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Survey of water quality, groundwater, sediments and benthic habitats at Coral Bay, Ningaloo Reef, Western Australia

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Survey of water quality, groundwater, sediments and benthic habitats at Coral Bay, Ningaloo Reef, Western Australia

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EXECUTIVE SUMMARY

The presence of elevated concentrations of inorganic nitrogen and faecal coliforms in the groundwater along the shoreline of Coral Bay and adjacent marine waters of the inner southeastern corner of Bills Bay indicate that groundwater, contaminated by sewage, is entering Bills Bay. The groundwater contamination is highest at sites adjacent to the Coral Bay Hotel/Ningaloo Reef Resort complex and the Peoples Caravan Park suggesting the leach drain sewage disposal systems of these two facilities are the sources of the contamination. Phytoplankton biomass, light attenuation through the water column and algal growth are significantly higher at sites in the inner part of Bills Bay suggesting that the input of nutrients to these waters is causing a measurable biological response. These effects are mostly confined to an area within 100-200 m of the Coral Bay shoreline.

Juvenile corals are colonising the substratum and surviving in the inner part of Bills Bay and, together with the evenness of juvenile coral density at four sites throughout the bay and the general increase in live coral cover since the major natural coral 'kill' in 1989, indicate that the input of nutrients is not preventing the settlement and survival of corals in these waters.

The increase in algal biomass in the inner part of Bills Bay was significantly higher than at the current commercial fish-feeding site and is probably due to the higher nutrient availability, as a result of the influx of contaminated groundwater, and restricted movement of the waters adjacent to the Coral Bay foreshore. Dissolved nutrients at the fish-feeding site are likely to be removed rapidly northward by the relatively strong currents at this site and possibly into the southeastern part of Bills Bay.

The results of the microbiological survey of Bills Bay suggest that the conclusion from the Shire of Carnarvon's monitoring program, that there is no significant risk to public health in Bills Bay from faecal pollution via contaminated groundwater inflow, may be premature.

The results of the heavy metal and organic contaminant surveys indicate that, in relation to these substances, the sediments of Bills Bay and surrounds are generally 'pristine'. Two sites off Mauds Landing had concentrations of arsenic, chromium, iron, manganese and zinc that were considerably higher than most other sites and may represent residual contamination from the historical commercial activities that occurred at Mauds Landing.

Organotin contamination of the sediments was extremely high at several of the sites in the study area. In particular, tributyltin (TBT) the active ingredient of organotin anti-fouling paints applied to the hulls of vessels, was extremely high at sites close to the mooring locations of large boats using Bills Bay. Significant contamination occurred at several other sites indicating a significant level of contamination exists throughout much of the study area. The relatively low concentration of breakdown products of TBT in the sediments suggests that much of this contamination is relatively recent. The extreme toxicity of TBT to a range of marine flora and fauna make this an issue of significant concern.

5.0 RECOMMENDATIONS

Recommendation 1
That the owners of the Peoples Caravan Park and the Coral Bay Hotel/Ningaloo Reef Resort and the Shire of Carnarvon, in consultation with the Departments of Conservation and Land Management, Health and Environmental Protection, investigate alternative sewage disposal systems to the current leach drain system operating from the Peoples Caravan Park and the Coral Bay Hotel/Ningaloo Reef Resort with a view to implementing, as soon as practicable, an alternative disposal system that prevents contaminants from domestic waste disposal from these developments entering the adjacent marine environment of Bills Bay.

Recommendation 2
That the Department of Conservation and Land Management identify current activities that contribute significant quantities of nutrients directly to the waters of Bills Bay.

Recommendation 3
That the Department of Conservation and Land Management investigate whether there are current sources of TBT input to Bills Bay.

Recommendation 4
That the Department of Conservation and Land Management develop strategies to reduce the current TBT contamination of Bills Bay to acceptable levels.

Recommendation 5
That a comprehensive baseline survey of contaminants in the Mauds Landing area be undertaken by the proponents of the Coral Coast Marina development prior to the commencement of construction.

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1.0 INTRODUCTION

Coral Bay township is a small coastal tourist resort located about 200 km north of Carnarvon adjacent to the Ningaloo Reef, off the northwest coastline of Western Australia (Figure 1). The town was first established in the 1960s and, currently, has a resident population of about 50. Visitors increase the population by up to 3-4000 during school holidays, particularly in the winter months, and are mostly accomodated in caravan and camping areas close to the beach. A range of marine-based activities, including fishing, diving and swimming, are popular and commercial diving and coral viewing operations are run by local tourist operators. Bills Bay (Figure 2) is a unique part of the Ningaloo Reef in that extensive coral gardens existed to within about 20 m of the shoreline until 1989, when a major natural disturbance killed most of the corals (Simpson *et al.* 1993). Despite this event the area remains popular with snorkellers wanting to view corals, fish and other marine life.

Over recent years there have been a number of environmental issues raised by local residents in Coral Bay regarding a perceived decline in the quality of adjacent lagoon waters. These concerns initially centred around sewage leachate which was believed to be entering Bills Bay from nearby camping areas with the major issues being public health and, to a lesser extent, ecological impacts. A preliminary study was conducted in 1989 and found that there was little scientific evidence for these concerns (Stoddart, 1990). A further limited survey by CALM in October 1993 found faecal coliforms and faecal streptococci and high total inorganic nitrogen concentrations in the beachwater and seawater suggesting that sewage was entering Bills Bay via groundwater seepage. Since then, the Shire of Carnarvon has undertaken regular monitoring of the microbiological status of the nearshore waters adjacent to the townsite and found that the level of faecal coliform contamination does not present unacceptable risks to public health (D. Myers, personal communication). Recently, the environmental issues at Coral Bay have expanded to include the potential impacts of fish feeding, particularly in relation to the indirect effects of nutrient-enrichment of the waters of Bills Bay and fish health. Observations of a high incidence of what appeared to be fungal or parasitic infections on fish, particularly on juvenile female parrotfish (i.e. *Scarid* spp.), in Bills Bay in late 1993 (K. Holborn, personal communication) also served to increase concern over the potential detrimental side-effects of fish feeding activities.

In response to the above concerns, the Department of Conservation and Land Management requested assistance from the Department of Environmental Protection in early 1994 to design and implement a collaborative study to examine these issues in greater detail. Funding and operational support were provided by CALM and the DEP provided scientific advice, project management and a report with recommendations. This report is the final outcome of the agreement.

1.1 Study area

The study area was located at Coral Bay on the Ningaloo Reef, a fringing-barrier coral reef enclosing a shallow lagoon that extends for about 280 kilometres along the west coast of Australia between latitudes 21° 47' - 24° S (Figure 1). The width of the lagoon ranges from 0.5 to 6 km (average about 2.5 km) and has an mean depth at AHD of about 2 meters (Hearn *et al.* 1986). Tides are semi-diurnal with spring tidal amplitudes of less than 2 m and seawater temperature extremes in the lagoon range from about 20-30° C (Simpson and Masini, 1986). Water flow through the lagoon is controlled by wave, tidal and wind forcing and lagoon flushing times, under 'typical' conditions, are generally less than 24 hours (Hearn *et al.* 1986; Hearn and Parker, 1988). Current speeds are highly correlated to wave height, and lagoon flushing times, under mean wave conditions, range from 5 to 23 hours depending on the width and depth of the lagoon. Under very low swell conditions, tidal flushing is of order 24 hours at spring tides and a factor of 2 greater at neap tides (Hearn and Parker, 1988). Wind forcing may also facilitate flushing of nearshore waters depending on wind speed and direction.

The lagoon is about 2 - 2.5 km wide at Coral Bay and has an average depth of about 3 m with extensive coral thickets, predominantly *Acropora* and *Montipora* species, covering most of the study area. The tops of many of the larger coral colonies become exposed at spring low tides. Bills

Bay, the area between the Coral Bay townsite and Point Maud (Figure 2), was a closed area under the Fisheries Act from 1974 to 1987, and most of this area is now in the Maud Sanctuary Zone in the Ningaloo Marine Park which was declared in 1987. The southeastern corner of Bills Bay is a Recreation Zone in the marine park. Fishing and the collection of fauna were prohibited in the marine reserve and are currently prohibited in the sanctuary zone. A major natural disturbance occurred in these waters in March 1989 when coral spawn slicks were trapped in the inner part of Bills Bay during a protracted period of extremely calm weather. Most corals, benthic invertebrates and over 1 million fish died over an area of about 3 km^2 as a result of widespread anoxia (i.e. oxygen depletion) of these waters (Simpson *et al.* 1993)

1.2 Sewage disposal at Coral Bay

A review of current sewage disposal facilities at Coral Bay has been recently undertaken by Bradley and Latto (1995). Approximately half of the accommodation facilities at Coral Bay are serviced by septic tanks and evaporation/leach drains associated with the Coral Bay Hotel/Ningaloo Reef Resort complex and the Peoples Caravan Park (Figure 2b). The remainder, including the Bayview Holiday Village, are serviced by septic tanks and a filtration pond system located north of the townsite (Figure 2a). Generally existing sewage treatment and disposal methods are inadequate, especially during the peak tourist season which is from April to September (Bradley and Latto, 1995).

2.0 METHODS

Water quality and sediment sampling methodologies and chemical analyses are consistent with previous water quality and contaminant studies conducted by the DEP (Cary *et al.* 1991; 1995 a, b; Simpson *et al.* 1993a; Burt *et al.* 1995; Burt & Ebell, 1995) to allow comparison of results where appropriate.

