POSSIBLE EFFECTS OF SEA LEVEL RISE ON KAILUA, OAHU AND IMPLICATIONS FOR PACIFIC ATOLLS

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ABSTRACT

This study considers effects of a 1 m eustatic sea level rise on shoreline migration and groundwater in detail for Kailua, Oahu, Hawaii, and briefly for Laura, Majuro, in the Marshall Islands.

Previous studies have suggested a three cell system of littoral transport with a 30 year cycle, with shifts in prevailing tradewinds suggested as an explanation. Tradewinds north of Hawaii from 1900-1985 were analyzed and no evidence of a cycle was found; a trend toward more easterly winds was observed. The north to central sections of the beach exhibit accretion with more easterly winds, and shoreline migration exhibits a long term trend of accretion. Future shoreline movement is likely to be accretionary, even taking into account the erosion anticipated using the above scenario.

Increased flooding for Kailua would be expected in the event of sea level rise in view of the magnitude and contributing factors of past floods.

Hydrology of atolls would be severely affected by sea level rise; this is demonstrated with a simple geometric model of the Ghyben-Herzberg lens on Laura. A sea level rise of 1 m could make Laura uninhabitable.

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I. INTRODUCTION

The accumulation of carbon dioxide, methane, and other greenhouse gases in the earth's atmosphere because of industrial and land use activities is well documented (e.g. Keeling, et al., 1976; Bolin, et al., 1986). A future rise in earth's surface equilibrium temperature of 1.5-4.5°C may be associated with this change in atmospheric composition (e.g. National Research Council, 1983; Barth and Titus, 1984). This temperature change is predicted to be distributed differentially around the globe, with the greatest warming near the poles. Estimates of the magnitude and distribution of warming and other associated climate changes can not be made with extreme confidence using available data and modeling techniques. However, significant warming would almost certainly increase rates of glacial melting and thermal expansion of ocean waters which could result in a rise in global sea level. The relative contribution of each effect and the rate of such a rise are subject to debate, and a sea-level rise of 40 to 200 cm in the next century has been postulated (e.g. National Research Council, 1987). Other effects on global climate may include an increase or decrease in precipitation and frequency of tropical storms; effects on particular geographic areas are difficult to assess with certainty now.

If accurate predictions of climatic and sea level variation were available, it would still be difficult to anticipate the impacts of these changes for planning purposes without adequate knowledge of the environmental parameters likely to be affected. This study discusses the environmental effects of one sea-level rise scenario for a coastal community in Hawaii. Given the uncertainty of climate-change predictions, the goal of this study is to identify some systems and processes likely to be affected by climate change, and to create a baseline study for anticipating some effects of a possible sea-level rise.

Previous work has identified three broad implications of sea-level rise: loss of coastal land caused by inundation and accelerated beach erosion, saltwater intrusion in groundwater supplies, and additional storm damage and flooding (Barth and Titus, 1984). The town of Kailua on Oahu, Hawaii, has thousands of residents in low-lying areas and a heavily-used beach. This investigation identifies systems in Kailua likely to be affected by a sea-level rise, contributes to an understanding of affected geologic parameters, and provides guidelines for similar studies elsewhere, particularly on low-lying oceanic islands.

Chapter II reviews the literature concerning the greenhouse effect, global climate modeling, and scenarios for suggested sea-level rise and challenges associated with recognizing sea-level trends. One moderate range accelerated sea-level rise scenario is selected for the purpose of this investigation.

Chapter III reviews the regional geology of the Kailua area, particularly as it applies to the problem at hand: climate, topography, and drainage/flooding.

Chapter IV deals with the potential loss of coastal land. A study of Kailua Beach was initiated in order to analyze the effects of sea-level rise on shoreline position. Profiles were surveyed at two transects on the north and central sections of the beach, and evidence of historic shoreline migration was sought. Previous work had demonstrated the possibility of a 30-50 year erosional cycle for the beach, and a cycle of similar period in the prevailing tradewinds had been proposed as an explanation. These hypotheses were based on study of beach erosion from 1949-1978, as revealed by surveys and aerial photographs of the beach (Noda, 1977; Hwang, 1981), and of relative frequency of prevailing tradewinds from 1905-1945 (Wentworth, 1949).

In an attempt to test these propositions with a view to anticipating possible future changes, the present work extended the length of record available for wind data to 1900-1985, using the Comprehensive Ocean-Atmosphere Data Set of shipboard observations north of Hawaii. A search of the state land court records was also initiated to find evidence of shoreline locations prior to 1949. Examination of these data yields two conclusions. First, a shift in direction of the prevailing tradewinds as noted in Wentworth's (1949) paper is observed in the early years for which data are available, but there is no evidence of cyclicity in the data. There is a trend toward increasingly more easterly winds. The second conclusion is that the Kailua area shows a long-term trend of beach accretion. In order to understand the possible effects of sea-level rise, erosion resulting from such a rise is analyzed along four segments of Kailua beach. Results of this analysis point to an accretion of about 0.5 m/year along most of the beach. An erosional trend south of the boat ramp is difficult to determine with the available data. Even with a sea-level rise of 1 m, the accretionary trend may continue.

Chapter V discusses potential groundwater changes for the Kailua area resulting from a sea-level rise, which might include a rise of the water table, and reduced head as the size of the freshwater lens diminishes with land area. Such diminishment in land area would be caused by erosion and inundation, processes discussed in Chapter IV. The Kailua area does not draw groundwater from the low-elevation lens, because the water underlying the town is brackish; the primary effect of lens uplift would therefore be increased flooding. The problem of the possibility of increased flooding in the Kailua area is analyzed: a discussion of the problem, its history, magnitude and causes, forms the critical background for suggesting how a sea-level rise might exacerbate the flooding hazard. A sea-level rise could cause flooding with higher tides blocking drainage to the sea, and a water table closer to the land surface. The flood of January 1, 1988 is discussed and its implications for a scenario of a future sea-level rise and resulting potential flood hazards are analyzed.

Chapter VI concludes the thesis with an exploration of some effects that sea-level rise may have on low-lying islands, using as a case study Laura on Majuro Atoll in the Marshall Islands. Although less developed than the Kailua area, losses from inundation and erosion, storm flooding, and diminishment of groundwater supplies caused by sea-level rise might endanger both life and livelihood on such small islands. A review of some facets of atoll hydrogeology is presented, and a simple model is developed, demonstrating the potential effects of sea-level rise on Laura's freshwater lens geometry. The critical role of baseline geologic and environmental studies is emphasized.

II. THE GREENHOUSE EFFECT AND SEA-LEVEL RISE

General Comments

The well-documented increasing accumulation of carbon dioxide and methane and other greenhouse type gases in the atmosphere has engendered considerable concern among many scientists and government researchers that major environmental changes are in store for the planet in the next century. Greenhouse gases have earned that name because of their ability to trap heat in a fashion similar but not indentical to that of a greenhouse. These gases are transparent to short-wave radiation entering the atmosphere from the sun, but are opaque to infrared long-wave energy reflected back from the earth. This trapping of energy leads to global warming, and is responsible for keeping global temperatures at an inhabitable level. Increasing evidence suggests that strong connections exist between atmospheric concentrations of the greenhouse gases and a variety of other climatic parameters including global sea level.

Estimations of the effects of CO_2 increase on sea level depend upon the climate models being used. Figure 1 shows the range of sea-level rise scenarios

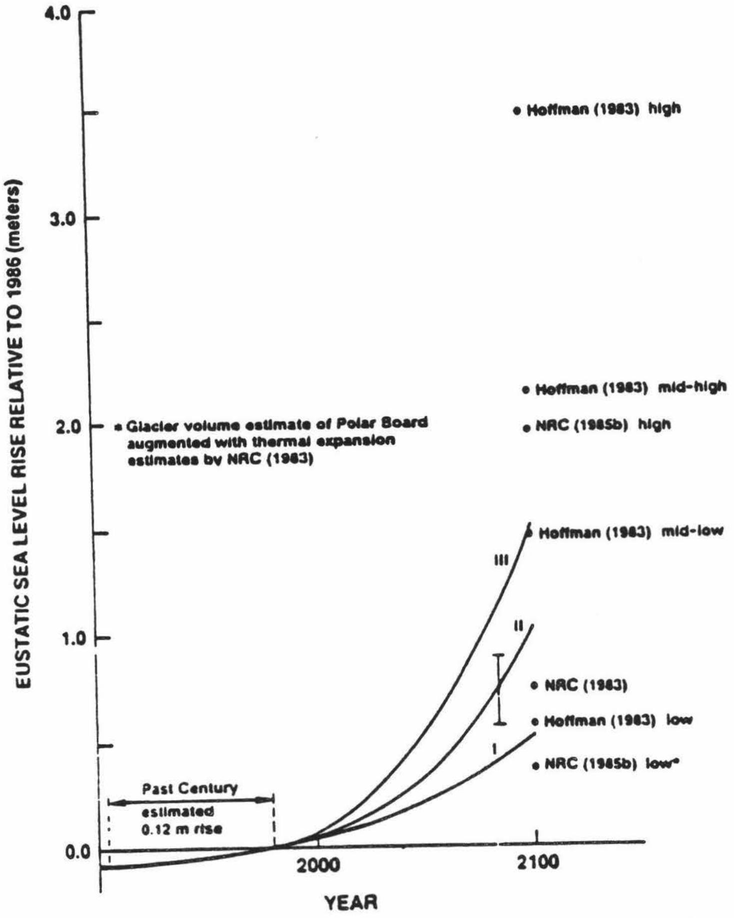

Figure 1. Estimates of future sea level rise. After National Research Council, 1987.

which have been proposed. The National Research Council's Committee on Engineering Responses to Sea-Level Rise (National Research Council, 1987) discusses scenarios of a 50 cm, 1 m and 1.5 m sea-level rise over the next one hundred years. This study accepts a mid-range scenario projecting a 1 m sea-level rise in the next century as proposed by Hoffman (1984). This value has been used for the EPA sponsored studies of effects of greenhouse gas induced sea-level rise (e.g. Barth and Titus, 1984; Leatherman, Titus et al., 1985) as well as for the National Research Council report. Some considerations which guide the formation of these models are discussed below.

It is necessary to determine three factors to estimate the effects of increasing atmospheric greenhouse gases. First, the amounts of greenhouse gases presently being added to the atmosphere and their sinks must be determined, as well as the course of future emissions. A variety of scenarios for future emissions have been presented, considering various political and economic controls. Models estimate global sinks and sources of carbon dioxide and other gases. Secondly, it must be determined what climatic changes may be associated with increasing greenhouse gases in the atmosphere. Both theoretical modeling and empirical evidence of paleoclimatic conditions have been used to make these determinations. Finally, once a scenario for changing atmospheric composition is developed, the effects of such changes must be estimated.

Measurements of atmospheric CO_2 concentrations made by Keeling et al. (1976) at Mauna Loa observatory show a steady increase in this atmospheric gas since 1958. Evidence from polar ice cores has also indicated an increase in CO_2 in the past 200 years (Neftel, et al., 1985). Most investigators associate these changes in the composition of the atmosphere with activities of humankind including increased burning of fossil fuels and destruction of the tropical forests which originally formed a sink for CO_2. Several attempts have made to project future emmissions of CO_2. Seidel and Keyes (1983), for example, present several scenarios of increasing fossil fuel burning for the next several hundred years. A slow increase in fossil fuel burning results in an estimate of a doubling of atmospheric CO_2 in the next century.

What effects might result from such a doubling in atmospheric carbon dioxide? Both theoretical modeling and empirical evidence have been used to understand global environmental atmospheric response to changes in CO_2 content. Modeling has taken increasingly complex forms, using one- two- and three- dimensional GCMs (global carbon models or general circulation models). Examinations of empirical evidence have concentrated on the relationship of past levels of atmospheric CO_2 to temperature and sea level.

Theoretical models of effects of atmospheric carbon dioxide vary in complexity. The simplest models assume oceanic circulation as a single layer ("swamp type") system; more complex attempts use mixed-layer models. Additionally, feedback effects depend both on chemical reactions and albedo effects which may increase or decrease cloud cover, depending on the technique used.

Recent work on a deep (2 km) Antarctic ice core compared temperature as inferred from deuterium data with temperature results from oxygen isotopes and sea levels (Jouzel, et al., 1987), and then CO_2 content with temperature (Barnola, et al., 1987). There is a strong correspondance between the different signals, but the cause and effect relationship is not clear.

Other greenhouse gases exhibiting recent increases in atmospheric concentration may have warming effects equal to or greater than that of carbon dioxide. Notable among these are CH_4 (methane), NO_2, O_3 (ozone), and the chlorofluorocarbons, or CFCs. Figure 2 shows estimates of relative contributions of the major trace gases to

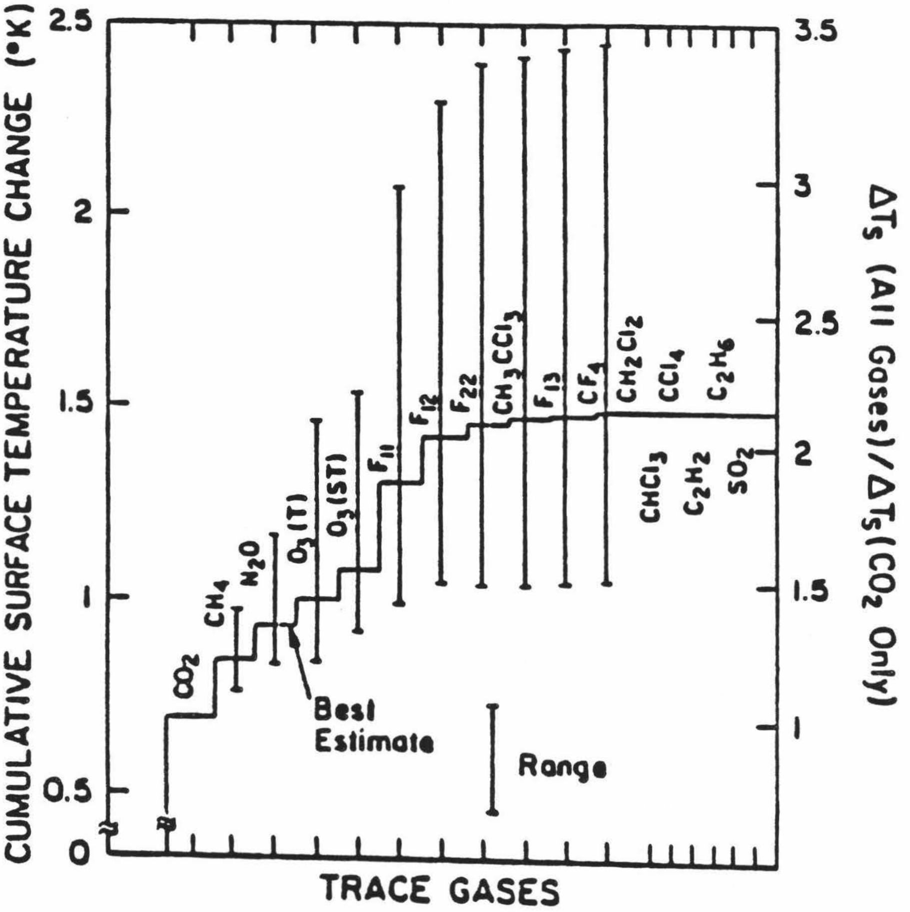

Figure 2. Estimated contribution of trace gases to global warming, 1980-2030. After Ramanathan, et al., 1985.

global warming in the next fifty years as estimated by Ramanathan (1985).

Different models have suggested other climatic changes which would accompany a doubling of CO_2 in the next hundred years. Geographic distribution of these climatic changes can not be predicted with confidence using present techniques, but several attempts at suggesting broad trends have been attempted. Manabe and Wetherald (1980) suggest that temperature effects on the lower latitudes would be less than those poleward. Emanuel (1987) modeled effects of the warmer temperatures expected to accompany a CO_2 doubling and predicted an increase of 40-50% in hurricane frequency and intensity. Projected implications for Hawaii include higher temperatures, increased precipitation and greater damage from tropical storms. The Pacific atolls which lie closer to the equator and are very vulnerable to storm damage now may be harder hit.

The following section discusses some of the problems of identifying global sea level trends. The models presented for sea-level rise cannot be tested until we know better how to identify changes.

Measuring Sea Level Change

Both understanding the limitations of global sea level projections and careful measurement of relative sea level change in Hawaii are necessary for anticipating the extent and effects of such a rise. The following section discusses some difficulties of determining sea level trends, and the recent sea level change history of Hawaii.

