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Terrestrial Nutrient and Sediment Fluxes to the Coastal Waters of West Maui, Hawai'i[1]

A. J. SOICHER AND F. L. PETERSON[2]

ABSTRACT: Water-quality degradation is often linked to land use practices in adjacent and upstream areas. Such linkages are here explored for the Lahaina District of Maui, Hawai'i, where severe algae blooms in 1989 and 1991 prompted public concern and a subsequent search for the factors contributing to algal growth. Because we expected that elevated nutrient levels might play a role in the blooms, this study examined the nutrient and sediment budgets from terrestrial sources entering the coastal waters. Although our work did not show any definitive causal relationship between algal growth and terrestrial nutrient and sediment loading, it clearly established that the principal agricultural activities in the area of sugarcane and pineapple cultivation contribute elevated loads of nutrients and sediments to the coastal waters. Likewise, disposal of treated domestic sewage effluent into subsurface injection wells contributes substantial nutrient loads to the coastal waters. Conversely, golf courses appear to have negligible impacts on the nutrient and sediment loading of coastal waters in the area. Finally, although groundwater discharges substantially greater annual nutrient loads than streamflow, the groundwater discharge is fairly evenly distributed in time and is dispersed over nearly 25 km of shoreline. Streamflow, however, often discharges intensely for short periods of time at a few discrete locations, and thus may have substantial impact locally on coastal water quality.

THE LAHAINA DISTRICT comprises the western half of the West Maui volcano, extending from Ukumehame Valley in the south to Honokōhau Valley in the north (Figure 1). The geology of the area is that of a deeply dissected volcano, the present landscape of which has been shaped by extensive water and wind erosion combined with sea level fluctuations (Mink and Lau 1990). Extremely steep interior sections give way to the more gently sloping lands of the coastal plain. Along contour, deeply incised large amphitheater and straight, narrow valleys alternate with broad, sloping lands. Valley floors and the coastal plain are blanketed in posterosional volcanic and sedimentary materials.

Water from land enters the ocean through either subsurface groundwater discharge or surface flow in streams. Groundwater on West Maui occurs as a basal freshwater lens that extends 3–6 km inland, beyond which dike impounded and perched systems dominate. The dike zone is saturated by substantial rainfall (up to 635 cm/yr) in interior sections and loses some water as seepage to the basal lens. The Wailuku Volcanic Series (wherein lies the basal lens) is highly permeable basalt with thin beds, heavy jointing, and a frothy nature (Stearns and Macdonald 1942), all of which make it a productive aquifer. Groundwater heads generally increase inland and to the north, where rainfall (and thus groundwater recharge) is highest. Coastal groundwater discharge is presumed to occur at a fairly constant and continuous rate throughout the year.

Base streamflow in the area originates as spring discharge from the upland dike complex. Of the eight major streams in the region, all but Honokōhau Stream are diverted for irrigation purposes. This leaves the streams dry during most of the year, with flow at lower elevations occuring only during storms with heavy rainfall. Because most rain falls at higher elevations, many upland rain events do not cause water to

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[2] Department of Geology and Geophysics, School of Ocean and Earth Science and Technology, University of Hawai'i at Mānoa, Honolulu, Hawai'i 96822.

