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Primary Research Paper

Phytoplankton and zooplankton as indicators of water quality in Discovery Bay, Jamaica

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Abstract

Several investigations exist which use planktonic communities as indicators of water quality in Jamaican and Caribbean Bays, however, few are conducted before there are obvious effects of eutrophication. Therefore, most of our 'baseline' data are for bays already severely affected by pollution. This study was conducted to assess water quality in Discovery Bay, Jamaica, before there were severe signs of eutrophication. The bay was monitored over a 12-month period (October 1995–September 1996) using 10 stations. Physicochemical data indicated a well mixed upper 5 m of water column, below which discontinuities in temperature/salinity profiles indicated the influence of colder, more saline waters associated with deep offshore currents. Physicochemical variables were within the range for oligotrophic systems with a tendency towards mesotrophic in localized areas close to the shoreline. Signs of anthropogenic stress were associated with the eastern, southwestern and western sections of the bay. Of the over 120 species of phytoplankton found in the waters of Discovery Bay, most were neritic/oceanic and diatoms dominated while 11 were found to be potentially harmful species. While these harmful species occurred at all stations they occurred most frequently at stations on the eastern side of the bay. About 107 zooplankton species were identified, 52 of which were copepods. The species also represented a mix of neritic and oceanic taxa and mean abundances for the area ranged from 1077 m^{-3} at the mouth of the bay to 3794 m^{-3} close to the south shore (station 6). Generally stations closest to shore had greater zooplankton abundances than centrally located bay stations and stations close to oceanic influence. *Acartia tonsa* and *Lucifer faxoni* showed greatest densities at shoreline areas of the bay while *Oithona plumifera*, *Undinula vulgaris* and *Temora stylifera* were important at stations closest to oceanic influences. These species were thus considered as indicators of these different areas within the bay. From physicochemical data and the planktonic assemblage, Discovery Bay cannot be considered polluted, it is still more accurately classified as generally pristine with mesotrophic zones in the eastern and southeastern sections of the bay. These data therefore provide a real baseline of conditions for similar tropical coastal embayments.

Introduction

Discovery Bay is situated on the north coast of Jamaica (latitude 18°27.5′ N–18°28.2′ N, longitude 77°25.1′ W–77°24.0′ W) and is about 1.3 km across. It has a narrow opening to the open ocean (120 m wide) that forms a ship channel. The western end of the bay, near the UWI Marine

laboratory, is bordered by rocky shores with limited mangrove stands. Rocky shores are present from western portions of the bay to southern portions near Columbus Park. Southern to eastern shores are characterized mostly by sandy shores along which two fishing beaches, recreational beaches and private homes and establishments are situated (Fig. 1). The bay is cut off from open-ocean by the west fore reef and back reef and the east fore reef, with the ship channel running in between the two. The west fore reef and back reef is comprised of several species of coral including *Acropora palmata*, *Montastrea annularis* and *Agaricia* spp. (Woodley et al., 1981) and is a popular area of study. Immediately in front of the Marine laboratory is a shallow lagoon environment of about 1–5 m deep with sea grass, sand and small coral heads as major features. Remaining portions of the bay slope from shallow depths to 30 m with the deepest portion being about 57 m near the center of the bay. Salinities and temperatures are often high with occasional low salinities in areas believed to have freshwater seeps (D'Elia et al., 1981).

The Discovery Bay area can be considered as one involved in industrial activity, artisanal fishery, recreation and tourism. Bauxite is mined inland and loaded onto vessels at Port Rhoades in the southwestern portion of the bay (Fig. 1). Private homes, tourist resorts and other recreational attractions are located along the eastern and southeastern shores of the bay. These activities along with fishing in the bay are expected to and may have already started to impact the ecology of the bay and its ecosystems. Various analyses of the artisanal fishery in Discovery Bay have shown a decline in fish communities (Picou-Gill et al., 1996). This decline has been attributed to heavy over-fishing, but it was also suggested that heavy commercial activity and subsequent pollution of the bay waters contribute to the decline.

While no previous water quality assessments exist, Discovery Bay is generally considered to be a pristine environment with no point sources with high levels of nutrient inputs or other pollutants. However, absence of a proper sewage treatment system and widespread use of soak-away pits, occasional oil spills, high levels of recreational activity and over-fishing are some of the many negative elements impacting the Discovery Bay environment.

Port Rhoades was situated in Discovery Bay and started shipping bauxite in 1967. Observations of declining fish stocks and increase in benthic algae, especially *Enteromorpha* spp. (J. Woodley, former Director, D.B.M.L, personal communication),

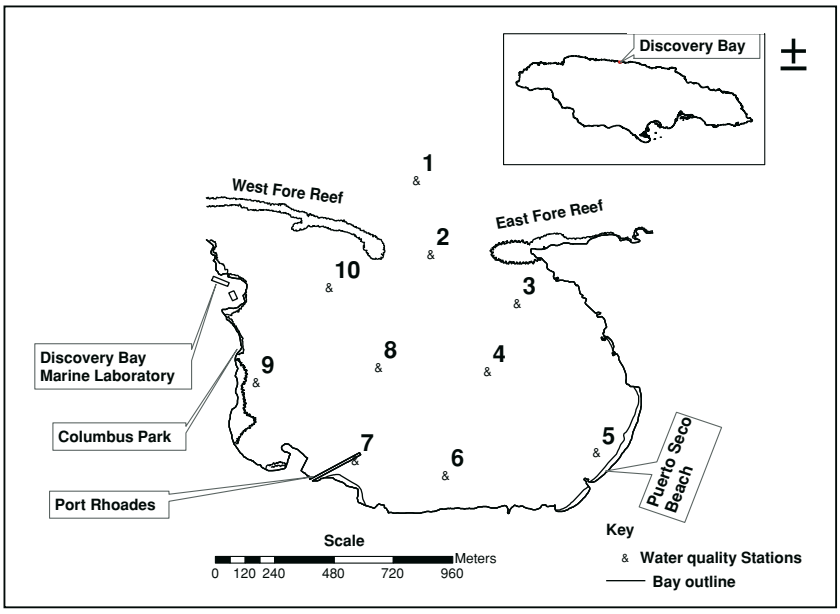

Figure 1. Map showing the location of Discovery Bay, its major features and the 10 stations sampled during the study.

suggested that the bay may be experiencing unknown levels of stress from the range of activities. The study was therefore designed to use physico-chemical data and the planktonic populations to investigate if Discovery Bay was indeed a pristine bay or if the impacts to the bay were sufficient to reduce the water quality and result in eutrophication. In either scenario the findings of this study will constitute a water quality baseline of the Discovery Bay area relevant to other coastal embayments.

Planktonic populations have long been used as ecological indicators (Bary, 1959; Jones, 1968; Lindo, 1991; Webber & Webber, 1998). There are no previous studies providing information on the planktonic populations throughout Discovery Bay. Ohlhorst (1982) observed diel migration patterns of the demersal reef plankton found east of the boat channel into the bay and also reef plankton at various depth gradients in observations on plankton associated with the coral reefs in Discovery Bay.

