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Scientific Studies and History of the Ala Wai Canal, an Artificial Tropical Estuary in Honolulu[1]

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ABSTRACT: Fifteen studies of the Ala Wai Canal, O'ahu, Hawai'i, initially were spawned by two federally funded summer research programs designed to introduce high-school students from around the state of Hawai'i to the challenges, practicalities, and excitement of work in the natural sciences and engineering. This special issue reports on the end products of 10 of those studies. The canal is an artificial estuary created in the 1920s to drain coastal wetlands and borders the present tourist mecca of Waikīkī. Today, it is polluted and hypereutrophic, and it receives high levels of nutrients that sustain levels of primary production that rival all but a few of the world's water bodies. Acting as a sediment trap for the combined drainage of the Mānoa and Pālolo Streams, the midportion of the canal contains two large sedimentary sills that restrict seawater exchange. This restricted flow and the high rain rate of organic matter result in severe oxygen depletion behind the sill. The canal's small reservoir size, variably oxygenated water column and sediments, single oceanic outlet, and receipt of natural freshwater drainage—within the confines of a rapidly developed major metropolitan area—combine to make it an excellent aquatic laboratory for the study of present and historical water exchange characteristics; phytoplankton, zooplankton, and benthic foraminifer behavior; biogeochemical responses of shallow, tropical water masses to hypereutrophication; and historical records of heavy metals, radionuclides, and other pollutants over the past 60 yr. We believe this special issue will attract the attention of a variety of scientists and academicians, as well as administrators and others interested in the environmental quality of Hawai'i.

THE ALA WAI CANAL is a narrow man-made tropical estuary that extends 3.2 km from the ocean along the back perimeter of the community of Waikīkī (Figures 1 and 2). It was constructed between the years of 1921 and ca. 1927–1928 to drain wetlands extending 1–2 km behind the Waikīkī shoreline. These wetlands previously were crossed and fed by two major streams that drained Mānoa and Pālolo Valleys and contained numerous scattered duck ponds and fishponds, taro patches, and rice fields (Figure 3). The dredging was contracted to the Hawaiian Dredging Company and proceeded landward from the present mouth of the canal back toward Diamond Head Crater (Figure 4). The canal walls were subsequently lined with quarried blocks of basalt. The Mānoa and Pālolo Streams were diverted to form a single drainage canal constructed during the building of the main Ala Wai Canal (Figure 1; Acson 1983). To clear the Ala Moana area for

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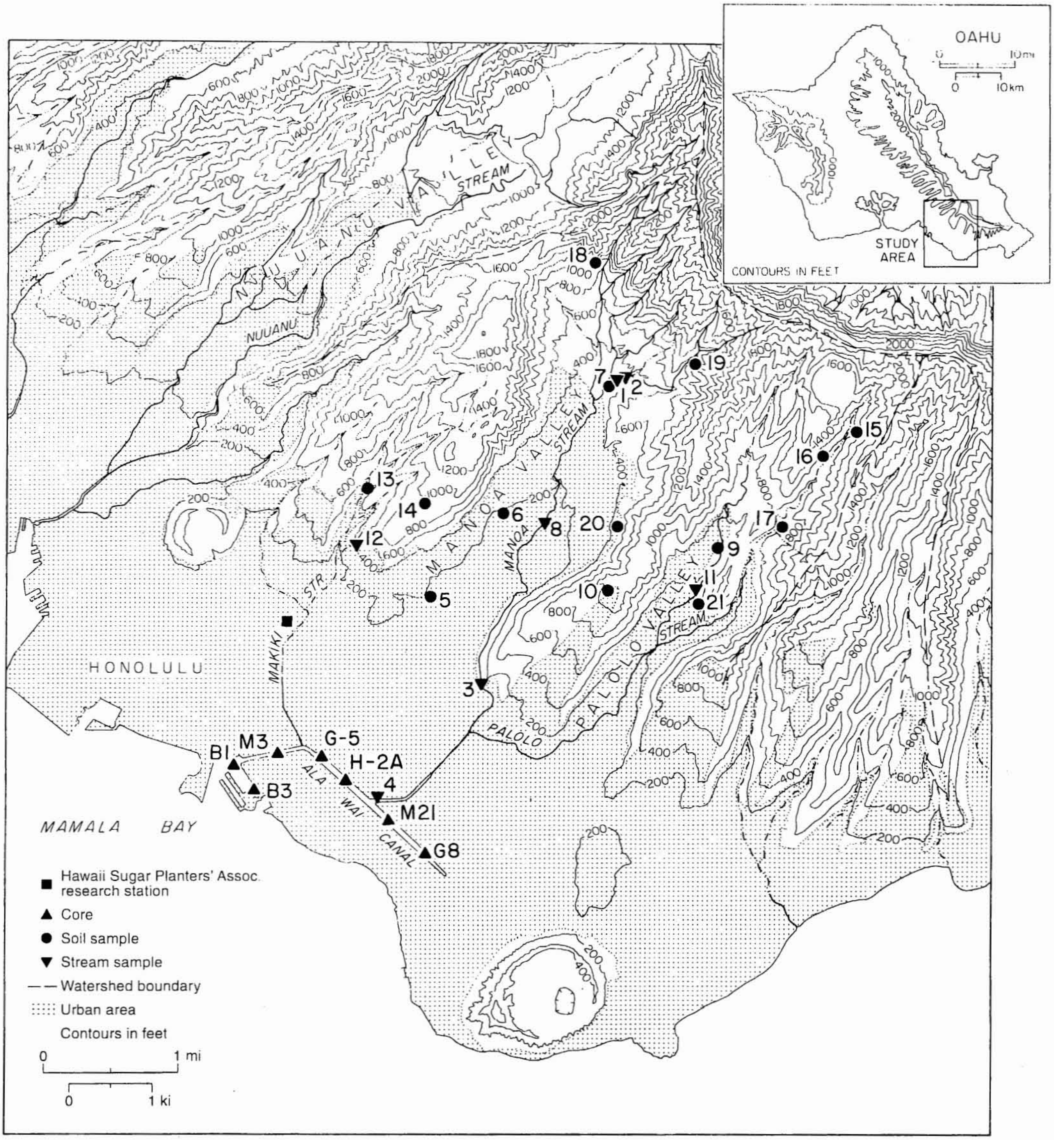