2.1 Location of study sites

Most field work was undertaken between 18 September and 5 October 1994. Coral transplant survival and algal growth experiments were conducted between October 1994 and February 1995. Water quality, sediment (CB sites) and groundwater (GW sites) sampling sites are shown in Figure 2a, b. These sites were located on the assumption that, if pollutants were leaching into Bills Bay along the Coral Bay shoreline, then the impacts would likely be concentrated in the immediate (i.e. 100-200 m) vicinity of the shoreline. The presence of beachrock on the shoreline adjacent to the filtration pond system (Figure 2a) prevented groundwater monitoring bores being established at this location. The relative cover of the major benthic habitats was recorded at the sites (± 50 m) of a previous study (Figure 2c; Simpson *et al.* 1993). Site locations were determined by Global Positioning System (GPS).

2.2 Water quality

2.2.1 Sampling

Seawater

Five litre water samples were collected from 0.5 m below the water surface and from 0.5 m above the seabed using a Niskin bottle (General Oceanics) at each site (Figure 2). The water samples were bulked and a 6 litre sub-sample was filtered through a 1.2 µm G/FC Millipore filter paper (Whatman Ltd. England) which was blotted dry, wrapped in aluminium foil and stored on ice in the field and subsequently stored frozen in the laboratory prior to photosynthetic pigment analysis. Three 150 ml sub-samples of the filtered water were retained for inorganic nutrient analyses. Two 150 ml samples of unfiltered water was used for total nutrient determinations. All water samples were stored in sealed polyethylene bags ("Whirlpak", Nasco Ltd., Kansas, USA.) in darkness on ice in the field and frozen upon return to the laboratory until analysed.

Seawater temperature (±0.05 °C) and salinity (±0.05 pss) were measured at 1 m below the surface of the water column using a salinity-temperature meter (Yeo-Kal Model 602). The instrument was

calibrated against water of known salinity and a high precision mercury thermometer. Before use, the probe was soaked in 0.1 M HCl for 10 minutes to clean the platinum electrode thereby minimising instrument 'drift'. Photosynthetically available radiation (PAR, 400-700 nm) was measured (±5%) at 0.5 m intervals through the water column using an Integrating Quantum Sensor (LiCor-192S) and an Underwater Quantum Meter (LiCor-188B). The light attenuation coefficient was calculated as the slope of the line of best fit through the plot of $\log_{10}$ PAR versus depth and expressed as positive values in units of m^{-1}.

Groundwater
Ten groundwater bores were located at approximately 30 m intervals across the Coral Bay beachfront and dug to depths of between 1 to 1.5 m to ensure groundwater flows into Bills Bay were intercepted (Figure 2b). An additional two bores were placed either side of the Mauds Landing pylons as controls (Figure 2a). Five hundred millilitre water samples were taken from each of the bores and filtered through a 1.2 µm G/FC Millipore filter paper (Whatman Ltd. England). Three 150 ml sub-samples of the filtered water were retained for inorganic nutrient analyses. The salinity (±1 pss) of each sample was measured with a Beckman refractometer. The water samples were stored frozen prior to analyses.

2.2.2 Analytical methodology

Seawater samples were analysed for orthophosphate-phosphorus (PO_4-P), total-phosphorus (TP) ammonium-nitrogen (NH_4-N), nitrate/nitrite-nitrogen (NO_3+NO_2-N), total kjeldahl-nitrogen (TKN) and chlorophyll *a*. Groundwater samples were analysed for PO_4-P, NH_4-N and NO_3+NO_2-N. All analyses were undertaken within approximately 30 days of sample collection. PO_4-P (±2 µg L^{-1}) was determined by the single solution method of Major *et al.* (1972), TP (±10 µg L^{-1}) by analysing for PO_4-P after a perchloric digest (Anon., 1977), organic-P was calculated as the difference between TP and PO_4-P, NH_4-N (±3 µg L^{-1}) by the phenol-prusside method (Dal Pont *et al.* 1974), NO_3+NO_2-N (±2 µg L^{-1}) was determined, after copper-cadmium reduction, with a Technicon Autoanalyser 11 (Anon. 1972), TKN (±200 µg L^{-1}) by analysing for NH_4-N with a Technicon Autoanalyser 11 after a sulphuric acid digest (Anon., 1977), organic-N was calculated as the difference between TKN and NH_4-N and chlorophyll *a* concentrations (±0.01 µg L^{-1}) were determined spectrophotometrically according to the methods of Jeffrey and Humphrey (1975).

2.3 Sediment quality

2.3.1 Sampling

All sampling equipment was washed in redistilled methanol and dried at a temperature of 50 °C. Vials, caps and plugs were soaked in 10% nitric acid for at least 12 h, washed with redistilled methanol and dried at 50 °C.

Core samples
At each site 10 approximately equally-spaced replicate cores were taken by divers over 5 m^2 by pressing a 42 x 100 mm polycarbonate vial into the sediment to a maximum depth of 80 mm. A 10 mm hole in the base of the vial allowed excess water to escape and was plugged before the sediment core was withdrawn, after which the vial was capped, secured in a stainless steel diving rack and carefully transported to the surface. On board the vessel, each sample was checked, labelled, excess water was decanted off and then frozen on dry ice in an 'esky'. All samples were stored frozen in the laboratory prior to analysis.

Scoop samples
At each site approximately one kilogram of the surface 20 mm of sediment was taken by divers using a stainless steel scoop and placed in a plastic bag and sealed. On board the vessel, each sample was checked, labelled and any excess water was carefully decanted off. All samples were stored frozen in the laboratory.

2.3.2 Sample preparation

In the laboratory, cores were partially thawed and then removed from each vial. The top 20 mm of sediment of each core was removed with a titanium knife. The ten replicate 20 mm sections from each site were then bulked and homogenised. The homogenised sample was separated into five sub-samples for heavy metal, organotin, pesticide, hydrocarbon and nutrient analysis. The samples were stored in acid-cleaned, glass jars and then stored frozen until the analyses were undertaken.

2.3.3 Analytical methodology

Analyses were performed at four laboratories:

- Particle size and mineralogical analyses at the Mineral Processing Laboratory, Chemistry Centre of Western Australia.
- Nutrient and chlorophyll *a* analyses at the Marine and Freshwater Research Laboratory, School of Environmental Sciences, Murdoch University.
- Heavy metal, pesticide and hydrocarbon analyses at the Environmental Chemistry Laboratory, Chemistry Centre of Western Australia.
- Organotin analyses at the Centre for Advanced Analytical Chemistry, CSIRO, Lucas Heights New South Wales.

Particle size analysis of scoop samples
The thawed scoop sample was first washed through 1000 µm and 38 µm screens. The remaining sediment was then washed through 600 µm and 150 µm screens. All five fractions were decanted, dried at 105 °C and weighed. Further details of the methodology can be found in Burt *et al.* (1995).

Mineralogical analysis of core samples
Strontium, silicon, titanium, aluminium, iron, magnesium, calcium, sodium, potassium, manganese, phosphorus and sulphur were determined by X-ray Fluorescence (XRF). Corrections were made using loss on ignition (LOI) data. The moisture content (dried at 105 °C to constant weight) and LOI at 550 °C (organic carbon fraction) and 1050 °C (inorganic carbon fraction) were determined for each sample. Further details of the methodology can be found in Burt *et al.* (1995).

Sediment nutrient analysis of core samples
Sediment samples were analysed for TP and TKN. All analyses were undertaken within approximately 30 days of sample collection. Analytical methodologies are outlined in section 2.2.2.

Heavy metal analysis of core samples
All heavy metals, apart from mercury, were analysed by Inductively Coupled Plasma Atomic Emission Spectrophotometry (ICP-AES). Mercury analysis was carried out by Vapour Generation Atomic Absorption Spectrophotometry (VGAAS). All procedures incorporated blanks, replicates, certified reference standards and spiked samples. Further details of the methodology can be found in Burt *et al.* (1995).

Organochlorine & organophosphorus pesticide, polychlorinated biphenyl and aliphatic & polycyclic aromatic hydrocarbon analysis of core samples
Identification and quantification of the above organic compounds were carried out by Capillary Gas Chromatography using Flame Ionisation Detection (GC-FID), Thermionic Specific Detection (GC-TSD), and Electron Capture Detection (GC-ECD)) and Mass Spectrometry (GC-MS; Figure 3). Procedural blanks, calibration standards and recovery samples were run routinely throughout the analyses. Further details of the methodology can be found in Burt *et al.* (1995).

Organotin analysis of core samples
Organotin analyses were carried out by an electrically heated quartz furnace atomic absorption spectrophotometer. External calibration standard and reagent blank determinations were performed in conjunction with the sample analysis. Further details can be found in Batley *et al.* (1988).

2.4 Microbiological quality

2.4.1 Seawater and groundwater

A 250 ml surface seawater sample was collected at each site (CB1-27; Figure 2) by dipping a sterilised glass bottle 20 cm below the surface of the water. At each of the groundwater sites (Figure 2b), a weighted copper sampler was lowered into the PVC bore to extract a 250 ml sample. To prevent cross contamination the sampler was washed with methylated spirits and set alight between samples. Gloves were worn during sampling operations. The salinity of the seawater and groundwater samples were also measured as outlined in section 2.2.1. All samples were transported on ice for same-day analyses at the State Health Laboratory in Perth.