Methods

Sampling stations and in situ data collection

Ten sampling stations were occupied monthly during the 12-month sampling period (October 1995–September 1996). About 8 of the 10 stations were located within the bay, one at the entrance of the bay and another immediately outside the bay (Fig. 1). Of the eight stations within Discovery Bay, five stations (3, 5, 6, 7 and 9) were sited close to the shore in areas expected to be affected by land drainage and other activities. Stations 4, 8 and 10 were in the deeper areas of the bay with station 8 being the deepest due to its central position.

Physical data collections were made at each station through the water column using a Version 2.10 C (1991), Hydrolab Multi-Parameter probe. Temperature (± 0.15 °C precision), Salinity (± 0.15 precision), dissolved oxygen (D.O.) (± 0.2 mg l^{-1} precision), potential for hydrogen (pH) (precision ± 0.2 pH units) and oxidation/reduction potential (ORP) (precision ± 0.2 mV) were determined at the surface and at 1 m intervals through the water column for the first 15 m; after which values were read every 5 m. Light intensity was measured at the surface and at 2 m intervals to the 10th metre after which readings were taken at 5 m intervals to the 20th metre using a Licor integrating quantum radiometer/photometer with a spherical bulb (model # LI188B).

Phytoplankton methods

Phytoplankton collections were made at each station via whole water samples from 0.5 m (representing surface), 8 m (or in circumstances where the station has a depth less than 8 m, the readings were taken at a depth close to the bay bottom without touching it), 20 m and at 40 m depths using a 6 l Niskin bottle. A 4 l aliquot of the Niskin sample was poured into opaque, round bottom plastic bottles for later chlorophyll *a* determination and a 230 ml aliquot was fixed using 5 ml of Lugol's iodine solution for later identification of the phytoplankton (Steidinger, 1979).

Each whole water sample was filtered for chlorophyll *a* analysis within 4–6 h after collection. Pseudo-replicates of each station and each depth were taken by first inverting the bottles so as to homogenize the contents, then dividing the water sample into 2 l portions. The water was then poured through a size fractioning Nalgeen filtering tower fitted with Nitex screening (pore size 20 μm), Whatman GFD glass fibre filter (pore size 2.7 μm) and Whatman GFF glass fibre filter (pore size 0.7 μm). This effectively divided the phytoplankton into $\geq$20 μm (netplankton), 2.7–20 μm (nanoplankton) and 0.7–2.7 μm (picoplankton). The filtering towers were attached to a vacuum pump adjusted between 10 and 20 mm Hg (Li & Dickie, 1985).

For chlorophyll extraction, the vials were first allowed to come to room temperature before 6 ml of 90% acetone (Lorenzen & Jeffrey, 1978) was added to each. The extraction was allowed to proceed at room temperature in the dark for 24 h. The quantity of extracted chlorophyll *a* was determined using a Turner Sequoia model 450 fluorometer with 660 and 580 μm filters. Chlorophyll *a* concentrations (chlorophyll *a* mg m^{-3}) were determined by using the Strickland equation after corrections made to compensate for the residual water content of the GFD and GFF filters (Hopcroft & Roff, 1990).

$$\text{Chlorophyll } a \text{ (mg m}^{-3}) = R \times D_F \times v/V$$

where R = fluorometer reading; D_F = door factor; v = volume of acetone used in extraction (ml) and V = volume of water filtered (l) (Parsons et al., 1984).

For the purposes of identification of the phytoplankton, the contents of the 230 ml preserved sample were homogenized by gently inverting and pouring into settling chambers of 10, 50 and 100 cm^3 volumes. The chambers were allowed to stand for between 3 and 48 h before examination. The time for settling the sample was dependent on the height or volume of the settling chamber (Edler, 1979). A Leitz Labovert inverted transmitted light microscope model #090-122.012 was used to carry out examinations (Mag. 320×). Four diagonals of the settling chamber were examined in addition to the circumference in order to eliminate the edge effect in the settling of phytoplankton cells (Utermohl, 1958). Individual cells were identified to species level so as to provide information which would assist in performing community analyses, however enumeration was not conducted. Identification was conducted with the aid of keys and plates (Kofoid & Swezy, 1921; Lebour, 1930, 1962; Schiller, 1933,1937; Davis, 1955; Brunel, 1962; Cupp, 1967; Saunders & Glenn, 1969; Steidinger & Williams, 1970; Newell & Newell, 1977; Bellinger, 1992; UNESCO, 1995).

Zooplankton methods

Zooplankton collections were done contemporaneously with phytoplankton using replicate vertical hauls ($n = 2$) with the cod end of the net 0.2 m off the bottom through the entire water column. Two plankton nets, each with 200 and 64 μm meshes (SCOR, WP2 pattern; UNESCO, 1968) were used for collections. These were hauled at a speed of $\sim$0.5 m s^{-1}. Samples were fixed immediately in the field using 10 ml of full strength formalin (37% v/v formaldehyde in water).

Samples were later preserved in 10% formalin in filtered seawater and sub sampled using the beaker split method (Van Guelphen et al., 1982) or in the case of the 64 μm mesh collections, a 60 ml graduated syringe was used for sub sampling (Dunbar & Webber, 2003). All taxonomic groups were enumerated from the 200 μm net with the exception of copepodites of small copepods (e.g. *Paracalanus* spp. and *Oithona* spp.), copepod nauplii and small larvae which passed through the 200 μm meshes. These were enumerated from the 64 μm mesh net.

The mean filtering efficiency of each net was determined at 85% for the 200 μm mesh net and 68% for the net with 64 μm meshes. Filtration efficiencies were determined using a pair of general oceanics (GO) flow meters attached to each net such that one flow meter (FM1) was influenced by water flowing through the net and the other (FM2) by water flowing past the net. The ratio of number of revolutions of FM1:FM2 yielded the filtration efficiency (Chisholm & Roff, 1990). These correction factors were applied to the calculation of numbers of zooplankton m^{-3} of water sampled. On two occasions (beginning and end of the sampling period), sampling (15–17% C.V.) and sub sampling (15–19% C.V.) variability was determined for replicate hauls ($n = 5$) and sub samples ($n = 5$).

Zooplankton identification and enumeration was done on preserved samples using a Bogorov tray and a Wild M7 stereomicroscope (Mag. 60×). The taxonomic guides employed were: Gonzales & Bowman (1965) and Owre & Foyo (1967), Yeatman (1976) for copepods; Michel (1984) for chaetognaths; Davis, 1955, Wickstead (1976), Newell & Newell (1977), Todd et al. (1996) and Gerber (2000) for general taxa.

Nutrient analysis

Water for nutrient analysis was collected from the filtrate from the size fractionization filtration of the phytoplankton. At each station approximately 20 ml from each depth (i.e. surface, subsurface, 20 and 42 m) were bottled and frozen. Defrosted samples were analyzed using a Technicon Auto Analyzer II continuous flow autoanalyser. As was the case for the phytoplankton, nutrient values from each depth were averaged to give values representing the entire water column.

Dissolved inorganic nitrogen as nitrate (nitrate + nitrite) was determined using the automated version of sulfanilamide–diazo colorimetric method following copper–cadmium reduction column (Armstrong et al., 1967; Grasshoff, 1969).