Challenges of Determining Global Sea Level Change

The anticipation and even recognition of global sea-level rise can be complicated by several classes of problems. The first type of problem arises because, as discussed above, the global climate system is extremely complex and the interrelationships between the atmosphere and oceans, their composition, and circulation are not fully understood and can not be directly related to sea level change.

The second class of problem deals with difficulties in data collection. Tide gage stations are irregularly scattered across the globe, and many are concentrated in areas of isostatic instability such as Scandinavia and Japan. To compound the problem, the few data available from sparsely monitored regions, such as South America and Africa, are of varying record length and generally of suspect quality (Emery, 1980; Barnett, 1984).

Another difficulty results because each tide gage station can measure only local relative sea level change. The greenhouse effect with its postulated sea-level rise is only one of many diverse factors that may affect local sea level. Subsidence, which may be caused by tectonism, sediment loading or groundwater pumping, can create a rise in local relative sea level. Isostatic rebound may cause a relative drop, as in Scandinavia, which is rebounding in response to unloading from the glaciers of the last ice age (e.g. Gornitz, et al., 1982). Adjustments in the geoid in response to variations in earth's internal temperature and rotation also affect sea level observations (van de Plassche, 1986). If the precise rate of these local processes could be measured, data from each station might be adjusted to find true global change.

Another problem in interpreting tide gage records is the tendency for the data to be obscured by both short-term and long-term trends and seasonal noise. Revelle (1983) observed that the average sea-level rise for the past 15,000 years has been about 1 m/century; only in the past thousand years has sea-level risen on the order of only a few cm/century. Barnett (1984) pointed out that this change in the rate of sea-level rise leads to a search for a signal with a signal-to-noise ratio of about 1 to 10. In addition, shorter (decadal scale) cycles and episodic events such as the El Nino Southern Oscillation are not yet well understood. For example, Wyrtki (1987) reported a 27 cm relative sea level drop across the Western Pacific in June 1987. Elucidation of these types of phenomena is one requirement for more precise prediction of sea level changes for the next 100 years.

A number of papers document efforts to detect recent changes in both relative and mean sea level using increasingly sophisticated statistical techniques. Tide gage data for relative sea level are available for about the last 100 years. Emery (1980) analyzed records of 725 tide gage stations and eliminated those which were too short, irregular, or interrupted. His regression analysis of the data revealed only 211 stations with significant changes in sea level at the 95% confidence level. To improve the geographic distribution of usable stations, an 85% confidence level was accepted for some stations in Oceania and South America. Emery noted sea-level rises in low and middle latitudes, relative sea level drop (attributed to post-glacial rebound) at higher latitudes, and local irregularities caused by factors such as tectonism and sediment loading.

Gornitz et al. (1982) excluded stations with short records and those in seismically active (e.g. the Pacific coast of Japan) and rapidly subsiding areas. They divided the globe into fourteen geographically and tectonically similar regions and analyzed the records to find regional sea level curves. Individual station records were then reduced to a common reference point by fitting a least-squares regression to sea level as a function of time with zero as the value of the regression curve for 1940. Regional sea level curves were calculated and averaged to find a global average (excluding Scandinavia), and long-term (6000 year) sea level trends previously obtained from ^{14}C dating were removed. The results of Gornitz et al. are shown in Figure 3.

Other regional approaches to deciphering sea level history have been attempted with use of single, widely spaced stations. Barnett (1984) used a regional approach to approximate a global sea level trend. He eliminated stations with suspect data and averaged very dense stations, using a normalizing factor to compensate for different record lengths. Results for the six regions were discussed. Although he cautioned against identifying a "global" sea level change because of the limitations of the data, he did plot an overall average

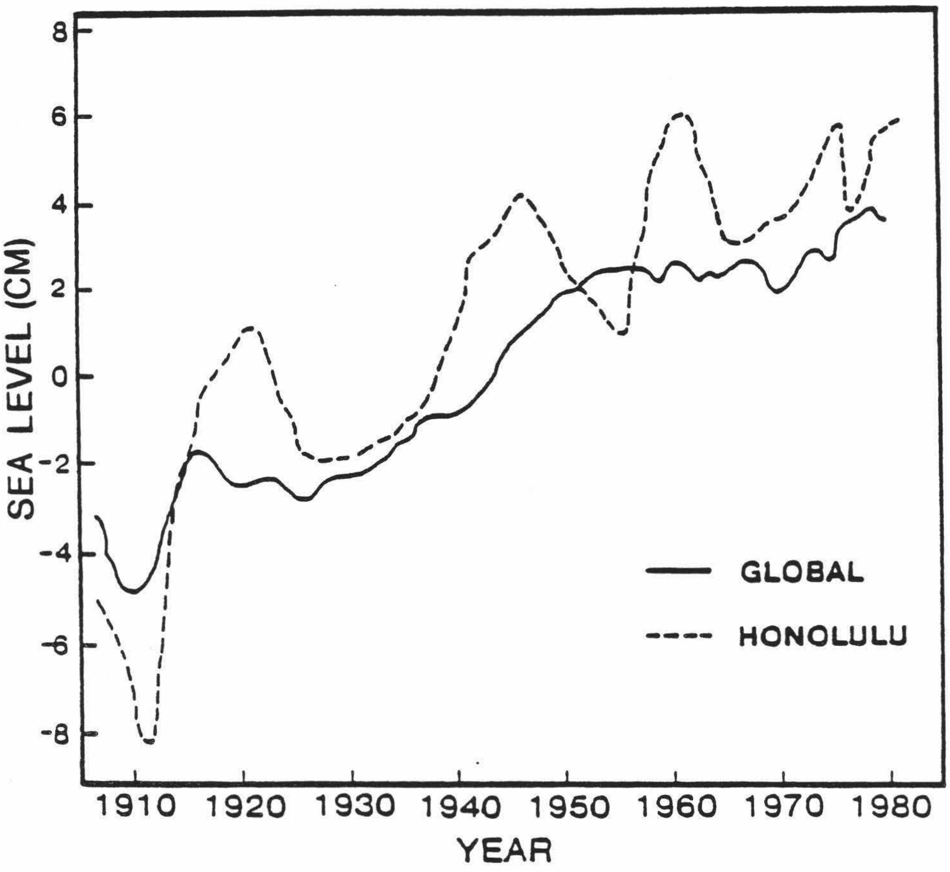

Figure 3. Sea Level Change Measured by Tide Gages. Global rise calculated by Gornitz, et al. (1982); Honolulu data from Hicks (1983).

trend, R_o. A trend in regional sea-level rise was observed for the 1900s: an increase by 1.4 mm/year was found for the total time of record, but the 1930-1980 data showed an increase of 2.3 mm/year, exhibiting a simple linear relationship.

Barnett concluded by suggesting that any increase in sea level caused by human-induced changes in atmospheric greenhouse gas composition will be extremely difficult to detect against the low-frequency variability resulting from glacial epochs and continental rebound.

Recent Sea Level Change in Hawaii

The subsidence caused by volcanic loading has been observed on the island of Hawaii and other volcanic islands. Tide gage records for Honolulu are available from 1905. This record is the longest time series available in the state. The data, presented by Hicks (1983), are plotted annually. Figure 3 shows the superimposition of global sea level change calculated by Gornitz et al. on the sea level trend observed at the Honolulu station. Barnett (1984) found a 0.76 correlation of Honolulu sea level change with global change.

In a study of isostatic adjustment in Hawaii, Moore (1971) analyzed tide gage records since 1905. He found close agreement between the sea-level rise measured at Honolulu and that at San Francisco, Seattle, and San Diego - about 2 mm/year for the period of record. This value closely agrees with the rate at Boston and New York of about 2.2 mm/year, which Moore accepted as representing a global trend. Moore therefore concluded that Oahu was a stable reference point; this conclusion was accepted by Campbell (1986) in his study of submerged terraces in Hawaii. In contrast, relative sea-level rise on the island of Hawaii, only 750 km south of Oahu, is about 4.1 mm/year, decreasing away from the active volcanic center. Subsidence caused by volcanic loading appears to explain much of the submergence and the tilt of the submerged reefs in Hawaii (Moore and Campbell, 1987).

This evidence suggests that Oahu may be relatively free of the isostatic adjustments which complicate sea level measurements in many other locations. Until short-term variations in sea level are better understood, it will be impossible to identify and anticipate global sea-level trends from the limited data available for any one location.

III. REGIONAL GEOLOGY

Even were it possible to predict the precise amount of sea-level rise to be expected in the coming century, an understanding of local environmental parameters is crucial to dicussions of the effects of sea level changes. The extent to which coastal erosion, flooding and saltwater intrusion are problems in any location depends critically upon geologic setting.

The study area of Kailua is located on the north coast of southeastern Oahu, Hawaii. The island of Oahu was formed 2-1.8 Ma (Mac Donald, Abbott, and Peterson, 1983) and is composed primarily of basaltic lava flows from tholeiitic shield-building volcanoes. The most recent active volcanism on the island of Oahu was the Honolulu Volcanic Series (Mac Donald, Abbott, and Peterson, 1983). There is a reef system partially encircling the island and feeding many kilometers of white sand beaches.

Climate

Temperatures at sea level in Hawaii average 21-30^{o} C; the prevailing tradewinds blow from the east-northeast and annual rainfall at the Honolulu airport weather station averages 60 cm. The average annual temperature at the weather station has increased from 22° to 25° C during the period of record, which extends back to 1905 (National Weather Service). This change is reflected both in local sea surface temperature trends and rises seen in global temperature change studies (Nullet, 1988).

Rainfall on Oahu is measured at Honolulu airport and at other gages around the island. There are several gages in Maunawili Valley inland of Kailua; two gages, one in and one near Kailua are autographic gages that record rainfall continuously and thus can pinpoint the time of peak storms. Annual rainfall averages 210 cm at the Maunawili gage (elevation 200 m), and 100 cm at the fire station in Kailua (Figure 4; Giambelluca et al., 1984).

The tradewinds blow steadily most of the year from the east-northeast, and are usually interrupted only by the Kona winds approaching from the southwest. Variations in the prevailing tradewinds are discussed in more detail in Chapter III.

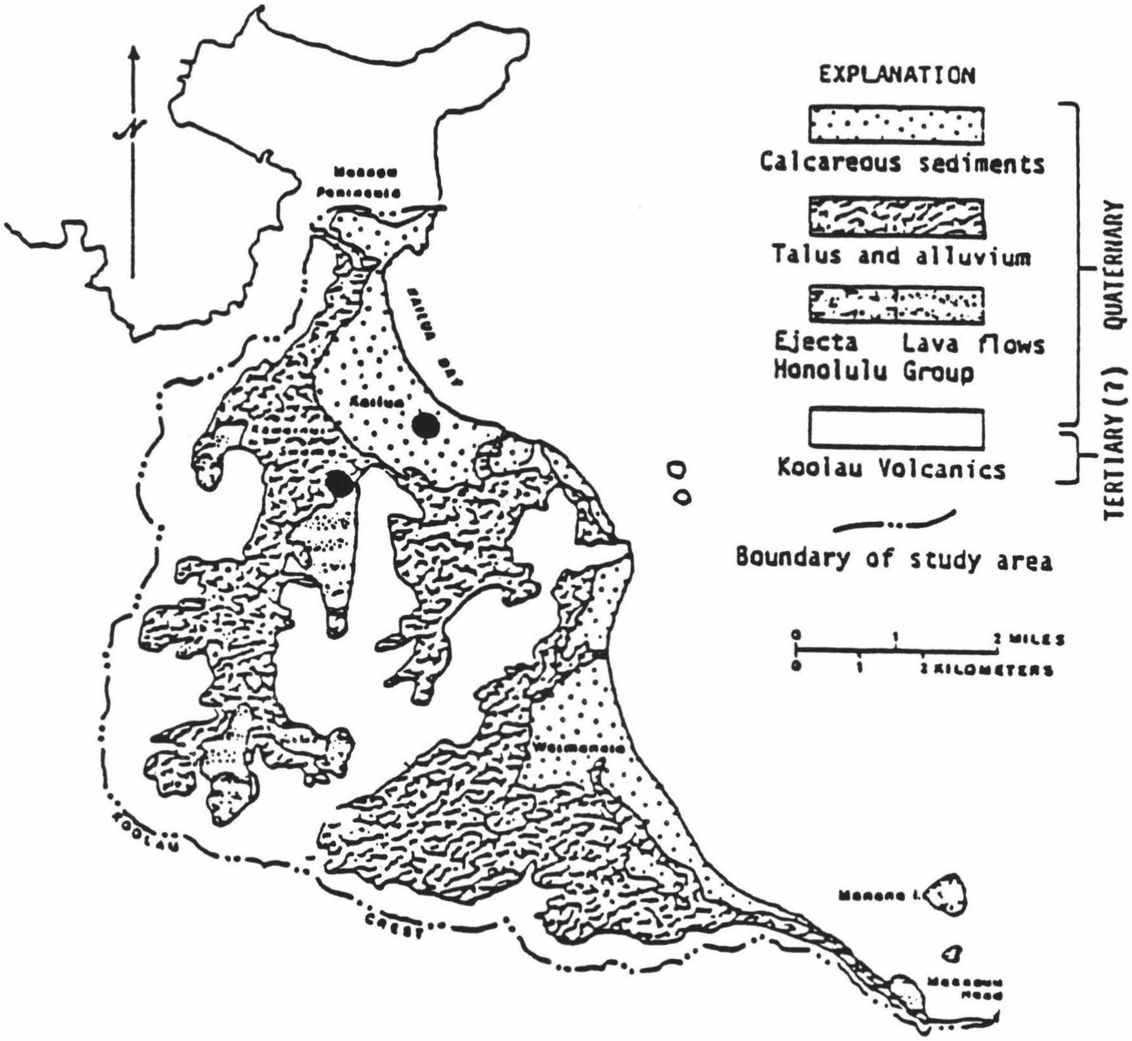

Figure 4. Geologic map of the Maunawili Drainage Basin and surrounding areas. Geology from Stearns and Vakstvik (1935). Dots mark locations of autographic rain gages.

The Study Area

The Honolulu suburb of Kailua is located on the windward, or northeast, side of Oahu in the Koolaupoko District. The steep Koolau Mountains above Kailua are composed of many layers of thin, contiguous pahoehoe and aa flows, which are cross-cut by thousands of dikes (Walker, 1986). Figure 4 shows the boundaries of the Maunawili Stream drainage basin. Maunawili and Kahanaiki Streams flow from the Koolau cliffs into the Kawainui Swamp. A sandy terrace and ancient dune system, covered by residential subdivisons, forms the barrier between the swamp and the active beach along Kailua Bay.

The original NW-SE trending rift zone of the Koolau Volcano serves as the backbone of the present Koolau mountain range. The entire eastern flank of the volcano has been extensively eroded.

Maunawili Valley was created by action of the Maunawili and Kahanaiki Streams and contains a drainage area of 47 km^2. It is bordered to the north and south by ridges which form the borders of Kaneohe on the north, and Waimanalo to the south. The two streams are fed directly by rainfall. The steady base flow is fed from dike impounded groundwater in the lower parts of the mountains.

Kawainui Swamp is the destination of the flow from these streams; the swamp encompasses 3 km^2 and varies in elevation from 2 to 3 m. The swamp is covered by a dense mat of grasses more than 2 m high and provides shelter to several species of native Hawaiian birds. A quarry, a landfill, and an automobile junkyard border the swamp. Much of the swamp itself is a special management area. The clay-rich soil of organic mud is not very permeable. Kawainui swamp serves as a flood control basin by virtue of its large size and drainage to the ocean (Towill, 1964; Swain and Huxel, 1971).

The suburban town of Kailua has been built largely upon the barrier beach with the Coconut Grove subdivision occupying much of the area. Coconut Grove has an area of 3.8 km^2, and is bordered to the north and south by ridges and to the east and west by the ocean and the swamp, respectively. Ideally, flood outflow from the swamp into Coconut Grove is redirected by the Inner Canal draining to Kaelepulu Stream and a 3 m levee, built by the Army Corps of Engineers and completed in 1966. Topography in Coconut Grove is in places lower than that of the swamp, and slopes gently from the dunes at the beach to an elevation of 1.3 m where houses border the swamp.

Kailua beach is a 4 km long white sand beach of varying width. The beach rises steeply from the water to an elevation of 3.5 m; lower elevation dunes are located behind the berm. The beach fronts a calm bay with gentle waves at the shore and shallow bathymetry, and is oriented almost perpendicular to the prevailing east-northeast tradewinds. This beach is very popular for bathing, windsurfing, and sailing.

