SUBMARINE GROUNDWATER DISCHARGE: FRESHWATER AND NUTRIENT INPUT INTO HAWAII'S COASTAL ZONE

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE
UNIVERSITY OF HAWAI'I IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

GEOLOGY AND GEOPHYSICS

DECEMBER 2004

By
Marc P. McGowan

Thesis Committee:

Craig R. Glenn, Chairperson
Fred T. Mackenzie
Gary R. McMurtry
Ken H. Rubin

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

ACKNOWLEDMENTS

I would like to first thank Craig Glenn for giving me the opportunity to come Hawaii to work on submarine groundwater discharge and for giving me the freedom to steer the project in the manner I felt fit. I also thank him for his insight into other marine geological disciplines especially with respect to understanding oxygen and carbon isotopes in carbonate rocks and their use in interpreting paleoclimates.

Geoff Garrison played a crucial role in getting this project underway and also had useful insightful into Hawaii's geology, hydrology, and local way of life. I appreciate his consultations even after he departed Hawaii for the mainland. Many thanks to Ken Rubin for taking time to discuss geochemistry with me as well as assisting in the statistical analysis and interpretation of my data.

This project would not have been possible had it not been for the numerous field assistants who helped with collecting water and sediment samples. I would especially like to thank Chris Stoebenau for being an outstanding dive buddy and overall field assistant.

Big mahalos to Eden Feirstein for all the enlightening discussions on submarine groundwater discharge, politics, and life in general as well as assistance in proof reading early drafts of my thesis.

Major funding for this research was provided by the Hawaii SeaGrant Program. I would like to thank Gordan Grau for sponsoring me and allowing me access to the research vessels at Coconut Island. The Harold T. Stearns and William T. Coulborn Fellowships administered through the department of Geology and Geophysics also contributed to the success of this project.

Last, but not least, I would like to thank my Mom and Dad, brothers Mike and Matt, and my many good friends in McHenry who have been extremely supportive through out my college career.

ABSTRACT

Submarine groundwater discharge (SGD) is any flow of water on continental margins from the seabed to the coastal ocean, regardless of fluid composition or driving force. In the Hawaiian Islands, SGD is a significant process for the transport of fresh water and dissolved nutrients into the coastal marine environment, although few direct measurements have been carried out. Nutrient-rich SGD is thought to be a potential nutrient subsidy for several nuisance benthic algae that are proliferating around the islands.

Water samples were collected at three separate coastal areas: Kaneohe Bay on the northeast coast of Oahu (March 2002 through April 2004), Maunalua Bay on the southeast coast of Oahu (April 2003 through December 2003), and Kealakekua Bay on the west side of the island of Hawaii (April 10, 2003). Salinity was used as a natural conservative tracer to quantify the input of terrestrial derived SGD, while concentrations of nitrate, orthophosphate, ammonium, and silica were measured to understand the biogeochemistry of the different systems. Due to the wide range of geological materials found in the bays, a variety of water sampling techniques were used including: benthic seepage meters, hand-dug pits, piezometers, and sediment cores.

In Kaneohe Bay, the largest embayment in the Hawaiian archipelago, terrestrial derived ("fresh") SGD was restricted to the nearshore environment (<250 m from shoreline) and was twice as voluminous as the only previous estimate performed by a land-based hydrological water balance. SGD occurs in the nearshore environment due to a variety of forces including tidal pumping, oscillatory wave flushing, and advection due to the hydraulic gradient between the bay sediments and the terrestrial aquifer.

The lagoon environment of Kaneohe Bay consists of relatively low permeability fine grained sediments in which diffusion and bioirrigation processes control the transport of nutrients out of the sediments and into the water column. The breakdown of organic matter in the sediment results in a flux of ammonium, nitrate, and phosphate while the dissolution of biogenic opal in the sediments is thought to result in a flux of dissolved silica.

Five discrete submarine springs and extensive beachface seepage were discovered at Maunalua Bay. The terrestrial springs were located within 50 m of the shoreline in ~1 m of water and could be seen as circular "boils" at the surface. There was a good linear correlation between the concentrations of nitrate, silica, phosphate and water salinity suggesting that terrestrial groundwater is a major source of dissolved nutrients to this bay.

At Kealakekua Bay, terrestrial SGD emanates from discrete points in the substrate and is easily identified due to its colder temperature (~5° C less than ambient bay water) and the visual "shimmering" affect produced from the mixing of the low salinity SGD and the saltier ambient bay water. Concentrations of nitrate, phosphate, and silica were two orders of magnitude greater in the SGD than the receiving bay water. However, due to the rubble substrate and extensive coral coverage, sampling is restricted to noninvasive techniques that require sampling directly from the water column.

The results from these three locations reiterates the notion that SGD in Hawaii is an important process for the delivery of fresh water and dissolved materials, especially dissolved nutrients, to coastal waters. Further work is needed to implement noninvasive sampling techniques to further document the extent of SGD around the islands where traditional methods are inadequate.

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INTRODUCTION

In the past 25 years, submarine groundwater discharge (SGD) has been recognized as an important process for the transport of fresh water and dissolved chemical constituents into the coastal marine environment (e.g. Bokuniewicz, 1980; Johannes, 1980, 1985; Lewis, 1987; Moore, 1996, 1999; Burnett et al., 2003). SGD is any flow of water on continental margins from the seabed to the coastal ocean, regardless of fluid composition or driving force (Burnett et al., 2003). Historically, SGD was considered as a mere scientific curiosity because of the difficulty in assessment and the perception that the process was unimportant (Burnett et al., 2003). Most early studies (prior to ~1980) of SGD dealt with measuring large easily-detected offshore springs. However, increased interest and attempts at quantifying the magnitude and chemical nature of SGD have recently shown that it can be an important component of chemical and water budgets from local to global scales (Johannes, 1980; Valiela and D'Elia 1990, Zekster, 2000, Burnett et al., 2003).

A recent collaborative effort to understand better the magnitude of SGD and its influence on coastal biological and chemical processes was undertaken by a group of scientists in a co-sponsored project under the auspices of the Scientific Committee on Oceanic Research (SCOR) and the Land-Ocean Interaction in the Coastal Zone (LOICZ) project. Results of this groups' (SCOR working group 112) efforts to develop standardized approaches for evaluating and reporting measurements of SGD, assess deficiencies in the present knowledge concerning the magnitude of fluxes of SGD, and to examine the use of typological studies over broad areas are the subject of an 11 article special publication (Biogeochemistry 66, 2003). It was found that SGD is a complex phenomenon which can be difficult to quantify, although significant progress has been made in recent years (Burnett et al., 2003). The difficulty in quantifying SGD lies in the fact that it can occur over large areas in a wide range of geological media, can contain terrestrially-derived fresh water and re-circulated seawater, and can be driven by numerous-independent forces (e.g. hydraulic head, sediment dewatering, tidal pumping) over a range of time scales. This complexity usually precludes the use of a single measurement technique to measure accurately the magnitude of flow and therefore requires the use of multiple tools.

Despite the increased interest in studying SGD in recent years, much of the world's coastlines remain unstudied. The majority of studies have been performed on the east coast of the United States, Europe, Japan and in Oceania (Taniguichi, 2002) with fewer studies on the west coast of the United States and Hawaii. Of significance is the fact that there are no SGD assessments currently available in the literature that deal with South America, Africa, and southern Asia (Burnett et al., 2003).

Freshwater Input into the Coastal Zone

Rivers are believed to be the dominant pathway for water to move from the land to the ocean. Relatively precise estimates of the riverine input into the ocean have been made due to their simple, well-defined open channels (Berner and Berner, 1987). Quantifying the global extent of SGD on the other hand has proven to be more difficult. The overall input of SGD can be significant because the length of coastline where SGD can occur is great (Taniguichi, 2002), whether or not rivers are present (Kay et al., 1977).

Global estimates of the input of terrestrially-derived "fresh" submarine groundwater into the ocean vary over an order of magnitude with the majority of estimates in the

1000-3000 km^3/yr range (Burnett et al., 2003). One of the most comprehensive computations of global terrestrial SGD is presented in Zekster (2000). Using a combined hydrological and hydrogeological method, 480 groundwater discharge drainage areas were determined from either potentiometric maps when available or the world hyposometric map on a 1:2,500,000 scale. In each of these areas, the specific groundwater discharge values were taken from published maps of groundwater flow and were extended to hydrogeologically similar areas whose groundwater discharges directly into the sea. The total value of SGD was then calculated by multiplying the average SGD amount by the area over which the SGD occurred. This value was further divided for each drainage area into the discharge per one square kilometer of drainage area of land and the linear discharge of groundwater per one kilometer of coastline.

The global terrestrial SGD amount calculated by this method is about 2400 km^3/yr or 6.4% of the mean river input of 37,400 km^3/yr (Berner and Berner, 1987). An interesting aspect of this calculation is that of the total discharge amount more than 35% (915 km^3/yr) is from major islands. In the Pacific Ocean, the discharge from major islands (615 km^3/yr) is roughly equal to the amount from continents (685 km^3/yr). This disproportionately high percentage of discharge by major islands may be explained by several physical characteristics of the islands including: heavy precipitation in tropical-humid climates, mountainous topography, high permeability of fractured solid rocks and terrigenous formations, and poorly developed river network systems (Zekster, 2000). These characteristics are all expressed on the island of Oahu, Hawaii. With its unique fractured basalt/alluvial caprock structure, along with the presence of lava tubes and cavernous-karst features, the volume of SGD on Oahu is suspected to be significant although estimates are very poorly constrained (Hunt, 1996).

Nutrient Input into the Coastal Zone

Nutrient enrichment due to human activities is one of the most significant problems affecting coastal ecosystems around the world. On a global scale, anthropogenic inputs have increased the flux of nitrogen (N) and phosphorous (P) to the oceans by approximately a factor of 2 and 3, respectively (Howarth et al., 2002). The distribution of the loading is not uniform and is primarily a function of coastal population density and agricultural production (Seitzinger et al., 2002).

Coastal counties in the U.S. account for 17% of the U.S. landmass, yet they contain over half the population (U.S. Bureau of the Census, 1998). The large coastal population and the activities associated with it have increased the fluxes of nitrogen and phosphorous to coastal rivers and estuaries by up to 8 fold (Howarth et al., 2002). This increased nutrient loading has impacted in some way (e.g. anoxic waters, increased turbidity, harmful algae blooms) nearly 67% of the conterminous U.S. estuarine waters (Bricker et al., 1999).

Nitrogen loading sources include the application of synthetic inorganic fertilizers, sewage effluent, the conversion of atmospheric N into biologically available forms of N from the combustion of fossil fuels, and production of N-fixing crops in agriculture (Howarth et al., 2002). Phosphorous fluxes to the coastal zone are dominated by the essentially one-way flow of P carried in eroded materials and wastewater from the land to the oceans via surface water and to a lesser extent groundwater (Hedley and Sharpley, 1998). Global phosphorous fluxes to the oceans have tripled due to anthropogenic practices with the application of fertilizers dominating the flux (Howarth et al., 2002).

Productivity in coastal waters is more often than not limited by the amount of available nitrogen (Howarth, 1988; Vitousek and Howarth, 1991; Nixon, 1995; Paerl, 1997) although phosphorous limitation may also occur (Smith and Atkinson, 1984; Lapointe and O'Connell, 1989; Short et al., 1990; Howarth, 1995). Increased nitrogen and phosphorous loading from contaminated water can lead to increased primary productivity (Lapointe and O'Connell, 1989, Kinney and Roman, 1998; McClelland and Valiela, 1998). The effects of increased productivity can be extensive and multifaceted resulting in shifts in the dominant flora and fauna living in coastal waters. For example, shifts from seagrass dominated systems to macroalgae (green, red, and brown) dominated systems has been observed and described in areas of Waiquot Bay, Massachusetts (Valiela et. al., 1990, McClelland and Valiela, 1998), the Mediteranean (Meinesz et al., 1993), and parts of the Black Sea (Meinesz et al., 1993). The replacement of coral reef communities by macroaglae has also been observed in parts of the Great Barrier Reef (Bell, 1992) and Oahu, Hawaii (Smith et al., 1981).

Extensive growth of several invasive marine algae in coastal environments around Oahu has recently received considerable attention because these algae can overgrow and asphyxiate coral colonies, out-compete native algae species creating a non-diverse ecosystem, and can wash up onto beaches where they decay creating unpleasant sights and odors (Smith et al., 2002). An assessment of nonindigenous marine species in Kaneohe Bay revealed that of twelve invasive species identified, the five invasive macroalgae (*Acanthophora spicifera, Gracileria salicornia, Hypnea Musciformis,* *Kappaphycus alvarezii,* and *Kappaphycus striatum*) species found in the bay were considered to pose the greatest and most pervasive negative impact on the bay's marine community (Coles et. al., 2002). Although work has been done to document the types of algae present and their abundance and distribution (Coles et al., 2002; Smith et al., 2002), little is known of the hydrological and nutrient dynamics of the coastal systems in which they are thriving. It has thus been suggested that some of the algae growth might be partially sustained by nutrients emanating from sediments (Smith et al ., 1981; Larned and Stimson, 1996; Stimson and Larned, 2000).

SGD and Oahu, Hawaii

The island of Oahu has an extensive freshwater resource which has supported large agricultural industries (sugar cane and pineapple) as well as a human population of ~950,000 (DBEDT, 2002). Average groundwater withdrawals are typically between 215 and 225 million gallons per day (mgd) (State of Hawaii, 2002). This large demand for water has led to a number of studies dealing with various components of the aquifer system (e.g. Stearns and Vaksvik, 1935; Takasaki et al., 1969; Hirashima, 1971; Takasaki and Mink, 1982; Hunt, 1996). However, despite these investigations, few studies have attempted to quantify the amount and chemical composition of SGD and its effects on the biogeochemisty of Oahu's coastal environments.

The first major studies of SGD on Oahu were made by Garrison (2003) who concentrated on quantifying the amount and chemical comparison of SGD in a small, relatively pristine embayment (Kahana Bay) on the leeward coast of Oahu. This study found that total SGD (terrestrial derived water + recirculated seawater) was comparable to the amount of riverine input into the bay and that 16% of that amount was terrestrially derived water. Of even greater importance was the fact that fluxes of total dissolved phosphorus (TDP) and nitrogen (TDN) by SGD to the bay were 500 and 200% greater than fluxes via surface water, respectively. This study raised concern that SGD may be an important source of biologically available nutrients to other Hawaiian coastal environments as well.

Objectives of this Research

The incentive for this study was to extend SGD measurement and modeling techniques in order to compare and contrast the magnitude and chemical composition of SGD in the relatively pristine Kahana Bay system (Garrison et al., 2003), with new studies of Kaneohe Bay, a system known to be anthropogenically impacted. Unlike Kahana Bay, watersheds around parts of central and northern Kaneohe Bay are used for agricultural purposes and contain domestic underground cesspools and septic systems which are potential sources of nutrients to the groundwater system (Freeman, 1993). Salinity is used here as a natural chemical tracer to calculate the terrestrial and re-circulated seawater components of the SGD in Kaneohe Bay. Further, this study endeavors to quantify the input of dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) via SGD, which can potentially act as an important nutrient subsidy to several invasive benthic macroalgae that are currently present in the bay. It should be pointed out that dissolved organic nitrogen (DON) and dissolved organic phosphorous are volumetrically significant components of the nutrient flux (Smith et al., 1981) but were not measured in this study.

Lastly, preliminary information on seepage rates and nutrient loading via SGD from two other locations, Maunalua bay on the southeast facing coast of Oahu and

Kealakekua Bay on the southwest (leeward) facing coast of the island of Hawaii are presented. The Maunalua Bay data were collected because there has been abundant invasive macroalgae growth in this area in recent years and terrestrial SGD was previously estimated to be a significant portion of the freshwater input into the bay (Stearns, 1935), although the biochemistry of the SGD remained unknown. Water quality measurements were taken in Kealakekua Bay because previous estimates of terrestrial SGD into this region are quite large (Kay et al., 1977; Dollar and Atkinson, 1992) and could be a potential pathway for nutrients to go from the land to coastal waters.

KANEOHE BAY

Located on the northeast coast of Oahu, Kaneohe Bay is the largest embayment in the Hawaiian archipelago and the northern-most barrier reef complex in the Pacific (Hunter and Evens, 1995). The bay and adjacent watersheds have been extensively studied, due in part to the presence of the Hawaii Institute of Marine Biology, a research facility located at Moku O Loe (Coconut) island in the south bay. Much of the work has dealt with assessing the effects of various anthropogenic impacts (e.g. increased runoff and sedimentation, sewage discharge, over fishing) on the bay water and corresponding coral reef ecosystems.

Geology

The island of Oahu is composed of the eroded remnants of two previously much larger shield volcanoes, the Waianae Volcano to the west and the Ko`olau Volcano to the east (**Fig. 1**). Subsidence of Oahu (~2000 m) occurred during the shield-building phase of these volcanoes (Moore, 1987). Evidence of this subsidence is found in numerous V-shaped submarine canyons on the eastern flank of Oahu that line up with present day subaerial valleys and paleosols and weathered rock found at depth in drill cores (Stearns, 1967, 1974). During and after the Ko`olau Volcano was built, several large landslides occurred ultimately removing approximately 30 to 40% of the eastern sector of the volcano. Evidence of the landslide deposits have been identified to the east of the island of Oahu (Moore, 1964). Coupled with the removal of material from the landslides, fluvial erosion on the eastern flank of the volcano has cut deep stream valleys (100s of meters below sea level) with individual valleys eventually coalescing into U-shaped composite valleys with broad amphitheater heads (Stearns, 1967, 1974). During the

Holocene as sea level rose to its present position, coral reefs and reef-derived sediments along with terrigenous sediments infilled these paleo-river valleys. Kaneohe Bay occupies parts of several of these drowned valleys.

There are three basic geologic units in the valleys adjacent to central and northern Kaneohe Bay, the Koolau basalts and two alluvium deposits. The Koolau basalts are divided into two water-bearing units: a high-level, unconfined, dike impounded unit and a basal, confined, dike impounded unit which are identified by the Hawaiian Aquifer codes 30603212 and 30603211, respectively (Mink and Lau, 1987). The term high-level refers to freshwater that is not in contact with seawater because it is impounded in compartments produced by nearly vertical basaltic dikes (**Fig. 2**). Basal water refers to freshwater that is in contact with seawater and it is this basal water that makes up the Ghyben-Herzberg aquifer system of Oahu (Stearns and Vaksvik, 1935) (**Fig. 2**). Overlying the basalts in stream valleys at elevations below ~200 meters is a separate aquifer that is composed of consolidated noncalcareous alluvium of Pleistocene age which is identified by Hawaiian Aquifer code 30603116 (Mink and Lau, 1987). This material generally consists of mottled brown to red-brown, deeply weathered, poorly sorted, boulders, cobbles, gravel and sand (Stearns, 1938). Near the heads of the valleys, it grades into coarse angular talus and landslide deposits which can carry considerable water (Stearns, 1938). At lower altitudes, in valleys and along the coastal plain, a younger (Holocene) and generally poorly-sorted alluvium overlies the older alluvium. Collectively these two units are referred to as caprock because they overlie and confine the underlying volcanic-rock aquifers (**Fig. 2**).

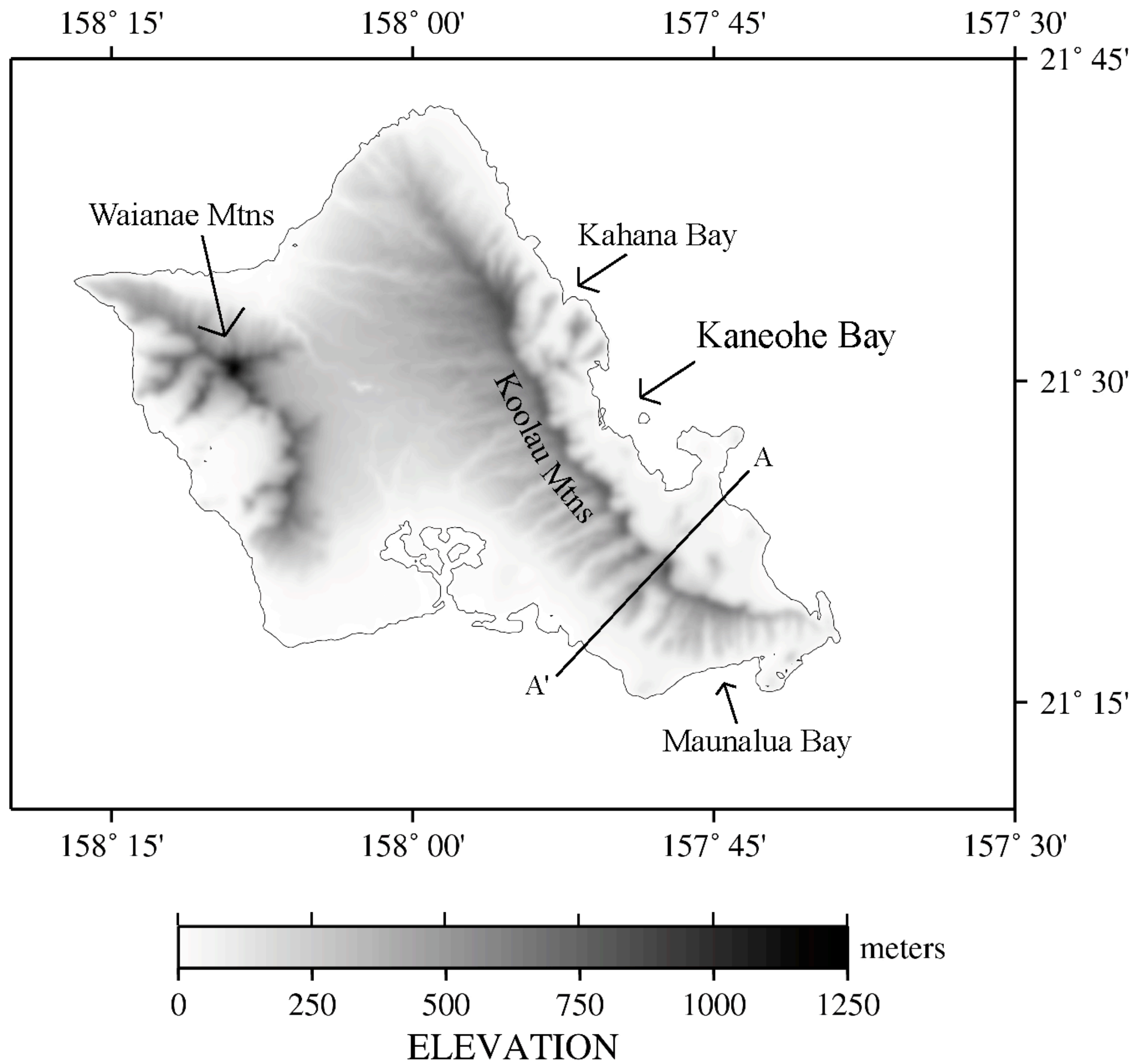


Figure 1. Topographic map of the island of Oahu showing the location of the Kaneohe Bay and Maunalua Bay study sites. The SGD study site of Kahana Bay (Garrison et al., 2003) is also indicated along with the line of cross-section A-A´ shown in figure 2. Image generated using the GMT (2004) and a data grid from Smith and Duennebier (2001).

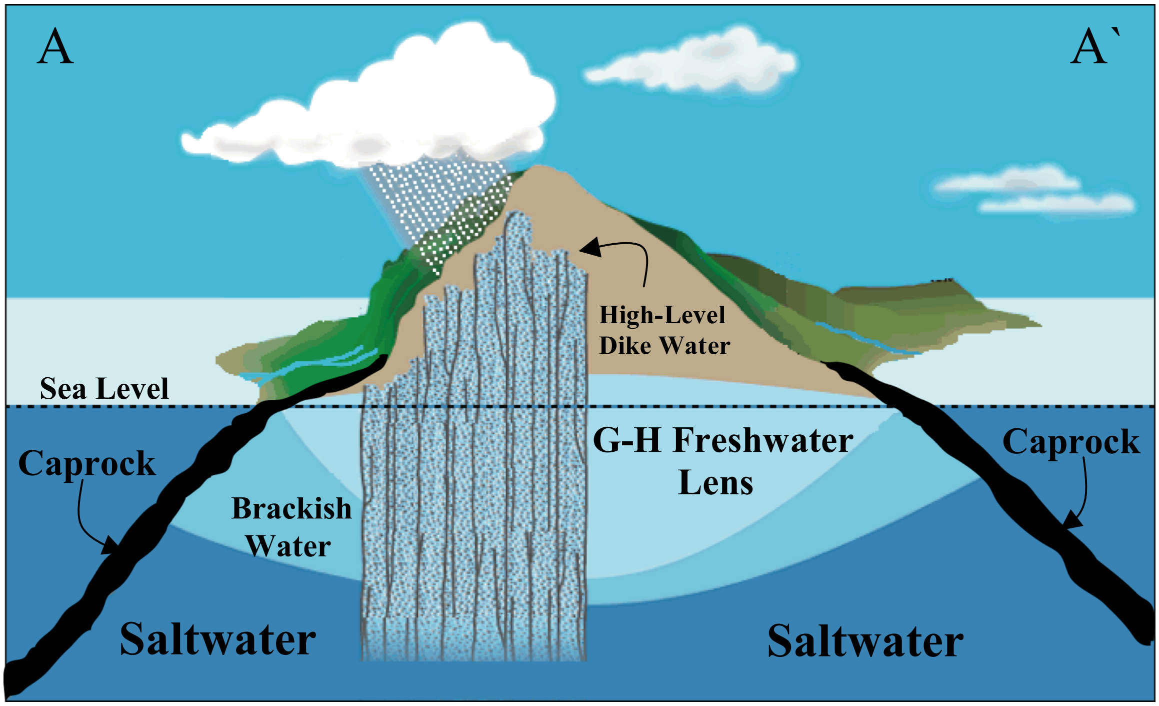


Figure 2. Generalized conceptual model of the hydrogeologic system of the island of Oahu showing the high-level dike impounded water and the Ghyben-Herzberg (G-H) freshwater lens. The field of view is to the southeast, see Figure 1 for line of cross-section (Figure modified from Honolulu Board of Water Supply, 2002).

Physiography

Traditionally, Kaneohe bay has been divided into two parts, an inner bay and outer bay (**Fig. 3**). The outer bay consists of a barrier reef complex and two navigable channels that cut across it, the Mokolii Channel in the north and the Sampan Channel in the south (**Fig. 4**) (Smith et al., 1981). The inner bay consists of a lagoon, patch reefs that rise up from the lagoon floor, and fringing reefs that extend out from the shoreline (Fig. 4). The inner bay has a maximum length of 13.5 km, a width of 4.5 km, and covers an area of approximately 32 km^2 (Smith et al., 1981). Water depths of the inner bay are roughly tri-modally distributed; approximately 47 percent of the bay has a depth between 10 and 16 meters (lagoon floor), 33 percent of the bay is shallower than 1.5 m (patch and fringing reefs and other shoaled areas), and 20 percent is between 1.5 and 10 meters depth (reef slopes) (**Fig. 5**) (Smith et al., 1981).

The inner bay has been further divided into four geographic areas or sectors: outfall (OF), southeast (SE), central (CE), and northwest (NW) based on the amount of surface water runoff that enters each sector and the degree of circulation (Smith et al., 1981) (Fig. 3). The northwest sector of the bay has a more active circulation than that of the southeastern sector because of the deeper channel (Mokolii) in the north and the semi-enclosed nature of the south bay which results in mean water residence times in the north bay of about 3 to 7 days and in the south bay of 13 to 26 days (Sunn, Low, Tom & Hara, Inc., 1976).

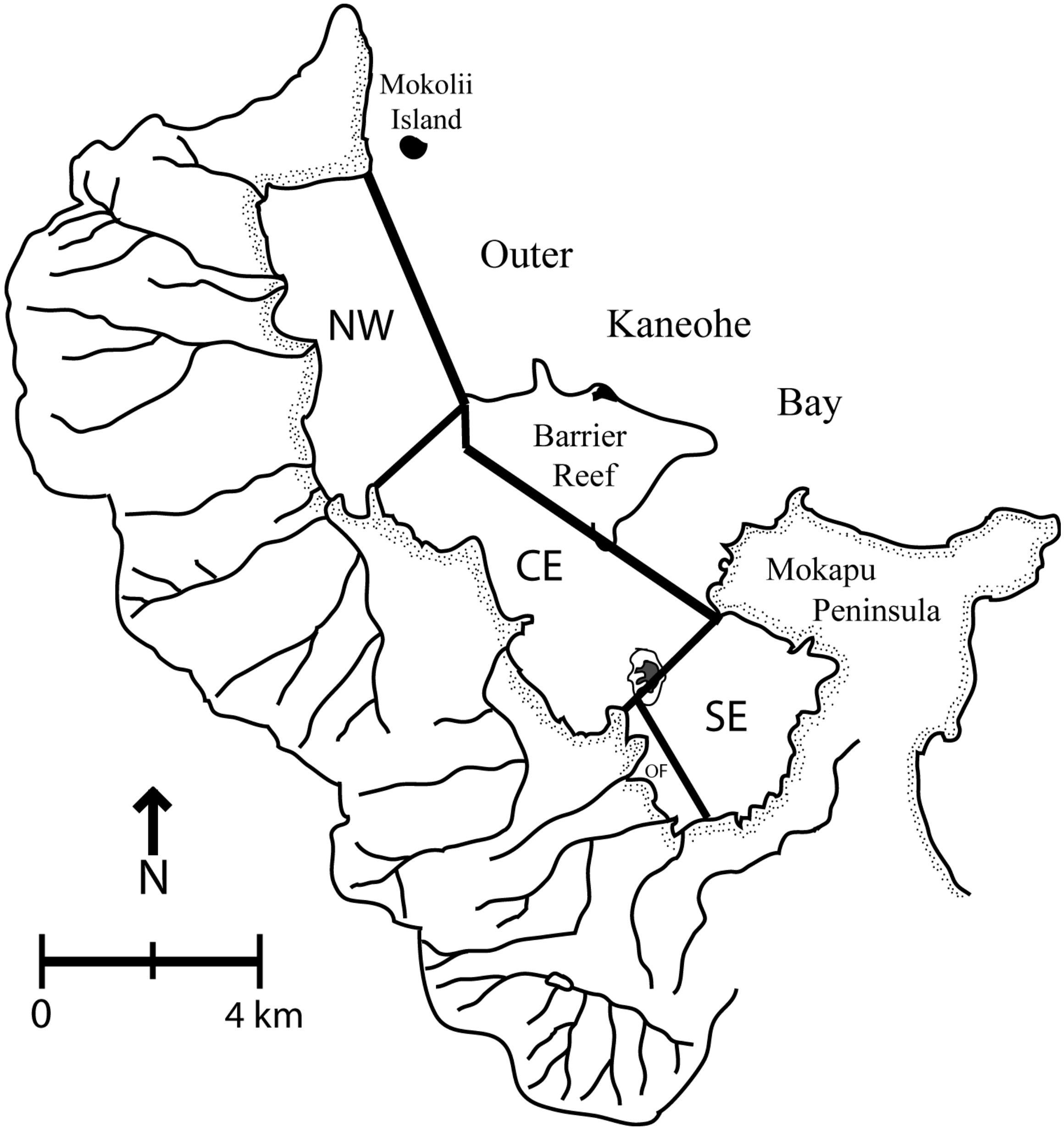


Figure 3. Map of Kaneohe Bay divided into the inner bay and outer bay. The inner bay is further divided into the northwest (NW), central (CE), southeast (SE) and outfall (OF) sectors (After Smith et al., 1981). See figure 4 for a detailed map of the physiography of the bay and figure 5 for a bathymetric map.

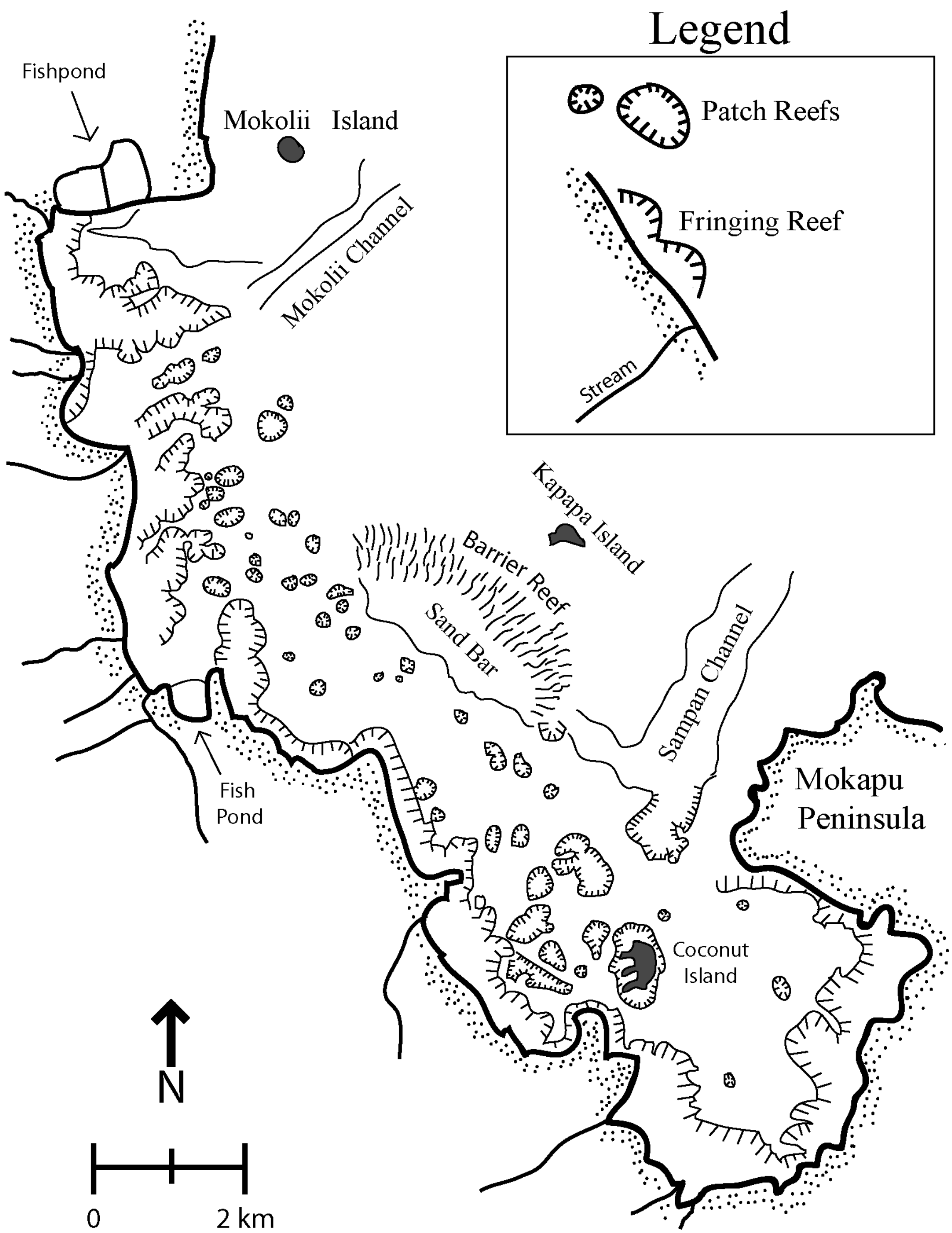


Figure 4. Map showing the basic physiography of Kaneohe Bay. Image drawn from NOS (2004) aerial photos: 2585, 2586, and 2826-2832.

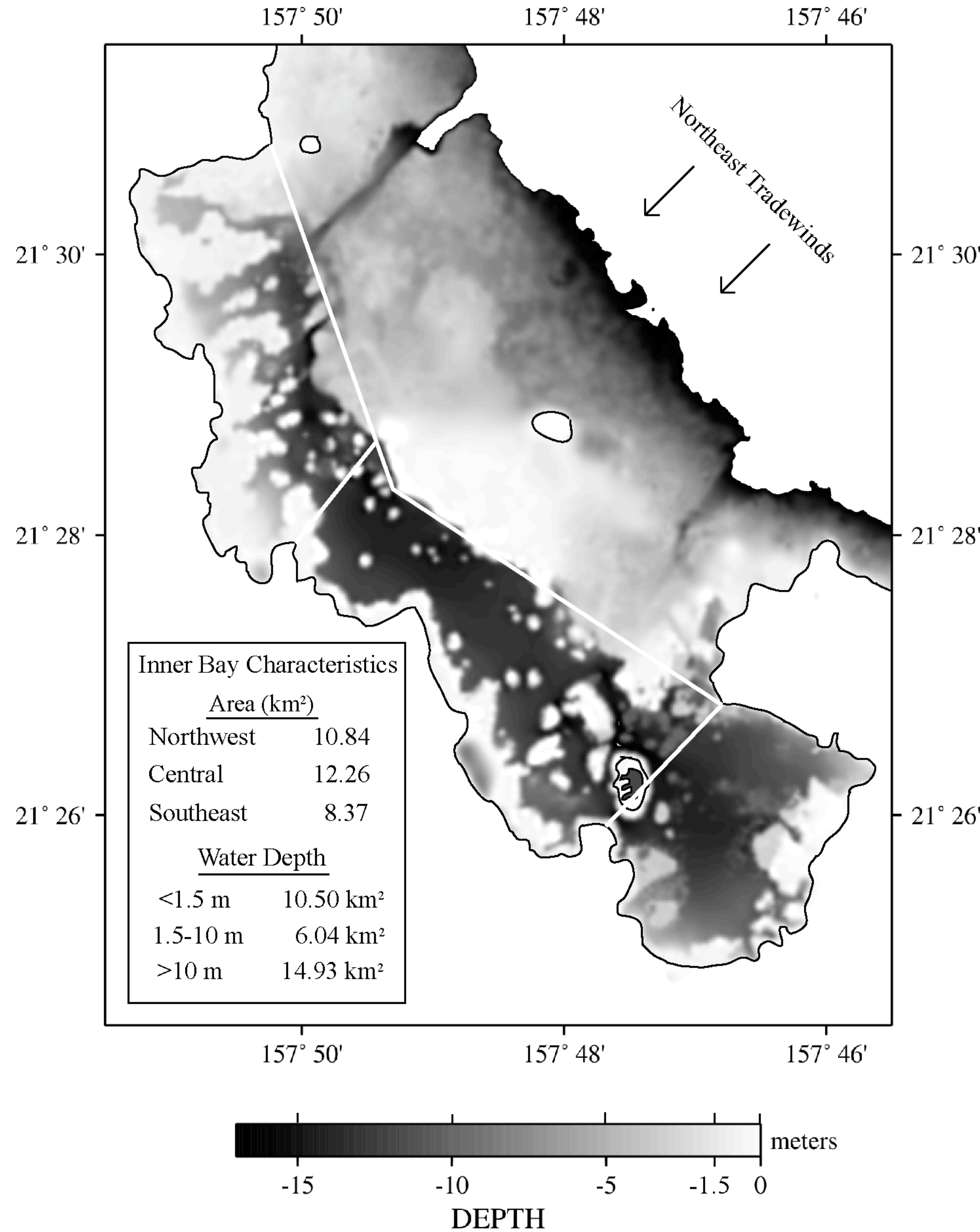


Figure 5. Bathymetry of Kaneohe Bay. Image generated using the GMT (2004) and a data grid from Smith and Duennebier (2001).