It has a detection limit of 0.1 μmol. l^{-1} with a coefficient of variation 0.59%. Dissolved ortho phosphorus as phosphate (PO_4^{3-}) was determined using the automated versions of the phosphomolybdenum colorimetric method (Murphy & Riley, 1962). The detection limit of this process is 0.08 μmol l^{-1} with a coefficient of variation of 1.98%.

Statistical tests

ANCOVA tests were performed on normalized data to determine the existence of significant spatial differences within the bay with respect to the various parameters collected. A p-value of less than 0.05 was taken to indicate significant differences. A correlation matrix was generated for biological parameters in an effort to show associations between different groups. Statistical analysis (MANOVA, cluster analysis, correlation matrix and forward stepwise multiple regression) was done using the statistical programme STATISTICA release 6 for Windows by STATSOFT Inc., 1998.

Results

All physicochemical (*in situ* measurements and nutrients) and phytoplankton data collected at discrete depths were averaged so as to represent the entire water column. This facilitated comparison with the zooplankton which was collected by hauls through the water column.

Physicochemical data

There was no significant temporal (monthly) or spatial variation (across stations) in many of the physicochemical variables examined. However, mean ($n = 12$) temperature and salinity profiles determined over the sampling period for each station were examined in an effort to see whether there was significant influence from subsurface water masses at particular stations. Stations 3, 4, 5 and 6 seemed to show the sub-surface influence between 5 and 15 m while at stations 8 and 10 the influence was seen between 5 and 10 m. These were demonstrated as a column of water with lower temperature (2 °C difference) and higher salinity (difference of 2) between 5 and 15 m than temperature and salinity above and below (Fig. 2a and b – salinity and temperature profiles, respectively).

Light values were not consistently sampled and the data were not sufficient to allow for statistical analysis. However, extinction coefficients could be calculated for each station. Average extinction coefficient (Fig. 3a) at each station showed greatest light penetration (minimum extinction coefficient) at stations 1, 2 and 10. Worst light penetration was observed at station 3.

Average nitrate concentrations varied significantly across stations during the 12 months of sampling ($p = 0.0003$). Values ranged from a high of $\sim$2 μmol at station 7 to just under 1 μmol at stations 1 and 5. There was a general increase in average nitrate concentrations from the eastern to the western side of the bay (Fig. 3b). Despite lack of significant spatial variability ($p = 0.940$) in mean salinity (averaged through the water column), values were plotted (Fig. 3c) to facilitate comparison with the nitrates (as fresh water seeps are often high in nitrates; D'Elia et al., 1981). Areas with lowest mean salinity were station 7 (near Port Rhoades) and station 9 (near Columbus Park). These were also the stations with the highest nitrates, however, no statistical correlations were obtained (Table 1).

Biological data – phytoplankton

Over 120 phytoplankton species (from net and larger nanoplankton fractions) were observed in the waters of Discovery Bay during the study (Appendix 1). The phytoplankton community was dominated by diatoms with significantly fewer dinoflagellates, and rare occurrences of the groups flagellates, chlorophytes and cyanophytes. The number of species identified was however a gross underestimation, as the picoplankton fraction which dominated the biomass could not be identified without oil immersion or electron microscopy. Neither of which were possible in this study.

It was also determined that a group of species could be considered characteristic (occurring more than 65% of the time) for each station (Table 2). Only at station 1 was there an absence of phytoplankton groups which could be considered characteristic and at station 2 only one species was identified. Characteristic species at stations 3, 4, 5,

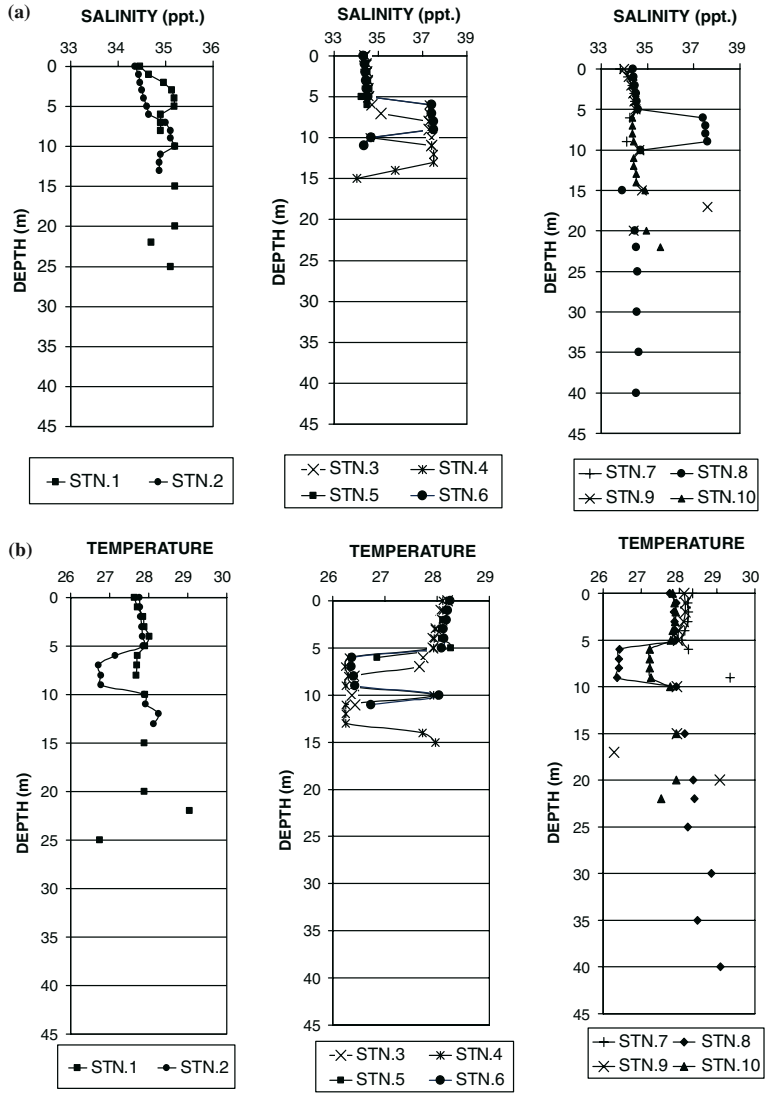

Figure 2. Temperature and salinity profiles for each station.

6 and 7 were similar to each other while at stations and 10 characteristic groups were different. Eleven species of potentially harmful phytoplankton (IOC, 2002) were found within the waters of Discovery Bay. These were: *Nitzchia pungens*, *Pyrodinium bahamense*, *Prorocentrum* sp., *Nitzchia seriata*, *Skeletonema costatum*, *Nostoc commune*, *Skeletonema subsalsum*, *Nostoc piscinall*, *Thalassioria aestivalis*, *Oscillatoria tenius* and *Thalassioria gravida*. These occurred more frequently at stations 3, 4 and 5 (Table 3), albeit with low abundances.