2.5 Biological data

2.5.1 Survey of major benthic habitats

The mean percentage of live coral, dead coral (i.e. reef) and sand were measured on replicate 25 m transects using the line-intercept method of Loya (1978). The transects were oriented east-west and were 25-30 m apart at each site. Sites are shown in Figure 2c.

2.5.2 Density of juvenile corals

The number of juvenile (< 5 cm in diameter) corals was counted in three one meter square quadrats, randomly located on non-sand substrata within a five meter radius at sites 1, 5, 9 and 12 (Figure 2c).

2.5.3 Survival of coral transplants

Branchlets of about 15 cm length were broken off a large arborescent *Acropora* colony at CB15 and individually attached to racks with plastic cable ties. Ten branchlets were fastened vertically to each of eight racks. Randomly selected racks were placed in a water bath and transported by vessel to each of the three test sites (CB1, CB7 and CB12; Figure 2c) where the racks were secured to the substratum with steel pegs. A replicate pair of racks was also transported from the collection site to the furthest test site and returned to a control site about 1 km west of CB22 (Figure 2a). After two months a visual assessment was made and the number of branchlets that were alive, bleached, partially or completely dead was recorded.

2.5.4 Benthic algal production

The increase of algal biomass on pre-weighed plastic mesh mats was used to determine relative algal growth rates over a period of 61 days. Three replicate 0.04 m^2 (i.e. 200 x 200 mm) mats were attached to each of 18 racks of reinforcing mesh and enclosed in 10 mm mesh wire to prevent grazing by large fish. All racks were initially located at CB15 for 14 days to allow algae to colonise the mats after which three racks were relocated to each of the 6 experimental sites (CB1, CB8, CB12, CB19, CB21, CB27; Figure 2) and secured to the substratum with steel pegs. Site CB27 is the current fish feeding site. After two months the racks were retrieved and each mat was dried to constant weight at 105 °C and re-weighed. The increase in algal biomass was calculated by subtraction.

3.0 RESULTS

3.1 Water Quality

3.1.1 Seawater

A summary of the water quality data is shown in Table 1. In general the nutrient concentrations and phytoplankton biomass (expressed as chlorophyll *a*) are low as would be expected in tropical waters (Crossland, 1983). For comparative purposes the sites were initially grouped into inner Bills Bay sites (CB1-12), outer Bills Bay sites (CB13-21, CB26, CB27) and control sites (CB22-25) on the basis of that preliminary circulation studies indicate that the innermost southeast part of Bills Bay, approximately described by sites CB1-12, is relatively poorly flushed compared with the rest of the Bay (Hearn *et al.* 1986; D'Adamo, unpublished data) and the control sites were outside the Bay. Preliminary parametric and non-parametric statistical analyses (Student's t-test, Mann-Whitney U-test) of the water quality data indicate no significant difference between the outer Bills Bay sites and the control sites in any of the nine water quality parameters. As a result sites in these groups were combined and termed outer Bills Bay sites (OBB) and compared with the inner Bills Bay (IBB) sites.

Students t-tests between IBB sites and OBB sites for the nine water quality parameters (i.e. Table 1 excluding salinity and temperature) indicate that there are significant differences (i.e. $p \leq 0.05$) for Org-P, TP, NH_4-N, NO_3+NO_2-N, Org-N, chlorophyll *a* and light attenuation coefficient. NO_2+NO_3-N and ORG-N are marginally significantly different with $p=0.03$ and $p=0.04$ respectively. Mann-Whitney U-tests (i.e. the non-parametric analogue of the t-test) show identical results apart from NO_2+NO_3-N and ORG-N which are not significantly different when this test is applied. The agreement between the parametric and non-parametric tests for mean ORG-P, TP, NH_4-N and chlorophyll *a* and vertical light attenuation coefficient provides added confidence in the statistical differences found between the IBB and OBB sites for these parameters.

3.1.2 Groundwater

Inorganic nutrient concentrations in the groundwater from bores along the Coral Bay foreshore are shown in Table 2. Concentrations of PO_4-P at sites along the foreshore (34-123 $\mu g\ l^{-1}$) were significantly higher than at the control sites GW11 and GW12 (i.e. 23 and 25 $\mu g\ l^{-1}$ respectively). A similar pattern was evident for NH_4-N. Concentrations of NO_3+NO_2-N at most sites, apart from GW4 and GW5, were lower or similar to the control sites. Concentrations at site GW4 and GW5 were 1250 $\mu g\ l^{-1}$ and 2125 $\mu g\ l^{-1}$ respectively compared to the <100 $\mu g\ l^{-1}$ at both control sites.

3.2 Sediment quality

3.2.1 Sediment nutrient analysis of 'core' samples

The nutrient status of the sediments of the study area are shown in Table 3. Total Phosphorus in the sediments was generally higher at the IBB sites although the highest value was recorded at a control site off Mauds Landing (i.e. CB24). Total kjeldhal nitrogen concentrations in the sediments were close to or less than the level of detection.

3.2.2 Particle size analysis of 'scoop' samples

The particle size composition of the sediments is shown in Table 4. These data indicate that the sediments of Bills Bay are relatively homogeneous although a slightly higher proportion of fine (i.e. < 150 μm) material occurs in the innermost part of Bills Bay (i.e. around sites CB1-9). In general, grain size increases with distance from the shoreline. The least amount of fine material occurred at the two sites off Mauds Landing (Figure 2).

3.2.3 Mineralogical analysis of 'core' samples

The mineralogy of the sediments in the study area is shown in Table 5 and indicate a strong terrestrial influence as shown by the the high correlation between aluminium and potassium (r=0.97, p<0.001, n=26). Further evidence can be seen in the generally higher silicon and lower calcium content at shoreline sites compared with the sites further offshore.

3.2.4 Heavy metal analysis of 'core' samples

Heavy metal concentrations in the sediments of the study area are shown in Table 6. Apart from aluminium, chromium, iron, managenese and zinc concentrations, which are generally higher at the IBB sites, no clear trends are evident in the data. Concentrations of all metals at most sites were low. Exceptions to this general rule were the control sites at Mauds Landing (CB24 and CB25) where arsenic, chromium and manganese were considerably higher than the Bills Bay sites and the two control sites off Monks Head (CB22 and CB23; Figure 2a).

3.2.5 Organic contaminant analysis of 'core' samples

Organochlorine and organophosphorus pesticide, polychlorinated biphenyl and aliphatic & polycyclic aromatic hydrocarbon (PAH) concentrations in the sediments of the study area are shown in Tables 7 and 8. Most of these substances were below the level of detection. Traces of DDT & metabolites and PAHs were found, particularly at sites close to the Coral Bay foreshore.

3.2.6 Organotin analysis of 'core' samples

Monobutyltin, dibutlytin and tributyltin (TBT) concentrations in the sediments of the study area are shown in Table 9. Extremely high levels of TBT were found at sites CB7, CB8, CB10, CB18, CB20, CB22 and CB23.

3.3 Microbiological quality

3.3.1 Seawater and groundwater

The microbiological quality of the seawater and groundwater of the Coral Bay foreshore is shown in Table 10. Total coliforms, thermotolerant coliforms and faecal streptococci were common in the seawater collected at IBB sites and absent from the OBB sites apart from CB13, CB16, CB19 and CB26. All six of the innermost sites in Bills Bay (i.e. CB1-6) were above the health guidelines for direct contact recreation of 150 organisms per 100 ml (EPA, 1993). Faecal streptococci were also above the criteria of 35 organisms per 100 ml in both the seawater (CB5) and groundwater (GW5). Faecal coliform concentrations in these waters were also above the guideline for the protection of human consumers of fish and other aquatic organisms of 14 organisms per 100 ml at CB1-13 and CB16.

3.4 Biological data

3.4.1 Survey of major benthic habitats

The relative cover of live coral, dead coral (i.e. reef) and sand at 17 sites throughout Bills Bay are shown in Table 11. Coral cover was lowest (i.e. <10%) on the the eastern side of Bills Bay increasing to over 50% further offshore. Dead coral cover was generally high with some inshore and central sites in Bills Bay having over 80% cover of dead coral. The cover of sand habitat ranged from 48% at site 1 to 0 % at sites 3, 7 and 17 (Figure 2c).

3.4.2 Density of juvenile corals

The mean density of juvenile (< 5 cm in diameter) corals was nine colonies per square meter at sites 1, 9 and 12 and six colonies per square meter at site 5.

3.4.3 Survival of coral transplants

Mean survival of branchlets was 22 %, 0 %, 60 % and 7 % at sites CB1, CB7 and CB12 and the control site 1 km west of CB 22, respectively.

3.4.4 Benthic algal production

Mats were recovered from only three of the six experimental sites. Mean increase in algal biomass over the experimental period was 11.4, 16.5 and 4.2 g dry weight/mat at sites CB1, CB8 and CB27 respectively. The biomass increases at CB1 and CB8 were not significantly different but were both significantly greater (Mann-Whitney U-test, $p<0.001$) than at CB27.

