calculations of total loading over time allow for comparisons among the sites. Total loading over the period of study for TSS, PN, and TDN are listed in Table 4. For various reasons (power failure, storm damage...), continuous data was not evenly collected from all the sites. Comparisons of the values in Table 4 are therefore not legitimate.

TABLE 4

Total Calculated Stream Loading During Study

Stream	PN (kg)	TDN (kg)	TSS (metric tons)
Honokahua	1,500 - 2000	800 - 1,000	80 - 100
Upper Honokowai	3,000 - 3,500	2,000 - 2,500	100 - 120
Lower Honokowai	6,500 - 7,500	3,500 - 4,000	350 - 400

The great disparity between the total loads of Honokahua and Honokowai Streams presented in Table 4 are due in large part to the storm of 3/30-3/31/96, for which data in Honokahua Stream is unavailable. The hydrographs for Honokowai Stream (Figure 13) show that this event represents a large proportion of the total volume of water that flowed in the stream during the study period. In fact, flow in Honokahua Stream was so powerful during that storm that it overwhelmed the sampling equipment, causing it to fail. So extensive was the debris and sediment load in the stream that the Fleming Beach Park (the discharge site of Honokahua Stream) was closed for three days following the storm. In Honokowai Stream, discharge rates remained high for over a 24 hour period. While the instantaneous discharge rate at any point during the storm did not greatly exceed those measured during other storm events, the duration of these high flow rates made this storm extremely significant with respect to total constituent loading. 75-80% of the sediment load, 70% of the PN, and 40% of the TDN discharging over the entire study period came from this one event. Figures 14 and 17 show that the trend in Honokahua Stream is toward even higher PN and TSS than in Honokowai Stream. These results highlight the significance of individual, intense storms in inundating the coastal waters with large quantities of nutrients and sediment.

To make more valid comparisons, total loading from the available sites are presented for the storm of March 3-4, 1996. The hydrographs from this storm show a similar magnitude and duration of flow at the three sites (Figure 18). Figure 19 reveals that TSS loading in lower Honokowai Stream was almost triple that observed in the upper reaches of the stream. Notice that most of the discharge occurs over a very short period of time (less than two hours), and in two distinct pulses (typical of most observed storms during the study period). Honokahua Stream produced nearly double the TSS of lower Honokowai Stream. Particulate nitrogen loads followed a similar trend (Figure 20), while lower Honokowai Stream carried the greatest quantity of dissolved nitrogen (Figure 21).

RESULTS AND CONCLUSIONS

From Table 4, it is clear that the lower reaches of Honokowai Stream discharge significantly higher nitrogen and TSS than the upper reaches of the stream. Particulate phosphorus and dissolved nitrogen appear to a slightly lesser degree than particulate nitrogen, while dissolved phosphorus (as a pollutant) appears negligible.

Difficulties arise in extending the measured and calculated results of this study to all of the streams in the Lahaina District. Figures 19-21 show that substantial variability exists just between Honokahua and Honokowai Streams. The variability both within each stream (evident from the scatter in concentration-discharge curves) and among streams makes it difficult to estimate "typical" loading rates for the district. The very limited data set available for this analysis (<30 samples for any constituent in any stream) reduces confidence in these results. Further, the sample collection period coincides with an atypically low rainfall year (Figure 22). Constituent loading is influenced by land use practices but is also controlled by natural spatial and temporal variations in rainfall intensity, soil types, topography and vegetative cover. Thus to accurately describe the total loads emanating from all streams in the area, each stream would have to be monitored and samples analyzed for a variety of flow rates and storm events. This type of investigation is, unfortunately, beyond the resources and time

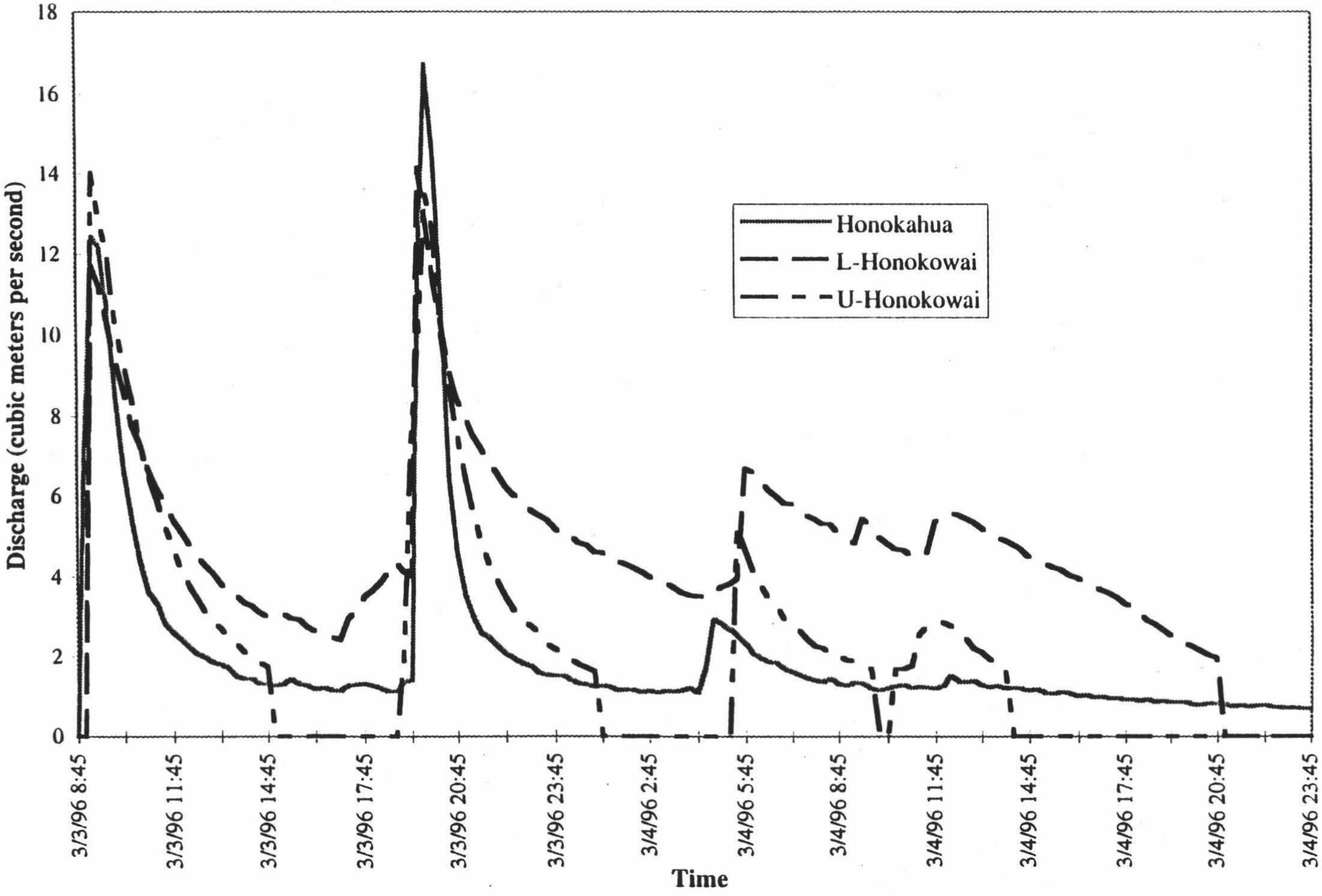


Figure 18. Hydrographs from the Storm of 3/3-3/4/96

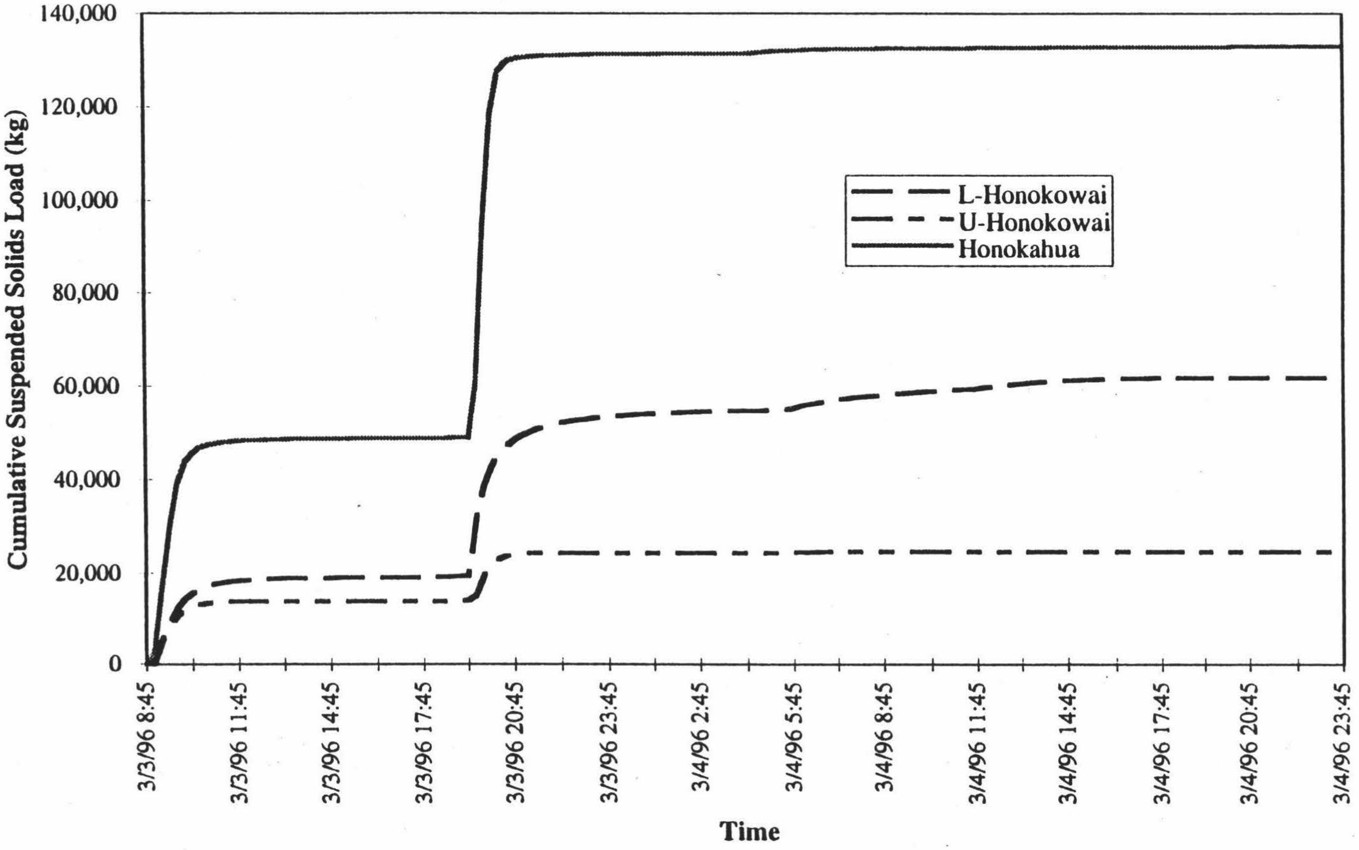


Figure 19. Total Suspended Solids Loading during 3/3-3/4/96 Storm.

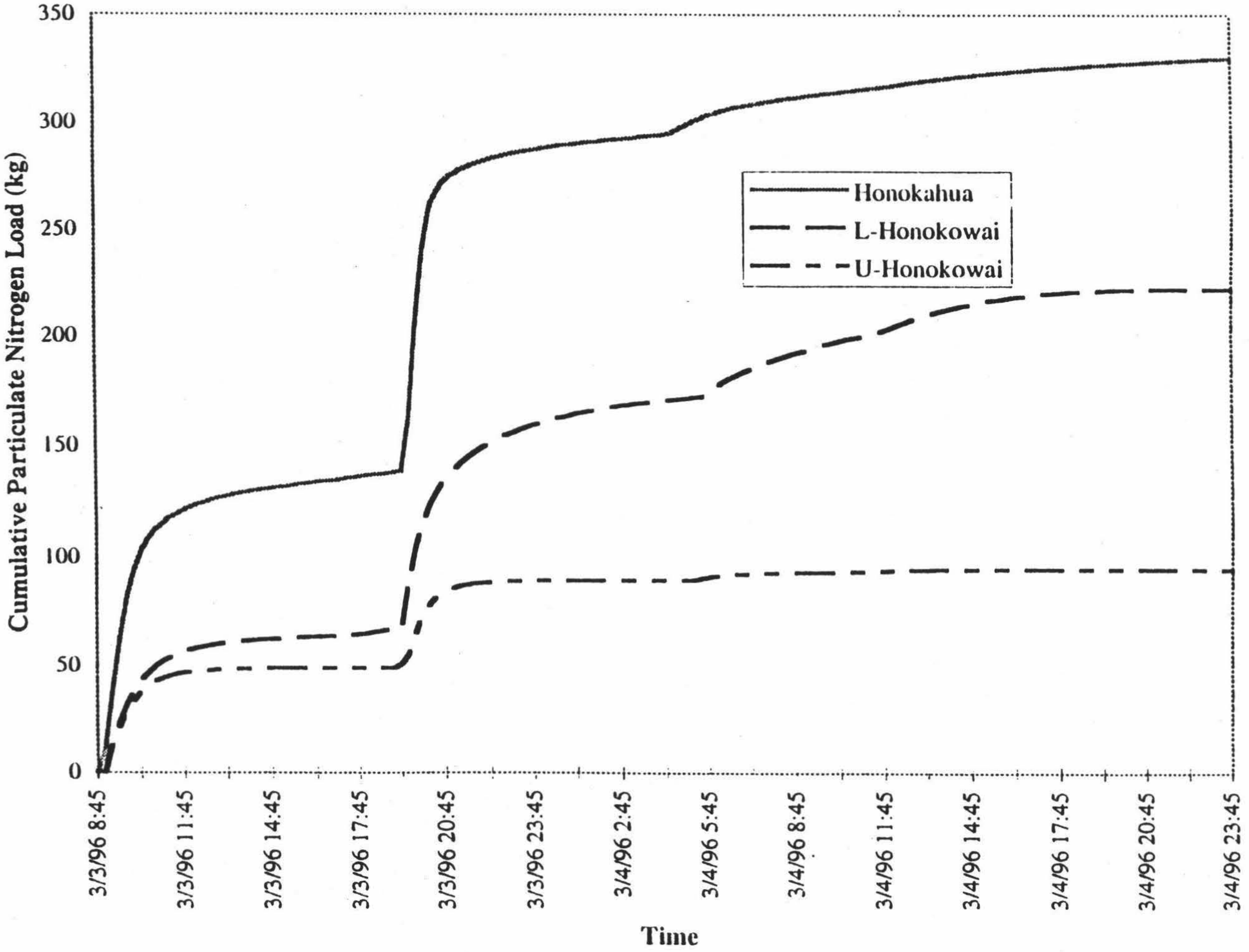


Figure 20. Particulate Nitrogen Loading during 3/3-3/4/96 Storm.