IV. SHORELINE MIGRATION AT KAILUA BEACH

There is agreement in previous studies that sea-level rise accelerates the rate of erosion. Most analyses assessing response of particular geographic locations to sea-level rise scenarios have focused on historic erosion rates and applications of the Bruun rule (Bruun, 1962). In this chapter, historic shoreline movement at Kailua Beach is analyzed and associated with wind data. The goal is to assess proable effects of a sea-level rise on shoreline erosion based on an understanding of the history of the area and associated meteorologic controls on shoreline migration.

Previous erosion studies of Kailua beach (Noda, 1977; Hwang, 1981) indicated that 30 to 40 year erosional cycles operate on the beach. Noda (1977) proposed changes in the direction of the prevailing tradewinds as an explanation. Neither study, however, explicitly examined records of both historic wind and shoreline conditions. In this study, the record of shoreline migration and prevailing wind direction are compared. Based on the observed trends in shoreline migration in conjuction with meteorological conditions, a future shoreline scenario for Kailua in response to a 1 m sea-level rise is presented. The long-term trend of accretion, which correlates with a long-term shift in the prevailing wind direction and is most pronounced in the northern area of the beach, is expected to continue, barring other changes in meteorological conditions.

Previous Work

Measurement of shoreline change by use of transects from stable reference points perpendicular to the coast was attempted by Valentin (1954), who studied sea cliff erosion at Holderness, Scotland. He measured the distance from 307 stations along 61.5 m of shoreline to the edge of sea cliffs in 1952, and compared the measured distances to those on a 1852 large scale shoreline map. Analysis of 30 stations with an average recession of more than 1.5 m/year revealed that erosion was greater at times of high sea level.

More recent studies have used aerial photographs to determine past shoreline changes (e.g. Leatherman, 1983; Hwang, 1981). The Bruun rule, discussed below, is one attempt to associate sea-level rise and beach erosion.

Shoreline Response to Sea-level rise

The Bruun rule (Bruun, 1962) provides a relationship between sea-level rise and beach erosion, assuming that the nearshore profile is maintained as sea-level rises. This principle is illustrated in Figure 5. Bruun's method assumes an equilibrium profile with material being transported into the system at the same rate that it is lost. This is a two dimensional model, with no longshore transport and uniform sediment size throughout the system. For nearshore bathymetry to be maintained during sea-level rise, the volume of material sufficient to fill in the bottom to maintain the appropriate water depth must be transported from the shore. The amount of shoreline recession resulting from sea-level rise can be obtained by calculating what the shoreline location will be after bottom-filling material has been removed from the dunes, using the equation:

$$x = (ab)/(e+d),$$

where x is the distance of shoreline recession, a is the change in sea level, b represents the distance to the limit of onshore-offshore transport (where net flux is zero), d is the depth to the bottom at the offshore extreme of point b, and e is the height of dunes. Experimental evidence (Schwartz, 1967) supports this

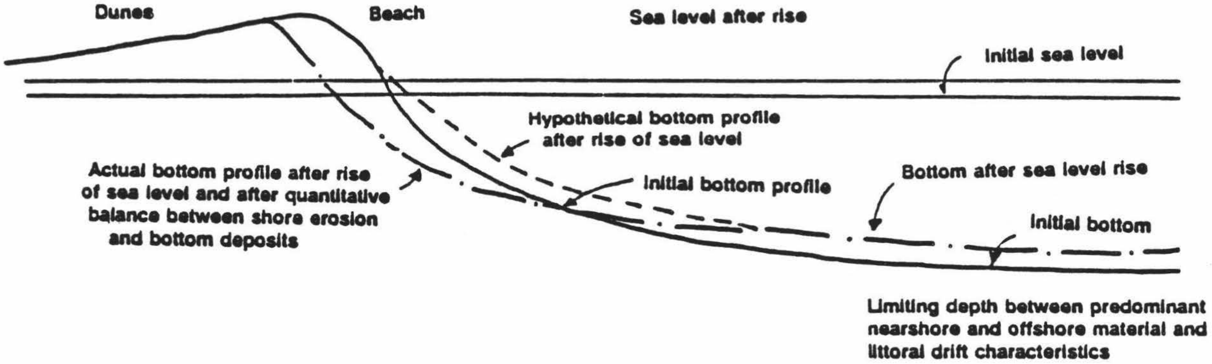

Figure 5. The Bruun Rule (Bruun, 1962). Shoreline recession is related to volume of material needed to maintain nearshore equilibrium (see text for explanation).

relationship, and Hands (1981) has confirmed the utility of the Bruun rule in the Great Lakes area.

Several studies have presented shoreline change scenarios in response to a sea-level rise resulting from a greenhouse effect. Leatherman (1983, 1985) rejected the use of the Bruun rule, because it is a two-dimensional model, and because it is usually difficult in practice to assess the limit of sediment transport. He developed (1983) and used (1985) a metric mapping technique to plot historic shoreline trends and associate previous shoreline movement with rise in sea level. He extrapolated these trends assuming a direct correlation between sea-level rise and shoreline retreat; if rate of sea-level rise triples, the rate of shoreline retreat will do the same. Leatherman preferred this method to use of the Bruun rule, because it automatically accounts for differences in geomorphology between locations owing to its being based on historic trends.

Everts (1985) compared the Bruun Rule with his own method for anticipating shoreline retreat as a response to sea-level rise. Everts applied a sediment budget model accounting for gains and losses to the system caused by longshore transport, loss of sand at the base of the shoreface, overwash, aeolian transport, inlets, mining, and replenishment to create a new shoreline scenario for Ocean City, Maryland.

Kana et al. (1984) studied possible effects of several sea-level rise scenarios on the shoreline of Charleston, South Carolina. They plotted new shoreline positions for a number of stations after accounting for local elevations, historical erosion rates, station geomorphology, and sediment type. Erosion was not predicted for human-made structures such as seawalls. For each station, and each time span, they found a baseline rate from which to extrapolate shoreline movement. The new shoreline for each scenario was calculated by adding predicted inundation caused by sea-level rise to accelerated erosion caused by the rise.

Kailua Beach

Erosion at Kailua Beach Park, which is at the southern end of Kailua Bay, was of sufficient concern in the late 1970s that the Army Corps of Engineers commissioned a study (Noda, 1977) to analyze the problem. Noda's study determined actual beach migration using ground surveys and aerial photographs of the beach from 1949-1977.

Noda created a ray-tracing program to model littoral processes in the beach park area. He assumed a two season system; the angle of approach for waves used in the model was based on eight years of data, with random variation within and between the seasons. He modeled the bathymetry of Kailua Bay and simulated shoreline migration at Kailua Beach Park over thirty years. This model (Figure 6) exhibits random beach movement each year with a cumulative trend. The range of shoreline movement is predicted by the model to be about 35 m. Observed shoreline variation over the 28 year period of record was about 30 m. The model run presented was not based on actual data, but intended just to show the expected range of shoreline change to be expected in the system being modeled. Noda proposed a thirty to forty year cycle in beach erosion and suggested that the 1949 value may represent maximum probable retreat. Although earlier air photo evidence was not available, he cited interviews with long-time local residents to support this cyclic theory.

Hwang (1981) studied shoreline changes on Oahu as seen in aerial photographs using Kailua Beach as his type locality. He measured relative beach width at 15 transects perpendicular to the shoreline along Kailua Beach as indicated by photographs taken in 1949, 1957, 1963, 1970, and 1978. Hwang also suggested that a thirty to forty year erosional cycle is operating at the beach.

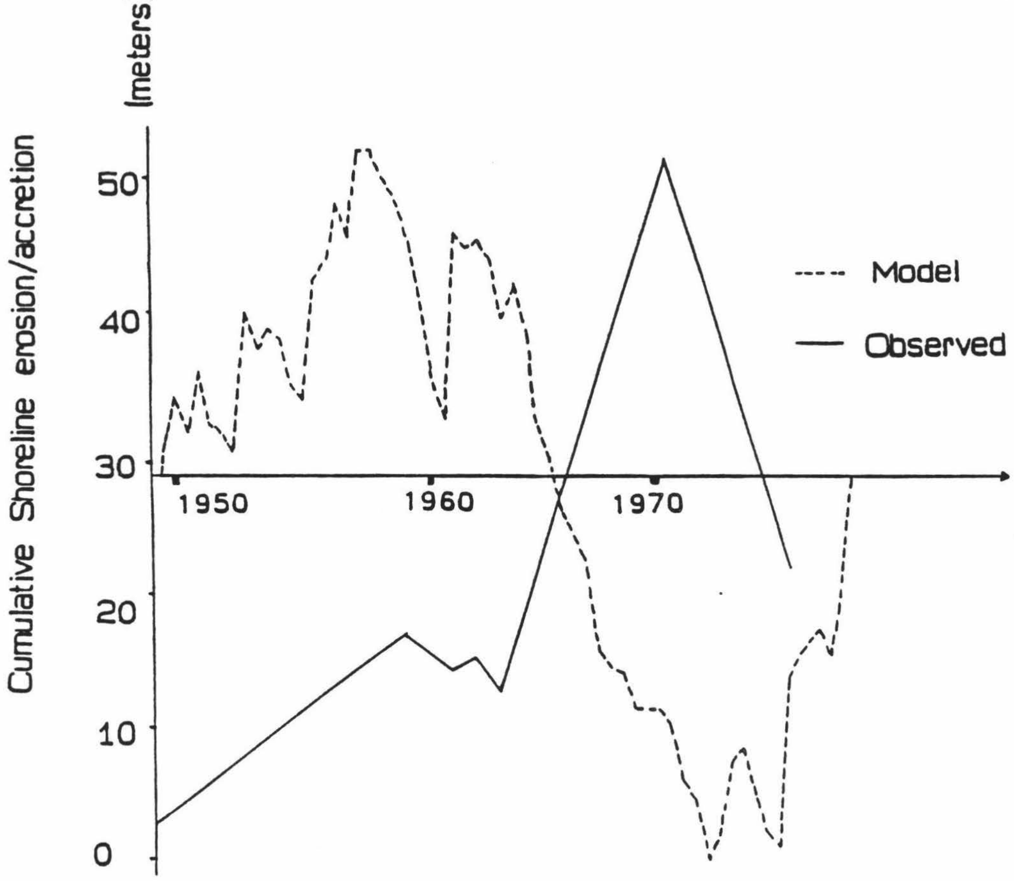

Figure 6. Shoreline change at Kailua: Noda's simulation and observed change. The simulation shows a range of movement close to that actually observed from 1949-1977.

Both studies proposed a three-cell system of littoral transport as a mechanism to explain these cycles. As the northern end of the beach erodes, the southern end accretes and the central portion remains relatively stable, serving as a buffer zone between the two opposite cells.

Beach erosion is caused by wave action and nearshore currents; the direction of wave approach in areas of wind-driven surface-gravity waves is governed by wind direction and otherwise governed by swell direction. The northwest to southeast orientation of Kailua beach is very nearly perpendicular to the direction of the prevailing tradewinds, so that although waves do not approach from the prevalent wind direction, a small variation in the angle of approach of the wind can make a dramatic difference in the direction and quantity of littoral transport (Noda, 1977).

Both Noda and Hwang pointed to a 1949 article by Wentworth which analyzed wind data from 1905-45 and suggested that there may be a forty to fifty year cycle in the prevailing direction of tradewinds.

Wentworth (1949) based his study on a similar 1927 study by E.A. Beals. Beals (1927) examined wind observations from Honolulu, Hilo, and California in his study of the tradewinds of the North Pacific. Beals noted a shift in direction of the Pacific trades from the northeast to the east between 1905 and 1924. He attempted to link this shift to variations in the circulation pattern in the Pacific anticyclone, but failed to obtain conclusive evidence of a link and recommended a study of ship observations as a key to solving the puzzle.

Wentworth's study (1949) analyzed hourly wind observations taken by the National Weather Service at downtown Honolulu. Noting that 81% of the observations showed winds from the northeast or east, he eliminated observations from other sectors, and computed the relative percentage of the time that the winds blew from either direction from 1905-1945. His results are shown in Figure 7. Using a five year running average, he observed a gradual shift in prevailing tradewind direction from the northeast to the east and back towards the northeast again, over the period 1905-1945. He predicted a corresponding swing back to the northeast between 1950 and 1960.

Noda (1977) ran his computer program to simulate only thirty years of beach migration for two reasons. The first was that the record provided by aerial photographs spanned only thirty years. The second is that Wentworth had postulated a cycle of 30-50 years in

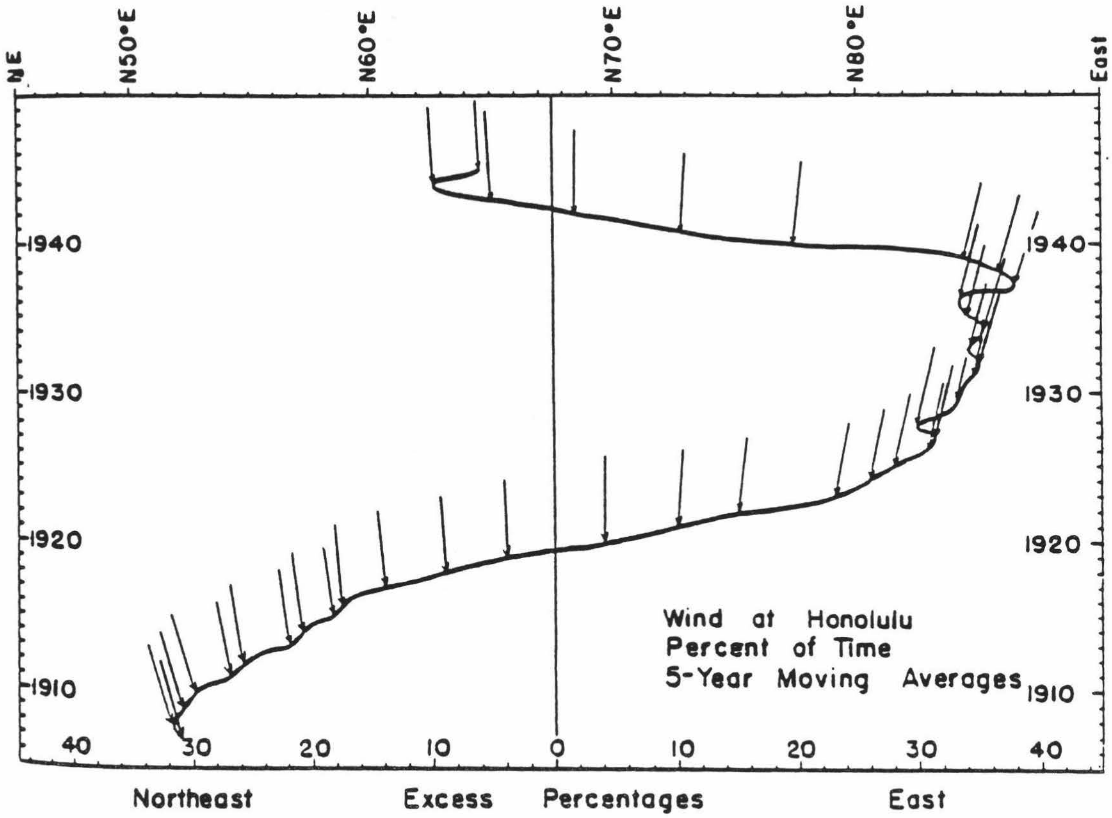

Figure 7. Shifts in the Prevailing Tradewinds in Hawaii 1905-1945 (Wentworth, 1949). Explanation of method in text.

wind direction. Noda's study, however, used wave statistics obtained from only eight years of data.

The Kailua erosion studies and the wind studies postulate cycles which are longer than the period of shoreline record. One objective of this study was to examine a longer record for both the wind and erosion data, and then to compare these records, seeking evidence of cycles and a relationship between wind direction and beach erosion. The erosion expected to be associated with sea-level rise could then be superimposed on predictable wind and erosion cycles to arrive at tentative conclusions concerning how Kailua Beach might be affected by a sea-level rise.

Data and Methods

The present study uses an extrapolation of past trends of shoreline migration and associated meteorological controls, to construct a shoreline scenario for Kailua in response to a 1 m sea-level rise.