FIGURE 1. Topographic map of the Honolulu area showing the location of the Ala Wai Canal and its surrounding watersheds. Locations of Ala Wai cores and positions of soil and stream samples described in this issue are also shown. Contour interval, 200 ft.

commercial development, the main stream draining Makiki Valley was also diverted into the Ala Wai Canal (Figure 1). These dredging and draining activities thus transformed ca. 2.6 km^2 (645 acres) of agricultural and aquacultural lands into areas suitable for commercial and residential development (Nakamura 1979, Hibbard and Franzen 1994). Dredge spoils produced in creating the canal were used together with coral dredged from offshore to raise and grade the areas around the canal, including the present resort area of Waikīkī (Nakamura 1979, Lum and Cox 1991; Figures 4*C* and 5). Dredge

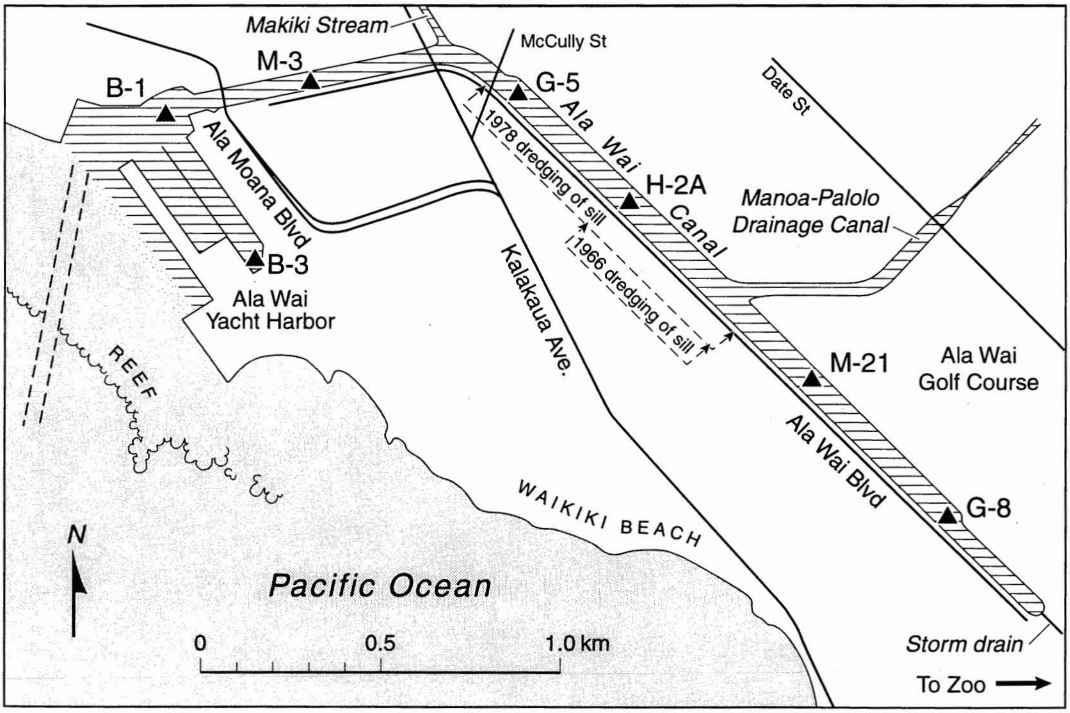

FIGURE 2. Detail of sediment core locations (solid triangles) in the Ala Wai Canal discussed in this issue. Completion of the canal was in 1927–1928. Since then, because of the persistent formation of a sedimentary sill at the mouth of the Mānoa-Pālolo drainage, two segments of the canal were dredged: in 1966 and 1978. The positions of these dredged segments are shown. Today, the canal contains another large sill at the mouth of the Mānoa-Pālolo Stream, and the bottom waters behind it (to the southeast) are dysaerobic to anoxic. Normally oxygenated seawater enters the canal through the Ala Wai Yacht Harbor.

spoils from the canal contained mud and coral; the latter is likely from upper Pleistocene reef carbonates that floor much of Honolulu and the ʻEwa Plain (e.g., Stearns 1974). Fifty meters wide near its mouth, the canal extends inland from the ocean for 0.75 km, makes a 45° bend, and ends 2.35 km after the bend, forming a landlocked back end (Figure 2). The longer, landlocked section receives fresh water discharge from the Mānoa-Pālolo drainage system (Figures 5*B* and 6).