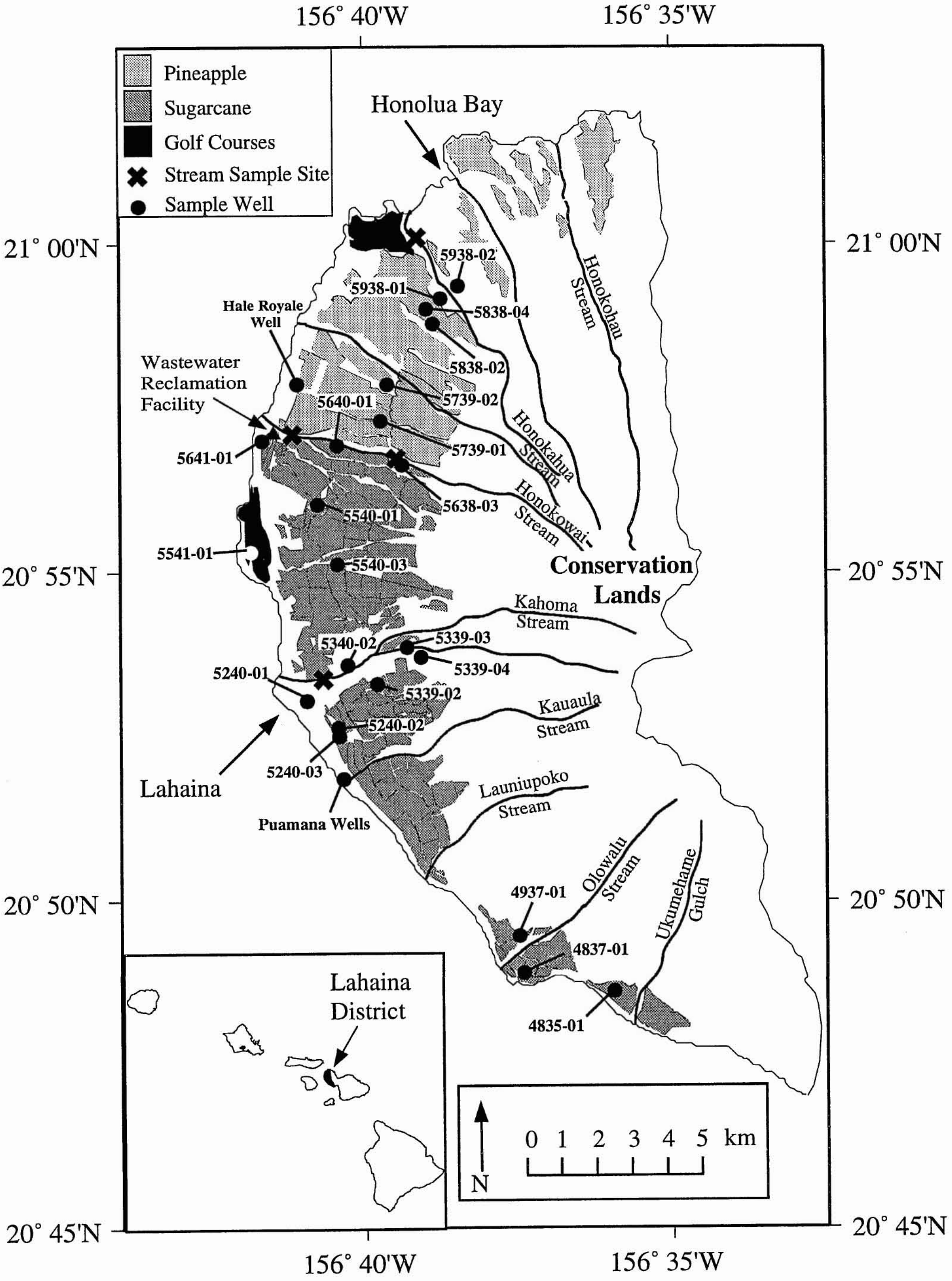

FIGURE 1. Study area, with major land uses and sampling locations.

overflow the diversion systems and discharge to the ocean.

Land Use

Figure 1 shows the current land use distribution in the district, which is zoned as 51% conservation, 42% agriculture, and 7% urban/other, according to County of Maui land use maps (in M & E Pacific 1991). In recent years, total landscape domination by sugarcane and pineapple has given way to a large influx of tourism and subsequent urbanization/resort development. Amfac/JMB Hawaii has developed a large resort at Kā'anapali including two golf courses with an area of 138 ha. A similar resort complex has been developed at Kapalua to the north, with three golf courses totaling ca. 205 ha. A rapidly expanding complex of hotels, resorts, and residences exists along the coast. Except for a small number of cesspools, all domestic and resort facilities are connected to regional sewer lines that flow into the Lahaina Wastewater Reclamation Facility (LWRF) near Honokōwai Point.

Sugarcane in the district is grown exclusively by the Pioneer Mill Company on roughly 2520 ha. Although acreage has declined in the recent past (from 3782 hectares in the 1970s [M & E Pacific 1991]), sugarcane is still the dominant agricultural crop on West Maui. Excluding higher-elevation fields and a parcel near the processing mill, irrigation has been converted from the furrow to the drip method. Sugarcane is now grown as far north as Honokōwai Stream and extends inland up to 5 km from the coast. Some cane fields have recently been replaced by coffee as an alternative agricultural crop.

Pineapple is grown by Maui Pineapple Company in the northern part of the study area, beginning near Honokōwai Stream. It currently covers roughly 2180 ha and extends up to 5 km 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 is drip irrigating their fields in an attempt to increase productivity (M & E Pacific 1991).

Nutrient Use and Potential for Contamination

The most direct source of nutrients to groundwater is through the injection of secondary treated wastewater effluent into salt water underlying the basal freshwater lens. The LWRF treats most of the wastewater generated in the Lahaina District. Its effluent supplies both nitrogen and phosphorus to the subsurface, a portion of which ultimately reaches the sea. The County of Maui originally planned to dispose of the effluent through agricultural application, using the injection wells as backup. All of the effluent is now injected. Although it is presumed that the bulk of the injected nutrients are carried by groundwater into the sea, their detailed fate is not well known because monitor wells do not exist between the injection wells and the coast.