4.0 DISCUSSION

The presence of elevated concentrations of inorganic nitrogen and faecal coliforms in the groundwater along the shoreline of Coral Bay and in the inner southeastern corner of Bills Bay indicate that these contaminants are entering Bills Bay via groundwater inflow. These results confirm the findings of a preliminary survey undertaken by CALM in October 1993. The groundwater contamination is highest at sites adjacent to the Coral Bay Hotel/Ningaloo Reef Resort complex and the Peoples Caravan Park suggesting the leach drain sewage disposal systems of these two facilities is the source of contamination. Phytoplankton biomass (expressed as chlorophyll *a* concentrations), light attenuation through the water column and algal growth are also significantly higher at sites in the inner part of Bills Bay suggesting that the input of nutrients to these waters is stimulating algal growth. These effects are confined to the area approximately prescribed by the IBB sites CB1-CB12 (Figure 2b).

The results of the survey of major benthic habitats indicates that coral cover in Bills Bay has increased since the catastrophic natural destruction of corals and other reef animals in Bills Bay in March 1989 (Simpson *et al.* 1993). A direct statistical comparison of these two data sets, however, is not valid as the locations of sites in the 1994 survey are not exactly the same as the 1989 sites. However broad comparisons can be made and indicate that coral cover in the eastern and southeastern parts of Bills Bay has increased over the past five years.

Juvenile corals are colonising the substratum and surviving in the inner part of Bills Bay and, together with the general evenness of juvenile coral density at the four sites throughout the bay and the increase in live coral cover since the major natural coral 'kill' in 1989, indicate that the input of nutrients is not preventing the settlement and survival of corals in these waters. The Coral Transplantation experiment results can not be interpreted as only 7 % of the controls survived.

The failure to recover the racks from three of the six Algal Growth experimental sites limit the interpretation of the results of this experiment to some extent. The increase in algal biomass at sites in the inner part of Bills Bay was 2-4 times higher than at CB27, the current commercial fish-feeding site. This difference probably reflects the higher availability of nutrients at the inner Bills Bay sites due to contaminated groundwater input and different small-scale circulation patterns of the two areas (see Figure 2c). Nutrients entering the water along the Coral Bay foreshore are likely to be remain in the area for longer periods due to the relatively restricted movement of these waters. By contrast stronger currents at the fish feeding site are likely to remove nutrients rapidly off-site. These nutrients, however, would generally move northward into Bills Bay proper and, therefore, may be contributing to the nutrient impacts observed in inner Bills Bay waters (i.e. at the IBB sites).

The results of the one-off microbiological survey of the waters of Bills Bay found concentrations of faecal coliforms near the swimming beach at Coral Bay to be above the public health criteria for direct contact recreation (i.e. swimming) and the protection of human consumers of fish. Faecal streptococci were also above the direct contact recreation criterion in both the seawater and groundwater. These findings conflict with the results of a similar survey at about the same time by the Shire of Carnarvon as part of their routine microbiological monitoring of these waters since October 1993. All three sites in this survey had very low levels of faecal coliforms and faecal

streptococci. A possible explanation for this difference is that our samples were analysed in Perth on the same day they were collected, whereas the Shire of Carnarvon samples were not. According to the State Health Laboratories, the results of microbiological analysis of seawater are significantly affected if the time between collection and analysis exceeds about 12 hours (R. Theobold, personal communication). The conclusion from the Shire of Carnarvon's microbiological monitoring program in Bills Bay is that there is no significant risk to public health in these waters from faecal pollution via contaminated groundwater inflow (D. Myers, personal communication). The results presented here suggest this conclusion may be premature.

The results of the heavy metal and organic contaminant surveys indicate that, in relation to these substances, the sediments of Bills Bay and surrounds are 'pristine'. Although slight traces of PAHs and organoclorine pesticides were found in the sediments at sites close to the Coral Bay shoreline, the levels are insignificant. The two 'control' sites off Mauds Landing provided some interesting results in that the concentrations of arsenic, chromium, iron, manganese and zinc were considerably higher than most other comparable sites. These results are surprising in that this area is probably the most 'exposed' of all the sites and, as such, the sediment is likely be more mobile and therefore less likely to accumulate heavy metals. The only plausible explanation for these higher concentrations is that they represent residual contamination from the historical activities that occurred at Mauds Landing.

Organotin contamination of the sediments was extremely high at several of the sites in the study area. In particular, tributyltin (TBT) the active ingredient of organotin anti-fouling paints applied to the hulls of vessels, was extremely high in sediments at CB7 and CB8, which are close to the mooring area of large boats using Bills Bay, and at CB22 and CB23, about 2 km south of the township. This area is used occasionally as a temporary mooring area for large vessels unable to enter Bills Bay (R. Karniewicz, personal communication). Concentrations over 10 µgTBT/kg in sediments are considered to be unacceptable (Waite *et al.* 1991) and these data, therefore, indicate that a significant level of contamination exists at most of the sites sampled, apart from the sites closest to the Coral Bay shoreline. TBT is extremely toxic to many marine organisms and is responsible for the reproductive disorder, *imposex*, in a bioindicator organism throughout most of the coastal waters off Perth (Field, 1993). The impacts of this substance on the marine life of Bills Bay are currently unknown.

Regulations restricting the use of TBT were promulgated in Western Australia from 1 November 1991 and, as a result, this substance is prohibited on boats under 25 m and restricted to low leaching forms on boats over 25 m. The relatively low concentration of breakdown products of TBT (i.e. dibutyltin, monobutyltin) in the sediments suggests that much of this contamination has occurred within the last 2-3 years. In addition the distribution and level of contamination suggests that the source of TBT to these waters is from vessels moored in Bills Bay for considerable periods. The contamination of sediments away from the main Bills Bay mooring area (i.e. near CB7 and CB8) may be the result of temporary mooring of vessels at these locations or from hulls scraping the seabed. The extreme toxicity of TBT to a range of marine flora and fauna make this an issue of significant concern.

5.0 RECOMMENDATIONS

Recommendation 1
That the owners of the Peoples Caravan Park and the Coral Bay Hotel/Ningaloo Reef Resort and the Shire of Carnarvon, in consultation with the Departments of Conservation and Land Management, Health and Environmental Protection, investigate alternative sewage disposal systems to the current leach drain system operating from the Peoples Caravan Park and the Coral Bay Hotel/Ningaloo Reef Resort with a view to implementing, as soon as practicable, an alternative disposal system that prevents contaminants from domestic waste disposal from these developments entering the adjacent marine environment of Bills Bay.

Recommendation 2
That the Department of Conservation and Land Management identify current activities that contribute significant quantities of nutrients directly to the waters of Bills Bay.

Recommendation 3
That the Department of Conservation and Land Management investigate whether there are current sources of TBT input to Bills Bay.

Recommendation 4
That the Department of Conservation and Land Management develop strategies to reduce the current TBT contamination of Bills Bay to acceptable levels.

Recommendation 5
That a comprehensive baseline survey of contaminants in the Mauds Landing area be undertaken by the proponents of the Coral Coast Marina development prior to the commencement of construction.

6.0 ACKNOWLEDGEMENTS

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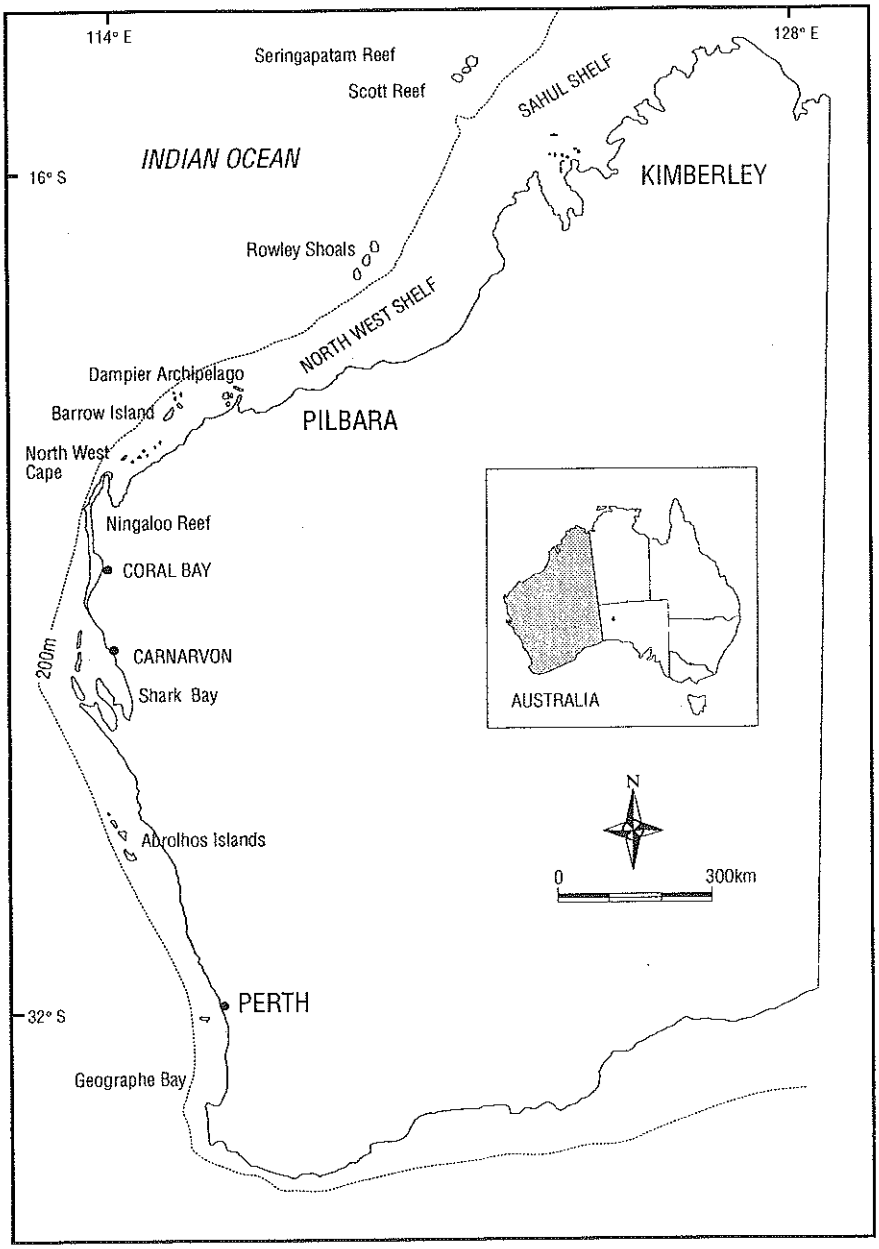

Figure 1. Location map of Western Australia.