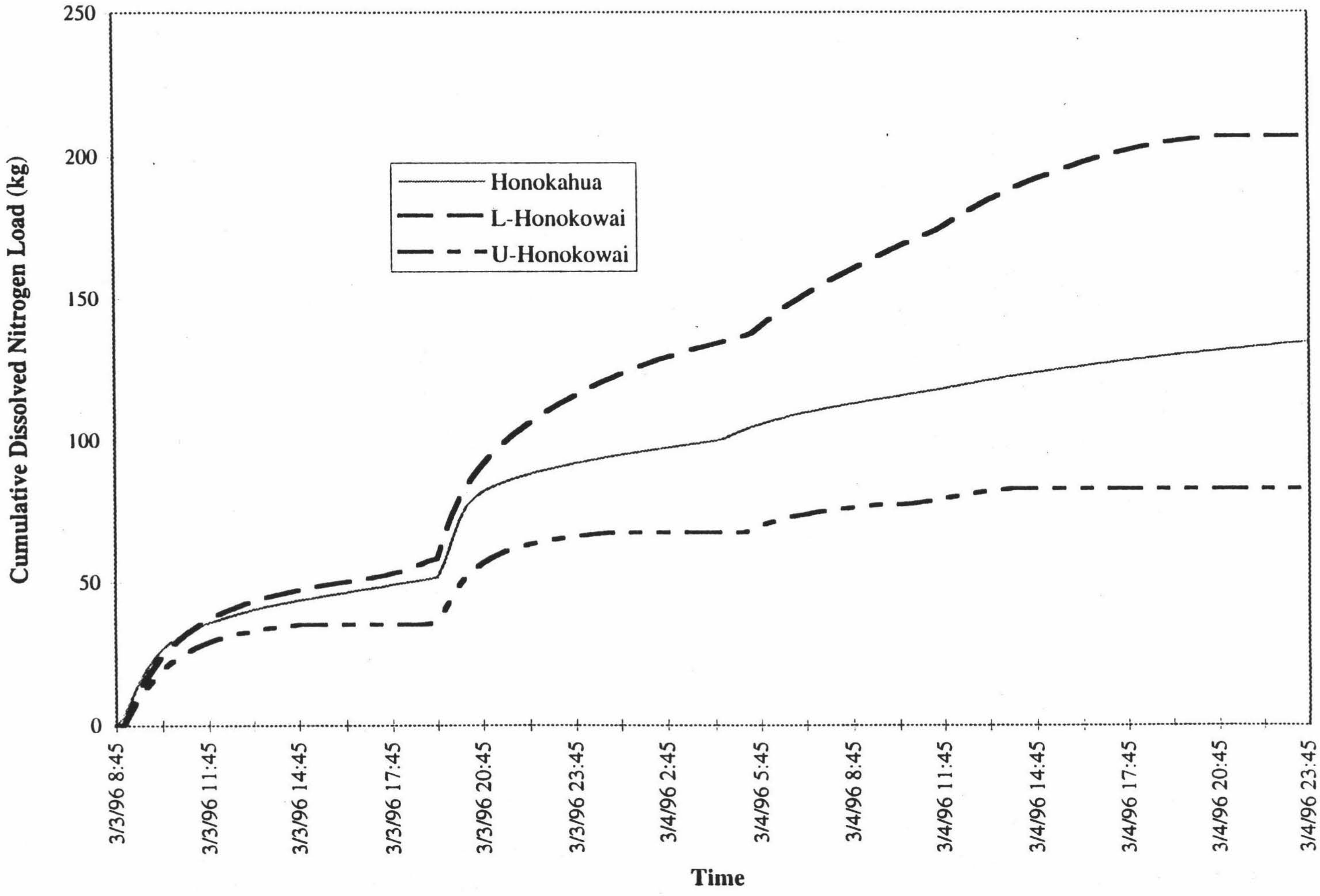


Figure 21. Dissolved Nitrogen Loading during 3/3-3/4/96 Storm.

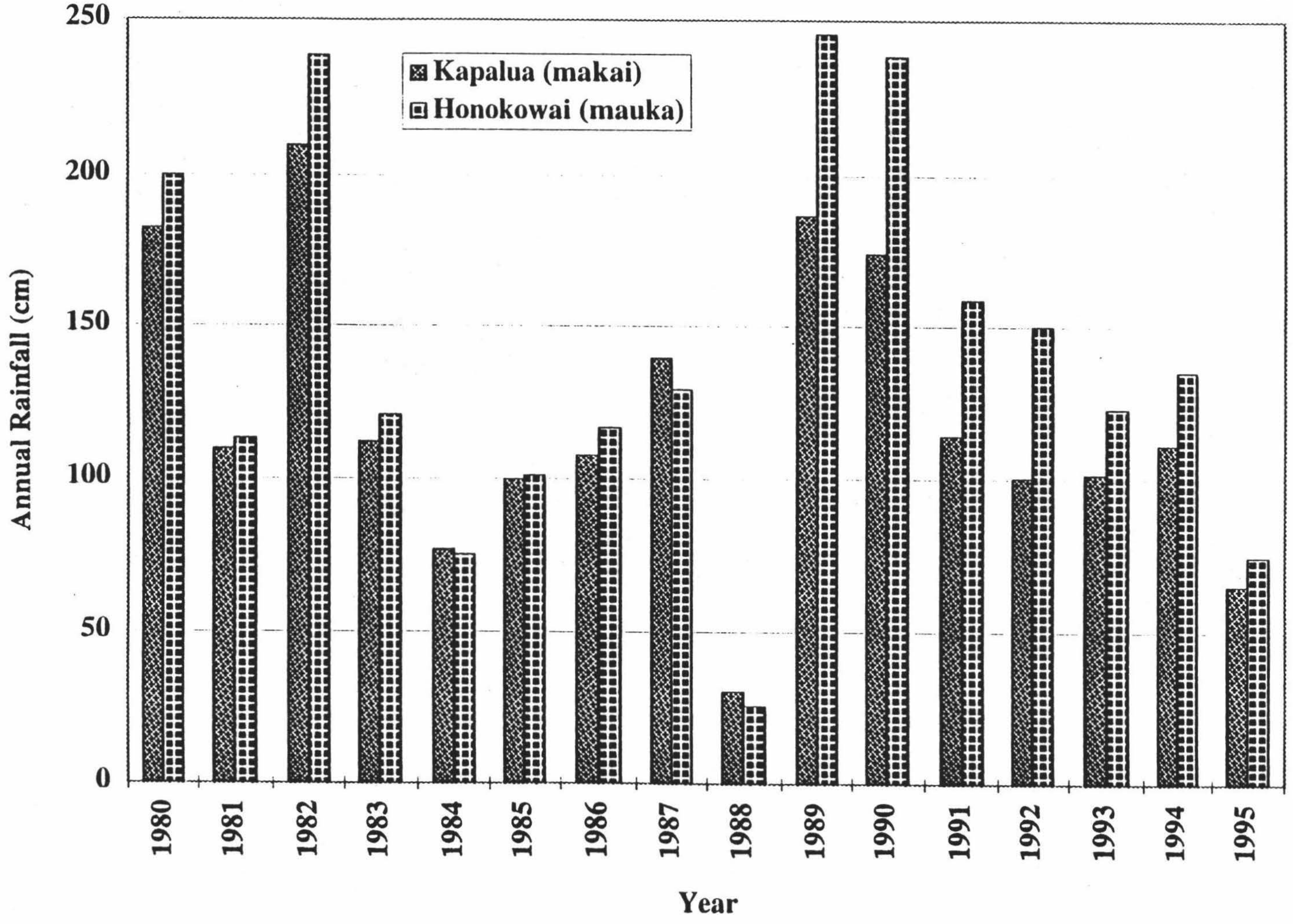


Figure 22. Annual Rainfall at Two West Maui Locations.

frame of this study.

Making the very crude assumption that Honokowai Stream is representative of the eight major streams in the region, total loads of roughly 50,000 kg of PN, 25,000 kg of TDN, and 30,000 metric tons of TSS were discharged over most of the 1994-96 winters. This estimated sediment load is agreeable with the Soil Conservation Service calculation of 5,100 metric tons per year for the Lahaina Watershed (USSCS, 1992), which contains 511 hectares of cane fields (compared with 2,500 hectares total in the area). Important to note is that stream discharge is mostly from individual, intense storms which temporarily inundate the coastal waters with nutrients and sediment. During especially wet winters, closely spaced storms are capable of providing extensive quantities of nutrients and sediment to localized areas in the coastal waters.

CHAPTER III. WATER IN THE SUBSURFACE

INTRODUCTION

This chapter deals with the fate and transport of nutrients in the subsurface. Infiltrated water from fertilized agricultural fields and injected sewage effluent provide anthropogenic sources of nutrients to the groundwater body, which ultimately discharges to the sea. Tracing the water along its flow path allows for the quantification of this nutrient source and is used to assess its significance in contributing to overall coastal water nutrient loading.

The conceptual framework for West Maui subsurface hydrology is illustrated in Figure 23. The basal lens is recharged in two ways, by percolation from the land surface above the lens and through leakage of trapped water from the dike complex. The first process involves the infiltration of rainfall and irrigation water into the soil. That water which leaches past the plant roots flows through the unsaturated zone of soil and rock until it reaches the groundwater body. Any dissolved nitrates in the leaching water are assumed to ultimately reach the groundwater lens. Leakage from the dike complex provides substantial quantities of "clean" water (natural, low background nitrate concentrations) to the basal lens.

This chapter first deals with unsaturated flow and transport and the mechanisms controlling infiltration from the land surface to the groundwater body. This water is then traced through the saturated zone to its eventual discharge into the sea. An areal groundwater model is developed to simulate contaminant transport while a cross sectional model is developed to help characterize the physical nature of the density dependent basal lens flow regime. A section on wastewater injection below the basal lens is also included here as this represents a subsurface nutrient source which ultimately reaches the coastal waters.

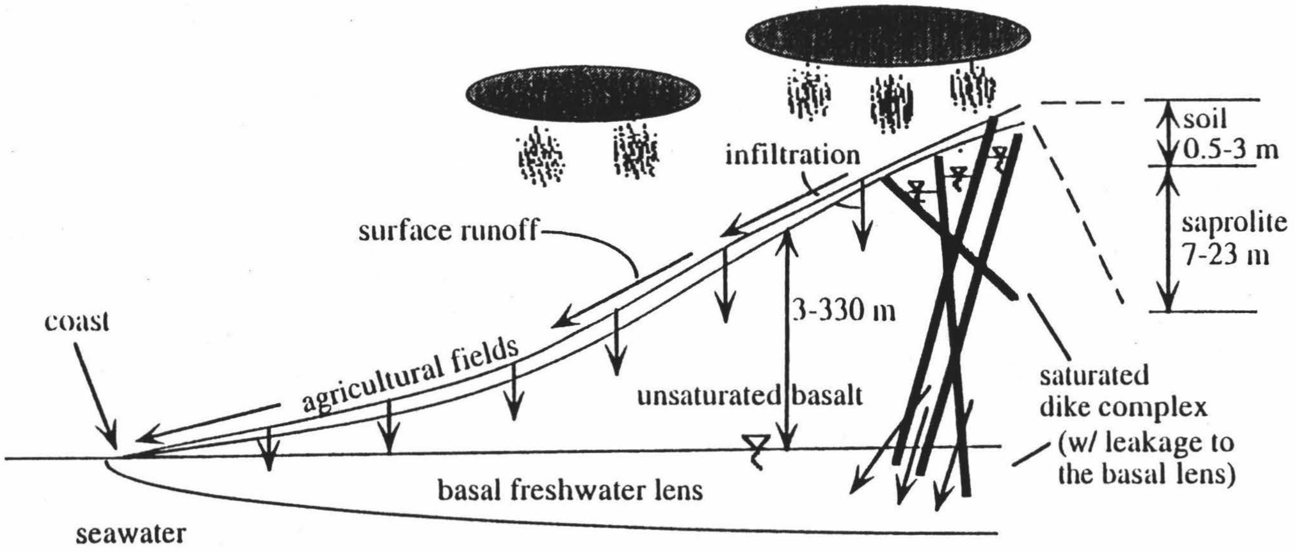


Figure 23. Cartoon of West Maui Hydrology.

UNSATURATED ZONE

As presented in Chapter I, the extremely complex nature of flow in the unsaturated zone makes mathematical representation of various flow and transport properties very difficult without extensive site specific field data. Unfortunately, such data do not exist for the Lahaina District and calibration techniques with groundwater models were used to estimate chemical contributions from the unsaturated zone. Establishing the quantity (or concentration) of nitrates leaving the root zone does not supply all of the necessary information for determining the source of nitrates found in groundwater. To decipher the history of groundwater nitrates one needs to consider the amount of time it takes for chemicals on the land surface to arrive at the groundwater body. Combining quantity and timing allows for a reconstruction of groundwater nitrate history and the land use practices which contribute to their existence. Nitrate travel time estimates are discussed in detail below.

Water quantities percolating through the unsaturated zone were estimated with a monthly water balance analysis provided by the USGS (Shade, personal communication). Based on the methods of Giambelluca (1983), this water balance modeling partitions rainfall into three categories: surface runoff, evapotranspiration, and through flow (which represents water leaving the plant root zone, all of which is assumed to recharge the groundwater body). In areas of irrigated agriculture (namely sugar and pineapple) irrigation water is combined with rainfall as the input water term. Surface runoff is estimated through consideration of land slope and soil type, while evapotranspiration is estimated according to radiation intensity and vegetative cover. The recharge term deduced from this analysis is thought to carry dissolved nitrates to the groundwater. Left for estimation then is the travel time of a chemical in the unsaturated zone.

Travel Time

The travel time of a constituent in the vadose zone here refers to the amount of time the chemical spends in the subsurface before reaching the groundwater table. For a conservative substance (such as nitrate is here assumed) this time can be estimated from the following equation (Orr, 1987):

$$\tau = \frac{\theta \cdot z}{R} \tag{3.1}$$

where:
θ = average water content [L^3/L^3]
z = thickness of the unsaturated zone [L]
R = average annual recharge [L/T]
τ = travel time [T].

To estimate maximum nitrate travel times on West Maui, calculations were performed for fields at elevations of 305 meters. From the USGS water balance analysis an average annual recharge rate of 2.0 m/yr under furrow irrigation and 1.1 m/yr under drip irrigation of sugarcane were estimated.