Fertilizers are currently applied to most sugarcane fields through a drip irrigation system, except for 283 ha still in furrow irrigation near the sugar mill, which use mill processing water (a sugar milling by-product) to supply the fields. Falconer (1991) reported that most Pioneer Mill sugarcane receives 363 kg of nitrogen per hectare (kg N/ha) per crop, with Olowalu and carbonate rock fields near the coast receiving up to 477 kg N/ha. Nitrogen is applied as a urea (10.7-0-0) solution through the drip lines, at rates of 33.6–56 kg N/ha/month for 9 months. Phosphorus is applied through the drip system in the green acid form (10-34-0), at rates varying from 0 to 112 kg P_2O_5/ha, depending on local conditions (Falconer 1991).

Pineapple fertilization occurs in various forms (Wes Nohara, pers. comm.). Before replanting, the previous pineapple crop is shredded, left in the field for 2 months to decay, then plowed into the top 76 cm of soil to lay fallow for the next 8–10 months. During that time, rock phosphate is incorporated into the soil at a rate of up to 2.5 metric tons/ha. Black plastic is then laid over up to 80% of the exposed field area (not including the extensive road network), followed by the application of 2.5 cm of water by slow-driving boom-sprayers. Fertilizers are sprayed once or twice a month for the period from 2 to 13 months after planting. Total applied nitrogen over that 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) and restarted for 6 months after harvest at a rate of 392 kg N/ha. Fertilization is again halted until the second crop's harvest, which marks the end of the pineapple growing cycle. This process begins on roughly 364–384 ha 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, Inc. (1993) reported nitrogen application rates of 1.1 kg N/ha/month on greens and tees, with half that quantity applied to fairways. Phosphorus applications are estimated at 1/10 those of nitrogen. On the ca. 344 ha of golf courses, total loads of 2404 kg N/yr and 240 kg P/yr are applied. Fertilization and irrigation practices for urban and resort landscaping are extremely variable and difficult to quantify (though likely orders of magnitude lower than the aforementioned agricultural practices).

Free nutrients applied on land can arrive at the coast through either 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 either dissolved or sorbed onto soil particles. All of the above mentioned nutrient sources (except wastewater injection) are capable of providing nutrients to the sea via surface water runoff and subsequent transport. Subsurface transport involves either leaching of nutrients applied on the surface or direct injection of nutrients, 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 and pineapple cultivation, golf courses, resort/residential-based landscaping, and injection of wastewater effluent. Because the nitrogen fertilizers used in West Maui agriculture are urea based, subsequent nitrogen transformation is to ammonium and ultimately nitrate. Only the nitrate, with its negative charge, is able to leach through the soil zone and reach groundwater (Green 1981). Leaching of applied phosphorus is unlikely because of both its low solubility and high reactivity (sorption) in soils (Green 1991). Hence, the only major source of phosphorus to groundwater is from direct wastewater injection.

Leaching from golf courses is extremely variable with regard 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 Hawai‘i are generally not known.

GROUNDWATER NUTRIENTS: METHODS AND RESULTS

Spatial and temporal nutrient concentrations in groundwater were assessed through a semiannual sampling program (from 1993 to 1995) from an array of wells throughout the study area (Figure 1). Although sampling sites in and downgradient of sugarcane fields offer good control of nutrient distribution, few wells were available downgradient of pineapple fields, golf courses, or the LWRF to determine their respective roles in subsurface nutrient loading. Groundwater samples were analyzed for dissolved chemical constituents including nitrate, nitrite, ammonium, organic nitrogen, total nitrogen, phosphate, organic phosphate, total phosphorus, chloride, and silica (see Soicher [1996] and Soicher and Peterson [1996] for complete groundwater sampling data).

Most sampling wells showed little variation over the 3-yr collection period. Nitrate is the dominant nitrogen species found in groundwater samples, with concentrations highest near the coast, downgradient of sugarcane production. A maximum measured concentration of 3.69 mg/liter-as-N was found in the 5541-01 Kā‘anapali well. Wells downgradient of sugarcane were generally in the 2–3 mg/liter range, whereas wells upgradient of agricultural fields showed concentrations of 0.3 mg/liter or less. Nitrate concentrations in wells sampled by Souza (1981) and also in this study have either remained the same or decreased slightly. The lowest measured groundwater nitrate concentration, 0.17 mg/liter-as-N, was from the County of Maui's Nāpili-B well (5838-04). As expected, phosphorus concentrations in groundwater were extremely low and averaged <0.1 mg/liter total dissolved phosphorus. A maximum concentration of 0.23 mg/liter-as-P was measured in Kā‘anapali's Hohakea-2 (5540-03) well.