Today, a small-boat harbor exists at the entrance to the canal (Figures 2 and 6). The canal contains four distinct features: a seaward-dipping channel extending for about 1 km inland from the mouth, a small basin having a maximum depth of 3.5 m between the Kalākaua Street and McCully Street bridges, a sediment-silled shoal region at the mouth of the Mānoa-Pālolo Stream, and a back basin inland of the sill (Figures 7 and 8). The canal generally displays the characteristics of a salt wedge estuary and is salinity and density stratified with a brackish surface water layer ca. 1 m thick overlying seawater (Figure 7; Gonzalez 1971, Miller 1975, Laws et al. 1993). Brackish surface waters flow out of the canal, entraining water from below and causing compensating flow into the canal at depth (Gonzalez 1971). Tidal flow in the deep layer decreases the flow on the ebb and intensifies it on the flood. The sill at the mouth of the Mānoa-Pālolo drainage currently becomes exposed at extreme low tide, although seawater still flows around it along its southwestern side. Waters in the back basin behind the sill are stratified. Since its

FIGURE 3. Waikīkī's first major hotel, the Moana, stands out in the foreground with agricultural lands behind in 1920, the year before the beginning of the Ala Wai Canal's construction. Photograph courtesy of Bishop Museum Archives.

creation, the canal has become a polluted, highly eutrophic water body. State Department of Health regulatory signs lining the canal warn that it is unsafe to swim there, and canoe paddlers who use the canal regularly complain of boils and staph infections (e.g., Pai 1994). Based on Department of Health records, Ala Wai Canal waters persistently have violated median total fecal coliform bacterial counts (Bills 1976). To increase ventilation and combat pollution and siltation in the channel, the sill was removed by dredging in 1966 and 1978 (Gonzalez 1971, Department of Land and Natural Resources, State of Hawai'i 1990, Lum and Cox 1991, Laws et al. 1993). The 1966 dredging removed a length of about 0.5 km of the sill, and the 1978 dredging removed about 1.0 km (Figures 2 and 8). The section seaward of the McCully Street bridge and the back basin of the canal (which has been dysaerobic to anoxic at least periodically) were not dredged. It is noteworthy that the spoils of the 1978 dredging emitted strong hydrogen sulfide vapors, indicating their anoxicity (e.g., Harada 1967, Lum and Cox 1991); local residents continue to complain about this odor, particularly at low tide.