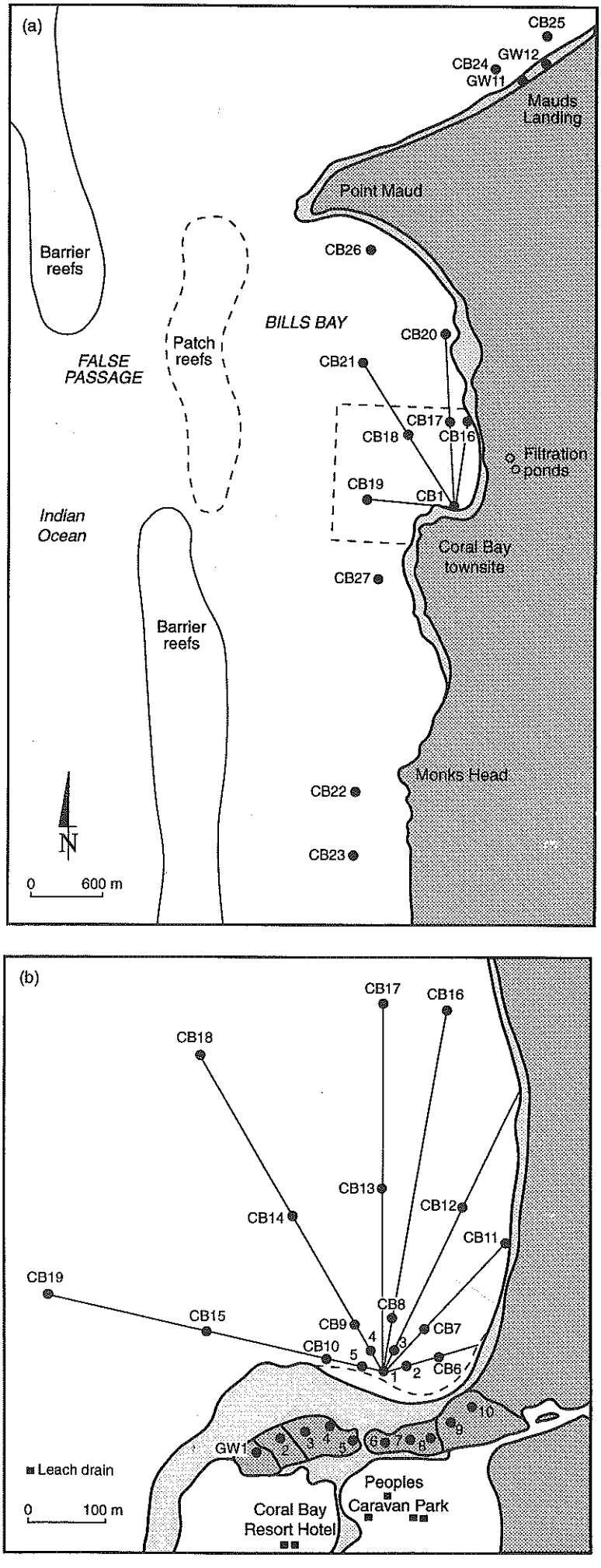

Figure 2. Location of water quality, sediment and groundwater monitoring sites.

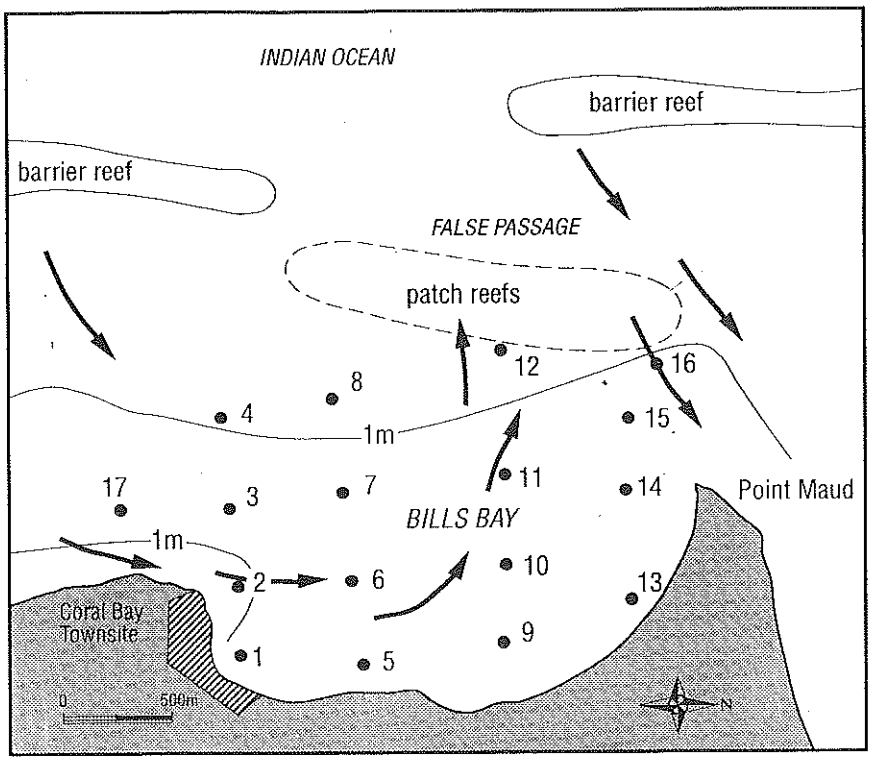

Figure 2c. Location of coral monitoring sites (from Simpson *et al.* 1993).

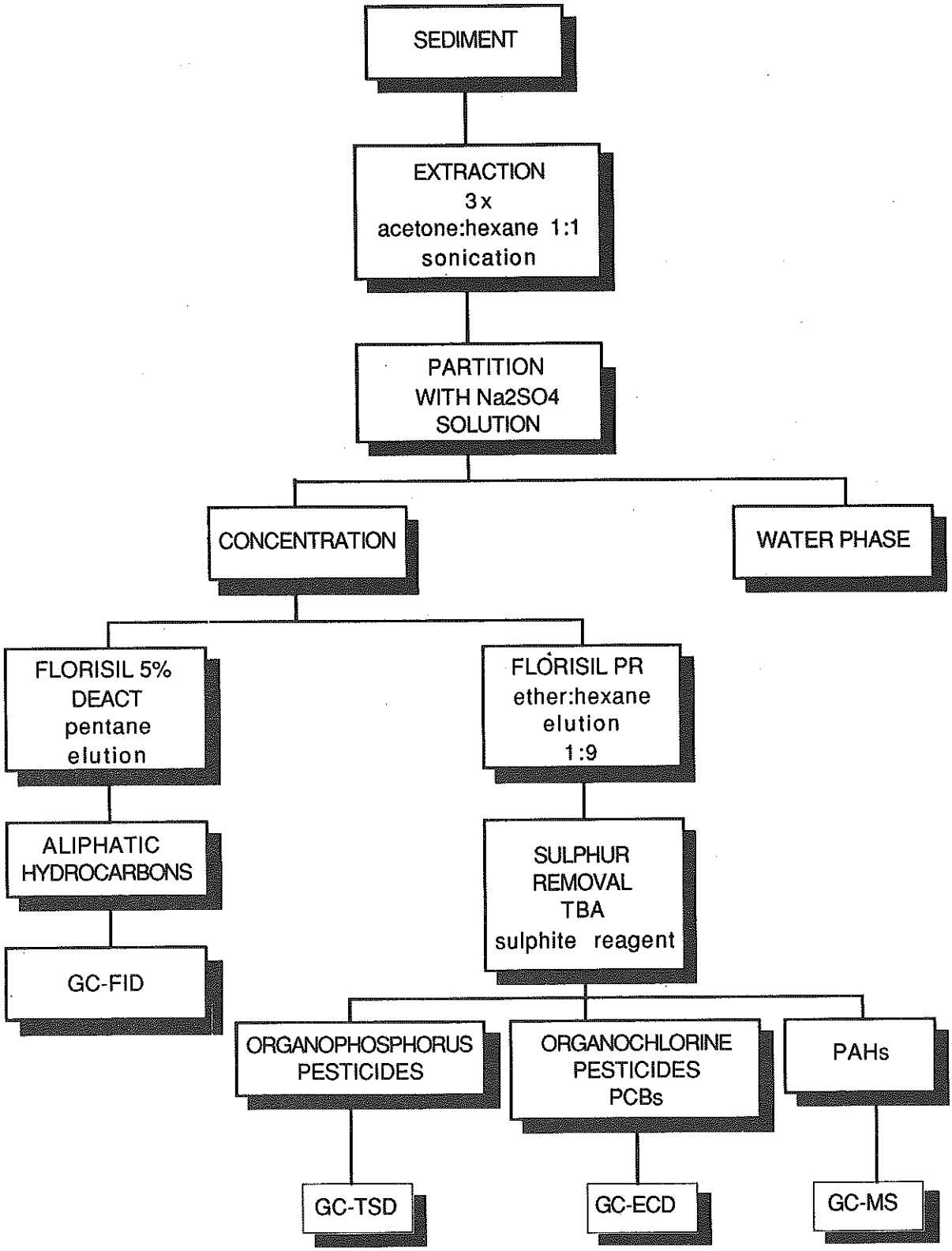

Figure 3. Analytical scheme for organic contaminants in sediments.