Groundwater flow and contaminant transport models were developed to estimate subsurface nitrate discharge along the coast. The USGS Method of Characteristics (MOC [Konikow and Bredehoeft 1978]) model was used for two-dimensional areal flow and nitrate transport modeling, and the density-dependent flow and transport model SUTRA (Voss 1984) was used for two-dimensional cross sectional simulations.

Recharge estimation for the groundwater models was provided by a USGS water balance analysis performed by P. Shade (1995, pers. comm.). This analysis includes natural recharge from rainfall together with irrigation water in agricultural areas. The boundaries of the areal model coincide with the hydrologic boundaries exerted by the rift zones of the West Maui volcano. The inland boundary is marked by the transition from upper level dike-confined water to the basal lens, and the seaward boundary is the coastline. The north and south boundaries permit no flow, the coastline boundary is held at zero pressure, and the inland boundary contributes a constant flux of water as estimated by Shade.

The MOC and SUTRA models were first used to estimate the flow field of the Lahaina District aquifer (for modeling purposes, the entire region was considered as one continuous aquifer). Two pumping periods were simulated to distinguish between the different historical irrigation and pumping practices of Pioneer Mill. The first period coincides with heavy groundwater pumpage and furrow irrigation typical of the time span from 1920 to 1980. The second period (1980–1995) marks the transition from furrow to drip irrigation and a decrease in groundwater pumping in favor of greater reliance on surface water irrigation sources. Calibration of the flow field was accomplished by matching simulated to historical heads for the two time periods.

With the flow field established, chemical transport modeling was undertaken. To accomplish this, constant chemical concentrations were assigned to groundwater recharge leaching through the agricultural fields. Numerous nitrate input concentration scenarios were run, and simulated nitrate distributions were compared with measured nitrate concentrations to reach a best fit. Figure 2 shows the results for sugarcane and pineapple recharge concentrations of 6.5 mg/liter nitrate. This match worked reasonably well for the sugarcane lands, but insufficient data in the pineapple areas made it difficult to verify/refute these modeling results there.

With these nitrate distribution results shown in Figure 2, element concentrations were multiplied by groundwater velocities to yield chemical discharge rates along the coast. Figure 2 shows annual nitrate discharge rates associated with the 6.5 mg/liter recharge scenario. It is not surprising that the areas of greatest nitrate discharge (between 2250 and 3600 kg/yr) are downgradient of the greatest density of sugarcane fields, and lower discharge rates (between 1350 and 1800 kg/yr) are downgradient of pineapple fields.

SURFACE WATER NUTRIENTS: METHODS AND RESULTS

Three streams in the Lahaina District were monitored during the study period (sampling sites are shown in Figure 1). These streams were chosen for their accessibility and the land use practices affecting their drainage areas. Kahoma Stream drains lands in sugarcane and forest reserve, Honokahua Stream drains both pineapple lands and the Kapalua golf courses, and lower Honokōwai Stream drains sugarcane to the south and pineapple to the north. To assess natural loading from forested lands, a site was maintained above agricultural fields in Honokōwai Stream (at an elevation of ca. 300 m). All of the streams are diverted and lowland flow occurs only during periods of heavy rainfall. Samples were analyzed for total suspended solids (TSS), turbidity, particulate nitrogen (PN), particulate phosphorus (PP), and the same dissolved constituents as for groundwater.

Flow meters and samplers were deployed at the start of the 1994–1995 rainy season (5 August 1994 for upper Honokōwai and Kahoma Streams, 9 September 1994 for Honokahua Stream, 15 October 1994 for lower Honokōwai Stream), and sampling continued through 28 April 1995. Sampling was resumed on 22 September 1995 at the lower Honokōwai, Kahoma, and Honokahua sites, and on 1 December 1995 at the upper Honokōwai site. Unfortunately equipment in Kahoma Stream was vandalized beyond repair in October 1995, which prevented the use of Kahoma Stream data in loading analy-