The Ala Wai Canal is of scientific interest for a variety of reasons. It has proven to be particularly convenient to study because of its close location to the University of Hawai'i at Mānoa. Like lakes, and in contrast to oceans, its small reservoir size makes the biogeochemistry of the canal respond rapidly to environmental perturbations that affect it. The papers in this issue discuss such effects as they have occurred on time scales of

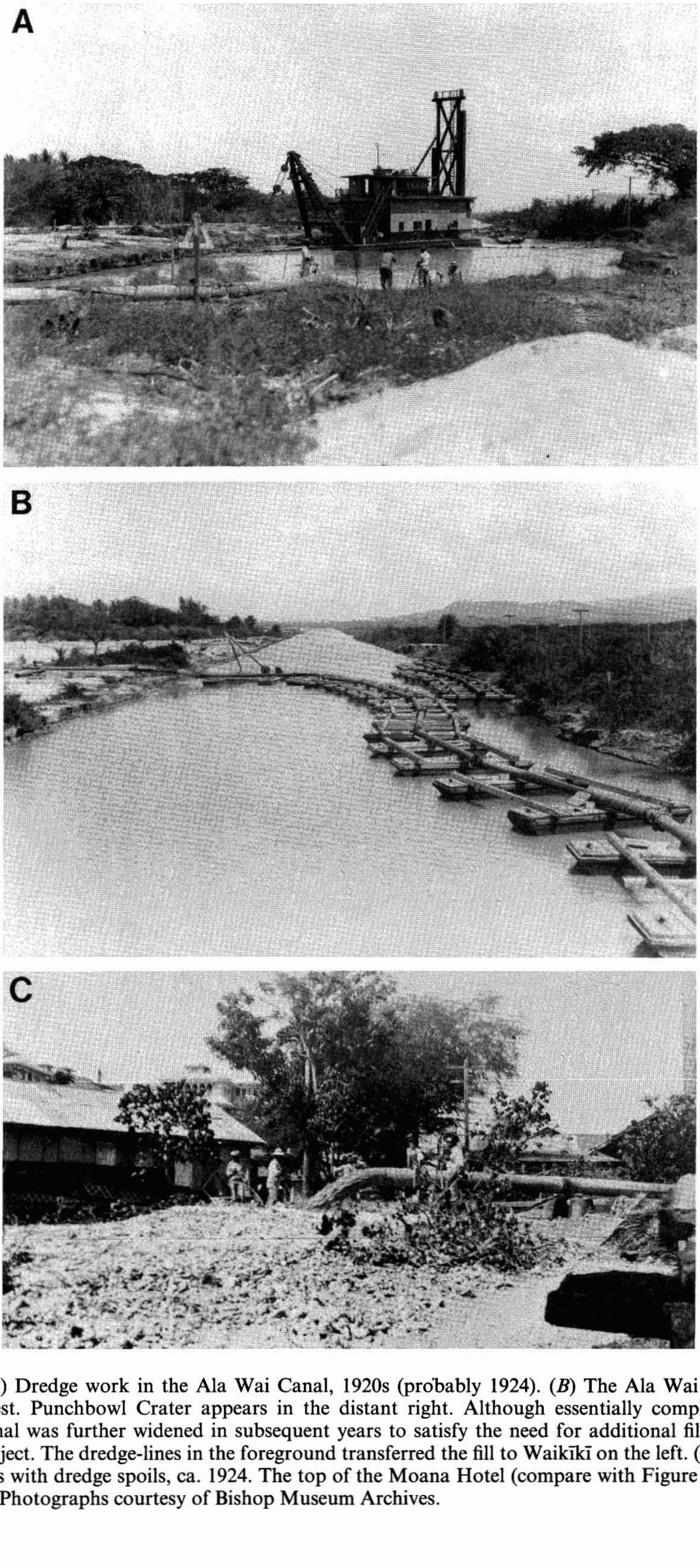

FIGURE 4. (*A*) Dredge work in the Ala Wai Canal, 1920s (probably 1924). (*B*) The Ala Wai Canal, ca. 1924, looking northwest. Punchbowl Crater appears in the distant right. Although essentially complete as originally specified, the canal was further widened in subsequent years to satisfy the need for additional fill for the Waikīkī Reclamation Project. The dredge-lines in the foreground transferred the fill to Waikīkī on the left. (*C*) The raising of Waikīkī wetlands with dredge spoils, ca. 1924. The top of the Moana Hotel (compare with Figure 3) appears in the far background. Photographs courtesy of Bishop Museum Archives.