Of the numerical data generated from the phytoplankton samples only number of species, phytoplankton biomass for total, nanoplankton and picoplankton were found to vary significantly between stations ($p = 0.00352$, 0.0019, 0.0001 and 0.0006, respectively). While homogenous group

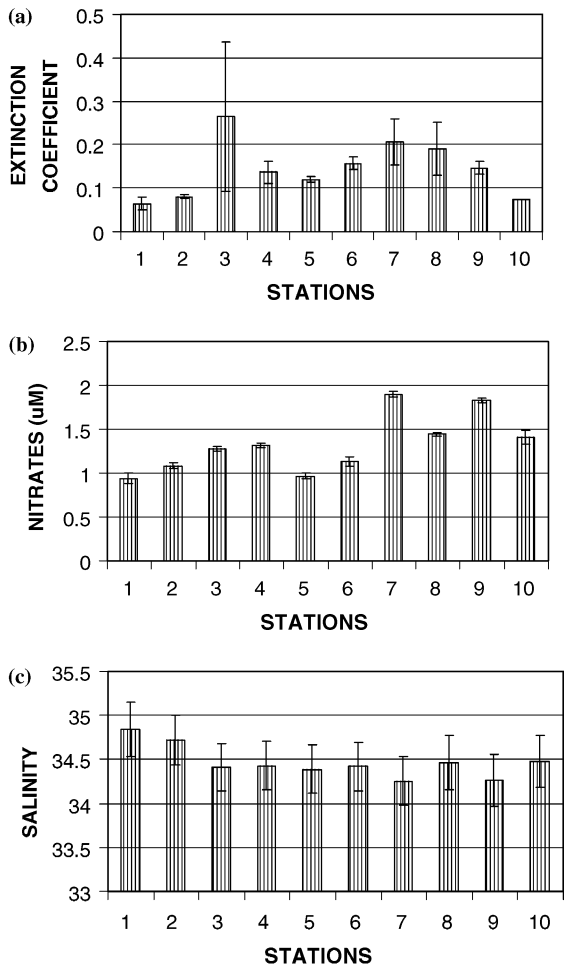

Figure 3. Selected physicochemical variables and their distribution across the 10 station in Discovery Bay. (a) Extinction coefficient as means and standard error bars. (b) Nitrates as means with standard error bars. (c) Salinity values as means with standard error bars.

categorization from ANCOVA analysis produced various patterns, stations 1 and 2 were constantly at the lower end of all groupings and stations 3, 4, 5 and 6 at the higher end. The average number of species found at each station for the entire water column ranged from 11 at station 1 to 18 at station 3 (Fig. 4a).

Total phytoplankton biomass as chlorophyll *a* was maximum at station 4 on the eastern side of the bay, moderately high at station 9 on the western side of the bay and minimum at station 1, just outside the bay (Fig. 5). Low oceanic values penetrated from station 1 to stations 2, 8 and 10 at the centre of the bay. Greatest fluctuations about the mean were recorded at stations 4, 5 and 6. Generally nano and picoplankton size fractions (2.7 and 0.7 μm, respectively) were consistently dominant, while the netplankton (20 μm) accounted for a smallest portion of the phytoplankton biomass (Fig. 6) and did not vary significantly across stations ($p = 0.5188$). Net, nano and picoplankton accounted for 10, 43 and 47%, respectively of the total phytoplankton biomass found in the bay.

Biological data – zooplankton

Among 107 different zooplankton, 52 were copepods, were identified in the Discovery Bay area. Appendix 2 lists the zooplankton species found in this study. There were eight taxonomic groups that were considered of numerical importance. The eight groups were; Cnidaria, Calanoida, Cyclopoida, Harpacticoida, Larvacea, Chaetognatha, Larvae and 'others' which included foraminiferans, molluscs, cladocerans, amphipods, salps and others. Individual species which were numerically important or believed to be indicators of particular masses were: *Acartia tonsa*, *Lucifer faxoni*, *Calanopia americana*, *Temora stylifera*, *Oithona plumifera*, and *Undinula vulgaris*.

The numeric zooplankton parameters examined were all found to show significant spatial variation across stations. These included number of species, abundance of total zooplankton as well as numerically important groups and individual species. The number of species varied significantly across stations ($p \leq 0.0001$). Station 1 (just outside the bay) had highest mean total numbers of species (richness) while stations 5, 6 and 7 which were closest to shoreline areas, had lowest numbers (Fig. 7a). Mean total abundances across stations were significantly different ($p \leq 0.0001$). Station 6 had maximum values of 3794 nos m^{-3} and station 1 had minimum values of 1077 nos m^{-3} but generally stations 5, 6 and 7, which were closest to shoreline areas, had highest abundances (Fig. 7a).

Of the eight taxonomic groups assessed, calanoids were dominant contributors at most stations (4–10) while cyclopoids were the most significant contributors at stations 1, 2 and 3 (Fig. 7b). Larvae and larvaceans were also prevalent at most stations. Larval abundances were highest at

Table 1. Correlation matrix of significant variables and Salinity (SAL)

VAR	NANO	PICO	TOTAL	NO_3	ZSPP	ZTOT	MED	CAL	CYC	HAR	LUCI	LAR1	CHAE	LAR2	NAUPL	SAL
NANO	1.00	**0.43**	**0.87**	**−0.37**	0.19	0.02	0.11	−0.1	−0.17	−0.224	−0.25	0.19	0.02	0.05	−0.22	0.17
PICO		1.00	**0.82**	−0.13	0.17	0.2	−0.03	0.11	−0.16	−0.33	−0.13	−0.05	0.08	0.17	−0.30	0.37
TOTAL			1.00	−0.30	0.22	0.12	0.06	−0.00	−0.20	−0.32	−0.22	0.09	−0.03	0.12	−0.30	0.31
NO_3				1.00	−0.05	−0.36	−0.28	−0.15	−0.33	**0.48**	**0.53**	−0.31	−0.08	0.02	0.16	0.19
ZSPP					1.00	−0.01	0.34	0.06	−0.25	−0.03	0.11	0.13	0.07	0.03	−0.33	0.32
ZTOT						1.00	**0.52**	**0.83**	**0.42**	−0.04	0.08	**0.52**	**0.44**	**0.62**	0.1	−0.1
MED							1.00	0.35	0.32	−0.21	0.23	**40**	**0.55**	0.39	−0.01	−0.33
CAL								1.00	0.05	0.01	0.18	0.20	.27	**0.49**	0.22	0.02
CYC									1.00	0.05	−0.35	0.33	0.30	−0.02	−0.17	−0.3
HAR										1.00	0.05	0.04	0.18	−0.06	0.12	0.11
LUCI											1.00	0.06	0.17	**0.40**	0.32	0.02
LAR1												1.00	**0.49**	0.37	0.13	−0.03
CHAE													1.00	**0.41**	−0.11	−0.11
LAR2														1.00	0.23	0.12
NAUPL															1.00	**−0.42**
SAL																1.00

Significant correlations (at $p < 0.05$) are in bold. NANO – nanoplankton chlorophyll *a*, PICO – picoplankton chlorophyll *a*, TOTAL – total phytoplankton chlorophyll *a*, NO_3 – Nitrates, ZSPP – zooplankton species number, ZTOT – zooplankton total nos m^{-3}, MED – medusae numbers, CAL – calanoid numbers, CYC – cycopoid numbers, HAR – harpacticoid numbers, LUCI – *Lucifer faxoni* numbers, LAR1 – Larvacean numbers, CHAE – chaetognath numbers, LAR2 – Larval numbers, NAUPL – copepod nauplii numbers and SAL – salinity values.