Table 1: Water quality results.

Parameter		PO4-P	ORG-P	TOTAL-P	NH4-N	NO3+NO2-N	ORG-N	TKN	CHL-A	ATTEN. COEFF.	SALINITY	TEMPERATURE
Unit		(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(/m)	(pss)	(°C)
Limit of detection (µg/L)		2	10	10	3	2	200	200	0.01	-	0.05	0.05
Site	Depth (m)											
CB1	1.5	4	24	28	8	5	14	27	0.13	0.09	35.1	22.8
CB2	2	4	28	32	10	4	12	26	0.22	0.22	35	22.8
CB3	1.5	4	14	18	12	5	20	37	0.19	0.25	34.95	22.8
CB4	1.5	4	19	23	10	4	12	26	0.24	0.21	35.1	23.2
CB5	1.5	4	24	28	9	4	13	26	0.24	0.17	35.1	23.2
CB6	2	4	23	27	10	5	22	37	0.13	0.1	35.2	22.1
CB7	1.5	4	18	22	9	4	23	36	0.19	0.09	35	22.5
CB8	1.5	3	18	21	7	5	25	37	0.19	0.09	35.1	22.7
CB9	1.5	4	16	20	6	4	29	39	0.15	0.13	35.1	22
CB10	1.5	4	21	25	7	5	19	31	0.24	0.19	35.1	22.4
CB11	1.5	4	17	21	7	4	19	30	0.11	0.24	35.2	22.8
CB12	2	4	23	27	10	4	59	73	0.15	0.12	35.2	21.2
CB13	2.5	3	18	21	5	4	56	65	0.13	0.08	35.2	21.5
CB14	2.5	4	16	20	4	4	57	65	0.19	0.08	35.1	21.8
CB15	2.1	4	14	18	8	7	53	68	0.15	0.09	35.25	21.6
CB16	1.2	4	13	17	9	5	43	57	0.09	0.14	35.2	21.2
CB17	2.5	3	14	17	8	5	44	57	0.15	0.12	35.1	21
CB18	3	4	12	16	9	5	26	40	0.13	0.11	35.1	21.4
CB19	3	4	9	13	7	8	28	43	0.11	0.08	35.25	21.6
CB20	2	4	13	17	6	5	29	40	0.11	0.17	35.2	21
CB21	2.5	4	10	14	5	6	13	24	0.09	0.08	35.2	21
CB22	3.4	5	10	15	8	5	18	31	0.07	0.07	35.2	22.6
CB23	3	5	14	19	10	9	16	35	0.09	0.06	35.2	22.1
CB24	2.5	4	14	18	6	4	29	39	0.11	0.09	35.3	21.8
CB25	3	4	15	19	3	4	32	39	0.28	0.16	35.35	21.1
CB26	3	3	19	22	5	5	13	23	0.13	0.11	35.3	21
CB27	2.5	5	19	24	6	4	-	-	0.11	0.12	35.1	20.9

Table 2: Groundwater results.

Parameter	PO4-P	NH4-N	NO3+NO2-N	SALINITY
Unit	(µg/L)	(µg/L)	(µg/L)	(pss)
Limit of detection (µg/L)	2	3	2	1
GW1	58	45	150	5
GW2	132	147	138	10
GW3	90	205	168	10
GW4	34	9	1250	7
GW5	113	333	2125	5
GW6	113	105	9	5
GW7	78	37	6	5
GW8	123	238	27	5
GW9	101	53	5	2
GW10	132	45	13	4
GW11	23	6	56	32
GW12	25	16	96	32

Table 3: Sediment quality results.

Parameter	TOTAL-P	TKN
Unit	(mg/g)	(mg/g)
Limit of detection (mg/g)	0.01	0.2
CB1	0.31	0.2
CB2	0.39	0.2
CB3	0.31	0.3
CB4	0.35	0.3
CB5	0.25	0.2
CB6	0.22	0.3
CB7	0.18	0.3
CB8	0.24	0.5
CB9	0.2	0.2
CB10	0.27	0.1
CB11	0.23	0.2
CB12	0.15	0.3
CB13	0.26	0.3
CB14	0.25	0.4
CB15	0.23	0.4
CB16	0.21	0.2
CB17	0.12	0.2
CB18	0.1	0.3
CB19	0.1	0.2
CB20	0.21	0.2
CB21	0.14	0.3
CB22	0.34	0.3
CB23	0.24	0.2
CB24	0.54	0.1
CB25	0.14	0.1
CB26	0.06	0.3
CB27	0.27	0.3

Table 4: Particle size analysis of sediments.

Size range (µm)	>1000	1000->600	600->150	150->38	≤38
Unit	(%)	(%)	(%)	(%)	(%)
Site					
CB1	1	2.8	46.6	46.6	3
CB2	3.3	9.7	63.8	21.8	1.4
CB3	4.7	8.4	67.9	17.7	1.3
CB4	5	7.1	70.2	16.1	1.6
CB5	2.9	12.9	78.8	4.9	0.5
CB6	6.6	5.7	50	33.8	3.9
CB7	5.1	5.2	59.9	27.7	2.1
CB8	6.7	7.5	64.1	19	2.7
CB9	6	5.9	59	26.8	2.3
CB10	0.9	5.9	89.7	3	0.5
CB11	5.8	18.8	65.7	8	1.7
CB12	6.1	4.6	63.5	21.9	3.9
CB13	11.2	7.1	48.7	31.6	1.4
CB14	9.9	7.5	52.9	28.7	1
CB15	6.3	13.6	66.2	13	0.9
CB16	7.7	10.2	71.3	10	0.8
CB17	5.2	7	69.8	17	1
CB18	10.5	8.2	49.1	29.9	2.3
CB19	7.3	18.9	66.9	6.5	0.4
CB20	8.2	8.6	66.6	15.5	1.1
CB21	21.7	6.5	42.6	26.9	2.3
CB22	4.8	5.6	63.3	25.5	0.8
CB23	8.8	12.8	63.5	14.2	0.7
CB24	9.2	23.6	65.2	2	<0.1
CB25	4.9	23.7	70.7	0.7	<0.1
CB26	10.4	6.8	58.4	23.5	0.9
CB27	11.3	17.5	62.6	7.9	0.7

Table 5: Mineralogical analysis of sediments.

Parameter	Sr	SiO2	TiO2	Al2O3	Fe2O3	MgO	CaCO3	Na2O	K2O	MnO	P2O5	S
Unit	(mg/kg)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
CB1	2780	19.4	0.06	0.41	0.14	1.87	72.3	0.33	0.27	<0.05	0.12	0.09
CB2	2700	14.5	<0.05	0.26	0.1	1.99	77	0.28	0.19	<0.05	0.12	0.1
CB3	2630	24.2	0.82	0.4	0.16	1.64	67.5	0.37	0.26	<0.05	0.1	0.06
CB4	3080	21.2	<0.05	0.3	0.12	1.58	71.6	0.3	0.22	<0.05	0.11	0.08
CB5	2660	14.8	<0.05	0.18	0.12	1.97	77.5	0.25	0.13	<0.05	0.12	0.09
CB6	2640	21.1	0.07	0.43	0.14	1.77	70.5	0.34	0.28	<0.05	0.11	0.09
CB7	2680	25.1	0.07	0.46	0.13	1.57	67.7	0.27	0.3	<0.05	0.1	0.07
CB8	3940	20.4	<0.05	0.32	0.11	1.25	72.9	0.3	0.21	<0.05	0.09	0.08
CB9	3960	22	0.06	0.36	0.12	1.42	71.3	0.3	0.24	<0.05	0.1	0.08
CB10	2470	16.6	<0.05	0.18	0.11	1.95	75.5	0.27	0.14	<0.05	0.12	0.09
CB11	2750	18.2	<0.05	0.24	0.08	1.78	74.6	0.35	0.14	<0.05	0.1	0.09
CB12	5320	15.5	0.05	0.25	0.09	0.96	77.5	0.34	0.19	<0.05	0.07	0.09
CB13	3050	34.8	0.12	0.62	0.17	1.2	58	0.33	0.4	<0.05	0.09	0.05
CB14	3200	33	0.11	0.55	0.16	1.15	59.8	0.26	0.37	<0.05	0.09	0.06
CB15	3780	28.4	<0.05	0.35	0.08	1.05	65.9	0.36	0.23	<0.05	0.1	0.07
CB16	4820	15.6	<0.05	0.18	0.07	1.21	78.6	0.33	0.14	<0.05	0.09	0.08
CB17	5280	13.6	<0.05	0.27	0.08	1.13	79.8	0.41	0.17	<0.05	0.08	0.08
CB18	4720	13	<0.05	0.21	0.08	1.25	80	0.32	0.14	<0.05	0.09	0.1
CB19	4370	15	<0.05	0.09	0.06	1.35	79.6	0.31	0.08	<0.05	0.09	0.08
CB20	4350	11.5	<0.05	0.21	0.08	1.43	81.3	0.4	0.14	<0.05	0.1	0.08
CB21	3230	6.9	<0.05	0.13	0.07	2	87.1	0.32	0.08	<0.05	0.11	0.11
CB22	5950	2.2	<0.05	<0.05	0.06	1.21	90.5	0.33	<0.05	<0.05	0.08	0.1
CB23	3580	3.5	<0.05	0.07	0.07	2.14	87.9	0.33	0.05	<0.05	0.11	0.12
CB24	2210	16.2	<0.05	0.25	0.17	2.35	77.3	0.28	0.12	<0.05	0.15	0.06
CB25	2160	18.4	<0.05	0.23	0.14	2.17	75	0.22	0.11	<0.05	0.14	0.07
CB26	3420	13	0.08	0.3	0.14	1.68	79.3	0.3	0.16	<0.05	0.13	0.08
CB27	3590	30	<0.05	0.29	0.1	1.06	64.1	0.35	0.22	<0.05	0.1	0.06

