TOWNSVILLE PORT AUTHORITY CAPITAL DREDGING WORKS 1993: ENVIRONMENTAL MONITORING PROGRAM

Edited by:
L J Benson, P M Goldsworthy and
I R Butler of Sinclair Knight Merz and
J Oliver of GBRMPA/AIMS

TPA
TOWNSVILLE PORT AUTHORITY

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No 1 The Strand, Townsville Q 4810

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FOREWORD

Townsville Port Authority, a statutory body established under Queensland Government legislation, is charged with the duty of managing the business of the Port of Townsville in a responsible manner. Satisfying commercial, environmental and societal sectors that management decisions have been "responsible" in regard to individual areas of interest is not an enviable task but it is one which the management team of Townsville Port Authority performs well.

The development works undertaken at the Port in recent years are an excellent example of pro-active management through co-operation, planning and a balanced perspective. Economic reality dictated that major works were needed and the Authority recognised at an early stage that assistance from various regulatory agencies would be necessary to ensure all legislative requirements were satisfied. The Technical Advisory Committee so established, worked very well and I compliment its members on their performance.

The extension and deepening of the approach channel to the Port was an area of particular concern. The Port is the gateway to a thriving city set in an attractive environment and bordering on the Great Barrier Reef Marine Park. The Authority was ever mindful that the people of Townsville and the responsible management agencies had every right to expect that a suitable environmental monitoring program would be emplaced. Considerable negativity from sectional groups regarding the project in its initial stages was based on information which was often anecdotal. The Authority was of the view that in order for monitoring results to be believed by those who held these strong views, a rigorous scientific program was required. The program finally adopted is a landmark in monitoring and management procedures. The program not only, as is often the case, measured impacts after they occurred, but predicted impacts such that rapid management actions could ensure that they did not occur. The results reported in this volume are evidence that the goal was achieved. Seagrass beds in Cleveland Bay were unaffected and not one of the hundreds of monitored coral colonies on Magnetic Island fringing reefs died as a result of dredging.

I would like to take this opportunity to thank all members of the monitoring teams for their diligence and enthusiasm. I would also like to thank the Authority's appointed Project Managers, Sinclair Knight, for designing a program, in at times difficult circumstances, which produced excellent scientifically defensible results and was described by the North Queensland Conservation Council as a "win-win" situation.

Prof. Mike Reynolds, A M
Chairman
Townsville Port Authority

FOREWORD

The Great Barrier Reef Marine Park Authority is charged, amongst other responsibilities, with ensuring that the Marine Park is not subject to adverse environmental effects. Dredging, with the sediment plumes associated with the dredging itself and the dumping of the material at sea, clearly has the potential to cause damage to coral reefs and other bottom dwelling fauna and flora such as seagrass meadows. In 1993 the Port of Townsville was developed to cater for larger vessels than could previously enter the port and this required that major dredging was necessary both in the port itself and along the access channel.

It is probably a reflection of our more enlightened times that, although none of the works took place in the Marine Park but were close to the reefs of Magnetic Island, the Townsville Port Authority saw fit to fund a detailed and comprehensive monitoring program to ensure that adverse effects were not only monitored but that, if adverse effects were detected, then the dredging operation would be modified, or even stopped, until solutions could be found. To achieve this 'reactive monitoring' for the protection of environments both adjacent to the works site, that is the fringing reefs off Magnetic Island, and within the site itself, required both foresight and a strong commitment to best practice.

The resultant monitoring was carried out at a number of levels and involved many individuals. The Queensland Department of Environment and Heritage employed a site supervisor (seconded from the Marine Park Authority) to observe day-to-day operations and to convene the designated multi-agency Initial Response Group if he felt that greater consideration was necessary under the conditions he observed. This Group could also be convened if the observations of corals, specifically tagged for monitoring, showed that certain preset limits had been exceeded. The overall program was overseen by a Technical Advisory Committee which drew strongly on the scientific community in the design of the work.

All parts of the work involved close liaison between the Port Authority, the Marine Park Authority, Queensland Department of Environment and Heritage, the project manager - Sinclair Knight & Partners, as well as experts in a plethora of disciplines. The degree of cooperation that led to mutually acceptable decisions is unprecedented in my many years of experience in marine management and I congratulate all concerned for their dedication and enthusiasm in the completion of a complex and difficult but ultimately rewarding task. The monitoring of the dredging sets a benchmark by which future, similar assessments of impacts can be measured.

In a global sense, it may be that the most important outcome of the work will be that developers, managers and scientists have confidence that they not only have the technical abilities to carry out this kind of work, but also the knowledge that the combination of skills and the commitment to apply them in a bigger picture can lead to synergistic outcomes that benefit all concerned.

Dr Wendy Craik
Executive Officer
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INTRODUCTION AND OVERVIEW

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1. INTRODUCTION

Since its establishment in 1864 to provide a service to the burgeoning northern cattle industry, the Port of Townsville has grown into northern Australia's premier port and north Queensland's gateway to European, Asian and Pacific Rim markets.

Townsville Port Authority was established in 1895 to administer and plan the Port's activities which have consistently expanded in order to meet the growing needs of national and international trade. With forward planning and commitment to improving and expanding Port facilities and operations, the Authority has, over the years, served the demands of new trades and new trading partners.

Total trade throughput for the Port of Townsville continues to grow at record levels with 187.8% increase over the eight year period (1986/87 to 1993/94). Currently, 6.5 million tonnes of raw and value-added cargo is moved by the Port annually with a total value of over $2 billion.

Current exports (1993/94) total 2.5 million tonnes consisting mainly of minerals (zinc concentrate, lead products and refined copper), sugar and molasses, general cargo, meat and associated products, and live cattle.

Imports, (mainly nickel ore, oil and liquid gas, general cargo, cement and copper concentrate) currently total 4.0 million tonnes (1993/94).