Table 2. Characteristic phytoplankton species at each station

Station #	Characteristic species
1	None
2	*Monoraphidium* sp.
3	*Nitzchia longissima, Prorocentrum dolrolus, Rhizosolenia bergonii, Rhizosolenia setigera*
4	*Navicula clavata, Prorocentrum dolrolus, Rhizosolenia bergonii, T. longissima*
5	*Nitzchia closterium, Prorocentrum dolrolus, Rhizosolenia bergonii, T. longissma*
6	*N. closterium, P. dolrolus, N. longissma, R. setigera, T. longissima*
7	*R. setigera, N. clavata, R. bergonii, T. longissma*
8	*N/A*
9	*N. clavata, R. bergonii, N. closterium, Prorocentrum nudum, Rhizosolenia hebetata,*
10	*P. nudum, P. dolrolus*

N/A means 'not assessed'.

shore-based stations while station 1 had minimum numbers. Larvaceans were more prevalent at inshore and central bay stations, while those stations closest to influence from the open ocean had minimum abundances. Chaetognath abundances were very low (maximum of 25 m^{-3}) at station 5. The group 'other' had maximum abundances (35 m^{-3}) at station 9. Maximum medusa abundances occurred at station 5. Harpacticoid abundances were below 4 individuals m^{-3} at all stations.

It was observed that individual species were consistently abundant in particular areas of the bay and could possibly be deemed indicative of the water masses from which they were sampled. *Acartia tonsa* and *L. faxoni* was prevalent at the inshore stations. The deeper central bay stations with significant oceanic influence and possible fresh water influence had significant abundances of *C. americana*. The stations closest to oceanic influence (stations 1, 2 and 3) had higher abundances of *O. plumifera*, *U. vulgaris* and *T. stylifera* than central and inner bay stations (Fig. 8).

Discussion

Discovery Bay is a relatively small bay and so it is expected that a high degree of homogeneity may exist for various physical parameters. This was evident in the lack of significant spatial variability for most physicochemical parameters and the inability of these parameters to 'explain' the variability in biological parameters (no valid coefficient of determination values were obtained from multiple regressions). For the physicochemical parameters that showed significant spatial variation there were clear trends. The eastern and southwestern sections of the bay had lower salinities, high average light extinction coefficients and higher nitrates; suggesting that these were the most 'eutrophic' areas of the bay. Possible sources of freshwater and associated nitrates are, Port Rhoades (station 7), Columbus Park (station 9) and fresh water seeps within the bay (D' Elia et al., 1981).

Another physicochemical parameter examined in order to determine the zones of stress in Discovery Bay was light extinction coefficient.

Table 3. Frequencies of harmful phytoplankton species at each station

Species	Stations									
	1	2	3	4	5	6	7	8	9	10
Nitzchia pungens	22	22	22	22	22	22	22		11	25
Nostoc commune				6						
Nostoc piscinall		11	22	22	6		17		6	20
Oscillatoria tenius		6		6	6	11	6			
Prorocentrum sp.			6							
Pyrodinium bahamense			17	6	6		11			7
Skeletonema costatum	17		6	6	6	11				7
Skeletonema subsalsum			11			6				
Thalassioria aestivalis			6	6	6	11	6			
Thalassioria gravida	11	11								

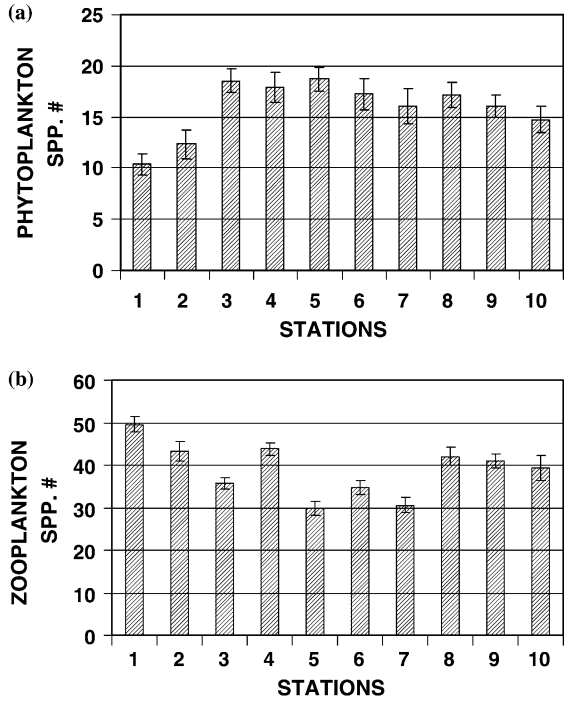

Figure 4. Number of (a) phytoplankton and (b) zooplankton species (taxonomic richness) at each station.

Stations with highest extinction coefficient were again were in the eastern and southern areas of the bay (Stations 3 and 7) as well as station 8 at the centre of the bay. However, while light extinction coefficient can be a good indicator of water quality, it may not be conclusive to eutrophication as water clarity may be affected by non-biological turbidity (sediment load or silting) or by biological turbidity (phytoplankton and zooplankton) (Webber & Webber, 1998).

The occurrence of high phytoplankton biomass (chlorophyll *a*) was therefore compared with incidence of high light extinction coefficients. It was observed that while high phytoplankton biomass occurred at stations in close proximity to those with high extinction coefficients the poor light climate could not always be explained by algal biomass. The more likely cause for poor light penetration was resuspension of sediments due to shipping activity as especially stations 7 and 8 are associated with ship channel marker buoys or the actual bauxite pier, from which spillage occasionally occurs. This is further supported by the high fluctuation about the mean extinction coefficient (high standard error bars). While non-biological turbidity may be a temporary feature associated

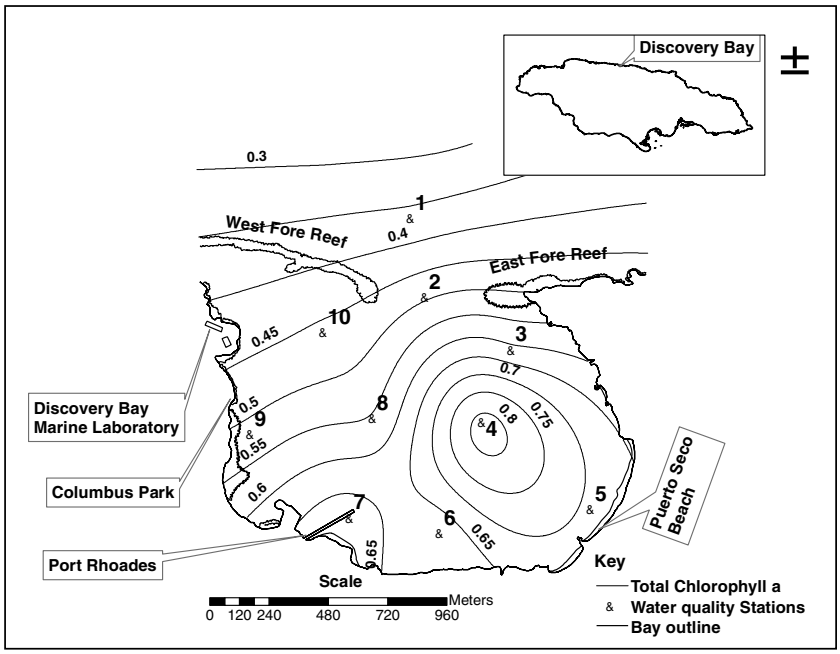

Figure 5. Map showing chlorophyll *a* spatial distribution across Discovery Bay.