Water contents for the various subsurface materials are uncertain and vary tremendously over short periods of time, yet can be considered to reach a steady state over long time periods. Miller (1988) provides analyses of hydrologic properties of unsaturated materials on Oahu in relation to pesticide transport to groundwater. Three general zones exist in the subsurface, as shown in Figure 23. Well logs from drilling projects in the upper reaches of the Maui sugarcane fields (provided by the CWRM) lack descriptive detail and report saprolite and soil zones ranging from 7.3 to 21.3 meters thick. The uppermost soil zone is relatively thin and has properties generally conducive to water flow. Underlying this is a zone of saprolite, weathered in-place basalt, which retains original structure with much of its bulk weathered away. As rainwater infiltrates through the upper reaches of the unsaturated zone, mineral transformations occur as certain cations are removed and new minerals form, which ultimately increases porosity

(Miller, 1988). As the water continues to percolate, it becomes saturated with respect to the dissolved species and is no longer effective in reacting with minerals in the rock. As a result, porosity may be very high near the surface and decreases with depth. Miller found porosity in the soil and saprolite ranging from 0.455 to 0.721, with (on average) half the porosity comprising interconnected pores which contribute to effective porosity.

Those pores not contributing to effective porosity are known as micropores, which result from the formation of clay mineral aggregates. These micropores are sufficiently small to retain water within the aggregates while vertical flow continues in the surrounding macropores between aggregates (Green and Young, 1970). Thus the water entering these aggregates (together with its dissolved load) may remain bound in the soil for long times, until favorable conditions arise for its mobilization. This mechanism may allow dissolved (and adsorbed) chemicals to remain in the soil for long periods before resuming their paths toward the groundwater. This qualitative description suggests that calculated travel times only represent the time in which some chemicals reach the groundwater, while other constituents may remain bound in the soil, providing a source of contaminants long after the initial application of chemicals on the surface.

Volumetric water content, θ, is defined as the ratio of water volume in the medium to the total volume of the medium. At saturation, then, water content is equal to porosity. Miller (1988) shows that the percent of saturation in the soil column shows large temporal variations near the surface, but generally remains high at depth (up to 100%). Thus, as a conservative estimate, water contents are assumed to be equal to the effective porosity in this analysis. Assuming $\theta_{(soil+saprolite)} = 0.45$, and $\theta_{(basalt)} = 0.03$ (Orr, 1987), and saprolite thickness z_s=15 meters,

$$\tau_{drip} = (.45\ (15m)+.03\ (290\ m))\ /\ 1.1 m/yr = 14.0 \text{ years}$$

$$\tau_{furrow} = (.45\ (15m)+.03\ (290m))\ /\ 2.0 m/yr = 7.7 \text{ years}$$

Travel times for fields at lower elevations (especially those near sea level) may be on the order of days during periods of heavy rainfall or irrigation. The above calculations show that nitrates may be introduced into the aquifer 15 years after their application on the surface. These calculations ignore the aggregated structure of the soil (discussed above), which may lengthen (or shorten in the case of macropores) this time considerably.

The shorter travel time calculated under furrow irrigation may help explain the temporal variations in concentration presented by Tenorio (1971)(see Chapter I, Previous Investigations). The greater quantities of water leaking to groundwater under furrow irrigation allowed for faster movement of water through the unsaturated zone (as unsaturated hydraulic conductivity increases with water content). Thus, defined plumes of nitrate laden water entered the aquifer as sharp pulses, creating zones of high concentration nitrates in the aquifer. Under drip irrigation, however, the water, on average, moves more slowly through the unsaturated zone, which effectively spreads out the nitrate plume. The distribution of recharge water thus becomes more uniform and enters the aquifer with a steadier nitrate concentration. This leads to a more uniform distribution of nitrates in the aquifer over time, as was found during the current sampling program (with concentrations in the aquifer under drip irrigation slightly lower than those measured under furrow irrigation).

While the above discussion on unsaturated flow and transport does not provide specific predictions or estimations of nitrate leaching rates, it is included to address qualitatively the influences governing the phenomena. An understanding of the complexity of vadose zone hydrology affirms the practicality of using groundwater model calibration with measured groundwater nitrate concentrations in this study. Development of unsaturated zone models for West Maui without site specific data for calibration would lack meaning and uniqueness, especially in light of the extreme variability of nitrate leaching presented by other workers (described in Chapter I). This discussion is therefore intended simply to provide a conceptual basis for connecting nitrates in the groundwater with their origin on the land surface.

SATURATED ZONE

The ultimate goal of this section is to estimate the subsurface contribution of nutrients to the West Maui coastal waters. To achieve this goal, groundwater flow and transport models are developed to simulate nutrient transport from their points of entry in the groundwater body to their discharge at the sea. Properly modeling groundwater flow and transport in the Lahaina District is best achieved using three dimensional models which integrate density dependent flow with the transport of a second solute. Such codes exist but are extremely cumbersome to use and require spatially extensive data. Simplifications are therefore necessary to reduce the complex system to a more manageable state.

The most common of these assumptions is to approximate the aquifer as a two-dimensional areal system, with water flowing essentially in the horizontal plane. Using this approach, the boundary of the West Maui model was drawn along the coastline and the quantity of nutrients leaving the model domain corresponds with nutrient discharge to the sea. To examine the contribution of nutrients from different land uses, simulations are run individually for each land use (i.e. input of nitrates is limited to areas under pineapple cultivation when simulating the effects of pineapple fertilization on groundwater quality). Previously measured groundwater nutrient levels and heads as well as samples analyzed for this study are used to calibrate the models. To incorporate the influences of density variations and vertical flow components, a two dimensional cross sectional model is developed to aid in estimating the physical structure and velocity profile of the aquifer, and to provide input and calibration parameters for a two dimensional areal model.

CROSS SECTIONAL MODELING

Theory

The source code SUTRA (Voss, 1984) is used for the cross-sectional modeling because of its ability to simulate density dependent flow in cross section. SUTRA is a two dimensional finite element model which solves the fluid mass balance equation coupled with the following solute mass balance equation (Souza and Voss, 1987):

$$n\rho\frac{\partial C}{\partial t} + n\rho V \bullet \nabla C - \nabla \bullet \left[n\rho(D_m I + D) \bullet \nabla C \right] = Qp(C^* - C) \tag{3.2}$$

where C = solute concentration [M/L^3]
n = aquifer porosity[L^3/L^3]
V = fluid velocity [L/T]
D_m = molecular diffusivity [L^2/T]
I = identity tensor
D = dispersion tensor [L^2/T]
Q_p = fluid mass source [L^3/T]
C^* = concentration of solute [M/L^3]
ρ = fluid density [M/L^3]
t = time [T]

Darcy's Law is used to yield the mass-average fluid velocity term:

$$V = -\left(\frac{k}{n \cdot \mu}\right) \cdot (\nabla p - \rho g) \tag{3.3}$$

where k is the aquifer permeability [L^2], μ is the fluid viscosity [$M/L \cdot T$], g is gravitational acceleration [L/T^2], p is the fluid pressure [$M/L \cdot T^2$], with others as defined above. These equations require the solution of two coupled equations to produce three variables: pressure, density, and concentration. Assuming density is a linear function of concentration:

$$\rho = \rho_o + \frac{\partial \rho}{\partial C}(C - C_o) \tag{3.4}$$

the fluid pressures and concentrations are solved for at each time step at each node, thereby reducing the number of unknowns to two.

Mesh Construction and Boundary Conditions

The cross sectional model is developed for a vertical slice of aquifer just south of Honokowai Stream (A-A' in Figure 7). This region is chosen for its central location in the study area and for its proximity to the wastewater injection wells. Further, some head data exist along the section allowing for limited calibration of the flow model. Figure 24 shows the finite element mesh used for these numerical simulations. Vertical spacing of two meters is used in the top portion of the grid which contains the freshwater. Below 90 meters, the vertical spacing increases to 5, 20, and 100 meters for a total vertical depth below sea level of 500 meters. Similarly, the horizontal spacing is smallest near the coast (12.5 meters) and largest inland (100 meters). Fine spacing is especially critical near the coast, near areas of pumping or injection of water and near the transition zone, where gradients are steepest. The third dimension (in which complete mixing is assumed) is arbitrarily assigned a thickness of one meter.

The boundary conditions for the simulations are shown in Figure 24. The types of boundaries include recharge, no flow, and constant pressure. Recharge to the aquifer was estimated from the USGS water balance analysis and includes dike water leakage to the basal lens (input through the top 20 meters of the mauka boundary) and

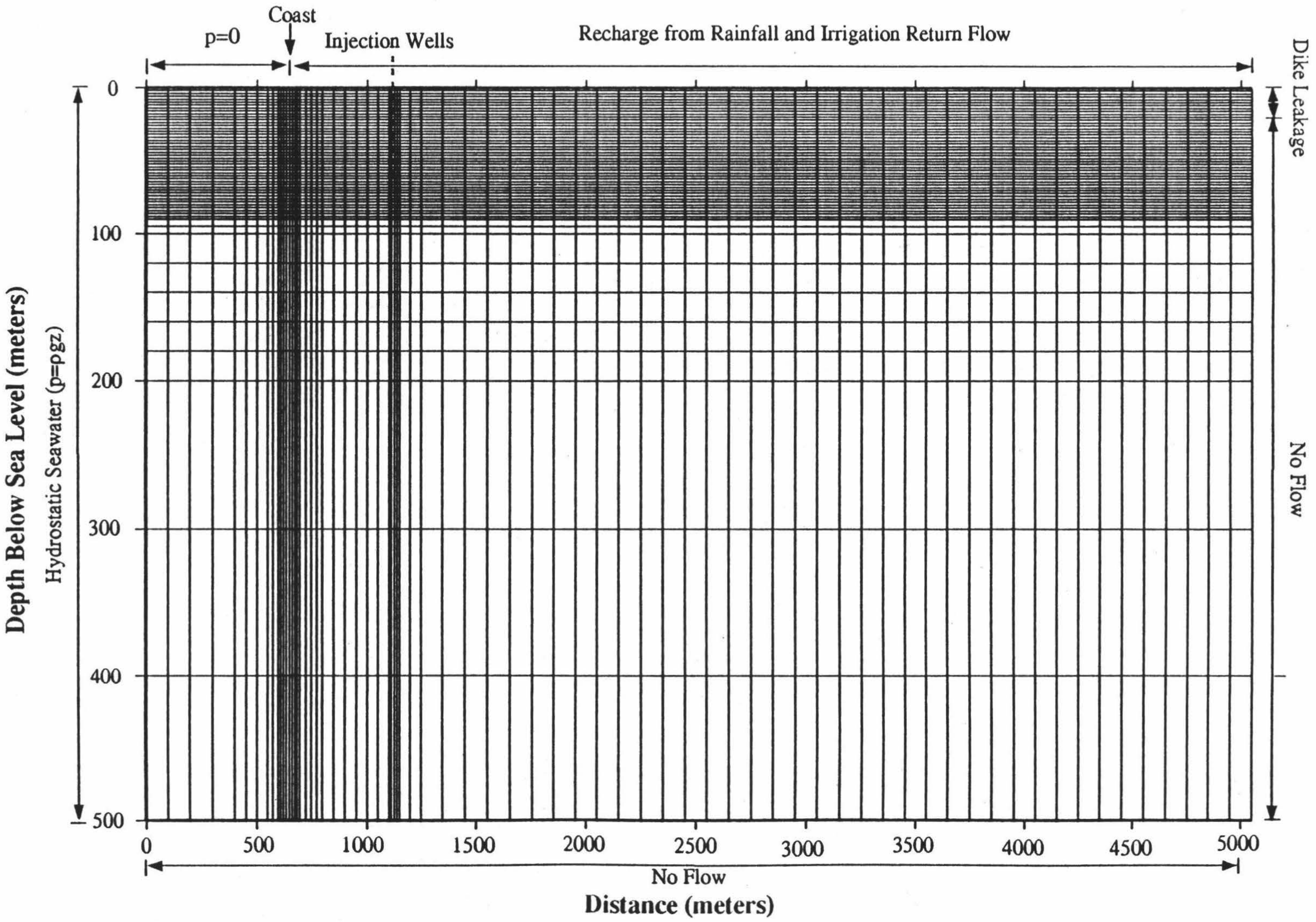


Figure 24. Mesh for Vertical Finite Element Groundwater Simulation.

recharge from irrigation and rainfall above the basal lens. The seaward boundary is held at hydrostatic seawater pressure and concentration, as are the westernmost 600 meters of the top boundary (which represents the ocean surface). All other boundaries permit no-flow.

Modeling Methodology and Calibration

Density dependence of the flow and transport regime requires that transient simulations are always run. An initially salt water domain is recharged with freshwater until a freshwater lens developed. The stable, steady state freshwater lens then becomes the starting point of all subsequent simulations. Each run lasts 4,000 time steps at an interval of two days per time step, which is sufficient to reach a steady state (roughly 22 years).

Calibration of the model is extremely difficult given the severe lack of data. General head gradients are known, but aquifer thickness and the thickness of the transition zone are poorly known. Thus sensitivity analyses plays a crucial role in constraining parameter estimation. The recharge estimated from the water balance analysis is not varied in the simulations. It is instead held constant, reducing the number of unknowns and allowing for greater constraint in estimating the other unknown parameters. This is assumed valid since the water balance modeling provides the best known method of determining groundwater recharge and has been found successful in previous studies (Giambelluca, 1983). Other parameters are determined as described below.

Permeability

Various horizontal hydraulic conductivities for Hawaiian basalt have been reported, with values ranging from 150 to 1,250 m/day (Williams and Soroos, 1973, Mink, 1977). Simulations within this range are run, showing that horizontal permeability controls the thickness of the resulting freshwater lens (lower permeability yields a thicker lens). Heads and aquifer thickness are used to analyze the results. Documented groundwater heads in the area are very limited, with each well having been measured at a different time. Recent measurements at two wells, however (one near the coast (5641-01) and one near the mauka boundary (5539-01), both without pumping effects), show heads of one meter near the coast and two meters near the mauka boundary. Other, older measurements support maximum heads of two to two and one half meters at the mauka boundary and thirty centimeters to one meter near the coast. Table 5 provides a list of calibrated parameter estimates for the cross sectional modeling.

A horizontal conductivity of 700 m/d yields an aquifer roughly 75 meters thick with a corresponding head nearly two meters at the mauka boundary (Figure 25). Assuming the Ghyben-Herzberg approximation (thickness = 40*head) is valid in the interior reaches of the aquifer, heads of two meters would correspond with an aquifer roughly 80 meters thick, adding confidence to the model results. Increasing permeabilities decreases both the head and thickness of the aquifer. Decreasing permeability restricts the flow of water, allowing pressure in the aquifer build.

Simulations are run to determine the effect of anisotropy on the shape of the freshwater lens. Anisotropy ratios of 50, 100, and 200 all yield similar results, but as the ratio is lowered to one (isotropic conditions), a freshwater lens does not develop and an extremely thick transition zone results. Thus, for the given simulation conditions (and as geologic conditions would suggest), the horizontal conductivity must be greater the vertical conductivity.

