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Hypereutrophication of the Ala Wai Canal, Oahu, Hawaii: Prospects for Cleanup[1]

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ABSTRACT: Studies of trophic conditions in the Ala Wai Canal were carried out during a 6-week period during the summer of 1991. The canal is a partially mixed estuary whose water quality and trophic status are impacted to a large extent by run-off from residential and light industrial portions of the City of Honolulu. Gross photosynthetic rates are about 5.5 g C m^{-2} d^{-1} and increase by a factor of three from the mouth to the head of the estuary. Photosynthesis appears to be limited only by the availability of light and the concentration of phytoplankton. Allochthonous inputs of organic carbon exceed photosynthetic rates by about 60%. Of the total allochthonous plus autochthonous organic carbon input to the system, respiration consumes about 70%, 18% accumulates in the sediments, and about 12% is flushed out at the mouth of the canal. Sedimentation amounts to about 7–8 × 10^3 m^3 yr^{-1} and has greatly altered the bathymetry of the canal. Concentrations of particulate carbon, particulate nitrogen, and chlorophyll *a* are comparable to values reported 20 yr ago, despite dredging of the canal in 1978–1979. Surface waters are supersaturated with oxygen during the day and undersaturated at night. Shallow subsurface waters undergo even greater diel oxygen changes because of inefficient oxygen exchange with the atmosphere. Oxygen concentrations below a depth of 3 m frequently violate Environmental Protection Agency water quality criteria. Flushing the canal by pumping in seawater at its head at a rate of about 10^4 m^3 hr^{-1} will probably do much to improve the aesthetic condition of the canal and increase oxygen concentrations in the bottom waters.

CONCERN OVER CULTURAL eutrophication of estuaries has existed for at least several decades (Carpenter et al. 1970, Ketchum 1970, Jaworski 1981). The problems caused by cultural eutrophication have tended to be most apparent in so-called type B estuaries, in which the volume of the tidal prism (V_p) is 10–20 times the volume of fresh water discharged during half a tidal period (V_f) (Biggs and Cronin 1981). In type B estuaries very little of the sediment introduced from land run-off escapes through the estuary to the sea, and the level of biological productivity is generally higher than in other types of estuarine systems (Biggs and Cronon 1981). One of the largest and most thoroughly studied type B estuaries in the world is Chesapeake Bay. In that system oxygen concentrations in

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the bottom waters near the head of the estuary frequently decrease to undetectable levels in the summer months as a result of intense biological activity and high water temperatures (Biggs and Cronin 1981).

Much of the early work to control nutrient inputs to estuaries focused on point sources such as sewage treatment plants (Jaworski et al. 1972), but in recent years there has been increasing awareness of the impact of nonpoint source nutrient inputs on both freshwater and marine systems (Welch et al. 1980, Jaworski 1981, IJC 1987). Jaworski (1981), for example, estimated that in 1971 about 70% of the external nitrogen loading to Chesapeake Bay came from land runoff.

The Ala Wai Canal is an artificial type B estuary created by the U.S. Army Corps of Engineers in 1927 for flood and mosquito control and to provide fill material for development of the Waikiki area of Honolulu, Hawaii. The V_p/V_f ratio is about 16 (Gonzalez 1971). Although quite small compared to most natural estuaries, the Ala Wai Canal displays many of the characteristics and problems of type B estuaries. It is a hypereutrophic system (Harris 1972) whose physical characteristics are heavily influenced by sedimentation and in which anoxic conditions are common in the bottom waters farthest from the ocean (Gonzalez 1971). Although inputs to the canal are virtually all derived from land run-off, the majority of these inputs are associated with a few point sources. This latter fact combined with the small size and simple geometry of the canal facilitate both observational and theoretical scientific studies. The research reported here was undertaken in part to gain a better understanding of processes that occur in type B estuaries, particularly fluxes and transformations involving carbon and oxygen. Additional motivation was provided by the fact that the Hawaii state legislature recently appropriated $800,000 to evaluate the feasability of cleaning up the canal. Issues of concern include the accumulation of trash and debris in the water and sediments (Dayton 1990), sedimentation (Gonzalez 1971), eutrophication (Harris 1972), heavy metals (Louma 1974, Department of Health 1980), pesticides (Shultz 1971), and pathogens (Cox 1969, Gonzalez 1971). It is expected that the information provided here will prove useful to those responsible for predicting how conditions in the canal will change in response to proposed flushing with nearshore seawater (Mariani 1990).

Physical Setting

The Ala Wai Canal extends along the landward side of Waikiki for a distance of ca. 3.1 km from the Ala Wai yacht harbor to Ainakea Way (Figure 1). The canal makes a 45° bend near Kalakaua Avenue and McCully Street. The portion of the canal from the Ala Wai yacht harbor to McCully Street is about 50 m wide. The canal is ca. 75 m wide from McCully Street to Liliuokalani Avenue, but narrows to about 50 m again from Liliuokalani Avenue to Ainakea Way. The total area of the canal is about 2×10^5 m^2. The canal was originally dredged to a depth of 3–6 m from its head to the 45° bend and to a depth of 3–4 m from the 45° bend to the Ala Moana bridge. A channel about 7.5 m deep was dredged about 150 m seaward from the Ala Moana bridge (Gonzalez 1971). Portions of the canal are presently close to 4 m deep, but sedimentation has greatly reduced the depth of the canal along much of its length (Figure 2). The shallowest portions of the canal are now less than 1.0 m deep at mean lower low water (MLLW), which is the "zero" found on tidal charts constructed from U.S. Coast and Geodetic Survey tide tables. This shoaling has been caused largely by the accumulation of sediments washed into the canal from several streams, principally the Manoa-Palolo drainage canal and Makiki Stream. The estuary has been dredged from time to time to remove these accumulated sediments, most recently in 1966 and in 1978–1979. In 1978–1979 the canal was dredged to a depth of 3 m from McCully Street to the mouth of the Manoa-Palolo drainage canal. Thus much of the sedimentation apparent in Figure 2 has occurred since 1978–1979.