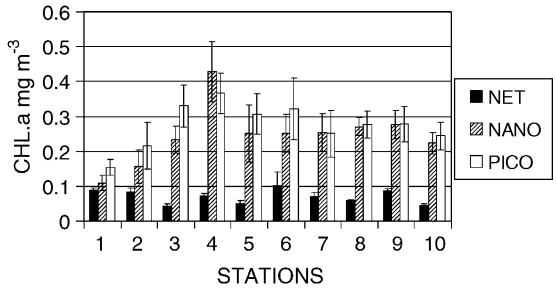

Figure 6. Phytoplankton biomass across stations as chlorophyll *a* values for different size fractions with standard error (S.E.) bars.

with increased mixing, biological turbidity is a feature of increased eutrophication (Webber & Webber, 1998). This latter statement supports the theory that areas within the bay are being affected by increased eutrophication.

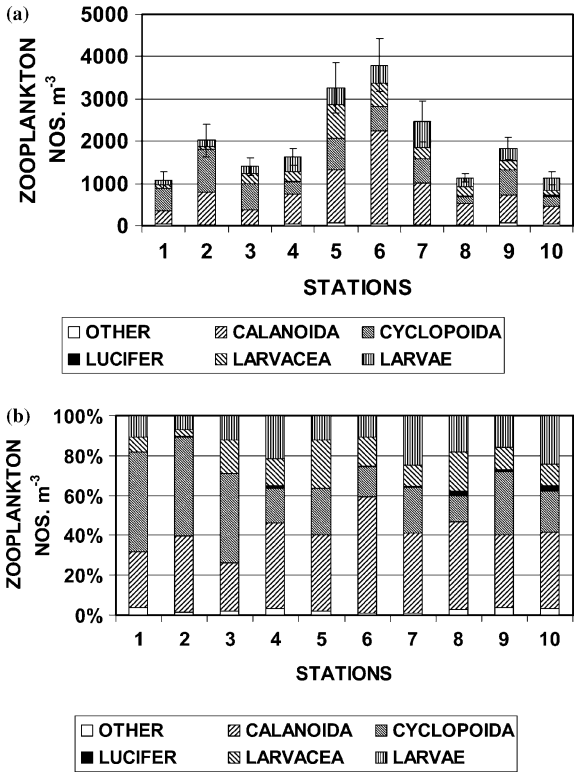

Figure 7. Zooplankton abundances for (a) actual numbers of contributing groups. S.E. bar represents variation about the mean total numbers m^{-3} and (b) % contribution of the major groups of zooplankton.

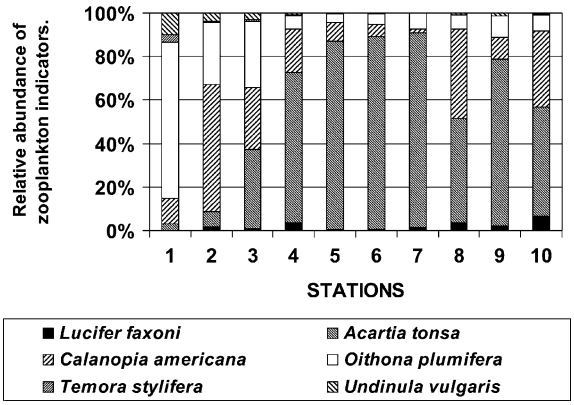

Figure 8. Relative abundance of 6 'indicator species' at each station.

The areas of Discovery Bay with higher chlorophyll *a* also tended to have higher frequency of occurrence of potentially harmful phytoplankton species. Waters near stations 3, 4 and 5 had the highest incidence of harmful phytoplankton species that occurred at frequencies to be categorized as 'occasional' visitors. While these potentially harmful phytoplankton species were found in Discovery Bay, at the time they did not occur in sufficiently high concentrations to be of concern, but this should be noted in the event of any further changes in the area which would result in conditions favouring these phytoplankton.

The number of phytoplankton species (taxonomic richness) was used as an index of diversity (Magurran, 1996). However, this was not conclusive because although the parameter showed significant spatial variation, the more pristine areas (outside the bay and at the bay entrance) had lowest diversity. This was not unexpected as the dominant phytoplankton group (the picoplankton) were not identified and therefore not represented in the species number and they would have been more important in the 'oceanic' areas of the bay.

The zooplankton taxonomic richness, however, was more in keeping with the expected with maximum diversity at northern and deeper stations and minimum at stations close to the southern shore. The shallow nature of inshore stations may effect low species numbers as a result of absence of those individuals common at deep levels. Generally the deeper central bay stations had more

species than inshore stations but fewer than outer bay stations. This kind of spatial variation in species numbers was also observed in Jobos Bay, Puerto Rico, where inner bay regions had fewer species than outer bay areas (Youngbluth, 1980). The overall number of zooplankton taxa identified can be compared to Kingston Harbour (54 species), Hellshire coast (61 species) and the Port Royal Cays (70 species). These areas are considered ranging from eutrophic to mesotrophic on the south coast shelf (Webber et al., 1996). The 107 species identified from Discovery Bay which has comparable depths would suggest oligotrophic conditions. The number of copepods found in this study was also comparable to that found offshore Discovery Bay (Webber & Roff, 1995) in which 69 copepods were identified from collections from 60 to 200 m. Fifty-two copepod species from inshore collections from significantly shallower depths in this study further supports the pristine nature of the bay.

It was difficult to identify species of phytoplankton which could be considered as indicator species within the bay as the community covered a wide range from oceanic, brackish, saline, eutrophic, neritic and littoral occurring phytoplankton. The attempt at characterizing each station by a distinct assemblage of phytoplankton saw significant overlap and in some cases no characteristic species could be identified. This supports the homogeneity of the bay. However, the domination of the phytoplankton community by diatoms over dinoflagellates is a clear indication that the bay should not be termed eutrophic since eutrophic waters are usually characterized with dinoflagellate dominance, especially in coastal embayments (Webber & Webber 1998). It should be noted that species of *Cosmarium*, *Euglena* and *Oscillatoria*, while occurring infrequently only occurred on the eastern portion of the bay at stations 3, 4, 5 and 6 and are consistent with the introduction of nutrient rich water from coastal runoff or freshwater intrusion from seeps.