Leatherman's method is inappropriate for Kailua, because his assumption of a direct correlation between sea-level rise and erosion does not approximate the observed shoreline movement during the period for which aerial photographs are available. Leatherman's historic trends method works well for his study areas, which were Galveston Texas, and Ocean City, Maryland. This result is probably because relative subsidence, caused primarily by groundwater pumping, was sufficient to overshadow any natural processes operating in those locations. In Kailua, the change in relative sea level for the period of historic record is quite small (a few cm) compared to the rise predicted for the scenario presented here.

Using the Bruun rule as the previous studies have done is problematic for this area, because key conditions for use of the rule are not met on Kailua Beach. Shoreline studies of Kailua suggest that longshore transport is important, and that the long-term trend of accretion along the beach is a result of sediment is being added to the system. In addition, the sediment size is not constant in the system: the beach dunes are composed of finer grained sand than the coarser material found in the surf zone. With these caveats, the Bruun rule is used to give a first order estimate of erosion which might result from a sea level change, considered in conjunction with historic shoreline change.

This investigation contributes to the understanding of beach processes at Kailua by associating shoreline migration with variation in the prevailing tradewinds. Considering historic variations in the tradewinds and shoreline position, and the accelerated erosion anticipated with sea-level rise, the response of the Kailua shoreline to a sea-level rise of one meter over a period of 100 years is assessed.

Shifts in the Prevailing Tradewinds

There are several data sets available for analysis of tradewinds since 1945: the National Weather Service data for Honolulu, the TDF-14 surface observations from military airports, including the Kaneohe Marine Corps Air Station, and the National Oceanic and Atmospheric Administration's Comprehensive Ocean-Atmosphere Data Set (COADS).

The Marine Base record, while geographically close to the study area, dates only from 1945; it represents one third of the period covered by COADS. The National Weather Service data are available from 1905, in hourly observations with monthly and annual resultants given. Analyzing the National Weather Service data presents two difficulties. The first deals with a series of changes in the record format. In 1951 the 8-point wind rose (as was studied by Wentworth and Beals) was replaced by a 16 point rose. Beginning in 1964, wind resultant direction was expressed in 10^{o} increments, and since 1984, resultant wind direction has been given to the nearest degree. In addition, the anenometer was moved in 1922, and then moved again in 1964 to its present location at the Honolulu Airport.

The COADS is a collection of voluntarily-contributed shipboard wind observations. The number of observations per month per location is dependent on the number of ships passing through the area. The record extends back to 1854, but owing to the extreme scarcity of records before 1900, only observations in this century were processed. The observations for this study were taken from individual ship records from an area north of the Hawaiian Islands, from 21° to 24° N and 152° to 159° W. Direction is expressed as azimuth in degrees from north and magnitude in meters per second. Values for steadiness and number of observations available for the month are also included.

The data were condensed for this study into one 4° by 8° block and the monthly and annual resultant wind vectors were computed. Monthly resultants were calculated with a weighting for the number of observations available; annual resultants were not weighted. Figure 8 shows the number of observations recorded in the study area; recent studies of this data suggest that 30 observations per month are needed for a

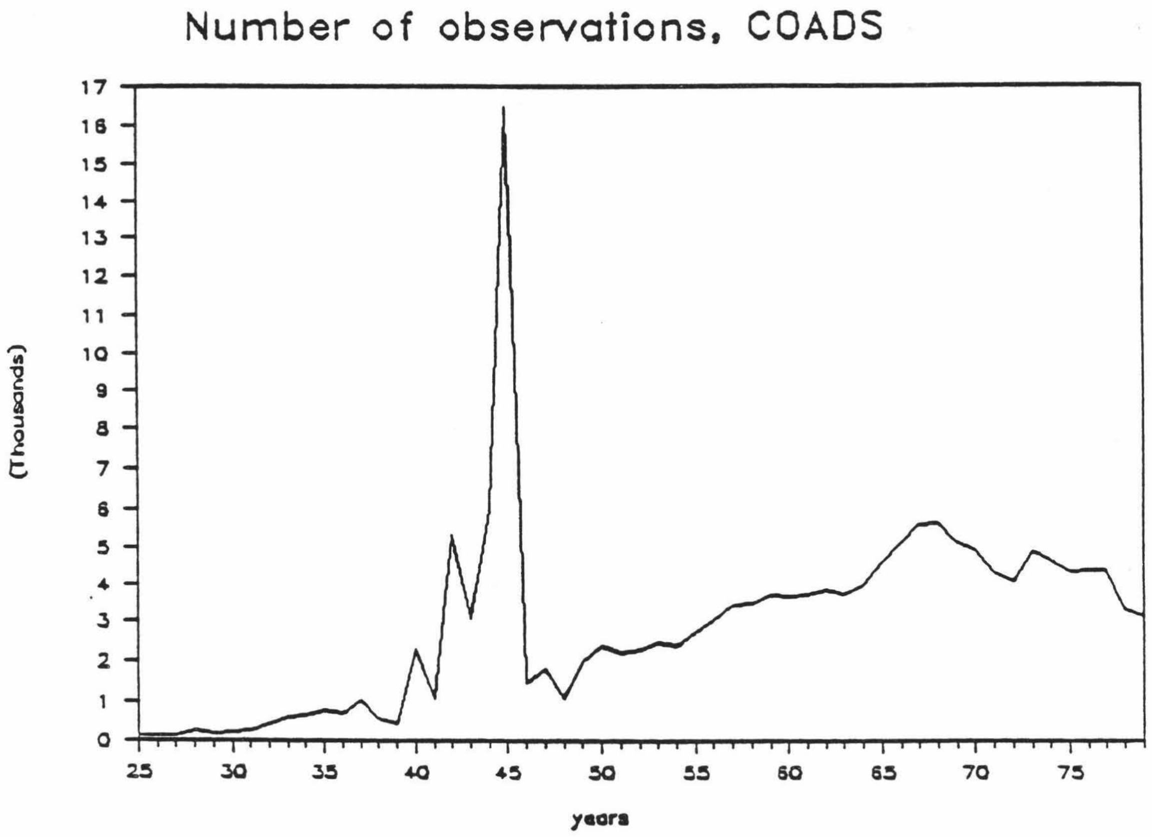

Figure 8. Number of wind observations per year from the Comprehensive Ocean Atmospheric Data Set between 21° and 24° N, and 152° and 159° W.

statistically significant result (Halpern, 1987). Even with the data culled from a large block, there is not a significant number of observations regularly available until the 1920's, and in addition there are many months for which no data are available.

Figures 9 and 10 compare annual, January and July winds. Most of the annual wind variation occurs during the winter months; the summer winds are generally steady.

A comparison of the COADS and National Weather Service data is given in Figure 11, using the airport data since 1964. There is approximately a 10° difference in average azimuth between the two data sets. This difference may be because the prevailing winds from the east-northeast are diverted northward around the Koolau and Waianae mountains, yielding a stronger northern component.

Another analysis of the data was performed for comparison to the results of Beals (1927) and Wentworth (1949). For these calculations, azimuths from 23° to 66° were assigned to the northeastern sector, and those from 69° to 113° were assigned to the east. Values of greater than 113° or less than 23° were discarded, and values of 67° and 68° were discarded to provide differentiation between the two sectors.

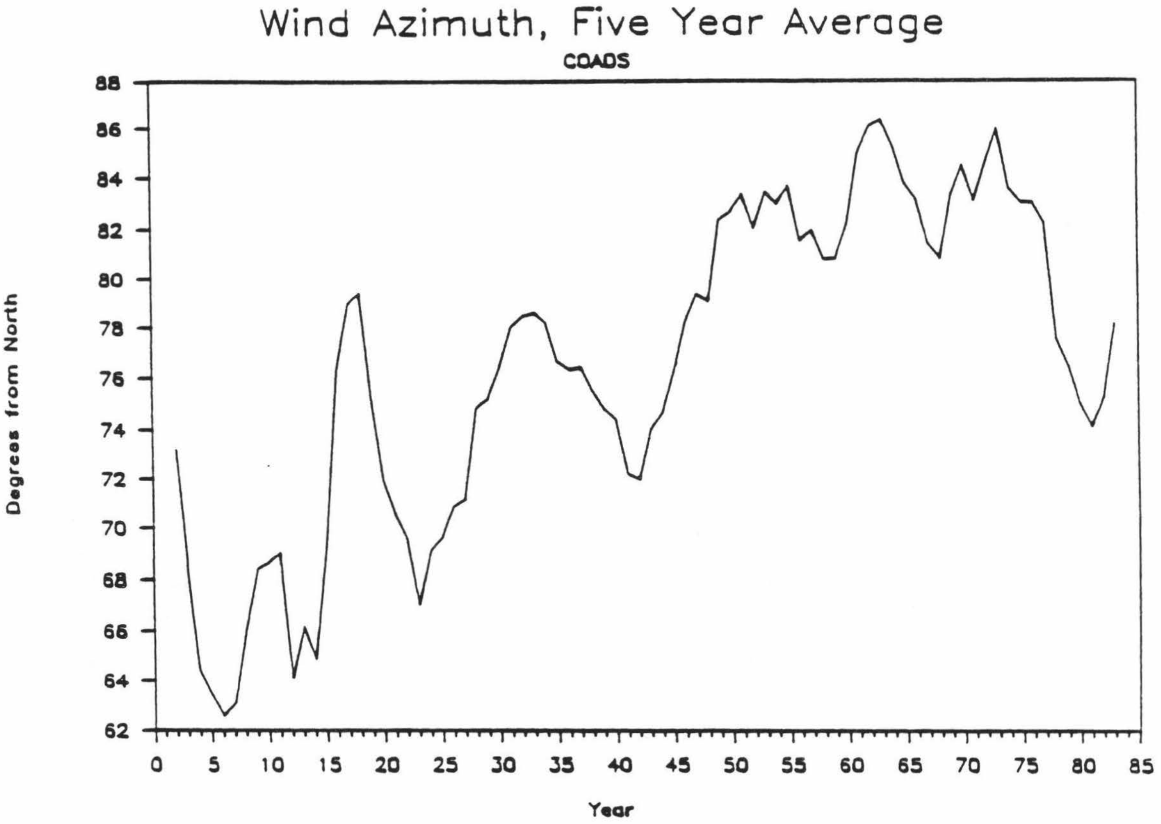

Figure 9. Wind azimuth (five year running average).

Tradewind Azimuths
5 yr averages
from ships in
Hawaiian Waters

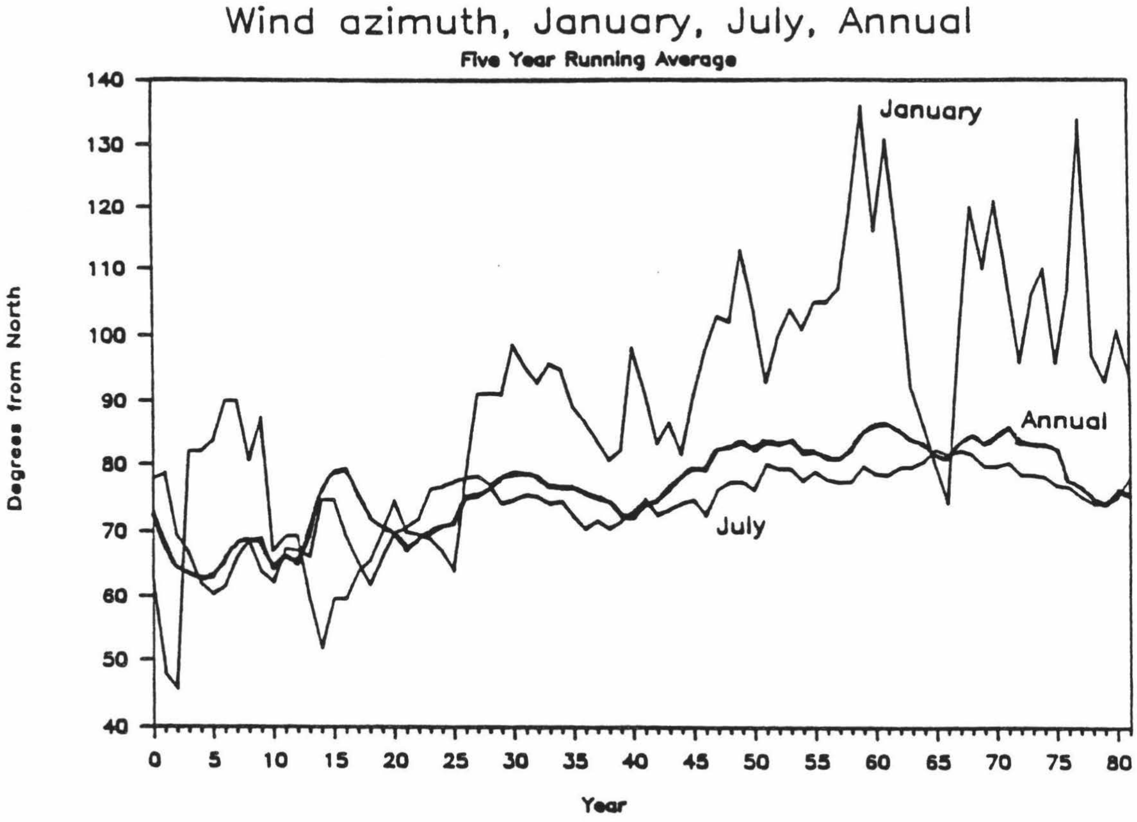

Figure 10. Wind azimuths: annual, January, and July (five year running average). Source: COADS.

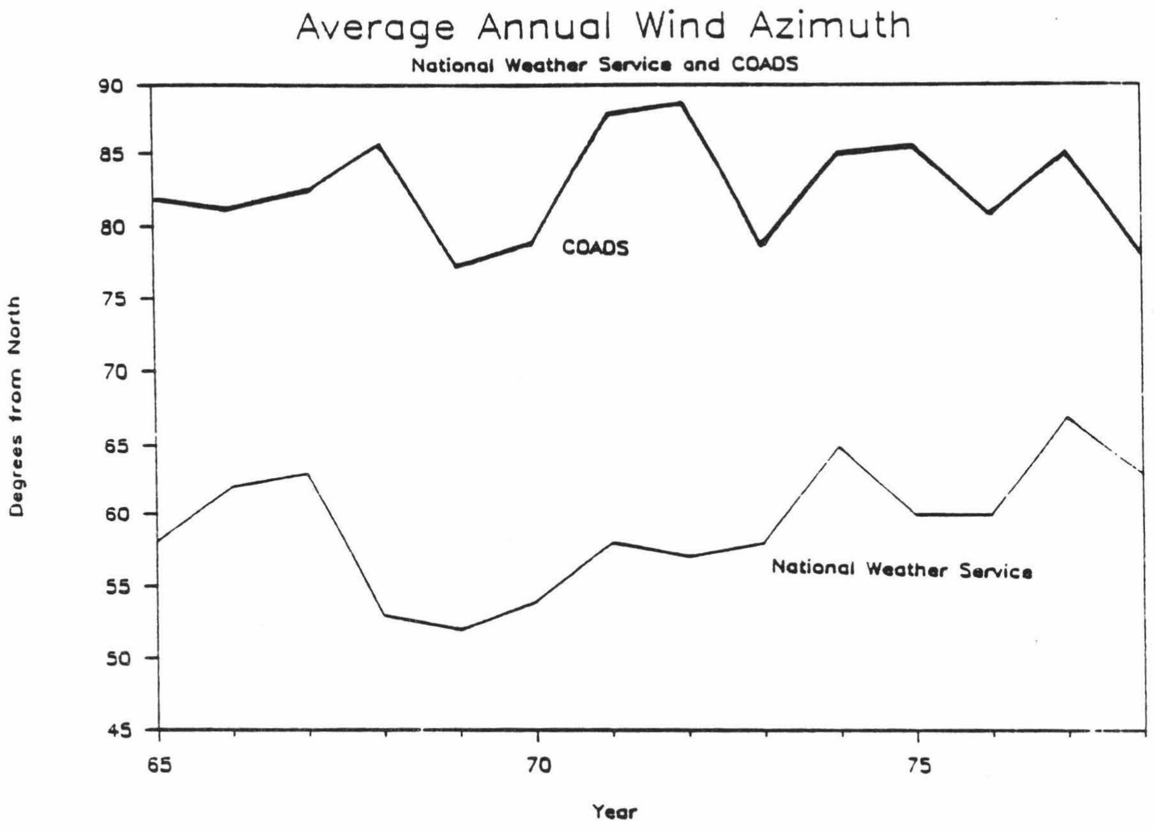

Figure 11. National Weather Service (Honolulu) and COADS average annual wind azimuths.