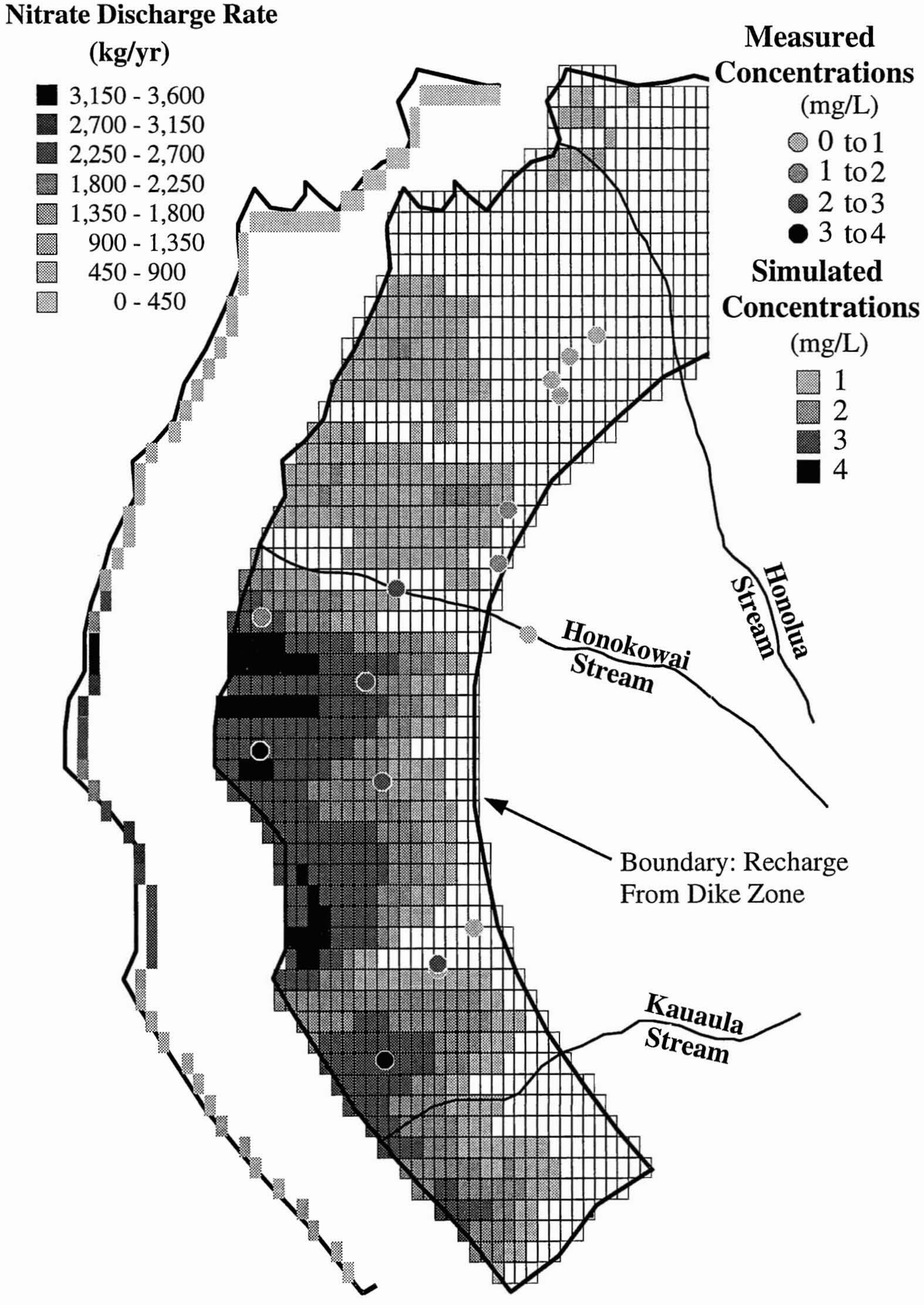

FIGURE 2. Groundwater nitrate concentrations assuming 6.5 mg/liter nitrate recharge and simulated nitrate coastal discharge rates.

ses. Sampling was terminated in Honokahua Stream on 15 March 1996 and in Honokōwai Stream on 23 April 1996. Samples were collected automatically at 20- to 40-min intervals during storm events once a preset threshold water level was exceeded. A maximum of 24 samples was collected per storm from each stream. Of those, five to 10 samples from each stream were retrieved for analysis generally within 1–3 days after the event (see Soicher [1996] and Soicher and Peterson [1996] for complete stream sampling data).

Water levels were used to calculate flow with the Manning Equation (Dunne and Leopold 1978). Figure 3 shows the resulting hydrograph during the sampling period for the lower Honokōwai site. Plots were generated of flow versus concentration for particulate and dissolved nitrogen and phosphorus, and total suspended solids (Figure 4). Where present, mathematical relationships were deduced between flow and concentration parameters. Power functions were fit to the data through regression analyses, with *R* values offering a measure of the function's representation of the relationship ($R = 1$ is a perfect fit). These curves were used to calculate the concentration of a given constituent at any flow rate, ultimately yielding total constituent loading over the entire period of study.