Dispersivity

Various longitudinal and transverse dispersivity values are used to determine their role in shaping the freshwater lens. Lack of field measured dispersivity in Hawaiian basalt leaves these parameters to be fitted during calibration. Since flow lines generally run parallel to chloride isochlors, longitudinal dispersivity does not have a

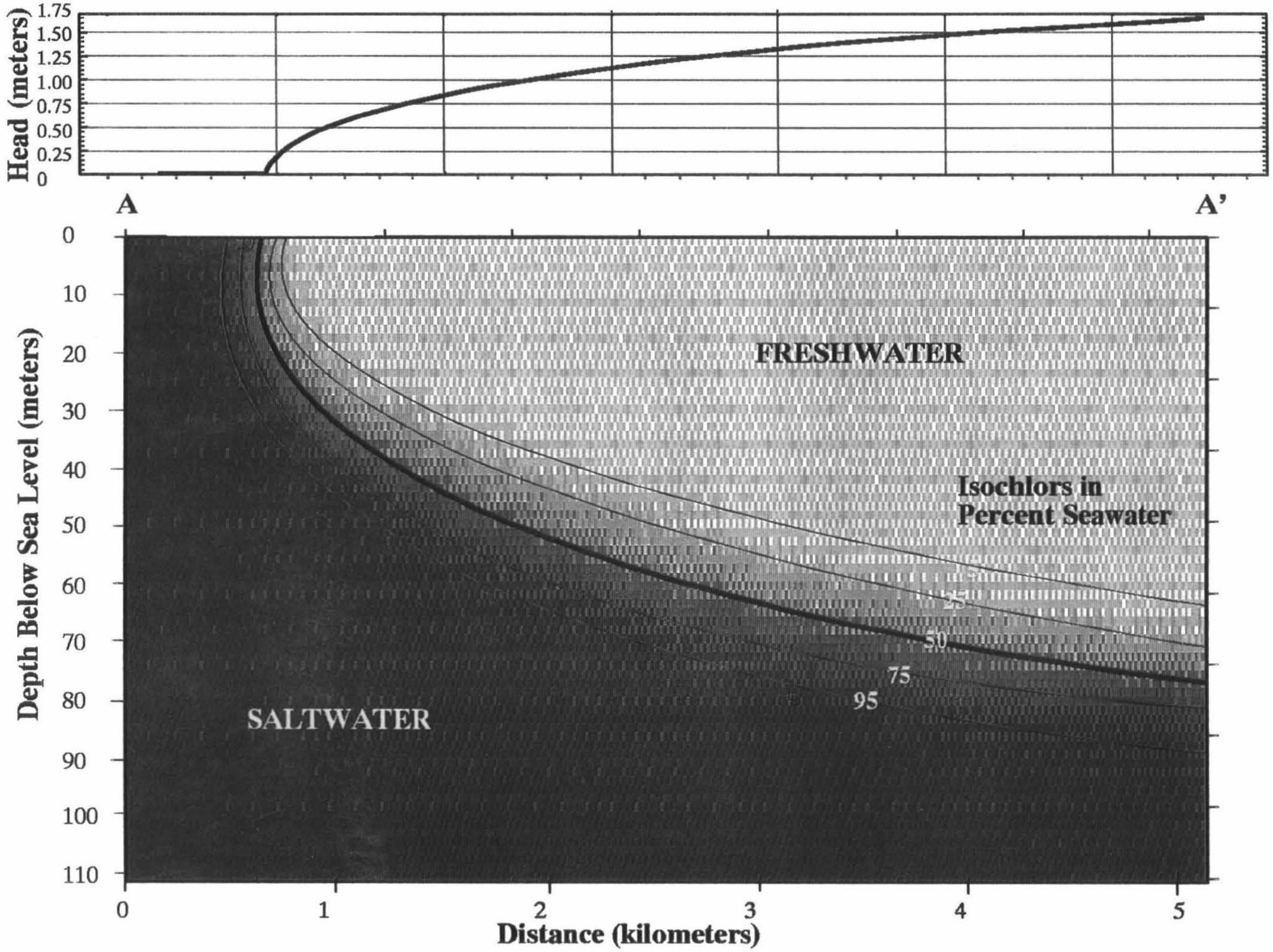


Figure 25. Simulated Freshwater Lens and Associated Head Distribution.

significant effect on the lens (Souza and Voss, 1987). Values of 20, 50, and 80 meters all yield similar results. Transverse dispersivity, on the other hand, is dominantly responsible for controlling the thickness of the transition zone. Unfortunately, only wells close to the coast (the wastewater injection wells) penetrate the transition zone, showing thicknesses of 30 to 40 meters. Simulations with transverse dispersivities of two, five, and ten centimeters (holding all other parameters constant) are run with resulting transition zone thicknesses of roughly 15, 34, and 50 meters, respectively. While the transition zone thickness varies greatly with the transverse dispersivity, the location of the 50% isochlor (which, for this study, defines the bottom of the aquifer) does not significantly change among simulations. Thus, for the purposes of estimating aquifer thicknesses, dispersivity does not play an important role.

TABLE 5

Calibration Parameters for Cross Sectional Aquifer Modeling

Parameter	Range	Best Model
Horizontal Hydraulic Conductivity (Kh) [m/d]	100 to 1,220	700
Anisotropy Ratio (Kh/Kv)	1 to 200	<10
Longitudinal Dispersivity [m]	10 to 200	all
Transverse Dispersivity [cm]	0 to 50	all
Porosity [%]	5 to 20	all

Other Parameters

The effect of varying porosity within the range of 5 to 15 percent is found to be negligible with respect to the shape of the lens but alters the velocity profile according to Equation (3.3). SUTRA allows for anisotropic longitudinal dispersivity, applying different dispersivity in the maximum and minimum permeability directions. Using anisotropic dispersivity does not show any appreciable difference among the resulting lenses. This insensitivity to other parameters adds confidence to the conclusions drawn above.

Cross Sectional Modeling Results and Conclusions

The cross sectional modeling results show that the thickness of the freshwater lens is dominantly controlled by the permeability of the rocks. The lack of dependence on various other parameters within reasonable ranges and the simulated near horizontal flow paths of freshwater in the inland reaches of the aquifer add confidence to the use a two dimensional areal model which neglects density influences on freshwater flow. Since the Ghyben-Herzberg relationship does not hold near the coast, the cross sectional modeling also provides a more accurate picture of the aquifer thickness, which is used in the two dimensional areal modeling. Finally, calibrated vertical profile modeling results yield estimates of aquifer properties, which aid in assessing the reasonableness of calibrated areal model aquifer parameters.

WASTEWATER INJECTION

The Lahaina Wastewater Reclamation Facility (LWRF) consists of two plants working in parallel, the 1985 plant extending the capacity of the original 1975 plant. Secondary treated wastewater is injected into the subsurface at a depth of approximately 61 meters below sea level and 610 meters from the coast. The injection depth, shown in Figure 26, releases the effluent into saltwater approximately 30 meters below the 50% isochlor of the simulated freshwater lens. Injection is through four 51 centimeter diameter wells roughly 180 meters south of Honokowai Stream.

Table 1 summarizes the injection rates and chemical concentrations of the effluent. While injection rates and effluent concentrations have varied over time, average annual loading rates of total dissolved nitrogen and phosphorus to the subsurface were calculated using average, 1990-1991 flows and concentrations as follows:

$$M = C * Q \tag{3.5}$$

where M = average nutrient loading rate [M/T]
C = average effluent nutrient concentration [M/L^3]
Q = average injection rate [L^3/T]

Results of these calculations are shown in Table 6. Recent upgrades to the facility have reduced effluent concentrations substantially, also shown in Table 6.

Physical and numerical models have been developed to assess the fate of wastewater injected into the subsurface beneath a freshwater lens. In general, buoyant forces cause the injected wastewater to rise until it reaches the freshwater lens (with which it shares a similar density). Flow is then with the freshwater, ultimately discharging to the ocean. Discharge at the coast likely occurs near the fresh/saltwater boundary. Physical models developed by Williams (1977) and Heutmaker et al. (1977) and a numerical model by Wheatcraft (1978) show that the rate and depth of a resulting wastewater plume is dominantly controlled by the rate and depth of injection and the ambient flow regime in the freshwater lens. Williams (1977) shows that the greater the depth of injection, the farther upgradient (mauka) the plume will extend. This can be explained with the aid of the simulated seawater flow profile in Figure 26. As deep seawater flows inland, it rises, and changes course to flow toward the sea together with the overlying freshwater lens. The position of the injection well within this ambient saltwater flow regime controls the extent to which injected water will be "carried" upgradient. If the injection wells are located deep enough that they inject into seawater

TABLE 6

Lahaina Wastewater Reclamation Facility Nutrient Loading

Period	Facility	Annual Flow (cubic meters)	Mean N Conc. (mg/L)	Mean P Conc. (mg/L)	Total N Flux (kg/year)	Total P Flux (kg/year)
1989-1991	1975 Plant	2.26E+06	12.1	10.2	2.70E+04	2.30E+04
1989-1991	1985 Plant	4.60E+06	11.9	10.2	5.50E+04	4.70E+04
				Annual 89-91:	8.20E+04	7.00E+04
1995	Total	6.90E+06	5.7	1.7	3.90E+04	1.20E+04

flowing horizontally landward, the wastewater plume will flow farther inland. The extent to which the wastewater plume is brought upgradient partly controls the length of shoreline over which the plume ultimately discharges to the sea, as lateral dispersion of the plume is proportional to the length over which it flows. These models, while aiding in understanding the physics and controlling factors involved in wastewater injection in a vertical plane, do not provide site-specific quantitative results with which to estimate the three dimensional migratory pathway of the effluent plume.

Burnham et al. (1977) developed two and three dimensional flow models for wastewater injection at Kahalui, Maui. While a number of differences exist between that study and the Lahaina injection system (most notably the confined nature of the Kahalui aquifer due to a sedimentary caprock), ambient groundwater velocities are similar as are the depths of injection (51 meters below sea level in Kahalui). Results of that modeling effort may be cautiously applied to the Lahaina area. Modeling simulations show a maximum upgradient plume extending 300 meters inland and lateral migration of up to 550 meters on either side of the injection wells. Applying this simulated lateral spreading to the Lahaina system, and considering the effects of transverse spreading as the plume migrates toward the ocean, the injected effluent may be discharging along 1.6 kilometers of the coastline. Alternatively, the injected effluent may flow preferentially through lava tubes or clinker zones, thus discharging in higher concentrations at discreet locations along the coast. While the Kahalui analysis was based on extensive hydrogeologic field surveys in the vicinity of the injection wells, no data exist near the Lahaina injection wells as the County of Maui has not opted to monitor subsurface water quality in and around the injection sites.

Nutrients in injected wastewater effluent may be subject to transformation along their flow paths. Oberdorfer and Peterson (1982) found that some nitrates may degrade in the presence of algal biomass growing near the injection wells, and some may be

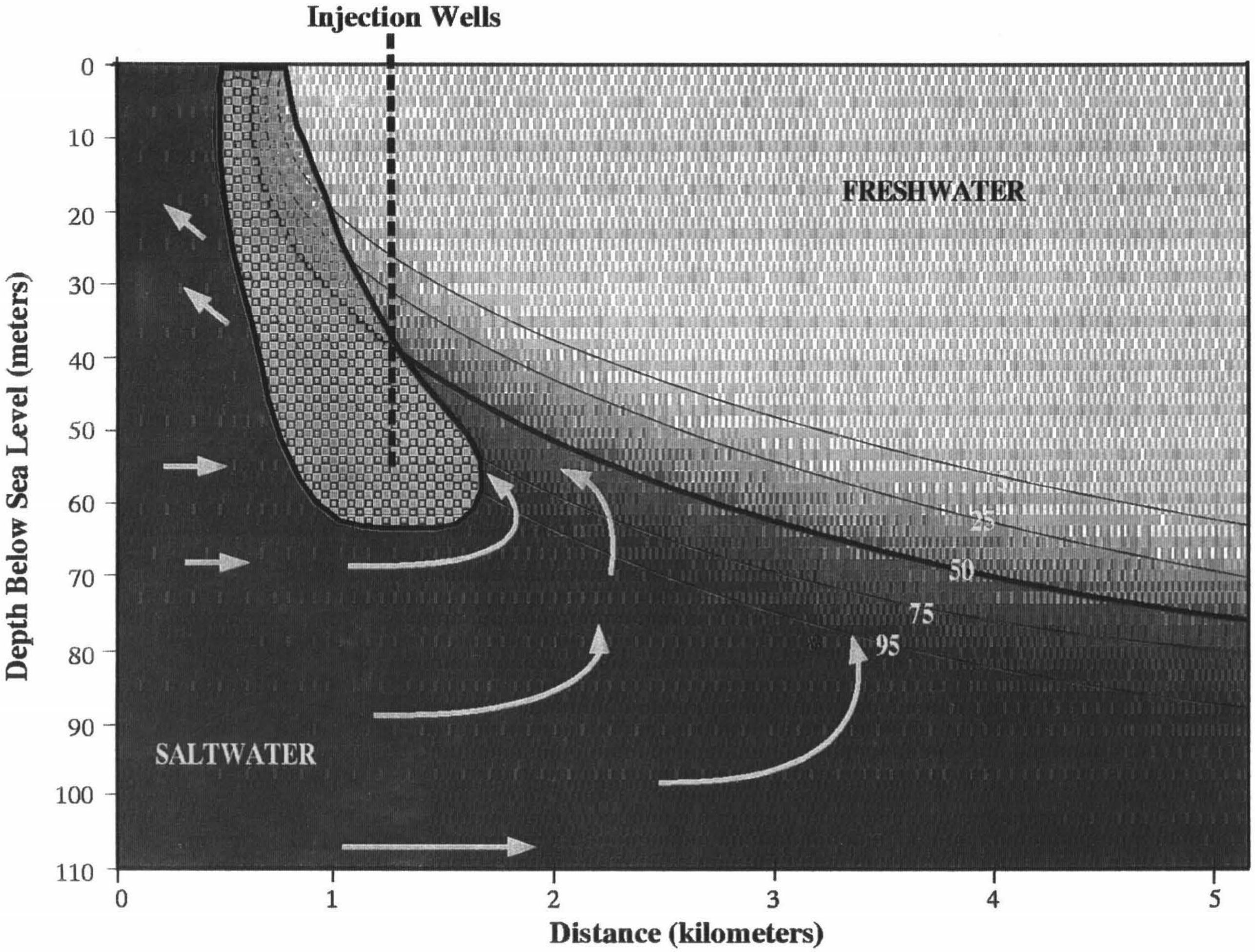


Figure 26. Schematic of Wastewater Injection Into Flowing Seawater.

converted to nitrogen gas by denitrifying bacteria. The study also found evidence that some dissolved phosphate may be adsorbed along its flow path. This observation did not hold at all locations, however, showing that adsorption of phosphates is not a uniform process. Due to the limited available data on these mechanisms and how they relate to the Lahaina injection facility, the "worst-case" assertion that all injected nutrients are available for ocean discharge is here assumed.