Climate and Hydrology

The watershed adjacent to Kaneohe Bay covers an area of approximately 97 km^2 (Smith et al., 1981) and has nine sub-watersheds that contain perennial and intermittent streams (**Fig. 6**). Over 80% of the watershed is under 250 m elevation with the highest peaks approaching 825 m (**Fig. 6**). Data recorded at a weather station "Kaneohe Mauka 781" are used in this study to document the monthly and seasonal trends in temperature and precipitation that occur over the watersheds.

The climate of Kaneohe Bay is semi-tropical with annual mean air temperatures ranging between 18 and 29° C with extremes of 13°C and 34°C (**Fig. 7**). The distribution of rainfall across the Kaneohe Bay drainage area is highly dependent on geographic location and elevation. Median annual rainfall increases from approximately 85 cm on the Mokapu Peninsula in the southeast to over 630 cm at the head of Waikane Valley (Taliaferro, 1959). This strong rainfall gradient towards the mountains is the result of the orographic lifting of moist trade-wind air arriving from the northeast. Average seasonal variations in precipitation occur with a wet season occurring during the months of October thru May and a dry season the remainder of the year (**Fig. 8**). Large differences from the mean values do occur from year-to-year as can be seen by the maximum and minimum monthly values for the 49 year period (Fig. 8), especially during the winter months when torrential downpours (>15 cm/hour) can occur from large Kona (Hawaiian for south) storms and/or hurricanes (Banner, 1968).

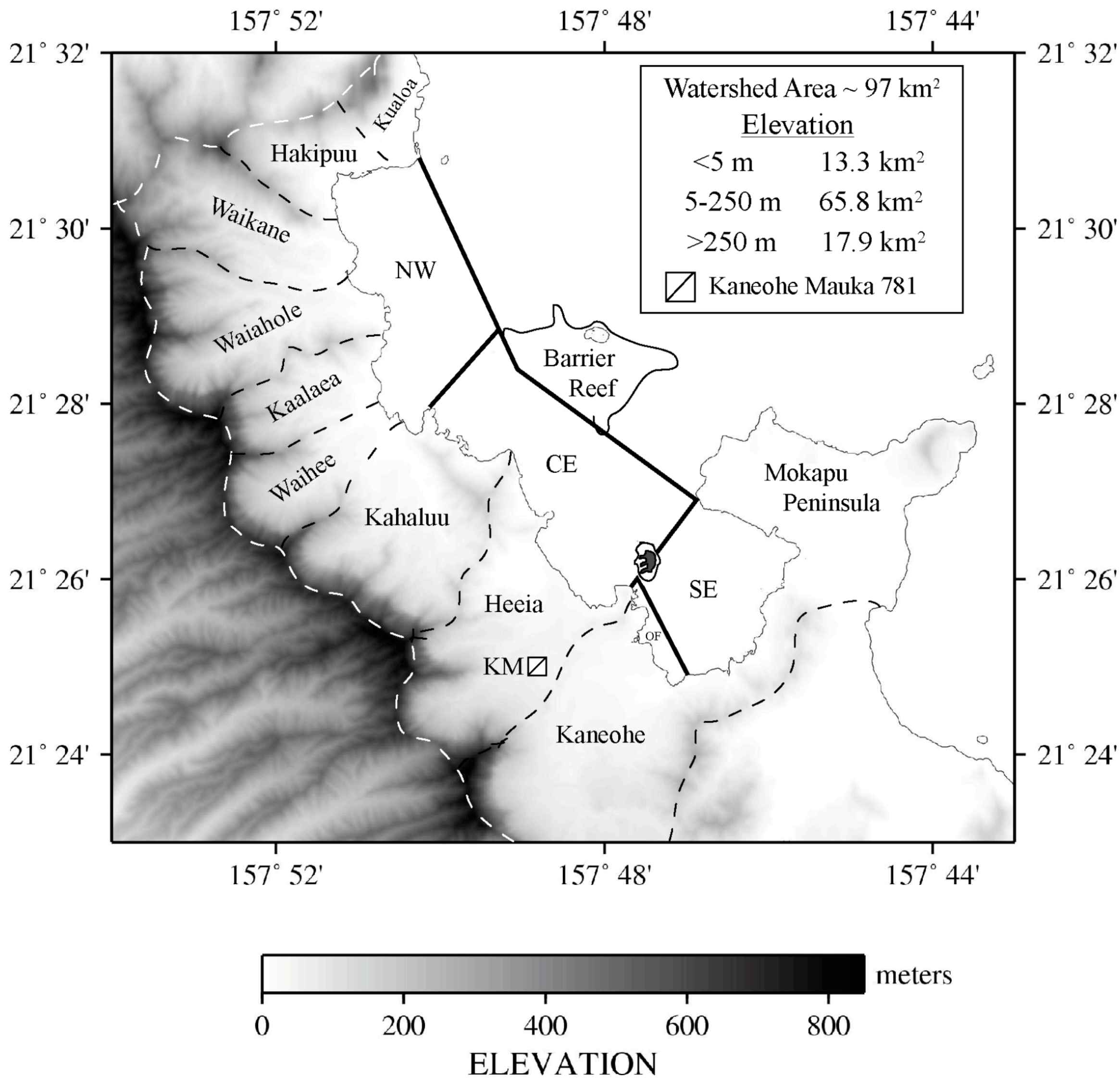


Figure 6. Topographic map of the Kaneohe Bay watershed (area that drains directly into the bay) along with individual sub-watersheds (after Devaney et al., 1976). The upper watershed boundaries depicted here correspond with topographic divides, although the true hydrologic divides are probably located slightly west (Takasaki et al., 1969). The four sectors (NW, CE, SE, and OF) of the inner bay are also shown. Image generated using the GMT (2004) and a data grid from Smith and Duennebier (2001).

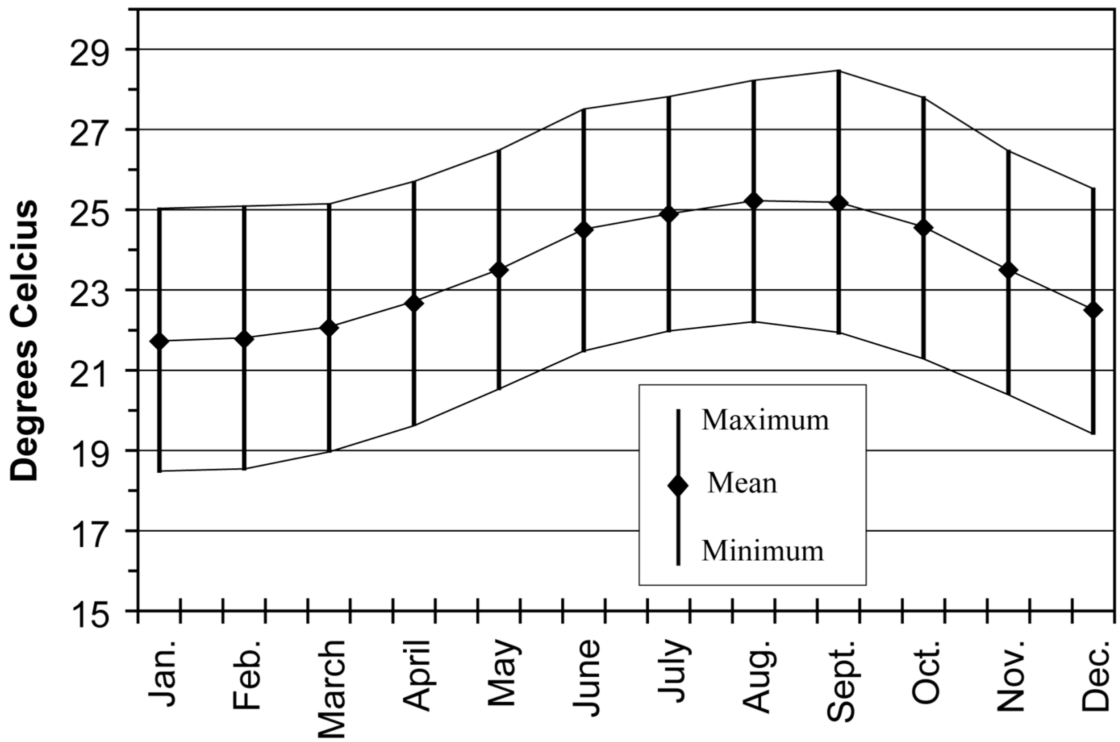


Figure 7. Average monthly maximum, mean, and minimum air temperature values (degrees C) at the Kaneohe Mauka 781 weather station (21° 25′ N, 157° 49′ W) from 1949 to 1998 (WRRC, 2004) illustrating the seasonal changes in temperature in the Kaneohe Bay watershed. See figure 6 for location of Kaneohe Mauka 781.

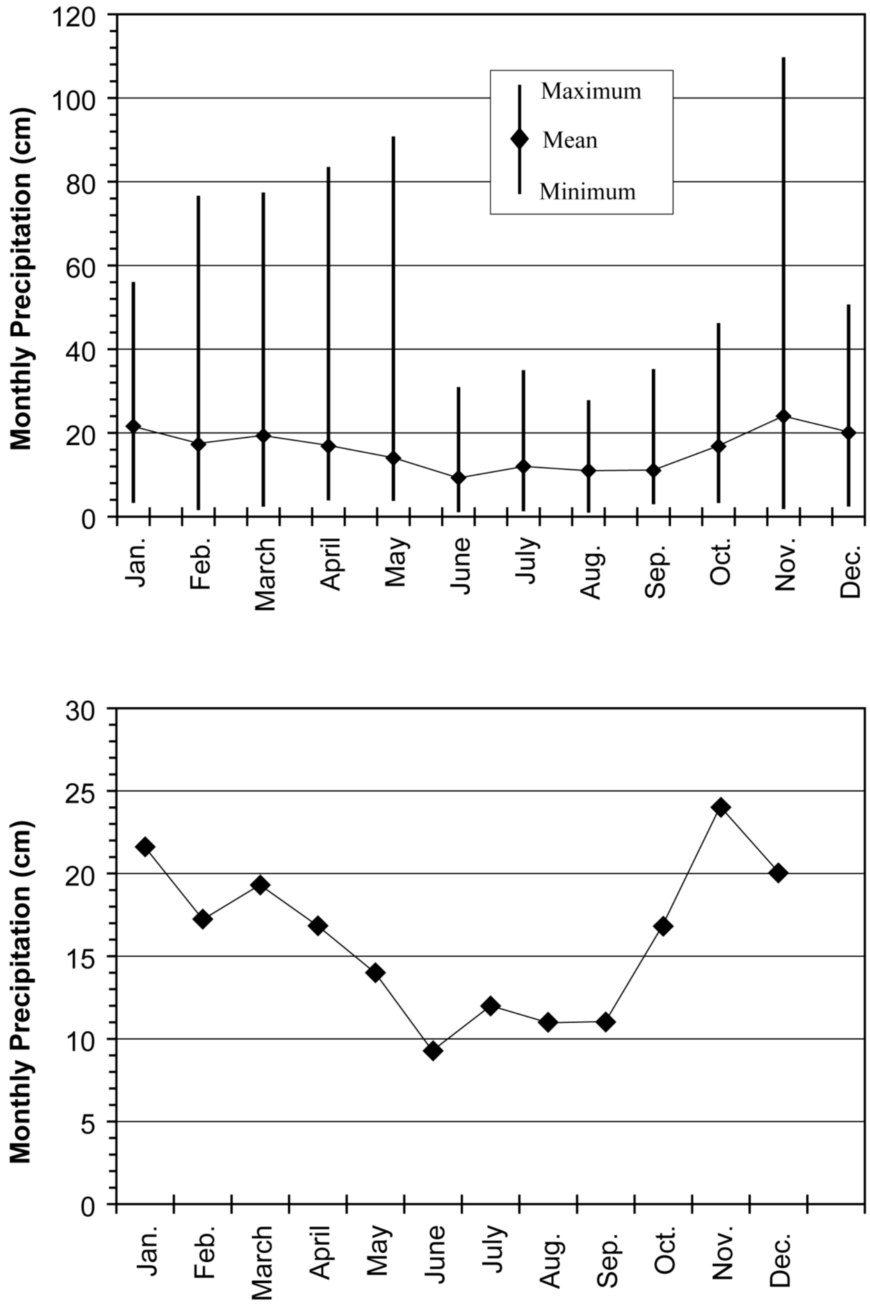


Figure 8. Top: Monthly maximum, mean, and minimum precipitation values at the Kaneohe Mauka 781 weather station from 1949 to 1998 (WRRC, 2004). Bottom: Expanded view of the mean monthly precipitation values showing the seasonal variability from the drier summer months (June-Sept.) to the wetter winter months (Oct.-Apr.).

Takaski et al. (1969) estimated a water budget for the Kaneohe Bay drainage area based on precipitation data over the 25 year period from 1933-1957 (Taliaferro, 1959), evapotranspiration (ET) data estimated from pan-evaporation measurements at 18 stations on four of the main Hawaiian islands, and stream discharges from gauging stations in streams in several of the watersheds. Their water budget was subsequently refined by Cox et al., (1973) who took into account updated stream flow and tunnel/ditch withdrawal measurements and "rough estimates" (by difference) of intermittent stream flow and SGD. Using information on the drainage basin area (103.6 km^2), precipitation rate (6.44×10^8 l d^{-1}), and ET rate (3.22×10^8 l d^{-1}) reported by Takasaki et al. (1969), Cox et al. (1973) estimated the total yield for the entire drainage basin was approximately 3.56×10^8 l d^{-1}. Perennial and intermittent stream discharges accounted for 57.7% of the water yield while tunnel/ditch diversions accounted for 35.8%, leaving 6.4% (2.27×10^7 l/day) for SGD as calculated by difference.

The SGD flux of Cox et al. (1973) was further distributed amongst the geographical sectors (NW, CE, SE, OF) based on the length of shoreline encompassing each sector (Smith et al., 1981). Based on this method, 32% of the 2.27×10^7 l/day occurs in each of the NW and CE sectors, 23% occurs in the SE sector, and 13% occurs in the OF sector.

Historical Anthropogenic Impacts

The human population residing in the Kaneohe Bay watershed experienced considerable growth during the 20th century from less than 5000 people just before 1920 to over 63,000 in year 2000 (Devaney et al., 1976; DBEDT, 2002). This increase in population was accompanied by considerable anthropogenic stresses to the bay. One of the earliest anthropogenic impacts to the bay occurred between the years 1939 and 1945, at which time an estimated 11,630,000 m^3 of reef material was dredged from different parts of the bay for construction of a ship channel and seaplane landing area. Much of the dredged material (4,700,000 m^3) was used as fill for the construction of Marine Corps Base Hawaii (formally Kaneohe Marine Corps Air Station) on Mokapu Peninsula, while 1,700,000 m^3 were documented as being dumped into the bay. The disposal of the remaining 6,600,000 m^3 of dredged material was not officially documented and was believed to be dumped offshore into the ocean as well as into the bay. Dumping of dredge spoils into the bay is supported by bay areas that underwent significant amount of shoaling at locations (away from stream mouths) where no documented disposal of spoils occurred (Hollett and Moberly, 1982).

The most noticeable and detrimental anthropogenic stress to the bay occurred between 1940 and 1978, when primary and secondary treated sewage was discharged into the bay from three separate point source treatment plants, reaching a maximum discharge rate of 18,000 m^3/day in 1977 (Smith et al., 1981). Two of the outfalls that contributed 95% of the total point source discharge to the south bay were later diverted to a deep offshore outfall in 1977-1978, while a third outfall, located in the northwestern area of the bay was removed in 1986. Anticipating the total-ecosystem experiment created by diverting the sewage from the bay, a group of researchers conducted a detail investigation of the physical, chemical, geological, and biological characteristics of the bay from January 1976 through August 1979 (Smith et al., 1981). They found that the sewage acted as a nutrient subsidy to phytoplankton and benthic algae resulting in extensive eutrophication of the bay which led to serious deterioration of the coral reefs.

Widespread growth, up to 1,000 g dry weight/m^2 (Soegiarto, 1973), of a green bulbous alga, *Dictyosphaeria cavernosa,* in the central sector of the bay overgrew living coral colonies, with about 24% of the corals in the lagoon portion of the bay being killed (Maragos, 1972). The nutrients from the sewage also supported the development of a benthic community in the southern bay that was dominated by filter-feeding organisms such as sponges, barnacles, tunicates, and zoanthids, which overgrew many of the former coral reefs (Laws, 2000). Although hermatypic corals are also filter feeders, they derive most of their nutrition from their algal symbionts rather than from plankton (Laws, 2000). Therefore, the sewage discharge stimulated dense populations of plankton which favored the growth of noncoral filter feeders (Laws, 2000). By August 1979, a little over a year after the sewage was diverted, the biomass of both phytoplankton and benthos decreased rapidly (Smith et al., 1981).

A survey of live coral and *D. cavernosa* (green bulbous alga) coverage in 1983 showed that coral coverage in the lagoon as a whole almost doubled compared to a survey of the same 15 sites in 1970-1971 (Maragos 1972), while bay-wide coverage of *D. cavernosa* decreased by 25%, with major population collapses at seven of eight stations in the central bay (Maragos et. al., 1985). The significant decline in *D. cavernosa* in the years following sewage diversion further supported the notion that the sewage dumped into the southern bay acted as a major nutrient subsidy for the thriving algae. In 1990, the same 15 sites were again resurveyed, and it was found that the rapid recovery of coral observed between the 1971-1972 and 1983 surveys did not continue, and at some sites coral abundance had actually declined and *D. cavernosa* almost doubled in percent cover (Hunter and Evens, 1995). The authors suggest that the increase in *D. cavernosa* coverage may have been in response to nutrient subsidies from sediment release and recycling, fixation and export of nutrients from reefs, land runoff, cesspools, municipal sewage bypasses, and human wastes from commercial and recreational boaters (Hunter and Evans, 1995).

Analysis of the water chemistry of the bay during the three year period from 1989 to 1992, over a decade after sewage diversion, showed that nutrient concentrations in the water column were significantly lower than the year following diversion (1978-1979) with dissolved inorganic nitrogen and phosphorous concentrations almost below limit of detection. Chlorophyll *a* concentrations had declined by 35-45 % and Secchi depths increased by 15-35% (Laws and Allen, 1996).

METHODS

The overall approach of this study included the use of salinity as a natural chemical tracer to calculate the amount of SGD into Kaneohe Bay. The concentrations of nitrate (NO_3), ammonium (NH_4), dissolved silica (Si), and orthophosphate (PO_4) were measured to understand further the biochemical composition of the SGD. Due to the wide range of sediment sizes (mud to cobbles) and water depths (0-17 m) (Fig. 5) encountered in the bay and in the adjacent off-shore waters, I used a variety of techniques to collect and analyze water samples (**Fig. 9**). Typical Lee-type seepage meters were emplaced in the seafloor and were used to calculate seepage rates and to collect water emanating from the sediments for chemical analysis (Lee, 1977). Polyvinyl chloride (PVC) piezometers and hand dug pits were used to collect porewater samples in the intertidal and subtidal zones where seepage meters could not be used. A series of cores were taken from the deeper-muddy areas (lagoon) within the bay, from which pore water samples were obtained and analyzed. Continuous water column profiles and discrete measurements of pore water salinity, temperature, and pH were conducted in real time to identify areas of high SGD as well as to track stream runoff. To expand further our study and assess the potential impact of nutrient-enriched SGD on the biological ecosystem, I also conducted benthic surveys to quantify the abundance and distribution of several nonindigenous macroalgae species. Data acquisition occurred from March 2002-April 2004.

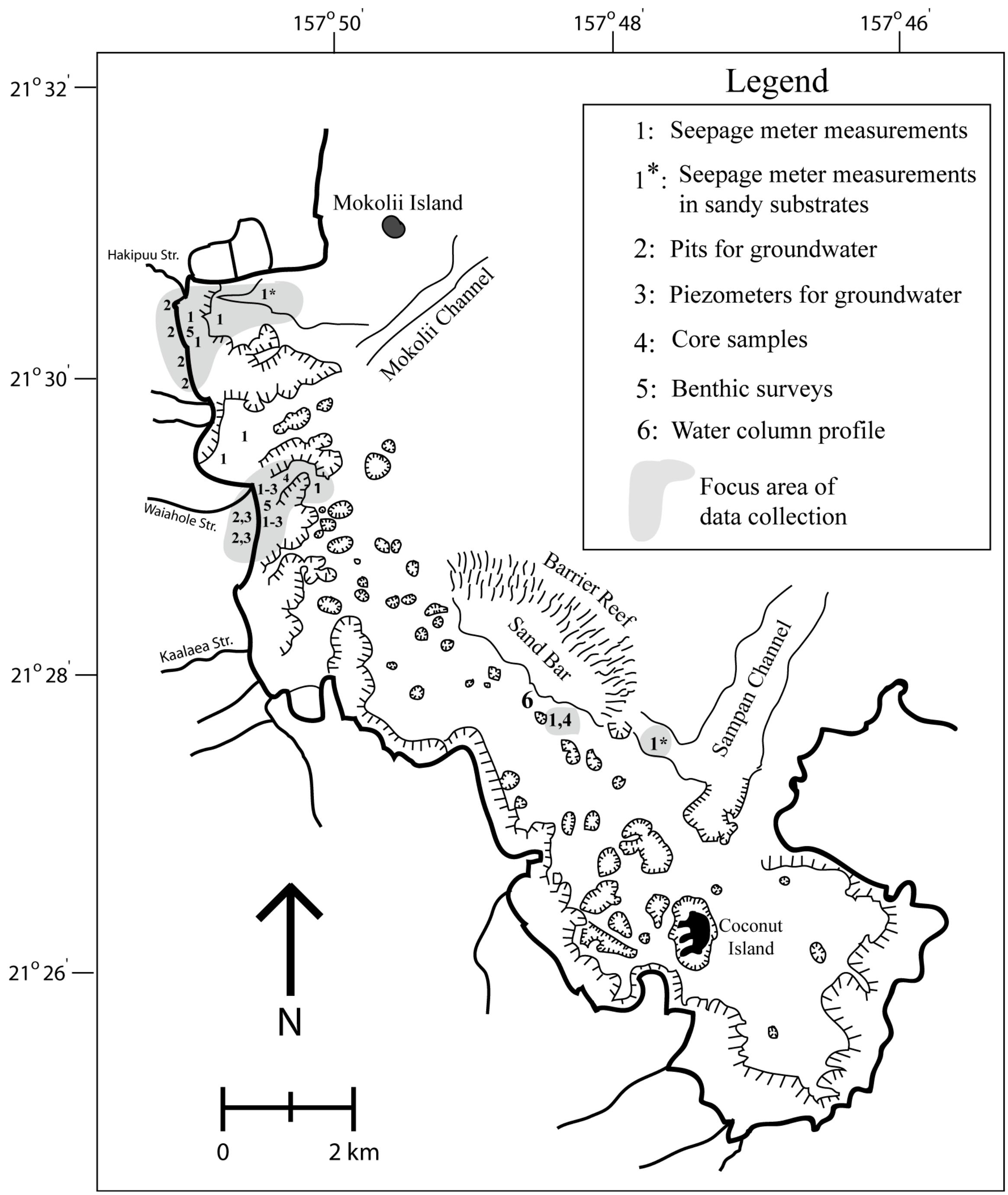


Figure 9. Map of Kaneohe bay showing the location of different sampling sites. See Figure 5 for a bathymetry map of Kaneohe Bay and figure 22 for water column profile.

I chose to focus data collection in two areas of northern Kaneohe Bay (**Fig. 9**). These two locations were chosen for intensive investigation because the substrate close to the shoreline is composed of unconsolidated sediments rather than the consolidated coral reef that lines much of the bay and because water depths in most of the area were great enough to permit the use of our seepage meters. Furthermore, the number of basaltic dikes which tend to impede lateral groundwater flow to the bay decreases from the southern sector of the bay to the north in the direction away from the former caldera (Walker, 1987). The first study area is located adjacent to Hakipuu stream in the northern northwest sector of the bay (Fig. 9). Water column profiles, seepage meter measurements, hand dug pits, and benthic surveys were carried out in this area (**Fig. 10**). The second focus area is located between Waiahole stream and Kaalaea stream also in the northwest sector of the bay. Groundwater samples were collected at this location from seepage meters, hand dug pits, and shallow PVC piezometers (**Fig. 11**). Water column profiles and sediment cores were also taken at this site along with a benthic substrate survey (**Fig. 11**).

To assess if other areas of the bay contained significant amounts SGD, sediment core samples, seepage meter measurements, and water column profiles were taken from the lagoon adjacent to the sand bar in the central sector of the bay and along the Sampan channel in the outer bay (Fig. 9). These study sites were a greater distance from land than the two focus areas in the northern sector of the bay and the Sampan channel site was dominated by a mud-free, moderately to well sorted carbonate sand.

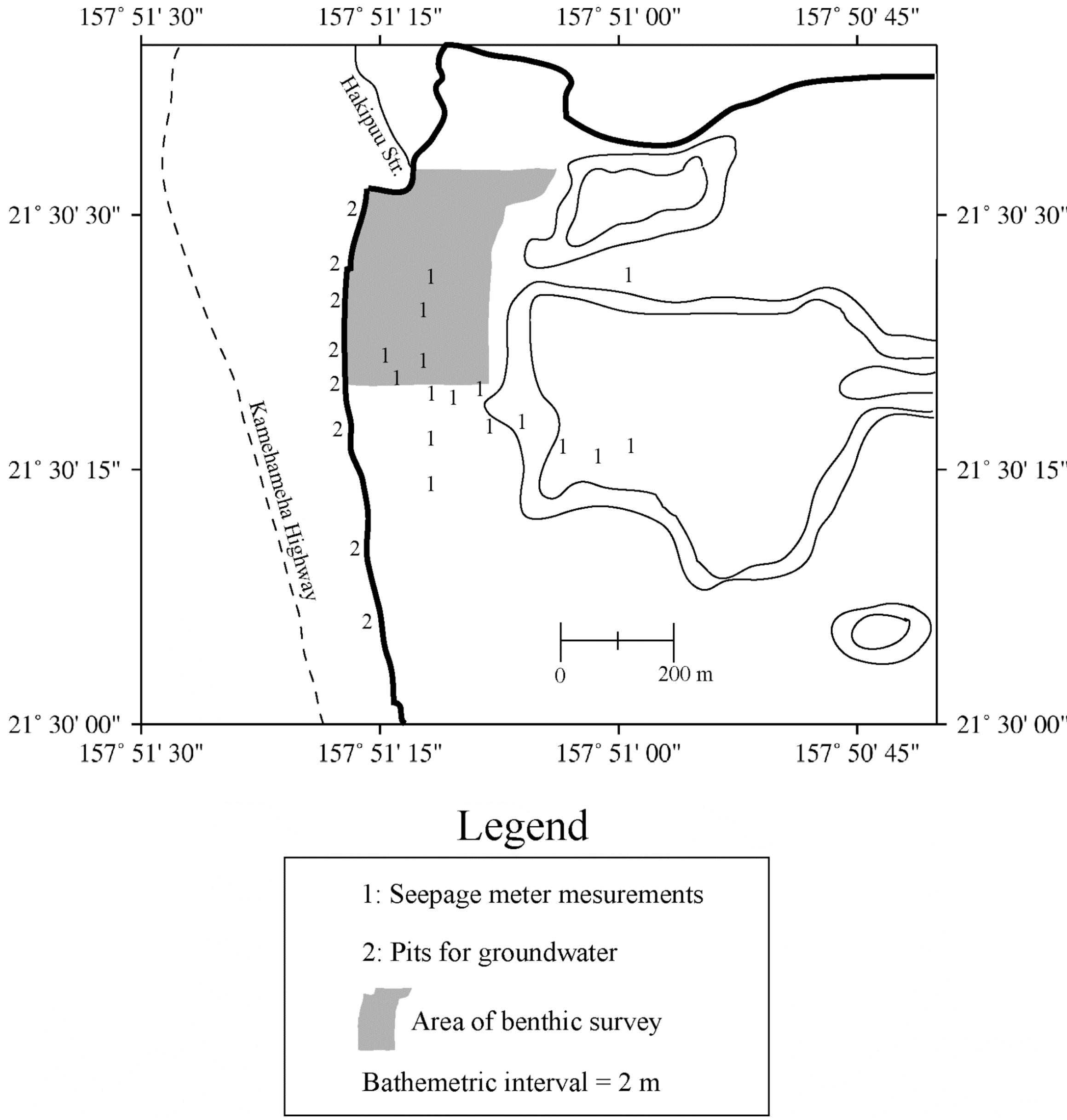


Figure 10. Map of Hakipuu study area showing the locations of different sampling sites. See Figure 18 for details of benthic survey. Image generated using the GMT (2004) and a data grid from Smith and Duennebier (2001).

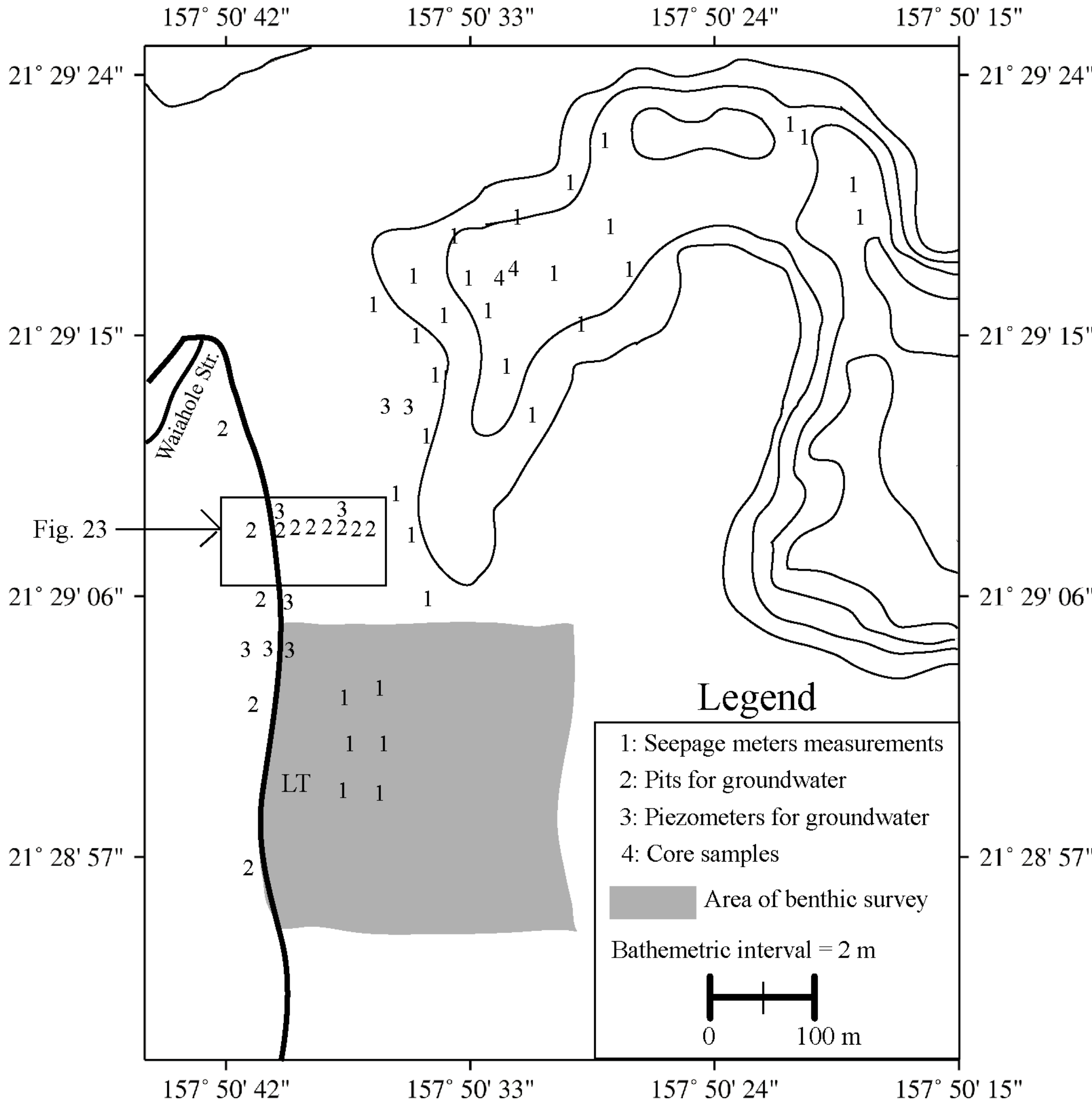


Figure 11. Map of Waiahole study site showing the location of different sampling sites. LT is the location of piezometer-LT shown in figures 25-27. See Figure 18 for details of benthic survey. Image generated using the GMT (2004) and a data grid from Smith and Duennebier (2001).

Analytical Techniques

The majority of nutrient concentrations were determined using standard spectrophotometric flowthrough autoanalyis techniques (UNESCO, 1994) on a five channel Technicon AAII auto analyzer by Kathy Krogslund of the University of Washington Marine Chemistry Laboratory. A limited number of samples were analyzed using similar spectrophotometric flowthrough techniques by David Hashimoto of the Department of Oceanography at the University of Hawaii. Minimum detection limits (MDL) are presented in **Table 1**.

Orthophosphate (PO_4) was analyzed using a modification of the Bernhardt and Wilhelms (1967) method. Ammonium molybdate is first added to a water sample to produce phosphomolybdic acid, which is then reduced to phosphomolybdous acid (a blue compound) following the addition of dihydrazine (or hydrazine) sulfate. The sample is passed through a 50 mm flowcell and absorbance is measured at 820 nm (UW, 2004).

Silicate ($Si(OH)_4$) was analyzed using the basic method of Armstrong et al., (1967). Ammonium molybdate is added to a water sample to produce silicomolybdic acid which is then reduced to silicomolybdous acid (a blue compound) following the addition of stannous chloride. The sample is passed through a 15 mm flowcell and absorbance is measured at 820 mm (UW, 2004).

A modification of the Armstrong et al., (1967) procedure was used for the analysis of nitrate (NO_3) and nitrite (NO_2). For NO_3 + NO_2 a water sample is first passed through a cadmium (Cd) column where the NO_3 is reduced to NO_2. This NO_2 is then diazotized with sulfanilamide and coupled with N-(1-naphthyl)-ethylenediamine to form an azo dye. The sample is then passed through a 15 mm flowcell and absorbance is measured at 540 nm. A 50 mm flowcell is used for the nitrite. The procedure is the same for the NO_2 analysis less the Cd column. Nitrate concentration equals the (NO_3 + NO_2) concentration minus the NO_2 concentration (UW, 2004).

A modification of the Slawyk and MacIssac (1972) procedure was used for the analysis of ammonium (NH_4). A water sample is treated with phenol and alkaline hypochlorite in the presence of ammonia (NH_3) to form idophenol blue (Berthelot reaction). Sodium nitroferricyanide is used as a catalyst in the reaction. Precipitation of Ca and Mg hydroxides is eliminated by the addition of sodium citrate complexing reagent. The sample stream is passed through a 55º C heating bath, then through a 50 mm flowcell and absorbance is measured at 640 nm (UW, 2004).

	[PO_4]	[$Si(OH)_4$]	[NO_3]	[NO_2]	[NH_4]
UW	0.02	0.21	0.15	0.01	0.05

	[PO_4]	[SiO_2]	[NO_3+NO_2]		[NH_4]
UH	0.1	0.2	0.13		0.13

Table 1. Minimum detection limits (μM) of nutrient analysis performed using spectrophotometric methods. UW = Measurements performed at the University of Washington Marine Chemistry Laboratory; UH = Measurements performed at the University of Hawaii Department of Oceanography.

Salinity (psu) values were calculated from specific conductivity measurements using an YSI® conductivity sensor. The sensor was calibrated at the onset of the field sampling period and then approximately every 2 to 3 hours after using a 10,000 mSiemen/cm conductivity solution.