The shift from northeasterly to easterly winds noted by Beals and Wentworth in the first quarter of this century is apparent in the COADS (Figure 12). Northeasterly winds were more common than easterly in the first years of the century with more easterly winds during the 1920's, but there is no corresponding shift back to the northeast as Wentworth had predicted. When a five year running average was applied to the data as a smoothing function, there is an apparent trend towards more frequent easterly winds. This pattern agrees with the results of Whysall et al. (1987) in their analysis of Pacific winds. The COADS result should be viewed cautiously because many months of data are missing; for the earlier years (1905-09) half of the months have no observations. It is included because it is the only long-term continuous data set free from topographic effects.

Evidence for beach erosion or accretion is more difficult to find than wind data. The aerial photographs used by Hwang are available only from 1949. Earlier photos show insufficient detail for the purposes of this study. A search of the state survey records was initiated in an effort to trace previous shoreline locations as beachfront lots were resurveyed to show accretion or erosion. The original survey map of the

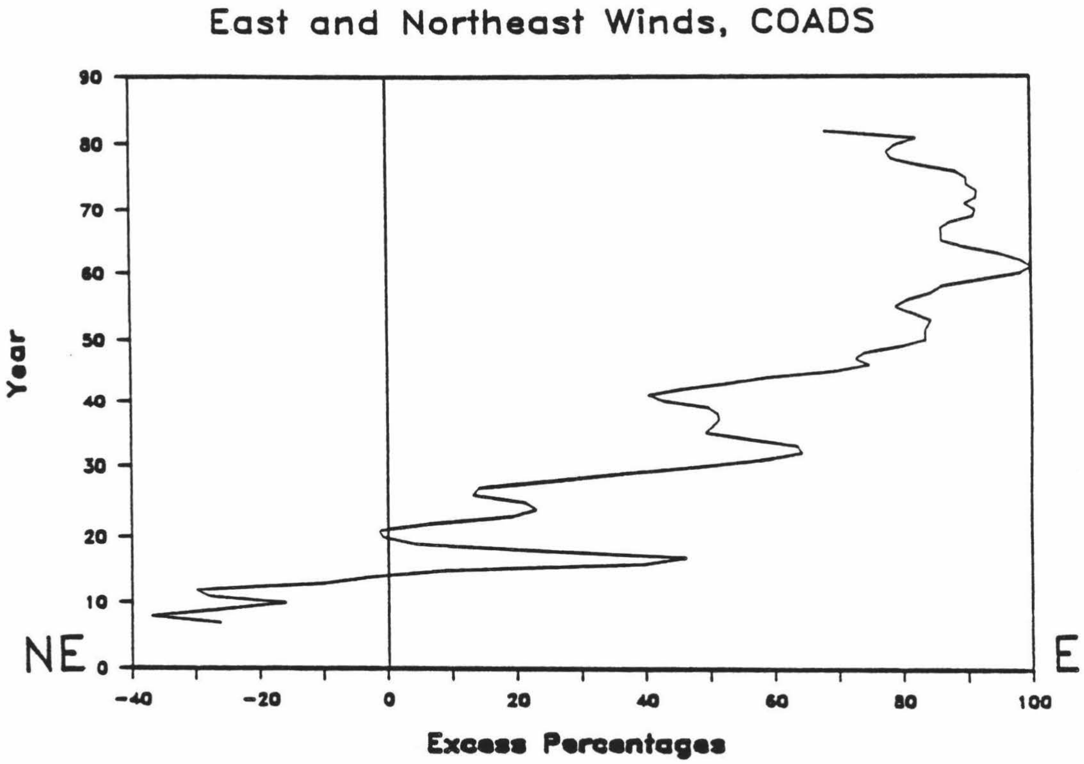

Figure 12. Average annual azimuth, for comparison with Wentworth (1949).

Kailua beachfront was filed with the territorial land court system based on a 1927 physical survey of the area. Although resurveying of individual lots was common after about 1970, the beach was surveyed only rarely before that. Only one major survey record was found for Kailua Beach between 1927 and 1960. The Kailua Beach Park area was purchased by the city in 1922 and was not resurveyed to show shoreline migration until the time that the aerial photographs are available. One large lot just north of the Beach Park and marked as a dashed line in Figure 13 was surveyed in 1927 and again in 1950 and showed accretion of approximately 30 m.

Kailua Beach was divided into northern, central and southern sections, slightly modifying the divisions of Hwang, (1981). Hwang's transects 1 and 2 were excluded because only two observations were available from each of these locations. Transects 3, 4, 5 and 6 were classified as north, transects 7, 8, 9, and 10 were the central portion, and transects 11, 12, and 13 comprised the southern segment of the beach. Figure 13 shows the locations of these transects and the surveyed beach profiles.

Beach profiles perpendicular to the shoreline at locations in the northern and central sections of the beach were surveyed for this study. These areas were

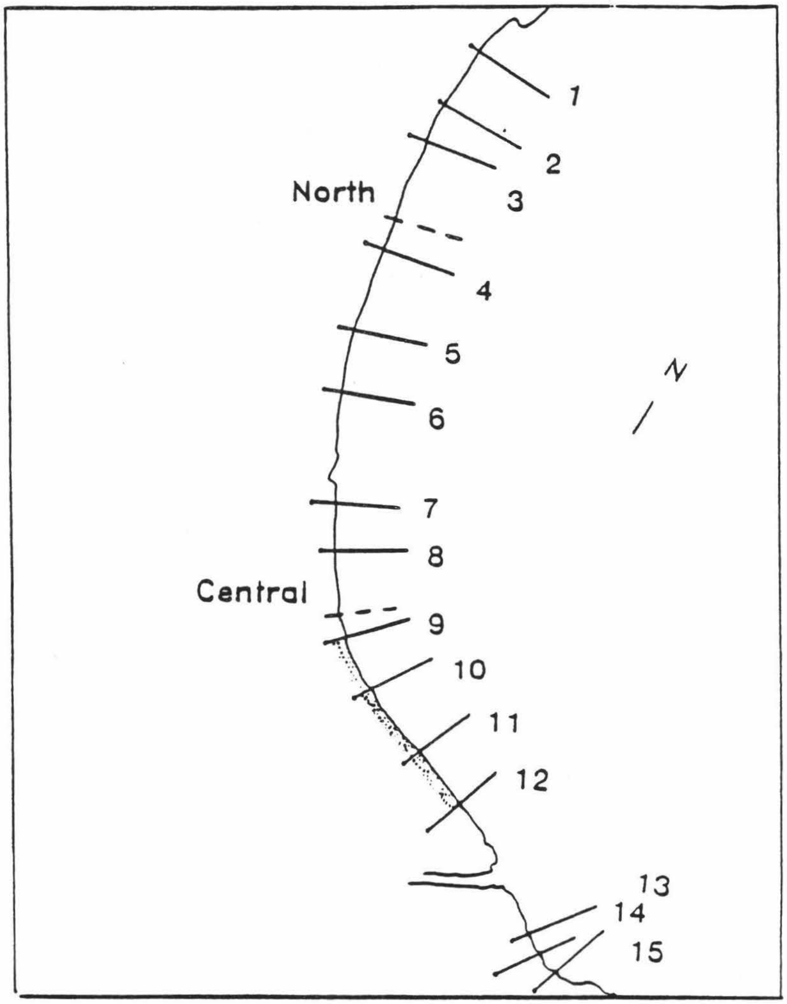

Figure 13. Transects perpendicular to Kailua Beach measured by Hwang (1981). Dashed lines mark profiles surveyed for this study, and dotted area was section surveyed in 1926 and 1950 (see text for explanation).

chosen to compare with the profiles of Moberly and Chamberlain (1964) to check the stability of the bottom profile. Moberly and Chamberlain surveyed the beach on six occasions at different seasons in 1962 and 1963. The present surveys were carried out on land by use of a transit, and in the water using a line from the shoreline and a weight attached to a line measuring depth. Height was scaled to mean lower low water. The 1988 profiles, compared to those measured by Moberly and Chamberlain (1964) are shown in Figures 14 and 15. The zone of net sediment transport is assumed to end where the bathymetry levels out. The bottom is reef with very little sand beyond this point (Moberly, 1963). Because the conditions for the use of the Bruun rule are not met here, it is not possible to use that method with confidence to predict shoreline erosion. The stability of the beach profile over the past 25 years, suggests that it may be possible to use the assumption of nearshore profile stability as a first, probably conservative, approximation for shoreline erosion. For values shown in Figure 14,

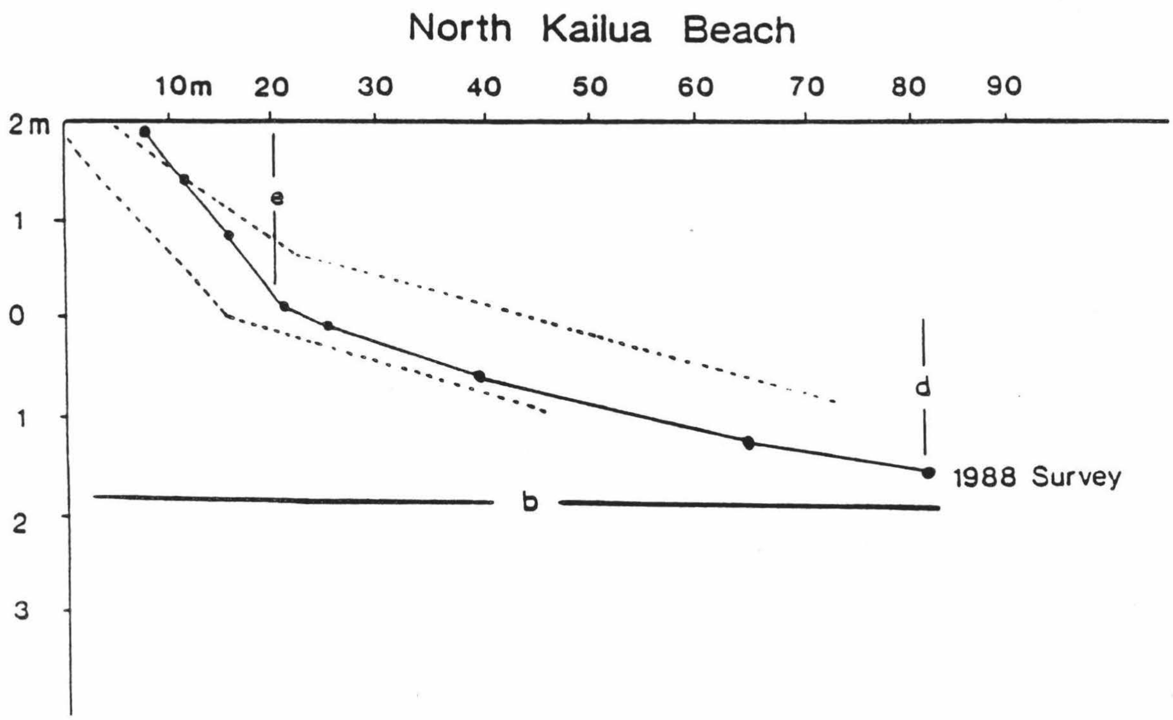

Figure 14. Beach profile, North Kailua Beach. Dotted lines mark range of profiles measured by Moberly and Chamberlain (1964). Letters indicate distances measured for application of the Bruun Rule (see Figure 5).

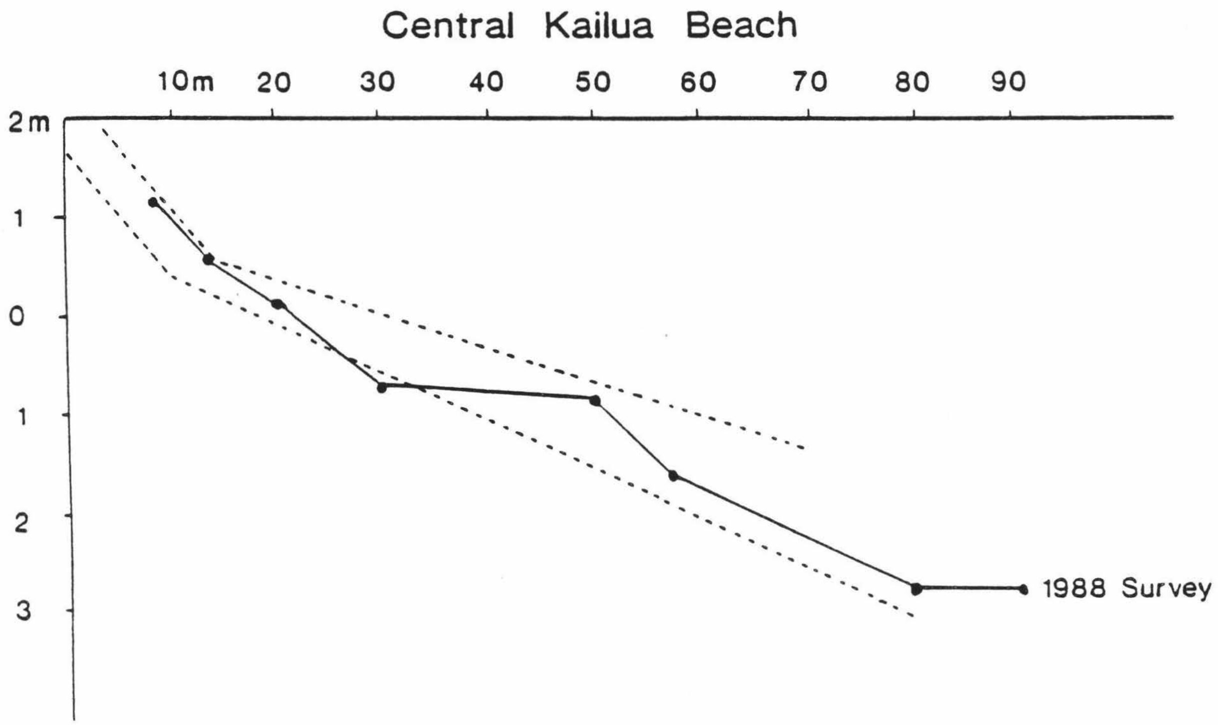

Figure 15. Beach profile, Central Kailua Beach. Dotted lines mark range of profiles measured by Moberly and Chamberlain (1964).

a = 1 m,

b = 80 m,

d = 2 m,

e = 2 m, and

x = 80/4 = 20 m

This value for projected shoreline recession is fairly small because the distance of sediment transport is short. This result represents a trend of about 20 cm/year erosion over the 100 years spanned by the sea-level rise scenario. Although this is a conservative estimate, it is less than the present trend for accretion, particularly on the northern end of the beach, assuming that associated meteorological controls are unchanged.

On another, shallower beach, the effects may be far greater. For example, Waimanalo Beach is just a few kilometers south of Kailua on the Windward coast of Oahu. The foreshore of this beach has a very shallow slope and the zone of onshore-offshore sand transport is limited by the reef flat beginning 420 m offshore (Moberly, 1963). Erosion could be 60 m, using the conservative estimate of the Bruun rule. According to Hwang, erosion on this section of Waimanalo Beach has been minimal since 1949;

a 1:60 ratio of sea-level rise to erosion might be expected. The Bruun rule is used with the caveats mentioned above, and only as a general guideline.

Results and Discussion

Wind and Erosion

Although there is some evidence for an inverse relationship between accretion and erosion on opposite ends of Kailua beach, this pattern is overshadowed by the overwhelming trend of accretion. Net accretion occurred for each of the 15 transects along the length of the beach (Figure 16). Therefore it appears that any predicted erosion of Kailua beach resulting from sea-level rise should be superimposed upon this long-term, opposing, accretionary trend.