When zooplankton species composition was combined with relative abundance, a pattern of distribution of 'neritic' and 'oceanic' species was evident. While the zooplankton species identified were a mix of offshore and inshore plankton due to the fact that the narrow north coast shelf facilitated significant mixing of coastal and oceanic waters, the 'oceanic' species like *O. plumifera*, *U. vulgaris* and *T. stylifera* were more important at stations closer to the northern exposed areas of the bay. Coastal species like *A. tonsa* and *L. faxoni* were only of significance near the southern shore, especially in areas experiencing fresh water inputs. Furthermore, the relatively low numbers of *L. faxoni* throughout the bay adds support to its oligotrophic nature (Lindo, 1991; Webber et al., 1996). *Acartia tonsa* is a common bay species (Hopkins, 1977; Youngbluth, 1980; Buskey, 1993; Dunbar & Webber, 2003) and its prevalence in Discovery Bay is not surprising. *Acartia tonsa* was a permanent feature of inshore stations that possibly received organic input from land runoff and other processes impacting the coast. It is a hardy species which can thrive under conditions which may be considered extreme as was found in the rainy and dry season in the eutrophic, Bojorquez lagoon (Alvarez-Cadena et al., 1996). Dominance of *C. americana* at deep central bay stations that may be slightly turbid suggests diel migratory patterns as a part of its existence. Youngbluth (1980) caught *C. americana* only in night samples and Clarke (1934) found that during the day it lives very close to the bottom possibly buried in mud. *Temora stylifera* and *O. plumifera*, common oceanic species were prevalent at the stations closest to oceanic influence. The latter species was also present inshore, and may suggest that conditions are pristine enough for its survival or that it is a hardy species. Therefore, *A. tonsa* and *L. faxoni* best defined possible inshore influence, *C. americana*, central bay influence, and *T. stylifera* and *O. plumifera* best define oceanic influence.

The dominance of the picoplankton size fraction in coastal embayment is indicative of oligotrophic conditions (Hopcroft, 1988; Webber & Roff, 1995; Webber & Webber, 1998). However, in Discovery Bay there was an approximate equal dominance of pico and nanoplankton thereby suggesting a tendency towards a mesotrophic water mass. By contrast, the phytoplankton community of, Kingston Harbour, a polluted estuary located along the southeastern coast of Jamaica, was dominated by netplankton which accounted for approximately 43% of the total biomass (Webber & Roff, 1996). The total chlorophyll *a* values which were overall at a level of $\sim$0.5 mg m^{-3}, were also well below what is typical of coastal bays exposed to mild eutrophication

($\sim$2 mg m^{-3}) but above the values for offshore oligotrophic systems ($\sim$0.2 mg m^{-3}) (Sieburth et al., 1978). The observation of maximum chlorophyll *a* values and largest fluctuation in chlorophyll *a* at stations 4, 5 and 6 on the eastern side of the bay provides evidence of episodic nutrient enrichment in that area. These areas have also been suggested as possible non-point sources of enrichment from housing and tourism development. This variability indicates the episodic nature of the influence in a localized area.

It has been suggested that the north coast of Jamaica is influenced by nutrient deficient waters from the Antilles current which enter the Caribbean via the Windward passage (Hallock & Elrod, 1988). This is in contrast to the lower salinity and higher nutrient waters of the Caribbean current which affects the south coast of Jamaica (Webber & Roff, 1995). Chlorophyll *a* concentrations of 0.111 mg m^{-3} and 0.911 mg m^{-3} for north and south coast waters, respectively may further explain these observations (Roff et al., 1995). This factor in association with the narrow shelf may explain the relatively low abundance of zooplankton in the bay. The Discovery Bay numbers are similar to that obtained for South–East Cay which is the furthest of the Port Royal Cays from the eutrophic Kingston Harbour (Lindo, 1991; Webber et al., 1996).

The southeastern shores of Discovery Bay is the site of a recreational beach, a coast guard station, the Bauxite loading pier (Port Rhoades), tourist resorts and houses, some of which may serve as sources of significant nutrient input. The stations in this area (5, 6 and 7), therefore had highest zooplankton abundances as phytoplankton, bacteria and detrital matter can be sustained by nutrient inputs and serve as a food source for the zooplankton. Central bay stations, being further from influence of any possible nutrient influxes at the coast, still had higher abundances than offshore stations which had significant oceanic influence and minimal impacts from land based processes. Calanoid dominance at most stations is in keeping with the general dominance of the group (Longhurst & Pauly, 1987). Cyclopoid dominance at outer bay stations was attributable primarily to high numbers of *Oithona plumifera* a common oceanic species (Björnberg, 1971). Central and inner bay stations had significant larval abundances possibly because of higher food availability and relative degree of shelter for larval survival. The choice of these areas by the species (including fish populations) could suggest that environmental conditions are favourable for development of the young and pollution stress is minimal. The only other groups of significance were the Larvaceans and Larvae. The latter was significantly influenced by the large numbers of crustacean larvae and fish eggs and larvae associated with this sheltered coastal embayment. Low medusae and chaetognath abundances throughout the study could further suggest a pristine bay, as these individuals are sustained by high herbivorous zooplankton populations. Low *Lucifer faxoni* abundances throughout the bay could again suggest that the bay is pristine as high numbers of *L. faxoni* has been described as indicative of eutrophic waters (Webber et al., 1996). Harpacticoid populations are associated with shallow/littoral areas dominated by grass beds, which were not represented by the stations sampled in Discovery Bay, and so low harpacticoid abundances were not surprising.

Conclusions

Discovery Bay cannot be considered as experiencing high levels of pollution stress with a single major source of input. However, there are areas of the bay that seem to be experiencing nutrient input which impact stations in close proximity. These areas are primarily the eastern, southern and southwestern areas. However, when overall conditions are compared to other coastal areas of Jamaica, Discovery Bay may be considered a pristine tropical embayment and therefore its planktonic community provides a real baseline of conditions in a bay before any obvious effects of eutrophication.

Nevertheless, although the bay is not as polluted as previously envisioned, there are indicators that contaminants are present. As a result, developers and residents should be cognizant of the fact that construction along the coastal zone should be carefully regulated and monitored. Additionally all waste and/or wastewater systems should be closely monitored so as to prevent detrimental effluent from getting into the waters of the bay.