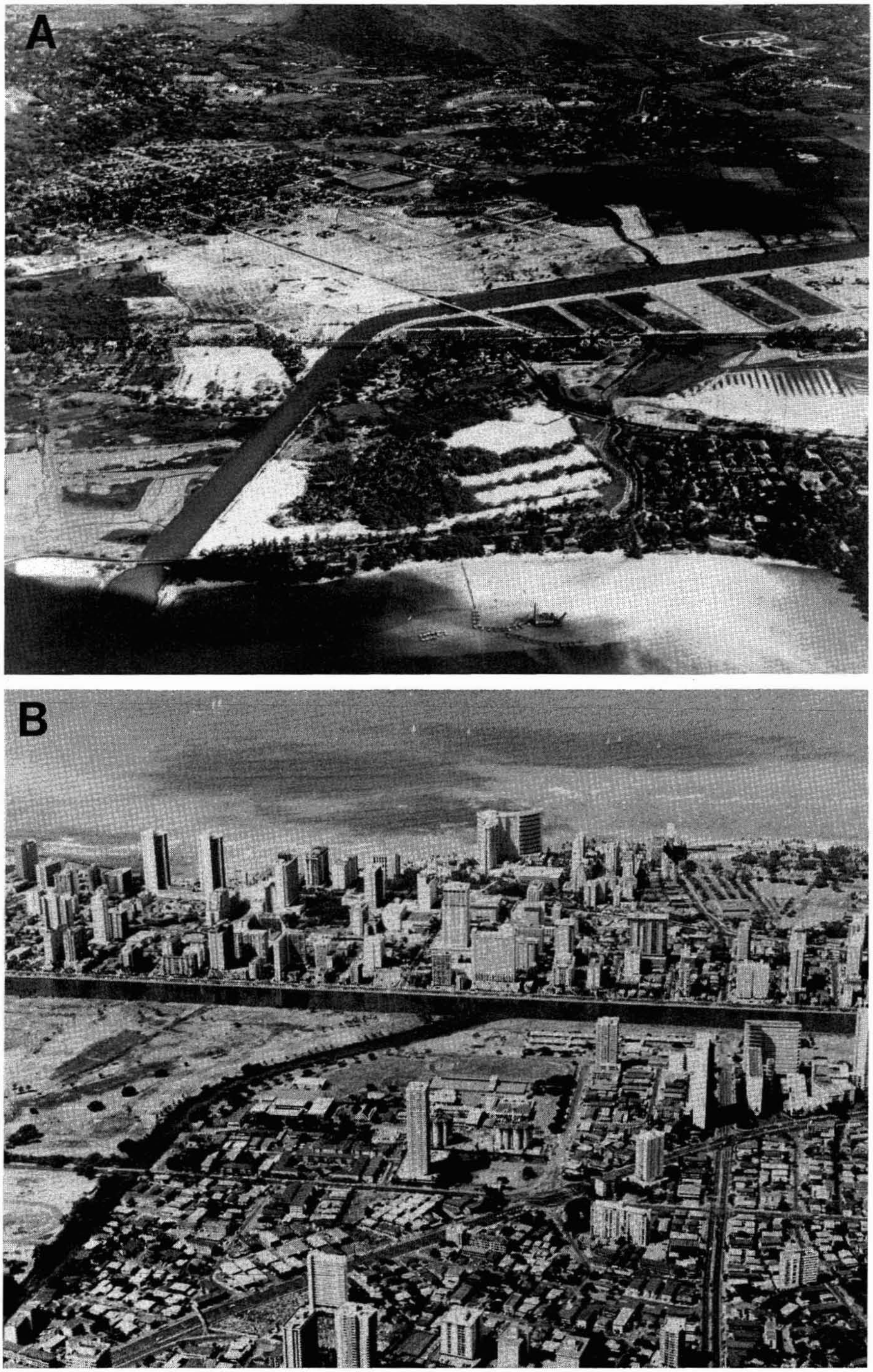

FIGURE 5. (*A*) Aerial view in 1927 near the time of the Ala Wai Canal's completion. The Ala Wai Yacht Harbor has not yet been constructed (compare with Figure 2) and dredging of coral continues in the reef tract offshore. Photograph courtesy of Bishop Museum Archives. (*B*) Waikīkī and the Ala Wai Canal, 1978. The Mānoa-Pālolo Stream drainage canal (lined with scrubs) feeds freshwater and high volumes of sediment to the midsection of the canal where a sedimentary sill develops. The Ala Wai Golf Course is to the left of the Mānoa-Pālolo Stream. Photograph courtesy of Bishop Museum Archives.