During the twentieth century, the prevailing tradewinds become increasingly more easterly. Figure 17 compares the prevailing winter winds and the beach erosion data. Because the winter winds are the most variable, it is expected that shifts in winter wind direction will have the greatest impact on the shoreline. For example, the winter of 1968-69 was exceptionally stormy, and there was accretion on the southern end of the beach by 1970. A similar effect was noticed at

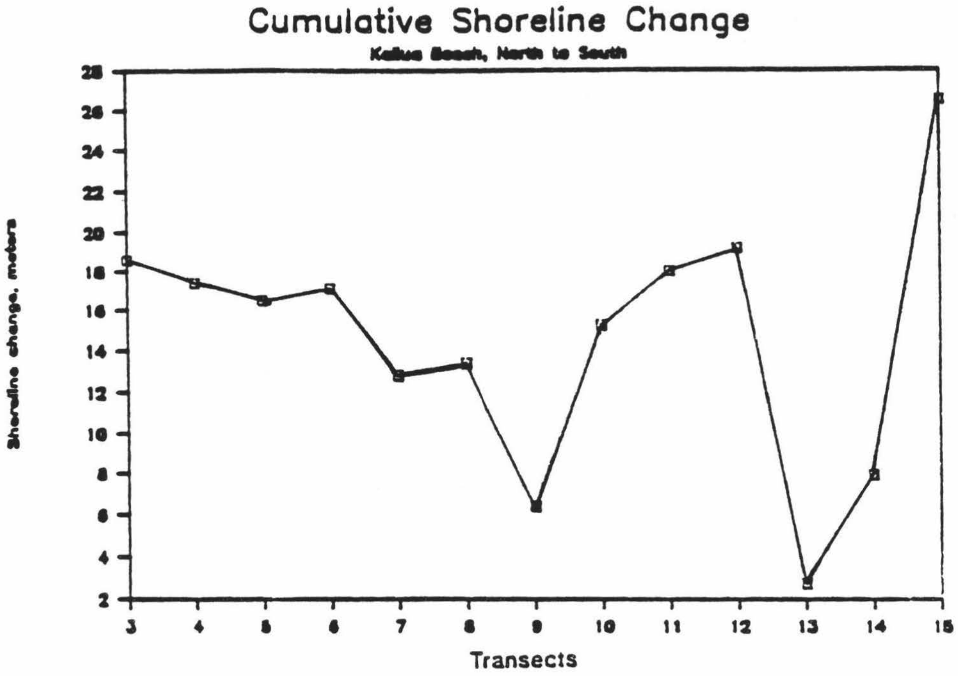

Figure 16. Accretionary trend along Kailua Beach. For each transect measured by Hwang (1981) the cumulative shoreline movement from 1949-1978 was accretionary.

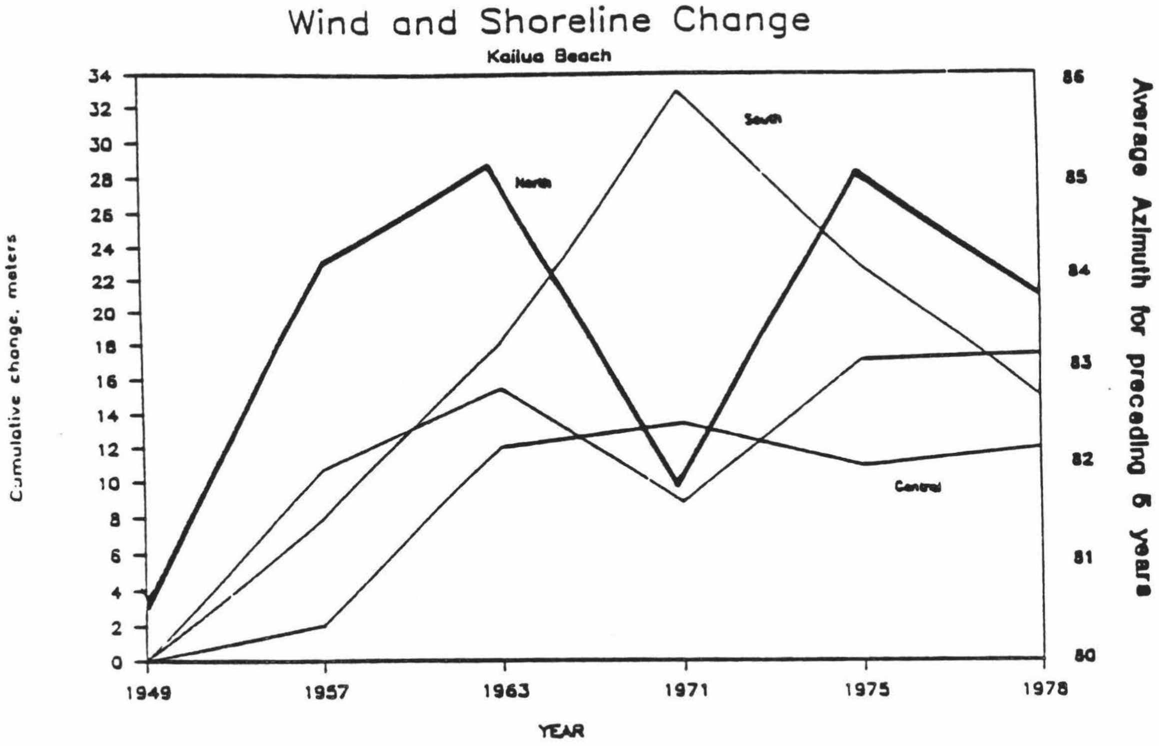

Figure 17. Prevailing wind direction and beach erosion at Kailua. Cumulative shoreline movement plotted against average wind azimuth for the preceding five years for a.) the northern transects (3,4,5,6), b.) the central transects (7,8,9), and c.) the transects immediately north of Kailua Beach Park (10,11,12).

Lanikai Beach during the years of 1970 and 1971 (Hwang, 1981).

It is difficult, given the data available, to quantify a direct relationship between wind direction and beach erosion for most of the beach. The northern end of the beach does show a trend for accretion with more easterly winds. The correlation decreases to the south. This observation may be explained by a variety of complicating factors affecting littoral transport near the beach park. These factors include the presence of Popoia (Flat Island), flow from Kaelepulu Stream, and the construction of the boat ramp (completed in 1962). One suggestion for future work would be to design a program similar to that used by Noda (1977), substituting observed winds for the randomly generated winds used in his program, and to consider the northern end of the beach.

Anticipating Future Shoreline Migration

As discussed previously, available evidence suggests that accretion has been the dominant trend on Kailua Beach. The northern end of the beach, transects 3 through 6, shows accretion of about 18 m in the 30 years of record. The mid-section, transects 7, 8, and 9, accreted about 12 m, the portion just north of the beach park has accreted about 18 m, and the southern end of the beach has varied in a manner not easily predicted, but still showing an accretionary trend. The transects north of the park show average accretion of 0.4-0.7 m/year. The erratic history of shoreline migration near Kailua Beach Park may be related to construction of a boat ramp there in 1962.

The increasingly easterly Pacific tradewinds are associated with accretion along the length of Kailua Beach. Because the observed change in the prevailing wind direction has occurred within this century, the continuation of this trend cannot be predicted with certainty. Study of changes in the wind direction may help, however, to anticipate shoreline changes in the Kailua area through understanding the association of wind and shoreline migration shown above. Although accretion along the length of Kailua beach appears to be a long-term pattern, the evidence for erosional periods of months and years is clear. This study does not suggest that the beach will never erode back as far as its position in 1949; it does suggest that if the prevailing wind continues to blow from east, the overall trend probably will be accretionary.

V. SEA-LEVEL RISE AND GROUNDWATER CHANGE

Almost all of Oahu's drinking water is drawn from the freshwater lens underlying its surface. Rainwater percolates through Oahu's highly permeable basalts and either floats on the denser salt water below or is trapped by dikes. Lens geometry and hence pumping strategy may be affected by a change in sea level. While sea-level rise of only a few meters would be unlikely to affect Oahu's fresh water supplies, it could dramatically increase flooding problems. It could also impact the freshwater lenses of smaller islands which have different geology and less topographic relief, as is discussed in Chapter VI.

Principles of insular groundwater hydrology are discussed below, with consideration given to the problems of saltwater intrusion. The water underlying Kailua is brackish. A sea-level rise would not affect the town's drinking water supply. The pertinent hydrologic problem for Kailua, which is related to the height of the water table, is the persistent flooding in the Coconut Grove subdivision. The remainder of the chapter will discuss the flooding problems of Coconut Grove. Historic flooding and previous analyses of the problem are explored, with a goal of understanding how the water table and associated environmental factors might be affected by a sea-level rise.

Previous Work

Groundwater Hydrology

In continental coastal aquifers, the problem of saltwater intrusion is generally confined to a saltwater wedge. In an insular system, however, the boundary touches the entire lower surface of the lens, increasing the surface area vulnerable to intrusion. Saltwater intrusion is affected by a number of factors including recharge and discharge (including flow and pumping) rates and tides.

Several applications of the principles of groundwater hydrology to the Hawaiian islands are discussed in a review article by Lau (1967). The boundary between fresh and salt water is not sharp but gradational. Saltiness of water is usually determined by the abundance of chloride ions: potable water is defined as having 250 mg/l or less of chloride; ocean water has an average chloride content of 19,000 mg/l. The transition zone represents the gradation between these chloride concentrations. One goal of groundwater modeling has been to determine the effects of changing boundary conditions on the transition zone and resulting intrusion of salt into the freshwater lens (e.g. Sa da Costa and Wilson, 1979).

The lens responds to discharge (pumping and leakage) by losing head. Hydraulic head is the sum of the pressure on a free water surface and the distance from an arbitrary datum. In Hawaiian groundwater lens research, head is usually given as the height of the unconfined water table surface above sea level. When excessive discharge lowers head, the freshwater storage capacity of the lens is correspondingly lowered.

The basic model for understanding insular groundwater hydrology is the Ghyben-Herzburg relation, which states simply that the shape of a freshwater lens floating on saltwater is governed by the difference in the densities of the two fluids; with a typical freshwater density of 1.000 g/cc and saltwater density of 1.025 g/cc (at a chloride concentration of 19,000 mg/l), depth to the saltwater boundary is 40 m for each meter of freshwater head above sea level (Figure 18). Use of this relationship requires three simplifying assumptions: (1) the system is in a state of static equilibrium, (2) the geologic parameters are homogeneous and isotropic, and (3) there is a sharp fresh-saltwater boundary. The Ghyben-Herzberg relation can provide, however, a good

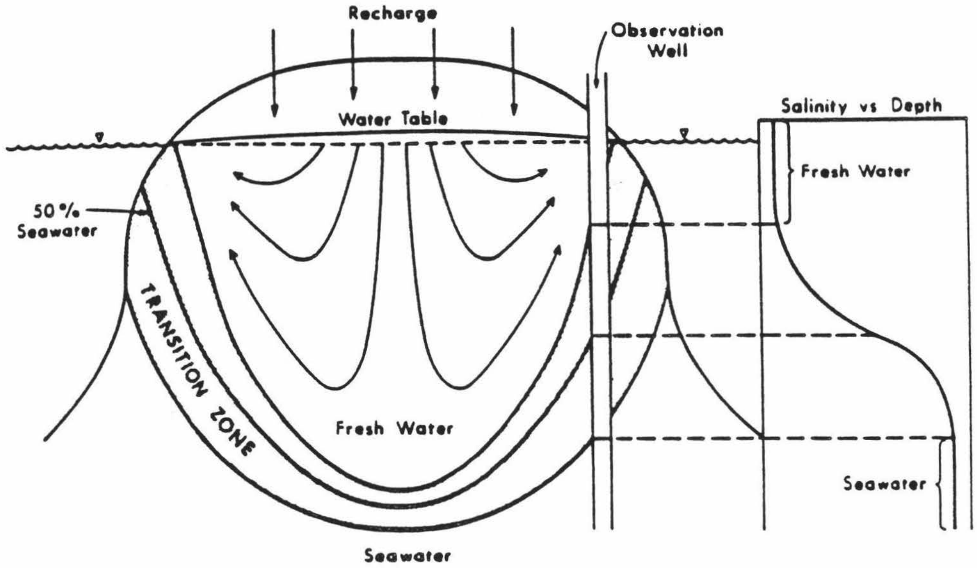

Figure 18. The Ghyben-Herzberg relationship. From Anthony and Peterson (1987).

first approximation of depth from the water table to saltwater. This approach will be used to make a simple model of sea level change effects on the freshwater lens at Laura, on Majuro Atoll in the Marshall Islands (Chapter VI). More data acquisition and use of more sophisticated modeling techniques are required for coping with more complicated and realistic conditions. Increasingly complex approaches may account for the presence of a transition zone, variable geologic parameters, tidal fluctuations, or changing rainfall. One such model has been used by Griggs et al. (1987) at the University of Hawaii to study the development of a freshwater lens for the Laura area on Majuro Atoll in the Marshall Islands.

Existing case studies predicting the effects of projected sea-level rise have addressed the problem of salt water intrusion only briefly. In their study of Charleston, Kana et al. (1984) used the Ghyben-Herzberg relationship to estimate that the interface of fresh to saltwater may move inland about 60 m from the new shoreline. They emphasized that alterations in boundary conditions brought about by excessive pumping are likely to cause saltwater intrusion problems long before sea-level rise does.

Kailua has never obtained drinking water from the freshwater lens under the town. The Kailua golf course once had a well to water the greens. This water, always brackish, became too salty even for this purpose and has not been used since the 1950's. Chloride records (Swain, 1973; Miyamoto et al., 1986) indicate that this high salt content is prevalent throughout the area. Given this information, an attempt to model the effects of sea-level rise for the purpose of estimating impact on the drinking water supply would be irrelevant. The problem of sea-level rise effects on drinking water systems will be discussed in Chapter VI. Flooding would be increased by a sea-level rise and the associated rise in the water table. The history of Coconut Grove in Kailua suggests how severe those effects may be.

Flooding History of Coconut Grove

The Coconut Grove subdivision was developed as a coconut plantation about the turn of the century and remained as such until housing development began in the 1920s. As an outwash from the Kawainui swamp, the area experienced frequent floods. The Oneawa channel was designed to protect against the 100 year flood, which is defined as having a 1% probability of occurring in any given year (US Army Corps of Engineers, 1947). The project was designed in the early 1940's and then put aside during World War II. In 1948, another project evaluation was completed, and construction was recommended, but no money was appropriated until after the flooding of 1951.

The "pilot project" for the canal was completed after the 1951 flood, during which some 250 homes were evacuated and nearly $100,000 worth of damage was done. Flooding occurred again in 1963 and 1965 and the levee was completed in late 1966. In late 1968 and early 1969, Coconut Grove was flooded again, with standing water up to 20 cm deep in many locations.

Swain and Huxel (1971) analyzed why the Coconut Grove area continued to flood even after completion of the flood control project and as a response to rains which were not exceptionally intense. The report concluded that the flood waters were not overflow from the swamp, and were not significantly affected by swamp or tide levels, but were rather the result of low topography and local geology. The land surface slopes downward from a maximum elevation of several meters, directly behind the beach dunes, to a low of about 1 m above sea level elevation near the swamp. The water table rises from sea level at the beach to within 50 cm of the surface near the swamp. Boreholes from along

Oneawa Street show the soil to be sandy down to at least sea level except in two holes drilled in the locations where flooding was most persistent. At those locations, the sandy soil is covered by 50-100 cm of silt. This type of geology has two ramifications. First, the sandy soil in most of Kailua allows capillary action to keep it nearly saturated, reducing its capacity to accept more water. Secondly, the silt has low permeability relative to sand, increasing the potential for flooding.

Data and Methods

Swain and Huxel (1971) presented a cross section of the water table under Kailua showing the height of the water table as measured from boreholes on four occasions. Figure 19 illustrates the convergence of the ground and the water table near the swamp. Maps of water table elevation and topography given by Swain and Huxel were combined for this study to give a map of depth to the water table from data collected on October 27, 1969 (see Figure 20). The map in Figure 20 was redrawn to show the depth to the water table in Kailua given a 1 m sea-level rise (see Figure 21).

The results in Figure 21 assume that the Ghyben-Herzburg lens rises as sea level does and continues to

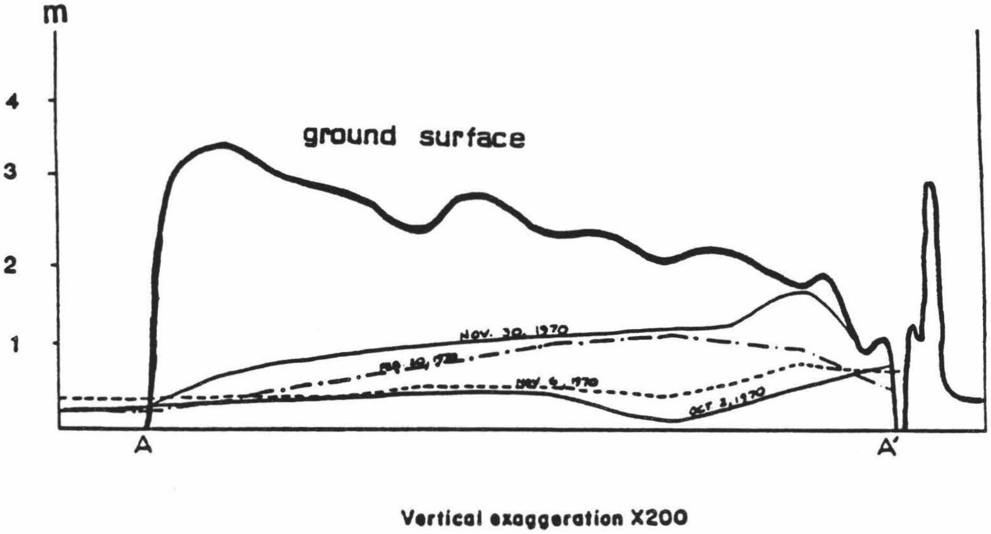

Figure 19. Cross section of Kailua including Coconut Grove, showing depth to the water table on four occasions (Swain and Huxel, 1971).