Terrestrial Groundwater

Samples were collected from local streams and piezometers to determine the freshwater end-member tracer and nutrient concentrations. Grab samples were collected from Waiahole, Waikane, and Hakipuu streams during low flow conditions in order to sample base flow (**Fig. 12**). Published results of chemical analysis (Lau et al., 1976; NWIS, 2004) of water taken from wells located in the Koolau and Pleistocene aquifers were used to constrain further freshwater end-member tracer and nutrient concentrations. Groundwater samples were also collected near the shoreline of the bay (Figs 10 and 11) from shallow hand dug pits (**Fig.13**). The pits were dug with a shovel and were drained below the water table with a mechanical hand pump. Groundwater was allowed to flow into the pit and was subsequently sampled with a 1000 ml syringe (**Fig. 13**). All groundwater samples were collected using 0.1 M hydrochloric acid (HCl) washed and deionized water rinsed syringes and stored in pre-cleaned high-density polyethylene (HDPE) bottles. Nutrient samples were filtered using Whatman® GFC filters, stored on ice in a cooler, and frozen to -20 C° at the University of Hawaii.

Seepage Meters

Because of its simple design and relatively low construction and operating cost, seepage meters have become a popular instrument for measuring the exchange of fluids between sediments and the overlying water column. Seepage meters were initially developed in the 1940s to measure seepage from canals (Israelsen and Reeve, 1944), and were later described and made popular by Lee (1977) to measure groundwater discharge into lakes. A seepage meter typically consists of part of a 55 gallon drum that has an exit port on the top to which a collection bag is connected (**Fig. 14**). The drum is inserted into the sediment and a fluid flux (e.g. $l/m^2/day$) is calculated by dividing the volume of water collected in the bag by the surface area covered by the seepage meter by the amount of time the collection bag is attached. Dissolved solute fluxes are calculated by multiplying the fluid flux ($l/m^2/day$) by the concentration (μM) of the solute in the SGD resulting in units of $\mu mol/m^2/day$.

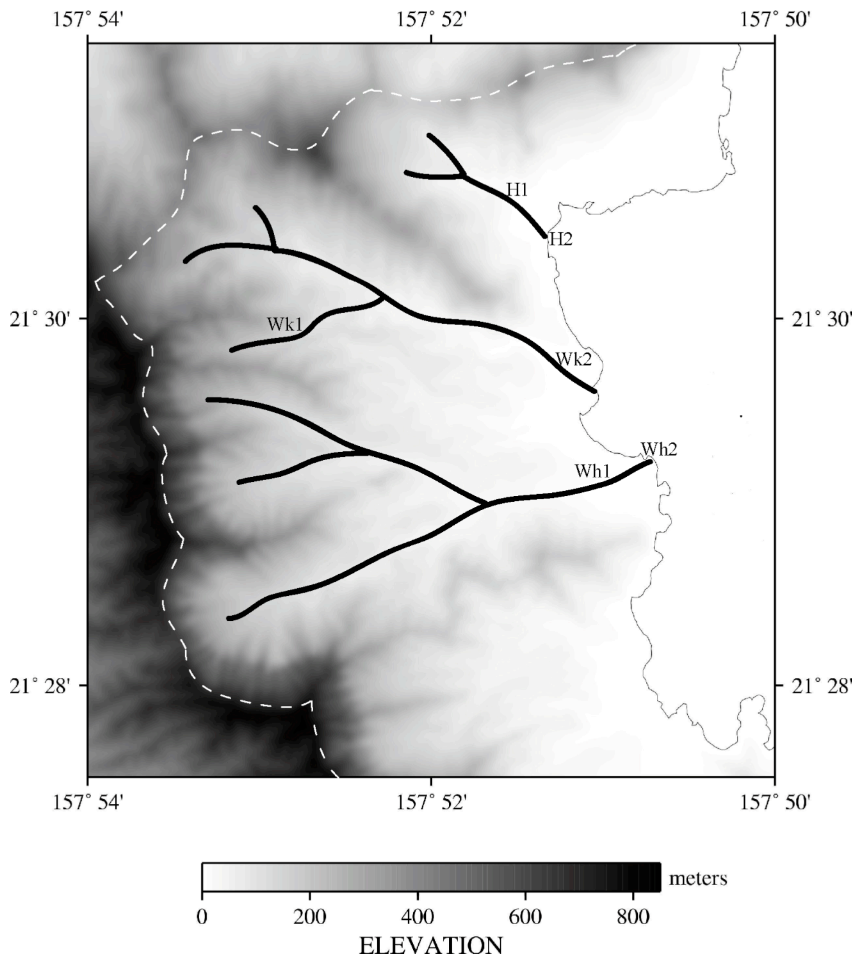


Figure 12. Topographic map showing locations of stream sampling stations in this study: H = Hakipuu stream; Wk = Waikane stream; Wh = Waiahole stream. Dashed white line is the topographic divide. Image generated using the GMT (2004) and a data grid from Smith and Duennebier (2001).

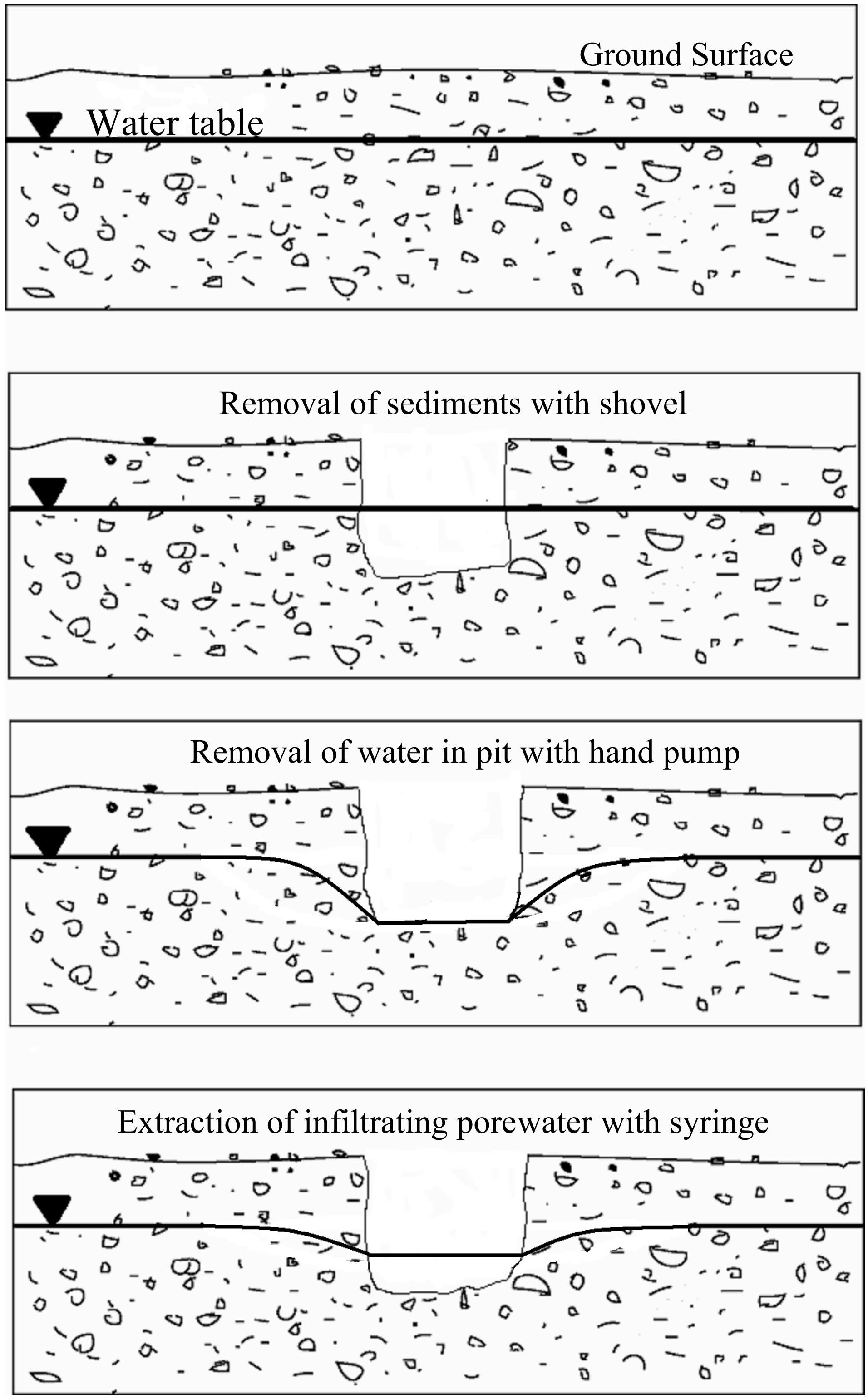


Figure 13. Diagram illustrating porewater extraction from hand dug pits with syringe. Depth to the water table varied between a few cm to 1 m below the ground surface.

The seepage meters I constructed were 15 cm high and covered an area of 0.25 m^2. A 2.54 cm diameter PVC nipple was fitted to the seepage meter to which a 10-liter HDPE sampling bag was attached (**Fig. 14**). The meters were inserted into the sediments to a depth of at least 10 cm and whenever possible to the entire 15 cm and allowed to equilibrate for 18 to 24 hours. Prior to sampling, the sample bag was pre-filled with 1.00 liter ultrapure deionized water (18+ MΩ resistance) to prevent anomalous influx (Shaw and Prepas, 1989) and to supply a volume of water for measuring seepage into the sediments. The bag was then attached to the nipple, after which a ball-valve was opened to allow fluid flow between the seepage meter and collection bag. A goal was to have the bags filled with at least 3 liters of analyte, at which time the ball-valve was closed and the time recorded. On the boat, the volume of water in the bag was measured using a 1-liter graduated cylinder.

At the Hakipuu study site, 15 seepage meter sampling sites were established that extended from ~50 m offshore in water depths <2 m out to a distance of 500 meters in water ~ 4 m deep (Fig. 10). At the Waiahole site, over 30 seepage meter sites were used that went from ~ 60 m offshore in water <2 m deep out to a distance of 600 meters in water ~7 m deep (Fig. 11). Bottom water samples were also collected adjacent to the seepage meters which are used as the marine water end-member tracer concentrations for mixing calculations. Measurements of the bottom water salinity, pH, and temperature were done using an YSI® 600 XLM probe. Samples analyzed for nutrients were filtered using Whatman® GFC filters, stored on ice in a cooler and subsequently frozen (-20°C).

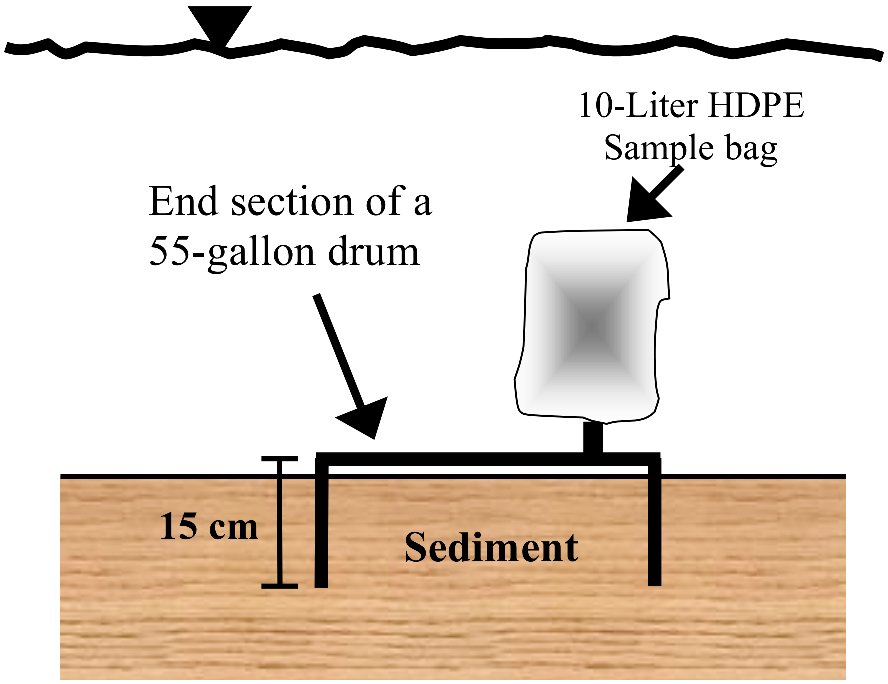


Figure 14. Schematic diagram of seepage meter. The seepage meters were 15 cm high and covered an area of 0.25 m^2.

The flux of freshwater in the shallow (<2 m depth) nearshore environment was calculated using a simple mixing model (after Garrison et al. 2003) assuming salinity is a conservative tracer:

$$C_{SGD} = (f_{tgw} \cdot C_{tgw}) + (f_{mw} \cdot C_{mw}) \quad (1)$$

$$f_{mw} = 1 - f_{tgw} \quad (2)$$

$$f_{tgw} = (C_{SGD} - C_{mw})/(C_{tgw} - C_{mw}) \quad (3)$$

where C_{SGD} is the salinity concentration measured in fluids collected in seepage meters, C_{tgw} is the mean salinity concentration in the terrestrial groundwater, C_{mw} is the mean salinity concentration in the sea water surrounding the dome, and f_{tgw} and f_{mw} are the fraction of SGD as terrestrial groundwater and marine water, respectively.

Real-time Water Parameters

In order to identify areas of fresh SGD and to track stream runoff, water column profiles and discrete porewater measurements were taken with the YSI® probe at the Hakipuu and Waiahole study sites. Water column profiles were conducted by lowering and raising the probe from the side of the research skiff.

In areas of the bay that became exposed during low tide and thus were unsuitable for the use of seepage meters, shallow hand pits were dug to collect pore water samples (Figs. 10 and 11) in a way similar to the freshwater porewater samples (Fig. 13). The depth to the water table ranged from a few centimeters below the ground surface to >1 m below the ground surface at the high tide line.

To monitor changes in pore water chemistry as a function of time, several piezometers (**Fig. 15**) were installed from 15 m landward of the high tide line to a distance of 50 m offshore (Fig. 10). The piezometers consisted of 5 cm outer-diameter PVC casings which contained 20 to 30, 2 mm diameter holes that allowed water to be exchanged between the casing and the sediments. The depths of the open interval ranged from 5 cm to 2 m below the ground surface. The YSI® probe was inserted into the piezometers and programmed to record measurements at a specified interval of time, usually every 2 to 10 minutes depending on the anticipated length of deployment.

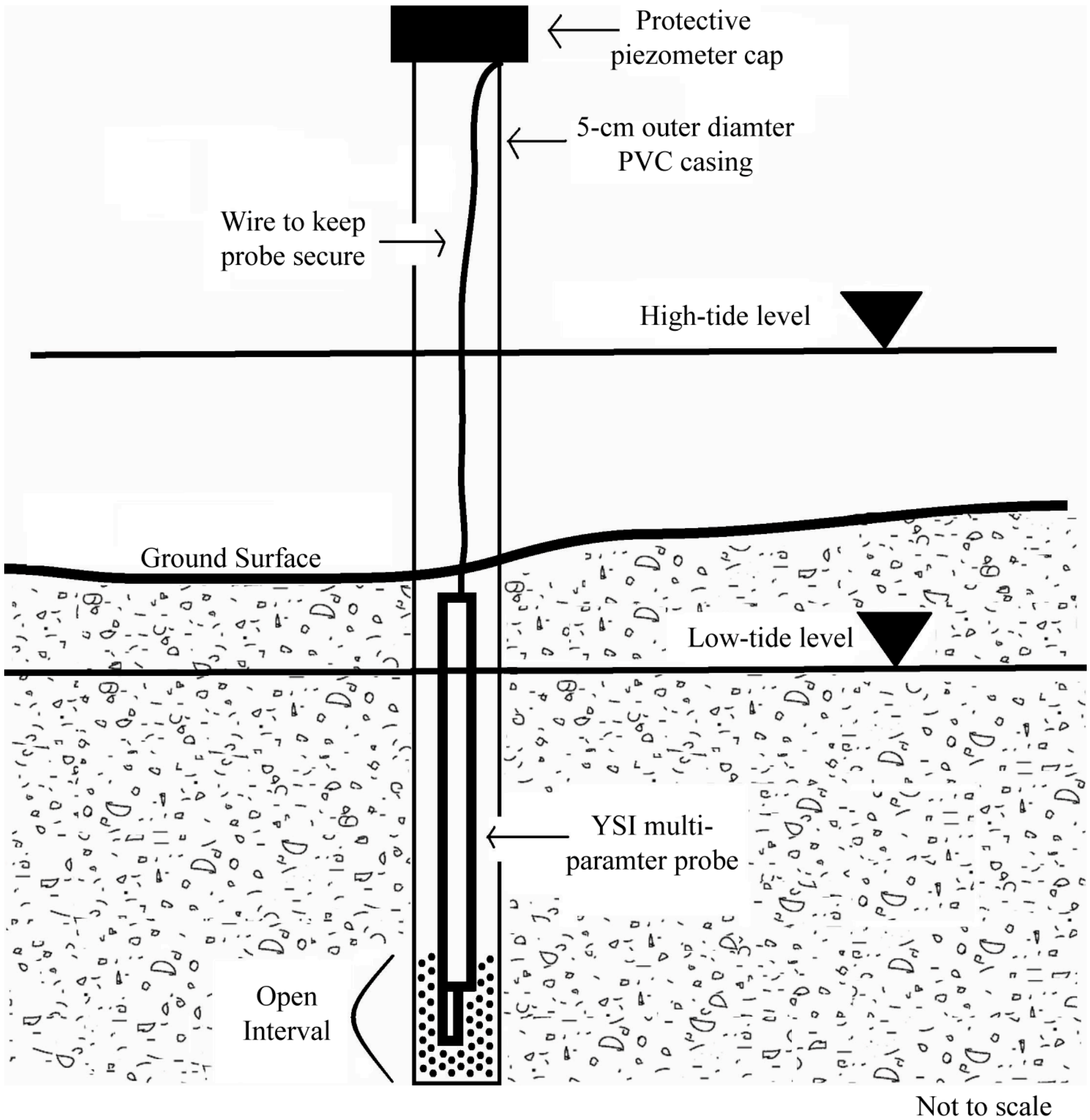


Figure 15. Schematic diagram of PVC piezometer with multi-parameter probe installed. See Figure 11 for piezometer locations.

Sediment Cores

Sampling Techniques

Push cores were taken at 2 different sites in the NW and CE sectors of the bay (Fig. 9). The core liners were either composed of clear acrylic or PVC and ranged in diameter from 5 to 10 cm. The liner was inserted by SCUBA divers as slowly as possible as to not disturb the sediment to a sufficient depth to either fill the entire liner with sediment or until the sediments became too compacted or lithified as to no longer allow penetration. A sheet of Parafilm® was placed over the top of the core liner to help create a good seal and a plastic cap was placed over the core liner at which time it was pulled out of the sediments. Once the core was extruded from the sediments, another plastic cap was placed over the bottom of the core liner. On the research skiff, the core was photographed, the ends further sealed with tape, and the sediment-water interface was marked on the core liner in order to measure any compaction that might occur until the core was processed. The cores were transported back to the University of Hawaii and were processed within a few hours of collection.

Pore water samples were extracted from the sediment cores using a pore water squeezer similar to the one described by Reeburgh (1967). A tapered rubber stopper attached to a PVC pipe was first used to force the sediment out of the core liner. The bottom cap on the core liner was removed and the rubber stopper was inserted into the core liner and the pipe was pushed upward to force the sediment out of the top of the core liner (**Fig. 16**). The sampling interval length (3-10 cm) was chosen based on the sediment type, the diameter of the core, and the volume of analyte needed for a particular analysis (salinity = 15 ml, nutrients = 25 ml). The outer 1 to 2 cm of the core sample was removed from the extracted sediment sample to remove any material that might have been smeared during the coring process.

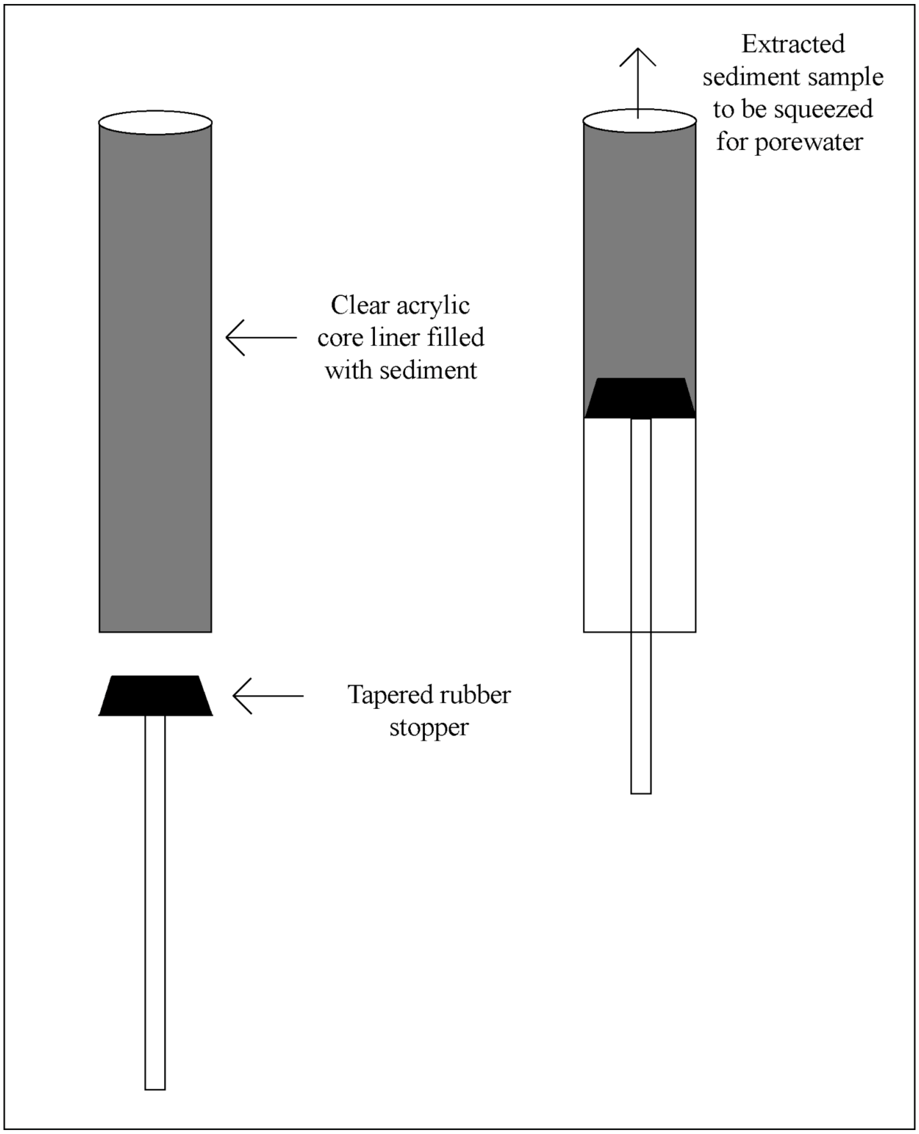


Figure 16. Diagram illustrating the extraction of sediment from a core liner. The extracted sediment sample is then placed in a Reeburgh (1967) type porewater squeezer. See Figure 17 for porewater squeezer schematic.

The extracted sediment was then placed between the two plastic cylindrical cases that make up the porewater squeezer (**Fig. 17**). The bottom case in which the sediment is placed has a small drainage port which is overlain by a mesh screen and a piece of Whatman® GFC filter paper. A thin rubber sheet (dental dam) is placed on top of the bottom case containing the sediment sample which is then covered with the top solid plastic case that has an inlet gas port (**Fig. 17**). The two pieces are sealed with a C-clamp, and pressurized with bottled gas (N_2). The gas pressure forces the rubber membrane down on the sediment, forcing the porewater through the filter and out of the bottom exit port into an attached syringe. Pressures less than 100 psi were used and the length of time of squeezing was typically 10 to 15 minutes per sample. All porewater samples were extracted in an ambient air atmosphere.

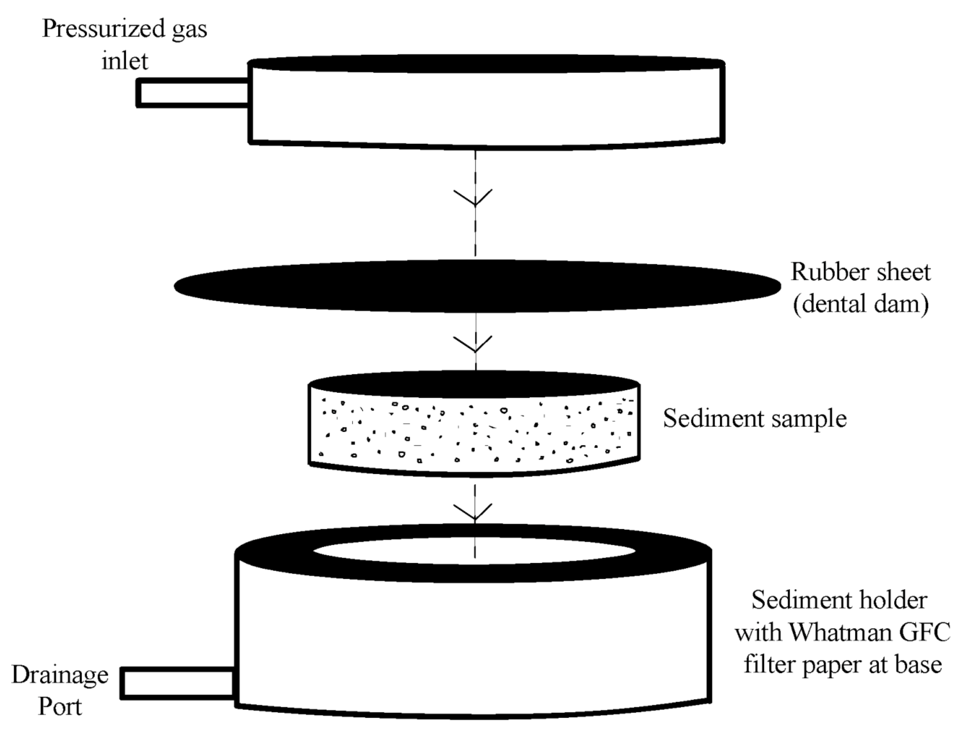


Figure 17. Schematic diagram of Reeburgh (1967) type porewater squeezer.

Numerical Modeling

A one-dimensional advection-diffusion model was applied to the observed salinity porewater concentration profiles to estimate seepage rates assuming that

$$\text{salinity (ppt)} = 1.80655 \times \text{chlorinity} \quad (4)$$

where chlorinity is defined as the mass in grams of chloride ions that can be precipitated from 1000 g of seawater by Ag^+ and that the $[Cl^-]/[\text{salts}]$ is constant. Equation (4) can be rewritten as:

$$1 \text{ ppt} = 15.6133 \text{ mM } Cl^- \quad (5)$$

The model assumes that the system is in steady-state, the diffusion rate is uniform with depth, and no sources or sinks of the chemical species are present.

The concentration of a solute with depth for a given flow rate has been described by Bredehoeft and Papadopulos (1965) as

$$C(Z) = C_1 + (C_1 - C_2)(e^{-V*Z/Ds} - e^{-V*Z_1/Ds})(e^{-V*Z_1} - e^{-V*Z_2/Ds}) \quad (6)$$

where C(Z) is the concentration at depth Z, C_1 is concentration at Z_1, C_2 is the concentration at Z_2, V is the flux rate in m/s and D_s is the whole sediment diffusion coefficient in m^2/s. If one assumes that C_1 is the concentration at Z = 0 (sediment-water interface) and let Z_2 go to infinity, then (Langseth et al., 1988)

$$C(Z) = C_1 + (C_2 - C_1)(1 - e^{-V*Z/Ds}) \quad (7)$$

The whole sediment diffusion coefficient (D_s) is calculated as

$$D_s = D_w / (\phi) (FF) \quad (8)$$

where D_w is the diffusion coefficient in seawater (Li and Gregory 1974), ϕ is porosity, and FF is the formation factor. A FF is the ratio of the measured resistance of the sediment to the electrical resistivity of the interstitial water. A range of porosity values between 73 and 83% were tested in the model corresponding to values taken from previous studies of Kaneohe Bay sediments (Roy, 1970; Hollett and Moberly, 1977). A range of formation factors (FF) was then determined using the relationship between electrical formation factor and porosity (Archie, 1942, Manheim, 1970):

$$FF = \phi^{-n} \qquad (9)$$

where n varies between 1 and 2 (Manheim and Waterman, 1974), .

Diffusive efflux rates of dissolved nutrients were calculated using Fick's First Law for sediments as described by Berner (1980):

$$J = \phi D_s(dC/dz) \qquad (10)$$

where J is the rate of efflux (μmol/m^2/day), ϕ is porosity, D_s is the effective diffusion coefficient (m^2/day) as described above, and dC/dz is the concentration gradient in the sediments (μmol/m^4).

Benthic Surveys

A point line transect sampling technique was utilized to collect information on the abundance of benthic macroalgae (Madsen, 1999). In northern Kaneohe Bay, an 800 x 250 m (200,000 m^2) area was sampled next to Hakipuu valley (Fig. 10) and an 300 m x 300 m (90,000 m^2) area was sampled adjacent to Waiahole valley (Fig. 11). Six main transect lines with an azimuth of 90° were used at the Waiahole site and 8 lines also at 90° were used at the Hakipuu site (**Fig. 18**). On each of the main lines, five or six 25 m transects were laid out at a heading chosen from a random number generator (Random, 2004) (**Fig. 18**). On each of the 25 m transect lines, the substrate was identified at 10 points also selected at random. Chris Stoebenau of the University of Hawaii at Manoa and Hollie Kerr of the University of Wisconsin-Superior assisted with algae identification. Unknown algae species were placed in plastic bags, frozen, and later properly identified. Percent bottom coverage of each substrate type was then calculated.

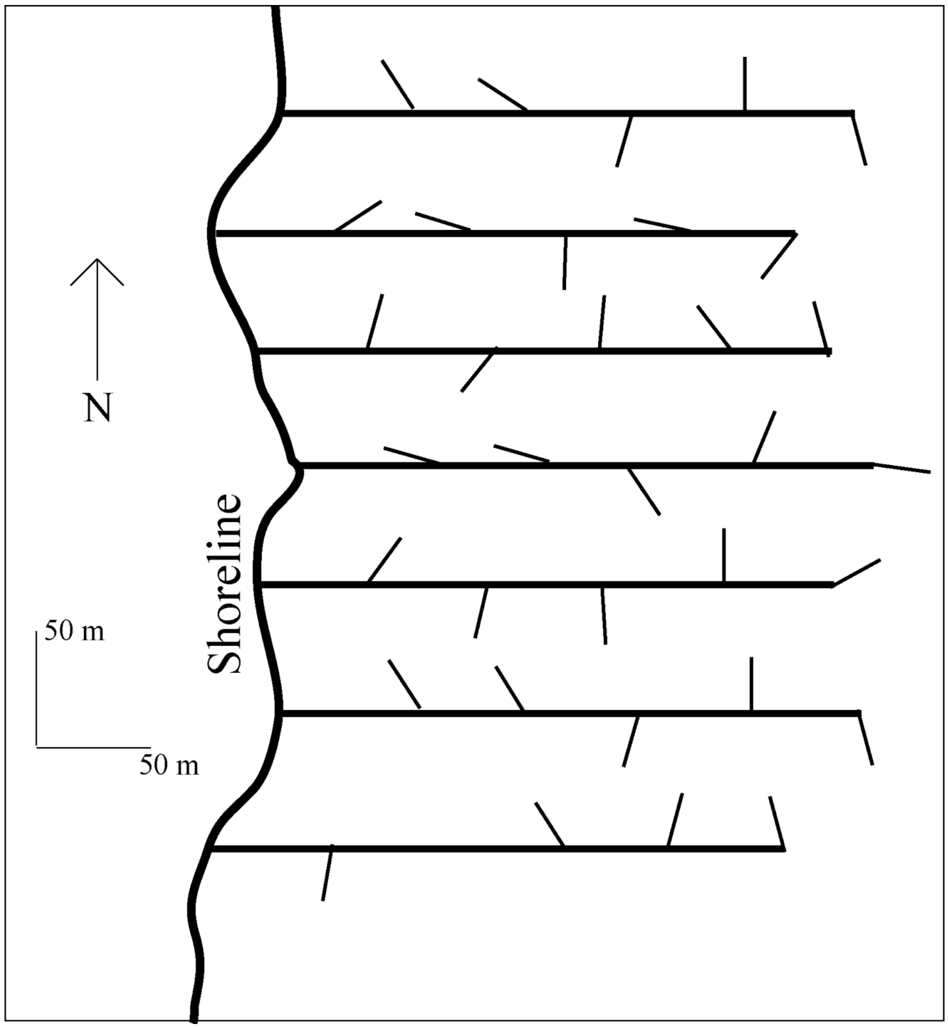


Figure 18. Schematic diagram of the benthic survey transects. The main lines (250 or 300 m long) were laid at an azimuth of 90° and the 25 m transect lines were laid out based on headings from a random number generator (Random, 2004). On each of the 25 m transect lines, the substrate was identified at 10 points which were also selected using a random number generator (Random, 2004).

RESULTS

Sampling locations have been divided into four groups based on water depth and sediment type in order to clarify the results and allow for the extrapolation of measurements to similar areas. The first group consists of sampling locations that were within ~300 m from the shoreline and where the water was less than 2 m deep. The substrate in this region consists of sediment types ranging from poorly sorted muddy gravels to moderately sorted medium to coarse grained sands, predominantly of terrigenous origin. This group is called the nearshore environment (**Fig. 19**). The second group of samples was collected in water depths between 2 and 12 m and where the sediment was dominated by mud and fine-grained sand. This category is referred to as the lagoon (**Fig. 19**). The third group of samples was taken from areas of the bay dominated by medium to coarse-grained carbonate sand and where water depths were between 2 and 5 meters (**Fig. 19**). This category of samples is referred to as reef sand. A fourth environment in which was unable to be sampled adequately due to the hard substrate that occurs throughout the northwest sector of the bay essentially consists of intact coral reefs and coral rubble (**Fig. 19**).

Streams and Terrestrial Groundwater

Mean concentrations of orthophosphate and ammonium were less than 1 µM and salinity values were 0.13 practical salinity units (psu) in baseflow samples collected in streams. Nitrate concentrations averaged 11 µM and silica had the highest concentration of the dissolved species analyzed at about 500 µM (**Table 2**).

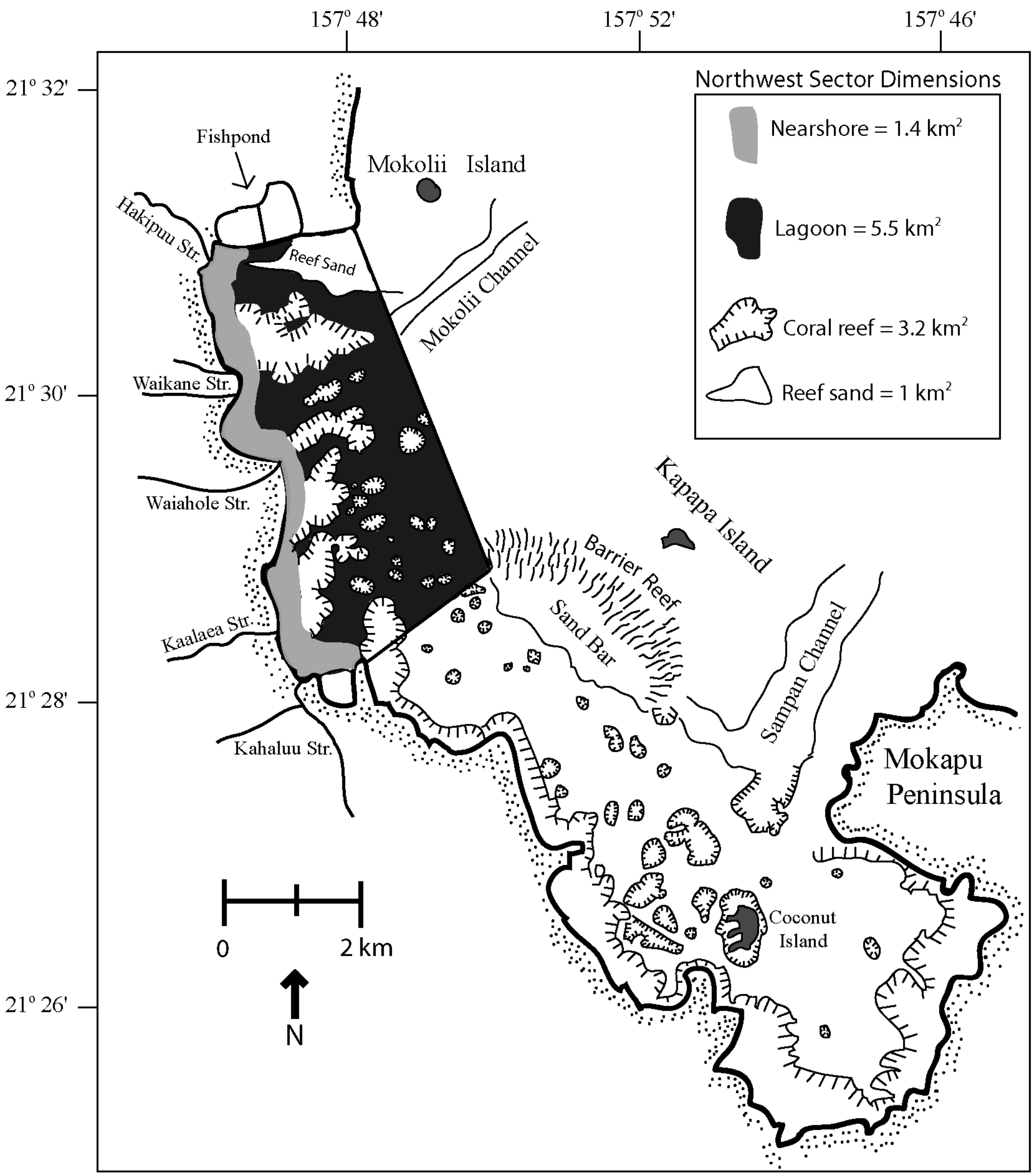


Figure 19. Physiographic map of Kaneohe Bay showing the sampling classification scheme for the northwest sector. Surface areas for each region modified from Smith et al., (1981).