From the foregoing discussion, it is clear that a three dimensional model with the capacity to handle density dependent flow (for freshwater/saltwater dynamics) and the introduction of another fluid (injected wastewater) is necessary to accurately describe effluent migration in the subsurface. Both the model and the data necessary to calibrate such a model are not readily available for this study. Tetra Tech (1993) developed a two dimensional model to describe the flow of injected wastewater toward the sea. While their approach neglects most of the complexities of the real physical system (vertical flow, density dependence, upgradient migration, etc.), their results show that the wastewater plume may discharge along a 610 meter stretch of coastline. Preferential flow may also occur through lava tubes or clinker beds, thereby narrowing this zone of discharge. Without further detailed investigations, the actual nature of the zone of discharge will remain a mystery.

AREAL MODELING

Theory

Regional groundwater flow in the Lahaina District is simulated, in this study, using a recently updated version of the USGS Method of Characteristics (MOC) computer program. MOC is a two dimensional finite difference code which solves the following groundwater flow equation for head over time (Konikow and Bredehoeft, 1978):

$$\frac{\partial}{\partial x_i}\left(T_{ij}\frac{\partial h}{\partial x_j}\right) = S\frac{\partial h}{\partial t} + W \qquad i,j=1,2 \qquad (3.5)$$

where T_{ij} = transmissivity tensor $[L^2/T]$
h = hydraulic head [L]
S = storage coefficient
W = source or sink term [L/T]
x_i, x_j = coordinate directions [L]

Groundwater velocities are computed as follows:

$$V_i = \frac{K_{ij}}{n}\frac{\partial h}{\partial x_j} \qquad i,j=1,2 \qquad (3.6)$$

The solute transport equation is then solved to yield chemical concentrations in the flowing groundwater over time (Konikow, 1978):

$$\frac{\partial (Cb)}{\partial t} = \frac{\partial}{\partial x_i}\left(bD_{ij}\frac{\partial C}{\partial x_j}\right) - \frac{\partial}{\partial x_i}(bCV_i) - \frac{C\,W}{n} \qquad i,j=1,2 \qquad (3.7)$$

where D_{ij} = hydrodynamic dispersion tensor
b = saturated thickness of the aquifer
C' = concentration of recharge water

A number of simplifying assumptions are used in developing these governing equations. A critical evaluation of how these assumptions hold for the West Maui aquifers reveals the model's limitations. These include the following (Konikow, 1978):

[1]. Flow is justly approximated by Darcy's law, and viscosity, temperature, and density gradients do not significantly influence fluid flow.
[2]. Porosity is constant in time and space and hydraulic conductivity is constant in time.
[3]. Dispersion is dominated by advection and molecular diffusion is negligible.
[4]. Flow is essentially horizontal, and vertical variations in concentrations and heads are negligible.
[5]. Longitudinal and transverse dispersivity are homogeneous and isotropic properties with respect to the aquifer.

[1] generally holds for Hawaiian aquifers on a regional scale, as flow is laminar and the basalt aquifers can be considered as continuous porous media. Although some thermal water exists in the Olowalu region, thermal effects on regional flow are considered negligible as are viscous effects. Density certainly plays an important role in the existence of the freshwater lens, but does not drive flow within the freshwater. [2] does not strictly hold, for the aquifers are comprised of interlayered lava flows, ash flows, ash falls, and a host of other volcanic deposits, all with differing hydraulic and physical properties. Without detailed observations of the subsurface, however, only average porosity and hydraulic conductivity can be estimated. [3] is generally valid as West Maui groundwater moves quickly, allowing advective forces to dominate over diffusive effects.

[4] is the most difficult to justify for West Maui aquifers. As described previously, vertical flow components are significant near the coast, where the groundwater lens pinches out and discharges to the shallow coastal waters. Vertical variations in heads are probably only significant close to the coast (which drives the vertical component of flow), but vertical variations in nitrate concentrations may exist everywhere. The model assumes complete mixing of chemicals throughout the thickness of the aquifer, but in reality concentrations are likely highest in the top few meters of the aquifer (where agricultural recharge water enter the aquifer). Finally, [5] does not strictly hold due to the directional properties of the lava flows which make up the aquifers. As with [2], however, lack of detailed data necessitates the use of average, constant values for dispersivities. While these assumptions are required for the development of the governing equations, their existence must be noted when drawing conclusions from model results.

Mesh Construction and Boundary Conditions

Figure 27 shows the modeled portion of the Lahaina District aquifers discritized with rectangular elements in a sixty by sixty mesh (199 by 363 meters). Those elements falling outside the aquifer boundaries are assigned zero transmissivity and are effectively ignored in the calculations. The aquifers are considered homogeneous and anisotropic. The maximum conductivity direction is east-west, generally coinciding with lava flow directions in the area. The minimum conductivity direction is north-south, or perpendicular to lava flow directions. Specification of aquifer thickness increases gradually from 8 meters near the coast to a maximum of 76 meters at the mauka boundary. The values assigned are estimated from the cross sectional modeling. Table 7 shows the parameter estimates used in this analysis. Note that for the areal modeling, the longitudinal dispersivity is in the east-west direction and the transverse dispersivity is in the north-south direction. This is in contrast to the cross sectional modeling, where the longitudinal dispersivity is in the east-west direction, but the transverse dispersivity is in the vertical plane. The anisotropy directions parallel those described for dispersivity. Recharge from rainfall and irrigation return flow is provided by the USGS water balance analysis (Shade, personal communication).

The perimeter of the modeling area is specified with fixed parameters

TABLE 7

Calibration Parameters for Areal Aquifer Modeling

Parameter	Range	Best Model
Hydraulic Conductivity in E-W direction [m/d]	100 to 1,220	640
Conductivity Anisotropy Ratio (E-W/N-S)	1 to10	1.4
Porosity [%]	5 to 20	10
Longitudinal Dispersivity [m]	3 to 60	30
Transverse Dispersivity [m]	1 to 30	3

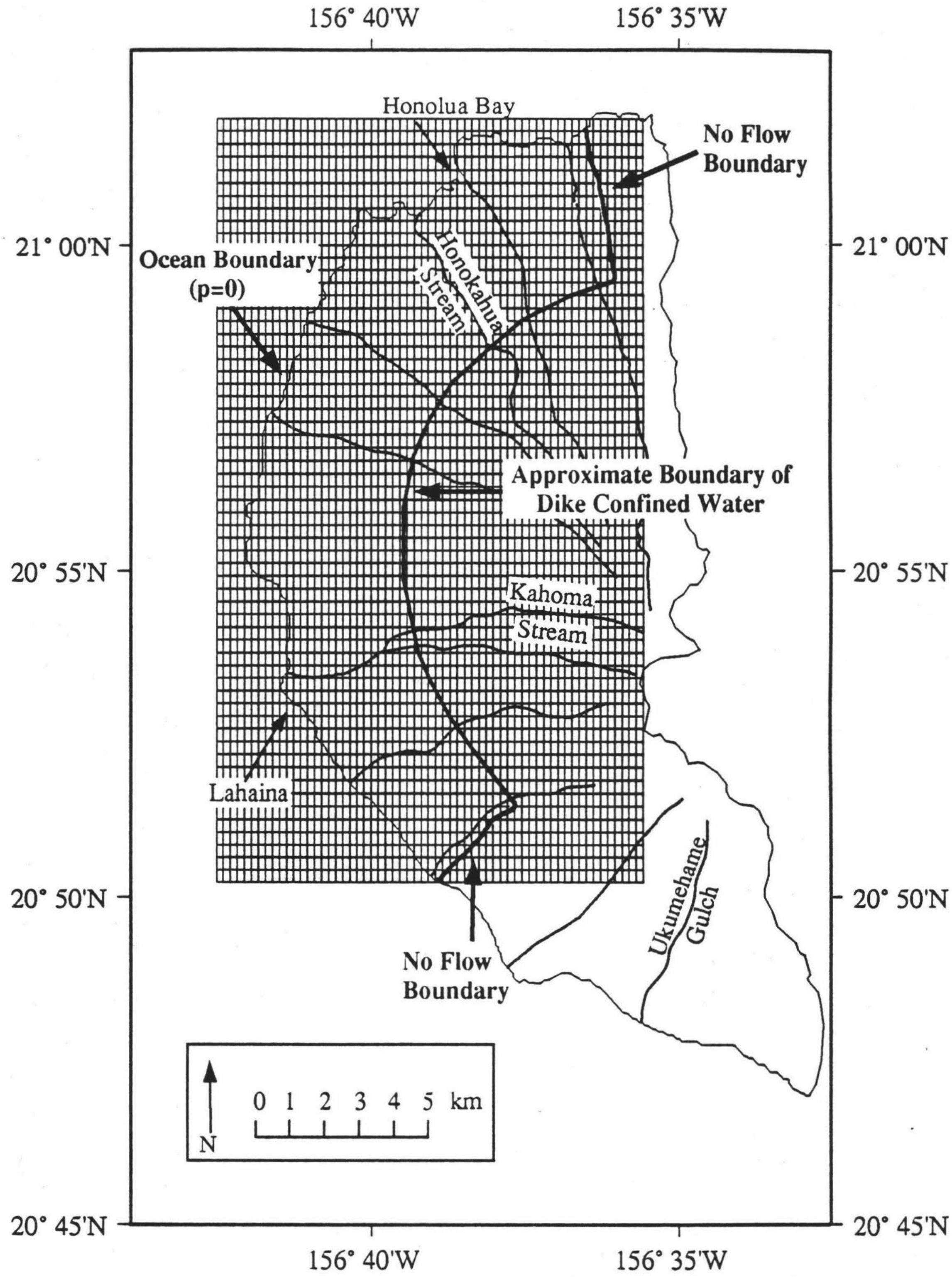


Figure 27. Mesh for Areal Groundwater Flow and Transport Model.

representing natural conditions. The mauka boundary is defined by the transition from the basal lens to dike confined high level water. Leakage from the dikes into the basal lens is estimated assuming steady state conditions in the dike water complex, that is, the volume of water in the dike system remains constant. Thus the amount of water leaving the dike zone is approximated by the amount of water entering the system (through recharge of rainfall). The recharge to the dike complex is provided by the USGS water balance analysis. Water leaves the dike complex in two modes, through leakage to the basal lens and as discharge to the streams (providing baseflow). Baseflow is estimated from Yamanaga and Huxel (1969) and the Maui County Water Use and Development Plan (M&E Pacific, 1991) and is removed from the total dike complex recharge to obtain the contribution of dike confined water leaking to the basal lens (25% from the high level regions 1 and 2 of Mink and Lau (1990) and 15% from Regions 3 and 4 (Figure 4)). The makai boundary for the area is held at zero head, representing the terminus of the basal lens, and the north and south ends are considered no-flow boundaries. The southern and northern boundaries correspond with the Olowalu and Honokohau Rift Zones, respectively. The northern boundary is placed inside the topographic hydrologic boundary because of difficulties in handling flow toward the north-northeast while the general flow direction for the rest of the model area is toward the west. Differences in recharge resulting from this discrepancy are incorporated into the analysis. Note that some sugarcane and pineapple fields (sugar: roughly 350 hectares in Olowalu; pineapple: approximately 194 hectares north of Honokohau Stream) do not fall within the boundaries of the model area.

Pumping Periods and Simulation Scenarios

The bulk of groundwater pumping in the Lahaina District has historically been for sugarcane cultivation. Records indicate an average pumping rate of 114.6 m^3/min between 1923 and 1978, during which time sugar was grown under the furrow irrigation method. A transition period ensued as the conversion from furrow to drip irrigation took place in the early to mid-1980s. The late 1980s and early 1990s have seen a significant decrease in pumping for sugarcane irrigation water and an increase in domestic water supply pumpage. Mean overall pumpage in the area was 46 m^3/min from 1986-1993.

Two pumping periods are simulated in this analysis. The first period spans 60 years, from 1920-1980, incorporating irrigation return flow and heavy groundwater drafts in the model. The second period spans 15 years from 1980 to present, with lower drip irrigation return flow, lower sugarcane groundwater pumpage, and an increase in domestic water supply pumping. Low pineapple irrigation rates (2.6 m^3/min) are incorporated into the recharge calculations. Groundwater flow is simulated as steady state while chemical transport calculations are run under transient conditions. Pumping period one (1) simulations begins with an initially nitrate-free aquifer (though background concentrations around 0.1 mg/L likely existed) and final concentrations from period (1) are used as initial conditions for period (2).

Model Calibration and Results

Groundwater heads in the late 1970s are used to calibrate the model for period (1) and present day heads are used for period (2). Calibration efforts for the flow model are coupled with matching the nitrate concentration distributions in the area. Data from Souza (1980) are used for period (1) and data collected from this study are used for period (2). Once a "best fit" model is achieved, sensitivity analyses are performed to test model dependence on various input parameters.

Period (1) simulations are able to match head and concentration data reasonably well. Figure 28 shows the steady state head distribution calculated for pumping period (1). The difficulties discussed earlier with regards to two-dimensional flow simulation near the coast are evident within a kilometer of the makai boundary, where simulated heads are consistently lower than measured heads. Nevertheless, these results represent conditions elsewhere in the aquifer reasonably well. Heavy drafts in the early days of sugar cultivation also add to the low heads near the coast. Pumping rates were so heavy that without reducing them slightly, the model consistently calculates negative heads. During this time period, sugar was also grown on fields currently under pineapple cultivation north of Honokowai Stream.

Recharge concentrations for sugarcane fields during this pumping period are deduced through model calibration with measured concentrations. Simulation of chemical input to the groundwater body is accomplished by introducing recharge water with a fixed nitrate concentration. The model only allows a constant input concentration. Thus, for example, when simulating chemical leaching under pineapple fields, all groundwater recharge from those fields are fixed with a constant concentration. This concentration represents an average, steady flow of chemicals into the aquifer, which is not truly representative of actual conditions since recharge waters likely contain higher concentrations immediately following fertilization. This is, unfortunately, an unavoidable model limitation. An input concentration of between 5 and 6 mg/L leaching past the root zone under sugarcane fields yields the closest match to the measured concentration distribution (Figure 29).

Period (2) simulated heads are calibrated with measured head data as seen in Figure 30. This head distribution looks similar to that of period (1) because dike water contributions remain unchanged between the pumping periods while return irrigation flow somewhat counters the heavier pumpage during period (1). Heads near the coast, however, rebound slightly during period (2).