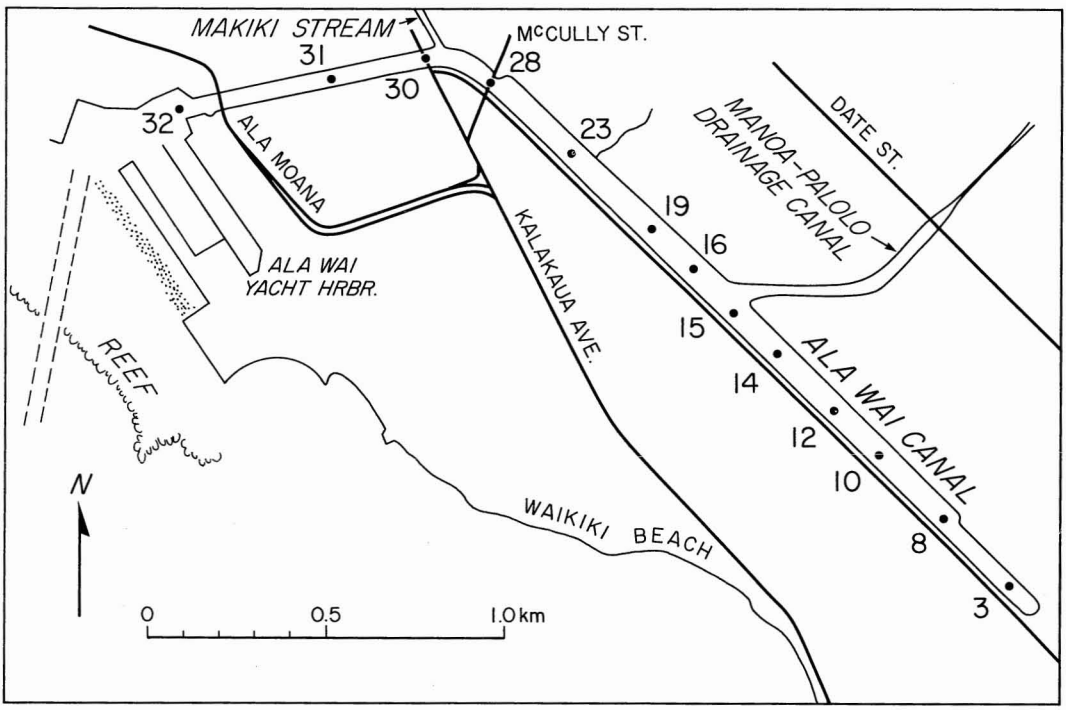

FIGURE 1. The Ala Wai Canal and sampling stations used in this study.

MATERIALS AND METHODS

Sampling was conducted on a weekly basis at a total of 13 stations along the length of the canal using a 5-m Boston Whaler during the month of July 1991. The station locations are shown in Figure 1. Not all measurements were made on each sampling date. Samples were taken at a point approximately equidistant from both sides of the canal. Preliminary studies indicated little variation in water column characteristics across the width of the canal. Secchi depths were determined using a 30-cm white plastic disk weighted from below with a piece of lead. The depth of the water column was determined by lowering the Secchi disk until it touched bottom. Water column depths were corrected to MLLW using local tide tables. According to Gonzalez (1971), tides in the canal are of the same phase and amplitude as those predicted for Honolulu Harbor. Conductivity and temperature measurements were made with a conductivity-temperature meter (Extech Instruments Corp.). Conductivity measurements were converted to salinities in terms of NaCl equivalents by intercalibration with a salinity refractometer (Extech Instruments Corp.).

Particulate carbon (PC), particulate nitrogen (PN), and chlorophyll *a* (chl *a*) measurements were made by drawing water through silicone tubing into a 1-liter glass flask. A partial vacuum of ca. 0.15 atmosphere was created in the flask using a hand-operated vacuum pump. Aliquots of 100–300 ml were filtered onto glass fiber (GF/C) filters for analysis of PC, PN, and chl *a*. The filter to be used for PC and PN analysis was placed on a precombusted (500°C) square of aluminum foil, placed in a plastic petri dish, and stored in an ice chest. The filter for chl *a* analysis was placed in a black plastic film container, covered with ca. 5 ml of 100% acetone, and also placed in an ice chest. Upon return to the

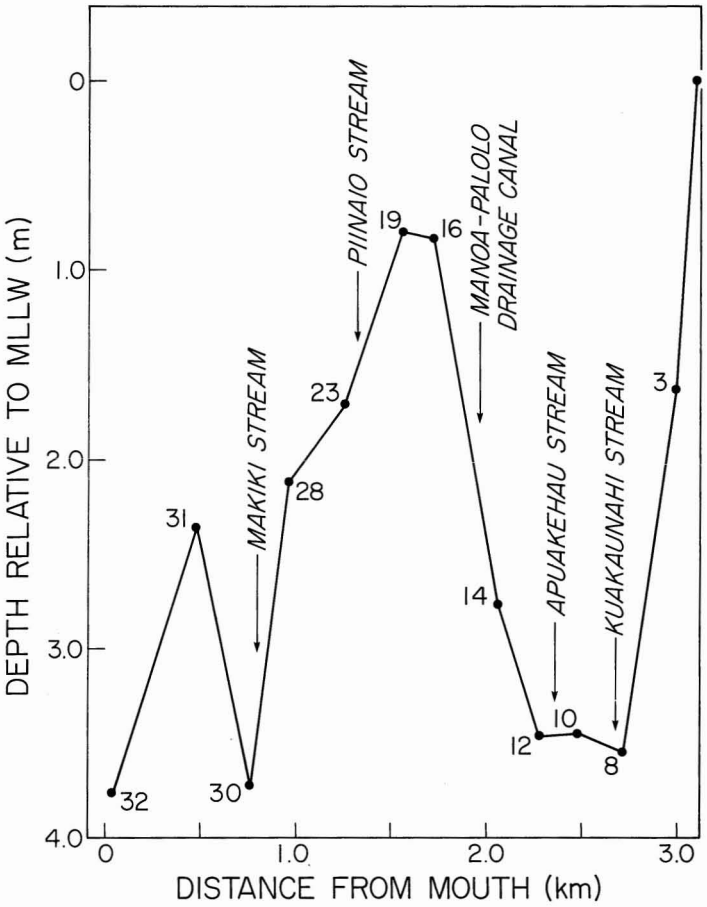

FIGURE 2. Bathymetry of the Ala Wai Canal and location of major freshwater inputs.

laboratory, the PC, PN, and chl *a* samples were all stored in a freezer at −4°C until they were analyzed. The PC and PN analyses were made on a CHN analyzer (Perkin-Elmer model 2400). Chl *a* concentrations were measured 2 days after sampling on a spectrophotometer (Varian model DMS 100S) using a 10-cm pathlength cell. Phaeo-pigment corrections were made following the procedures in Strickland and Parsons (1972).

Vertical oxygen concentration profiles were measured using an O_2 meter (either a Yellow Springs Instrument model 57 or an Orion model 820). The meter readings were standardized to oxygen concentrations measured by Winkler titration (Strickland and Parsons 1972) from samples collected either at the surface or at a depth of 1 m. Surface water samples for Winkler analysis were collected by holding the lip of a 300-ml biochemical oxygen demand (BOD) bottle just below the surface and slowly filling the bottle. Subsurface samples were collected using a 125-ml plastic bottle that was taped to a rigid support and lowered into the water while closed. When the top of the bottle was at the desired depth, the bottle was filled by pulling on a cord attached to a silicone rubber stopper inserted in the 1-cm-diam. mouth of the bottle. The bottle was then returned to the surface and a portion of its contents dispensed into a 60-ml BOD bottle. The first two Winkler

reagents were added immediately, and the BOD bottles were stored in the dark. Titrations were performed in the laboratory 2 days after sampling.