Groundwater samples collected from shallow pits located 1 to 3 meters landward of the high tide line showed more variability in chemical species concentrations (**Table 3**) than did samples collected from streams (**Table 2**). Mean concentrations of orthophosphate, nitrate, and ammonium were greater than samples collected from streams while silica concentrations were slightly less. However, it should be pointed out that two samples collected from shallow pits had nitrate concentrations of ~535 μM which are much greater than any other samples collected in the shallow pits, therefore making the mean nitrate value (122 μM) considerably higher than the median value (1.6 μM). Subsequent water collected at the same location three months later did not have elevated nitrate suggesting that the elevated nitrate measured previously was possibly the result of an infrequent pollutive source (e.g. backed up septic system) or the result of some type of sampling or analysis error.

	Salinity	$[PO_4]$	[Si]	$[NO_3]$	$[NH_4]$
minimum	0.06	0.2	387.7	2.9	< 0.1
maximum	0.62	0.8	955.5	33.4	2.5
mean	0.16	0.5	524.1	11.9	0.9
median	0.09	0.7	459.1	10.6	0.8
stdev	0.20	0.3	198.6	9.9	0.9
n	18				

Table 2. Salinity (psu) and dissolved inorganic nutrient concentrations (μM) of streams (Waiahole, Waikane, and Hakipuu) during baseflow conditions. See Figure 12 for sample locations.

	Salinity	$[PO_4]$	[Si]	$[NO_3]$	$[NH_4]$
minimum	0.07	0.2	159.0	< 0.2	2.5
maximum	0.83	35.4	528.4	534.8	10.6
mean	0.45	5.4	350.1	122.8	5.1
median	0.48	1.0	349.9	1.6	4.2
stdev	0.27	11.3	97.7	228.5	3.2
n	12				

Table 3. Salinity (psu) and dissolved inorganic nutrient concentrations (μM) for groundwater samples collected in northern Kaneohe Bay from shallow pits located 1-3 meters landward of the high tide line. See Figures 10 and 11 for sample locations.

Ambient Kaneohe Bay Water

During most of the year water column profiles showed variable amounts of stratification near stream mouths, with less-dense, lower salinity water located on top of the denser ambient bay water. The magnitude of stratification decreased away from the coastline (**Fig. 20**) and was a function of stream discharge and therefore rainfall. A period of heavy rainfall (~100 cm) on the crest of the Koolau Mountains from November 29 through December 7, 2003 resulted in depressed salinities of ambient bay water out to a distance of at least 2 km from the nearest river mouth (**Fig. 21**). This same location typically showed a subtle decrease in salinity with depth during most of the year (e.g. August 20, 2003) (Fig. 22). This observation reiterates the fact that large storms and the corresponding surface runoff in streams dominates the overall volume of freshwater input into Kaneohe bay (Banner, 1967; Cox et al., 1973; Hoover, 2003).

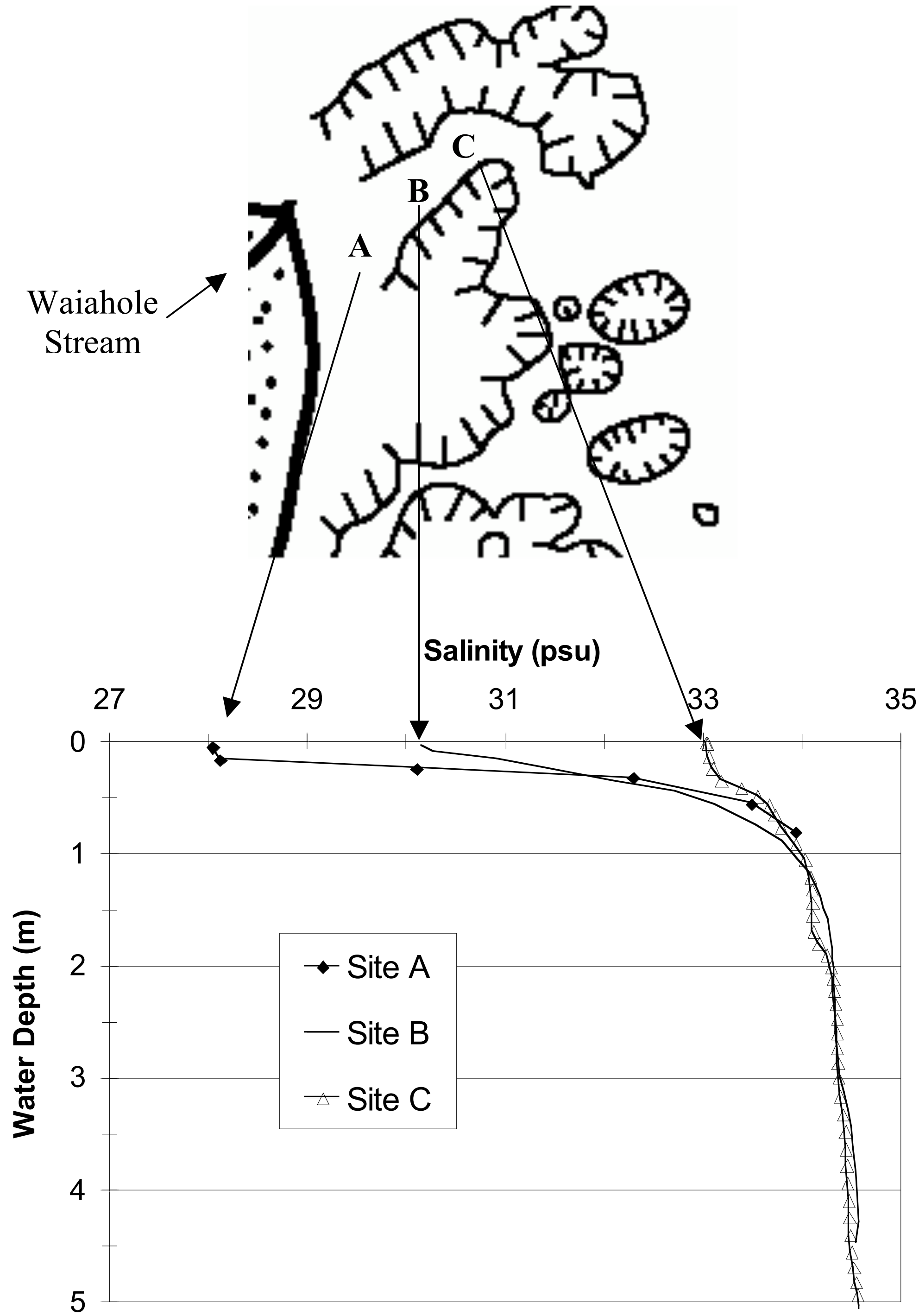


Figure 20. Salinity values (psu) as a function of water depth at three locations in the Waiahole paleochannel showing the freshening of surface waters due to stream runoff on Feb. 1, 2003. See Figure 9 for location of Waiahole stream and paleochannel.

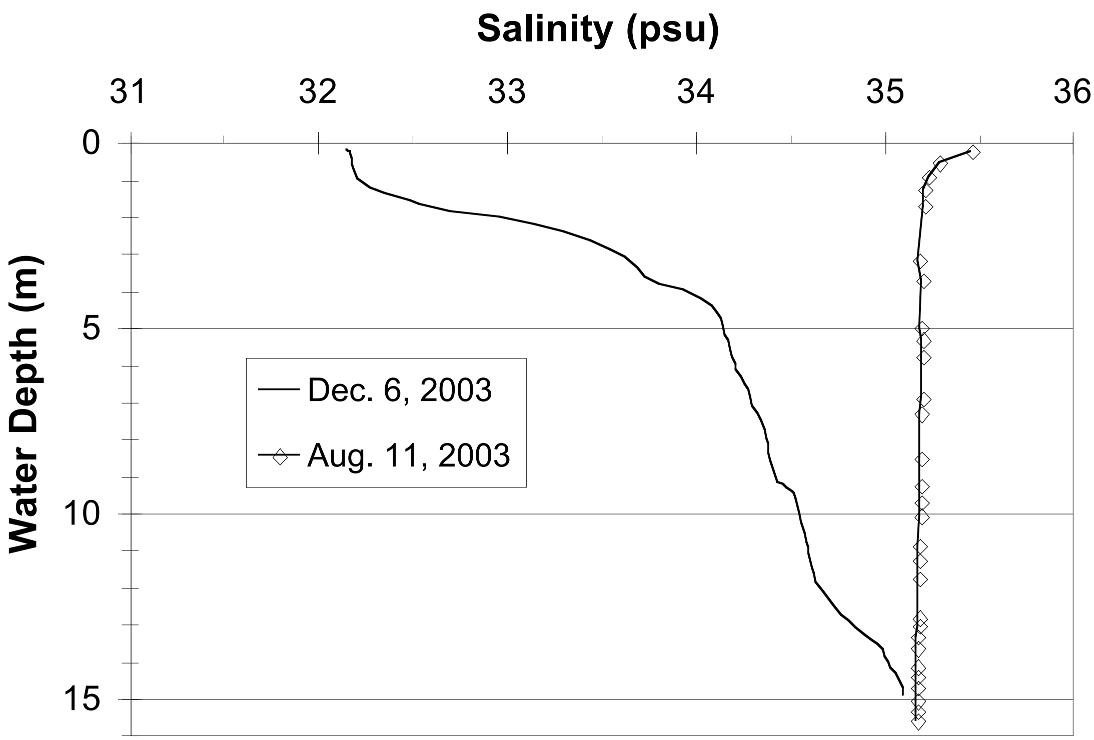


Figure 21. Salinity (psu) as a function of water depth on August 11 and December 6, 2003 at the focus area in the CE sector of the bay adjacent to the sand bar (Fig. 9). Over 100 cm of rainfall was recorded on the crest of the Koolau Mountains from November 29 through December 07, 2003. See Figure 9 for sample location of profile in central bay.

During low stream flow conditions, the water column of Kaneohe Bay is oligotrophic with concentrations of orthophosphate, nitrate, and ammonium near the level of detection of standard spectrophotmetric analysis. Results of ambient surface water and bottom water samples collected in the nearshore environment are presented in **Tables 4** and **5**, respectively. Mean concentrations of orthophosphate, nitrate, and ammonium were similar in both surface and bottom samples and were less than 1 μM. Mean salinity values were slightly lower and silica concentrations were slightly higher in surface water samples than bottom water samples, reflecting the presence of a freshwater lid from stream runoff.

	Salinity	$[PO_4]$	[Si]	$[NO_3]$	$[NH_4]$
minimum	20.86	< 0.1	6.9	< 0.2	< 0.1
maximum	34.65	0.1	106.4	0.6	0.9
mean	30.70	0.1	36.4	0.2	0.2
median	33.89	0.1	14.5	0.2	0.1
stdev	5.29	0.0	37.3	0.2	0.2
n	38	14	14	14	14

Table 4. Salinity (psu) and nutrient concentrations (μM) of all ambient surface water (~10 cm depth) samples collected in the nearshore environment (water depth < 2 m).

	Salinity	$[PO_4]$	[Si]	$[NO_3]$	$[NH_4]$
minimum	33.38	< 0.1	5.6	< 0.2	< 0.1
maximum	35.12	0.2	28.6	0.4	0.9
mean	34.37	0.1	13.1	0.2	0.3
median	34.53	0.1	11.9	0.2	0.1
stdev	0.59	0.0	5.9	0.1	0.3
n	38	25	25	25	25

Table 5. Salinity (psu) and nutrient concentrations (μM) of all ambient bottom water samples collected in the nearshore environment (water depth < 2 m).

Ambient bay water sample analyses collected in the lagoon are listed in **Tables 6** and **7**, respectively. Mean concentrations of orthophosphate, nitrate, and ammonium were similar between surface and bottom water samples and were less than 0.3 μM. Mean silica concentrations were ~9 μM in both surface and bottom waters, and salinity values of surface and bottom water samples were 34.23 and 34.87 psu, respectively.

	Salinity	$[PO_4]$	[Si]	$[NO_3]$	$[NH_4]$
minimum	33.31	< 0.1	8.2	0.2	< 0.1
maximum	34.94	0.1	11.4	0.3	0.2
mean	34.23	0.1	9.5	0.3	0.1
median	34.33	0.1	9.1	0.3	0.1
stdev	0.77	0.0	1.4	0.0	0.1
n	15	10	10	10	10

Table 6. Salinity (psu) and nutrient concentrations (μM) of all ambient surface water (~10 cm depth) samples collected in the muddy lagoon (water depth between 2 and 12 m).

	Salinity	$[PO_4]$	[Si]	$[NO_3]$	$[NH_4]$
minimum	33.98	< 0.1	5.6	< 0.2	< 0.1
maximum	35.09	0.1	13.8	0.3	0.8
mean	34.87	0.0	8.4	0.2	0.2
median	35.03	0.0	7.9	0.2	0.2
stdev	0.44	0.0	3.1	0.1	0.3
n	15	13	13	13	13

Table 7. Salinity (psu) and nutrient concentrations (μM) of all ambient bottom water samples collected next to seepage meters in the muddy lagoon (water depth between 2 and 12 m).

Ambient bay water sample analyses collected next to seepage meters in the reef sand areas (Sampan channel in the central bay) are listed in **Table 8**. Salinity values averaged 35.23 psu and concentrations of phosphate, nitrate, and ammonium were under 0.2 µM. Silica concentrations averaged 3.6 µM.

	Salinity	$[PO_4]$	[Si]	$[NO_3]$	$[NH_4]$
mean	35.28	0.1	3.6	< 0.2	0.1
n	8	2	2	2	2

Table 8. Salinity (psu) and nutrient concentrations (µM) of all ambient bottom water samples collected next to seepage meters in reef sand (water depths between 2 and 5 m).

Seepage Meters

Seepage measurements were taken during 28 different days over the 19 month period from March 2002 to September 2003. A total of 326 individual seepage measurements were made at 58 different sites (Figs. 9, 11, and 12) and 53 of the samples were analyzed for nutrients.

Fluid Fluxes

Seepage measurements taken in the nearshore environment were highly variable with fluid flux values ranging over two orders of magnitude. Median and mean flux values were 385 and 690 $l/m^2/day$, respectively (**Table 9**). Fluid fluxes in seepage meters placed in the muddy lagoon were variable and also ranged over two orders of magnitude with median and mean values of 23 and 57 $l/m^2/day$, respectively (**Table 9**).

Histograms of the seepage meter fluid flux at both the nearshore and lagoon areas are skewed towards high fluxes (**Fig. 22**) suggesting that a two sigma rejected mean (2σ r.m.) value may be more representative of the true flux rate rather than the mean value because the high fluid flux values (Fig. 19) may be an artifact of the seepage meter design (see DISCUSSION section). To calculate a 2σ r.m., all values above or below two standard deviations of the mean are removed from the data set and the mean and standard deviation are recalculated on the revised data set.

Seepage measurements taken in reef sand areas were less variable compared to the other two sites with median and mean values of 798 and 796 $l/m^2/day$, respectively (**Table 9**). It should be noted however, that due to the difficulty in emplacing seepage meters in the reef sand, the number of samples collected was only 16 compared to 237 and 73 for the other two environments.

Location	(n)	mean	stdev	median	mean*	stdev*	min	max
nearshore	237	690	672	385	560	496	16	3313
lagoon	73	57	76	23	24	21	1	312
reef sand	16	796	176	798	737	131	545	1161

Table 9. Fluid fluxes ($l/m^2/day$) for all seepage meter measurements. See Figure 9-11 for sample locations and Appendix A for raw data. Mean* = 2 σ rejected mean.

Chemical Composition of SGD

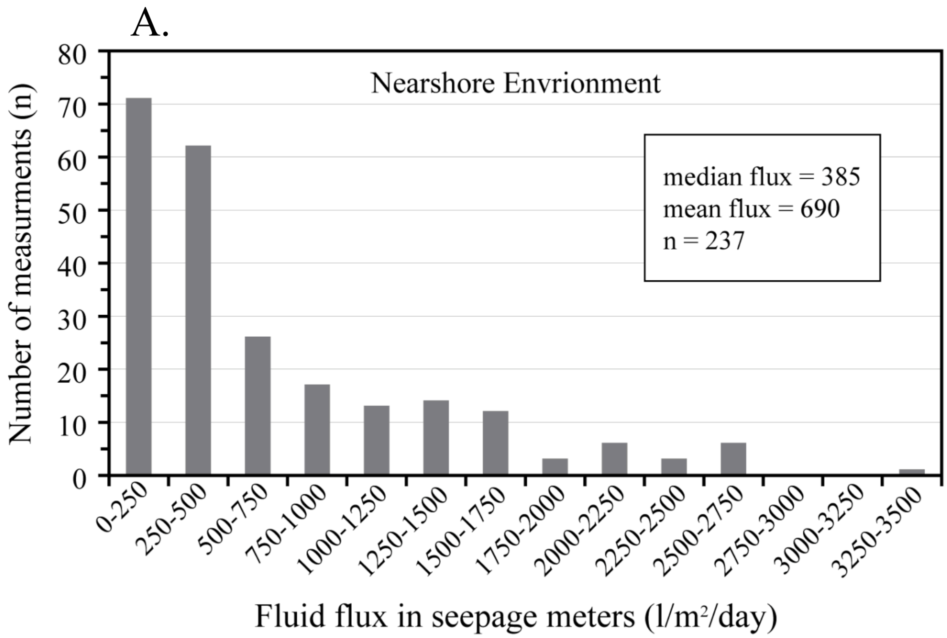
Samples collected from seepage meters placed in the nearshore environment (**Table 10**) had an average salinity value of 33.48 psu which was 1 psu less than the ambient bay water collected next to the seepage meters (Table 5). Phosphate concentrations were low and also similar to bottom water at about 0.1 μM. Concentrations of nitrate in the SGD averaged 1.2 μM, about 5 times greater than the concentration of average bottom water (Table 5). Silica concentrations varied over an order of magnitude from 15.7 to 109.1 μM and averaged 32.2 μM, which is about 2.5 times the concentration of ambient bottom water (Table 5). Concentrations of ammonium were scattered over two orders of magnitude and ranged from 0.1 μM to 19.1

μM with mean and median concentrations of 3.1 μM and 1.0 μM, respectively. These values were higher than the mean and median bottom water ammonium concentrations of 0.3 and 0.1 μM, respectively (Table 5).

	Salinity	$[PO_4]$	[Si]	$[NO_3]$	$[NH_4]$
minimum	29.01	< 0.1	16.5	< 0.2	0.1
maximum	36.87	0.2	109.1	15.6	19.1
mean	33.48	0.1	32.6	1.6	3.1
median	33.24	0.1	31.3	1.0	1.0
stdev	1.84	0.1	14.6	2.4	5.1
n	96	38	38	38	38

Table 10. Salinity (psu) values and nutrient concentrations (μM) of all SGD collected in seepage meters in the nearshore environment (water depths <2 m). See Figures 10 and 11 for sample locations and Appendix A for the raw data.

SGD in the muddy lagoon had similar salinity values (~34.90 psu) (**Table 11**) to the ambient bay water collected next to the seepage meters (Table 7). Phosphate and nitrate concentrations were low (~0.2 μM) and similar to bottom water concentrations. Silica concentrations were greater by a factor of 8 in the SGD (65 μM) compared to average bottom water (8 μM). Ammonium concentrations in the SGD varied over two orders of magnitude in the lagoon from 3.08 to 105.57 μM with mean and median concentrations of 49.57 and 43.10 μM, respectively. Ammonium concentrations in the SGD at these sites were nearly 250 times greater than the ambient water next to the seepage meters (~0.20 μM) (Table 7).



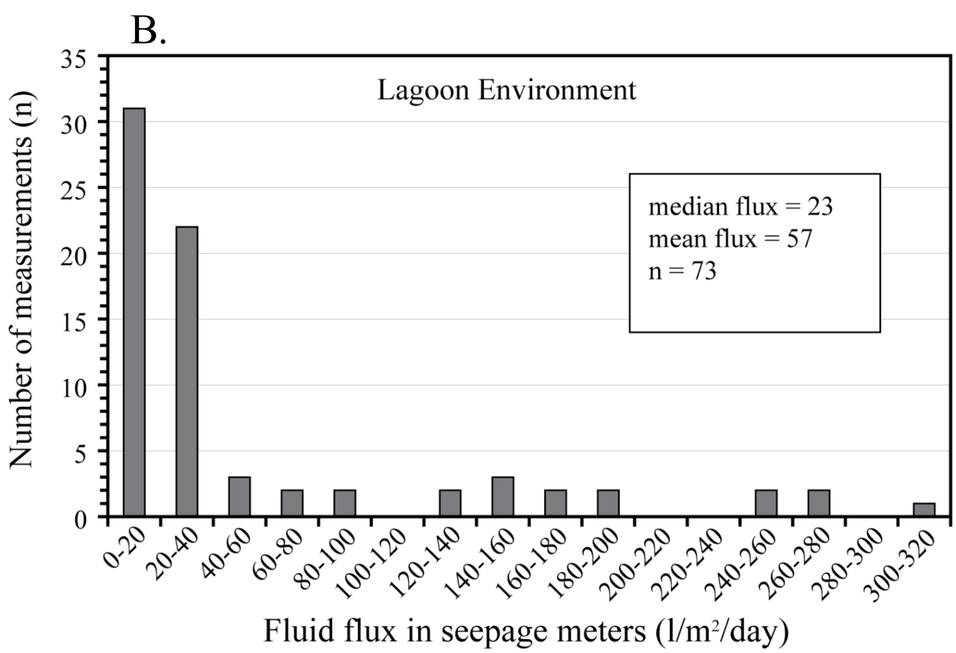


Figure 22. Histogram of fluid flux measurements in seepage meters. A: nearshore environment (water depths <2 m). B: lagoon environment (water depths: 2-12 m). Note the different X and Y-axis for the graphs.

	Salinity	$[PO_4]$	[Si]	$[NO_3]$	$[NH_4]$
minimum	33.69	0.1	26.7	< 0.2	5.9
maximum	35.63	3.0	103.4	0.5	102.6
mean	34.75	0.3	52.3	0.2	41.1
median	34.78	0.1	48.4	0.1	28.4
stdev	0.59	0.7	22.0	0.2	32.1
n	20	17	17	17	17

Table 11. Salinity values (psu) and nutrient concentrations (μM) of all SGD collected in seepage meters in the muddy lagoon (water depths between 2 and 12 m). See Figures 9 through 11 for sample locations and Appendix A for the raw data.

Seepage meter measurements in water depths between 2 and 5 meters in reef sand located in the Sampan channel had similar salinity values (~35.16 psu) to ambient bay water (Tables 8 and 12). Concentrations of nitrate, phosphate, ammonium, and silica were 38, 6, 4, and 1.3 times greater than the ambient bay water next to the seepage meter (Tables 8 and 12).

	Salinity	$[PO_4]$	[Si]	$[NO_3]$	$[NH_4]$
mean	35.19	0.9	4.9	1.9	0.5
n	16	2	2	2	2

Table 12. Salinity values (psu) and nutrient concentrations (μM) of all SGD collected in seepage meters located in reef sand in the Sampan Channel (water depths between 2 and 5 m). See Figure 9 for sample location and Appendix A for raw data.

Freshwater Fluxes

The difference in salinity values between the SGD collected in seepage meters and bottom water collected next to the seepage meters was negligible within the accuracy of the measurement techniques used here at both the lagoon sites and the reef sand sites. It should be kept in mind that the sandy areas had a limited number of samples taken and that a significant amount of terrestrial SGD may occur in these sandy areas of the bay during certain times of the year (e.g. very low tide).

The terrestrial SGD flux was however significant in the nearshore environment and is calculated from seepage meter measurements from the Hakipuu (Fig. 11) and Waiahole (Fig. 12) study sites. Using equations 1 through 3 and assuming a mean marine end-member salinity value of 34.37 psu (Table 5) and a terrestrial end-member salinity value of 0.16 psu (Table 1), the mean SGD salinity value collected in seepage meters of 33.48 psu (Table 10) represents 2.5% terrestrial water. Therefore, multiplying the 2σ r.m. fluid flux (560 l/m^2/day) by 2.5% gives a freshwater flux of 14.0 ± 13.4 l/m^2/day (**Table 13**). Assuming a representative nearshore area of 14 x 10^5 m^2 (Fig. 19), the total freshwater flux to the northern sector of the bay is 19.6 x 10^6 ± 18.7 x 10^6 l/day. This value is 2.8 times greater than the value reported by Smith et al. (1981) for the northwest sector.

Dissolved Nutrient Fluxes

The flux of a particular dissolved solute is the product of the flux rate of water (l/m^2/day) (Table 8) leaving the submarine sediments and the concentration of the solute (μM) in the water (Tables 10 through 12). Due to the variability in the fluid flux measurements and the skewness of data towards very high fluxes (Fig. 20), calculated solute fluxes using the 2σ r.m fluid flux (Table 9) and the mean solute concentration (Tables 10 through 12) are more likely closer to the true solute flux than if the mean fluid flux value is used.

The highest flux of dissolved silica (18,200 μmol/m^2/day) occurred in samples taken in the nearshore environment (**Table 13**). Average ammonium fluxes were higher in samples collected in the nearshore environment (1710 μmol/m^2/day) than those collected in the lagoon (985 μmol/m^2/day) and reef sand environments (377 μmol/m^2/day) (**Tables 13 through 15**). The average fluxes of nitrate (1,540 μmol/m^2/day) and phosphate (711 μmol/m^2/day) were highest in the reef sand environments (**Table 15**).

	Freshwater	[PO_4]	[Si]	[NO_3]	[NH_4]
mean	17.3 ± 17.9	69 ± 79	22500 ± 24100	1080 ± 1980	2110 ± 4080
mean*	14.0 ± 13.4	56 ± 60	18200 ± 18100	879 ± 1570	1710 ± 3240

Table 13. Average freshwater (l/m^2/day) and dissolved solute fluxes (μmol/m^2/day) measured in seepage meters in the nearshore environments (water depths <2 m). Number of samples = 38. See Figures 10 and 11 for sample locations. Mean* = 2 σ rejected mean.

	Freshwater	[PO_4]	[Si]	[NO_3]	[NH_4]
mean	0.0	17 ± 45	2980 ± 4170	9.7 ± 16	2340 ± 3620
mean*	0.0	7.2 ± 17	1260 ± 1220	4.1 ± 5.4	985 ± 1160

Table 14. Average freshwater and dissolved solute fluxes (μmol/m^2/day) measured in seepage meters located in the lagoon (water depths between 2 and 12 m). Number of samples = 13. See Figures 9-11 for sample locations. Mean* = 2 σ rejected mean.

	Freshwater	[PO_4]	[Si]	[NO_3]	[NH_4]
mean	0.0	711	3880	1540	377

Table 15. Average freshwater and dissolved solute fluxes (μmol/m^2/day) measured in seepage meters located in reef sands (water depths between 2 and 5 meters). Number of samples = 2. See Figure 9 for sample locations.

Sediment Porewater

In-Situ Measurements

Pore water measurements taken by inserting an YSI® probe directly into the sediment or from collecting water from hand dug pits showed depressed salinity values in all areas of the bay compared to ambient bay water. Pore water measurements taken in the intertidal zone at the Waiahole site exhibited the lowest salinities with a linear change in salinity from about 4 psu at the high-tide line to about 32 psu at a distance of 200 m offshore from the high tide mark (**Fig. 23**). The coarse reef sands located in water depths between 2 and 5 meters at the barrier reef complex in the central bay, the Sampan Channel in the south bay, and an area in the northern sector showed salinity values as low as 20 psu in porewater less than 50 cm below the seafloor. Measurements taken in the lagoon sediments were between 25 and 32 psu at a sub-bottom depth of approximately 50 cm. Although it was difficult to take readings in the fringing and patch reef areas due to the presence of coral rubble and live coral colonies, the few measurements that were taken in sandy areas between the coral patches also exhibited depressed salinities (~27 psu) compared to the overlying water column (~35 psu).

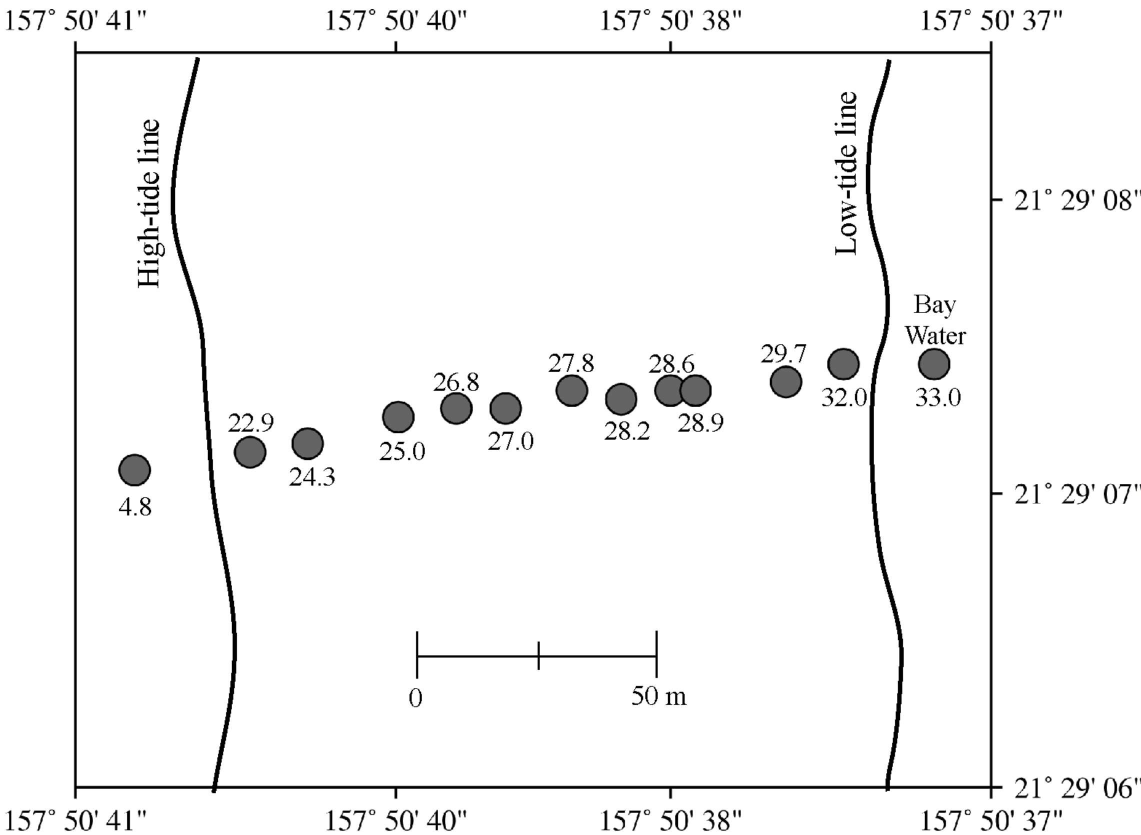


Figure 23. Salinity values of porewater extracted from shallow hand dug pits. See Figure 13 for description of sampling procedure.

Water level and salinity values recorded in a piezometer are presented that illustrate the dynamic nature of the near shore environment in Kaneohe Bay. Piezometer-LT was located in the intertidal zone at the Waiahole study site (Fig. 11) and had an open interval located 50 cm below the ground surface. The water level in the piezometer ranged from 25 cm below the ground surface to 60 cm above the ground surface and salinity values ranged from 11.8 (March 31, 2004) to 33.8 psu (Feb. 15, 2004). Measurements were taken from Jan. 24 through Feb. 29 and again from March 11 through April 3, 2004. The break in the record was due to low battery power of the YSI® probe.

Changes in porewater salinity are observed over several different time scales from minutes to weeks (**Fig. 24**). Over the entire 70 day record, the salinity changes can be broken up into three linear segments: days 1 through 10 when salinity values decreased at ~1 psu/day; days 10 through 22 when salinity values increased at ~0.8 psu/day; and days 22-70 when the salinity decreased at ~0.4 psu/day (**Fig. 24**). These fluctuations may reflect changes in the neap-spring lunar tidal cycle or changes in the hydraulic head between the adjacent terrestrial aquifer.

Superimposed on the semi-monthly changes in porewater salinity are hourly to daily changes that correlate with fluctuations in the semi-diurnal tidal cycle. Changes up to 7 psu per day are observed with the low tides correlating with lower salinity values and high tides correlating with higher salinity values (**Figs. 25** and **26**). Comparison of the water level recorded in the piezometer and the tidal signal recorded (station 1612480 at Coconut Island) in the southern sector of the bay shows that during periods of time when the porewater salinity is decreasing (i.e. getting fresher) the water level in the piezometer is above the water level recorded at the tide station (**Figs. 25** and **26**) and that the two curves match up with one another during times when the porewater salinity is increasing (**Figs. 25** and **26**). The difference in head between the piezometer and that of the tidal signal is most likely due to the hydraulic head created from the adjacent terrestrial aquifer.

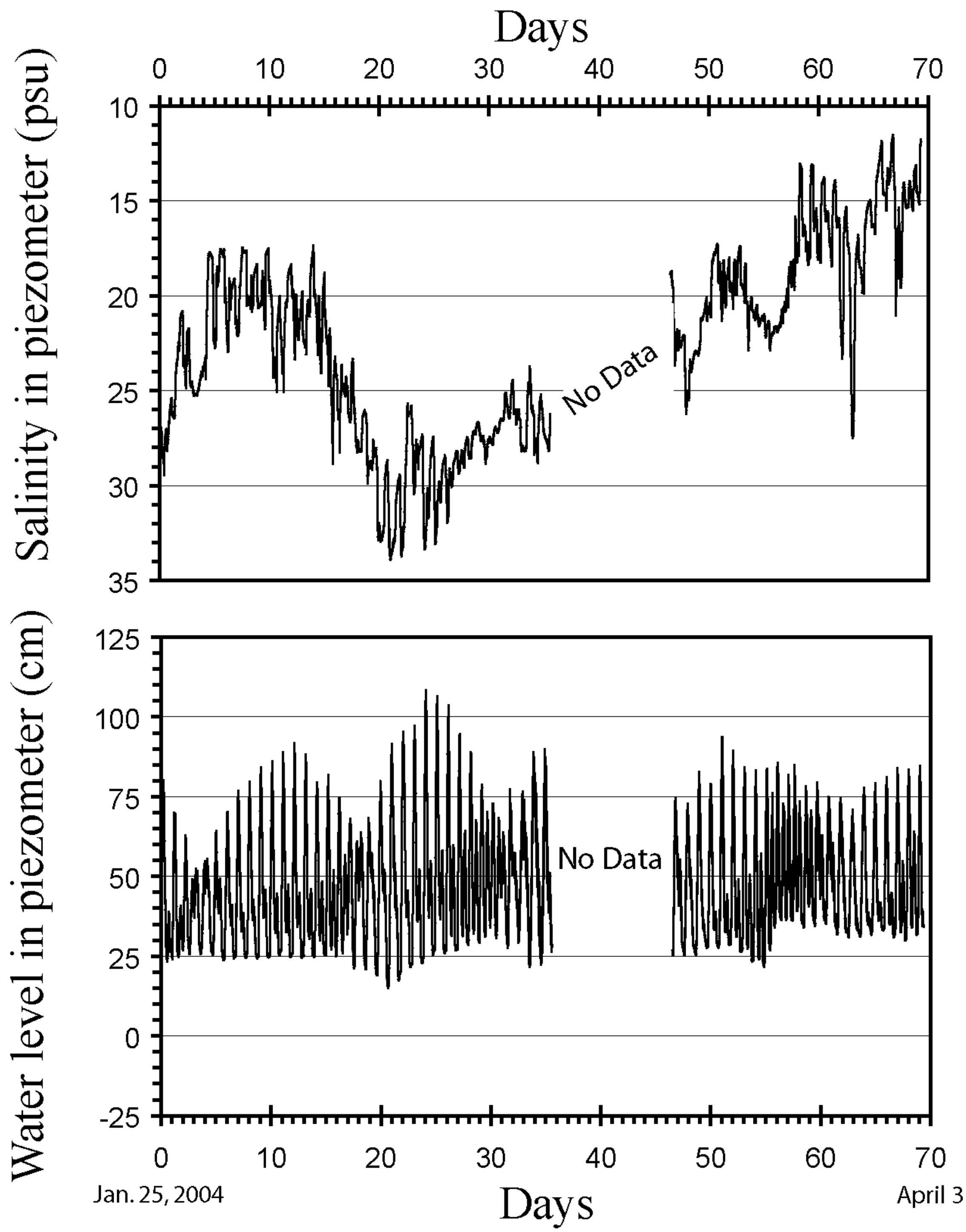


Figure 24. Salinity and water level measurements in piezometer-LT (50 cm below seafloor) from January 25, 2004 to April 3, 2004. See Figure 11 for piezometer location.