Table 6: Heavy metal, water content and loss on ignition (LOI) analysis of sediments.

Parameter	Al	As	Cd	Co	Cr	Cu	Fe	Hg
Unit, dry weight	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)
CB1	1100	9.4	1.2	2.3	10	1	490	<0.005
CB2	690	8.9	1.1	2	9.3	0.89	350	<0.005
CB3	1100	8.6	1.2	1.9	8.9	0.84	560	<0.005
CB4	790	8.4	1.1	1.9	8.1	0.78	420	<0.005
CB5	480	9	1.2	2.2	8.7	1	420	<0.005
CB6	1100	8.6	1.1	2	8.8	1	490	<0.005
CB7	1200	9.2	1.1	2.1	9.1	0.82	450	<0.005
CB8	850	8.1	1	1.9	5.2	0.85	380	<0.005
CB9	950	7.4	1	1.9	5.3	0.73	420	<0.005
CB10	480	9.7	1.2	2.2	11	0.92	380	<0.005
CB11	640	8.4	1.1	2.2	7.8	1.2	280	<0.005
CB12	660	8	1.2	2.3	3.8	0.83	310	<0.005
CB13	1600	7.3	1	2	4.7	0.73	600	<0.005
CB14	1500	7.4	1.1	2.1	5.1	0.77	560	<0.005
CB15	930	6.9	1	1.9	3.8	0.7	280	<0.005
CB16	480	7.8	1.1	2.2	5	0.76	240	<0.005
CB17	710	7.4	1.1	2.2	3.4	0.76	280	<0.005
CB18	560	8.1	1.1	2.2	4.1	0.83	280	<0.005
CB19	240	7.3	1.2	2	3.7	0.8	210	<0.005
CB20	560	8.4	1.2	2.1	6.1	0.83	280	<0.005
CB21	340	7.3	1.2	2.1	2.9	0.83	240	<0.005
CB22	<10	8	1.2	2.2	2.7	0.88	210	<0.005
CB23	180	8.1	1.3	2.4	5.6	0.86	240	<0.005
CB24	660	10.6	1.3	2.3	18.7	0.9	590	<0.005
CB25	610	10.6	1.3	2.3	18.4	0.86	490	<0.005
CB26	790	8.4	1.1	2.3	7.8	0.83	490	<0.005
CB27	770	9.2	1.2	2.3	8.6	0.8	350	<0.005

Table 6: continued.

Parameter	Mn	Mo	Ni	Pb	V	Zn	H2O	LOI (105-550)	LOI (550-1050)
Unit, dry weight	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(%)	(%)	(%)
CB1	5.9	2.4	5.2	4.9	6	2.4	25.9	3.3	38.1
CB2	5.7	2.2	4.8	5.1	5.7	2.7	23.6	2.7	35.2
CB3	5.3	2.2	4.8	5.1	5.7	1.9	23.1	3	35.3
CB4	5.3	2.2	4.6	5	5.3	1.5	21.3	2.7	36.7
CB5	6.4	2.2	4.9	5.8	5.7	3	23.2	3.3	38.2
CB6	5.1	2.1	4.8	4.8	5.6	2.2	22.7	2.9	36
CB7	5.4	2.3	4.9	5.7	5.6	1.7	23.9	2.9	34.2
CB8	3	1.9	4.5	3.9	5	2.5	23.5	2.9	37.3
CB9	3.3	2	4.5	4	4.9	0.8	21	2.7	36.7
CB10	8.4	2.2	5.1	5.4	5.8	1.6	22.4	2.1	36.4
CB11	5.7	2.3	4.9	4.1	5.5	1	21.7	3.5	37.2
CB12	2.2	2.3	5.1	4.9	5.4	1	24.7	3.1	40
CB13	3.2	2.1	4.5	4.2	4.9	0.6	21.1	3	34.6
CB14	3.4	2.1	4.6	4.2	5.2	1	23.6	3.1	33.1
CB15	2.6	1.9	4.1	3.1	4.6	0.6	23.4	3	33.9
CB16	3.4	2.3	4.8	4.4	5.2	0.7	23.7	3.2	38.8
CB17	2	2.2	5	4.4	5.1	0.5	26.3	3.3	40.3
CB18	2.7	2.4	5.1	4	5.4	0.6	24.9	3.4	40.4
CB19	2.4	2.2	5.1	3.5	5.4	0.5	25.4	3.4	39.3
CB20	3.3	2.4	5.2	6.7	5.6	0.7	23.6	3.6	42.3
CB21	2.6	2.2	5.1	4.7	5.1	0.6	23.8	3.9	44.7
CB22	3	2.2	5.3	4.8	5.5	0.6	25.7	4	42.3
CB23	5	2.4	5.5	4.9	5.9	0.9	27.6	4.2	45
CB24	11	2.6	5.6	4.9	6.5	1.5	19.4	3.5	32.8
CB25	11	2.5	5.5	5	6.3	1.3	19.2	3.6	47.1
CB26	5.2	2.4	5.2	5.1	5.4	0.7	22.6	3.4	50.2
CB27	3.7	2.6	5.4	5	6	0.8	19.5	3.2	29.3

Table 7: Pesticide, polychlorinated biphenyl (PCB) and aliphatic hydrocarbon analysis of sediments.

Parameter	Aldrin	Alpha and Beta Chlordane	Oxychlordane	Heptachlor	Heptachlor Epoxide	HCB	Dieldrin	Lindane	DDT & metabolites	Organo-phosphorous pesticides	PCBs	Aliphatic hydrocarbon C9-C25
Unit (dry weight)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)	(mg/kg)
Limit of detection (mg/kg)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.01	1
CB1	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<1
CB2	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<1
CB3	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	<0.01	<1
CB4	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	<0.01	<1
CB5	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<1
CB6	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	<0.01	<1
CB7	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<1
CB8	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<1
CB9	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<1
CB10	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<1
CB11	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	<0.01	<1
CB12	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<1
CB13	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<1
CB14	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	<0.01	<1
CB15	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<1
CB16	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<1
CB17	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	<0.01	<1
CB18	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<1
CB19	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<1
CB20	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<1
CB21	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<1
CB22	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<1
CB23	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<1
CB24	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<1
CB25	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<1
CB26	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<1
CB27	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<1

Table 8: Polycyclic aromatic hydrocarbon (PAH) analysis of sediments.

Parameter	1-methyl naphthalene	2-methyl naphthalene	Ace-naphthalene	Ace-naphthene	Anthra-cene	Benzo (a, h) anthracene	Benzo (a) anthracene	Benzo (a) pyrene
Unit, dry weight	(µg/kg)	(µg/kg)	(µg/kg)	(µg/kg)	(µg/kg)	(µg/kg)	(µg/kg)	(µg/kg)
Limit of detection (µg/kg	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
CB1	1.3	1.7	0.5	<0.1	<0.1	<0.1	<0.1	<0.1
CB2	1	1.5	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
CB3	0.9	1.3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
CB4	1.2	1.7	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
CB5	2.2	4	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
CB6	0.9	1.4	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
CB7	1.5	2.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
CB8	1.7	2.6	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
CB9	1.1	1.6	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
CB10	1.1	1.7	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
CB11	1.1	1.5	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
CB12	1.3	1.9	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
CB13	1.4	2.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
CB14	2.1	3.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
CB15	1.3	2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
CB16	1.1	1.6	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
CB17	1.2	1.7	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
CB18	1.4	1.6	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
CB19	1	1.6	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
CB20	<0.1	3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
CB21	1	1.5	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
CB22	0.7	0.9	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
CB23	<0.1	1.4	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
CB24	<0.1	1.5	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
CB25	<0.1	1.3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
CB26	1.5	1.2	1	<0.1	<0.1	<0.1	<0.1	<0.1
CB27	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

Table 8: continued.