Photosynthesis and respiration rates were measured using the oxygen light-and-dark bottle method (Strickland and Parsons 1972) at stations 6, 15, and 32 (Figure 1). Water was drawn into a 4-liter glass flask using silicone tubing and a hand-operated vacuum pump as previously described. Samples were taken from 0.5 m and 1.5 m at all three stations and from 3 m at stations 6 and 32. The water was dispensed into triplicate 300-ml BOD bottles. The oxygen in the initial bottles was immediately fixed by adding the first two Winkler reagents, and the bottles were stored in the dark. The remaining triplicate light and dark bottles were incubated in situ for times ranging from 4 to 5 hr in the afternoon. The bottles were recovered and the incubations terminated by adding the first two Winkler reagents between 1730 and 1800 hours local time. Dark-bottle incubations were performed only on the samples taken from a depth of 1.5 m. The bottles were titrated for oxygen content 2 days after the incubations. Daily gross photosynthesis was estimated by dividing the sum of net community production and respiration in the incubation bottles by the estimated fraction of daily solar radiation that occurred during the incubation period. Solar radiation was assumed to follow a half sine wave curve between sunrise and sunset. Daily respiration rates were estimated by assuming respiration to be constant throughout the day and night. Photosynthesis and respiration rates in terms of oxygen were converted to equivalent rates in terms of carbon by assuming photosynthetic and respiratory quotients of 1.2 and 1.0, respectively (Strickland and Parsons 1972).

RESULTS

The bathymetric survey (Figure 2) indicated a sedimentation pattern very similar to that reported by Gonzalez (1971), with most of the sediment accumulation occurring downstream of the Manoa-Palolo drainage canal and Makiki Stream. If one assumes that the canal was indeed dredged to a depth of 3 m from McCully Street to the Manoa-Palolo drainage canal in 1978–1979, the shoaling apparent in Figure 2 between stations 14 and 28 corresponds to a sedimentation rate of about 8×10^3 m^3 yr^{-1}. This figure agrees rather well with Gonzalez's (1971) estimate of 7×10^3 m^3 yr^{-1} based on changes in bathymetry during the 40 months following dredging of the canal in 1966. Thus sedimentation in the Ala Wai Canal appears to have changed very little during the last 25 yr.

Concentrations of PC, PN, and chl *a* generally increased from the mouth to the head of the canal (Figure 3). This pattern is consistent with the observations of Harris (1972), who studied the canal during a 13-month period in 1970–1971. Although our data provide no information on temporal variability, our horizontal resolution is much greater than that of Harris (1972), who sampled at only three locations in the canal. Her sampling stations were located ca. 500 m, 1500 m, and 2300 m from the mouth of the canal. The average concentrations of PC, PN, and chl *a* reported by Harris (1972) at those stations at depths of 0.9–1.2 m are listed in Table 1. Our values are quite comparable to hers with the exception of her station nearest the mouth of the canal, where our concentrations are consistently higher. Our PC data show obvious peaks near the Manoa-Palolo drainage canal and Makiki Stream. These peaks would not have been apparent at the stations sampled by Harris (1972). The highest chl *a* concentrations, however, were found near the head of the canal, about 500 m upstream from the Manoa-Palolo drainage canal.

Seston compositional ratios are shown in Figure 4. PC/PN ratios almost all fell in the range of 6–7 by weight, with the exception of values of about 10–11 in samples taken near the Manoa-Palolo drainage canal and Makiki Stream. Most PC/chl *a* and PN/chl *a* ratios fell in the range of 50–80 and 8–14 by weight, respectively, with the exception of higher values in samples taken near the Manoa-Palolo drainage canal and at the head of the Ala Wai Canal. Harris (1972) did not report mean seston compositional ratios, but the ratios of her mean values (Table 1) lie in the

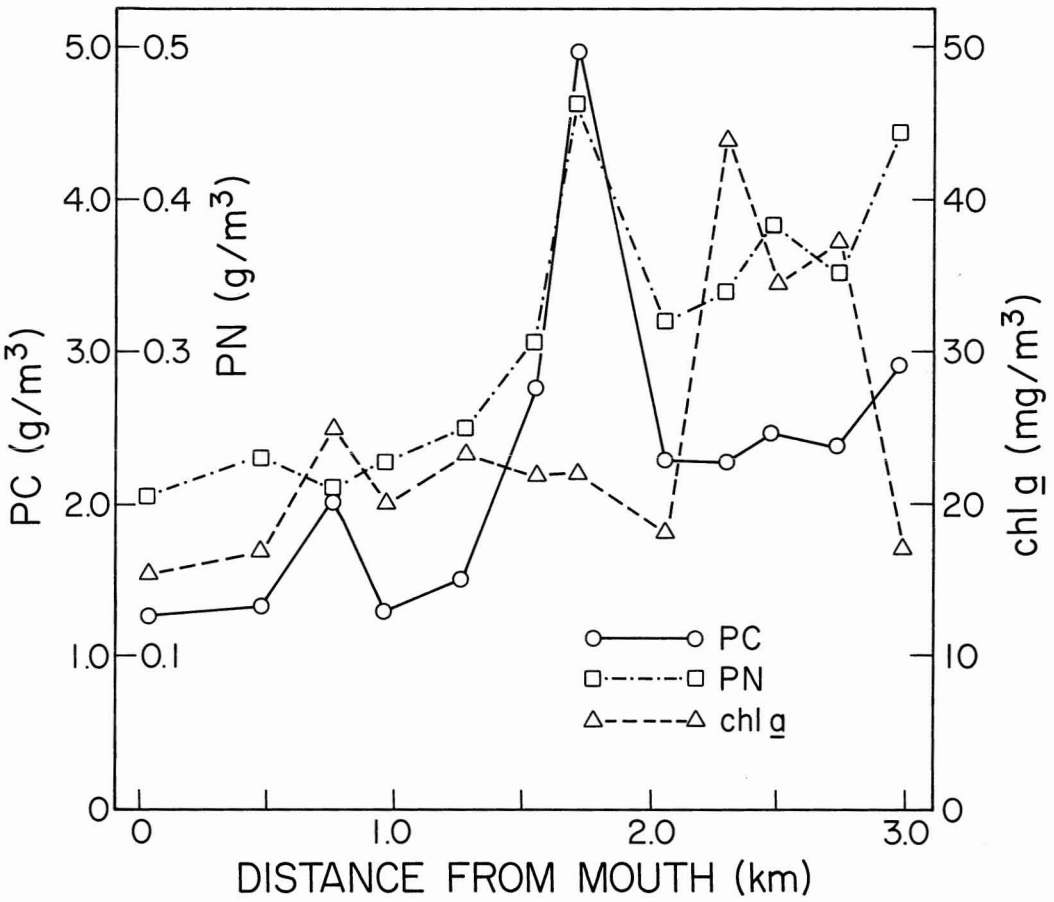

FIGURE 3. Concentrations of particulate carbon (PC), particulate nitrogen (PN), and chlorophyll *a* (chl *a*) measured at a depth of 1.0 m on 16 July 1991. The coefficients of variation for PC, PN, and chl *a* measurements are about 1%, 1%, and 10%, respectively.