FIGURE 6. Aerial view of Waikīkī, the Ala Wai Canal, and the Ala Wai Yacht Harbor, 1962. Mouth of the Mānoa-Pālolo Stream drainage canal enters the canal at left. Diamond Head Crater is in the distance. Photograph courtesy of Bishop Museum Archives.

days, seasons, years, and decades. In past studies, the canal has been shown to support extremely high levels of primary productivity—so high, in fact, that it is rivaled by few other water bodies in the world (see discussions in Glenn et al. 1995). Gross photosynthetic rates (ca. 5.5 g C m^{-2} d^{-1} estimated by Harris [1975]; 3.9 g C m^{-2} d^{-1} estimated by Laws et al. [1994]) increase by a factor of 3 to 4 from the canal's mouth to its head. This primary productivity is driven and maintained by sustained elevated inputs of phosphate, nitrate, silica, and ammonia that enter the canal (Miller 1975, Laws et al. 1994), particularly from a storm drain at the canal's head (back basin), from the Mānoa-

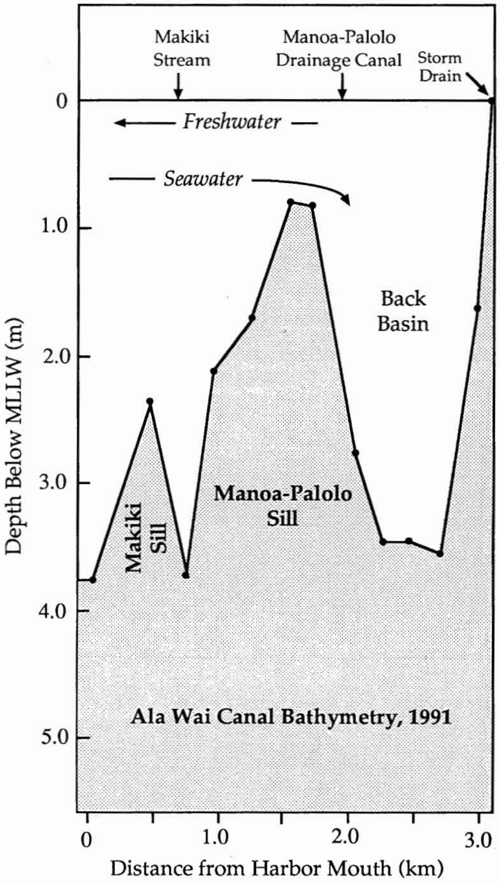

FIGURE 7. Bathymetric profile of the Ala Wai Canal in 1991 (after Laws et al. [1993]); water column depths were corrected to mean lower low water (MLLW) using local tide tables. Although the canal was dredged in 1978 (see Figure 2), the 1991 bathymetry closely resembles that measured by Gonzalez (1971) in 1969. Originally dredged to a depth of 3–6 m in the 1920s, the mean depth of the canal in 1969 was estimated to be only 2 m (Gonzalez 1971). Today, the sediment sill at the mouth of the Mānoa-Pālolo Stream becomes exposed at extreme low tides.

Pālolo drainage at the midsection of the canal, and from the Makiki Stream near the bend in the canal (Figure 2). Concentrations of inorganic nitrogen and phosphorus are well above levels associated with nutrient limitation and have been found to be especially elevated following storm events (Laws et al. 1994). Although dissolved silica certainly enters these systems as a component of groundwater and streams, leached from O'ahu soils and basalts, the origin of the other nutrients entering the canal currently is not known. Fertilizer runoff and leaky sewers appear to be likely candidates. Nutrients released from fertilizers used in the Ala Wai Golf Course also may enter the canal and, as in other low-oxygen aqueous systems (cf. Gächter et al. 1988), phosphorus also may be regenerated from the canal sediments where they are anoxic, particularly in the back basin.

Contents of This Issue

This issue of *Pacific Science* presents papers elucidating results of recent scientific investigations of the Ala Wai Canal, O'ahu, Hawai'i. Our recent collective interest in the Ala Wai Canal initially arose from two summer programs in 1991 and 1992 at the University of Hawai'i at Mānoa—the Young Scholars Program—which is discussed in the following paper of this issue (Fryer 1995). During both summers, this program provided high-school students with an opportunity for involvement in applied scientific research, using a multidisciplinary approach to solving environmentally relevant problems. Many of the papers contained in this issue were initiated from these summer programs and now largely reflect continued and rigorous studies that took place during interluding academic sessions and in subsequent years.