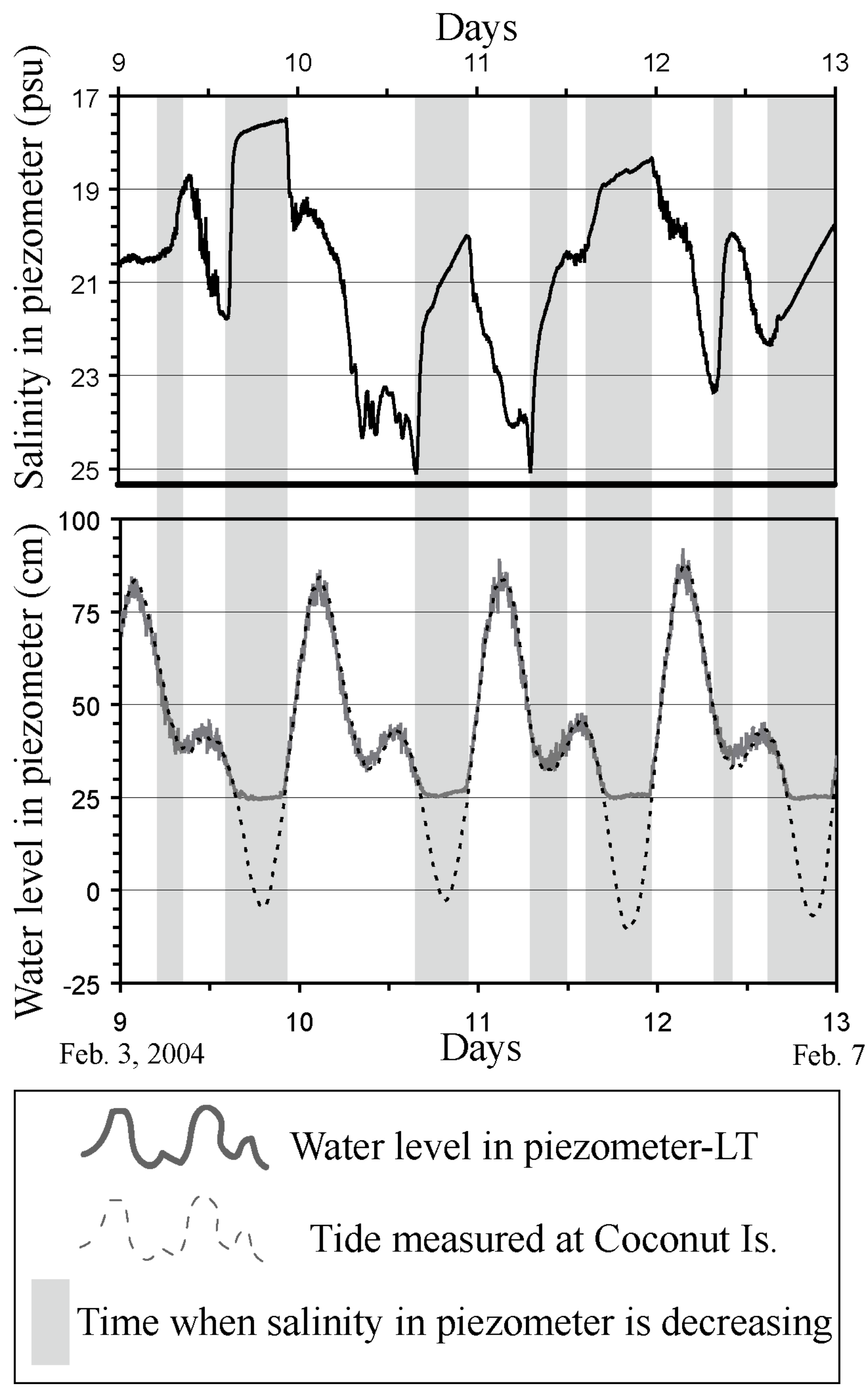


Figure 25. Salinity and water level measurements in piezometer-LT (50 cm below seafloor) plotted along with the bay water level recorded at tidal station 1612480 at Coconut (Mokuole) Island (CO-OPS, 2004). See Figure 11 for piezometer location.

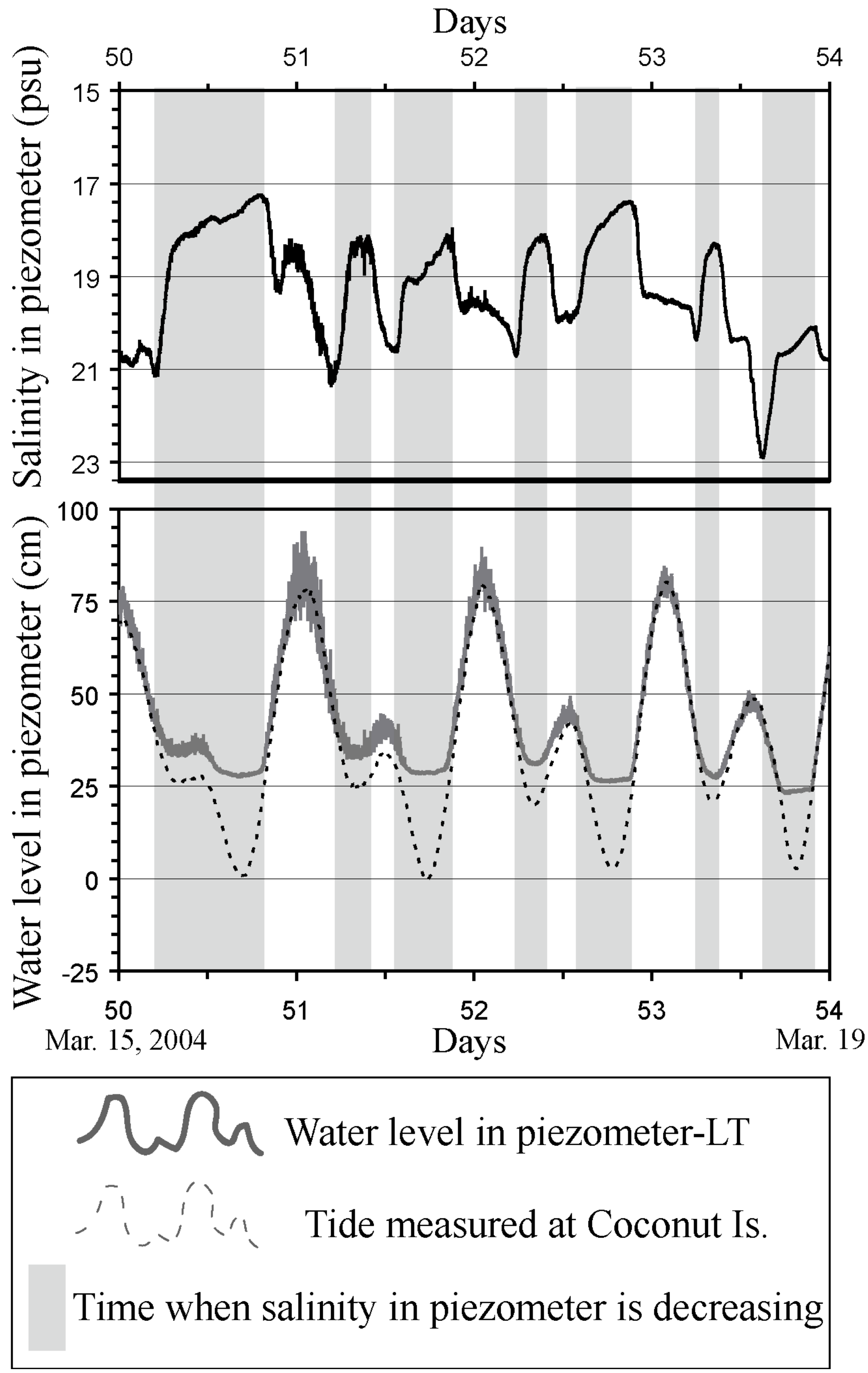


Figure 26. Salinity and water level measurements in piezometer-LT (50 cm below seafloor) plotted along with the bay water level recorded at tidal station 1612480 at Coconut (Mokuole) Island (CO-OPS, 2004). See Figure 11 for piezometer location.

Changes in porewater salinity and water level also occur over minute time scales due to changes in wave intensity that corresponds with changes in wind direction and magnitude. For example, during day 51 (March 18), winds out of the north-northeast (20-30°) at 20-50 kilometers per hour (12-30 mph) occurred which caused the water level in the piezometer to fluctuate up to 15 cm over a single sampling interval (6 min) which corresponded to changes in porewater salinity of ~ 0.6 psu (**Fig. 27**). This is in contrast to the much less variable curves that occurred during day 53 (March 18) when the winds were out of the north-northwest (300 to 310°) at 12-40 kilometers per hour (12-40 mph) which caused changes in the water level of ~ 4 cm over a single sampling period and corresponded with changes in pore water salinity of only ~ 0.01 psu.

<u>Sediment Cores</u>

The sediment porewater chemistry of three sediment cores (W-20, 44, and 210) taken from the Waiahole paleochannel (Fig. 9) and two sediment cores (C-81 and C-90) taken from the lagoon floor adjacent to the barrier reef complex in the central sector (Fig. 9) are presented. All core samples taken showed decreases in salinity values with increasing sub-bottom depth (Figs. 28 and 29) which co-varied with increases in the concentrations of ammonium, silica, and phosphate.

Three sets of diffusive fluxes (**Tables 16 and 17**) have been calculated for both the Waiahole and Central cores using equations 8 through 10. Two of the data sets assume the lower ($\phi = 0.73$) and higher ($\phi = 0.83$) porosity values calculated in previous studies of Kaneohe Bay sediments (Roy, 1970; Hollett and Moberly, 1977), while the third is the average ($\phi = 0.78$) of the two extremes (**Tables 16 and 17**). Nitrate and phosphate fluxes calculated by this method are similar to the flux rates calculated

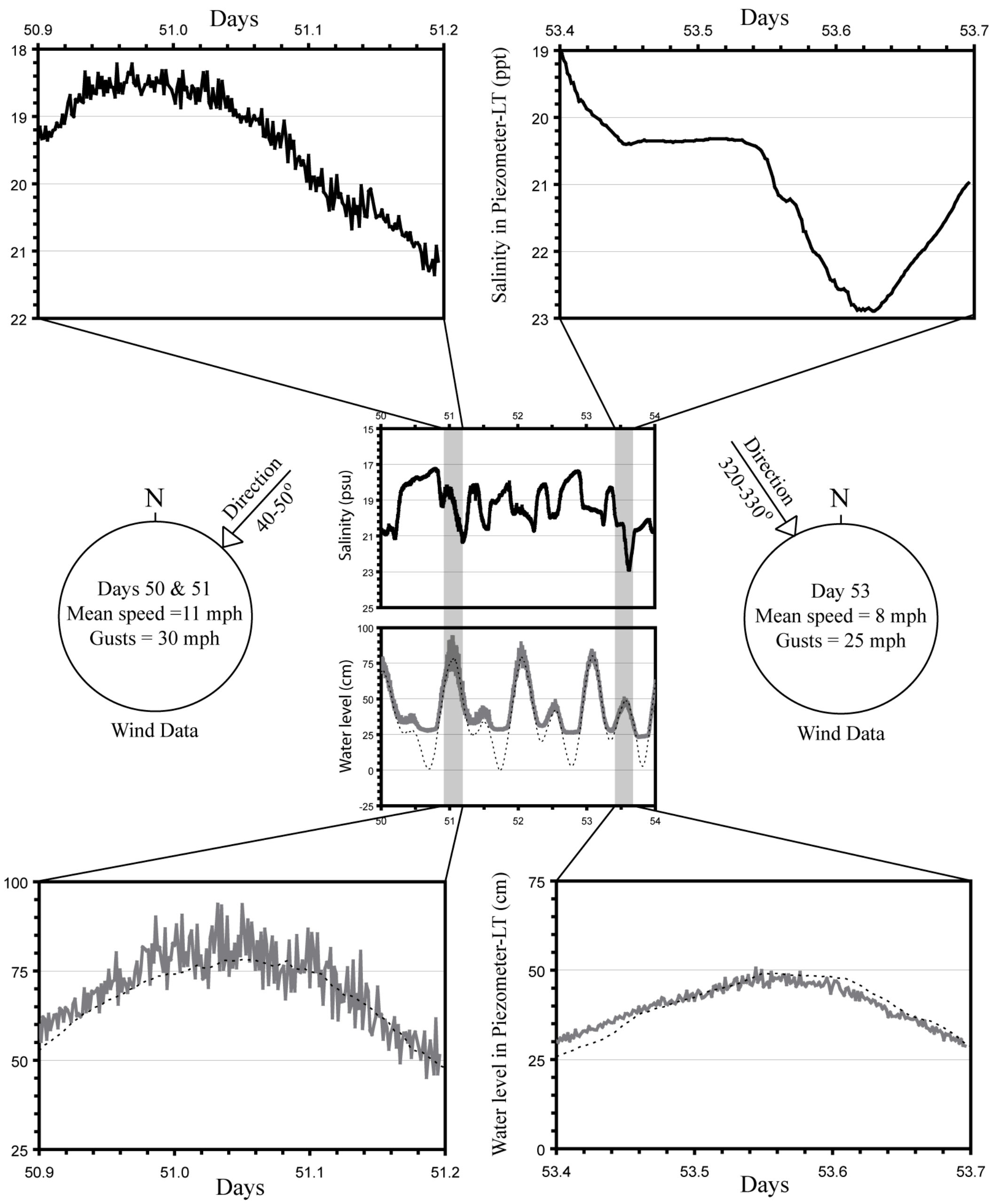


Figure 27. Close up of figure 26 showing the influence of wind direction on the salinity and water level in piezometer-LT (50 cm below seafloor). Trade winds (40-50°) occurred during days 50 and 51 which caused considerable scatter in the curves. This is in contrast to the much less variable measurements on day 53 when the wind was out of the north-northwest (320-330°) (NWS, 2004). The tide recorded at Coconut Island (CO-OPS, 2004) is also shown with a dashed line.

from seepage meter measurements in the lagoon while the flux of ammonium calculated from the sediment cores is about 30% of the flux calculated from the seepage meters (**Table 18**). The silica flux calculated for the Waiahole cores is about 6% the flux calculated from the seepage meters while the silica flux calculated from the central sector cores is about 33% that of the seepage meter flux (**Table 18**).

porosity (ϕ)	$[PO_4]$	[Si]	$[NO_3]$	$[NH_4]$
0.73	1.3 ± 0.4	81 ± 10	1.7 ± 1.2	330 ± 30
0.78	1.5 ± 0.5	97 ± 12	2.1 ± 1.4	390 ± 35
0.83	1.7 ± 0.5	110 ± 13	2.4 ± 1.7	450 ± 40

Table 16. Average diffusive flux rates ($\mu mol/m^2/day$) using equations 8 through 10 for the three sediment cores (W-20, 44, and 210) collected at the Waiahole study site. D_w = 16.4 x 10^{-5} m/day, FF = $\phi^{-2.5}$. See Figure 11 for sample location.

porosity (ϕ)	$[PO_4]$	[Si]	$[NO_3]$	$[NH_4]$
0.73	2.9 ± 0.6	410 ± 41	3.1 ± 1.6	250 ± 15
0.78	3.5 ± 0.8	490 ± 49	3.5 ± 1.7	300 ± 18
0.83	4.1 ± 0.9	570 ± 57	3.8 ± 1.9	340 ± 21

Table 17. Average diffusive flux rates ($\mu mol/m^2/day$) using equations 8 through 10 for the two sediment cores (C-81 and C-90) collected in the central lagoon. D_w = 16.4 x 10^{-5} m/day, FF = $\phi^{-2.5}$. See Figure 9 for sample location.

	$[PO_4]$	[Si]	$[NO_3]$	$[NH_4]$
Central cores ($\phi = 0.78$)	3.5 ± 0.8	490 ± 49	3.5 ± 1.7	300 ± 18
Waiahole cores ($\phi = 0.78$)	1.5 ± 0.5	97 ± 12	2.1 ± 1.4	390 ± 35
Seepage meters (mean*)	56 ± 60	18200 ± 18100	879 ± 1570	1710 ± 3240

Table 18. Comparison of average diffusive flux rates (μmol/m2/day) calculated from sediment cores and from seepage meter measurements located in the lagoon. Mean* = 2σ rejected mean.

Salinity

The upper 30 cm of porewater taken from the Waiahole lagoon showed a 0.32 to 0.64 psu decline in salinity compared to water collected at the sediment-water interface. Salinity values then decreased down core at a faster rate (~0.11 psu/cm) starting at a depth of approximately 25-30 cm and reached a minimum value of 15.50 psu at 207 cm depth (**Fig. 28**).

Core samples taken from the central lagoon showed similar salinity profiles to those taken from the Waiahole lagoon. Decreases of 0.32 to 0.51 psu occurred in the upper 30 cm of the sediment followed by a more substantial decrease in salinity values with depth reaching a minimum of 26.90 psu at a depth of 88 cm (**Fig. 29**).

Ammonium

In the Waiahole core samples, ammonium concentrations were less than 1 μM in water above the sediment cores and then increased to 100-200 μM at a sub-bottom depth of only 6 cm. The porewater concentrations then varied between 100 and 200 μM to a depth of 40 cm. Concentrations then increased steadily to a maximum of 1839 μM at a depth of 200 cm (**Fig. 30**).

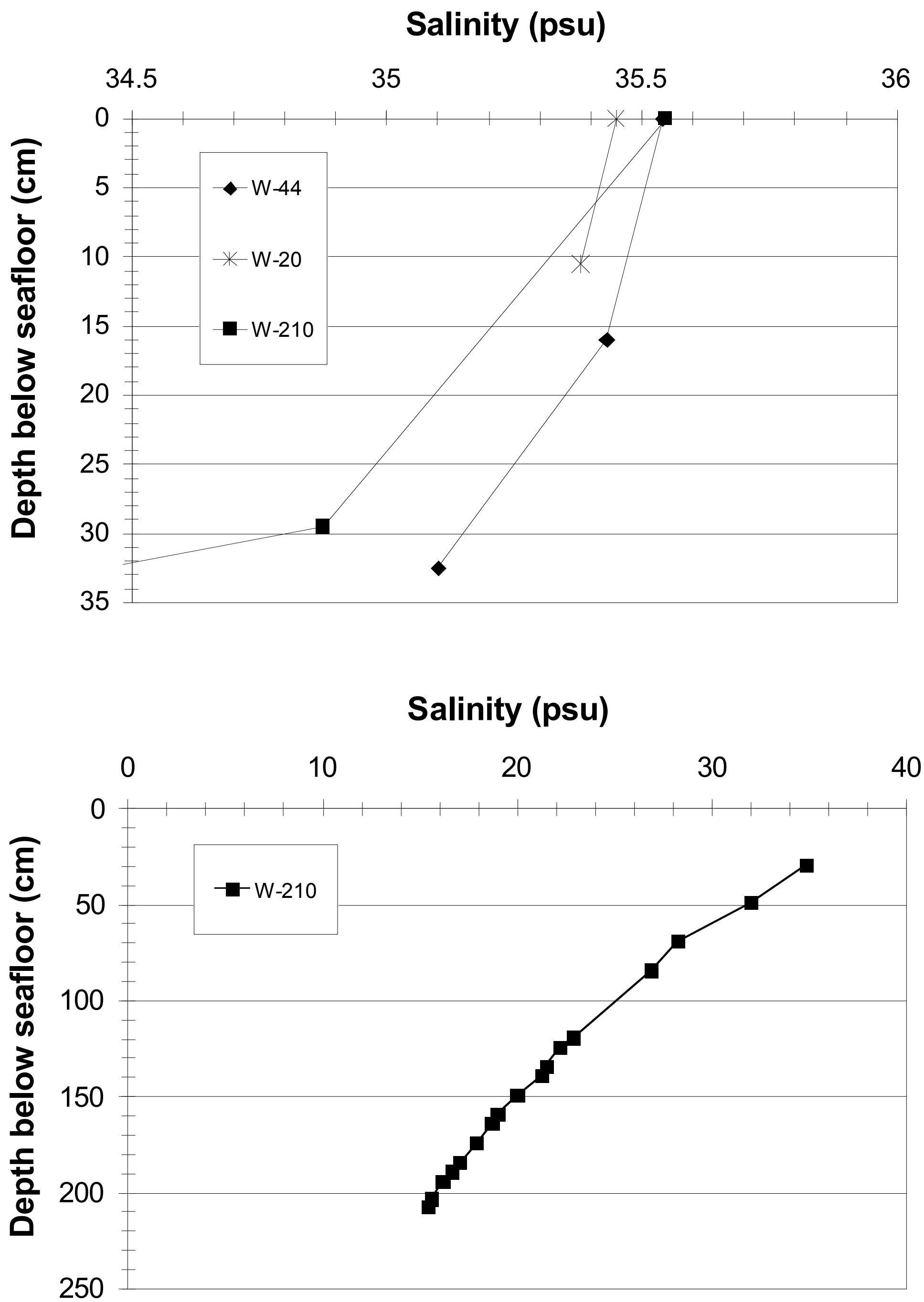


Figure 28. Sediment porewater salinity values (psu) as a function of depth below the seafloor (cm) at the Waiahole study site. Top graph: upper 35 cm. Bottom: entire W-210 core. See Figure 9 for core sample locations.

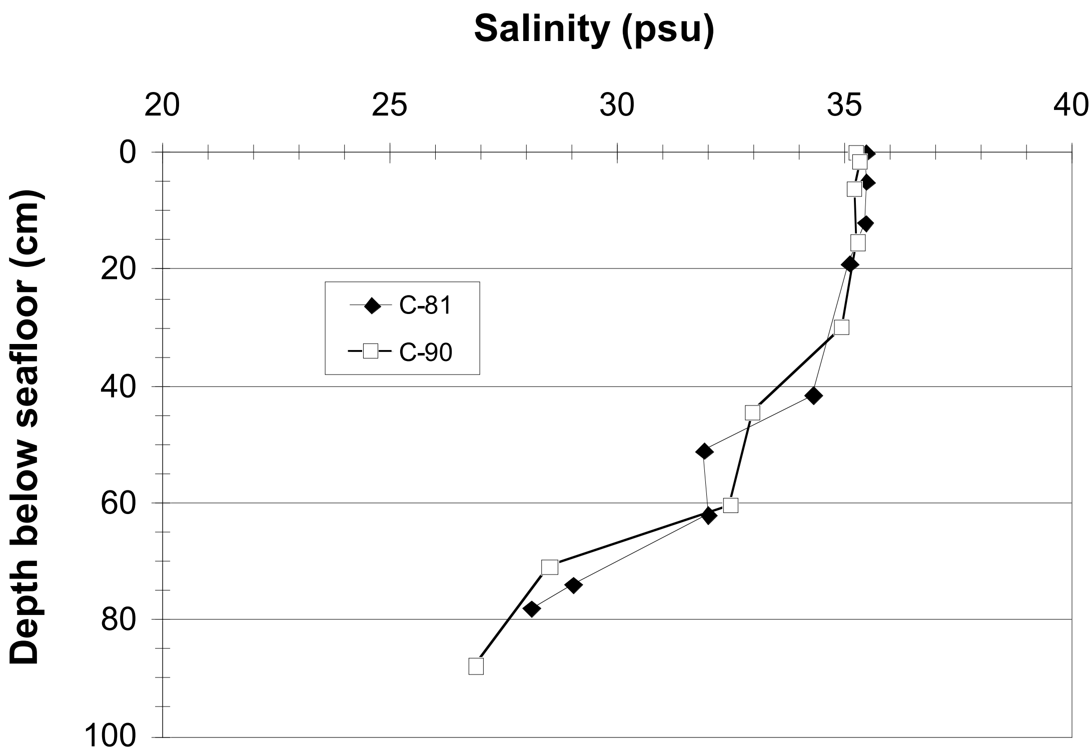


Figure 29. Sediment porewater salinity values (psu) as a function of depth below the seafloor in the central bay. See Figure 9 for core sample location.

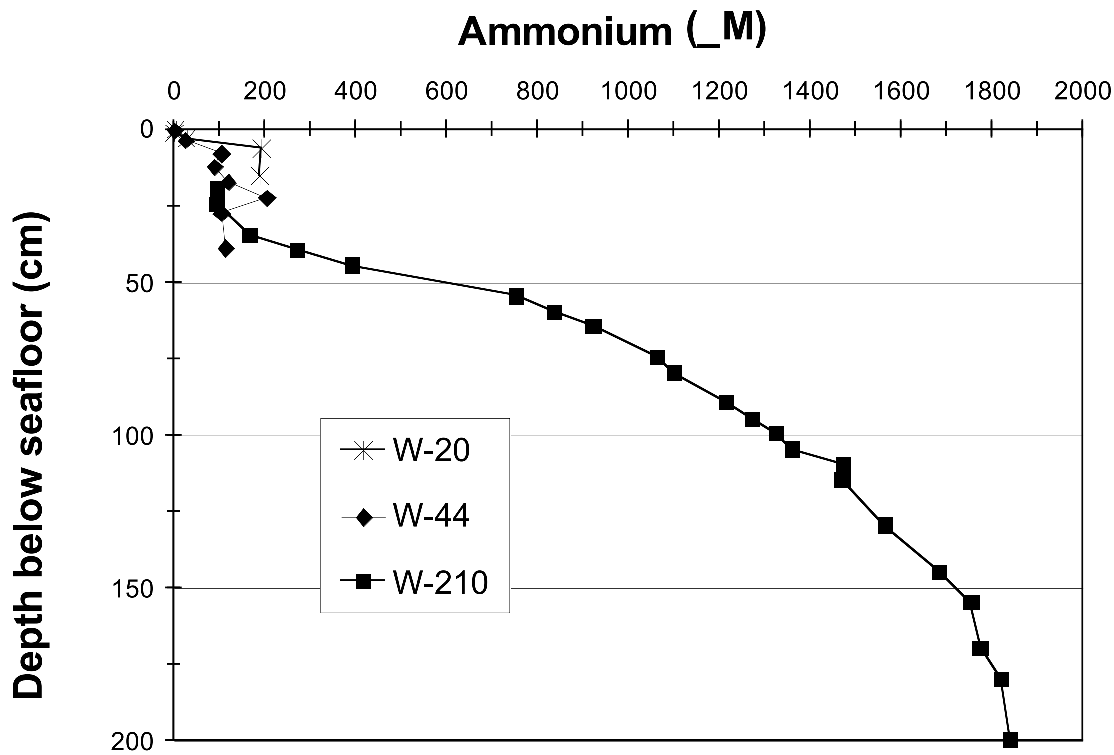


Figure 30. Sediment porewater concentrations (µM) as a function of depth below the seafloor at the Waiahole study site. See Figure 9 for core sample locations.

Ammonium concentrations in the water above the two sediment cores (C-81 and C-90) taken from the lagoon in the central sector of the bay were less than 1 µM. Both cores exhibited an increase in ammonium concentrations to about 110 µM at a depth of 5 cm which was followed by a decrease in concentration to 84 µM at a depth of 14 cm. Concentrations then increased slightly to 110 µM at a depth of 35 cm. Concentrations then increased more rapidly reaching a maximum of 550 µM at a depth of 78 cm (**Fig. 31**).

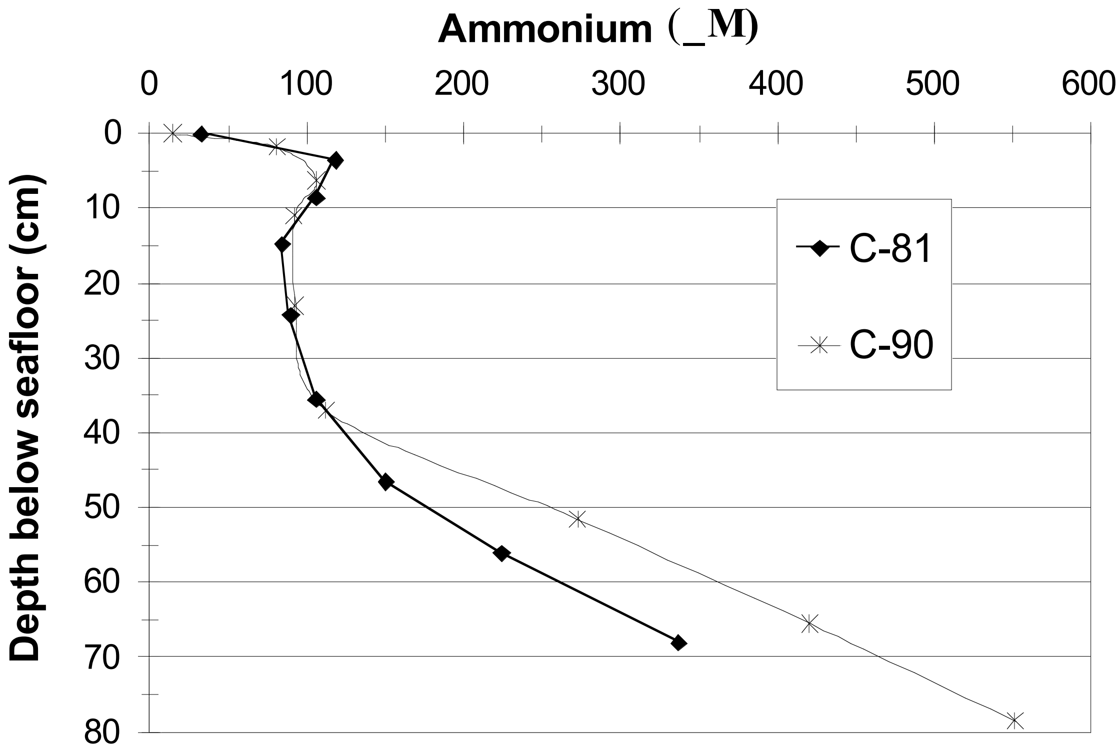


Figure 31. Sediment porewater ammonium concentrations (µM) as a function of depth below the seafloor in the CE sector of the bay. See Figure 9 for core sample locations.

<u>Nitrate</u>

Nitrate values were more scattered in the Waiahole core pore waters compared to the other nutrient species analyzed. Nitrate concentrations of overlying water for cores W-20 and W-44 were 1.5 and 0.2 µM, respectively. Concentrations then increased with depth in both cores and ranged between 3.2 and 7.3 µM in W-20 and between 2.2 and 11.5 µM in W-44. Core W-210 had a maximum nitrate concentration of 32.4 µM at a depth of 19.5 cm and decreased to a minimum value of 4.5 µM at 105 cm. Concentrations then increased to 14.2 µM at a depth of 200 cm (**Fig. 32**).

Concentrations of nitrate in water collected directly above cores C-81 and C-90 were 0.61 and 0.84 µM, respectively. Values increased in C-81 to a maximum of 24.5 µM at 14.8 cm depth and then decreased steadily to a minimum value of 1.0 at 79 cm depth. Core C-90 had a similar shape to C-81; however, the concentrations of nitrate were slightly less, reaching a maximum value of 6.2 µM at 11 cm depth and a minimum value of 0.5 µM at 78.5 cm depth (**Fig. 33**).

It should be pointed out that the nitrate values presented here (especially below ~50 cm in core W-210) should be viewed with caution because of the sampling techniques used to extract the porewater from the sediment cores. The core samples were exposed to air (i.e. oxygen) during the squeezing procedure which may have caused some of the abundant ammonium (100s µM) to be oxidized to nitrate, via nitrification as described by:

$$NH_4^+ + 1.5\ O_2 = NO_2^- + 2\ H^+ + H_2O \qquad (11)$$

$$NO_2^- + 0.5\ O_2 = NO_3^- \qquad (12)$$

Silica

Silica concentrations in water above the sediment water interface were less than 10 µM at both the Waiahole and central lagoon sites and all the cores showed increases in silica concentrations with depth.

Core W-20 showed the most rapid increase with depth, reaching a maximum value of 345 µM at a depth of 15 cm (**Fig. 34**). Core W-44 showed a similar shape to W-20 but concentrations reached only 180 µM at a depth of 38 cm. Concentrations increased from 154 µM at a depth of 19 cm in core W-210 to 300 µM at a depth of 65 cm and then varied between 280 µM and 325 µM from 65 to 200 cm depth (Fig. 34).

The shape of silica concentrations with depth in cores from the central lagoon were slightly different than those collected from Waiahole lagoon. Concentrations rapidly increase to a "local" maximum of 230 µM at a depth of 5 cm and then decreased to 90 µM at a depth of 20 cm. Concentrations then increased (~7.5µM/cm) with depth reaching a maximum concentration of 420 µM at 78 cm depth (**Fig. 35**).

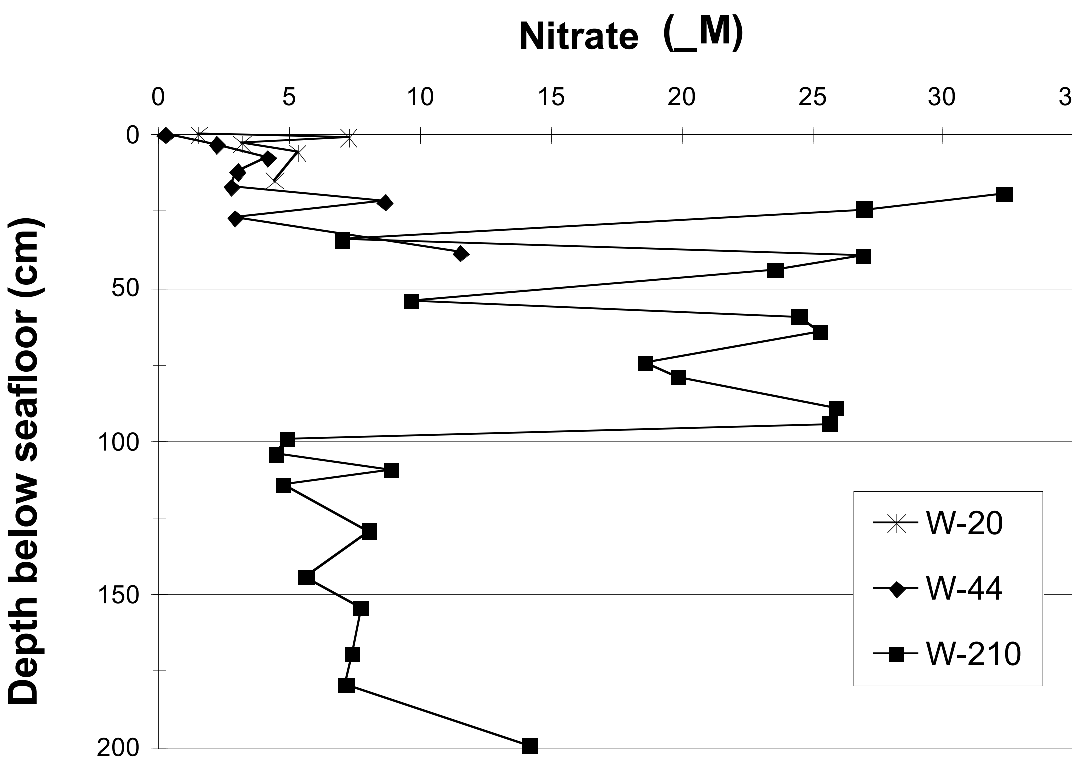


Figure 32. Sediment porewater nitrate concentrations as a function of depth below the seafloor at the Waiahole study site. See Figure 9 for core sample locations.

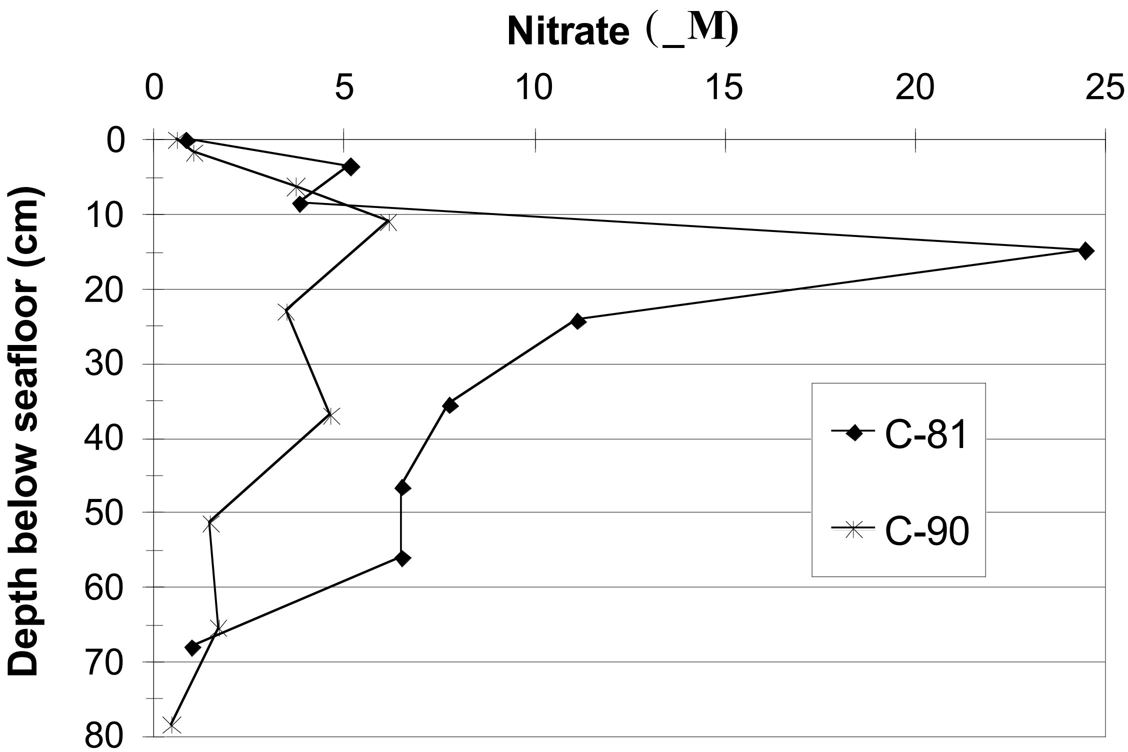


Figure 33. Sediment porewater nitrate concentrations as a function of depth below the seafloor in the CE sector of the bay. See Figure 9 for core sample locations.