TABLE 1

AVERAGE CONCENTRATIONS OF PARTICULATE (PC), PARTICULATE NITROGEN (PN), AND CHLOROPHYLL *a* (CHL *a*) REPORTED BY HARRIS (1972) AT DEPTHS OF 0.9–1.2 M IN THE ALA WAI CANAL

DISTANCE FROM MOUTH (m)	PC ($g\ m^{-3}$)	PN ($g\ m^{-3}$)	CHL *a* ($mg\ m^{-3}$)
500	0.65 ± 0.21 (12)	0.083 ± 0.030 (11)	12.8 ± 4.1 (31)
1,500	1.81 ± 0.60 (17)	0.268 ± 0.082 (17)	30.9 ± 7.2 (33)
2,300	2.68 ± 0.69 (15)	0.399 ± 0.094 (14)	48.0 ± 8.7 (33)

NOTE: Error bounds are 95% confidence intervals. Numbers in parentheses are number of sampling dates.

range 6.7–7.8, 51–59, and 6.5–8.7 by weight for PC/PN, PC/chl *a*, and PN/chl *a*, respectively. Our compositional ratios are therefore very similar to hers, with the exception of samples taken near stream inputs and at the head of the Ala Wai Canal.

The results of the photosynthesis and respiration measurements are shown in Table 2.

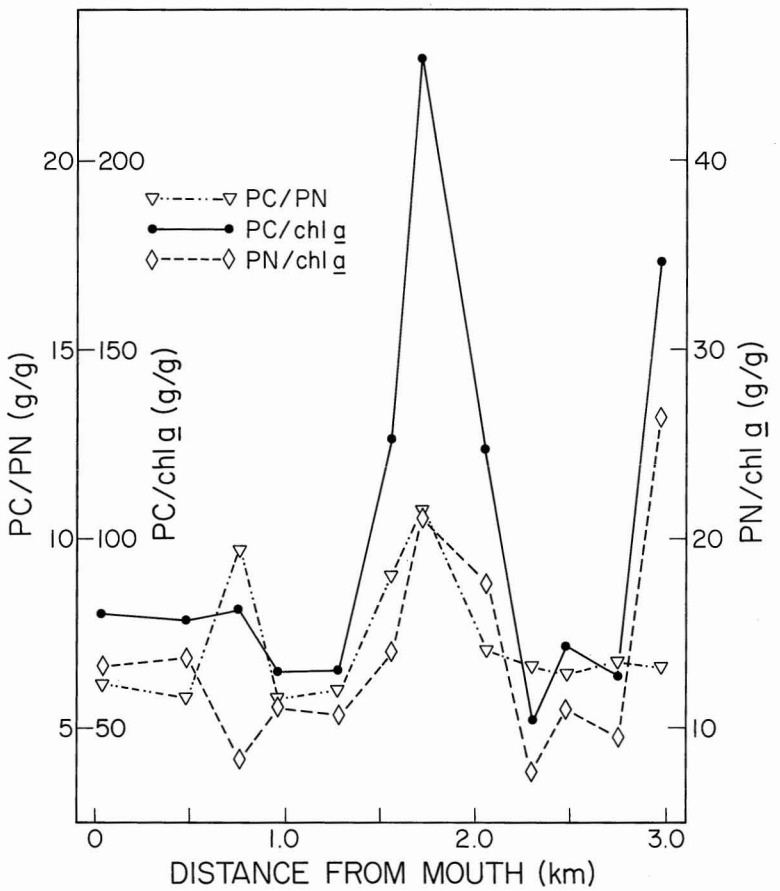

FIGURE 4. Seston compositional ratios based on data in Figure 3. The coefficients of variation for PC/PN, PC/chl *a*, and PN/chl *a* are about 2%, 2%, and 10%, respectively.

TABLE 2

RESULTS OF PHOTOSYNTHESIS AND RESPIRATION MEASUREMENTS MADE ON 23 JULY 1991, AT INDICATED STATIONS

STATION	G	R	G	R	PRODUCTIVITY INDEX
	$g\ O_2\ m^{-2}\ d^{-1}$		$g\ C\ m^{-2}\ d^{-1}$		$g\ C\ g^{-1}$ chl $a\ hr^{-1}$
32	8.5 ± 2.5	25.6 ± 9.4	2.7 ± 0.8	9.6 ± 3.5	26.8 ± 7.9
15	19.1 ± 1.7	14.1 ± 5.2	6.0 ± 0.5	5.3 ± 1.9	21.5 ± 1.9
6	25.3 ± 3.8	30.5 ± 11.9	7.9 ± 1.2	11.4 ± 4.5	21.6 ± 3.2

NOTE: Productivity indices were calculated at a depth of 0.5 m. Error bounds are standard deviations based on triplicate Winkler titrations. G, gross photosynthesis; R, respiration.

Results were integrated using the midpoint rule (Hornbeck 1975) to a depth of 4 m at stations 6 and 32 and to a depth of 2 m at station 15. The choice of integration depths at stations 6 and 15 is somewhat arbitrary, and the exact depth, of course, depends on the tidal cycle. The results are rather insensitive to the choice of integration depth, because no

more than 10–15% of integral production occurred in the bottom meter of the water column at those stations.

Gross production displayed an obvious gradient from the mouth toward the head of the canal, a pattern consistent with the distribution of chl *a*. The gross production rates of 6.0 and 7.9 g C m^{-2} d^{-1} at stations 15 and 6, respectively, are to be compared to Harris's (1972) average production figure of 5.3 g C m^{-2} d^{-1} based on uptake of ^{14}C-labeled inorganic carbon. One would expect the oxygen light-and-dark bottle estimate to exceed a measurement based on ^{14}C uptake, because the latter method tends to produce a value intermediate between net and gross photosynthesis (Peterson 1980). The productivity indices calculated at 0.5 m, where we expected irradiance to be saturating for photosynthesis, averaged 23 ± 3 g C g^{-1} chl *a* hr^{-1}, close to the theoretical maximum of 25 g C g^{-1} chl *a* hr^{-1} estimated by Falkowski (1981). The implication is that conditions near the surface of the canal are close to optimal for phytoplankton growth. The principal factors limiting photosynthetic rates in the canal appear to be the concentration of phytoplankton and light attenuation in the water column. This conclusion is consistent with studies conducted in a number of other estuarine systems (Cole and Cloern 1987).