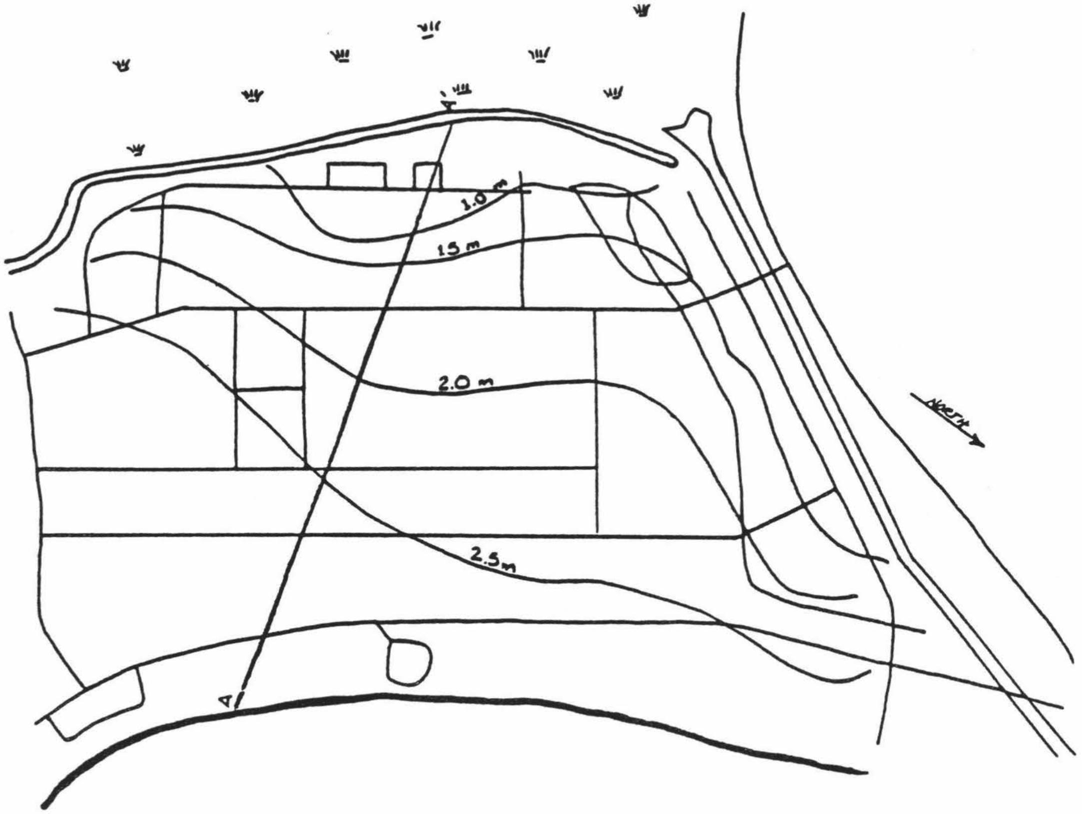

Figure 20. Depth to water table in Coconut Grove. Contours show depth to the water table on October 27, 1969. Compiled with topography and of water table elevation data from Swain and Huxel (1971).

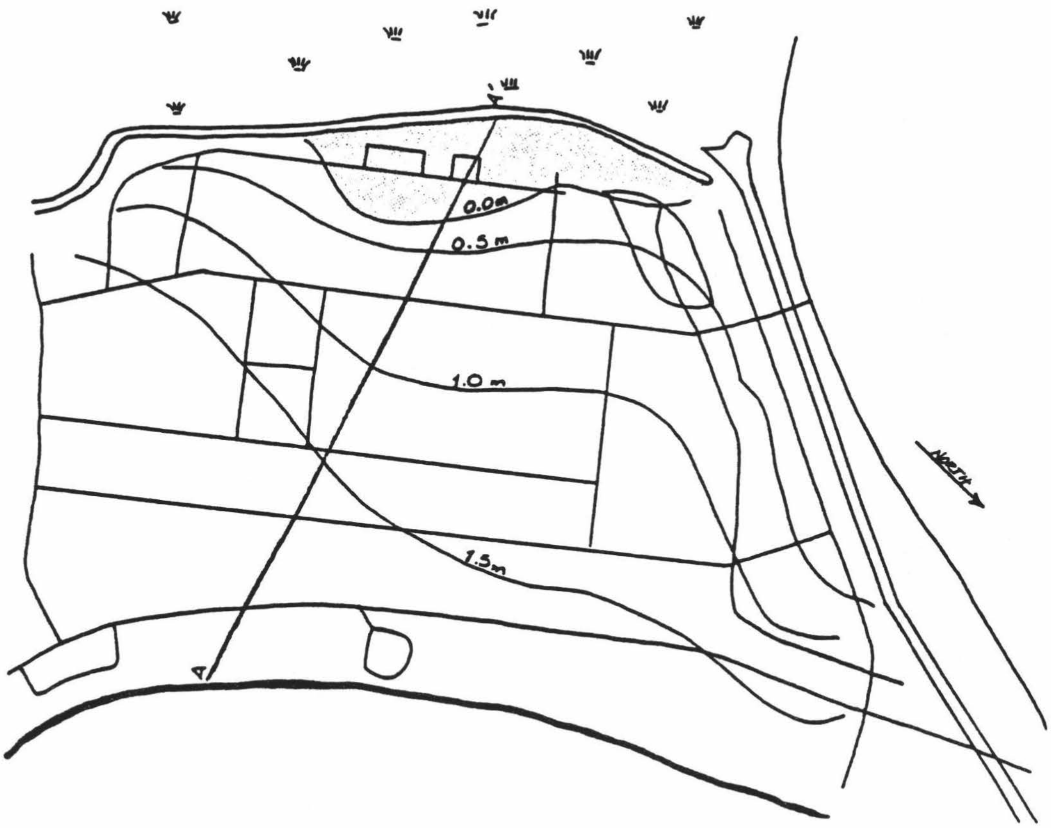

Figure 21. Depth to water table in Coconut Grove assuming a 1 m rise in sea level. Shading indicates areas that might be permanently flooded. Base topographic and water table elevation data from Swain and Huxel (1971).

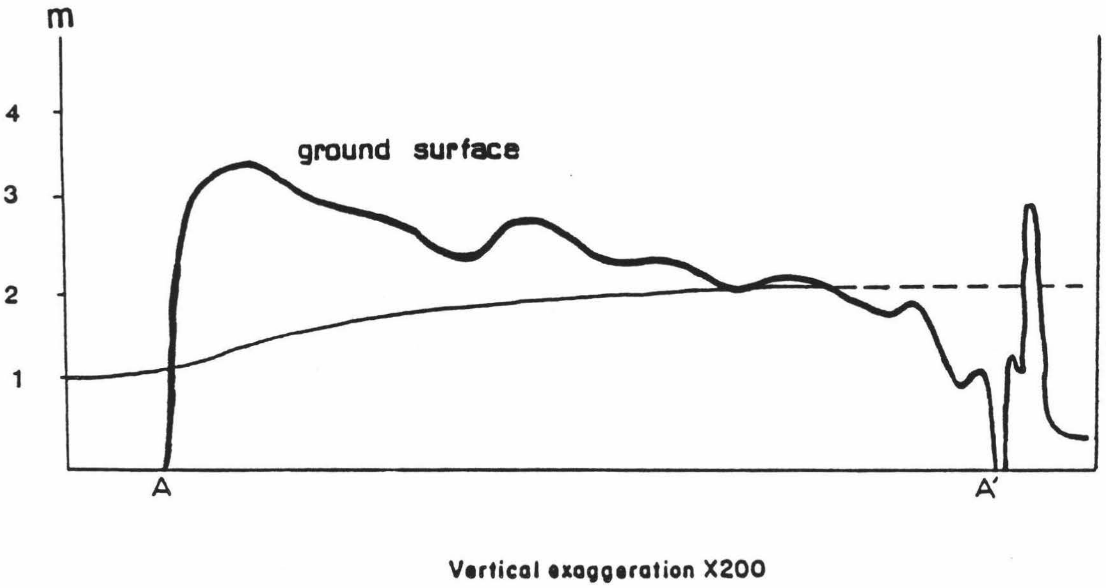

Figure 22. Cross section of Kailua, showing depth to the water table with conditions similar to those of November, 1969. (Modified from Swain and Huxel, 1971).

keep its size and configuration. This case differs from that of Majuro (discussed in Chapter VI), where the land area is assumed to be substantially reduced by a rise in sea level. In Kailua, where the beach width may actually increase (as discussed in the previous chapter), despite the erosive effects of sea-level rise, the groundwater lens geometry is not expected to be substantially affected.

Figure 19 showed the profile of the water table under Kailua as measured in boreholes on four dates. Figure 22 shows the effect of a 1 m sea-level rise on flooding conditions for a rainfall similar to that of late 1969.

Results and Discussion

Several factors interact to ensure that the flooding problem in Kailua would worsen with a rise in sea level. The problem of low topography and high water table in Coconut Grove would be exacerbated, as was shown in Figure 20. This would lead to increases in flooding frequency and intensity. Even low tides would be higher than the highest tides experienced today. Higher tides could inhibit drainage of overflow from the swamp into the ocean near Kailua. More construction would intensify the problem by paving over potential infiltration area and encouraging runoff.

One recent event highlights some of the problems Kailua might face more frequently if confronted with an average sea level 1 m higher than present. On New Year's morning, 1988, a heavy rain combined with a high tide and a tangle of vegetation, which impeded outflow from a swamp into the drainage canal, caused water to breach a 3.2 m levee and flooded the Coconut Grove. Water rose to a meter or more in 300 to 400 houses. The Army Corps of Engineers (Honolulu Advertiser, 1988) reported that flooding was caused by a "Triple Play" of heavy rains, a drainage channel clogged with vegetation, and an exceptionally high tide .

There was a high tide of 70 cm at Honolulu at 02:57 a.m. New Year's morning (NOAA Tide Officer, oral communication). According to the co-tidal charts for the Hawaiian islands, it should have reached its peak in Kailua one and a half hours earlier, or at about 1:30 (Laevastu et al., 1964). Residents nearest the breached levee have stated that they first noticed the flooding shortly after midnight, and that the flood waters reached a peak and began to recede after 3:30 am. Examination of the 1987 tidal chart (Dillingham, 1986) indicates that the tide stood above 60 cm only about 5% of the time last year. The month of December, however, had seventeen such tides. The high tide of January 1 probably did help to prevent the water from draining, but was not particularly unusual for the winter months. The stormy winter months are when an engineer might have anticipated potentially flood-inducing rains would occur.

The rain of New Year's Eve was unusually heavy. The autographic rain gage at Maunawili recorded 40 cm of rain between 6:00 and 10:00 pm before it overflowed, and the Kailua gage recorded a peak rainfall of 2.5 cm between 12:00 and 1:00 am. The island had been pelted with two rainstorms earlier that month, which had already made that December the wettest on record. On December 11th and 12th, some 20.5 cm of rain fell on Honolulu. An inspection of Coconut Grove carried out for this study, and in particular of the areas of persistent flooding described by Swain and Huxel (1971), on December 13, 1987 revealed no standing water except in a playing field on the swamp side of the subdivision. Given the proximity of the water table to the surface in the area, the previous rains and subsequent saturation of the soil probably played a key role in the extent of the flooding of New Year's morning. Had the soil been drier, the overflow from the swamp would have infiltrated the soil more quickly than it did. As it was, the soil saturation and high tide may have helped to lessen the groundwater gradient flowing to the ocean. Swain and Huxel also pointed out that the subdivision drains toward the swamp as well as toward the ocean. Flooding of the swamp would naturally make that outlet unavailable, and the subsurface geology would be the limiting factor.

A visual inspection of the levee in mid-January, 1988, conducted for this study revealed that the canal on the eastern side of the levee, which drains into Kaelepulu Stream and out to the ocean by Kailua Beach Park, was clear. The swamp side of the levee, however, which drains into Kawainui Stream, had no channel for runoff and the vegetation on that side had grown so high that the levee stood only about 1.5 m above the vegetation. Three dredges were clearing the debris composed of decaying swamp grass and silt, which was about 1.5 m thick and blanketing the canal lining of coral rock. The design specification of the levee was a 3 m elevation: it is not surprising that the levee, now only about 1.5 m high, was easily breached by the flood waters. Given the disastrous events of New Year's Day, 1988, it seems certain that plans for a permanent channel on the swamp side of Kaelepulu Stream will ensue.

Given the combination of factors contributing to the flood, a sea-level rise of one meter would intensify the flooding problems in Kailua. A channel is being cleared to assist drainage into Oneawa Channel, and the channel may be dredged regularly, making a future breach of the levee less likely. Tides averaging a meter higher, coupled with a higher water table, will increase the problems discussed by Swain and Huxel (1971). Changing precipitation patterns associated with climate change could mean increased rainfall and an associated increase in flooding.

Given the combination of drainage problems associated with a higher water table in Kailua and the possibility of increased precipitation, the area within the 500-year flood hazard zone can be anticipated to fall within a 100-year flood zone with a 1 m rise in sea level. A rise in the water table may also engender a variety of other engineering problems. One of these might result from increased near-surface soil saturation. A water table closer to the surface is likely to mean wetter soils. Soil moisture is an important consideration in soil stability. The same is true for cesspools and waste injection wells, which even at current sea level are often affected by heavy rains (Swain and Huxel, 1971).

VI. IMPLICATIONS OF SEA-LEVEL RISE FOR ATOLLS

The previous chapters have discussed implications of climate change and especially sea-level rise for a coastal community on a relatively wealthy, well-developed Pacific island. A 1 m sea-level rise would have a negligible effect on the drinking water supply of Kailua. The effects would be far more dramatic for a typical low-lying Pacific atoll. This chapter discusses Laura, on Majuro Atoll in the Marshall Islands, and presents a model for change in its Ghyben-Herzberg lens, because of sea-level rise.

Previous Work

Coral atolls are more susceptible to climatic changes, including sea-level rise, than volcanic islands, such as Oahu, because of their limited extent and low relief topography, Freshwater lenses in coral atolls lenses are influenced by the factors discussed in Chapter VI: rates of recharge, discharge, and extent of tidal incursion.

Precipitation triggers the formation of a freshwater lens. Adequate recharge is necessary to maintain it. If insufficient rain falls on an island, the lens cannot be recharged. Groundwater discharge is governed primarily by local flow systems and water use. For many Pacific islanders, groundwater use is secondary to individual catchment systems for drinking and bathing; water is collected on rooftops and in cisterns.

Local geology and island shape and size also affect lens development. The rock must be sufficiently permeable to allow recharge and impermeable enough to prohibit intrusion of saltwater during tidal fluctuations. The coralline limestone common to low-lying atolls suits this purpose well, but island width sufficient to form a buffer against salt water intrusion is necessary.

Fluctuations in hydraulic head caused by seasonal variation in discharge or recharge may threaten long-term lens stability. Discharge by pumping is greatest during the months when rainfall is at a minimum. Lens response to tidal fluctuations is controlled by both island size and rock permeability, but the relationship is complex and not directly proportional (Cox, 1951).

Dependent on the above factors, the freshwater lens of a coral atoll may indeed be fragile. Rising sea level and subsequent rise in water table may affect not only drinking water supplies but also brackish water reserves upon which the survival of vegetation depends. In a short article on atoll hydrology, Arnow (1956) notes that he cannot identify a single permanently inhabited atoll without a population of coconut palms. According to Cox (1951), taro and breadfruit tree growth is directly affected by groundwater salinity on Arno Atoll. The effects on vegetation of increased salinity of the lens transition zone may be more important to the lives of islanders than the loss of fresh drinking water.