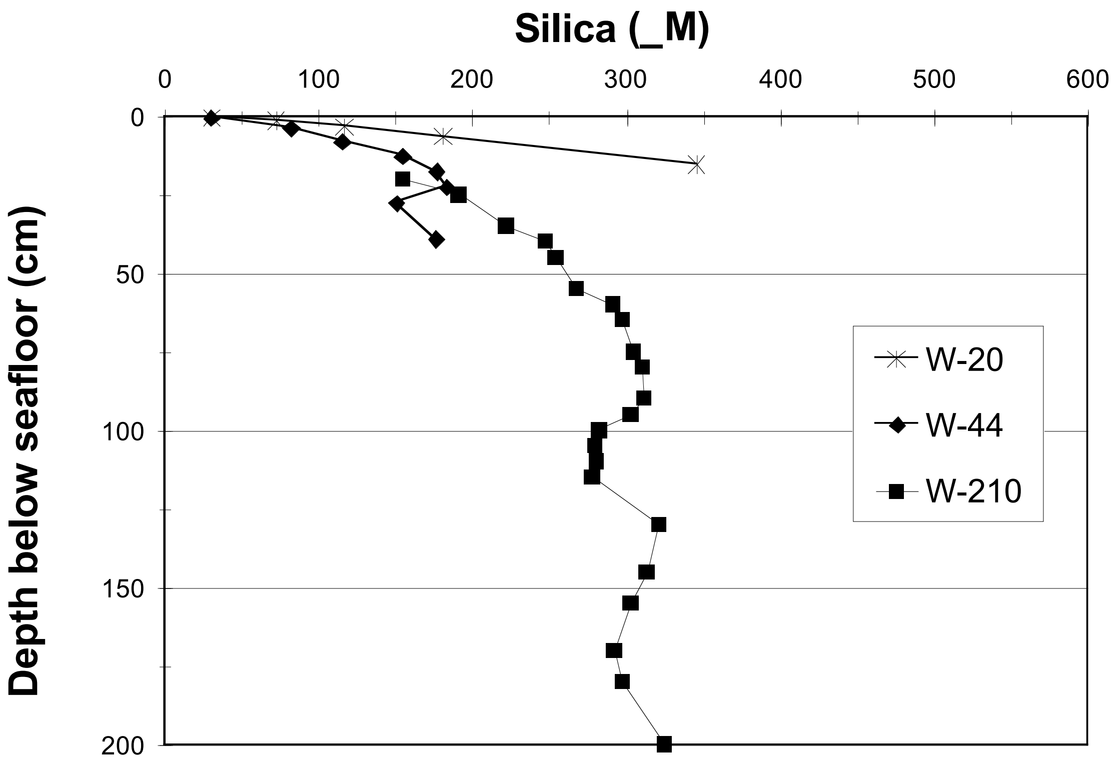


Figure 34. Sediment porewater silica concentrations as a function of depth below the seafloor at the Waiahole study site. See Figure 9 for core sample locations.

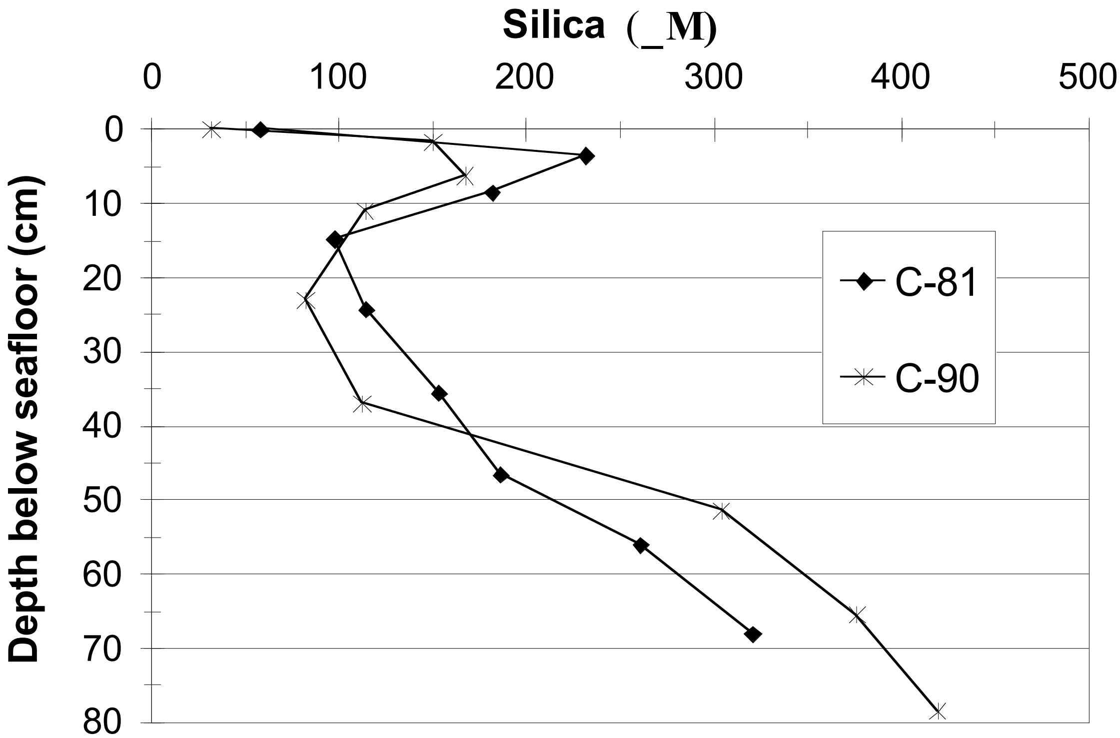


Figure 35. Sediment porewater silica concentrations as a function of depth below the seafloor at the CE sector of the bay. See Figure 9 for core sample locations.

<u>Orthophosphate</u>

Porewater collected in the Waiahole lagoon showed slight increases in phosphate concentrations in the upper 35 cm to about 3.5 µM. Values then increased more rapidly to a depth of 130 cm reaching a maximum concentration of 46 µM. Concentrations then decreased to 23 µM at a depth 170 cm and then increased slightly to 35 µM at 200 cm depth (**Fig. 36**).

Samples from the central lagoon showed phosphate increases to about 6 µM at a depth of 10 cm. Concentrations are then fairly constant for the rest of the core and vary between 5.5 and 7.5 µM (**Fig. 37**).

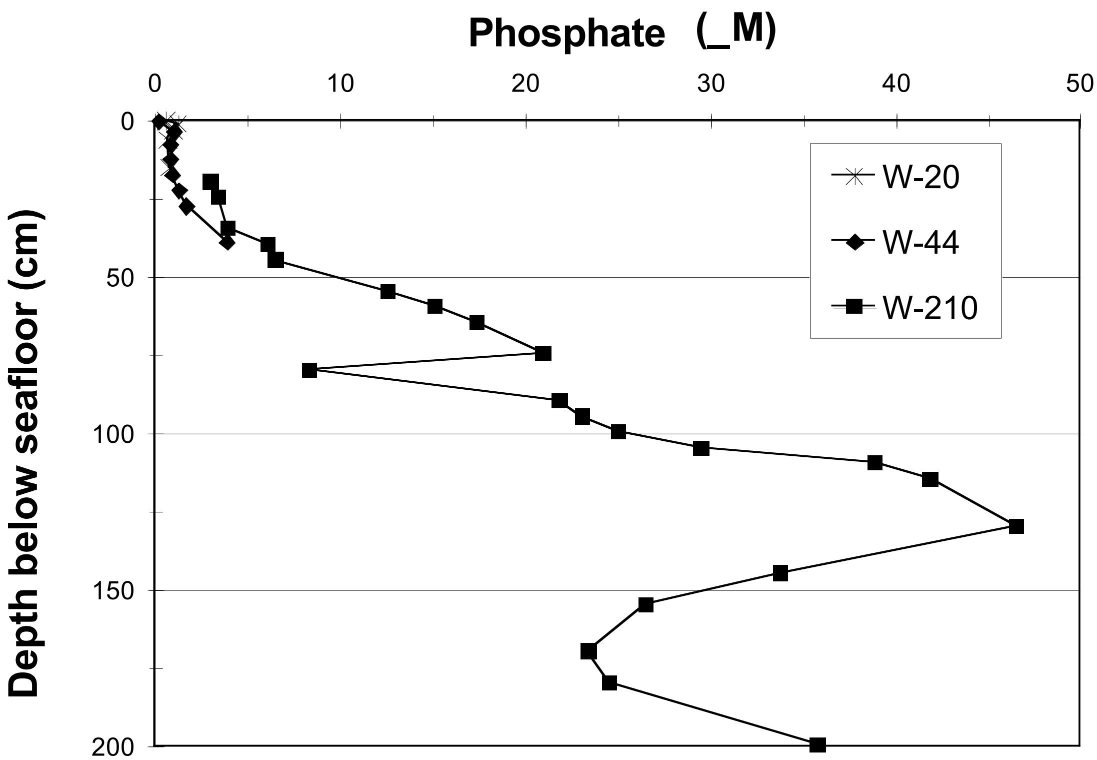


Figure 36. Sediment porewater orthophosphate concentrations as a function of depth below the seafloor at the Waiahole study site. See Figure 9 for core sample locations.

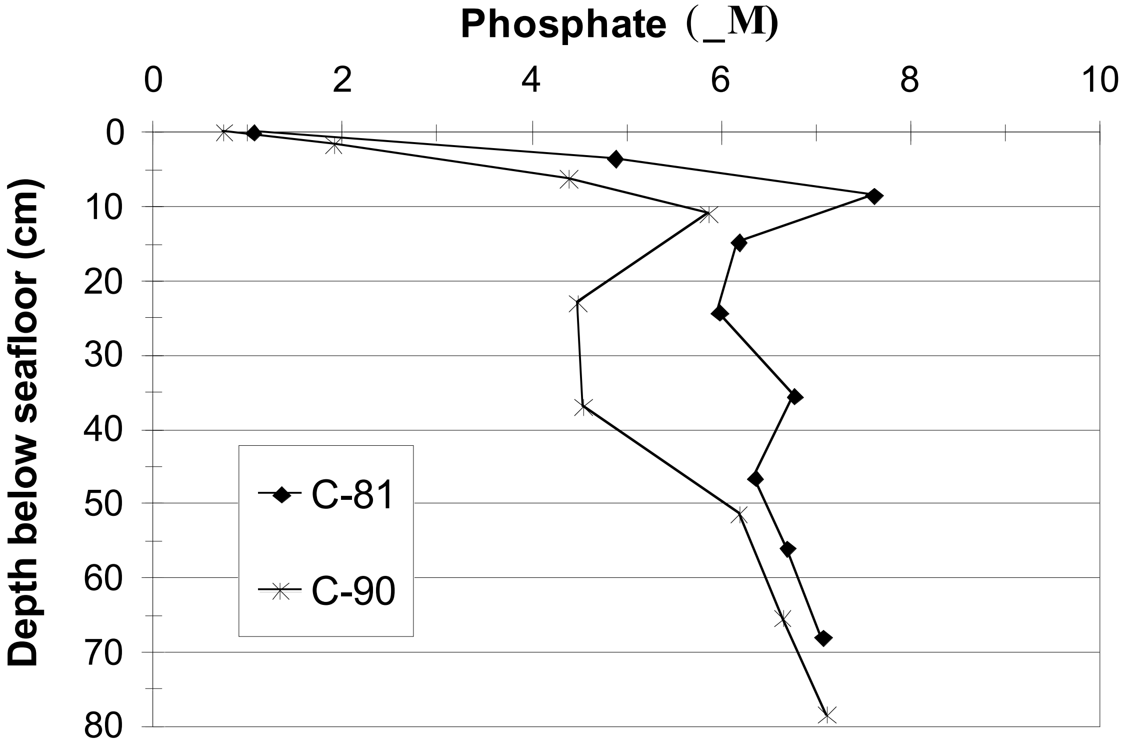


Figure 37. Sediment porewater orthophosphate concentrations as a function of depth below the seafloor at the CE sector of the bay. See Figure 9 for core sample location.

Benthic Surveys

The first survey was conducted on July 21, 2003 in the Waiahole study site and consisted of 6 main transect lines positioned 90° to the shoreline on to which 6 transects 25 m long were performed (**Figs. 11** and **18**). Uncolonized sediment (sand + coral rubble) was the dominant substrate type (80.3%) followed by the benthic algae *Acanthophora spicifera* (9.7%) and *Gracilaria salicornia* (7.2%) (**Table 19**).

The second survey was conducted adjacent to Hakipuu valley on August 19, 2003 and consisted of 8 main transect lines positioned 90° to the shoreline on to which 6 transects 25 m long were performed (**Figs. 10** and **18**). Uncolonized sediment (sand + mud) was the dominant substrate type (60.2%) followed by the benthic algae

Acanthophora spicifera (26.2%), *Gracilaria salicornia* (9.5%), and *Caulerpa sertularioides* (2.6%) (**Table 20**).

Substrate	% coverage
Uncolonized Sand and Coral Rubble	80.3
Acanthophora spicifera	9.7
Gracilaria salicornia	7.2
Bryopsis sp.	1.9
Caulerpa sertularioides	0.6
Padina sp.	0.3

Table 19. Results of benthic survey at Waiahole study site. The survey covered 900,000 m^2. See Figure 11 for survey location and Figure 18 for details on survey.

Substrate	% coverage
Uncolonized Sand and Mud	60.2
Acanthophora spicifera	26.2
Gracilaria salicornia	9.5
Caulerpa sertularioides	2.6
Liagora sp.	1.0
Lyngbya majuscula	0.2
Kappaphycus sp.	0.2

Table 20. Results of benthic survey at the Hakipuu study site. The survey covered 200,000 m^2. See Figure 10 for survey location and Figure 18 for details on survey.

Maunalua Bay

Five discrete submarine springs and extensive beachface seepage were discovered at Maunalua Bay along the 1 km stretch of shoreline from Wailupe Beach Park westward to the Waialae Country Club. The terrestrial springs were located within 50 m of the shoreline in ~1 m of water and could be seen as circular "boils" at the surface and felt due to their colder (~5° C less) temperature compared to the ambient bay water. There was a good linear correlation ($R^2 > 0.72$) between the concentrations of nitrate, silica, phosphate and water salinity (**Fig. 38**) suggesting that terrestrial groundwater is a major source of these nutrient species to the bay water column. Ammonium concentrations of the freshwater end member were low (<1 μM) which supports the idea that nitrate tends to be the abundant form of DIN in most freshwater systems. During most of the year, except directly after heavy rains, SGD is the sole source of freshwater to this section of coastline (no stream input) and therefore nutrient loading via SGD is volumetrically very significant.

Seepage meters were only deployed in a small (30 x 30 m) sandy area in Maunalua Bay due to the shallow water depths and hard substrate that occurs over most of the bay. Total fluid flux rates were high (749 l/m2/day) and similar to the nearshore and reef sand environments of Kaneohe Bay (Table 8). The SGD salinity averaged 33.09 psu which was 1.24 psu less than the marine end member salinity value. Therefore, assuming salinity is a conservative tracer, the SGD is composed of 3.8% terrestrial water and 96.2% re-circulated marine water. Concentrations of nitrate and phosphate of the SGD were low (<1 μM) while ammonium and silica values were higher at 3 and 65 μM, respectively (**Table 21**).

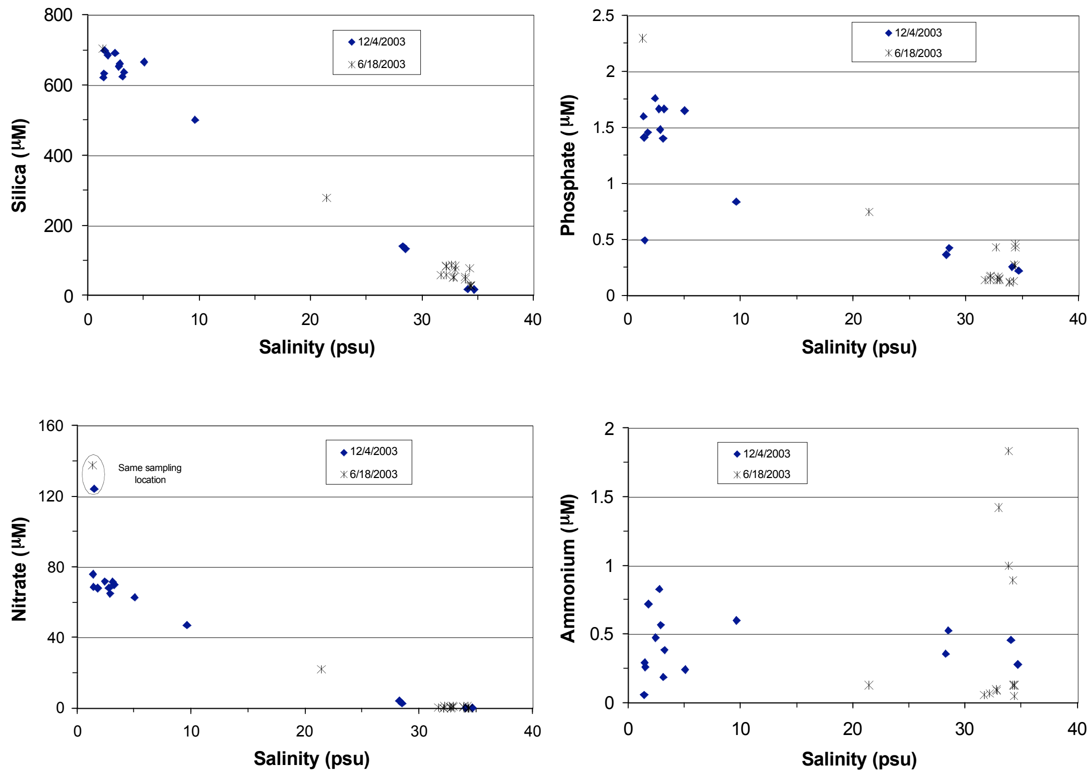


Figure 38. Nutrient concentrations (µM) as a function of salinity (psu) for water samples collected from the water column, hand dug pits, and seepage meters at Maunalua Bay adjacent to Wailupe Beach Park.

	Fluid Flux (l/m2/day)	Salinity (psu)	PO_4 (µM)	Si (µM)	NO_3 (µM)	NH_4 (µM)
minimum	515.8	32.10	0.1	47.8	0.2	0.9
maximum	1418.1	34.22	0.4	88.1	1.5	9.2
mean	864.1	33.09	0.2	74.6	0.9	3.9
median	787.7	32.95	0.1	81.2	1.0	2.1
st dev	323.8	0.82	0.1	15.2	0.5	3.4
n	8	8	8	8	8	8

Table 21. Fluid flux (l/m3/day), salinity (psu), and nutrient concentrations (µM) of SGD collected in seepage meters at the Maunalua Bay study site.

A benthic survey was conducted on June 24, 2003 to assess the abundance of benthic algae at the Maunalua Bay study site. A 1000 m by 1000 m area was surveyed using the technique illustrated in Figure 18. The most common substrate type was unconsolidated sediment (silt and sand) followed by *Acanthophora spicifera* (**Table 22**). Ten other algae species were identified and collectively covered 28.2 % of the substrate. It should be pointed out that the distribution of the algae was not uniform across the survey site and patches of algae were present that locally covered 100% of the bay floor.

Substrate type	% cover
Uncolonized sediment (silt and sand)	40.3
Acanthophora spicifera	23.9
Uncolonized rock	7.8
Avranvillea amadelpha	6.7
Lyngbya majuscula	5.7
Gracilaria salicornia	4.6
Padina spp.	4.3
Dictyosphaeria cavernosa	2.1
Halimeda spp.	1.6
Dictyota spp.	1.5
Sargassum spp.	1.1
Galaxaura spp.	0.3
Hypnea musciformis	0.3

Table 22. Results of benthic survey at the Maunalua study site. See Figure 18 for details on survey.

Kealakekua Bay

Twelve water samples were collected from discrete springs and the water column from the northwest corner of Kealakekua Bay on April 10, 2003. This area is locally known as Queens bath. At this location there was a very good correlation ($R^2 > 0.99$) between the concentrations of nitrate, silica, phosphate and salinity (**Fig. 39**). Concentrations of ammonium were less than 1 µM in all samples collected and displayed a very poor correlation ($R^2 = 0.01$) as a function of salinity.

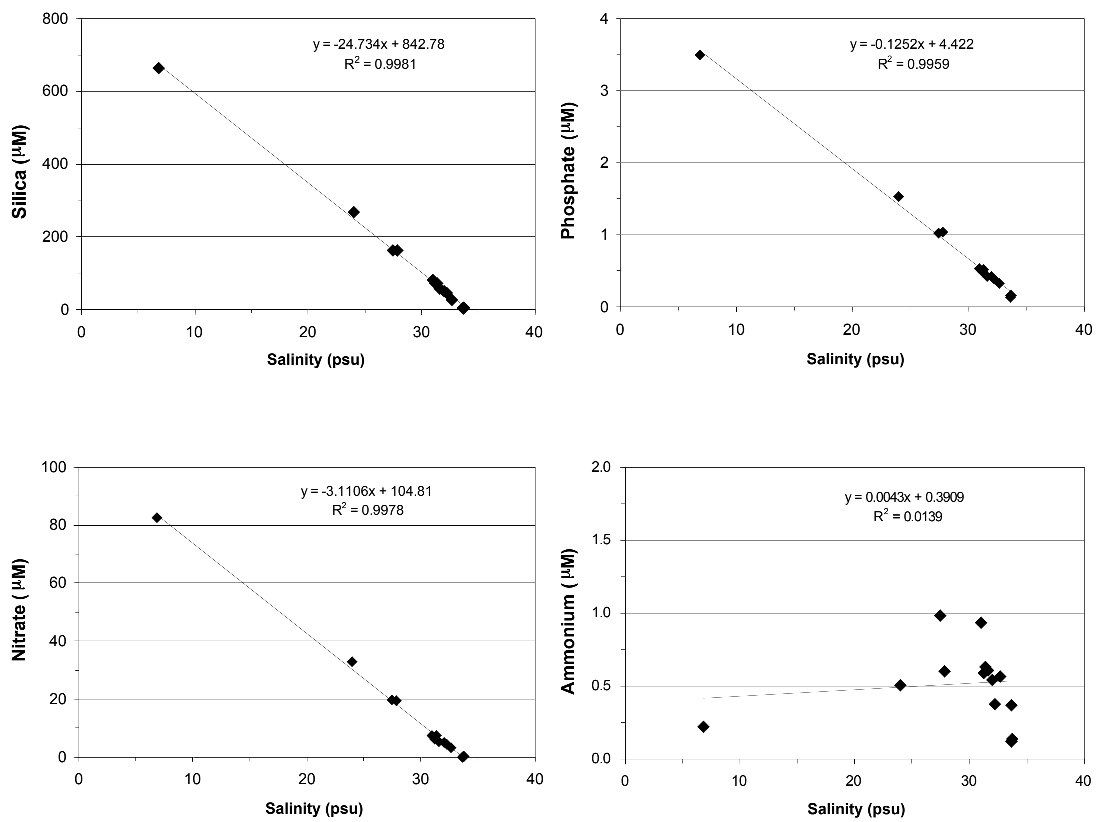


Figure 39. Nutrient concentrations (µM) as a function of salinity (psu) of water samples collected from the water column of Kealakekua Bay.

DISCUSSION

Streams, Terrestrial Groundwater, and Ambient Bay Water

A hypothesis that led to the development of this project was that cesspools, leaky septic systems, and fertilizers used on agriculture lands produced a significant nutrient load to the groundwater system in the northwest sector of Kaneohe Bay. This idea was based on the fact that the majority of groundwater samples were historically collected from diversion tunnels, streams, and public water supply wells located in the uplands of the watersheds and that the lower reaches of the watersheds, where the majority of the suspected anthropogenic loading would occur, were inadequately sampled. However, our subsequent analysis of baseflow in streams and terrestrial groundwater collected adjacent to the bay did not reveal any excessively high nutrient concentrations except one elevated nitrate value (535 μM) which was not reproducible upon further sampling. This suggests that the DIN, DIP, and dissolved silica values measured in this study (Table 1) are representative of the entire watershed of the northwest sector with concentrations in stream water similar to samples from previous studies of streams (Lau et al., 1976; Dugan, 1977; Hoover, 2003) and groundwater (NWIS, 2004).

Ambient water samples collected from the water column in the NW and CE sectors of Kaneohe bay also had nutrient concentrations similar to previous studies (Smith et al., 1981; Laws, 1996; CISnet, 2001) with sub-μM concentrations of orthophosphate, nitrate, and ammonium (Tables 3-7). Silica concentrations were similar (7-10 μM) to previous studies, although higher concentrations in surface water samples collected near stream mouths were observed corresponding with a lower salinity freshwater lid.

Submarine Groundwater Discharge in Kaneohe Bay

SGD is a source of terrestrial groundwater and nutrients into Kaneohe Bay and is volumetrically significant in both the nearshore and lagoon environments. The nearshore environment (Fig. 19) is characterized by shallow water depths (<2 m), coarse sediments, and high energy due to surface waves, tidal currents, and hydraulic gradients. In contrast, the lagoon (Fig. 19) is a lower energy environment with moderate water depths (2-12 m) and very fine-grained sediments that are actively bioirrigated by macrofauna.

In Kaneohe Bay, a series of oxidation-reduction reactions (Equations 13-17) signifying the remineralization of organic matter by bacteria are important processes that influence the concentrations of PO_4, NO_3, and NH_4 in the sediment porewater (Ristvet, 1978; Smith et al., 1981). The order in which the reactions occur in the sediments is based on the theoretical free energy yield of each process. Aerobic respiration has the highest energy yield and occurs at and just below the sediment water interface. Sulphate reduction has the lowest energy yield of those reactions listed and occurs at a depth when the other oxidants (NO_3, MnO_2, FeOOH) have been consumed.

Oxygen reduction:
$$O_2 + CH_2O = CO_2 + H_2O \quad (13)$$

Nitrate reduction:
$$0.5NO_3^- + CH_2O + H^+ = 0.5NH_4^+ + CO_2 + 0.5H_2O \quad (14)$$

Manganese reduction:
$$2MnO_2 + CH_2O + 2HCO_3^- + 2H^+ = 2MnCO_3 + 3H_2O + CO_2 \quad (15)$$

Iron reduction:
$$4\ FeOOH + CH_2O + 4HCO_3^- + 4H^+ = 4FeCO_3 + 7H_2O + CO_2 \quad (16)$$

Sulfate reduction:
$$0.5SO_4^{2-} + CH_2O + 0.5H^+ = 0.5HS^- + CO_2 + H_2O \quad (17)$$

The depth to which aerobic respiration (Equation 13) occurs is primarily a function of the rate of organic matter deposition and the depth to which oxygen rich water is driven from the water column into the sediments. Physical properties such as water depth, sediment permeability, wave energy, and bioirrigation processes influence the rate and depth to which the oxygen rich water is circulated through the sediments.

Nearshore Environment

In the NW sector of Kaneohe Bay, the flux of nutrients and freshwater out of nearshore sediments (SGD) is controlled by the advection of porewater due to oscillatory wave orbitals, unidirectional currents, the hydraulic gradient with the terrestrial aquifer, and the concentration of nutrients in the terrestrial groundwater. SGD in the nearshore environment is characterized by high fluid fluxes of relatively nutrient deficient and slightly lower salinity water (2.5% terrestrial water, 97.5% seawater).

Seepage meter fluid flux rates ($l/m^2/day$) were a factor of six greater than other seepage meter studies performed in silty sand, sand, and limestone environments (**Table 23**) and were only exceeded by values measured by Lewis (1987). The majority of the seepage meters were installed in difficult-to-penetrate coarse to very coarse sediments. This resulted in the top 5-10 cm of the seepage meters remaining exposed above the sea floor. The unusually high seepage rates that were obtained may be due to the positive relief of the seepage meters on the seafloor which can induce advection of porewater from the sediments due to the development of pressure gradients under a unidirectional current. This is the Bernoulli Effect (**Fig. 40**) which has been demonstrated in laboratory flume experiments (Huettell and Gust, 1992) and experiments in natural environments

(Shinn et al., 2002) to amplify seepage measurements. Asymmetrical ripple marks produced from unidirectional currents were observed in the nearshore environment with heights of 5 to 10 cm and wavelengths of ~25 cm further supporting the idea that the Bernoulli Effect may have impacted our measurements.

	($l/m^2/day$)		($l/m^2/day$)
This study, nearshore (mean)	690	Corbett et al., 1999	10.4 to 29.7
This study, nearshore (median)	385	Gallagher et al., 1996	15.1
This study, reef sand (mean)	796	Lewis, 1987	720 to 1121
This study, reef sand (median)	798	Rasmussen, 1998	1 to 10
This study lagoon (mean)	57	Reay et al., 1992	0.48 to 88.56
This study, lagoon (median)	23	Simmons, 1992	6 to 20
Garrison, 2003 (inner bay)	84	Simmons, 1992	5.4 to 8.9
Garrison, 2003 (outer bay)	23	Taniguichi, 2000	120 to 370
Bokuniewicz, 1980	40	Valiela et al., 1990	48 to 96
Cable et al., 1996	14.4 to 112	Vanek and Lee, 1991	205
Cable et al., 1997a	2.8 to 54	Whiting and Childers, 1989	3.6 to 18
Cable et al., 1997 b	24.8	Zimmerman, 1985	67 to 89

Table 23. Fluid flux rates determined by Lee-type seepage meters. References have been taken from the compilation in Taniguchi (2002). The average flux from all other studies is roughly 100 $l/m^2/day$.

Salinity is used here as a conservative tracer because its chemical behavior is controlled by physical processes (e.g. addition or removal of water) and because the physical transport is much faster than any chemical processes that alter it (Libes, 1992). A two component mixing model has been constructed to calculate the volume of nutrients that are generated in the sediments of the nearshore environment from digenetic processes (**Table 24**). Based on this model, it appears that sediment diagenesis accounts for 6.4 μM of the silica, 0.7 μM of the nitrate, and 4.8 μM of the ammonium concentrations in the SGD collected in the seepage meters. The increases in silica and nitrate are not significant given the variability in the terrestrial end member concentrations of those species (Figure 38). The excess ammonium measured in the seepage meters is most likely product of nitrate reduction (see Equation 14)

	Ctgw	Cmw	ftgw	fmw	expected SGD	measured SGD
salinity (psu)	0.16	34.37	0.025	0.975	33.51	33.48
$P0_4$ (μM)	0.5	0.1	0.025	0.975	0.1	0.1
Si (μM)	524	13	0.025	0.975	25.8	32.2
NO_3 (μM)	12	0.2	0.025	0.975	0.5	1.2
NH_4 (μM)	0.9	0.3	0.025	0.975	0.3	5.1

Table 24. Two component mixing model for SGD collected in seepage meters in the nearshore environment of Kaneohe Bay.

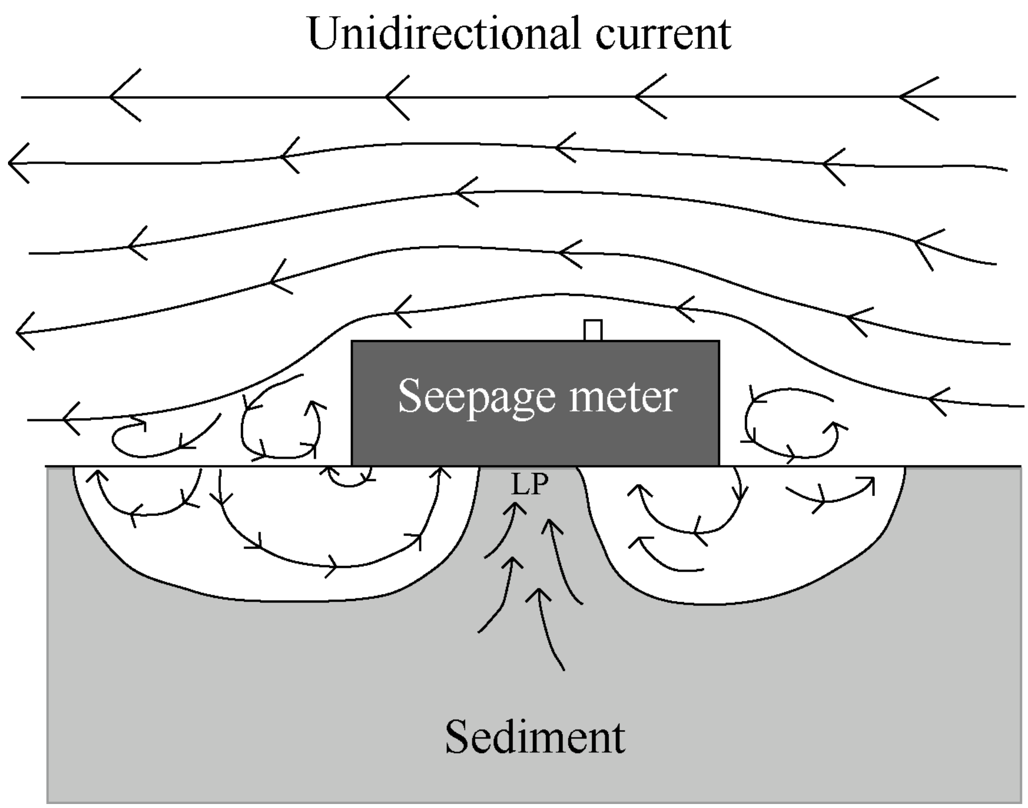


Figure 40. Diagram illustrating the Bernoulli Effect on a seepage meter affected by a unidirectional current (From Huettel and Gust, 1992). The white area in the sediments represents the zone that is flushed from impeding wave orbitals. LP = low pressure.

Our piezometer work (Figures 24 through 26) showed that the porewaters in the nearshore environment are influenced by several physical forces over a range of time scales. Semi-monthly changes in porewater salinity values (Fig. 24) may be the result of the neap-spring lunar tidal cycle (Kim and Hwang, 2002) or be due to changes in the hydraulic gradient between the bay and the adjacent terrestrial aquifer. Superimposed on those longer term changes are daily changes in salinity and water level reflecting the semi-diurnal tidal cycle. During periods of low tide, the hydraulic gradient between the porewater and the adjacent terrestrial aquifer is increased, resulting in the advection of lower salinity (and nutrient enriched) water upwards towards the sediment-water interface (**Fig. 41**). As the tide rises, unidirectional tidal currents and oscillatory wave orbitals from wind driven gravity waves are effective in filtering the lower salinity water out of the upper sediments and replacing it with higher salinity (nutrient depleted) bay water. Therefore, it is a combination of driving forces that cause the net flux of terrestrial groundwater and nutrients out of the nearshore environment sediments.

<u>Lagoon</u>

The sediments of the lagoon of Kaneohe Bay can be considered a two component system. The upper 30 cm is the zone of active bioirrigation, where water is flushed through the sediments by burrowing macrofauna (e.g. alpheid shrimp) (Smith et. al 1981). This was indicated by the near vertical salinity porewater profile of this zone (Fig. 28), a classic indicator of bioirrigation (Berner, 1981). Bioirrigation has been cited as one of the more important processes for increasing nutrient release rates from sediments in lagoon environments (Smith et. al 1981, Berner 1981). This is because the advection created by the burrowing action physically transports nutrients at a faster rate then would occur by molecular diffusion alone (Smith et. al 1981). In this zone elevated silica levels were also observed, the result of opal dissolution by hydrolysis (Ristvet, 1978). Below a depth of 30 cm, the porewater salinities decrease steadily with depth. Fluid velocities calculated from the one-dimensional advection-diffusion model only between 1 and 2 cm per year suggesting that diffusion dominates the transport of solutes through these sediments (**Fig. 42**). In this suboxic to anoxic zone, the breakdown of organic matter by microorganisms results in porewaters that are elevated in ammonium and phosphate (Ristvet, 1978).

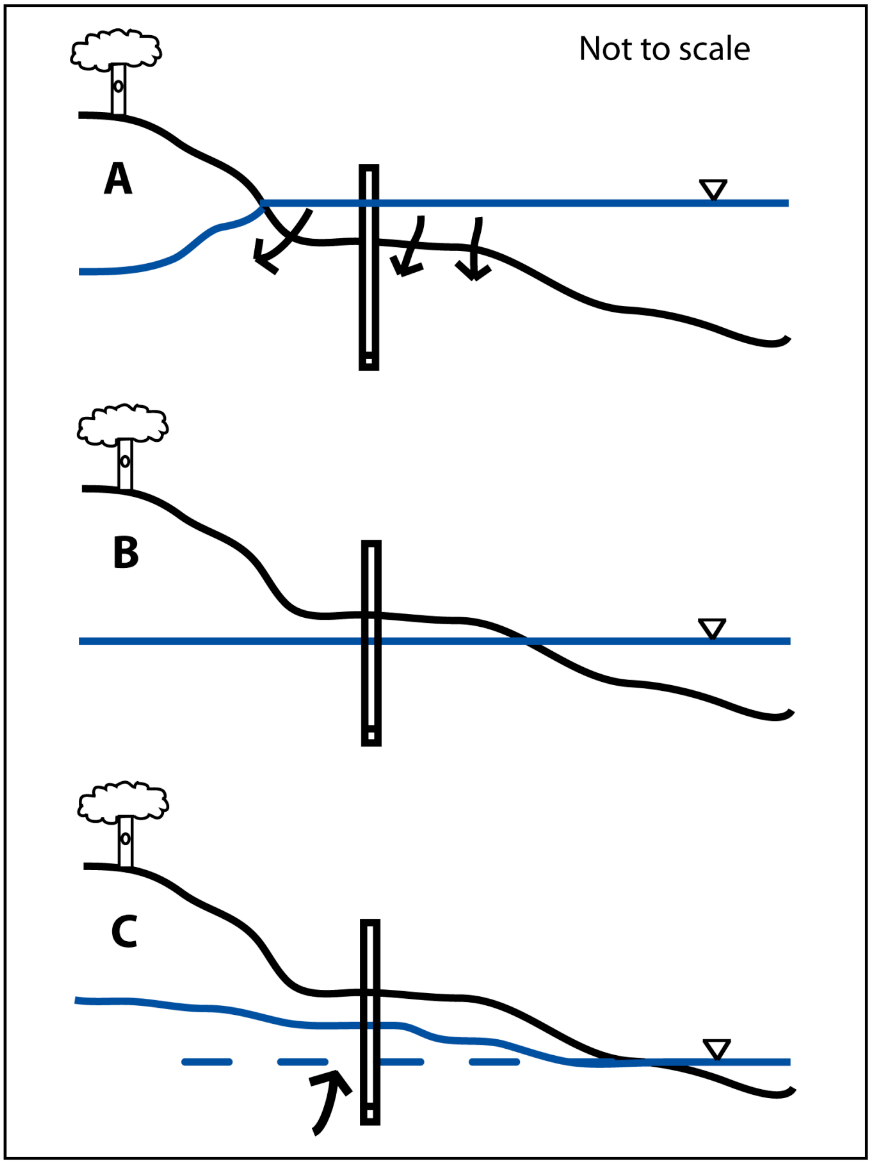


Figure 41. Schematic diagram illustrating the intertidal pump. A: During periods of high tide, the head in the bay is higher than the freshwater head and submarine groundwater recharge occurs. This causes the porewater salinity in the piezometer to increase. B: The freshwater and bay heads are equal. This reflects the infection point when porewater salinity in the piezometer starts to decrease. C: During periods of low tide, the freshwater head is higher than the bay water level and the water level in the piezometer is greater than what is predicted by the tidal signal and the porewater salinity decreases.