Total suspended solids shows the strongest positive correlation between flow and concentration. Particulate and total dissolved nitrogen (TDN) show similar relationships, with concentrations of the former (maximum = 8.9 mg/liter) generally an order of magnitude greater than those of the latter (maximum = 2.0 mg/liter). Particulate and dissolved phosphorus show little correlation between flow and concentration, pre-

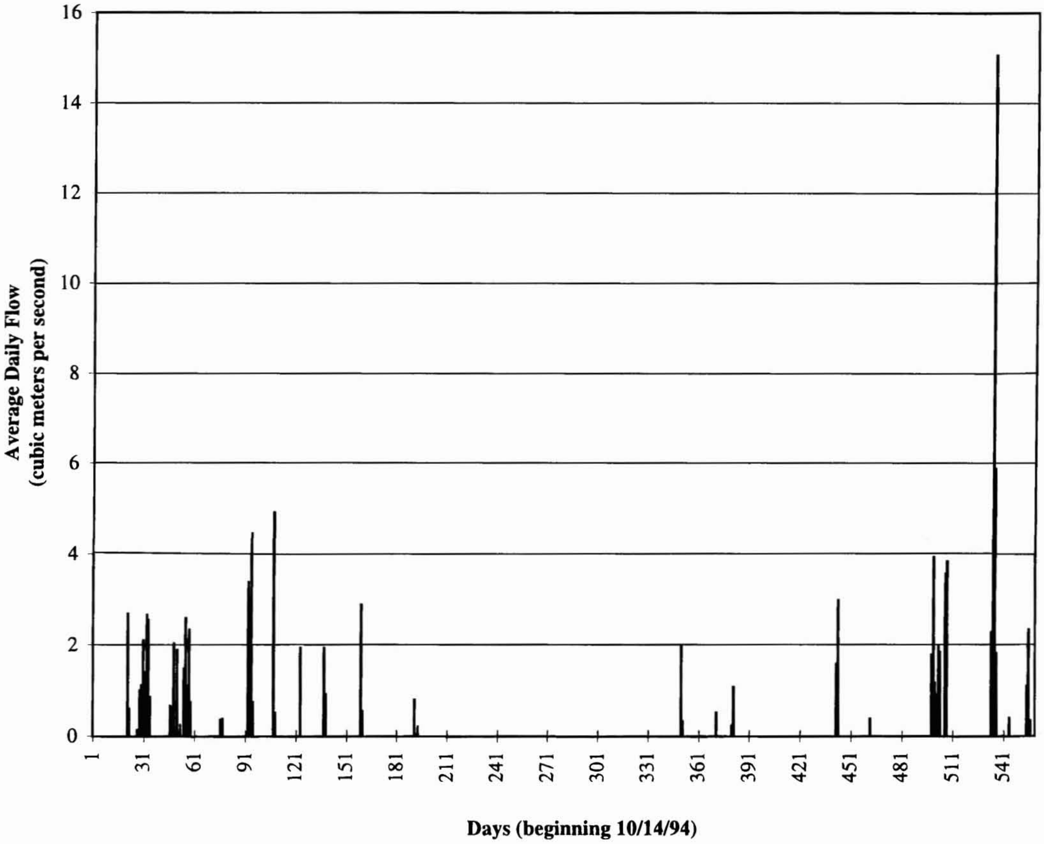

FIGURE 3. Flow hydrograph for Lower Honokōwai Stream sampling site.