Import growth demands are projected to increase 163% to 5.03 million tonnes per annum (Mtpa) over the 10 year period from 1990 to 2000 (Connell Wagner, 1991). Exports are predicted to rise by 43% over the same 10 year period to 2.64 Mtpa.

Townsville Port Authority recognises the need to improve and expand Port facilities in order to adequately facilitate the projected needs of port users into the next century. It is with this foresight that major Port development has recently been undertaken.

The Eastern Port Development (EPD) will ultimately transform the Port of Townsville by providing over 100 hectares of new reclaim for siting of industry and the provision of additional berths with dedicated loading and unloading capabilities. The EPD was partially funded by a grant under the "One Nation Statement" and was officially launched by the Prime Minister, the Honourable Paul Keating, on 28 July 1992.

Stage 1 works included harbour dredging, enlarging and deepening, channel deepening and lengthening, land reclamation, construction of an outer berth, construction of a rail balloon loop and a bulk cement handling facility.

Dredging of the channels of the Port of Townsville has taken place for over 100 years and continues to be vital for safe utilisation of the port. The deepening that has taken place in Stage 1 was completed to better accommodate the larger and deeper draughted Panamax class vessels which are commonly used today.

While necessary for the economic growth of the region, major port development works such as dredging have the potential to cause lasting impacts on the natural environment. The marine environment is an important facet of life in North Queensland with extensive community use of the foreshores, reefs and bays. The Port of Townsville lies adjacent to one of the most valuable biological phenomena in the world - the World Heritage listed Great Barrier Reef.

The shores of Magnetic Island have many fringing coral reefs, and seagrasses grow over extensive areas in parts of Cleveland Bay.

Townsville Port Authority recognised the possibility that port development activities, particularly dredging operations associated with the deepening and lengthening of the Port's access channels, could affect the coral reef and seagrass communities in the area.

In response, the Authority, after liaison with a Technical Advisory Committee, commissioned a comprehensive multidisciplinary monitoring program to assess the extent, if any, of marine environmental impacts. The monitoring program involved approximately 30 marine scientists from James Cook University of North Queensland (JCUNQ), Mapping and Monitoring Technology (MMT), Sinclair Knight, WBM Oceanics Australia, Queensland Department of Environment and Heritage (QDEH), Great Barrier Reef Marine Park Authority (GBRMPA) and the Commonwealth Environment Protection Agency (CEPA).

Scientists studied the coral reefs and seagrasses of Magnetic Island and Cleveland Bay, and examined waves, current and sediment patterns in relation to dredging activities.

Detailed management guidelines were designed to allow rapid reaction to any observed impacts. The guidelines were a first; scientists, management agencies and the project proponent (TPA) agreed to certain actions on the exceedance of designated threshold criteria.

Vast volumes of information were collected during the course of the program and final reports contained large amounts of technical information. In order to make this information more available to scientists, managers and the public, TPA commissioned Sinclair Knight Merz to produce a book which summarised the Environmental Monitoring Program.

Authors of respective chapters submitted summarised versions of their final reports, or reviewed and approved summaries compiled by Paul Goldsworthy and Ian Butler of Sinclair Knight Merz. Overall editing was undertaken by Lee Benson of Sinclair Knight Merz and Jamie Oliver of GBRMPA/AIMS.

Following is an overview of the results of the monitoring program.

2. OVERVIEW

2.1 Project Design and Management

Dr Brett Kettle of Sinclair Knight Merz (then Sinclair Knight) acted in a scientific advisory role to TPA from the earliest stages of program inception through to its completion and the submission of final reports by the various monitoring teams. Brett's chapter gives an historical review of the process, including rare insights into the roles of, and relationships between, the various responsible agencies. With hindsight, the strengths of the approach used in this program are described as:

☐ an effective Technical Advisory Committee;
☐ a mix of engineering and science skills within the Project Management team;
☐ a pro-active client (TPA);
☐ an extremely motivated team of subconsultants;
☐ the creation of the position of an Environmental Supervisor - supplied by government management agencies; and
☐ the presence of scientists on TPA's supervisory team.

Problems were also encountered, partly due to the pressure under which individuals were placed during the course of the program, and partly as a result of:

- ☐ suspicion by some parties of other parties motives;
- ☐ the objective measurement of quality in scientific studies;
- ☐ onerous time frames set by political agendas; and
- ☐ distorted financial perspectives.

2.2 Reactive Monitoring (Short Term Responses) of Corals

The regular (twice weekly) monitoring of the health of tagged coral colonies was the crux of the management decision protocols to be enacted during the program. Four coral species were selected by an expert panel as suitable for monitoring purposes. Twenty colonies of each species were tagged in each of three primary (and two secondary) impact locations and in two control locations. The relative difference between impact and control locations in terms of two aspects of coral health (white bleaching and partial mortality) was used to delineate three levels of management reaction. These levels were set after considerable debate and the program results suggest that the levels eventually set were appropriate for the dual purposes of environmental protection and efficient dredge operation. At the conclusion of the monitoring program, there had been no exceedance of trigger thresholds for partial mortality after control vs impact comparisons. In fact a simultaneous study using the same techniques and monitoring a further 500 colonies of 20 species found no colonies died and partial mortality was less than 5% in 99% of colonies. Three exceedances of the least severe threshold for white bleaching occurred in Weeks 5, 7 and 8 of the 13 week program but returned to below threshold levels thereafter and did not lead to mortality of colonies.

2.3 Coral Communities

A second monitoring program focussing on corals looked at longer term responses in a broader suite of community elements than did the Reactive Monitoring Program. Ten taxonomic groups were assessed; Acroporid/Pocilloporid group, Fungiids, *Turbinaria*, *Montipora*, Poritids, Faviids, Hard Corals, Soft Corals, Sponges, *Sargassum* and All Algae. The BACI (Before-After-Control-Impact) survey design was constructed to detect changes in cover of around 20%. Surveys were conducted prior to, during, and several months after dredging at 6 sites in each of 4 impact and one control location. The results were also compared to an earlier study of Magnetic Island corals by re-using some of the same locations.