Since present day concentrations in the aquifer are likely the combined result of past and present activities (discussed in the section on Travel Times), calibration of

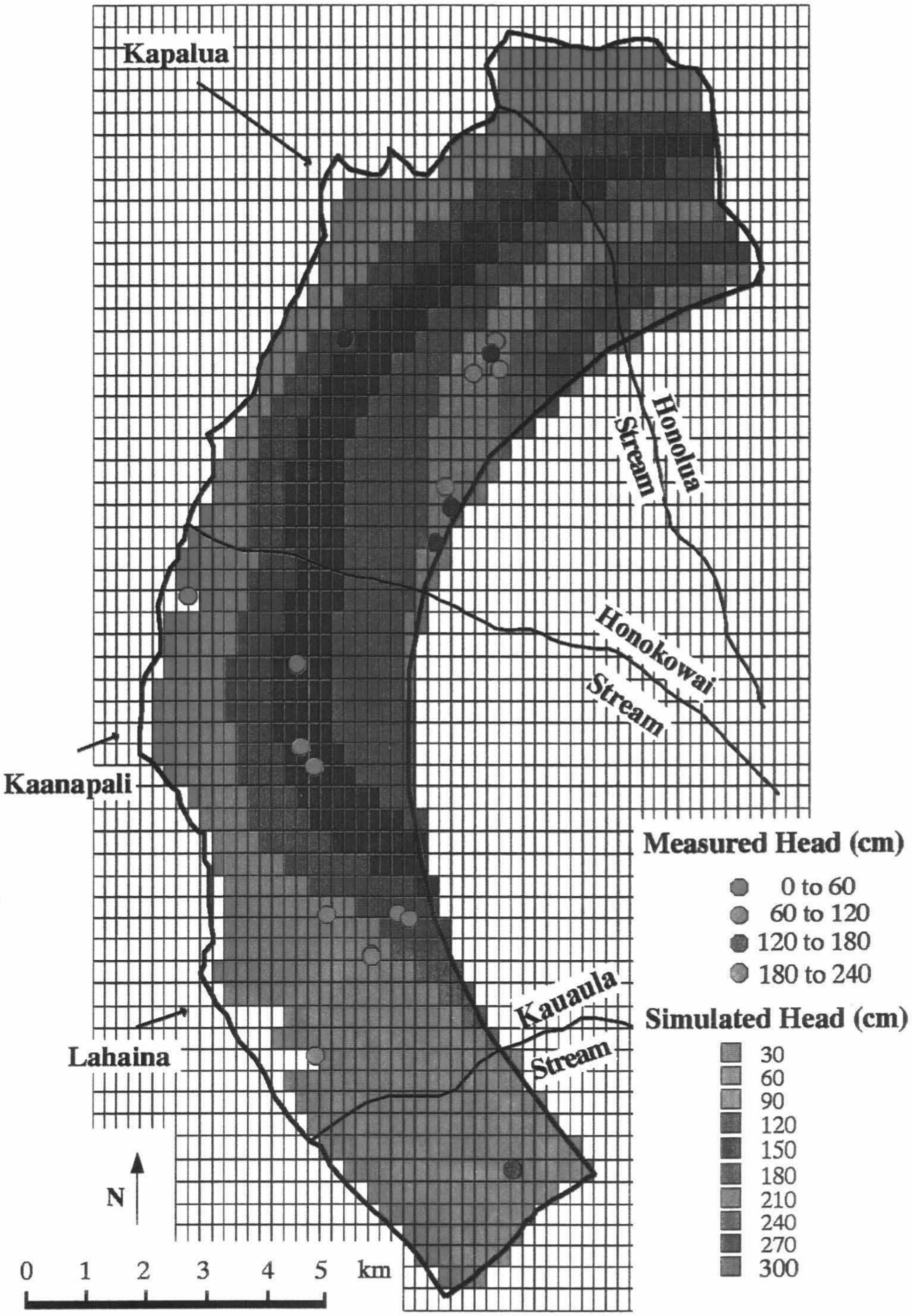


Figure 28. 1980 Simulated Head Distribution.

period (2) with present concentrations is not necessarily valid because a new steady state may not yet exist. Thus a range of input concentration scenarios are simulated to estimate present (and future) conditions under sugarcane fields. Work by El-Kadi (personal communication) on Oahu sugarcane fields under drip irrigation show that average concentrations of water beneath the root zone are likely between 5 and 10 mg/L. Since the travel time of some of the lower elevation fields is relatively low, it is safe to assume that current conditions represent a mixture of those arising from furrow and drip irrigation practices. The fact that present concentrations are equal to or slightly lower than 1980 concentrations, and significantly lower than the 1970 concentrations measured by Tenorio et al. (1970) supports the conclusion that present concentrations represent a maximum bound for the drip irrigation method. This line of reasoning helps in narrowing the range of input concentrations. Again note that these concentrations are average values held constant for all recharge waters over the sugarcane fields. Concentrations much higher than these have been found in leachate collected under sugarcane fields (as described in Chapter I, Potential Nutrient Sources), but those measurements were taken soon after fertilizer applications, thus representing the higher end of leachate concentrations. As described earlier, average leachate concentrations over longer periods of time are lower than these discrete measurements.

Figures 31 through 33 show concentration distributions for period (2) for input concentrations of 5, 6.5, and 8 mg/L, respectively. Average annual chemical discharge to the ocean from the 6.5 mg/L scenario (which produces a reasonable fit when compared with measured concentrations) is 68,000 kg/yr over the roughly 16.6 kilometer stretch of coastline (Table 8). The 5 mg/L scenario produces a discharge rate 16% less and the 8 mg/L scenario results in a 16% higher discharge to the ocean (shown in Table 8). Notice that the 8 mg/L scenario produces concentrations in the aquifer

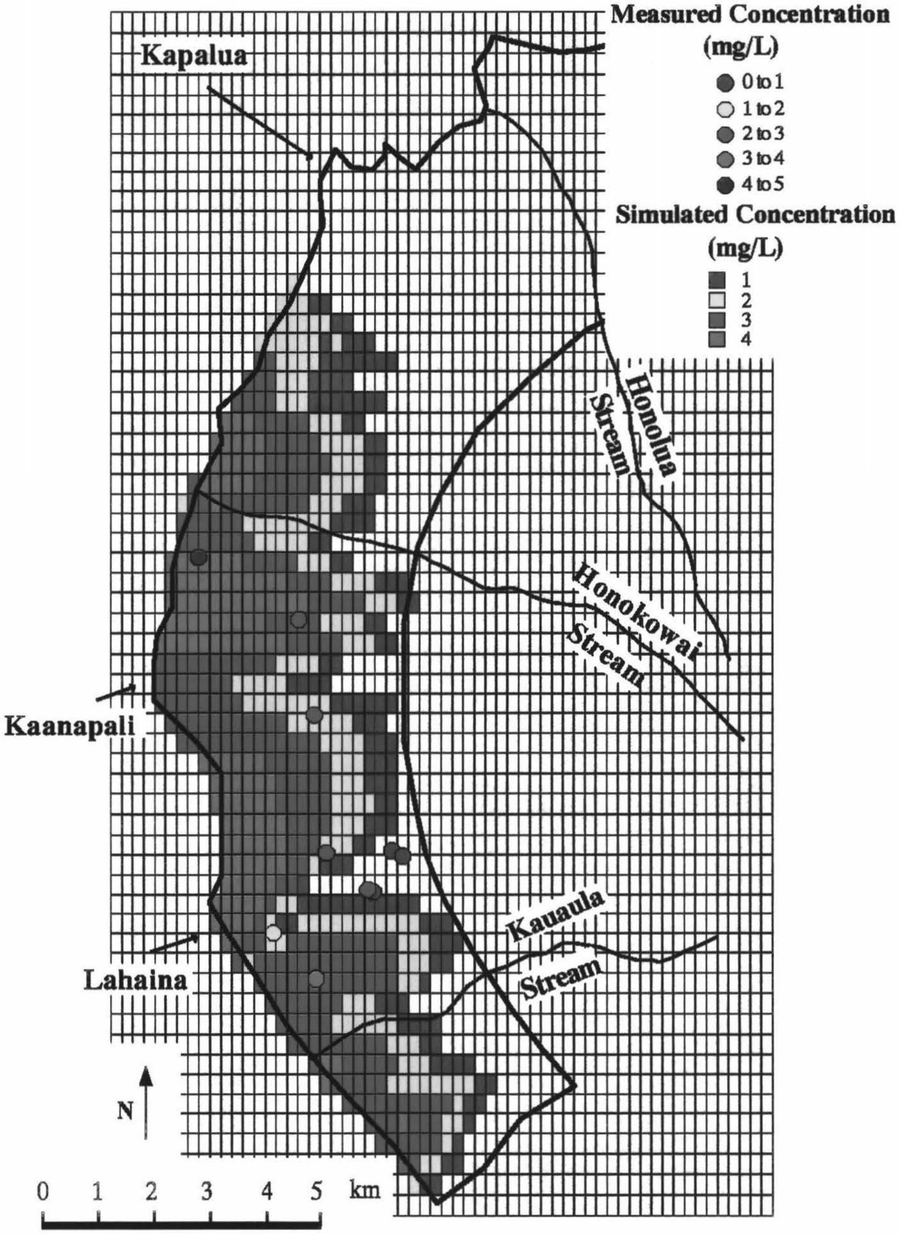


Figure 29. 1980 Simulated Nitrate Distribution for Sugarcane Recharge Concentrations of 5 mg/L.

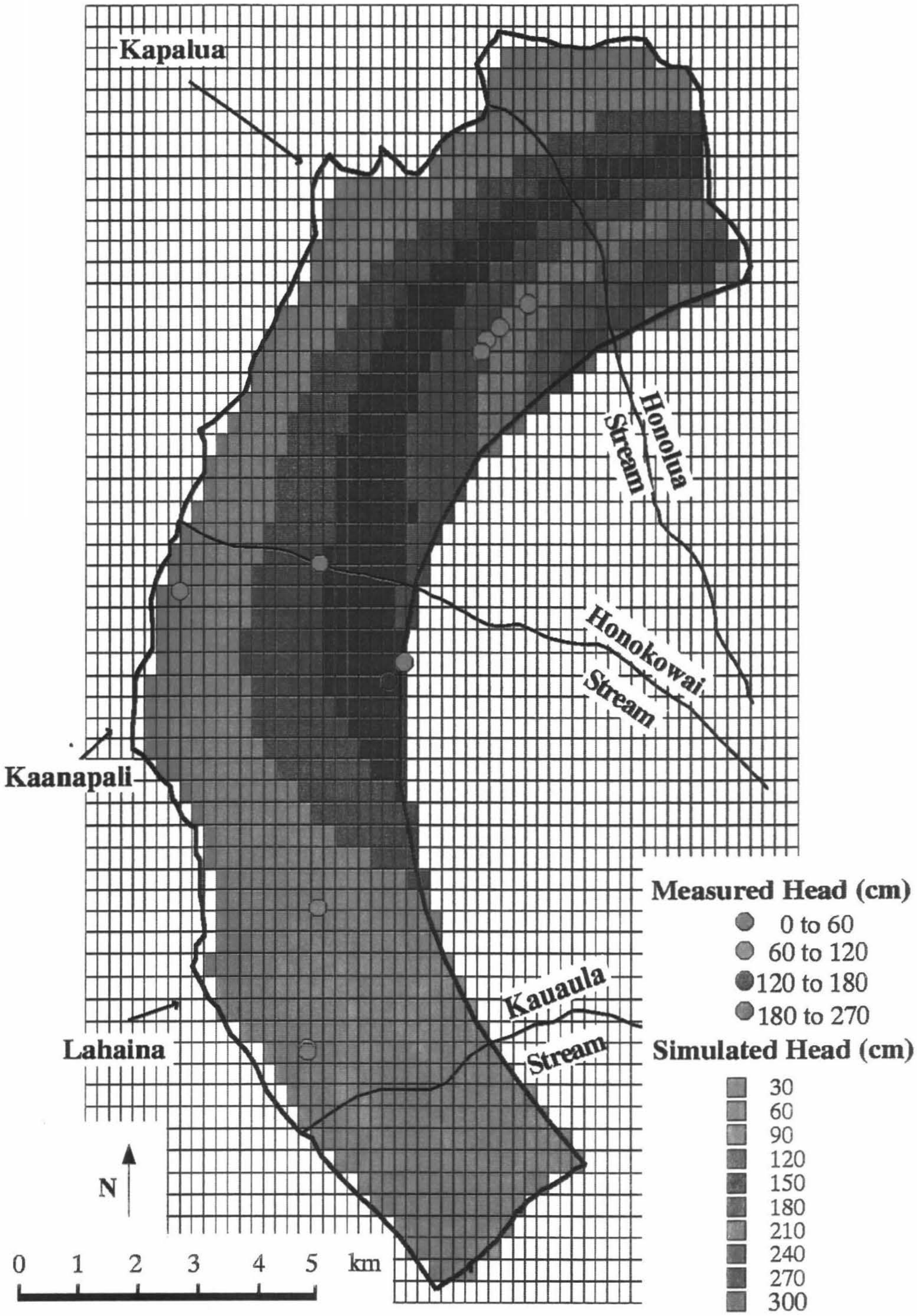


Figure 30. 1995 Simulated Head Distribution.

(5mg/L) higher than those currently measured in any wells (though there are no wells in areas of simulated higher concentrations with which to evaluate the model results).

Based on the lowest measured nitrate concentrations in groundwater samples, an average concentration for uncontaminated groundwater of 0.1 mg/L is here assumed. Thus natural volumes of recharge (estimated as 11.3×10^7 m^3/yr from the water balance analysis) to the basal lens from the dike zone supply:

$$(0.1\text{mg/L}) * (11.3 \times 10^7 \text{m}^3/\text{yr}) \rightarrow 11{,}260 \text{ kg-N/yr}$$

which contributes 8.7% of the total nitrogen loading to the basal lens. Compared with the loading from sugarcane fertilization (and the areally extensive distribution of this source), this quantity appears to be of moderate significance.