The role of light attenuation in limiting

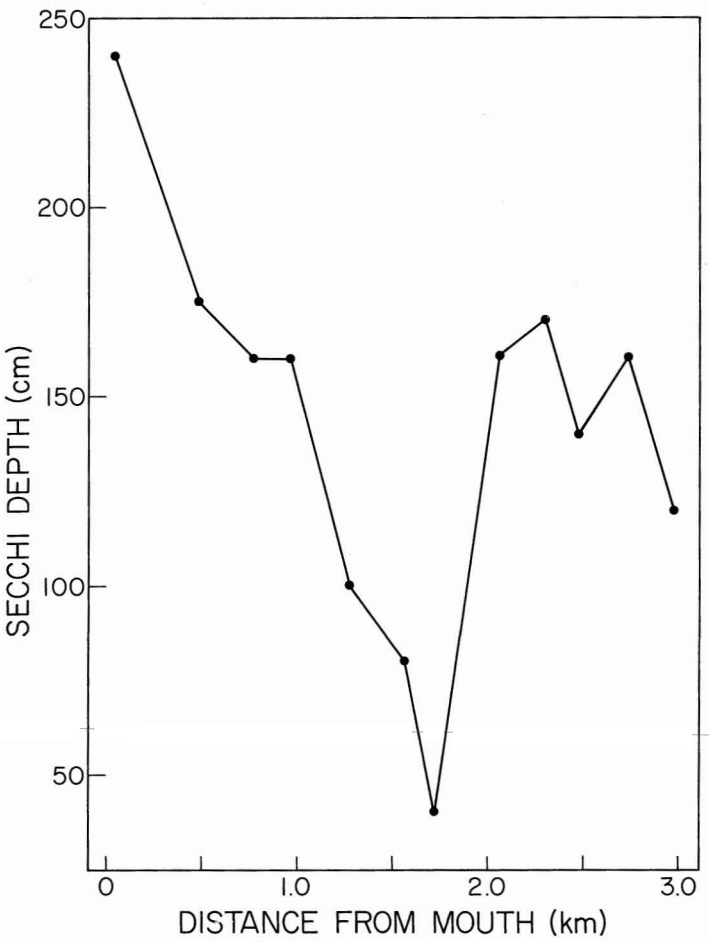

FIGURE 5. Secchi depths in the Ala Wai Canal measured on 16 July 1991. Readings are accurate to ±10 cm.

photosynthetic rates is clearly implicated in Figure 5. Secchi depths near the Manoa-Palolo drainage canal were as shallow as 40 cm, but increased to roughly 150 cm in the head of the canal and to 240 cm in the Ala Wai yacht harbor. If we assume the extinction coefficient of visible light to equal 1.7 divided by the Secchi depth (Poole and Atkins 1929), then the depth of the euphotic zone, commonly taken to be the depth at which the irradiance is reduced to 1% of the surface value, is about 1.1 m near the Manoa-Palolo drainage canal, 4.1 m in the head of the canal, and 6.5 m in the Ala Wai yacht harbor. The effective optical depths at stations 6 and 15 are therefore almost identical, and the higher areal photosynthetic rate at station 6 is due to the fact that the areal chl *a* concentration is about 40% higher at station 6 than at station 15. The average irradiance in the water column at station 32 is about 50% higher than at either station 6 or 15 because of the greater transparency of the water in the Ala Wai yacht harbor, but the areal chl *a* concentration, at least on the day of our sampling, was only 15–20% of the values at stations 6 and 15. The areal photosynthetic rate at station 32 was therefore substantially less than that at stations 6 and 15.

Respiration rates per unit volume increased from the mouth to the head of the canal, but the difference between the rates at stations 6 and 32 was less than 20%. The lower areal respiration rate at station 15 is due entirely to the shallowness of the water column at that station. Of the three stations studied, only

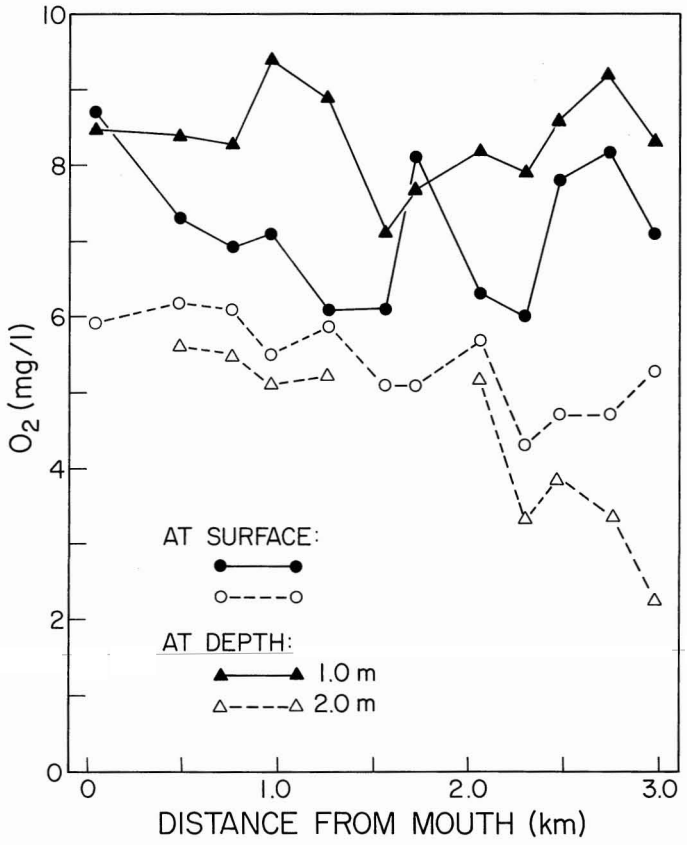

FIGURE 6. Oxygen concentrations measured 16 July and 2 August 1991. Filled symbols and open symbols refer to measurements made between 1430 and 1730 hours and 0330 to 0400 hours, respectively.

station 15 had a positive net community production over 24 hr, a result reflecting the lower areal respiration rate at that station.

Oxygen concentrations in the water are affected by photosynthesis and respiration, advection and diffusion, and exchange of O_2 with the atmosphere. Figure 6 summarizes the oxygen concentrations measured in this study. Surface water values showed the expected diel pattern of increase during the day and decline at night. Surface O_2 concentrations were in the range of 6–8 mg/liter in the late afternoon, but dropped to 4.5–6 mg/liter late at night. Surface water temperatures were 28–30°C in the late afternoon and declined to 25°C a few hours before sunrise. Salinities upstream of the Manoa-Palolo drainage canal were in the range of 33–34 ‰ throughout the water column. Surface salinities were about 10–13 ‰ near the Manoa-Palolo drainage canal and Makiki Stream, and a halocline extended from about 20 to 80 cm (Figure 7). Below 80 cm salinities were in the range of 33–34 ‰ throughout the canal. Under these conditions the saturation O_2 concentration in the surface water ranges from about 5.7 to 6.7 mg/liter upstream and downstream of the Manoa-Palolo drainage canal, respectively, during the late afternoon. It is therefore apparent that the surface waters in most parts of the canal are supersaturated with O_2 by late afternoon. Late-night surface water saturation O_2 concentrations ranged from about 6.2 to 7.2 mg/liter upstream and downstream of the Manoa-Palolo drainage canal, respectively. Surface waters are therefore undersaturated with O_2 by late evening.