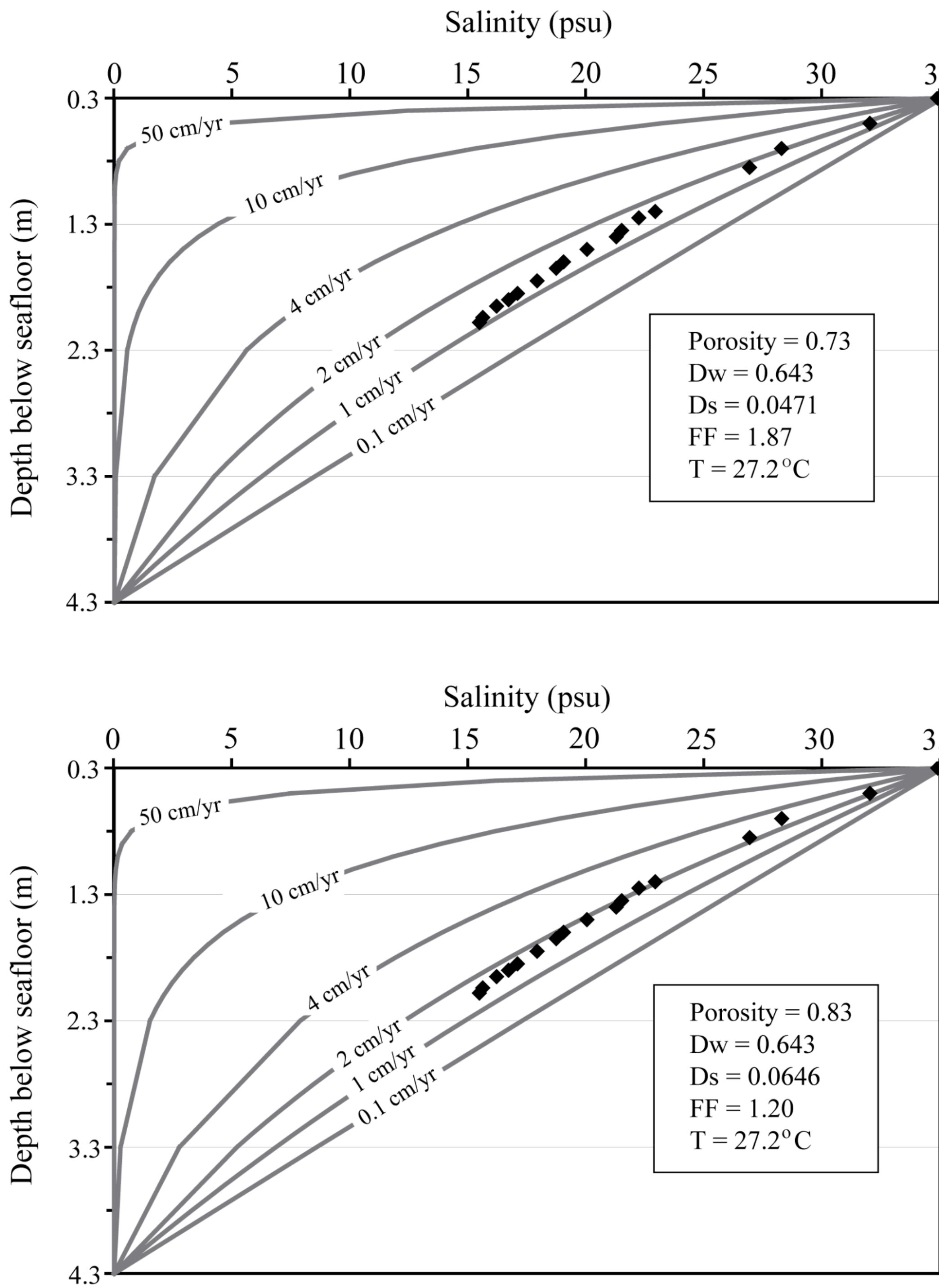


Figure 42. Seepage velocities calculated from a one-dimensional advection-diffusion model (see Equations 4 through 9) for core W-210. Dw = diffusion coefficient in seawater (m^2/yr), Ds = whole sediment diffusion coefficient (m^2/yr), and FF = formation factor.

The difference between the salinity of SGD collected in the seepage meters and that of water samples collected next to the seepage meters was negligible within the accuracy of our measurement techniques in the lagoon environment. As was observed in the nearshore environment, the histogram of fluid flux rates in the lagoon was skewed towards higher values (Fig. 20) which may have been the result of the Bernoulli Effect. Although the seepage meters were emplaced completely into the sediment, due to the soft-muddy substrate of the lagoon, the length of deployment of the seepage meters was relatively long (~18 to 24 hours) and therefore even small currents acting on the seepage meters might have induced a measurable amount of flow over the extended deployments.

The flux of ammonium calculated in this study from seepage meter measurements was roughly 1,000 μmol/m^2/day, which is similar to previous studies (**Table 25**). Silica fluxes calculated in this study (1503 μmol/m^2/day) were about 65% of the value of previous measurements performed in NW and CE sectors (**Table 25**). Nitrate flux estimates from previous studies for the lagoon are more scattered and vary from 0 to 295 μmol/m^2/day with the flux calculated in this study (3 μmol/m^2/day) near the low end of previous estimates (**Table 25**).

	DIN	DIP	DIN/DIP	NH_4	NO_3	Si
This study, lagoon (mean*)	989	7	141	985	4	1260
This study, lagoon (mean)	2990	17	176	2980	10	2340
S & L, 2000 lagoon (SE)	1338	75	18	1043	295	nd
Smith et al., 1981 lagoon (NW)	680	47	14	490	190	2570
Smith et al., 1981 lagoon (CE)	1070	16	67	1070	0	2340
Smith et al., 1981 lagoon (SE/OF)	1180	82	14	960	220	4440

Table 25. Dissolved nutrient fluxes ($\mu mol/m^2/day$) in Kaneohe Bay derived from seepage meter measurements. Fluxes calculated in this study are for the NW sector. S & L = Stimson and Larned. See Figure 19 for the delineation of the lagoon and nearshore environments depicted in this study. Mean* = 2σ rejected mean.

Assuming that porewater advection from hydraulic gradients is negligible (based on seepage meter measurements and salinity porewater profiles) the difference between the flux measured in the seepage meters and that calculated from the sediment cores (diffusion only) is the flux due to bioirrigation. Fluxes of nitrate and phosphate were small (~ 3 $\mu mol/m^2/day$) in both seepage meter and sediment core calculations. Fluxes of ammonium were about a factor of three greater in the seepage meter measurements than those calculated from the sediment porewater profiles. The flux of silica measured in the seepage meters was a factor of 10 greater than the flux calculated from the sediment porewater profiles. This large difference is likely due to the rapid production of silica (dissolution of biogenic opal raining down from the water column) and subsequent flushing (bioirrigation by macrofauna) near the sediment-water interface (Fig. 34).

Freshwater Flux

The only previous estimate for the amount of terrestrial SGD entering the NW sector was done by Smith et al (1981) who calculated a value of 2.27×10^7 l/day based on the water budget estimates of Takasaki (1969) and Cox et al. (1973). This is less than one half the value calculated in this study and although this initially appears to be a significant discrepancy, it may be easily accounted for by considering the poor constraint on the values of evapotranspiration (ET) and watershed area used in the water budget of Takasaki et al. (1969) and further by the way in which Smith et al. (1981) distributed the total terrestrial SGD amongst the different sectors.

A pressing problem with calculating quantities of terrestrial SGD from water budgets is that SGD is usually taken to be the volume of water that is "unaccounted for" and therefore inherently contains the cumulative errors of calculating the other components of the water budget (Smith and Nield, 2003). This is a problem because the volume of SGD in most coastal systems is a small fraction of the total water budget and thus small errors in the other components can dominate the overall SGD estimate. In Kaneohe Bay, terrestrial SGD is thought to represent only 3.5% of the total volume of water entering the hydrologic system (Cox et. al 1973) (**Fig. 43**).

The difference between the terrestrial SGD calculated in this study and that reported by Smith et al. (1981) can be accounted for by slightly adjusting the values of evapotranspiration (ET) and the watershed area used in the water budget of Takasaki et al. (1973). Of the total volume of precipitation that falls onto the Kaneohe Bay watershed, it was estimated that 45% evaporates or is transpired by plants back into the atmosphere (Cox et al., 1973). This volumetrically significant component of the water budget is not based on any direct measurements in the Kaneohe Bay area and is instead calculated from pan evaporation measurements at 18 different stations on four of the main Hawaiian Islands (Takasaki et al. 1969). If one decreases the ET value to 41.5% of the precipitation amount, this doubles the terrestrial groundwater flux. This is a reasonable estimate because the previous ET estimate is so poorly constrained (Takasaki et al 1969).

The exact location of the groundwater divide is unknown but it is thought to be located west of the topographic divide (Takasaki et al., 1969). This shift away from the topographic divide reflects higher precipitation values in the west which coincides with increased infiltration and therefore a higher water table. Assuming a precipitation rate of 2 cm/day near the topographic divide and an evapotranspiration and SGD rate of 6% the precipitation amount (Takasaki et al., 1969; Cox et al., 1973), a shift of the ground water divide in the NW sector 600 m to the west also doubles the volume of terrestrial SGD into Kaneohe Bay.

It is therefore possible that the excess terrestrial SGD measured in this study (compared to the value given by Smith et al., 1981) could realistically be accounted for by decreasing ET by 1.75% to 43.25% and increasing the watershed boundary 300 m to the west of the topographic divide in the NW sector.

Smith et al (1981) estimated the terrestrial SGD flux into the NW sector by dividing the total terrestrial SGD flux from Cox et al. (1971), by the length of shoreline for each sector. Distributing the total groundwater flux by this method may be inaccurate because rainfall is greater in the northwest sector and the number of basaltic dikes that decrease the lateral groundwater flow in the direction of the bay decrease in number from the southern sector to the NW sector (Walker, 1987). Also, the amount of the watershed in the NW sector covered by impervious surfaces which tend to decrease infiltration of rainwater is much less than in the other two sectors of the bay. Therefore, the flux of terrestrial groundwater per unit length of shoreline in the NW sector should probably be weighted higher than the other two sectors.

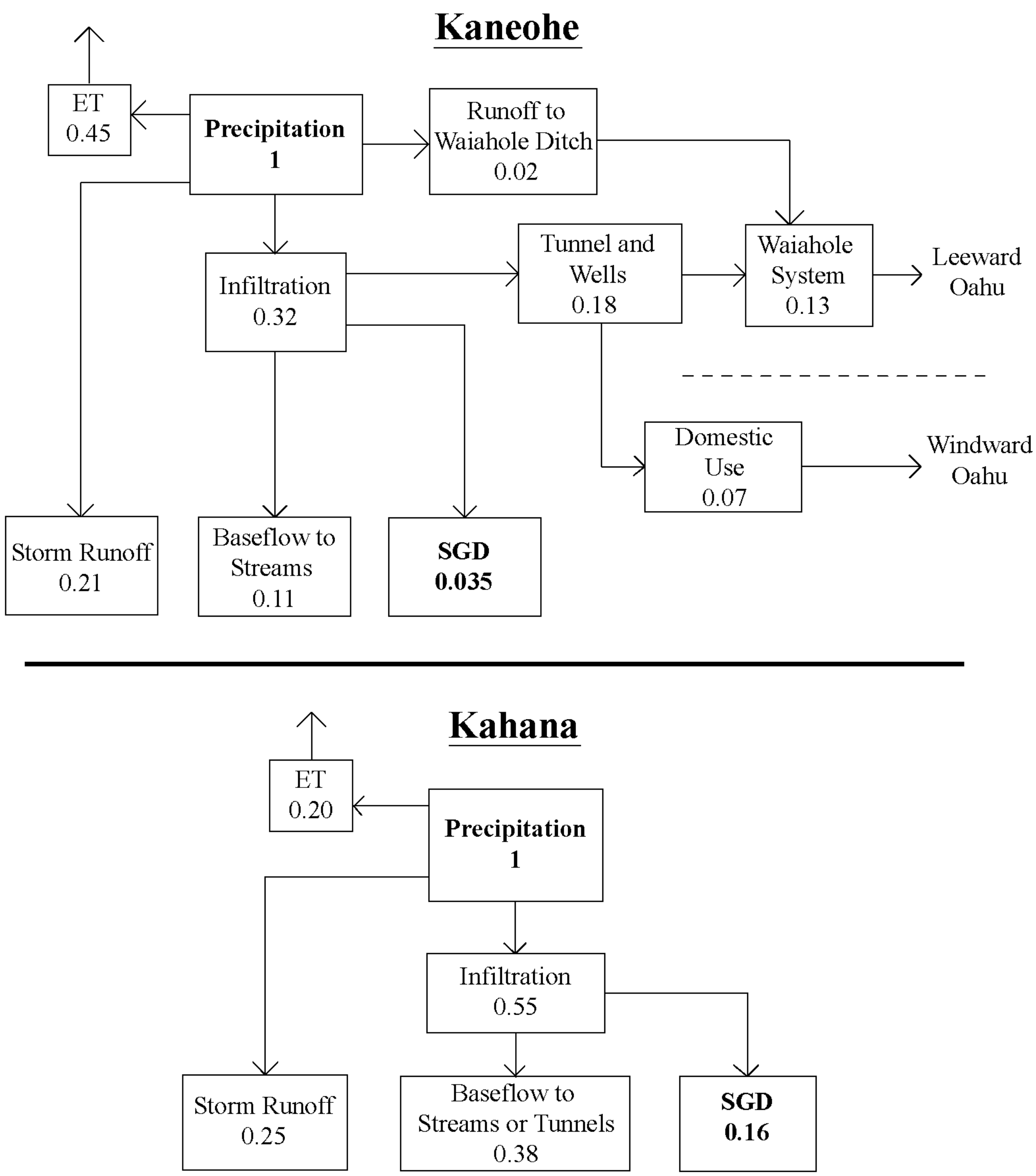


Figure 43. Water budgets for Kaneohe and Kahana watersheds scaled to precipitation. The Kaneohe budget is taken from Cox et al. (1973) and Kahana budget is from Takasaki et al. (1969).

Comparison of SGD in Kaneohe and Kahana Bays

Even though Kaneohe and Kahana are geographically close to one another (~ 5 to 10 km), the two areas are different in many aspects. First of all, the watershed surrounding Kaneohe Bay is developed with an urban city in the southern sector and agricultural/rural settings towards the north, whereas the Kahana watershed consists of relatively undeveloped forest land. This has important hydrological significance because urbanization tends to create impervious services (e.g. parking lots, roof tops, roads) that impede the infiltration of rainwater, therefore decreasing the amount of water that could potentially flow to the coastal zone as SGD. Land development also increases erosion rates in the watershed resulting in large fluxes of particulate material in streams that can eventually get broken down (remineralized) and released as dissolved nutrients into coastal waters via SGD.

Another important difference between the Kaneohe and Kahana regions is that much of the Kaneohe watershed lies in the Koolau dike complex whereas relatively few dikes are present in Kahana. The dikes in the Koolau run perpendicular to the regional groundwater flow system and have a relatively low permeability. This reduces the lateral groundwater flow towards Kaneohe Bay and causes a large fraction of the infiltrated rain water to become dike impounded, reaching elevations exceeding 700 meters (Fig. 2). These dikes are therefore effective in reducing the volume of groundwater that flows into the coastal waters as SGD.

These hydrogeologic differences between Kaneohe and Kahana are reflected in the percentage of precipitation that ends up as terrestrial SGD. In Kahana, 16% of the precipitation leaves the system as SGD, whereas in Kaneohe only 3.5% of the precipitation occurs as SGD (**Fig. 43**). This difference in proportions was observed in our seepage meter measurements (**Table 26**), where the fraction of terrestrial SGD in Kahana was 20% and that in Kaneohe Bay was only 2.5%.

	Kaneohe (NW) Nearshore	Kahana Inner	Kahana Outer
Area of seafloor (10^5 m^2)	14	9.3	5.1
Total fluid flux ($l/m^2/day$)	560	84	23
Total fluid flux (10^6 l/day)	784	78	12
Fraction terrestrial groundwater	0.025	0.2	0.003
Terrestrial SGD flux ($l/m^2/day$)	14.0	16.8	0.069
Terrestrial SGD input (10^6 l/day)	19.6	14	0.038

Table 26. Comparison of the SGD freshwater flux for the nearshore environment of the NW sector of Kaneohe Bay calculated in this study and the freshwater flux of inner and outer Kahana Bay calculated by Garrison et al., (2003).

Benthic Algae

Along with the well documented spread of *D. cavernosa* in Kaneohe Bay (Smith et al., 1981), several other macroalgae species have been found to have spread across parts of the bay from their points of introduction in the south bay. A bay wide survey conducted in the summer of 1996 found that the introduced rhodophytes *Kappaphycus alvarezii* and *Kappaphycus striatum* had spread at a rate of 250 m/yr and that *Gracilaria salicornia* had spread at rate of 280 m/yr from their points of introduction in 1974 and 1978, respectively (Rodgers and Cox, 1999).

Results of our benthic surveys in the NW sector showed that two species of benthic algae (*Acanthophora spicifera* and *Gracilaria salicornia*) previously undetected in this area were quite abundant (Tables 18 and 19). This suggests that the algae are continuing to thrive and are migrating farther to the north. In addition, they have the potential to advance into other coastal environments to the north such as Kahana Bay.

The spread of these benthic algae has occurred despite the fact that they cannot grow when only exposed to water from the oligotrophic water column (Larned and Stimson, 1996; Larned, 1998), suggesting that thalli must be exposed to either high advection rates of the low nutrient water column or to benthic nutrient sources (Stimson and Larned, 2000). Our seepage meter and piezometer work showed that SGD in the nearshore is a source of nutrients to the water column (and most likely to the algae located on the sediments) and that the water is very turbulent due to tides, waves, and hydraulic gradients.

Maunalua and Kealakekua Bays

The results of the limited sampling at these two locations suggest that SGD is a widespread and important process that occurs over much of the coastal zone around the Hawaiian Islands. During most of the year, SGD is the major source of freshwater and dissolved nutrients to these sites because stream input is essentially zero.

Applying a two component mixing model to the Maunalua Bay seepage meter measurements shows that 30.2 µM of the SGD silica and 3.5 µM of the ammonium are the result of sediment diagenesis (**Table 27**). The 3.5 µM increase in ammonium corresponds with a 3.5 µM decrease or consumption of nitrate (**Table 27**). This most likely reflects the process of nitrate reduction in which nitrate broken down to ammonium (see Equation 14).

	Ctgw	Cmw	ftgw	fmw	expected SGD	measured SGD
salinity (psu)	1.4	34.33	0.038	0.962	33.08	33.09
$P0_4$ (μM)	1.5	0.3	0.038	0.962	0.3	0.2
Si (μM)	670	20	0.038	0.962	44.5	74.6
NO_3 (μM)	95	0.6	0.038	0.962	4.2	0.9
NH_4 (μM)	1.1	0.4	0.038	0.962	0.4	3.9

Table 27. Two component mixing model for SGD collected in seepage meters in the nearshore environment of Maunalua Bay.

The benthic survey conducted in Maunalua Bay revealed that several benthic algae are abundant (Table 22) and locally cover nearly 100% of the bay floor. The extensive growth of these algae appears to be a somewhat recent phenomenon as was suggested by a local resident who observed the complete coverage of a section (~25 m x 30 m) of reef by *G. Salicornia* over the past eight years (Robert Chong, personal communication). It is clear that SGD is a major source of nutrients to this section of coastline (Fig. 37) and that the growth of the algae may be due to the SGD loading although a direct link is currently lacking.

CONCLUSIONS

Submarine groundwater discharge (SGD) was found to be a volumetrically significant source of nutrients into Kaneohe bay in both the nearshore and lagoon environments. Terrestrial SGD was restricted to the nearshore environment and was twice as voluminous as previously estimated.

Sources of nutrients in the nearshore SGD include the terrestrial SGD fraction as well as nutrients generated in the sediments (diagenesis). Nutrients are released from the nearshore sediments from tidal pumping, oscillatory wave flushing, and advection due to the hydraulic gradient between the bay sediments and the terrestrial aquifer.

The lagoon environment consists of relatively low permeability fine-grained sediments in which diffusion and bioirrigation processes control the transport of nutrients out of the sediments and into the water column. The source of nutrients is from the breakdown of organic matter (ammonium, nitrate, and phosphate) and the dissolution of biogenic opal (silica) deposited from the water column.

Several benthic algae species were locally very abundant at both the Kaneohe and Maunalua bay study sites. Although a direct connection is currently not available, algae growth is most likely partially sustained by nutrient rich SGD.

At the Maunalua and Kealakekua Bay study sites, terrestrial SGD is the dominant source of nutrients to the water column and during most of the year is the only source of terrestrial (fresh) water. These observations support the notion that SGD is likely a volumetrically significant source of nutrients and terrestrial water to most of Hawaii's coastal waters.

APPENDIX A

Kaneohe Bay Nearshore Seepage Meter Measurements

Date (m/d/yr)	Location (Latitude Longitude)	Water depth (m)	Total fluid flux ($l/m^2/day$)	Salinity (psu)	PO_4 [μM]	Si [μM]	NO_3 [μM]	NH_4 [μM]	NH4 [uM]
3/16/02	N21.50619 W157.85484	1.5	164.4	5.0	32.31	0.15	42.90	1.85	0.43
3/16/02	N21.50596 W157.85433	1.5	226.2	2.4	33.17	0.02	27.73	0.12	0.21
3/16/02	N21.50596 W157.85434	1.5	934.2	2.3	33.23	0.14	36.01	1.63	0.51
3/16/02	N21.50548 W157.85345	1.5	78.0	1.8	33.37	0.05	35.81	1.87	0.54
3/16/02	N21.50548 W157.85345	1.5	364.1	0.3	33.90	0.10	37.35	1.96	0.65
3/16/02	N21.50511 W157.85247	1.5	288.0	10.7	30.36	0.05	30.24	0.26	0.75
3/16/02	N21.50511 W157.85247	1.5	351.2	0.1	33.97	0.01	31.74	0.20	0.68
5/14/02	N21.50544 W157.85350	1.5	1779.8	5.8	31.45	0.03	41.31	1.29	0.86
5/14/02	N21.50544 W157.85350	1.5	2197.4	5.1	31.65	0.03	36.69	1.21	0.63
5/14/02	N21.50544 W157.85350	1.5	2407.7	2.8	31.97	0.02	33.72	1.14	0.98
5/14/02	N21.50544 W157.85350	1.5	2739.2	3.2	31.85	0.03	31.20	0.97	0.42
5/14/02	N21.50545 W157.85334	1.5	1084.8	3.5	31.75	0.05	30.94	0.96	1.03
5/14/02	N21.50545 W157.85334	1.5	1582.1	2.2	32.19	0.04	35.24	1.21	1.74
5/14/02	N21.50545 W157.85334	1.5	1664.6	2.6	32.03	0.05	37.68	1.23	1.37
5/14/02	N21.50545 W157.85334	1.5	1546.6	2.3	32.13	0.04	33.40	1.22	0.96
5/14/02	N21.50545 W157.85334	1.5	1681.9	2.2	32.19	0.05	33.27	1.20	1.25
6/7/02	N21.50583 W157.85408	1.5	356.3						
6/7/02	N21.50583 W157.85408	1.5	563.9						
6/7/02	N21.50549 W157.85315	1.5	561.6						
6/7/02	N21.50549 W157.85315	1.5	466.6						
6/7/02	N21.50583 W157.85408	1.5	660.3						
6/7/02	N21.50583 W157.85408	1.5	341.0						
6/7/02	N21.50549 W157.85315	1.5	1080.6						

Appendix A. (continued) Kaneohe Bay Nearshore Seepage Meter Measurements

Date (m/d/yr)	Location (Latitude Longitude)	Water depth (m)	Total fluid flux ($l/m^2/day$)	Salinity (psu)	PO_4 [μM]	Si [μM]	NO_3 [μM]	NH_4 [μM]	NH4 [uM]
6/7/02	N21.50583 W157.85408	1.5	1346.0						
6/7/02	N21.50583 W157.85408	1.5	921.6						
6/7/02	N21.50549 W157.85315	1.5	2034.4						
6/7/02	N21.50549 W157.85315	1.5	1364.0						
6/7/02	N21.50583 W157.85408	1.5	2479.7						
6/7/02	N21.50583 W157.85408	1.5	2342.9						
6/7/02	N21.50549 W157.85315	1.5	2609.3						
6/7/02	N21.50549 W157.85315	1.5	1728.0						
6/7/02	N21.50583 W157.85408	1.5	1520.6						
6/7/02	N21.50583 W157.85408	1.5	864.0						
6/7/02	N21.50549 W157.85315	1.5	1900.8						
6/7/02	N21.50549 W157.85315	1.5	1474.6						
6/7/02	N21.50583 W157.85408	1.5	326.4						
6/7/02	N21.50583 W157.85408	1.5	165.1						
6/7/02	N21.50549 W157.85315	1.5	374.4						
6/7/02	N21.50549 W157.85315	1.5	226.6						
6/12/02	N21.50568 W157.85359	1.5	161.3						
6/12/02	N21.50568 W157.85359	1.5	126.7						
6/12/02	N21.50568 W157.85359	1.5	142.8						
6/12/02	N21.50568 W157.85359	1.5	38.0						
6/12/02	N21.50604 W157.85456	1.5	86.4						
6/12/02	N21.50522 W157.85277	1.5	282.2						
6/12/02	N21.50522 W157.85277	1.5	388.8						

Appendix A. (continued) Kaneohe Bay Nearshore Seepage Meter Measurements

Date (m/d/yr)	Location (Latitude Longitude)	Water depth (m)	Total fluid flux (l/m^2/day)	Salinity (psu)	PO_4 [μM]	Si [μM]	NO_3 [μM]	NH_4 [μM]	NH4 [uM]
6/12/02	N21.50568 W157.85359	1.5	619.2						
6/12/02	N21.50568 W157.85359	1.5	87.8						
6/12/02	N21.50522 W157.85277	1.5	645.1						
6/12/02	N21.50522 W157.85277	1.5	956.2						
6/12/02	N21.50568 W157.85359	1.5	1697.3						
6/12/02	N21.50604 W157.85456	1.5	78.3						
6/12/02	N21.50522 W157.85277	1.5	1108.8						
6/12/02	N21.50522 W157.85277	1.5	1111.7						
6/27/02	N21.50525 W157.85243	1.5	109.0						
6/27/02	N21.50525 W157.85245	1.5	145.6						
6/27/02	N21.50525 W157.85243	1.5	105.1						
6/27/02	N21.50525 W157.85245	1.5	175.5						
6/27/02	N21.50525 W157.85243	1.5	305.5						
6/27/02	N21.50525 W157.85245	1.5	217.4						
6/27/02	N21.50525 W157.85243	1.5	342.1						
6/27/02	N21.50525 W157.85245	1.5	289.2						
6/27/02	N21.50525 W157.85243	1.5	87.2						
6/27/02	N21.50525 W157.85245	1.5	221.1						
6/27/02	N21.50520 W157.85233	1.5	56.2						
6/27/02	N21.50520 W157.85210	1.5	158.0						
6/27/02	N21.50520 W157.85233	1.5	66.4						
6/27/02	N21.50520 W157.85210	1.5	137.3						
6/27/02	N21.50520 W157.85233	1.5	176.4						

Appendix A. (continued) Kaneohe Bay Nearshore Seepage Meter Measurements

Date (m/d/yr)	Location (Latitude Longitude)	Water depth (m)	Total fluid flux (l/m^2/day)	Salinity (psu)	PO_4 [μM]	Si [μM]	NO_3 [μM]	NH_4 [μM]	NH4 [uM]
6/27/02	N21.50520 W157.85210	1.5	130.9						
6/27/02	N21.50509 W157.85273	1.5	232.8						
6/27/02	N21.50520 W157.85210	1.5	134.0						
7/17/02	N21.50558 W157.85290	1.5	168.2						
7/17/02	N21.50509 W157.85273	1.5	274.2						
7/17/02	N21.50558 W157.85290	1.5	213.3						
7/17/02	N21.50509 W157.85273	1.5	242.9						
7/17/02	N21.50558 W157.85290	1.5	286.7						
7/17/02	N21.50509 W157.85273	1.5	151.0						
7/17/02	N21.50558 W157.85290	1.5	254.1						
7/17/02	N21.50509 W157.85273	1.5	189.4						
7/17/02	N21.50558 W157.85290	1.5	335.4						
7/17/02	N21.50509 W157.85273	1.5	102.4						
8/1/02	N21.48767 W157.84311	1.5	240.6						
8/1/02	N21.48767 W157.84311	1.5	520.3						
8/1/02	N21.48767 W157.84311	1.5	912.0						
8/1/02	N21.48767 W157.84311	1.5	1710.0						
8/16/02	N21.48768 W157.84317	1.5	252.0	1.7	33.80	0.09	34.16	0.69	9.56
8/16/02	N21.48768 W157.84317	1.5	142.8						
8/16/02	N21.48768 W157.84317	1.5	324.8						
8/16/02	N21.48768 W157.84317	1.5	419.9						
8/23/02	N21.48768 W157.84317	1.5	414.7						
8/23/02	N21.48768 W157.84317	1.5	327.9						

Appendix A. (continued) Kaneohe Bay Nearshore Seepage Meter Measurements

Date (m/d/yr)	Location (Latitude Longitude)	Water depth (m)	Total fluid flux (l/m^2/day)	Salinity (psu)	PO_4 [μM]	Si [μM]	NO_3 [μM]	NH_4 [μM]	NH4 [uM]
8/23/02	N21.48768 W157.84317	1.5	158.4						
8/23/02	N21.48768 W157.84315	1.5	383.8						
8/23/02	N21.48768 W157.84317	1.5	267.7						
8/23/02	N21.48768 W157.84315	1.5	354.5						
8/23/02	N21.48768 W157.84317	1.5	356.9						
8/23/02	N21.48768 W157.84315	1.5	365.5						
8/23/02	N21.48768 W157.84317	1.5	414.0						
8/23/02	N21.48768 W157.84315	1.5	793.6	6.4	31.23	0.17	24.18	0.58	4.71
8/23/02	N21.48768 W157.84317	1.5	460.8						
11/23/02	N21.48763 W157.84332	1.2	470.4	5.9	31.40				
11/23/02	N21.48763 W157.84332	1.2	635.0	0.0	35.49				
11/23/02	N21.48763 W157.84332	1.2	367.7						
11/23/02	N21.48763 W157.84332	1.2	321.2						
11/23/02	N21.48763 W157.84332	1.2	339.5						
11/23/02	N21.48763 W157.84332	1.2	473.1						
11/23/02	N21.48763 W157.84332	1.2	506.9						
11/23/02	N21.48789 W157.84353	1.5	551.5						
11/23/02	N21.48789 W157.84353	1.5	383.3						
11/23/02	N21.48789 W157.84353	1.5	182.2						
11/23/02	N21.48789 W157.84353	1.5	190.3	0.2	34.31				
11/23/02	N21.48789 W157.84353	1.5	314.9						
11/25/02	N21.48789 W157.84353	1.5	320.3			0.13	24.96	1.02	1.53
11/25/02	N21.48763 W157.84332	1.2	614.4	0.0	34.56	0.14	26.11	3.36	0.54

Appendix A. (continued) Kaneohe Bay Nearshore Seepage Meter Measurements

Date (m/d/yr)	Location (Latitude Longitude)	Water depth (m)	Total fluid flux (l/m^2/day)	Salinity (psu)	PO_4 [μM]	Si [μM]	NO_3 [μM]	NH_4 [μM]	NH4 [uM]
11/25/02	N21.48763 W157.84332	1.2	589.4						
11/25/02	N21.48789 W157.84353	1.5	388.2						
11/25/02	N21.48763 W157.84332	1.2	877.4			0.12	26.55	4.20	0.17
11/25/02	N21.48789 W157.84353	1.5	133.1			0.20	31.31	0.77	5.06
12/21/02	N21.48805 W157.84338	1.8	139.8						
12/21/02	N21.48767 W157.84305	1.5	41.7						
12/21/02	N21.48629 W157.84295	0.9	397.4						
12/21/02	N21.48426 W157.84287	1.5	129.6						
12/21/02	N21.48476 W157.84316	1.2	368.6			0.10	20.11	15.62	0.13
12/21/02	N21.48426 W157.84287	1.5	250.0			0.10	28.03	0.74	3.88
12/21/02	N21.48805 W157.84338	1.8	192.6	1.3	35.09	0.10	21.54	0.48	16.75
12/21/02	N21.48767 W157.84305	1.5	205.0	1.8	34.91	0.12	49.08	0.78	14.42
12/21/02	N21.48629 W157.84295	0.9	849.6	1.3	35.07	0.14	109.05	0.62	0.13
12/21/02	N21.48426 W157.84287	1.5	508.8	2.5	34.65	0.10	24.63	0.89	2.42
12/21/02	N21.48476 W157.84316	1.2	1123.2	2.2	34.77	0.17	18.91	2.17	0.13
12/21/02	N21.48805 W157.84338	1.8	154.3			0.20	22.34	0.54	19.10
12/21/02	N21.48767 W157.84305	1.5	356.3						
12/21/02	N21.48426 W157.84287	1.5	76.3						
12/21/02	N21.48476 W157.84316	1.2	1458.7						
12/21/02	N21.48629 W157.84295	0.9	1123.2			0.16	17.44	0.76	0.13
12/22/02	N21.48805 W157.84338	1.8	212.1	1.2	35.11	0.10	24.72	2.68	0.13
12/22/02	N21.48767 W157.84305	1.5	250.7	0.6	35.34	0.10	21.89	1.00	18.21

Appendix A. (continued) Kaneohe Bay Nearshore Seepage Meter Measurements

Date (m/d/yr)	Location (Latitude Longitude)	Water depth (m)	Total fluid flux (l/m^2/day)	Salinity (psu)	PO_4 [μM]	Si [μM]	NO_3 [μM]	NH_4 [μM]	NH4 [uM]
12/22/02	N21.48476 W157.84316	1.2	253.4	2.7	34.60	0.10	24.72	2.68	0.13
12/22/02	N21.48426 W157.84287	1.5	384.0	2.5	34.64	0.10	23.91	1.07	2.01
12/22/02	N21.48805 W157.84338	1.8	213.1						
12/22/02	N21.48767 W157.84305	1.5	230.4						
12/22/02	N21.48629 W157.84295	0.9	514.0						
12/22/02	N21.48476 W157.84316	1.2	211.9						
12/22/02	N21.48426 W157.84287	1.5	345.6						
12/23/02	N21.48805 W157.84338	1.8	159.4	0.0	36.87				
12/23/02	N21.48767 W157.84305	1.5	683.0	2.2	34.75				
12/23/02	N21.48629 W157.84295	0.9	46.1						
12/23/02	N21.48476 W157.84316	1.2	677.6	2.2	34.75				
1/8/03	N21.48769 W157.84335	1.5	25.8						
1/8/03	N21.48795 W157.84358	1.5	165.7						
1/8/03	N21.48769 W157.84335	1.5	30.7						
1/8/03	N21.48795 W157.84358	1.5	230.4						
1/9/03	N21.48769 W157.84335	1.5	16.1						
1/9/03	N21.48795 W157.84358	1.5	118.4						
1/10/03	N21.48436 W157.84261	0.9	243.7						
1/10/03	N21.48437 W157.84258	0.9	39.9						
1/10/03	N21.48438 W157.84249	0.9	310.2						
1/10/03	N21.48436 W157.84261	0.9	203.8						
1/10/03	N21.48437 W157.84258	0.9	39.0						
1/10/03	N21.48438 W157.84249	0.9	267.6						