Beach et al. (1995) show that the canal supports at least 20 diatom genera, four dinoflagellate genera, and one cyanophyte (blue-green algae) genus. The diatom genera occur in various proportions in response to the particular environmental conditions that exist along different segments of the canal. Nauplius larvae, copepods, flatworm larvae, and polychaete larvae were the principal zooplankton detected in the canal. The distribution of the dominant diatom *Skeletonema costatum* (Greville) Cleve and other phytoplankton species appears to be largely controlled by tidal changes and variations in salinity. *Skeletonema costatum* dominates the plankton seaward of the sediment sill, whereas

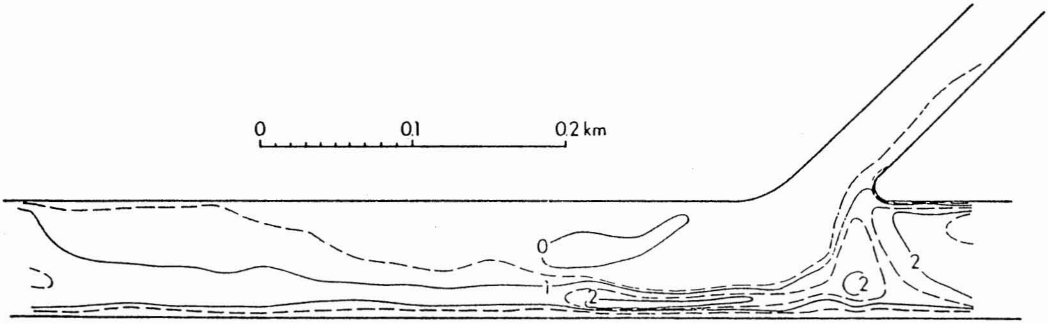

FIGURE 8. Bathymetric map of the Ala Wai Canal near the Mānoa-Pālolo Stream drainage canal from data of May 1965 showing the distribution of sediment deposited by stream discharge at that site. Contour interval, 0.5 m; 1.0-m intervals highlighted (solid lines). Depths are given in relation to mean lower low water. (From Gonzalez [1971].)

the back basin portion of the canal behind the sill is dominated by dinoflagellate algae (also see Laws et al. 1994). Resig et al. (1995) show that foraminifera diversity decreases from the harbor mouth back into the canal and that for at least the past 50 yr the canal has harbored five dominant benthic species, *Ammonia beccarii* (Linné) vars., *Bolivinellina striatula* (Cushman), *Cribroelphidium vadescens* (Cushman & Brönnimann), *Quinqueloculina poeyana* (d'Orbigny), and *Quinqueloculina seminula* (Linné). These species are facultative anaerobes, tolerant of nearly anoxic conditions present in the back basin portion of the canal. Maximum numbers of individuals are found in the back basin, where primary productivity is highest, despite the fact that that region is also where dissolved oxygen is lowest. Maximum diversity, however, was found to be highest near the canal's entrance. Pollutants in the canal have produced abnormalities in foraminifer test growth. Crustaceans, including crabs and shrimp, are the most abundant benthic invertebrates in the canal and appear to be less abundant to absent under low oxygen conditions present behind the canal's sill (Miller 1975).

Glenn et al. (1995) explore the geochemistry, mineralogy, and stable isotopic composition of sediments cored from the Ala Wai Canal, particularly those that occur beneath the most productive and oxygen-deficient waters of the canal's back basin. Although the sediments are dominated by detrital clays and silts, they also contain moderately high to high concentrations of organic carbon and calcium carbonate. Glenn et al. assembled several lines of evidence that strongly suggest that the calcium carbonate of the canal is the result of inorganic precipitation of aragonite and magnesian calcite that occurs as carbon dioxide is stripped from the canal's surface waters as a result of extreme rates of photosynthesis. Seawater uranium also appears to be very efficiently scavenged by the sediments during this process. Such biologically induced inorganic precipitation is analogous to carbonate precipitation in eutrophic lakes and to the still hotly debated process of "whitings" that may occur in the Bahamas and the Persian Gulf. Glenn et al.'s data, in terms of temporal changes in primary productivity in the canal, indicate that the canal has undergone two stages of progressive eutrophication since 1935, one before sill dredging in 1966 and 1978 and the other after.