How might climate change and sea-level rise affect low relief coral atolls? Recharge rate may change as rainfall patterns vary. Because climate is predicted to change least near the equator, it seems unlikely that recharge rates would be appreciably lessened. Similarly, because predicted climate change will probably not entail less rainfall in the lower latitudes, pumping prompted by dry weather would remain stable or lessen. Increasing population pressure may, however, increase pumping demands. While the range of tidal fluctuations may not change, island size may change dramatically. As an example, some possible effects of sea-level rise on the Laura section of Majuro atoll in the Marshall Islands are discussed below. An increase in mean sea level of 1 m would not only impact the groundwater there, but would also regularly put much of the island under water, making it barren for most plants and uninhabitable for humans.

Data and Methods

The Laura area (see Figure 23) on the western end of Majuro atoll in the Marshall Islands is small (total land area is about 1.8 km^2), has a total relief of about three meters, and supports a community of about 800 people. Most drinking water comes from individual catchment systems and a few dug wells. The Marshallese are currently attempting to develop their groundwater resources. Ongoing research at the University of Hawaii has focused on gaging the supply of freshwater (Anthony and Peterson, 1987) and predicting effects of various pumping strategies (Griggs, et al., 1987).

The freshwater lens lies within several formations. The Upper Sediment lithofacies is comprised of moderately well-sorted, unconsolidated coral fragments forming dunes at both the eastern and western shores. This unit is underlain by the Upper Limestone lithofacies on the western shore. The Lower Sediment lithofacies is comprised of poorly sorted unlithified wackestone (Anthony and Peterson, 1987). The development of the freshwater lens under Laura's surface has been substantially affected by Quaternary sea level

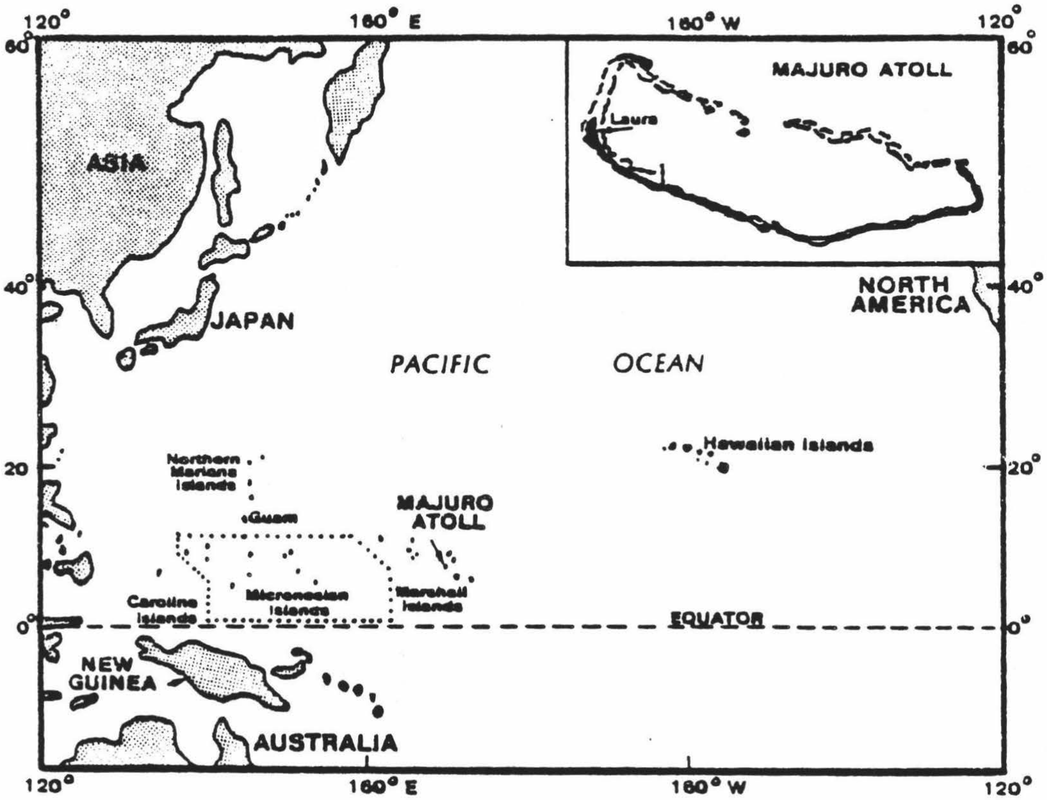

Figure 23. Location of Laura, on Majuro Atoll in the Marshall Islands (after Anthony and Peterson, 1987).

fluctuations with subsequent controls on limestone diagenesis. An average value for rock porosity of 20% for the Upper Sediment and Upper Limestone is assumed (Griggs, et al., 1987).

Figure 24a shows a cross section of the Ghyben-Herzberg freshwater lens under Laura (Anthony and Peterson, 1987). Because of local geology the freshwater lens is asymmetrical, but a symmetric lens, delineated by dashed lines in Figure 24b, was used for the Ghyben-Herzberg model. For a 1 m thick cross section of unit thickness, the decrease in island area responding to a 1 m sea-level rise was computed as follows.

Starting with an initial island width of 1130 m, loss of 150 m from each shore was estimated as a response to sea-level rise of 1 m by use of the Bruun rule (see Figure 5). The maximum height of the lens above sea level of 60 cm before sea-level rise (Griggs, oral communication, 1987) was assumed to decrease in a linear fashion from the center of the atoll toward the sea. The lens height was assumed to be directly proportional to distance from the sea. The original area is

$$(\text{base} \times \text{height}/2) \times \text{depth below SL}$$
$$= (1130 \text{ m} \times 0.6 \text{ m}) \times 41/2 = 14{,}000 \text{ m}^2.$$

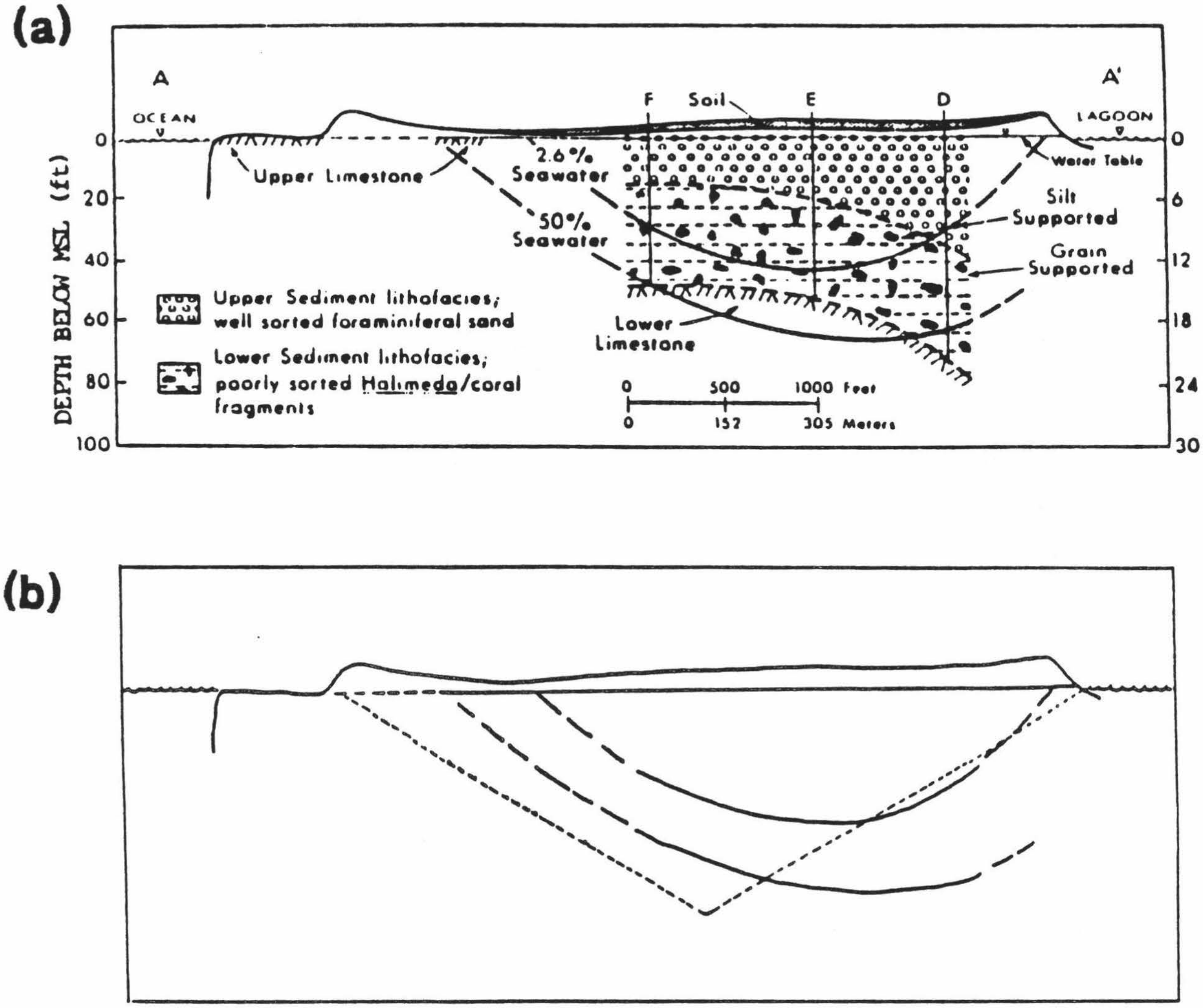

Figure 24. (a) Cross section of Laura, showing the Ghyben-Herzberg lens (Anthony and Peterson, 1987) and (b) approximation used for this study.

Should sea-level rise 1 m, the new area would be:

$$(830 \text{ m} \times 0.45 \text{ m}) \times 41/2 = 7660 \text{ m}^2,$$

a loss of almost half of the available area.

Another way of looking at the problem is to estimate changes in the volume storage capacity of the lens with sea-level rise. The area of the lens intersecting sea level cannot be easily approximated by a circle or an ellipse owing to the particular shape of Laura, which looks triangular in plan view. It was therefore deemed more appropriate to approximate the land area of Laura as an isosceles triangle, as shown in Figure 25. A check with a small grid indicates that this approximation covers an area equal to the actual surface. The volume of the freshwater lens above sea level was approximated as a pyramid with a height of 60 cm. The base of this pyramid is the surface area of Laura. Thus the volume of water in the freshwater lens above sea level is given by:

volume of a pyramid=(area of base x height)/3
with a base=1.8 km^2,
height=60 cm, and
porosity=20%, the volume is

$$(1.8 \times 10^6 \text{ m}^2 \times .60 \text{ m} \times 0.2)/3=720{,}000 \text{ m}^3.$$

Another pyramid was created to model the larger portion of the lens below sea level. Using the Ghyben-Herzberg relationship, the height of this inverted pyramid is

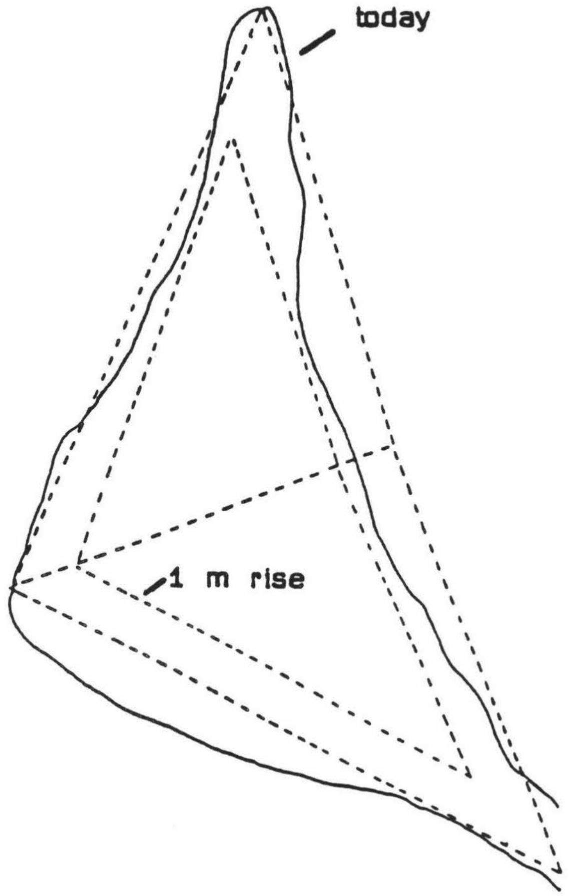

Figure 25. Plan view of Laura showing approximation of area at present and after a postulated sea level rise of 1m.

calculated to be 60 cm X 40 = 2400 cm. Similarly, the volume of this inverted pyramid is 40 times that of the first. This pyramidal approximation accords with the pinching out of the lens as the distance of head above sea level and atoll width simultaneously decrease near the northern and southern edges of Laura.

Results and Discussion

Loss of land from inundation is estimated by assuming that the dunes will migrate to preserve the nearshore profile as predicted by the Bruun Rule. Should sea-level rise one meter, the shoreline would recede 150 m inland on each coast. More than one quarter (about 28%) of Laura's surface area would be lost. Assuming that other geologic parameters are unchanged, and that freshwater head is a function of lens width, maximum head would be reduced from about 60 cm to about 45 cm, and lens depth would be reduced from 2400 cm to 1900 cm. Loss of 28% of the base and an equal percentage of head means that the volume of water is given by

$$
\begin{aligned}
\text{Volume} &= [(\text{base} \times \text{height})/2] \times \text{porosity} \\
&= [(.72 \times 1.8\text{km}^2) \times (.72 \times 60\text{ cm}) \times .2]/3 \\
&= 373{,}000\text{ m}^3
\end{aligned}
$$

Such a loss of surface area and lens depth would be reflected in a diminishment in volume of approximately 50% of the freshwater lens.

Two caveats accompany the simple model given here. First, geology is assumed to be homogeneous throughout the atoll. This is not the case, as is shown in Figure 24, and the freshwater lens may not exist at all on the narrow end of the island. Secondly, this study models the depth to the isochlor representing 50% of salt water content. Water must have less than 2.5% of saltwater content to be potable. Griggs et al. (1987) are using a complex density dependent groundwater modeling program to model changes in the transition zone considering the large range of local tides and geologic structure. Future work may compare results of the approach used here with their more complicated and computationally expensive technique applied to the problem of modeling effects of sea-level rise.

The freshwater lens at Laura will certainly be threatened by sea-level rise; so too will more than a quarter of the land area. Storm damage is also likely to increase. The combination of these effects may make living on Majuro and similar atolls difficult or impossible.

VII. CONCLUSIONS

Although sea-level rise, owing to the "greenhouse effect" and associated climate change, cannot be predicted with confidence now, it is not too early to discuss some possible implications of such a rise. Both coastal erosion and increased flooding would be expected with a sea-level rise of 1 m.

This investigation has expanded on the work of previous studies assessing effects of sea-level rise by investigating meteorologic controls on coastal erosion. Extension of the available wind record length and comparison with historic shoreline change for Kailua Hawaii, has set the stage for anticipating effects of the host of climatic changes which may accompany sea level change.

Examination of tradewinds from a 4° by 8° block in the Pacific Ocean northeast of Oahu since 1900 has failed to confirm a cyclic shift of prevailing wind direction as predicted by Wentworth (1949), but does indicate a tendency for more easterly average wind azimuths. Evidence of shoreline changes before aerial photographs are available is sparse, but beach surveys suggest a long-term history of accretion at Kailua Beach. It is not possible to find a direct correspondence between prevailing tradewinds and long-term beach erosion for the entire beach; the northerly and middle sections, however, show accretion accompanying the more easterly winds. A longer record of beach erosion and wind records would facilitate more precise analysis. The long-term trend of accretion at Kailua Beach may continue even with a 1 m sea-level rise.

The water supply of Kailua would not be endangered by a sea-level rise of 1 m. Flooding, now encouraged by a water table close to the ground surface, would increase. In a smaller, low relief atoll such as Majuro, Marshall Islands,groundwater supplies would be threatened, and a significant percentage of surface area of the atoll would be lost.

While the concept of eustatic sea-level rise may be interesting, regional planners need to prepare for local rather than global changes. Physical effects of sea level change, such as beach erosion, storm damage, and increased groundwater salinity, and resulting socio-economic impacts, will differ between locations and will depend as much upon the local environment as upon global change.

This study has some implications of potential sea-level rise for Kailua, Hawaii and for one Pacific atoll. An understanding of local geologic and hydrologic processes operating in any particular area is a prerequisite for anticipating changes resulting from sea-level rise, whether or not they are related to a greenhouse effect.

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