The variation in O_2 concentrations is even greater 1–2 m below the surface. During daylight hours the upper water column becomes thermally stratified, with surface temperatures being 1.0–1.5°C warmer than temperatures at a depth of 1 m by late afternoon. This stratification inhibits exchange of O_2 with the atmosphere from subsurface depths, and at depths where the subsurface irradiance

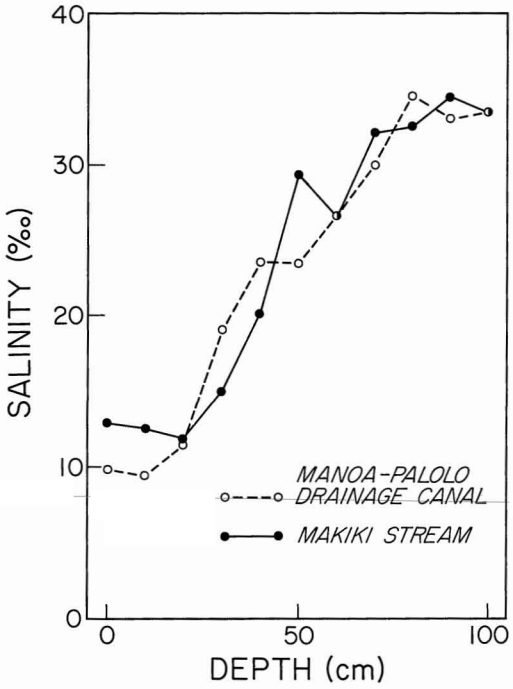

FIGURE 7. Salinity versus depth in the upper meter of the water column in the Ala Wai Canal near the Manoa-Palolo drainage canal and Makiki Stream on 30 July 1991.

is adequate to support rapid photosynthesis, O_2 levels build up to even higher concentrations than those observed at the surface. At a depth of 1 m, for example, late-afternoon O_2 concentrations were typically 1 mg/liter higher than surface values (Figure 6). During the night the canal loses heat to the atmosphere, and surface water temperatures were roughly 1.5°C cooler than the temperature of water at a depth of 1 m by the middle of the night. This thermal destabilization promotes mixing in roughly the upper meter of the water column, and O_2 concentrations are therefore more or less uniform in the upper meter of water at night. Thermal stratification was apparent, however, below a depth of 1 m, and O_2 concentrations at a depth of 2 m were consistently lower than surface values late at night. The differential amounted to about 0.5 mg/liter near the mouth of the canal, but increased to 1.5–3.0 mg/liter near the head (Figure 6). The differential presumably reflects the relative isolation of the deeper water from the atmosphere.

DISCUSSION

In most respects the results of this study are quite comparable to the results reported about 20 yr ago by Gonzalez (1971) and Harris (1972), but the much greater number of stations sampled for seston and the monitoring of O_2 concentrations during both day and night in the study reported here has provided some insights that were lacking in the earlier work. Carbon/nitrogen ratios of roughly 5.5–7.5 by weight are typical of marine phytoplankton and organic matter derived from marine phytoplankton (Copin-Montegut and Copin-Montegut 1983, Takahashi et al. 1985). Ratios two to three times higher are associated with macroalgae and terrestrial plants (e.g., Atkinson and Smith 1983). The peaks in PC concentrations near the Manoa-Palolo drainage canal and Makiki Stream (Figure 3) are presumably the result of stream inputs, and the corresponding peaks in PC/PN ratios (Figure 4) suggest that this organic matter contains a substantial terrestrial component. The seston in the rest of the canal appears to have been derived largely from phytoplankton. Carbon/chl *a* ratios of 50 by weight are often associated with nutrient-saturated phytoplankton, although ratios may differ by as much as a factor of two from this figure depending on the irradiance and species composition (Chan 1980, Laws and Bannister 1980, Laws et al. 1983). The lowest ratios are associated with extreme light limitation, a condition that does not appear to characterize the Ala Wai Canal. Gross photosynthetic rates (Table 2) are more than adequate to double the PC concentrations in a single photoperiod.

Harris (1972) estimated that phytoplankton accounted for 70–80% of the PC at the three stations she studied. Our PC/chl *a* ratios suggest that phytoplankton account for at least 60% of the PC in most parts of the canal, and are therefore consistent with Harris's analysis. The notable exceptions are the stations near the Manoa-Palolo drainage canal and the head of the Ala Wai Canal. The seston in the former location, as already noted, probably contains a substantial component derived from terrestrial sources. The seston near the shallow head (Figure 2) may contain much detritus stirred up from the sediments. If this interpretation is correct, the PC/PN ratio of this material implies that the organic matter in the sediments near the head of the canal is derived largely from phytoplankton. None of Harris's stations was closer than 350 m from the Manoa-Palolo drainage canal or the head of the Ala Wai Canal.

The gross photosynthetic rates in the Ala Wai Canal are quite high and are comparable to net production rates achieved in many intensive algal outdoor culture systems (Laws et al. 1986). At stations 6 and 15 gross photosynthetic rates at a depth of 0.5 m produced 15–16 mg O_2 liter^{-1} in a single photoperiod, a rate sufficient to supersaturate the water severalfold with O_2. Respiration would have consumed only 3.5–3.8 mg/liter of this O_2 during the same time interval. That measured O_2 concentrations never rose above 8–9 mg/liter (Figure 6) suggests that considerable O_2 degassing occurred during the photoperiod.

Gonzalez (1971) measured O_2 concentrations in the Ala Wai Canal on six occasions,

all during daylight hours. His contour plots of O_2 concentrations show subsurface O_2 maxima on only one occasion. His sampling depths are not specified, however, and it is not clear whether he actually measured surface O_2 concentrations. His chief concern seems to have been with the low O_2 concentrations in the bottom water. We measured surface and subsurface O_2 concentrations during the photoperiod on three occasions, and in each case found that O_2 concentrations at a depth of 1.0 m were higher than surface concentrations at almost every station. We believe that this phenomenon is probably quite common in the Ala Wai Canal and is caused by degassing of O_2 from the supersaturated surface waters and possibly to inhibition of photosynthesis at the surface by ultraviolet light (Jokiel and York 1984).