Fan et al. (1995) discuss the detrital mineral assemblages of the canal and contrast these with that of the soils and stream sediments of its surrounding drainages. Chemical and mechanical weathering products and aeolian inputs are differentiated and traced from the Makiki, Mānoa, and Pālolo Valleys, through their major streams, and finally as they accumulate in the Ala Wai Canal. McMurtry et al. (1995*a*) discuss the record of ^{137}Cs, a waste aerosol product of nuclear bomb testing in the atmosphere, in the sediments of the canal and in the soils of its surrounding watershed. These workers clearly show the inputs of ^{137}Cs to the watershed and canal and directly correlate these with historical records of nuclear bomb testing. They develop an erosion/redeposition model using ^{137}Cs that is used to historically date the sediments of the canal since nuclear testing began. The results of their dating scheme are employed in several other papers of this issue, including Glenn et al. (1995), De Carlo and Spencer (1995), Spencer et al. (1995), and Raine et al. (1995). Their method shows great promise as a way to assign recent dates to sediments and reveals that the widely used ^{210}Pb geochronometer does not work for sedimentation in this tropical island estuary.

The next set of papers deals with the concentrations of heavy metals (lead, copper, nickel, cobalt, mercury, cadmium, zinc) of the canal sediments and in the surrounding sediments and soils of the Honolulu area. McMurtry et al. (1995*b*) describe heavy trace metal pollution (Pb, Cu, Ni, Hg, Cd, and Zn) in coastal sediments of the island of O'ahu and provide a basis for evaluating human impact on O'ahu's coastal ecosystem. They find especially pronounced enrichments of Pb, Cd, and Hg in the carbonate sands of several of O'ahu's coastal bays and lesser enrichments of Cu, Zn, and Ni in highly contaminated areas associated with the naval industries at Pearl and Honolulu Harbors and with the cultivation of watershed soils. As expected, the dominant source of widespread Pb pollution has been from motor vehicle exhaust. Mercury deposition is also widespread and is attributed to local volcanic sources, whereas Cd deposition appears to be derived from motor vehicles, volcanic sources, and agriculture. As deduced from study of the Ala Wai Canal sediment cores, De Carlo and Spencer (1995) next describe the input record of Pb and other heavy metals into the sediments of the Ala Wai Canal against the background of pre-anthropogenic sources found in the bottom of the sediment cores. They track, for example, the advent, increase, 1970s apex, and subsequent phasing out of Pb-alkyl fuel additives beginning in 1975 in the Honolulu area over the past 60 yr. However, these workers also show that the levels of Pb fail to return to pre-anthropogenic levels in Ala Wai core top sediments and mainly attribute this to continued input from previously contaminated soils, in agreement with the ^{137}Cs erosion/redeposition model of McMurtry et al. (1995*a*). Cd, Cu, and Zn levels are also evaluated and attributed to various anthropogenic inputs as well as to natural weathering processes. Co and Ni do not seem to show an anthropogenic signal. Spencer et al. (1995) used stable isotopic signatures of Pb in the Ala Wai cores to further constrain the sources of Pb recovered and suggest that the overwhelming majority of it can be directly attributed to anthropogenic input. They show that elevated Pb concentrations continue to be washed out of Honolulu's watershed. Spencer et al. (1995) newly document how sources of Pb in soils and sediments can be deduced from combined isotopic investigations (e.g., Nd-Pb and Sr-Pb isotope data). Raine et al. (1995) conclude this special issue with a paper that focuses on the history of natural and anthropogenic Hg accumulation in the Ala Wai Canal and in the watershed of the central Honolulu area. They establish a compelling case for anthropogenic Hg accumulation in the Ala Wai Canal derived from antifouling paints in the Ala Wai Yacht Harbor at the canal's mouth. The levels of this dangerous contaminant in the Ala Wai apparently have waned since the U.S. Environmental Protection Agency's ban of such paints in 1972. The total Hg content in recent Ala Wai Canal sediments, however, remains relatively high with respect to values determined for when the canal was first constructed. These sustained concentrations are likely related to residual sources still generated in the yacht harbor at the canal's mouth, because Hg levels are low in the watershed soils. Raine et al. also note that a small peak in Hg accumulation in 1986 seems correlative with the last year of a 3-yr period of intense Kīlauea volcano fire-fountaining on the neighboring island of Hawai'i.

The Young Scholars Program became a

much bigger success for science than originally predicted and illustrates how a concerted educational program can blossom into a multifaceted scientific study. We believe this special issue of *Pacific Science* will attract the attention of a variety of scientists and academicians, as well as administrators and others interested in the environmental quality of Hawai'i. We also hope that the results reported here will be useful for future planning-use considerations of the canal and its environs, particularly with respect to water quality and future dredging operations, including relocation of the dredge spoils.

ACKNOWLEDGMENTS

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