Of the ten groups studied only faviids and soft corals showed significant declines in abundance consistent with an impact of dredging. Comparisons with the earlier Magnetic Quays study showed that coverage of all groups except *Montipora* varied significantly over time. Faviid coverage had increased between surveys such that the declines noted on Florence-Arthur bays during dredging returned coverage to only slightly less than that recorded in the earlier survey. The authors concluded that, at least in the short term, dredging works did not result in major changes in community composition of corals at the examined Magnetic Island reefs.

2.4 Seagrasses

Monitoring of seagrass communities in Cleveland Bay was initially intended to follow a BACI design but as no suitable Control site existed the monitoring was based on before-during-after assessments of density and distribution. This was supplemented with a comparison of historical photographs and interpretations of the areas of seagrass beds. Both aerial photographic and visual ground-truthing surveys were conducted covering the seagrass beds to the south-west of Magnetic Island and along the south-eastern shores of Cleveland Bay. This historical review revealed that seagrasses had fluctuated in distribution and extent between 1961 and 1991, with a noticeable low around 1974. From surveys conducted in this program it was concluded that no effect of dredging was detectible on the seagrasses of Cleveland Bay.

2.5 Remote Imagery

Weekly and "on-call" aerial photographic surveys following a set flight path were undertaken during the first 8 weeks of dredging operations. This photographic record of plume development enabled managers to interpret possible plume movement on a broad scale. Features noted in the photographs such as the eddies which formed off some of the headlands of Magnetic Island and the area of clear water which developed immediately adjacent to fringing reefs on ebbing tide, were of considerable assistance to the interpretation of site specific suspended sediment data. Satellite imagery also gave the "big picture" but it was unfortunate that the images could not be correlated with field measurements of suspended sediment. The reason for the lack of correlation is unknown.

2.6 Oceanographic Data Collection

The task of collection of oceanographic data was performed to enable interpretation of the observed patterns of sediment dispersal and to refine and validate hydrodynamic models. Data collection covered tide levels, water currents (speed and direction), wave height and period, wind speed and direction and barometric pressure. The program involved collection and analysis of data from existing systems as well as the in-field placement of several recording devices. The data collected proved suitable for use by the Data Interpretation team.

2.7 Sediment Data Collection

As with the Oceanographic Data Collection program the purpose of this study was to provide data suitable for interpretation by others. The sediment program collected:

- 356 samples of water column suspended sediment concentration using Niskin water sampling bottles;
- 268 successfully retrieved sediment traps (a 92% retrieval rate);
- 25 diver-driven cores from the dump site pre- and post-dredging; and
- 29 865 hours of suspended sediment concentration taken using logging nephelometers.

The latter collected data for up to 20 days of pre-dredging conditions, 77 days during dredging and 24 days post-dredging.

2.8 Data Interpretation

The Oceanographic and Sediment data collected in the programs described above was interpreted in terms of the likelihood that recognised events were dredge related, by a specialist team of analysts. (A significant degree of co-ordination was achieved between the various data collection programs, ensuring maximum utility in interpretation). The general conclusions from the analyses were that:

- dredge-related effects lay within normal variation at seagrass sites and at Middle Reef;
- no extreme suspended sediment concentration occurred at any of the Magnetic Island bays as a direct result of dredging;

- ☐ dump-events could be identified as turbid underflows lasting periods of hours; and
- ☐ swell-induced raised suspended sediment concentrations in outer Cleveland Bay lasted periods of hours-days.

2.9 Hydrodynamic Modelling

The Marine Modelling Unit of the Department of Civil and Systems Engineering, James Cook University of North Queensland, has undertaken chronologically separate, though developmentally linked, studies of the hydrodynamics of Cleveland Bay at the request of the Townsville Port Authority. The first study modelled the tidal and wind-driven circulation of Cleveland Bay while the second applied these results to a study of the flushing of the bay. These early studies were conducted prior to commencement of the capital dredging works and were used in the planning of the environmental monitoring program. The third study, conducted during the dredging program, was aimed at predicting the movement of suspended sediment under current and forecast weather conditions and thereby act as an early warning indicator of potential problems in sensitive areas. Management decisions regarding the operation of the dredge would be based on the predictions, avoiding or reducing the likelihood of environmental impacts. The final study was a three dimensional modelling study of the movement of sediment away from the dump site and it clearly showed that particles released at the outer edge of the dump site have significantly less potential to impact on Magnetic Island than those released closer to shore.

2.10 The Role of Management Agencies

Steve Raaymakers was appointed as Environmental Supervisor, employed by the Queensland Department of Environment and Heritage, in December 1992 and the position followed earlier involvement through his position at the Great Barrier Reef Marine Park Authority. Steve presents the position of the management agencies throughout the planning, permitting and monitoring processes and highlights the role of the Environmental Supervisor. The chapter presents something of an alternative view to that put forward by Brett Kettle on behalf of the Project Managers. Interestingly, the end result of the systems which were developed for this program, satisfied all parties concerned.

PROJECT DESIGN AND MANAGEMENT

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INTRODUCTION

In most development projects it is difficult, if not impossible, to predict with confidence what the actual environmental effects are likely to be. There are many possible responses that environmental managers or regulatory agencies can make in this situation. Almost invariably some participants will use this uncertainty to call for rejection of the proposed development. This is a simplistic response which, if based on logic, would have to assume that scientists, engineers, regulators and the public cannot find a better solution if they work together with the project proponent.

Fortunately for this project all parties concerned were prepared to look for ways to use scientific methods to build an environmental management system that permitted development and simultaneously protected the environment. The ultimate success of the dredging program (it came in below budget) and environmental protection measures (no damage was evident) underpins the general consensus that all parties worked well together and that the problem-solving approach used for this project was a success.