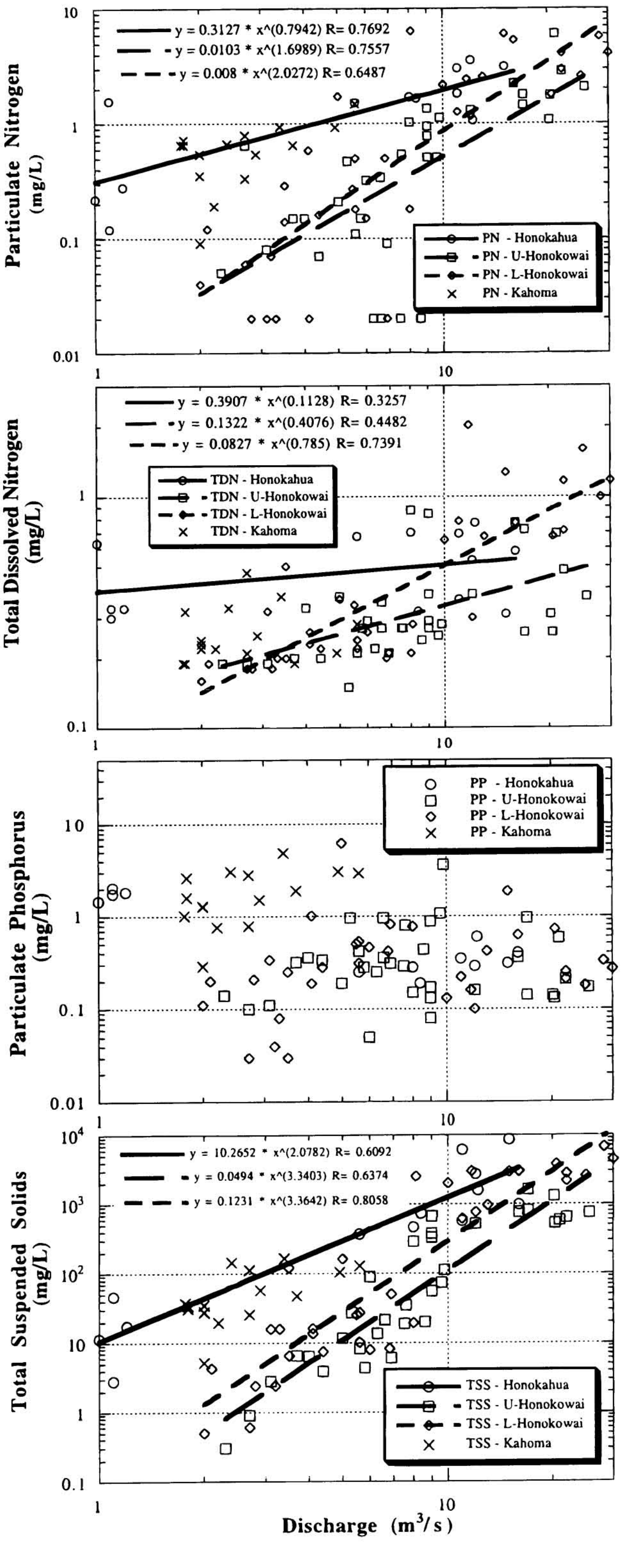

FIGURE 4. Concentration versus flow curves for stream sampling sites.

cluding the calculation of total phosphorus loading. Dissolved phosphorus concentrations are very low (generally <0.1 mg/liter), and particulate phosphorus concentrations (maximum = 22.3 mg/liter) are generally lower than those of particulate nitrogen.

Because concentration alone does not express nutrient magnitude in streams, calculations of total loading over the study period were performed for TSS, PN, and TDN and are listed in Table 1. For various reasons (power failure, storm damage, etc.), continuous data were not collected evenly from all sites, making direct comparisons of the values in Table 1 invalid.

The great disparity between the total loads of Honokahua and Honokōwai Streams presented in Table 1 is due in large part to the storm of 30–31 March 1996, for which data in Honokahua Stream were unavailable. The hydrograph for lower Honokōwai Stream (Figure 3) demonstrates the importance of this event with respect to the total volume of water that flowed in the stream during the study period. In Honokōwai Stream, discharge rates remained high for over a 24-hr period. Although instantaneous discharge at any point during the storm did not greatly exceed those measured during other events, the persistence of high flow rates throughout the storm's duration gave it considerable weight with respect to total constituent loading. For example, 75–80% of the sediment loading, 70% of the PN, and 40% of the TDN discharged over the entire study period came from that one event. Figure 4 shows that the trend in Honokahua Stream is toward even higher PN and TSS than in Honokōwai Stream. These results highlight the importance of individual, intense storms in temporarily inundating the coastal waters with large quantities of nutrients and sediment.

TABLE 1

TOTAL CALCULATED STREAM LOADING DURING STUDY PERIOD

STREAM	PN (kg)	TDN (kg)	TSS (metric tons)
Honokahua	1,500–2,000	800–1,000	80–100
Upper Honokōwai	3,000–3,500	2,000–2,500	100–120
Lower Honokōwai	6,500–7,500	3,500–4,000	350–400

From Table 1, it is clear that the lower reaches of Honokōwai Stream discharged substantially higher nitrogen and suspended solids than the upper reaches of the stream. Further, only the lower site's samples contained the fine "red dirt" that often discolors coastal waters during storms. Sediment in samples from the upper site was generally found to be coarser and dark brown. These results clearly show that current agricultural practices increase nutrient levels in surface water and greatly increase sediment production and release to the coastal waters.

Difficulties arise in extending the measured and calculated results of this study to all streams in the Lahaina District. 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 at any site) adds to the uncertainty. Further, the sample collection period coincided with an atypically low rainfall period, suggesting that our total loading estimates are probably low compared with true average annual values.