Our diel O_2 sampling unfortunately did not extend below a depth of 2 m, and we therefore have little information concerning O_2 concentrations in the bottom waters of the basin between stations 8 and 14. Gonzalez's (1971) photoperiod data show a rapid decline in O_2 concentrations between depths of 3 and 4 m on several occasions, with values at 4 m often being 1 mg/liter or less. These concentrations are presumably even lower at night. Our deepest O_2 measurements were made at a depth of 3 m between 1230 and 1400 hours during our photosynthetic studies. On that occasion the O_2 concentrations at a depth of 3 m were above saturation at station 32 and about 90% of saturation at station 6. Hence both our data and those of Gonzalez (1971) suggest that O_2 depletion is not a problem in the Ala Wai Canal during the photoperiod at depths shallower than 3 m. Federal Environmental Protection Agency water quality criteria (Environmental Protection Agency 1986) stipulate that in warm-water systems O_2 concentrations should not fall below 3 mg/liter at any time. This criterion appears to be frequently violated in the Ala Wai Canal at depths below 3 m (Gonzalez 1971), and at night the criterion is probably violated at even shallower depths (Figure 6).

The Ala Wai Canal has occasionally been reported to be the source of foul odors, presumably caused by the production of hydrogen sulfide when the water and/or sediments become anoxic. We sampled the Ala Wai Canal nine times during the course of this study and detected an unpleasant odor on only one occasion. In that case sampling was being conducted at night during a low tide near the Manoa-Palolo drainage canal. The tide was so low that the bottom of the Boston Whaler contacted the bottom of the canal on one occasion. We believe the odors we detected were the result of gases produced in the sediments, because water column O_2 measurements were well above zero. Oxygen readings rapidly dropped to zero, however, if the O_2 probe was allowed to settle into the upper layer of sediments.

Our photosynthesis and respiration measurements lead to some thought-provoking conclusions concerning the fate of organic matter in the Ala Wai Canal. Areal gross photosynthetic rates increase from the mouth to the head of the canal, and although the degree of linearity apparent in Figure 8 is perhaps deceptive, it is probably a fair approximation to model gross photosynthetic rates as a linear function of distance from the mouth. Using the regression equation fit to the data in Figure 8 and the appropriate widths for each segment of the canal, we estimate gross photosynthesis to be 1.1 tonne C d^{-1} or 3.5 tonnes O_2 d^{-1}. These figures are identical to the estimates made by Harris (1972). Because respiration rates per unit volume varied by less than 20% from station 6 to station 32, we simply calculated the average respiration rate per unit volume and multiplied it by the volume of the canal. The average volumetric respiration rate at stations 6, 15, and 32 was 7.0 g O_2 m^{-3} d^{-1} or 2.63 g C m^{-3} d^{-1}. The volume of the canal, calculated from the depth profile shown in Figure 2 and the appropriate channel widths, is 4.8×10^5 m^3. The respiration rate in the canal is therefore estimated to be 3.4 tonne O_2 d^{-1} or 1.3 tonne C d^{-1}.

The rate of loading of allochthonous organic matter into the Ala Wai Canal can be estimated only crudely, because neither tributary stream discharge rates nor the concentrations of materials in the streams have received much attention. The U.S. Geological Survey

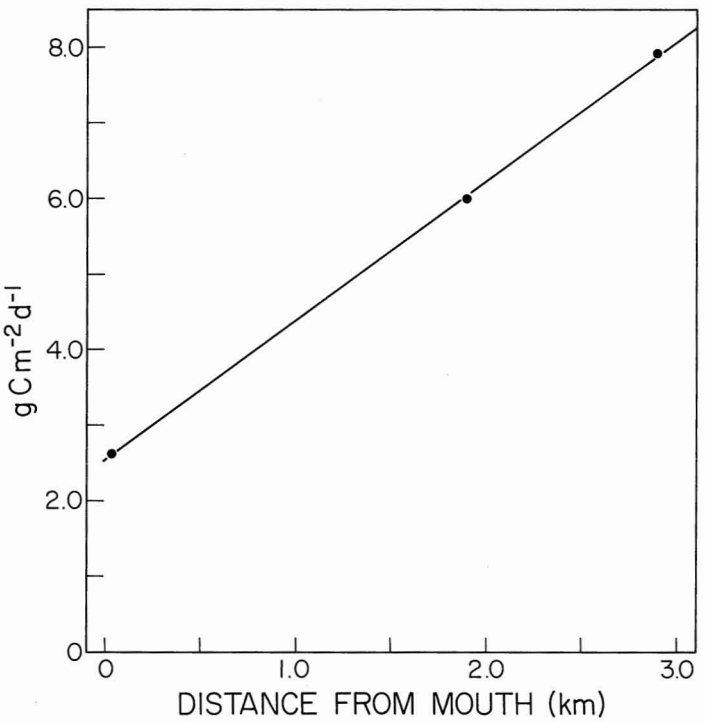

FIGURE 8. Gross areal photosynthetic rates measured on 23 July 1991, versus distance from the head of the Ala Wai Canal. The straight line is a least squares fit to the data.

does have continuously recording gauging stations on Palolo Stream about 0.5 km upstream of the point where it merges with Manoa Stream and on the two streams that merge to form Manoa Stream, but there are no comparable stations on Makiki Stream or on the Manoa-Palolo drainage canal. Gonzalez (1971) estimated run-off from the ungauged portion of the watershed using rainfall data, land use patterns, and empirical correlations between land use and percentage run-off. By adding this estimated run-off to the run-off from the gauged portion of the watershed, Gonzalez (1971) estimated freshwater discharge rates into the Ala Wai Canal that average 2.2×10^5 m^3 d^{-1}.

As noted by Biggs and Cronin (1981), it is technically difficult and very costly to measure the flux of mass through any cross section of an estuary. Fortunately in type B estuaries the amount of particulate material that escapes to the ocean is expected to be a small percentage of the external loading rate, and it is reasonable to assume that at the mouth of the estuary the flux of materials is controlled largely by advective processes. To estimate the net flux of PC out of the Ala Wai Canal, we therefore assumed that at the mouth of the estuary the net flux of PC out of the estuary is adequately described by the equation

$$\begin{aligned}\text{net flux} &= PC_{out}F_{out} - PC_{in}F_{in} \\ &= PC_{out}(F_{out} - F_{in}) + F_{in}(PC_{out} - PC_{in}) \quad (1)\end{aligned}$$

where PC_{out} and PC_{in} are the concentrations of PC in the water flowing out of and into the estuary, respectively, and F_{out} and F_{in} are the corresponding flow rates. If PC_{out} is equated to the PC concentration of 1.3 mg/liter measured at a depth of 1.0 m at station 32 (Figure 3) and $F_{out} - F_{in}$ to the estimated stream flow of 2.2×10^5 m^3 d^{-1}, then the first term on the right-hand side of equation 1 equals 0.29 tonne C d^{-1}. From sampling conducted at 0.5,

1.5, and 3.0 m on 23 July 1991, we estimate the ratio $PC_{out}/(PC_{out} - PC_{in})$ to be about 34, and according to Gonzalez (1971) the ratio $F_{in}/(F_{out} - F_{in})$ is 8. Hence the ratio of the first and second terms on the right-hand side of equation 1 is estimated to be about 34/8 = 4.25, and the total flux of PC out of the estuary becomes (5.25/4.25)(0.29) = 0.36 tonne C d^{-1}.