This chapter describes the overall project management context that scientific studies were conducted within. It describes the intent and position held by Townsville Port Authority (TPA), who were at all times the "client" and provider of funds for these activities. TPA's briefing to Sinclair Knight (SK) is related, and the chapter also puts into perspective the range of other studies, not specifically reported in this book, that set the scene for the environmental management approach used in this study. With the benefit of hindsight, this chapter concludes with a review of the major strengths and weaknesses of the study approach adopted here.

1. BACKGROUND

The first step in understanding the management of this project is to appreciate the significant factors existing at the time the study commenced. Major features of the management environment in which this project was conducted were:

Sensitive environment
Several types of sensitive natural resources exist in the local area. Arguably the most sensitive, but certainly the most frequently cited of these were locally and regionally significant coral reefs within about 1.3 km of some parts of the dredged channel. Further away (about 5 km) were locally and regionally significant seagrass beds supporting dugong and turtle populations. Many parts of the local coastline (within 5 to 10 km of dredging) also support mangrove forests.

Potential for impacts
Pre-indications from the earlier impact assessment phase suggested that although the geographical separation of dredging and sensitive resources would usually ameliorate potential impacts, dredging-related impacts were possible under some wind conditions.

No standards in place
This would have been a relatively easy project to manage if there had been legislated or other defacto standards by which to judge permissible levels for the release of turbid water from the dredging operation. In the absence of such standards it was necessary to first establish a common information base, erect a decision-making framework and then, using some form of consensus, decide on suitable standards for the conduct of environmental management of the dredging operation.

Strong and effective Technical Advisory Committee
Even at the start of SK's involvement in this project a Technical Advisory Committee (TAC) had been established to coordinate the inputs of various agencies to the environmental approvals process for this project. Internal communications between participants were good, and there were good communications between the TAC and participants' respective organisations. While there were few technical experts on the TAC, many members were well versed in the technical issues and all had good management experience in similar situations.

Local pool of experts
The Townsville region, home to James Cook University, Australian Institute of Marine Science and Great Barrier Reef Marine Park Authority (GBRMPA), contains a large body of world-class tropical marine scientists, many of whom had first hand experience with the reef areas in question.

Paucity of relevant information
Despite the fact that many scientists have conducted research on the very reefs in question, or that many more had conducted research on the effects of sediment or light on coral health in other areas of the Great Barrier Reef or other coral reefs around the world, few of the ecological factors necessary for scientifically-based decision-making on this project were well understood in advance of this project.

Summer a bad time for corals
Several coral scientists advised that dredging during the summer months (when the temperatures are at their highest) posed the highest risk to corals because temperature-induced stresses meant that some corals would already be approaching their lethal limit.

Public spotlight
The local conservation community was highly educated, articulate and motivated, and included amongst its ranks many scientists who, in other roles, might be providing advice to this project. The initial stance of this group was to call for a moratorium on dredging, and the group made effective use of the media to voice its concerns.

Precedent cases were problematic
At the time of planning this project, recent dredging exercises in Queensland and in New Zealand provided precedents to suggest that improperly addressed community concerns could lead to confrontation, delay the project and result in unnecessarily high project preparation costs or in the imposition of dredging methodologies which would lead to a dramatic increase in dredging costs.

Cost containment was very important
Given that the projected costs already exceeded the available budget, it was always necessary to spend only that required to answer relevant questions. This might sound self-evident, but in this and other high public profile studies there are usually continual requests for additional studies that, upon examination, prove to have little chance of successful completion, offer little hope for better management of environmental effects or are simply of academic interest.

Urgent time frame
In this case there was a very stringent time frame for commitment of project funds because of "One Nation" federal financing for over half of the TPA works. In effect, this meant that all stages of design, tendering, negotiation and baseline studies were conducted with little leeway for delays so that dredging could start in sufficient time to allow conclusion of capital expenditure before July 1993.

2. ROLE OF SINCLAIR KNIGHT

In early 1992, as a result of an open national bidding competition, SK were awarded the project management role of the Phase I Port Development Project. This gave SK responsibility for advising TPA, for preparing documents on their behalf and for managing other necessary works, for aspects of the project that TPA had direct control over. While the entire development project was frequently cited as costing $90 million, TPA were only responsible for approximately $34 million of this - the rest comprising commitments by other port users for infrastructure development on their own leased lands within the port area.

SK responsibilities included overall budgeting and management of works for reclamation of lands, design and construction of bunds and breakwater walls, design and construction of new rail facilities and management of the channel dredging operations. In terms of dredging, SK were to develop cost estimates, prepare dredging contracts and tender documents, negotiate with dredging tenderers and once dredging operations commenced, to supervise dredging operations on behalf of TPA.

Amongst the reasons favouring the choice of SK as project managers was SK's in-house experience in local dredge-related issues, which effectively meant that it would be possible to develop and implement environmental management controls while maintaining close and frank communications between the environmental management team and the project managers.

As environmental managers, SK were expected to develop an overall environmental management framework, provide advice and project management services to TPA for all environmental matters, and conduct specific studies either in-house, using contractors or as supervisors of other TPA contracted third parties, as appropriate.

Most scientific studies that were undertaken during the course of this project were conducted by third parties who were contracted directly by TPA. In these cases SK was responsible for establishing the scope of the studies, estimating budgets and - after approval from TPA - tendering, assessing and supervising studies on their behalf. In effect, all issues of scope, quality, timing and fees were dealt with by SK, with recommendations for any actions requiring approval by TPA.

Since TPA functions commercially as a government enterprise, the majority of decisions (and certainly all those involving significant financial commitments or corporate risk) required the approval of the TPA Board, which meets monthly for this purpose. In practise, only decisions involving less than a few thousand dollars could be made without Board approval, and it was customary that even these decisions were subsequently reviewed by the Board.

Thus SK had clearly defined responsibilities to provide TPA with sound, commercially responsible advice on the entire project, including both project implementation and ensuring that this was done in a sound environmental management context.