Appendix A. (continued) Kaneohe Bay Nearshore Seepage Meter Measurements

Date (m/d/yr)	Location (Latitude Longitude)	Water depth (m)	Total fluid flux ($l/m^2/day$)	Salinity (psu)	PO_4 [μM]	Si [μM]	NO_3 [μM]	NH_4 [μM]	NH4 [uM]
1/10/03	N21.48437 W157.84258	0.9	128.5						
1/10/03	N21.48438 W157.84249	0.9	303.1						
6/5/03	N21.48325 W157.84404	1.8	370.3	2.2	32.79				
6/5/03	N21.48337 W157.84409	1.8	171.6	1.9	31.93				
6/5/03	N21.48349 W157.84417	1.8	370.3	0.5	32.38				
6/5/03	N21.48367 W157.84415	1.8	72.8	0.0	35.34				
6/5/03	N21.48374 W157.84412	1.8	184.3	3.8	32.26				
6/5/03	N21.48350 W157.84394	1.8	42.4	3.4	32.39				
6/5/03	N21.48340 W157.84394	1.8	290.3	3.8	32.28				
6/5/03	N21.48329 W157.84392	1.8	146.5	3.8	32.26				
6/5/03	N21.48325 W157.84404	1.8	769.7	4.9	30.95				
6/5/03	N21.48337 W157.84409	1.8	298.5	5.0	30.91				
6/5/03	N21.48349 W157.84417	1.8	572.2	5.1	30.88				
6/5/03	N21.48367 W157.84415	1.8	387.8	3.2	31.50				
6/5/03	N21.48374 W157.84412	1.8	252.4	2.1	32.83				
6/5/03	N21.48350 W157.84394	1.8	373.9	0.2	33.49				
6/5/03	N21.48340 W157.84394	1.8	415.2	6.2	31.47				
6/5/03	N21.48329 W157.84392	1.8	289.0	7.2	31.13				
6/12/03	N21.48325 W157.84404	1.8	1197.0	0.4	33.42				
6/12/03	N21.48337 W157.84409	1.8	1389.0	2.3	32.76				
6/12/03	N21.48349 W157.84417	1.8	459.5	2.4	34.70				
6/12/03	N21.48367 W157.84415	1.8	1089.3	0.0	35.69				
6/12/03	N21.48374 W157.84412	1.8	886.7	1.6	34.97				

Appendix A. (continued) Kaneohe Bay Nearshore Seepage Meter Measurements

Date (m/d/yr)	Location (Latitude Longitude)	Water depth (m)	Total fluid flux (l/m^2/day)	Salinity (psu)	PO_4 [µM]	Si [µM]	NO_3 [µM]	NH_4 [µM]	NH4 [uM]
6/12/03	N21.48350 W157.84394	1.8	788.3	2.3	34.72				
6/12/03	N21.48340 W157.84394	1.8	1400.0	5.1	32.79				
6/12/03	N21.48325 W157.84404	1.8	1370.3	1.7	33.94				
6/12/03	N21.48337 W157.84409	1.8	1371.8	1.2	34.11				
6/12/03	N21.48349 W157.84417	1.8	622.1	0.6	35.32				
6/12/03	N21.48367 W157.84415	1.8	2656.4	0.3	35.45				
6/12/03	N21.48374 W157.84412	1.8	2158.3	0.9	35.23				
6/12/03	N21.48350 W157.84394	1.8	2559.6	0.2	35.46				
6/12/03	N21.48340 W157.84394	1.8	929.3	0.3	35.44				
6/12/03	N21.48329 W157.84392	1.8	3313.9	0.4	35.38				
6/12/03	N21.48325 W157.84404	1.8	1736.2	0.9	35.20				
6/12/03	N21.48337 W157.84409	1.8	2229.9	0.3	35.43				
6/12/03	N21.48349 W157.84417	1.8	437.8	0.4	35.40				
6/12/03	N21.48367 W157.84415	1.8	2622.7	0.6	35.32				
6/12/03	N21.48374 W157.84412	1.8	1242.5	0.4	35.41				
6/12/03	N21.48350 W157.84394	1.8	1351.7	0.0	35.61				
6/12/03	N21.48340 W157.84394	1.8	913.4	1.4	35.06				
6/12/03	N21.48329 W157.84392	1.8	2670.2	0.6	35.31				
6/12/03	N21.48325 W157.84404	1.8	1329.2	0.0	35.60				
6/12/03	N21.48337 W157.84409	1.8	731.1	1.5	35.01				
8/14/03	N21.50598 W157.85377	0.9	699.8	0.6	33.81	0.24	38.07	0.25	3.07
8/14/03	N21.50598 W157.85377	0.9	852.9	1.3	33.56	0.21	37.53	0.79	1.77
8/14/03	N21.50725 W157.84993	1.4	150.6	0.0	35.88				

Appendix A. (continued) Kaneohe Bay Nearshore Seepage Meter Measurements

Date (m/d/yr)	Location (Latitude Longitude)	Water depth (m)	Total fluid flux ($l/m^2/day$)	Salinity (psu)	PO_4 [μM]	Si [μM]	NO_3 [μM]	NH_4 [μM]	NH4 [uM]
8/14/03	N21.50604 W157.85411	0.9	664.1	2.2	33.26	0.14	38.12	0.69	3.14
8/15/03	N21.50598 W157.85377	0.9	394.3	2.7	32.11				
8/15/03	N21.50598 W157.85377	0.9	703.7	2.6	32.17				
8/15/03	N21.50598 W157.85377	0.9	802.0	4.8	31.42				
8/15/03	N21.50598 W157.85377	0.9	904.1	2.5	32.19				
8/15/03	N21.50598 W157.85377	0.9	1212.0	4.8	31.41				
8/15/03	N21.50598 W157.85377	0.9	714.2	4.8	31.44				
8/15/03	N21.50598 W157.85377	0.9	1949.3	5.7	31.14				
8/15/03	N21.50598 W157.85377	0.9	1388.2	5.9	31.07	0.14	42.88	0.76	2.10
8/15/03	N21.50604 W157.85411	0.9	460.8	7.9	30.39				
8/15/03	N21.50604 W157.85411	0.9	1169.0	5.7	29.26				
8/15/03	N21.50604 W157.85411	0.9	1676.2	6.4	29.01				
8/15/03	N21.50604 W157.85411	0.9	1739.5	2.4	30.26				
8/15/03	N21.50604 W157.85411	0.9	2149.2	1.6	30.52				
8/15/03	N21.50604 W157.85411	0.9	2208.0	1.0	30.69				
8/15/03	N21.50604 W157.85411	0.9	1612.8	1.3	30.62				
8/15/03	N21.50604 W157.85411	0.9	1094.4	2.7	31.14				
8/15/03	N21.50604 W157.85411	0.9	1329.2	3.0	31.05				
8/15/03	N21.50604 W157.85411	0.9	1447.7	4.0	30.72				

APPENDIX B

Kaneohe Bay Lagoon Seepage Meter Measurements

Date (m/d/yr)	Location (Latitude Longitude)	Water depth (m)	Total fluid flux ($l/m^2/day$)	Salinity (psu)	PO_4 [μM]	Si [μM]	NO_3 [μM]	NH_4 [μM]
8/1/2002	N21.48771 W157.84285	2.7	188.8					
8/1/2002	N21.48772 W157.84269	3.7	21.8					
8/1/2002	N21.48771 W157.84285	2.7	160.3					
8/1/2002	N21.48772 W157.84269	3.7	11.9					
8/1/2002	N21.48771 W157.84285	2.7	159.8					
8/1/2002	N21.48772 W157.84269	3.7	9.1					
8/1/2002	N21.48771 W157.84285	2.7	137.3	33.86	0.10	32.06	0.41	13.60
8/1/2002	N21.48771 W157.84285	2.7	136.9					
8/1/2002	N21.48772 W157.84269	3.7	12.5					
8/1/2002	N21.48771 W157.84285	2.7	170.9					
8/20/02	N21.48806 W157.84229	4.3	6.1	34.44	0.17	26.67	0.13	45.66
8/20/02	N21.48852 W157.84232	4.3	1.1					
8/20/02	N21.48988 W157.84017	5.8	2.2					
8/20/02	N21.48806 W157.84229	4.3	6.4					
8/20/02	N21.48852 W157.84232	4.3	8.1	35.08	2.97	57.79	0.00	86.26
8/20/02	N21.48988 W157.84017	5.8	3.6	35.11	0.05	33.88	0.00	12.93
8/20/02	N21.48806 W157.84229	4.3	14.5					
8/20/02	N21.48852 W157.84232	4.3	19.1					
8/20/02	N21.48988 W157.84017	5.8	6.4					
8/25/2002	N21.48806 W157.84229	4.3	20.1					
8/25/2002	N21.48852 W157.84232	4.6	29.5					
8/25/2002	N21.48988 W157.84017	5.8	16.4					
8/25/2002	N21.48806 W157.84229	4.3	45.2					

Appendix B. (continued) Kaneohe Bay Lagoon Seepage Meter Measurements

Date (m/d/yr)	Location (Latitude Longitude)	Water depth (m)	Total fluid flux ($l/m^2/day$)	Salinity (psu)	PO_4 [μM]	Si [μM]	NO_3 [μM]	NH_4 [μM]
8/25/2002	N21.48852 W157.84232	4.6	45.2					
8/25/2002	N21.48988 W157.84017	5.8	14.9					
8/25/2002	N21.48806 W157.84229	4.3	15.1	34.60	0.27	67.33	0.16	101.88
8/25/2002	N21.48852 W157.84232	4.6	33.1	35.57	0.17	71.28	0.10	40.54
8/25/2002	N21.48988 W157.84017	5.8	14.5	34.63	0.27	94.91	0.32	84.65
10/18/2002	N21.48506 W157.84290	2.1	21.2					
10/18/2002	N21.48806 W157.84310	1.5	267.7					
10/18/2002	N21.48840 W157.84311	2.1	25.7					
10/18/2002	N21.48865 W157.84200	4.6	25.0					
10/18/2002	N21.48912 W157.84132	5.2	5.6					
10/18/2002	N21.48850 W157.84133	5.2	6.9					
10/18/2002	N21.48793 W157.84097	5.2	37.5					
10/20/2002	N21.48506 W157.84290	2.1	33.4					
10/20/2002	N21.48840 W157.84311	2.1	11.9					
10/20/2002	N21.48865 W157.84200	4.6	18.3					
10/20/2002	N21.48850 W157.84133	5.2	31.2					
10/20/2002	N21.48793 W157.84097	5.2	38.8					
10/20/2002	N21.48840 W157.84311	2.1	31.5					
11/23/2002	N21.48866 W157.84201	2.1	72.8					
11/23/2002	N21.48866 W157.84201	2.1	29.9					
11/23/2002	N21.48866 W157.84201	2.1	190.8		0.12	39.43	0.44	19.05
11/23/2002	N21.48866 W157.84201	2.1	263.3	33.69	0.12	35.60	0.51	21.56
11/25/2002	N21.48866 W157.84201	2.1	312.0					

Appendix B. (continued) Kaneohe Bay Lagoon Seepage Meter Measurements

Date (m/d/yr)	Location (Latitude Longitude)	Water depth (m)	Total fluid flux ($l/m^2/day$)	Salinity (psu)	PO_4 [μM]	Si [μM]	NO_3 [μM]	NH_4 [μM]
11/25/2002	N21.48866 W157.84201	2.1	255.7	34.64	0.18	33.51	0.38	24.65
11/25/2002	N21.48866 W157.84201	2.1	259.8		0.18	37.76	0.15	25.87
12/23/2002	N21.48854 W157.84213	4.9	26.2	35.19	0.10	63.33	0.12	58.87
12/23/2002	N21.48716 W157.84146	4.0	14.9	35.05	0.10	47.07	0.22	14.22
12/23/2002	N21.48854 W157.84213	4.9	21.5	35.14	0.10	103.44	0.10	102.56
12/23/2002	N21.48716 W157.84146	4.0	29.8	35.63				
1/8/2003	N21.48842 W157.84236	4.6	21.7					
1/8/2003	N21.48768 W157.84153	4.3	9.0					
1/8/2003	N21.48844 W157.84062	5.2	14.5					
1/8/2003	N21.48954 W157.84108	5.5	20.8					
1/8/2003	N21.48983 W157.84017	6.1	2.5					
1/8/2003	N21.48940 W157.83891	6.7	8.9					
1/8/2003	N21.48940 W157.83891	6.7	19.7					
1/9/2003	N21.48842 W157.84236	4.6	29.5					
1/9/2003	N21.48768 W157.84153	4.3	26.2					
1/9/2003	N21.48844 W157.84062	5.2	26.2					
1/9/2003	N21.48954 W157.84108	5.5	23.7					
1/9/2003	N21.48983 W157.84017	6.1	3.0					
1/9/2003	N21.48940 W157.83891	6.7	12.1					
1/9/2003	N21.48940 W157.83891	6.7	4.9					
8/14/2003	N21.50480 W157.85114	4.0	17.1	35.34				
8/14/2003	N21.50480 W157.85114	4.0	89.8	35.30	0.19	64.72	0.00	36.36
8/14/2003	N21.50508 W157.85222	2.7	93.6	34.27	0.09	30.45	0.00	5.86

Appendix B. (continued) Kaneohe Bay Lagoon Seepage Meter Measurements

Date (m/d/yr)	Location (Latitude Longitude)	Water depth (m)	Total fluid flux ($l/m^2/day$)	Salinity (psu)	PO_4 [μM]	Si [μM]	NO_3 [μM]	NH_4 [μM]
8/14/2003	N21.50508 W157.85222	2.7	158.3	34.78	0.18	49.81	0.00	13.42
8/15/2003	N21.50480 W157.85114	4.0	45.8	35.17				
8/15/2003	N21.50480 W157.85114	4.0	22.5	34.58	0.08	52.48	0.00	30.96
8/15/2003	N21.50508 W157.85222	2.7	97.2	33.92				
8/15/2003	N21.50508 W157.85222	2.7	141.3	33.71				

APPENDIX C

Kaneohe Bay Reef Sand Seepage Meter Measurements

Date (m/d/yr)	Location (Latitude Longitude)	Water depth (m)	Total fluid flux ($l/m^2/day$)	Salinity (psu)	PO_4 [μM]	Si [μM]	NO_3 [μM]	NH_4 [μM]
9/6/2003	N21.45888 W157.79366	3.0	941.3	35.50	0.91	5.38	2.04	0.46
9/6/2003	N21.45888 W157.79366	3.0	847.5	35.34				
9/6/2003	N21.45888 W157.79366	3.0	852.5	35.41				
9/6/2003	N21.45888 W157.79366	3.0	995.7	35.84				
9/6/2003	N21.45888 W157.79366	3.0	1005.5	35.40				
9/6/2003	N21.45888 W157.79366	3.0	822.9	35.17				
9/6/2003	N21.45888 W157.79366	3.0	704.0	35.26				
9/6/2003	N21.45888 W157.79366	3.0	1161.3	35.17	0.87	4.37	1.44	0.49
9/6/2003	N21.45888 W157.79366	3.0	627.0	35.22				
9/6/2003	N21.45888 W157.79366	3.0	544.9	35.25				
9/6/2003	N21.45888 W157.79366	3.0	682.7	35.26				
9/6/2003	N21.45888 W157.79366	3.0	715.2	35.28				
9/6/2003	N21.45888 W157.79366	3.0	774.2	35.28				
9/6/2003	N21.45888 W157.79366	3.0	554.6	35.23				
9/6/2003	N21.45888 W157.79366	3.0	613.1	35.24				
9/6/2003	N21.45888 W157.79366	3.0	900.2	35.13				

APPENDIX D

Maunalua Bay Nearshore Seepage Meter Measurements

Date (m/d/yr)	Location (Latitude Longitude)	Water depth (m)	Total fluid flux ($l/m^2/day$)	Salinity (psu)	PO_4 [μM]	Si [μM]	NO_3 [μM]	NH_4 [μM]	NH4 [uM]
6/18/2003	N21.27827 W157.76679	1.2	1198.1	2.6	32.13	0.17	84.89	0.21	8.58
6/18/2003	N21.27843 W157.76700	1.2	313.9	4.0	31.70				
6/18/2003	N21.27807 W157.76713	1.2	648.0	2.6	32.14	0.14	84.43	0.17	2.38
6/18/2003	N21.27806 W157.76724	1.2	918.7	0.0	34.23	0.13	78.00	1.42	0.89
6/18/2003	N21.27807 W157.76723	1.2	656.6	3.1	32.96	0.14	84.70	1.01	5.64
6/18/2003	N21.27843 W157.76700	1.2	576.0	4.0	32.64	0.43	88.09	1.01	9.21
6/18/2003	N21.27807 W157.76713	1.2	515.8	3.1	32.94	0.15	74.14	1.45	1.42
6/18/2003	N21.27806 W157.76724	1.2	1418.1	0.5	33.85	0.12	47.81	0.99	1.00
6/18/2003	N21.27807 W157.76723	1.2	981.7	0.4	33.85	0.13	54.83	0.86	1.84

REFERENCES

Armstrong, F.A. J., C. R. Stearns, and J. D. H. Strickland. 1967. The measurement of upwelling and subsequent biological processes by means of the Technicon Autoanalyzer and associated equipment. *Deep-Sea Research*. **14**: 381-89.

Archie, G.E., 1942. The electrical resistivity log as an aid in determining some reservoir characteristics. *Tran. American Institute of Mining, Metallurgical and Petroleum Engineering* **146**: 54-62.

Bathen, K.H. 1968. A descriptive study of the physical oceanography of Kaneohe Bay, Oahu, Hawaii. University of Hawaii, Hawaii Institute of Marine Biology Technical Report 14. 353 pp.

Bell, P.R.F. 1992. Eutrophication and coral reefs-some examples in the Great Barrier Reef Lagoon. *Water Resources* **26**: 553-568.

Berner, R. A. 1980. Early diagenesis. A theoretical approach. Princeton University Press. 241 pp.

Berner, E.K. and R.A. Berner, 1987. The Global Water Cycle, Prentice-Hall, Englewood Cliffs, NJ, 398 pp.

Bernhardt, H., and A. Wilhelms. 1967. The continuous determination of low level iron, soluble phosphate and total phosphate with the AutoAnalyzer. *Technicon Symp.* 1:385-89.

Biogeochemistry, 2003. **66**: 3-202.

Bokuniewicz, H. 1980. Groundwater seepage into Great South Bay, New York. *Estuarine and Coastal Marine Science* **10**: 437-444.

Bredehoeft, J.D. and I.S. Papadopulos. 1965. Rates of vertical groundwater movement estimated from the earth's thermal profile. *Water Resources Research* **2**: 325:328.

Bricker, S.B., C.G. Clement, D.E. Pirhalla, S.P. Orlando, and D.G. Farrow. 1999. National Estuarine Eutrophication Assessment: Effects of Nutrient Enrichment in the Nation's Estuaries. Special Projects Office and the National Centers for Coastal Ocean Science, National Ocean Service, National Oceanic and Atmospheric Administration. Silver Spring, MD.

Burnett, W.C., H. Bokuniewicz, M. Huettel, W.S. Moore, and M. Taniguchi. 2003. Groundwater and porewater inputs to the coastal zone. *Biogeochemistry* **66**: 3-33.

Cable, J.E., G.C. Bugna, W.C. Burnett, and J.P. Chanton. 1996. Application of ^{222}Rn and Ch_4 for assessment of groundwater discharge to the coastal ocean. *Limnology and Oceanography* **41**: 1347-1353.

Cable, J.E., W.C. Burnett, and J.P. Chanton. 1997a. Magnitude and variations of groundwater seepage along a Florida marine shoreline. *Biogeochemistry* **38**: 189-205.

Cable, J.E., W.C. Burnett, J.P. Chanton, D.R. Corbett, and P.H. Cable. 1997b. Field evaluation of seepage meters in the coastal marine environment. *Estuarine, Coastal and Shelf Science* **45**: 367-375.

CISnet. 2001. Linkages between a tropical watershed and reef ecosystem. http://www.hawaii.edu/cisnet/contents.html

CO-OPS. 2004. Center for Operational Oceanographic Products and Services, a division within NOAA's National Ocean Service: http://www.co-ops.nos.noaa.gov/data_options.shtml?stn=1612480+Mokuoloe,+HI

Corbett, D., J. Chanton, W. Burnett, K. Dillon, and C. Rutkowski. 1999. Patterns of groundwater discharge into Florida Bay. *Limnology and Oceanography* **44**: 1045-1055.

COSAD II 1987. Fluid circulation in the crust and the global geochemical budge. Report of the second conference on scientific ocean drilling. 6-8 July.

Cox, D. C , P.F. Fan, K.E. Chave, R.I. Clutter, K.R. Gundersen, NC Burbank Jr., L.S. Lau, and J.R. Davidson. 1973. Estuarine Pollution in the State of Hawaii, Volume 2: Kaneohe Bay Study. Water Resources Research Center Technical Report No. 31.

DBEDT. 2002. State of Hawaii data book. State of Hawaii Department of Planning, Economic Development, and Tourism, Honolulu. http://www.hawaii.gov/dbedt/db02/

Devaney, D.M., M. Kelly, P.J. Lee, and L.S. Motteler. 1976. Kaneohe: a history of change (1778-1950). Bernice P. Bishop Museum, Honolulu. 271 pp.

Dollar, S.J. and M.J. Atkinson, 1992. Effects of nutrient subsidies from groundwater to nearshore marine ecosystems off the Island of Hawaii. *Estuarine, Coastal and Shelf Science* **35**: 409-424.

Dugan, G.L. 1977. Water quality of normal and storm-induced surface water runoff: Kaneohe Bay watershed Oahu, Hawaii, February 1975 to March 1975. University of Hawaii, Water Resources Research Center Tech. Rep. 106. 74 pp.

Freeman, W. 1993. Revised total maximum daily load estimates for six water quality limited segments of Oahu, Hawaii. Environmental Planning Office, Hawaii State Department of Health, Honolulu.

Gallagher, D.L., A.M. Dietrich, W.G. Reay, M.C. Hayes, G.M. Simmons Jr. 1996. Ground water discharge of agricultural pesticides and nutrients to estuarine surface water. *Ground Water Monitoring and Remediation* (Winter): 118-129.

Garrison, G.H., C.R. Glenn, and G.M. McMurtry. 2003. Measurement of submarine discharge in Kahana Bay, Oahu, Hawaii. *Limnology and Oceanography* **48**: 920-928.

GMT, 2004. The Generic Mapping Tool. http://gmt.soest.hawaii.edu/

Guillou, H., J. Sinton, C. Laj, C. Kissel, and N. Szeremeta. 2000. New K–Ar ages of shield lavas from Waianae Volcano, Oahu, Hawaiian Archipelago. *Journal of Volcanology and Geothermal Research* **96**: 229-242.

Hedley, M.J., and A.N. Sharpley. 1998. Strategies for global nutrient cycling, p. 70-95. *In* L. Currie (ed.), Long-Term Nutrient Needs for New Zealand's Primary Industries: Global Supply, Production Requirements and Environmental Constraints. The Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand.

Hirashima, G.T. 1971. Tunnels and dikes of the Koolau Range, Oahu, Hawaii, and their effect on storage depletion and movement of groundwater: U.S. Geological Survey Water Supply Paper 1999-M, 21 pp.

Hollett, K.J. and R. Moberly. 1982. Sedimentation, dredging, and spoil disposal in a subtropical estuarine lagoon. *Environmental Geology* **4**: 31-42.

Honolulu Board of Water Supply, 2002. http://hbws.org/waterforlife/chapter1/hydro.html

Hoover, D. 2003. Fluvial nitrogen and phosphorus in Hawaii: Storm runoff land use, and impacts on coastal waters. Ph.D. dissertation, University of Hawaii at Manoa.

Howarth, R.W. 1988. Nutrient limitation of net primary production in marine ecosystems. *Annual Reviews in Ecology and Systematics* 19: 89-110.

Howarth, R.W., H.S. Jensen, R. Marino, and H. Postma. 1995. Transport to and processing of phosphorus in nearshore and oceanic waters, p. 323-345. *In* H. Tiessen (ed.), Phosphorus in the Global Environment. John Wiley and Sons Inc.

Howarth, R.W., A. Sharpley, and D. Walker. 2002. Sources of Nutrient Pollution to Coastal waters in the United States: Implications for Achieving Coastal Water Quality Goals. *Estuaries* **25**: No. 4b, 656-676.

Huettel, M., and G. Gust. 1992. Solute release mechanisms from confined sediment cores in stirred benthic chambers and flume flows. *Marine Ecology Progress Series* **82**: 187-197.

Hunt, C.D. Jr. 1996. Geohydrology of the island of Oahu, Hawaii: U.S. Geological Survey Professional Paper 1412-B, 54 pp.

Hunter, C.L., and C.W. Evans, 1995. Reefs in Kaneohe Bay, Hawaii: Two centuries of western influence and two decades of data. *Bulletin of Marine Science* **57**: 501-515.

Israelsen, O.W., and R.C. Reeve. 1944. Canal Lining Experiments in the Delta Area, Utah, 52 pp.

Johannes, R.E. 1980. The Ecological Significance of the Submarine Discharge of Groundwater. *Marine Ecology Progress Series* **3**: 365-373.

Johannes, R.E., and Hearn, C.J. 1985. The effect of submarine groundwater discharge on nutrient and salinity regimes in a coastal lagoon off Perth, Western Australia. *Estuarine, Coastal and Shelf Science* **21**: 789-800.

Kay, A.E., L.S. Lau, E.D. Stroup, S.J. Dollar, D.P. Fellows, and R.H.F. Young. 1977. Hydrological and ecological inventories of the coastal waters of West Hawaii. Univ. Hawaii, Water Resources Research Center Technical Report 105, 94 p.

Kim, G., and D.W. Wang. 2002. Tidal pumping of groundwater into the coastal ocean reveald from submarine Rn-222 and Ch_4 monitoring. *Geophysical Research Letter* **29**: no. 14

Kinney, E.H., and C.T. Roman, 1998. The response of primary producers to nutrient enrichment in a shallow estuary. *Marine Ecology Progress Series* **162**: 89-98.

Langseth, M.G., M.J. Mottl, M.A. Hobart, and A. Fisher. 1988. The distribution of geothermal and geochemical gradients near site 501/504: implications for hydrothermal circulation in the oceanic crust. *In* Becker, K., Sakai, H., et al., *Proceedings Ocean Drilling Program Initial Reports* **111**: 23-32.

Lapointe B. E., and J.D. O'Connell. 1989. Nutrient-enhanced growth of *Cladophora prolifera* in Harrington Sound, Bermuda: eutrophication of a confined, phosphorous-limited marine ecosystem. *Estuarine and Coastal Shelf Science* **28**: 347-360.

Lapointe, B.E., J.D. O'Connell, and G.S. Garrett. 1990. Nutrient couplings between on-site sewage disposal systems, groundwater, and nearshore surface waters of the Florida Keys. *Biogeochemistry* **10**: 289-307.

Larned, S. 1998. Nitrogen versus phosphorus limited growth and sources of nutrients for coral reef macroalge. *Marine Biology* **132**: 409-421.

Larned, S., and J. Stimson. 1996. Nitrogen-limited growth in the coral reef chlorophyte *Dictyosphaeria cavernosa,* and the effect of exposure to sediment-derived nitrogen on growth. *Marine Ecology Progress Series* **145**: 95-108.

Lau, L.S., R.H.F. Young, S.K. Konno, R.J. Oldnall, and H.H. Lee. 1976. Wet-weather water quality monitoring, Kaneohe Bay, Oahu, Hawaii. University of Hawaii, Water Resources Research Center Tech. Rep. 100. 121 pp.

Laws, E.A. 2000. Aquatic Pollution: An introductory text- 3rd edition. John Wiley & Sons, Inc. 639 pp.

Laws, E.A., and C.B. Allen. 1996. Water quality in a subtropical embayment more than a decade after diversion of sewage discharges. *Pacific Science* **50**: 194-210.

Lee, D.R., 1977. A device for measuring seepage flux in lakes and estuaries. *Limnology and Oceanography* **22**: 140-147.

Lewis, J.B. 1987. Measurements of groundwater seepage flux onto a coral reef: Spatial and temporal variations. *Limnology and Oceanography* **32**: 1165-1169.

Li, Y.H., and S. Gregory. 1974. Diffusion of ions in sea water and in deep-sea sediments. *Geochemica et Cosmochimica Acta* **38**: 703-714.

Madsen, J. 1999. Point intercept and line intercept methods for aquatic plant management. Aquatic Plant Control Technical Note MI-02.

Mantoura, R.F.C., J.M. Martin, and R. Wollast [eds.]. 1991. Ocean margin processes in global change. John Wiley & Sons, Chichester, 469 pp

Maragos, J.E. 1972. A study of the ecology of Hawaiian reef corals. Ph.D. dissertation. University of Hawaii at Manoa, Hawaii.

Maragos, J.E., C.W. Evens, and P.Holthus. 1985. Reef corals in Kaneohe Bay six years before and after termination of sewage (Oahu, Hawaiian Archipelago). *Proc. 5th Intl. Coral Reef Congress*, Tahiti, **4**: 189-194.

McClelland, J.W., and I. Valiela. 1998. Linking nitrogen in estuarine producers to land-derived sources. *Limnology and Oceanography* **43**: 577-585.

Meinesz, A., J. de Vaugelas, B. Hesse, and X. Mari. 1993. Spread of the introduced tropical green alga *Caulerpa taxifolia* in northern Mediterranean waters. *Journal of Applied Phycology* **5**: 141-147.

Mink, J.F., and L.S. Lau. 1987. Aquifer identification and classification for Oahu: groundwater protection strategy for Hawaii. University of Hawaii, Water Resources Research Center Technical memorandum Report 179, 28 p.

Moore, J.G. 1964. Giant submarine landslides on the Hawaiian Ridge: U.S. Geological Survey Professional Paper 501-D, p. D95-D98.

Moore, J.G. 1987. Subsidence of the Hawaiian Ride, *in* Decker, R.W., and others, eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 85-100.

Moore, W.S. 1996. Large groundwater inputs to coastal waters revealed by 226Ra enrichments. *Nature* **380**: 612-614.

Moore, W.S. 1999. The Subterranean Estuary: A Reaction Zone of Groundwater and Sea Water. *Marine Chemistry* **65**: 111-126.

Nixon, S.W. 1995. Coastal Marine Eutrophication: a definition, social causes, and future concerns. *Ophelia* **41**: 199-219.

NOS, 2004. National Ocean Service aerial photography: http://biogeo.nos.noaa.gov/products/data/photos/hawaii.shtml

NWS, 2004. National Weather Service forecast office, Honolulu, Hi: http://www.prh.noaa.gov/hnl/pages/hiclimate.php

NWIS. 2004. National Water Information System, part of the United States Geological Survey: http://nwis.waterdata.usgs.gov/hi/nwis/qwdata

Paerl, H.W. 1997. Coastal eutrophication and harmful algal blooms: the importance of atmospheric and groundwater as "new" nitrogen and other nutrient sources. *Limnology and Oceanography* **42**:1154-1165.

Portnoy, J.W., B.L. Nowicki, C.T. Roman, and D.W. Urish. 1998. The discharge of nitrate-contaminated groundwater from developed shoreline to marsh-fringed estuary. *Water Resources Research* **34**: 3095-3104.

Presley, T.K., J.M. Sinton, and M. Pringle. 1997. Postshield volcanism and catastrophic mass wasting of the Waianae Volcano, Oahu, Hawaii. *Bulletin of Volocanolgy* 58: 597-616.

Random, 2004. Random number generator: www.random.org

Rasmussen, L.L. 1998. Groundwater flow, tidal mixing and haline convection in Coastal sediment. M.S. Thesis, Florida State University.

Reay, W.G., D.L. Gallagher, and G.M. Simmons Jr. 1992. Groundwater discharge and its impact on surface water quality in a Chesapeake Bay inlet. *Water Resources Bulletin* **28**: 1121-1134.

Reeburgh, W.S. 1967. An improved interstitial water sampler. *Limnology and Oceanography* **12**: 512-533.

Ristvet, B.L. 1978. Reverse weathering reactions within recent nearshore marine sediments, Kaneohe Bay, Oahu. Test Directorate Field Command, Kirtland AFB, New Mexico, 314 pp.

Rodgers, S. K., and E.F. Cox. 1999. The distributions of the introduced rhodophytes *Kappaphycus alvarezii, Kappaphycus striatum* and *Gracilaria salicornia* in relation to various physical and biological factors in Kane'ohe Bay, Oahu, Hawaii. *Pacific Science* **53**: 232-241.

Seiler, K.P. 2003. Potential areas of subsurface freshwater discharge to the oceans (abs.) In: Proceedings of the XXIII General Assembly of the International Union of Geodesy and Geophysics (IUGG). Sapporo Japan.

Seitzinger, S.P., C. Kroeze, A.F. Bouman, N. Caraco, F.Dentener, and R.V. Styles. 2002. Global Patterns of Dissolved Inorganic and Particulate Nitrogen Inputs to Coastal Systems: Recent Conditions and Future Projections. *Estuaries* **25**: 620-655.

Shaw, R.D., and E.E. Prepas, 1989. Anomalous, short-term influx of water into seepage meters. *Limnology and Oceanography* **34**: 1343-1351.

Shinn, E.A., C.D. Reich, and T.D. Hickey. 2002. Seepage meters and Bernoulli's revenge. *Estuaries* **25**: 126-132.

Short, F.T., W.C. Dennison, and D.G. Capone. 1990. Phosphorus-limited growth of the tropical seagrass *Syringodium filiforme* in carbonate sediments. *Marine Ecology Progress Series* **62**: 169-174.

Simmons, G.M. Jr. 1992. Importance of submarine groundwater discharge (SGWD) and seawater cycling to material flux across sediment/water interfaces in marine environments. *Marine Ecology Progress Series* **84**: 173-184.

Slawyk, L.R. and J.J. MacIsaac. 1972. Comparison of two automated ammonium methods in a region of coastal upwelling. *Deep-Sea Research*. **19**: 521-524.

Smith, J. E.; C.L. Hunter, and C.M. Smith. 2002. Distribution and Reproductive Characteristics of nonindegenous and invasive marine Algae in Hawaiian Islands. *Pacific Science* **56**: 299-315

Smith, J.R. and T. Duennebier. 2001. Data Grid Compilation, School of Ocean and Earth Science and Technology (SOEST), University of Hawaii at Manoa, copyright March 2001. Data sources: USGS 1:24,000 DEM; NGDC NOS Hydrographic bathymetry; Smoot/King NAVO bathymetry; George Pararas-Carrayannis.

Smith, S.V., W.J. Kimmerer, E.A. Laws, R.E. Brock, and T.W. Walsh. 1981. Kaneohe Bay sewage diversion experiment: Perspectives on ecosystem responses to nutritional perturbation. *Pacific Science* **25**: 279-395.

Smith, S.V., and M.J. Atkinson. 1984. Phosphorus limitation of net production in a confined aquatic ecosystem. *Nature* **207**: 626-627.

Soegiarto, A. 1972. The role of benthic algae in the carbonate budget of the modern reef complex, Kaneohe Bay. Ph.D. dissertation, University of Hawaii at Manoa, Hawaii.

Stearns, H.T. 1938. Geologic and topographic map of the island of Oahu, Hawaii. Division of Hydrogrophy. Bulletin 2, Plate 2.

Stearns, H.T. 1967. Geology of the Hawaiian Islands. 2nd ed. with supplement by G.A. Macdonald. Hawaii Division of Hydrography Bulletin. Vol. 8. 112 pp.

Stearns, H.T. 1974. Submerged shorelines and shelves in the Hawaiian Islands and a revisit of some of the eustatic emerged shorelines. *Geological Society of American Bulletin* **85**: 795-804.

Stearns, H.T., and K.N. Vaksvik. 1935. Geology and groundwater resources of the island of O'ahu, Hawaii. Hawaii Division of Hydrography Bulletin 1: 479.

Stimson J., and S. Larned. 2000. Nitrogen efflux from the sediments of a subtropical bay and the potential contribution of macroalgal nutrient requirements. *Journal of Experimental Marine Biology and Ecology* **252**: 159-180.

Takasaki, K.J., G.T. Hirashima, and E.R. Lubke. 1969. Water resources of Windward Oahu, Hawaii. U.S. Geological Survey Professional Paper 1894.

Takasaki, K.J., and J.F. Mink. 1982. Water resources of southeastern Oahu, Hawaii: U.S. Geological Survey Water-Resources Investigations Report 82-628, 82 p.

Taliaferro, W.J. 1959. Rainfall of the Hawaiian Islands. Hawaii Water Authority. 394 pp.

Taniguchi, M. 2000. Submarine groundwater discharge in Osaka Bay, Japan. *Proceedings of the Japan Association of Hydrology and Water Resources*, Kyoto, August 2000. 186-187.

Taniguchi, M., W.C. Burnett, J.E. Cable, and J.V. Turner, 2002. Investigations of submarine groundwater discharge. *Hydrological Processes* **16**: 2115-2129.

U.S. Bureau of the Census. 1998. *Statistical Abstract of the United States*: *1998* (118th edition). Washington, DC.

UW, 2004. University of Washington Marine Chemistry Laboratory. Laboratory manager: Kathy Krogslund.

Valiela, I., and C.D'Elia, 1990. Groundwater inputs to coastal waters. Special Issue *Biogeochemistry* **10**, 328 pp.

Vanek, V., and D.R. Lee. 1991. Mapping submarine groundwater area-an example from Laholm Bay, southwest Sweden. *Limnology and Oceanography* **36**: 1250-1262.

Vitousek, P.M., and R.W. Howarth. 1991. Nitrogen limitation on land and sea: How can it occur? *Biogeochemistry* **13**: 87-115.

Walker, G.P.L. 1987. The dike complex of Koolau volcano, Oahu: Internal structure of a Hawaiian rift zone. *in* Decker, R.W., and others, eds., Volcanism in Hawaii: U.S. Geological Survey Professional Paper 1350, v. 1, p. 961-993.

Whiting, G.J., and D.L. Childers. 1989. Subtidal advective water flux as a potentially important nutrient input to southeastern USA saltmarsh estuaries. *Estuarine, Coastal and Shelf Science* **28**: 417-431.

Wollast, R. 1991. The coastal organic carbon cycle: Fluxes, sources, and sinks, p. 365-382. *In* G. E. Likens et al. [eds.], Some perspectives of the major biogeochemical cycles. U.S. DOE CONF-8009140.

WRRC. 2004. Western Regional Climatic Center, Division of Atmospheric Sciences, Desert Research Institute: http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?hikane

Zektser, I.S. 2000. Groundwater and the Environment: Applications for the Global Community. Lewis Publishers, Boca Raton, 175 pp.

Zimmerman, C.F., J.R. Montgomery, and P.R. Carlson. 1985. Variability of dissolved reactive phosphate flux rates in nearshore estuarine sediments: effects of groundwater. *Estuaries* **8**: 228-236.