An interesting result of this analysis is that using the concentration distribution from period (1) and recharging the aquifer with clean water for ten years under present day pumping and recharge conditions leaves the aquifer completely flushed of all nitrates. Thus the initial conditions for the second pumping period simulations do not effect the final chemical distribution at the termination of the simulation (15 years). Groundwater modeling simulations assume, however, that recharge enters the aquifer instantaneously, whereas in reality nitrate carrying recharge waters may take long times before reaching the saturated zone (as described in Travel Times). This modeling result,

TABLE 8

Areal Model Results for Subsurface Discharge from Agricultural Sources

Source	Recharge Concentration (mg/L)	Annual Nitrate Contribution from Groundwater (metric tons/yr)
Sugarcane	5	53 - 60
	6.5	64 - 73
	8	75 - 85
Pineapple	5	8 - 10
	6.5	11 - 13
	8	15 -18

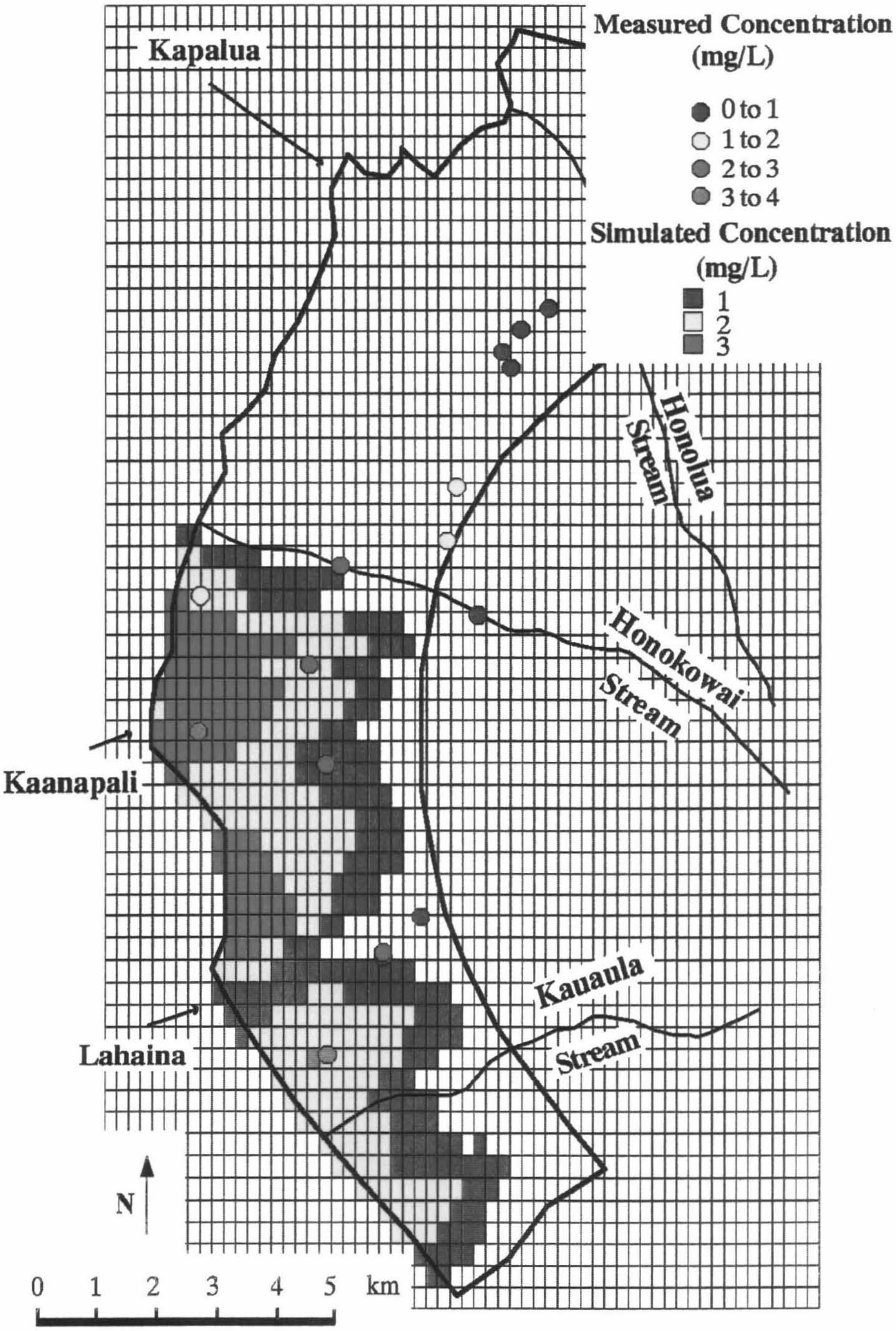


Figure 31. 1995 Simulated Nitrate Distribution for Sugarcane Recharge Concentrations of 5.0 mg/L.

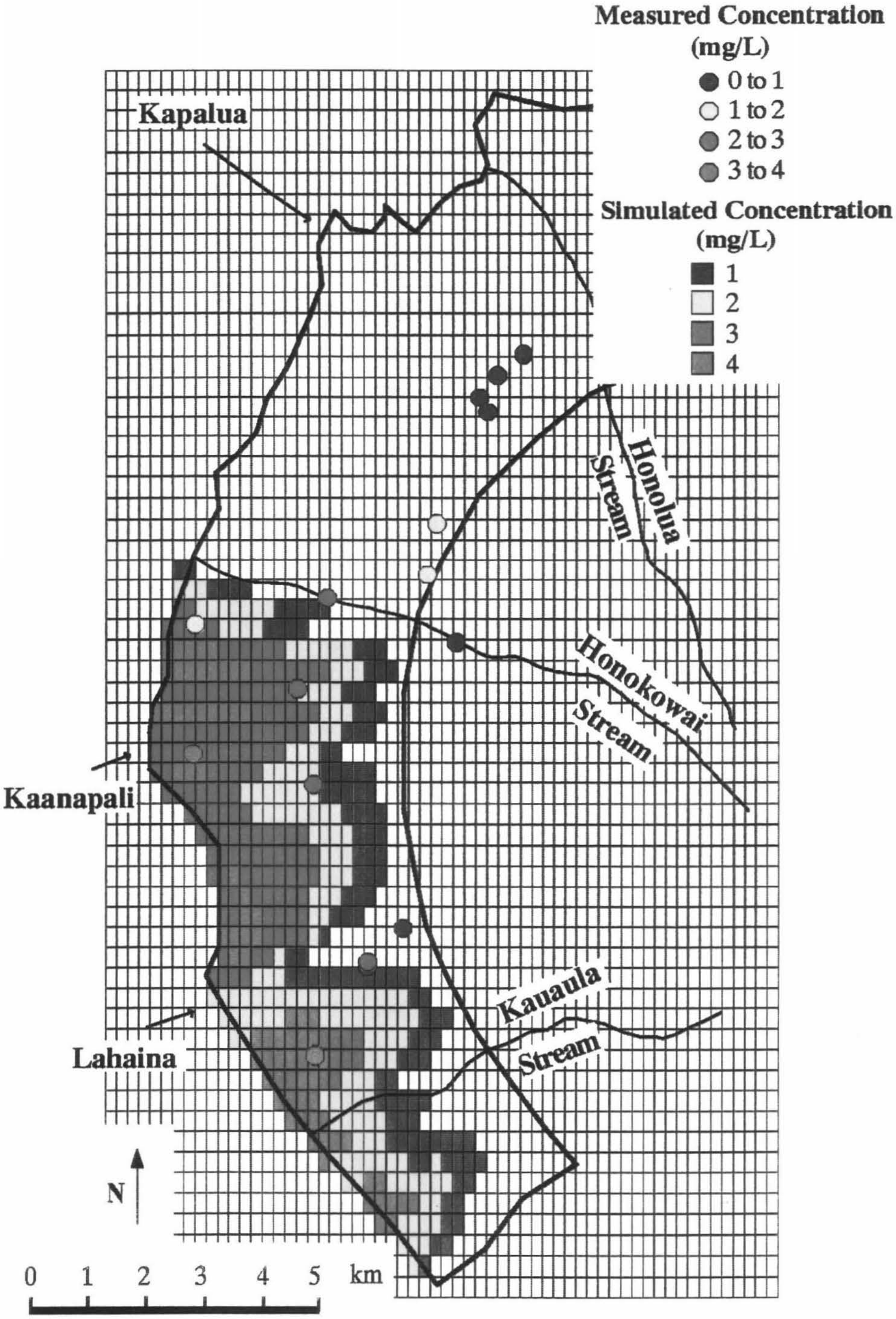


Figure 32. 1995 Simulated Nitrate Distribution for Sugarcane Recharge Concentrations of 6.5 mg/L.

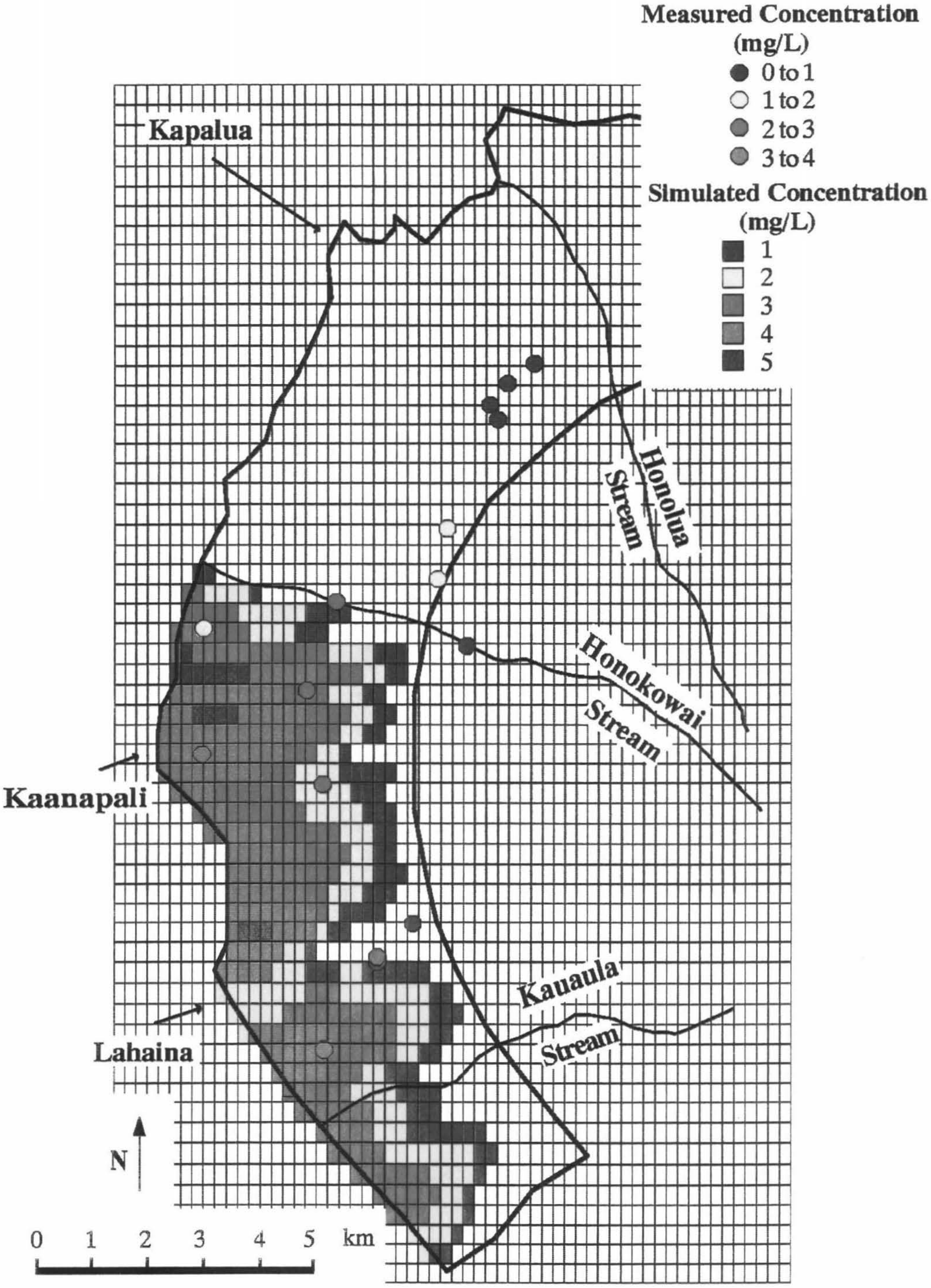


Figure 33. 1995 Simulated Nitrate Distribution for Sugarcane Recharge Concentrations of 8.0 mg/L.

then, does not accurately estimate remediation times, which, if all nitrogen loading at the surface were ceased, would take considerably longer than ten years.

In all simulations of groundwater contamination under pineapple fields, a maximum concentration of 2 mg/L prevailed in the aquifer (for recharge concentrations of 1, 5, 6.5, and 8 mg/L). With respect to the modeling, this is due to the fact that dike leakage provides so much water to the aquifer that any chemical leachate from the pineapple fields is quickly diluted. Irrigation rates are also much lower than those used in sugarcane cultivation, leaving less water available for leaching. Finally, the method of fertilizer application reduces the amount of chemicals that even reach the soil. Under a recharge concentration of 5 mg/L, 9,000 kg-N/yr discharge along roughly 18 kilometers of coastline, while less than double that amount escape under recharge of 8 mg/L (Table 8). Figure 34 shows the simulated nitrate distribution in the aquifer due to pineapple fertilization for a recharge concentration of 6.5 mg/L. Note that there is no available data to support or refute these results.

Zones of higher concentration due to sugarcane production are evident from Figures 31 through 33. These zones, however, do not directly correspond with the highest rates of chemical discharge to the ocean on an element by element basis because of the need to account for groundwater flow velocities. Outflow of nitrates to the ocean for each element is estimated by performing the following calculation:

$$L=V_{el}*n*C_{el}*A \tag{3.8}$$

where:
V_{el} = average groundwater velocity for each element [L/T]
C_{el} = simulated concentration in each element [M/L^3]
A = cross sectional area of element [L^2]
L = loading rate [M/T]

Figure 35 shows the quantity of total nitrates (with a sugarcane field recharge concentration of 6.5 mg/L) entering the ocean from each element. From this figure it is

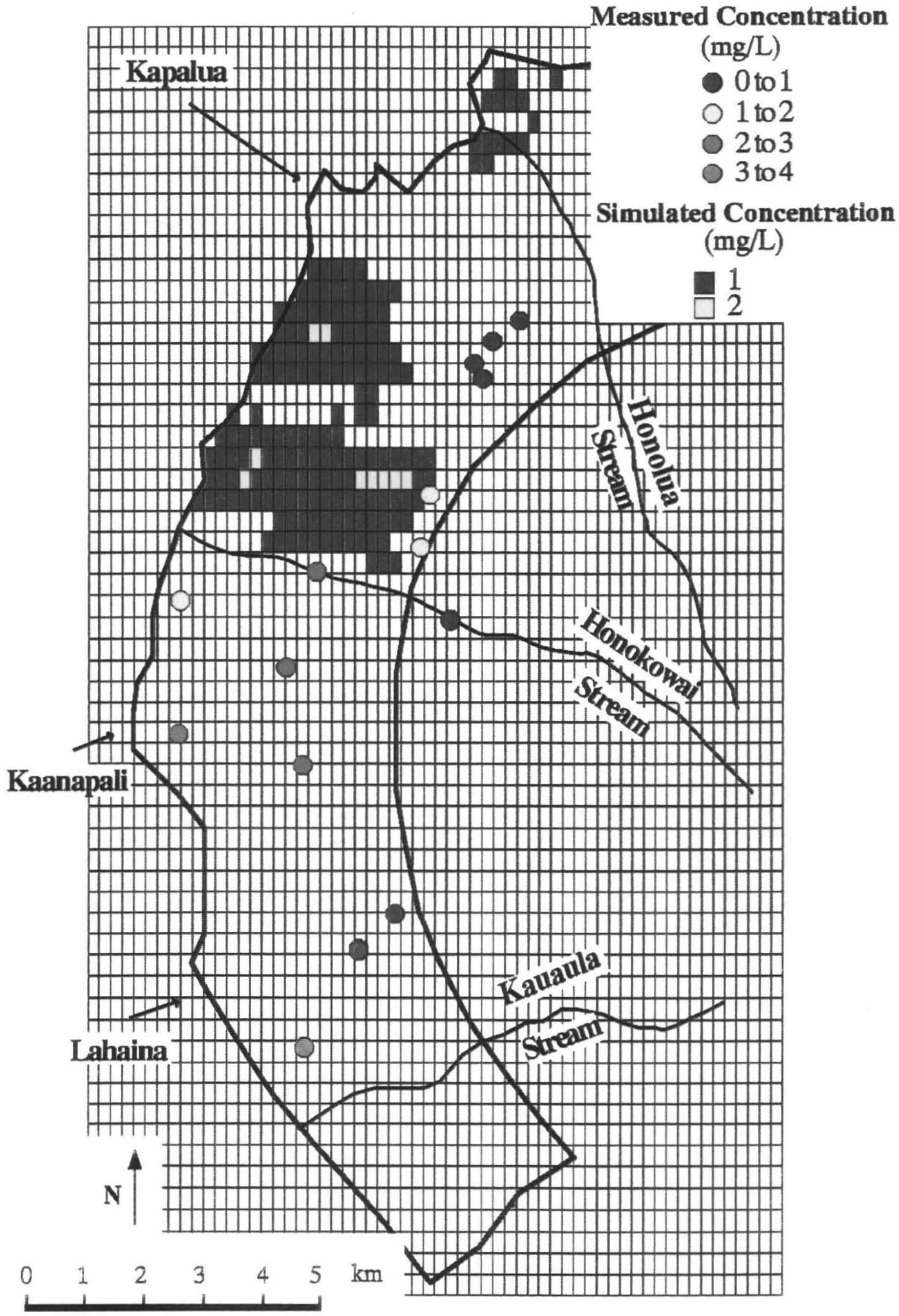


Figure 34. 1995 Simulated Nitrate Distribution for Pineapple Recharge Concentrations of 6.5 mg/L.