3. TPA's POSITION

During early discussions with TPA it became apparent that:

- ☐ they did not wish to cause significant adverse environmental effects;
- ☐ they did not possess in-house technical expertise which allowed them to judge the correct course of environmental management for themselves;
- ☐ the entire development was constrained to the available budget, which was already projected to exceed the available funds;
- ☐ they could therefore not afford to agree to requests for environmental work unless they could ascertain that the work was likely to lead to a significant reduction in their exposure (either financially or corporately); and
- ☐ therefore the lowest cost, scientifically defensible environmental protection program was necessary.

4. PROGRAM OVERVIEW

Whilst this book focuses primarily on the monitoring associated with the capital dredging program, it is useful to appreciate the context of this study amidst the other planning activities that were necessary. The following section provides a brief summary of major components that set the scene for the subsequent environmental management program for capital dredging works.

4.1 Previous Influential Studies

Coincidentally, it was SK that had previously completed the 1989 Impact Assessment Study (IAS) for long term expansion of the Port of Townsville. This study examined, among other things, the potential impacts of dredging approximately 1 million cubic metres of material in a program to deepen the existing channel to 13 m. The IAS concluded that dredging had the potential to cause elevated levels of sediments in adjacent coral reef areas under some conditions, and as such, had the potential to adversely affect coral reef communities. It also indicated that, given the range of dredge management techniques available, it was considered feasible to conduct the proposed development without significant environmental impacts.

In mid 1989 the Commonwealth Environment Protection Agency had asked TPA to undertake preparation of a Long Term Dredge Spoil Disposal Strategy (LTDSDS). This strategy was intended to ensure that future dredging requirements were conducted within a rigorous environmental planning framework. The LTDSDS included components to minimise the requirements for future dredging; to improve the quality of dredged materials; to seek productive or beneficial uses for dredged materials; and, for remaining materials, to seek the most appropriate disposal site (be that on land or at sea). Phase One of this study had been undertaken by the Queensland Department of Transport and subsequent stages were then being planned. Since these studies are not directly related to the present subject the LTDSDS will not be discussed further, but it is useful to note that other environmental studies were being conducted in parallel, and that - in some cases - studies for either purpose (LTDSDS or monitoring) actually addressed both objectives.

At the commencement of SK's involvement in the Stage One Port Development project (mid 1992) there was an urgent need to undertake maintenance dredging. Despite the forthcoming capital dredging program (then expected in late 1992), normal siltation had lead to shallowing of channel depths to the point where de-rating was imminent. An examination of the offshore dump site, which had been in use for about 20 years, suggested that approximately 70% of the material that had been placed there was still evident. Furthermore, faunal communities within and external to the dump site showed qualitatively similar characteristics, suggesting similar patterns of disturbance and recolonisation throughout much of Cleveland Bay. These observations formed the basis of a recommendation that, at least until completion of the LTDSDS, the old offshore dump site should continue to be used.

Whilst application for the continued use of the existing dump site was being made, GBRMPA sought and received advice from local oceanographers on the problem of "shoaling" in the vicinity of the dump site. Water depths become much shallower in the inner portion of the dump site, because the site straddles the natural slope from shallower bay waters to deeper lagoon waters. Waves approaching the bay begin to interact with the seabed as the depth decreases, resulting in increased resuspension of sediments. On the basis of this advice GBRMPA recommended that the dump site be shifted further offshore so that all dumping occurred below the 11 m depth contour. Despite the extra costs associated with increased travel time for the dredge, TPA were happy to agree with this. The subsequent permit incorporated this as a relocation in the dump site boundaries.

The required maintenance dredging project proved to be a good opportunity to investigate some of the dredging impact issues that had emerged in the earlier IAS. Three days of dredging were set aside for environmental study purposes. Many observations were made of suspended sediment levels in dredge plumes: the rate of build-up; lateral and vertical extent of plumes; and the rate of decay of plumes once dredging ceased. These observations suggested that plumes took 2 days to build up to the point where, under appropriate wind and tide conditions, they might lead to measurable elevations of turbidity in coral reef areas. They also suggested that plumes would dissipate to background levels in about 4 days. These plume observations suggested that moving the dredge's operations away from sensitive coral reefs would be a successful strategy, since only about one third of the required dredging was close to local coral communities.

A mathematical modelling study was undertaken to examine the likely range of weather conditions that would lead to the build-up of sediment plumes in areas containing sensitive habitats. This study concluded that wind direction, location of dredging and tidal range were key determinants of suspended sediment concentration patterns. While some wind conditions would favour sediment build-up, other wind conditions, or the regular occurrence of neap tides, would favour rapid dispersal of sediment plumes. It thus appeared that the regular spring - neap tidal cycle would also help to ensure that any turbid plumes that might build up would be regularly dissipated from reef areas.

At about this point in time, SK engineers, who were preparing dredging contract documents, incorporated contract clauses that would permit the intervention of TPA in dredge methodology, or the standing down of dredging operations if required, for environmental purposes. This was a rather unusual step, because dredge operators are usually given control over methodology or timing to permit them to choose the most effective dredging method thereby ensuring the most competitive bidding situation for a contract. These clauses also established procedures and responsibilities for various forms of environmental-related work interruptions, setting mechanisms that would minimise contractual problems that might otherwise occur if third parties wished to intervene in a dredging operation. Since dredge stoppages or dredging inefficiencies introduced through environmental management initiatives would increase costs (the dredge cost was approximately $65,000 per day) this opportunity was also taken to allocate a portion of the budget for extra costs that might be incurred if work was hindered. The sum set aside (approximately $1 million) was estimated to be the additional cost of standing down the dredge from the existing contract.

In the period leading up to the design of the capital dredging monitoring program, LTDSDS data requirements were also becoming apparent. Thus it appeared that the forthcoming capital dredging, with its data collection requirements, also provided an opportunity to collect oceanographic and sediment concentration data that would be very valuable for subsequent analysis of spoil dumping strategies, even though they might have little use in the day-to-day management of dredging operations.