Parameter	Benzo (g,h,i) pyrene	Chrysene	Fluor-anthene	Fluorene	Indeno (1,2,3-c,d) pyrene	Naphthalene	Phen-anthene	Pyrene	TOTAL PAH
Unit, dry weight	(µg/kg)	(µg/kg)	(µg/kg)	(µg/kg)	(µg/kg)	(µg/kg)	(µg/kg)	(µg/kg)	(µg/kg)
Limit of detection (µg/kg	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
CB1	<0.1	<0.1	0.4	0.7	<0.1	1.6	0.9	0.4	7.5
CB2	1.3	<0.1	<0.1	<0.1	1.3	1.2	0.7	0.3	7.3
CB3	1.1	<0.1	0.2	<0.1	1.2	1.1	0.7	0.3	6.8
CB4	1.3	<0.1	0.4	0.8	<0.1	1.6	0.9	0.4	8.3
CB5	<0.1	<0.1	0.6	1.3	<0.1	2.6	1.9	0.8	13.4
CB6	<0.1	<0.1	0.3	<0.1	<0.1	1.6	0.7	0.3	5.2
CB7	<0.1	<0.1	0.4	1.1	<0.1	2.1	1.2	0.4	8.9
CB8	<0.1	<0.1	<0.1	1.1	<0.1	2.4	<0.1	0.4	8.2
CB9	<0.1	<0.1	<0.1	<0.1	<0.1	1.4	<0.1	0.3	4.4
CB10	<0.1	<0.1	0.3	<0.1	<0.1	1.6	0.8	0.4	5.9
CB11	<0.1	<0.1	0.3	<0.1	<0.1	1.2	0.8	0.4	5.3
CB12	<0.1	<0.1	0.3	<0.1	<0.1	1.7	0.8	0.3	6.3
CB13	<0.1	<0.1	<0.1	<0.1	<0.1	2.2	<0.1	0.3	6
CB14	<0.1	<0.1	<0.1	<0.1	<0.1	3.7	<0.1	0.4	9.3
CB15	<0.1	<0.1	<0.1	<0.1	<0.1	1.6	<0.1	0.3	5.2
CB16	<0.1	<0.1	<0.1	<0.1	<0.1	1.5	0.8	0.3	5.3
CB17	<0.1	<0.1	0.2	<0.1	<0.1	1.4	0.7	0.3	5.5
CB18	<0.1	<0.1	<0.1	<0.1	<0.1	1.6	<0.1	<0.1	4.6
CB19	<0.1	<0.1	<0.1	<0.1	<0.1	1.4	0.9	0.4	5.3
CB20	<0.1	<0.1	0.4	<0.1	<0.1	2.7	1.3	0.5	7.9
CB21	<0.1	<0.1	<0.1	<0.1	<0.1	1.3	0.7	0.2	4.7
CB22	<0.1	<0.1	<0.1	<0.1	<0.1	2.6	0.8	0.2	5.2
CB23	<0.1	<0.1	<0.1	<0.1	<0.1	1.1	0.7	0.3	3.5
CB24	<0.1	<0.1	<0.1	<0.1	<0.1	1.8	0.7	<0.1	4
CB25	<0.1	<0.1	0.5	<0.1	1.7	1.3	0.9	0.5	6.2
CB26	<0.1	<0.1	<0.1	<0.1	<0.1	1.2	<0.1	<0.1	4.9
CB27	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

Table 9: Organotin analysis of sediments.

Parameter	Monobutyltin	Dibutyltin	Tributyltin
Unit, dry weight	(µg/kg)	(µg/kg)	(µg/kg)
Limit of detection (µg/kg)	0.4	0.6	0.7
CB1	< 0.4	3.1	7.1
CB2	1.2	1.6	3.4
CB3	2.4	< 0.6	6.1
CB4	1.8	< 0.6	1.0
CB5	1.5	1.2	< 0.7
CB6	-	-	-
CB7	121.1	107.8	3412.3
CB8	88.6	235.2	10237.0
CB9	-	-	-
CB10	8.9	5.9	170.6
CB11	-	-	-
CB12	-	-	-
CB13	-	-	-
CB14	-	-	-
CB15	1.2	1.2	2.9
CB16	-	-	-
CB17	-	-	-
CB18	2.2	6.3	182.8
CB19	-	-	-
CB20	0.9	9.8	190.1
CB21	-	-	-
CB22	3.5	31.4	463.1
CB23	1.2	10.0	199.9
CB24	< 0.4	2.0	17.8
CB25	0.7	2.0	9.7
CB26	3.1	0.8	3.9
CB27	-	-	-

Table 10: Microbiological analysis of seawater (CB sites) and groundwater (GW sites).

Parameter Unit: (organisms/100 ml)	Total coliforms	Thermotolerant coliforms	Faecal streptococci	Salinity (pss)
CB1	>200	8	14	35
CB2	>200	4	10	35
CB3	>200	2	6	35
CB4	>200	10	12	35
CB5	>200	20	60	35
CB6	>200	4	2	35
CB7	140	2	0	35
CB8	44	44	0	35
CB9	36	0	0	35
CB10	70	6	0	35
CB11	110	110	6	35
CB12	30	0	0	35
CB13	16	0	0	35
CB14	0	0	0	35
CB15	0	0	0	35
CB16	18	0	0	35
CB17	0	0	0	35
CB18	0	0	0	35
CB19	8	0	0	35
CB20	0	0	0	35
CB21	0	0	0	35
CB22	0	0	0	35
CB23	0	0	0	35
CB24	0	0	0	35
CB25	0	0	0	35
CB26	2	0	0	35
GW1	0	0	0	12
GW2	0	0	0	12
GW3	0	0	0	16
GW4	0	0	0	12
GW5	0	0	>200	20
GW6	0	0	0	10
GW7	0	0	0	7
GW8	0	0	0	10
GW9	0	0	0	8
GW10	0	0	0	10
GW11	0	0	0	32
GW12	0	0	0	32

Table 11: Major benthic habitat types

Parameter	Live coral	Dead coral	Sand
Unit	(%)	(%)	(%)
Site			
1	4.5	46.1	48.4
2	42.9	45.9	11.2
3	42.6	57.4	0
4	62.2	28.8	9
5	5.9	88.3	5.8
6	14.4	85.2	0.4
7	7.2	92.8	0
8	54.9	28.5	16.6
9	4	79	17
10	16.2	58.1	25.8
11	19.6	78.4	2
12	68.1	30.3	2.4
13	13.4	61	25.6
14	5	76.6	18.4
15	9.3	84.5	6.2
16	61.4	29.8	10.4
17	41.6	58.4	0

APPENDIX I: Latitude and longitude of the study sites as detemined by Global Positioning System (GPS).

Site	Latitude (° S)	Longitude (° E)	Site	Latitude (° S)	Longitude (° E)	Site	Latitude (° S)	Longitude (° E)
CB1	23° 8.701'	113° 46.206'	GW1	23° 8.777'	113° 46.109'	1	23° 8.711'	113° 46.242'
CB2	23° 8.696'	113° 46.210'	GW2	23° 8.767'	113° 46.141'	2	23° 8.683'	113° 46.091'
CB3	23° 8.736'	113° 46.247'	GW3	23° 8.763'	113° 46.160'	3	23° 8.665'	113° 45.846'
CB4	23° 8.729'	113° 46.225'	GW4	23° 8.762'	113° 46.174'	4	23° 8.659'	113° 45.576'
CB5	23° 8.737'	113° 46.214'	GW5	23° 8.772'	113° 46.198'	5	23° 8.402'	113° 46.227'
CB6	23° 8.715'	113° 46.268'	GW6	23° 8.775'	113° 46.218'	6	23° 8.366'	113° 46.079'
CB7	23° 8.692'	113° 46.268'	GW7	23° 8.779'	113° 46.238'	7	23° 8.433'	113° 45.813'
CB8	23° 8.685'	113° 46.203'	GW8	23° 8.752'	113° 46.253'	8	23° 8.469'	113° 45.488'
CB9	23° 8.702'	113° 46.203'	GW9	23° 8.757'	113° 46.269'	9	23° 8.070'	113° 46.180'
CB10	23° 8.695'	113° 46.189'	GW10	23° 8.740'	113° 46.282'	10	23° 8.114'	113° 46.052'
CB11	23° 8.581'	113° 46.322'	GW11	23° 7.075'	113° 46.820'	11	23° 8.092'	113° 45.530'
CB12	23° 8.182'	113° 46.289'	GW12	23° 7.062'	113° 46.604'	12	23° 8.182'	113° 45.289'
CB13	23° 8.450'	113° 46.105'				13	23° 7.757'	113° 46.019'
CB14	23° 8.450'	113° 46.115'				14	23° 7.783'	113° 45.736'
CB15	23° 8.669'	113° 46.042'				15	23° 7.821'	113° 45.514'
CB16	23° 8.419'	113° 46.293'				16	23° 7.712'	113° 45.376'
CB17	23° 8.384'	113° 46.140'				17	23° 8.919'	113° 45.858'
CB18	23° 8.455'	113° 46.104'						
CB19	23° 8.665'	113° 45.846'						
CB20	23° 8.078'	113° 46.167'						
CB21	23° 8.659'	113° 45.834'						
CB22	23° 9.769'	113° 45.728'						
CB23	23° 10.106'	113° 45.744'						
CB24	23° 6.984'	113° 46.241'						
CB25	23° 6.831'	113° 45.605'						
CB26	23° 7.727'	113° 45.854'						
CB27	23° 9.133'	113° 46.862'						

APPPENDIX II: Location map of Coral Bay and Point Maud townsites (from Bradley and Latto, 1995).