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Appendix

Appendix 1. List of phytoplankton taxa identified in Discovery Bay

Diatom taxa	Dinoflagellate taxa
Achnanthes periata	*Amphidinium asymmetricum*
Achnanthes pseudogroenlandica	*Amphisolenia bifurcata*
Actinocyclus octonarius	*Amphisolenia inflata*
Amphiprora alata	*Amphisolenia palaeotheroides*
Amphiprora hyperborea	*Ceratium furca*
Amphora bigibba	*Ceratium hircus*
Amphora marina	*Ceratium pentagonum*
Amphora venticosa	*Ceratium trichoceros*
Asterionella japonica	*Gonyaulax turbynei*
Asterionella notata	*Gonyaulux birostris*
Asterionella sp.	*Gonyaulux digitale*
Aulacodiscus kittoni	*Gymnodium fusus*
Biddulphia pulchella	*Peridinium conicoides*
Biddulphia rhombus	*Peridinium conicum*
Buddulphia puchella	*Peridinium nudum*
Campylodiscus simularis	*Peridinium pellucidum*
Chaetoceros teres	*Peridinium* sp.
Climacosphenia moniligera	*Phalacroma praetexium*
Cocconeis disculaides	*Prorocentrium* sp.
Cocconeis placentula	*Prorocentrium breve*
Coscinodiscus perforatus	*Protoperidinium claudicans*
Cyclotella operculata	*Protoperidinium trystilura*
Cymbella sp.	*Pyrodinium bahamense*
Diploneis chersonensis	
Diploneis crabro	Flagellate taxa
Diploneis smithii	*Euglena allorgei*

Appendix 1. (Continued)

Diploneis sp.	*Synura capitata*
Diplonesis bombus	*Synura spinosa*
Gramatophora marina	
Gramatophora oceanica	Chlorophyte taxa
Gramatophora sp.	*Closterium littorall*
Gyrosigma prolongatum	*Cosmarium botrytis*
Gyrosigma sp.	*Pediastrum clathratum*
Gyrosigma wans beckii	
Isthmia enervis	Cyanophyte taxa
Licmophora flabellata	*Nostoc commune*
Licomorpha abbreviata	*Nostoc piscinall*
Melosira westii	*Oscillatoria princeps*
Monoraphidium sp.	*Oscillatoria subtilissima*
Navicula atlantica	*Oscillatoria tenuis*
Navicula atoms	*Spirulina major*
Navicula cancellata	
Navicula clevata	*Spirulina subsalsa*
Navicula crucifera	
Navicula elegans	
Navicula phyllepta	
Navicula septentrionalis	
Navicula sp.	
Navicula vanhoffeni	
Navicula wawrikae	
Nitzchia bilobata	
Nitzchia closterium	
Nitzchia constricta	
Nitzchia longissima	
Nitzchia pacifica	
Nitzchia paradoxa	
Nitzchia pungens	
Nitzchia seriata	
Nitzchia sigma	
Oxytoxum diploconus	
Oxytoxum reticulatum	
Pinnularia cruciformis	
Pinnularia rectangulata	
Planktoniella sol	
Pleurosigma normanii	
Pseudoeunotia doliolus	
Rhabdonema adriaticum	
Rhabdonema arcuatum	
Rhabdonema sp.	
Rhizosolenia alata	
Rhizosolenia bergonii	
Rhizosolenia delicatula	

Appendix 1. (Continued)

Rhizosolenia hebetata
Rhizosolenia robusta
Rhizosolenia setigera
Rhizosolenia stolterfothii
Skeletonema costatum
Skeletonema subsalsum
Striatella delicatala
Surirella fastuosa
Synedra sp.
Synedra undulata
Thalassioria aestivalis
Thalassioria gravida
Thalassiothrix longissima
Tolypothrix tjipanasensis

Appendix 2. List of zooplankton taxa identified in Discovery Bay

PROTOZOA	MOLLUSCA
Foraminifera	*Creseis* sp.
MEDUSAE	*Cymbulia* sp.
Aglaura hemistoma	Heteropod
Amphinema rogusum	Pteropod
Bougainvilla sp.	CHELICERATA
Cladonema radiatum	Pycnogonida
Cosmititirella davisi	CLADOCERA
Dipurena sp.	*Evadne sp.*
Eutima sp.	*Penilia avirostris*
Leukartiara octona	OSTRACODA
Lovenella sp.	Ostracod sp.
Mitrocomella sp.	COPEPODA
Obelia sp.	**(Calanoida)**
Oceana armata	*Acartia spinata*
Phialella sp.	*Acartia tonsa*
Philidium sp.	*Calanopia americana*
Podocoryne minima	*Calocalanus pavo*
Rahtkea octopunctata	*Candacia* spp.
Rhopalonema velatum	*Centropages violaceus*
Sarsia eximia	*Clausocalanus arcuircornis*
Sarsia gemminifera	*Clausocalanus furcatus*
Sarsia prolifera	*Eucalanus elongatus*
Steenstrupia nutans	*Euchaeta marina*
Other Medusa	*Haloptilus longicornis*
SIPHONOPHORA	*Labidocera acutifrons*
Abylopsis sp.	*Labidocera aestiva*

Appendix 2. (Continued)

Bassia bassensis	*Lucicutia flavicornis*
Enneagonum sp.	*Mecynocera clausii*
Eudoxid sp.	*Neocalanus robustior*
Lensia sp.	*Paracalanus aculeatus*
Muggiea sp.	*Paracalanus crassirostris*
Nectopyramis diomedeae	*Pleurommama gracilis*
Nectopyramis spinosa	*Pleurommama quadrungulata*
Physonectid colony	*Pseudodiaptomus cokeri*
PLATYHELMINTHES	*Rhincalanus cornutus*
Flatworm	**(Calanoida contd.)**
NEMATODA	*Scolecithrix danae*
Nematodes	*Temora stylifera*
POLYCHAETA	*Temora turbinata*
Autolytus edwardsi	*Undinula vulgaris*
Tomopteris sp.	*Unknown Calanoid*
Other Polychaetes	Other Calanoids
	(Cyclopoida)
	Copilia mirabilis
Copilia quadrata	CHAETOGNATHA
Corissa parva	*Krohnitta subtilis*
Corycaeus speciosus	*Pterosagitta draco*
Corycaeus sp.	*Sagitta enflata*
Farranula sp.	*Sagitta hispida*
Lubbockia squillimana	*LARVAE*
Oithona nana	Actinula
Oithona occulata	Arachnactis
Oithona plumifera	Ascidian
Oncaea notopus	Brachiolaria
Oncaea venusta	Brachyuran
Saphirella tropica	Caridean
Sapphirina sp.	Copepodites
Other Cyclopoids	Cirripede cypris
(Harpacticoida)	Cirripede nauplius
Clytemenestra sp.	Cryptoniscid
Euterpina acutifrons	Cyphonautes
Harpacticoid A	Decapod
Macrosetella gracilis	Echinopluteus
Metis holothuriae	Fish Eggs and larvae
Microsetella rosea	Furcila
Miracia efferata	Gastropod
Pontellina plumata	*Lamellaria perspicua*
Other Harpacticoids	*Lamellibranch sp.*
MONSTRILLIDAE	Lanice
Monstrilla sp.	Megalopa
CUMACEA	Mysis
Cumacean sp.	Ophiopluteus
ISOPODA	Penaeid
Isopod	Phoronis
AMPHIPODA	Phyllosoma

Appendix 2. (Continued)

Gammarid Amphipods	Pilidium
Hyperiid Amphipods	Planula
DECAPODA	Polychaete
Lucifer faxoni	Porcellanid
MYSIDACEA	Protozoea
Mysid	Stomatopod
LARVACEA	Tornaria
Oikopleura spp.	Trochophore
Fritillaria spp.	Zoea
THALIACEA	
Doliolid	
Salpa sp.	