4.2 Project Design

In commencing a detailed design for the environmental monitoring program, several key points were recognised:

Relevance to dredge management

A set of monitoring activities should focus primarily on taking measurements that could be quickly incorporated in a decision about the day to day operation of the dredge. As a general rule, if such monitoring could not be used immediately to help manage the dredge, then it was of academic value only and could not be seriously considered within this subset of the program.

Document actual effects

Some monitoring activities were not of immediate use in managing the dredge, but provided the baseline and quantitative measure of effects that would be important to resolve whether there had or had not been environmental damage. This type of data would become important if claims of damage were made by the public; or if day-to-day monitoring lead us to believe that damage had occurred.

Minimal interference

In creating a monitoring and management framework it was important to allow the dredging contractor the greatest possible freedom of choice in methodology. This would help to ensure the best commercial conditions for TPA and maximise dredging efficiency, leading to a shorter period of disturbance.

Cope with natural variability

Recent trends suggested that coral deaths could be expected every two to five years, even without dredging operations, due to coral "bleaching". Since this is a naturally occurring event, and since other natural causes of coral deaths are also known to exist, it was important to select a monitoring design that gave the best chance of determining whether coral deaths were "natural", or related to the dredging operations.

Make use of old data for long term comparisons

Natural communities are rarely "stable". Even on relatively short time scales, species distribution and abundance patterns can change markedly. Thus it would be useful to compare any changes seen in communities during the course of this study with any previous measurements of community change. It was therefore necessary to choose methods that permitted comparison of new data with studies which had been conducted in the same reefs several years before.

Since the greatest expertise in local marine science lay in the academic and research institutions of James Cook University and the Australian Institute of Marine Science (and since these people would, in one way or another, be called upon to voice their opinions during the dredging program), these bodies were invited to send interested representatives to participate in a brain-storming session that would identify subjects worthy of inclusion in the monitoring program. For some people, participation in this session provided an opportunity to learn, in advance of formal tendering for the work, the general areas of work that would be required. For many participants though, the motivation to participate was entirely unrelated to any possible flow-on work. The majority of those present contributed because of their personal interest in sharing expertise for the sake of seeing the right project scope developed.

At this scoping meeting ten major areas of monitoring were recommended. These included:

- ☐ coral community monitoring using quantitative survey methods;
- ☐ monitoring of reef-associated fish communities;
- ☐ seagrass monitoring;
- ☐ beach profiling and sediment studies;
- ☐ remote sensing and aerial photography of sediment plumes;
- ☐ collection of near-bed and water column suspended sediment concentrations;
- ☐ collection of wave, water level and water current data from several locations;
- ☐ regular interpretation and reporting of oceanographic and sediment data trends;
- ☐ numerical hydrodynamic modelling of spoil dispersal; and
- ☐ "reactive monitoring" of coral community health.

TPA, recognising that no one group would possess high levels of experience and expertise in all 10 areas, decided to tender the works as separate packages. Since TPA required ongoing assistance with the management of the study, and since SK had been involved in the study planning over a protracted period, it was decided that SK would adopt a supervisory role on behalf of TPA rather than bidding on the work packages. Scopes of work and other tender documents were drawn up by SK and after national advertising, bids were received.

A subgroup of the TAC, including SK as supervisors of the study together with representatives of TPA, GBRMPA and the Queensland Department of Environment and Heritage (QDEH), was convened to assess the suitability of tenderers. Assessment proceeded by an evaluation method similar to that recommended by the Association of Consulting Engineers of Australia's "Value Selection" guidelines. Expertise, experience, methodology, management capability and price were ranked and weighted against a standard, pre-established set of criteria. The role of price was thus considered, but did not override other technical issues. It should be said that in most of the let contracts, awarded prices were not the lowest that was bid, and that in several cases the bid committee requested additional items to be added to the bid price to increase the technical capability of the proposed works packages.

No bids were received for seagrass studies. After considering this the TAC affirmed that these studies were desirable and SK, after discussing methodology with the Queensland Department of Primary Industries (who had undertaken previous seagrass studies in the area), put together a seagrass study that met with the TAC's approval.

Several groups expressed interest in conducting studies of small coral-associated fish. However, proposed methodologies were rated as having little chance of overcoming the technical difficulties of accurately assessing small changes in fish density in these environments, and the TAC therefore recommended that this monitoring component be dropped.

Bids were received for numerical modelling of the dispersal of soft sediments from the dump site. After independent review of proposed modelling methods the TAC deemed that present day modelling capabilities were unlikely to lead to an unambiguous conclusion for situations other than extreme events, which are already well known to resuspend large areas of the GBR lagoon and most of Cleveland Bay. The TAC therefore recommended that the necessary data collection programs go ahead, but that modelling studies be held in abeyance until better modelling tools existed.

Coastline and beach monitoring proposals contained novel analytical methods which had not been tested in the local environment, and for which bidders could not give a reasonable indication of success. The TAC therefore requested a simple beach profiling and sediment sampling program be undertaken by TPA in lieu of the originally proposed work.

Commissioned studies, totalling approximately $716,000, were commenced in December, with baseline studies being finished in early January 1993. Individual studies are reported in detail in Chapters 3 to 9.

5. CONCLUSION

With hindsight it is now possible to describe the major strengths and weaknesses of the approach - an exercise that should be done because it permits attainment of the maximum benefits from this project.

5.1 Advantages of This Approach

The entire project ran very smoothly and the end result is testimony to its success, not only in environmental management terms (no damage was detected), but also in port expansion project terms (the dredging component suffered no environmental delays and came in within budget) and in terms of the relationships between participating parties.

Key factors believed to have helped were:

Effective TAC

The composition of the TAC was very effective. In essence, members did not require technical expertise themselves, but needed to possess a broad range of knowledge to direct and review the work of the external experts who were available. Had these "experts" sat within the TAC, deliberations would have slowed down considerably. In effect, TAC members were managers and decision makers, representing their agencies' interests effectively in the design of the study. In future such a body should be titled the Management Advisory Committee.