Nonetheless, making the very crude assumption that Honokōwai Stream is representative of the eight major drainages of 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 1994–1996 winter seasons. This estimated sediment load is in reasonable agreement with the U.S. Soil Conservation Service (1992) calculation of 5100 metric tons of sediment per year for the Lahaina Watershed, which contains 511 ha of cane fields (compared with 2520 ha total in the Lahaina District). Emphasis must again be directed toward the occasional, extreme event, in which, during especially wet winters, closely spaced storms are capable of providing extensive quantities of nutrients and sediment to localized areas in the coastal waters.

CONCLUSIONS

Estimates of subsurface nitrate discharge from the major sources in the area are summarized in Table 2. Wastewater injection appears to have been the greatest contributor to groundwater nitrates in the late 1980s/early 1990s, with sugarcane fertilization ranking a close second and pineapple cultivation a distant third. With facility improvements, nutrient concentrations in injected wastewater have been more than halved in recent years, decreasing total loading considerably. Sugarcane fertilization currently accounts for approximately half of the subsurface nitrogen load in the study area. The length of coastline over which the sugarcane nitrates discharge is fairly long (ca. 16.6 km), but injected nitrogen from the LWRF is much more concentrated and discharges over a coastline perhaps <1 km in length. Pineapple's contribution to groundwater nitrates is considerably lower than the previously mentioned sources, though the bulk of its load enters the ocean just north of Honokōwai Stream where field density is greatest and rainfall is high. The zone of greatest groundwater nitrogen flux to the coastal waters is in and around the Kā'anapali and Honokōwai areas (Figure 2), 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 in 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 important with respect to groundwater nitrates, but has not been quantified in this study because of a lack of data and its small areal extent compared with the other nitrogen sources.

Much greater uncertainty exists in stream loading estimation for reasons described previously. Stream loading results are estimates only for the study period and may deviate somewhat from average long-term loading rates. Because of the low rainfall during the study period, one would expect that the stream loading rates presented here are low compared with average annual rates. It is clear, however, that sugarcane and pineapple cultivation are responsible for substantially elevated levels of sediment and nutrients in 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 earlier, however, the overwhelming impact of one storm on total calculated stream loading leaves substantial doubt as to an upper boundary for "typical" surface water nutrient and sediment discharge). Groundwater discharge 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 <1 day), generally restricted to winter months. Thus while groundwater sources provide a moderate, continuous supply of nitrogen over the entire coastline, streamflow can provide large amounts of nitrogen and phosphorus, and massive quantities of sediment, for short times to discrete locations along the coast. Thus on a local scale over short periods of time, the impact on coastal water quality from streamflow may far exceed that of groundwater sources.

Recommendations

The data from this study suggest general conclusions as to the relative quantities of nutrients and sediment derived from the major land uses in the Lahaina District of West Maui. However,

TABLE 2

COMPARISON OF MAJOR NITROGEN SOURCES TO GROUNDWATER

PARAMETER	INJECTION	SUGARCANE	PINEAPPLE	GOLF	FOREST
1990: loading (kg/yr)	82,000	68,000	12,000	240	11,260
% of total	47.3	39.2	6.9	0.1	6.5
1995: loading (kg/yr)	39,000	68,000	12,000	240	11,260
% of total	29.8	52.1	9.2	0.2	8.7

NOTE: LWRF values represent the worst-case scenario of all injected nitrogen reaching the coastal waters.

because the study was of relatively short duration and was principally of a reconnaissance nature, substantial data gaps have been identified that must be remedied before more rigorous quantitative analysis can be accomplished of nutrient and sediment delivery to the coastal waters. These include (1) collection of additional surface water quality and flow data from more streams over time periods spanning several years, and (2) collection of groundwater quality data downgradient of pineapple fields north of Honokōwai Stream and between the LWRF injection wells and the coast (presently impossible because monitor wells do not exist in those areas).

The data presented from this study do not conclusively single out one particular source as most responsible for the degradation of the West Maui coastal environment. In fact, the effect of nutrient and sediment loading from land sources on the coastal environment has not been well established. A few "common-sense" steps, however, can reduce the potential impact of certain land use practices. Most important, sediment erosion must be controlled at its source by keeping as much of the soil as possible on the fields. This requires the full implementation of soil-conservation practices such as contour farming and terracing. Further, because the extensive network of roadways (especially in pineapple) become sediment rivers during storms, their numbers must be substantially reduced. Although water/sediment retention basins are a potentially effective, albeit costly solution, they do not directly address the issues of agricultural soil erosion. Consideration should be given to taking fields on very steep slopes out of production and planting them in indigenous conservation crops. Minimizing the use of artificial fertilizer applications should be practiced where feasible. Finally, a broad-based educational program can help alert the public to the harm associated with poor land management practices and artificial chemical use in urban/resort landscaping while offering safe and natural alternatives.

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