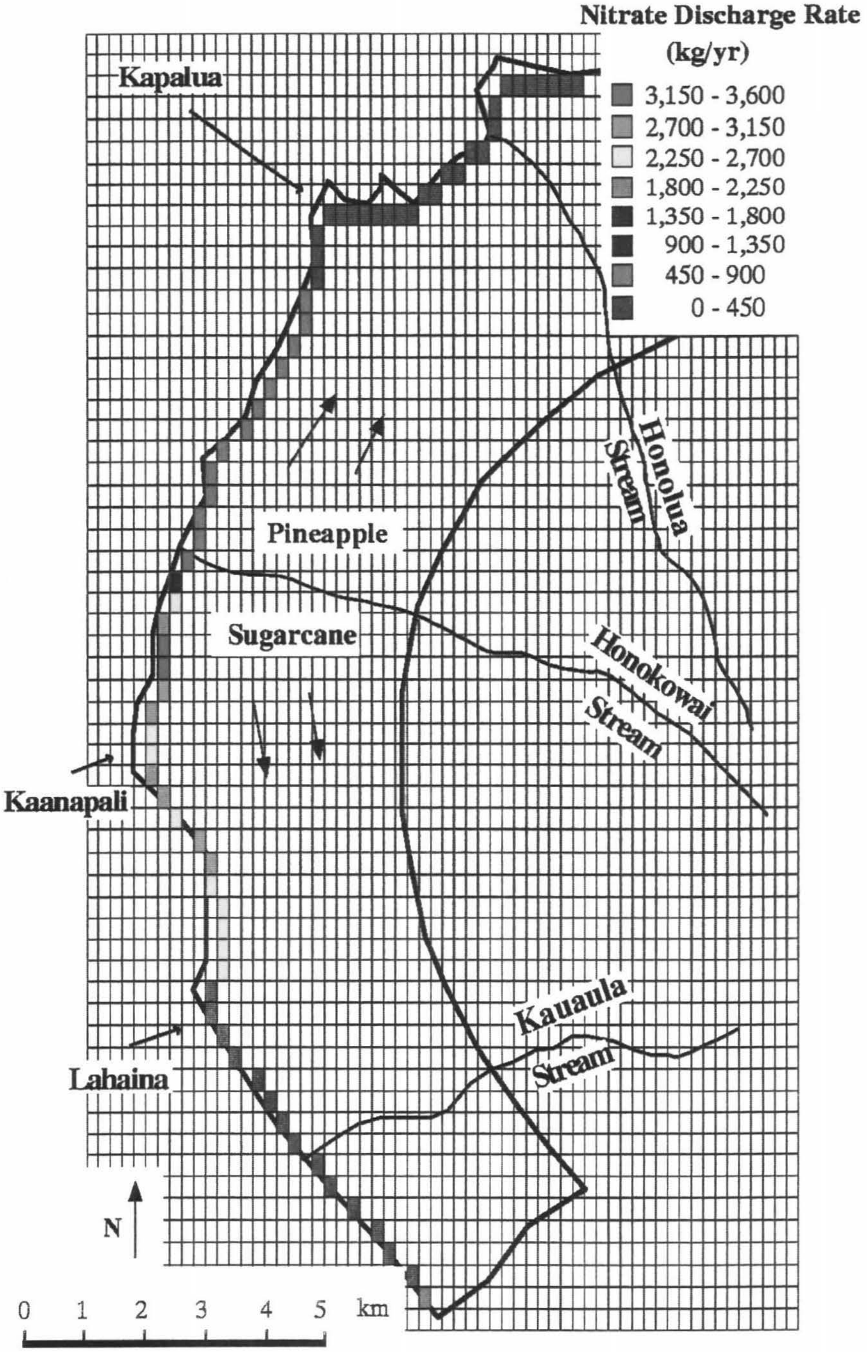


Figure 35. Subsurface Coastal Nitrate Loading Rates: Agricultural Sources.

clear that nitrate fluxes are greatest downgradient of the most densely cultivated areas just south of Honokowai Stream.

The modeling of nitrate leaching from golf courses is not undertaken for the following reasons:

1.) The golf courses are in close proximity to the coast, where accurate areal modeling is difficult to achieve (as previously described).
2.) There is no data in or downgradient of the golf courses with which to calibrate a model.
3.) The golf courses are too small to accurately simulate on the scale of this modeling effort.

Therefore, based on the work of Petrovic (1990), it is here assumed that 10% of the applied nitrogen leaches to groundwater from the golf courses, ultimately discharging to the ocean. Thus, for the Kaanapali courses, a total of 95 kg-N/yr was assumed to discharge along roughly three kilometers of coastline downgradient of the courses (see Table 9 for explanation of calculations). At Kapalua, an estimated 145 kg-N/yr discharge along the nearly three kilometer stretch of coastline downgradient of the Kapalua golf courses. Note that these numbers are orders of magnitude lower than the quantities released from the major agricultural sources.

TABLE 9

Golf Course Nitrate Loading to Groundwater (after Tetra Tech, 1993)

Golf Courses		Area (ha)	Loading Rates (kg/ha/yr)	N Loading (kg/yr)	N Leaching (kg/yr)
Kaanapali	Fairways	131	2.7	862	
	Greens and Tees	6	5.4	91	
	Total:	137		953	95.3
Kapalua	Fairways	196	2.7	1,315	
	Greens and Tees	9	5.4	136	
	Total:	205		1,451	145.1

Sensitivity Analysis

The sensitivity analysis performed shows that recharge rates and concentrations are the parameters which most strongly control chemical transport results. Transmissivity, while having a pronounced effect on head distributions, does not significantly alter transport results when recharge scenarios remain unchanged. Porosity shows an appreciable influence on the velocity field for the system, yet heads are unaffected and concentrations decrease only slightly with a decrease in porosity. Lowering the porosity from 0.1 to 0.05 decreases chemical discharge to the ocean by 5%, which results in a decrease in the chemical output to the ocean by 5%. Similarly, increasing porosity from 0.1 to 0.15 increased concentrations in the aquifer and total boundary discharge by 5%.

The quantity of recharge input to the system significantly influences the head distribution. The contribution to recharge of water from the dike system is generally an order of magnitude larger than that from directly above the basal lens, thus dominating the flow regime. Increasing and decreasing all recharge by 10% increases and decreases chemical output to the ocean by 15%. Decreasing the dike component of recharge by 10% and 20% while maintaining the same recharge over the basal lens yields an increase in concentration and a corresponding decrease in output quantities of 4% and 7%, respectively. These results arise as less dike water enters the system, providing less "clean" freshwater to dilute the incoming return irrigation flow. Concentrations therefore rise in the aquifer, but flow velocities decrease as well, countering the effect that higher concentrations would otherwise have on the chemical discharge rate. In all discussed recharge scenarios, concentration magnitudes vary slightly while the system maintains the same general distribution of high concentration areas. Predictably, the rate at which the agricultural leachate flows into the aquifer (and its concentration) largely controls the quantity of nitrogen discharging to the ocean.

Anisotropy in the permeability field has more of an influence on head than on concentration results. Decreasing the permeability in the north-south direction (generally perpendicular to lava flow directions) with respect to the east-west direction increases the heads in the aquifer (recharge waters cannot flow laterally and thus build up pressure as all waters push to flow toward the sea). These higher heads do not have sufficient force to significantly alter the transport results. Simulations run with anisotropy ratios of .7 and .5 yield outputs to the ocean 3% and 4% higher, respectively, than under isotropic conditions.

As long as the relative thickness of the aquifer does not change, its value alters results in a manner similar to that of changing the transmissivity (T=Kb). Chemical results are therefore not affected by variations in thickness. Dispersivity does not have great significance in the large scale non-point source pollution resulting from sugarcane and pineapple production on West Maui (though it is likely significant for the injection effluent). Increasing the dispersivity has the effect of slightly spreading the extent of contamination, most pronounced near the boundaries. Its effects on output to the ocean are negligible.

CHAPTER IV. CONCLUSIONS AND RECOMMENDATIONS

RESULTS AND CONCLUSIONS

The previous chapters of this report document the analytical methods and chemical data employed in estimating the contribution to coastal waters of nutrients and sediment from various land use practices. Emphasis is also placed on describing the inherent uncertainty associated with such large scale, short term studies. Indeed this uncertainty should weigh heavily in the minds of those who will use these results, from land users to regulators to those who set environmental policy, in developing practices on land. Despite this uncertainty, it is believed that the results presented here are as accurate as possible with existing technology, given the limited resources and time period for data collection.

Chapter III provides estimates of nutrient discharge through groundwater. Wastewater injection appears to have been the greatest contributor to groundwater nitrates in the late 1980's/early 1990's, with sugarcane fertilization ranking a close second and pineapple cultivation a distant third (Table 10). Wastewater injection loading has been more than halved in recent years, however, with recent improvements to the facility. Sugarcane fertilization currently accounts for at least half of the entire subsurface nitrogen loading in the study area. While the length of coastline over which the sugarcane nitrates discharge is fairly long (~16.6 km), wastewater injection nitrates are much more concentrated and discharge over a coastline perhaps less than one kilometer long. Pineapple's contribution to groundwater nitrates is considerably lower than the previously mentioned sources, but the bulk of its contribution is just north of Honokowai Stream, where field density is greatest and rainfall is high. The zone of greatest nitrate flux to the coastal waters is in and around the Kaanapali and Honokowai areas, where pineapple and sugarcane discharge their highest quantities and the LWRF contributes its entire load. Further, the LWRF discharges a considerable quantity of dissolved phosphorus, the only such subsurface source. The golf courses of the area are thought to contribute negligibly to nitrates in the groundwater as compared with the above sources. Resort and urban landscaping is also likely less significant with respect to groundwater nitrates, but has not been quantified in this study due to a lack of data and its small areal extent compared the other nitrate sources in the area.

TABLE 10

Comparison of Major Nitrogen Sources to Groundwater

Year		**LWRF**	**Sugarcane**	**Pineapple**	**Natural Recharge**
1990	Loading (kg/yr)	82,000	68,000	12,000	11,260
	% of Total:	47.3	39.3	6.9	6.5
1995	Loading (kg/yr)	39,000	68,000	12,000	11,260
	% of Total:	29.9	52.2	9.2	8.7

Chapter II provides a crude estimation of nitrogen and phosphorus loading from surface water sources. Stream loading results are estimates only for the study period and are not meant to represent typical, general loading rates. Because of the low rainfall over the study period, one would expect that the stream loading rates presented here are low compared with average annual rates. Despite this, it is clear that sugarcane and pineapple cultivation is responsible for substantially elevated levels of sediment and nutrients in the streams.

Comparison of groundwater and surface water impacts on coastal water quality must be done on two levels: quantity and timing. In terms of the quantity of nitrogen (and phosphorus from the LWRF), groundwater sources, over long periods of time, appear to exceed those of surface water. (As described in Chapter II, the overwhelming impact of one storm on the calculated total loading leaves significant doubt as to an upper bound for "typical" stream nutrient and sediment discharge). Groundwater discharge, however, is regarded as fairly continuous and constant throughout the year. Streamflow, on the other hand, occurs intensely over short periods of time (in some instances less than one day), generally restricted to winter months. Thus while groundwater sources provide a gradual, steady supply of nutrients to the coastal waters, streamflow occurs abruptly at discrete locations, providing the ocean with near point sources of nitrogen, phosphorus, and massive quantities of sediment. Perhaps a relationship exists connecting the most recent algae blooms (1989 and 1991) with above average rainfall and thus streamflow in those years (Figure 22).

RECOMMENDATIONS

Recommendations resulting from this study fall under two broad categories, those related to further defining the extent of the problem and those related to finding solutions by means of developing modifications of and alternatives to current land use practices.

●Further Defining the Problem

1.) Collect more surface water data

The most significant shortcoming of this study is the lack of surface water data. To accurately quantify loading from streams, a network of samplers must be deployed in more streams of the area for a sample period which spans at least a few high rainfall years.

2.) Install monitor wells around the LWRF injection wells.

Without any groundwater monitor wells in the vicinity of the wastewater injection wells, predictions involving the fate of the wastewater effluent cannot be verified.

3.) Obtain more groundwater samples for areas north of Honokowai Stream.

While it would appear that pineapple fertilization does not contribute significantly to subsurface nitrates, groundwater measurements near the coast have not been taken to confirm/refute this assertion.

4.) Broaden the scope to include all agricultural/landscaping chemicals.

To assess water quality in both fresh and nearshore waters, pesticide, herbicide, and insecticide contamination must be incorporated in the analysis. This source of contamination threatens both drinking water supplies and marine ecosystem health.

- Suggestions for Solutions

The data presented in this report do not single out one particular source as wholly responsible for the degradation of the West Maui environment. A few steps, however, can significantly reduce the impact of certain land use practices. Sediment erosion must be controlled at its source; keeping the soil on the fields. This requires the full implementation of soil conservation practices such as contour farming and terracing. Further, as the extensive network of roadways (especially in pineapple) become sediment rivers during storms, their numbers must be significantly reduced. While water/sediment retention basins are a costly and potentially effective solution, they do not directly address the issues of agricultural soil erosion. Fields currently on steep slopes should be taken out of production and planted in (indigenous) conservation crops. Minimizing artificial fertilizer applications would reduce nutrient concentrations in West Maui waters. Finally, a broad based education program can help alert the public to the harm associated with artificial chemical use in urban/resort landscaping while offering safe and natural alternatives.

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