Mix of engineering and science

The possession of both engineering and environmental science skills within TPA's project management team proved very useful, since it enabled TPA to receive balanced briefings in sufficient time to prepare material for TAC requirements. This was particularly important in terms of budgets and contractual issues, because these usually involved seeking the approval of the Board. If new matters had originated from the TAC without prior Board briefing, TPA's internal approval processes would have compounded the short time-frame problems that already existed.

The other notable example was for the main dredging contract, which had environmental protection clauses inserted prior to necessary tendering dates, and well before the TAC had considered likely contractual requirements to establish the necessary links between environmental controls and the dredging contract. This situation contrasts typical development projects, which often see environmental scientists and engineers pitted against each other in the late stages of project planning.

Proactive client

TPA was a model client throughout this project: acknowledging at an early stage the need of specialist environmental advice; commissioning studies in a pro-active manner, in advance of direct requests from regulatory agencies; always questioning and checking the advice they were given but prepared to listen and respond quickly to tabled recommendations.

Extreme motivation of participants

One of the key factors which enabled this project to run smoothly was the dedication of many team members, who pursued excellence in their studies, at all hours of the day and night, often 7 days a week, and often under physically demanding circumstances.

Position of Environmental Supervisor

The creation of this position ensured that regulatory authorities were always (7 days a week) well informed of emerging conditions and therefore briefed and prepared to make decisions when needed. This role was essential to the effective management of the project given the financial (or environmental) exposure that might have occurred under more typical regulatory decision-making time frames.

Scientists as supervisors

TPA's environmental supervisory team benefited by having several scientists who could deal with researchers and academics on behalf of the client. This was very successful in presenting necessary science to the client in lay terms and in weeding out unnecessary studies through technical negotiation with scientific experts.

5.2 Perceived Problems

It would be very unrealistic to suggest that there were no problems experienced with this project. Of course there were small incidents from time to time that reflected only the intense pressure that individuals were under to move the project along commercially dictated time scales, and due to genuine concerns on possible environmental impacts, but these were trivial. Only four areas are worthy of note:

Suspicion of motives

It is sad but true that a great many academics, regulators, conservationists and industry representatives commence their relationships with biased and preconceived notions of their respective roles in environmental management. In theses situations conflicts can quickly emerge from suspicion of other peoples motives. This reflects the "developer versus conservationist" picture painted so frequently by the media. It also reflects a lack of understanding (and willingness to understand) about the role of legislators, of scientific advisers and experts, of commercial pressures facing developers and of the legal frameworks that keep the system going. Perhaps many participants in this project now see the other players in a clearer light. Even so, problems of this nature in future projects will only be solved when education systems and the media portray the true roles and motives of the wide range of participants involved.

Measuring quality in science

Another area that requires a different approach in future is the objective measurement of quality in scientific studies. Scientists strive for excellence in their measurements and interpretations, but finding ways to quantify this in publicly bid tender situations and without the luxury of sufficient time frames for peer reviewed journal publications still requires thought. If legislation specified all necessary measurement techniques in advance then the situation would be simple, but this is a blind alley - even for these relatively well studied reefs the scientific community still had to come up with new methods to provide the answers that were necessary for this project. Whilst it may not have affected project outcomes, it is still desirable that objective measures of scientific quality be developed and incorporated more carefully at early stages of future projects, if only to save frustration and tension that develop when these issues are discussed mid-way through a project.

Onerous time frames

Time constraints in this project often put participants under a lot of pressure. In the early stages of project planning it looked like dredging would start in October 1992. It was necessary to fully spend federal "One Nation" funds by mid 1993 but dredging didn't commence until mid January, 1993. Had it not been for the superb efforts of the scientists and regulators involved, it would have been impossible to make the required deadlines. These feats were made all the more difficult when it was known that bad weather, dredge delays or other factors outside of the control of those involved could suddenly mean that last night's sleepless efforts were not really necessary because there had been a further delay. Unfortunately these aspects are all too often dictated by factors over which we have little control - in which case patience, explanation and understanding are all that can be wished for.

Distorted financial perspectives

Throughout this project it was important to spend the minimum amount of money to do a scientifically defensible job. Unfortunately this sometimes resulted in misguided effort and friction, since scientists and regulators were occasionally inclined to believe that TPA's cost cutting motives were so great that they would have been prepared to unnecessarily jeopardise the environment. This was reflected in a variety of comments that were made, including those to the effect that:

- more monitoring was justified in this case because proportionally more had been spent elsewhere;
- further monitoring was justified because the money allocated for dredge stand-by costs hadn't been spent and TPA were therefore ahead on budget;
- scientists didn't want to suggest a particular aspect of monitoring because they felt that it would exceed TPA's desired budget; and
- scientists wanted to know TPA's budget before suggesting what the monitoring requirements were.

In fact the people making these comments should have ignored the financial aspects, and provided their advice simply in terms of which studies or actions were necessary to ensure environmental protection. In effect, studies that wouldn't contribute to managing the dredge's effects, or those which might have been helpful but which had a high chance of technical failure should have been, and were, abandoned at the planning stage. Those providing advice are obliged to provide it at the best price, but must not let financial concerns override the need to do a task in a technically competent manner. This is an important lesson for the future - by proposing unnecessary or technically weak studies, scientists and regulators erode the confidence that developers must have in them if they are to be believed in the issues that really count.

REACTIVE MONITORING (SHORT TERM RESPONSES) OF CORAL SPECIES

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EXECUTIVE SUMMARY

This project, termed the Reactive Monitoring of Corals, involved the weekly assessment of the condition of colonies of four coral species (*Acropora latistella, Merulina ampliata, Montipora aequituberculata, Pocillopora damicornis)* at locations around Magnetic Island most likely to be impacted by dredging or dumping, and at locations well-removed from the channel which were unlikely to become impacted by the works. These species were selected on the basis of their abundance and susceptibility to sediment-related impacts. This design was used with a view to distinguishing impact-related changes in coral health in contrast to those which might be occurring naturally. Three major locations around Magnetic island (at Florence Bay, Geoffrey Bay and Middle Reef) and two subsidiary locations (Arthur Bay and Nelly Bay) were designated sites of potential impact. Control locations, unlikely to be affected by dredging, were located at Rattlesnake Island and Bay Rock.