Completing the carbon budget requires a knowledge of allochthonous PC inputs, benthic respiration, and the accumulation rate of organic carbon in the sediments. C. R. Glenn's (pers. comm.) studies, conducted in conjunction with the work reported here, indicated that the sediments at the bottom of the Ala Wai Canal near the Manoa-Palolo drainage canal contain about 22 kg of organic carbon per cubic meter of sediment. Multiplying this figure by our estimated sedimentation rate of 8×10^3 m^3 yr^{-1} gives a sediment organic carbon accumulation rate of 176 tonnes C yr^{-1} or 0.5 tonne C d^{-1}.

Benthic respiration rates were not measured as a part of this study, and allochthonous PC inputs, which are expected to be a large term in the PC budget, can be calculated only rather crudely from the estimated freshwater input and the PC concentration of 5 mg/liter measured at the mouth of the Manoa-Palolo drainage canal. Perhaps a more accurate way to complete the carbon budget is to make use of an empirical relationship between benthic respiration rates in estuaries and the sum of photosynthesis and allochthonous PC inputs reported by Nixon (1981). The relationship, derived from studies on 15 different systems, is highly linear, with $r^2 = 0.94$. According to Nixon's (1981) regression equation, benthic respiration equals 24% of the sum of photosynthesis and allochthonous PC inputs. Based on a materials balance, photosynthesis + stream inputs = washout + sedimentation + water column respiration + benthic respiration. Substituting previously calculated values and Nixon's (1981) empirical equation gives 1.1 + stream inputs = 0.36 + 0.5 + 1.3 + 0.24 (1.1 + stream inputs). Rearranging this equation and solving for stream inputs gives a figure of 1.74 tonnes C d^{-1} and an estimated benthic respiration rate of 0.68 tonne C d^{-1}. Had we estimated allochthonous PC inputs directly from our data, the result would have been (5.0 g C m^{-3}) (2.2×10^5 m^3 d^{-1}) = 1.1 tonne C d^{-1}. The agreement between this estimate and our derived value of 1.74 tonne C d^{-1} should probably be considered satisfactory considering the uncertainty in the quantity and characteristics of freshwater run-off to the canal.

Our conclusion, therefore, is that the allochthonous and autochthonous inputs of organic carbon to the Ala Wai Canal amount to about 2.84 tonnes C d^{-1} or about 14 g C m^{-2} d^{-1}, which is almost four times greater than the inputs to any of the estuarine systems analyzed by Nixon (1981). The estimated allochthonous loading of PN is about 1.74/10.7 = 0.16 tonne N d^{-1} = 0.8 g N m^{-2} d^{-1}. If this figure is not misleading, the Ala Wai Canal is one of the most heavily fertilized estuaries in the world. For comparison, the allochthonous inputs of nitrogen to Chesapeake Bay from all sources, dissolved and particulate, amount to only about 26 mg N m^{-2} d^{-1} (Jaworski 1981). Given this large external loading of organic matter, it is not surprising that the Ala Wai Canal is a heterotrophic system. The photosynthesis/respiration ratio is about 0.56. Respiration consumes about 70% of the allochthonous plus autochthonous carbon inputs to the system, sedimentation removes roughly 18%, and the remainder washes out into the Ala Wai yacht harbor.

How will this picture change if the Ala Wai Canal is flushed by pumping in seawater at its head? According to Gonzalez (1971), the circulation in the basin between stations 3 and 16 is driven by thermal processes. The seaward flow of brackish surface water near station 16 transports heat away from the shallow sill, and a temperature gradient develops between the sill and basin water. Cool subsurface sill water, with a salinity comparable to that of basin water, then sinks into the basin, sometimes all the way to the bottom. If seawater is pumped in at the head of the Ala Wai Canal, its temperature will very likely be less than that of the basin water. The temperature of offshore ocean water rarely exceeds 26°C (Laws 1977). The pumping process can

therefore be expected to effectively flush out the basin and eliminate the present subsurface flow from the sill toward the head.

As in other type B estuaries, there is a net outflow of water in the surface layer and a net inflow of water along the bottom of the Ala Wai Canal. On average the difference between these two flows balances the net input of fresh water. There is a net outflow of water at all depths on the ebb tide. The subsurface inflow on the flood tide is not associated with currents in excess of 10–15 cm s^{-1} during dry weather (Gonzalez 1971) and hence theoretically would not be expected to resuspend sediments (Shepard 1963). The inflow of bottom water on the flood tide may increase substantially, however, during periods of stormwater run-off because of entrainment of subsurface water by the outgoing surface flow. Current speeds of roughly 40–50 cm s^{-1} 1 m above the bottom would be required to resuspend the silt size particles that account for much of the sediment at the bottom of the canal (Cox and Miller 1976). Gonzalez (1971) postulated that sediment resuspension and transport by flood tides accounted in part for the distribution pattern of sediments in the canal.

Cox and Miller (1976) proposed that pumping in seawater at the head of the canal at a rate of about 10^4 m^3 hr^{-1} would be sufficient to reduce plankton concentrations without significantly altering the sediment accumulation pattern. The current speeds associated with this pumping would be only a few cm s^{-1} except in the sill area near stations 16–19, and the flow rate would be sufficient to replace all the water in the canal under present conditions in about 48 hr. This replacement time would increase to about 60 hr if the canal were dredged again to a depth of 3 m.

Certainly water clarity in the Ala Wai Canal can be expected to improve because of the flushing effects of the seawater. The bottom, which is presently littered with debris and trash (Dayton 1990), will become clearly visible. Some effort to remove this debris and trash and to eliminate or greatly reduce further inputs will be necessary if the canal is to become aesthetically appealing. Both photosynthesis and respiration rates in the water column can be expected to decline with the reduction in microbial biomass, but because these two rates appear to be in approximate balance under present conditions, their decline will not by itself cause much change in the fallout of organic matter to the sediments. Oxygen concentrations in the bottom waters of the canal, however, are likely to increase substantially, and this increase will very likely change the redox potential of the upper layer of sediments. This change may largely eliminate the occasional odor problem currently associated with the canal, and will probably increase the catabolism of organic matter in the sediments. Hence the net accumulation rate of sediments in the canal will probably decline.

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