At each location, 20 individual colonies of each of the four coral species were permanently tagged and photographed prior to the commencement of dredging (only 4 *Acropora latistella* at Middle Reef due to low incidence of colonies). Coral health was assessed as percentage of tagged colonies displaying partial mortality, bleaching and overlying sediment on their tissues. These were observed twice weekly at principal impact locations and once weekly at controls. Subsidiary locations were surveyed twice during the project.

Data on partial mortality of corals and white bleaching were assessed weekly in relation to three pre-determined threshold criteria (Decision Thresholds): (i) Immediate Response Group (IRG, data reviewed by day-to-day environmental management group); (ii) Review Panel (data reviewed by technical experts); (iii) Immediate Action (dredge put on standby or moved away from the sensitive area). The Decision Thresholds provided a mechanism by which the dredging could be modified or stopped. Additional information on sedimentation and turbidity was collected at each location at the same time that corals were being observed.

Neither the 'Immediate Action' threshold nor the Review Panel threshold was exceeded during the dredging program.

Partial mortality of individual colonies at principal impact locations was less than 12% of colony tissue area with one exception (*Merulina ampliata* at Geoffrey Bay). Complete death of this colony occurred but was not considered dredge related. Overall mortality levels did not exceed any control-versus-impact Decision Thresholds.

The highest levels of mortality were recorded towards the end of the dredging program at Rattlesnake Island (a Control location). There were obvious signs of disease at this location. Similar disease was not observed at any other locations. Since management decisions were based on control-versus-impact criteria the coincidence of this disease at a control location could, theoretically, have obscured real effects of dredging. This was not the case since, even prior to comparisons with controls, impact locations did not exceed critical thresholds for partial mortality.

White bleaching IRG thresholds were exceeded on several occasions but did not reach Review Panel levels. Other evidence of stress (significant moderate bleaching and changes characteristic of tissues prior to necrosis) was observed in one transect species at Geoffrey and Florence Bays during February. In general, the stress led to only minor partial mortality (less than 5%) but sporadic colonies showing up to 25% partial mortality were observed off the transect. It is probable that this species came close to its tolerance limits and that higher mortality would have occurred if adverse conditions had persisted. Informal surveys of coral communities adjacent to the coral transects indicated that other non-transect species were showing increases in white bleaching at this time. But severe stress similar to that of *Acropora latistella* was only observed in five colonies of two other species. This study is not able to evaluate the degree of mortality of non-transect colonies.

The co-occurrence of spring tide, wind-waves, ground swell and low surface light may all have affected coral health during the critical period in February by causing adverse sediment and light regimes. However, since coral stress was not observed at control locations at this time, it is concluded that dredging activities also contributed to the observed stress in corals at Geoffrey and Florence Bays.

This study focussed on short-term effects of dredging activities on specified target corals. Quantitative data for these corals showed no evidence of significant dredge-related mortality. However, enhanced levels of coral stress (particularly as measured by moderate bleaching levels) at Geoffrey and Florence Bays during February, support the contention that at least one species was close to its tolerance limits during this period. It is therefore recommended that major dredging within close proximity of Magnetic Island reefs be avoided or closely monitored when adverse natural conditions (such as spring tides, strong winds, ground swell and/or persistent low light) coincide.

1. INTRODUCTION

Coral biologists have long argued that corals are susceptible to turbidity and light attenuation in their environment, with changing community composition or reduced diversity in areas of high turbidity (Sheppard, 1982; Rogers, 1990). Some species tend to be more tolerant of sedimentation and occupy near-shore reefs where clear waters are rare (Bull, 1982; see review by Craik & Dutton, 1987). However, activities which further increase siltation levels (human development, cyclones etc) can lead to local or widespread damage to reefs (Fisk, 1983; Cortes & Risk, 1985). The effects of development on coral reefs is of increasing concern in North East Queensland where management bodies are engaged in a delicate balancing between human progress and preservation of the world's largest coral reef system, the Great Barrier Reef. Studies on the effects of developments on reef communities are of great importance for coral reef management.

Although studies which examine various types of stress on corals or coral communities are common (Brown & Howard, 1985) only a small proportion of these are focused on the effects of dredging or the dumping of sediments (Pastorok & Bilyard, 1985; Rogers, 1990). A few studies which focus on other forms of development, such as increasing run-off adjacent to farming communities and other activities which disrupt the natural coastal and hinterland vegetation are also of relevance here. The shortage of literature on similar projects may be because most major ports around the world have tended in the past to be concentrated in temperate and cooler climes, with large-scale port developments near coral reefs being unusual.

1.1 Effects of Dredging and Related Impacts

Early studies on the effects of dredging on adjacent coral communities were often approached qualitatively or semi-quantitatively with little opportunity for accurate descriptions of effects. Brock *et al* (1966) reported on the effects of large-scale dredging on Johnston Atoll (700 acres dredged) reporting large-scale declines (up to 40% loss in cover) in 1,100 acres of coral reef communities through sedimentation stress. In some areas, or types of operations, impacts are great, leading to large losses in coral cover (e.g. Dodge & Vaisnys, 1977; Chansang *et al*, 1981; Brown *et al*, 1990). In other dredging assessments very few impacts on coral communities were detected (Sheppard, 1980; Mapstone, 1990). In one study, the turbidity associated with dredging was considered small in relation to that observed during natural disturbance events (Zolan & Clayshulte, 1981). Ayling & Ayling (1992) examined the effects of run-off after the construction of an unsealed coastal road through an otherwise relatively undisturbed rainforest area in far-North Queensland on corals of fringing reef communities. They concluded that there was no effect of the silt on cover by hard corals (Acroporids and Montiporids) over the three year period of the study.

The presence of regular periods of high natural turbidity (cyclones, monsoons) and/or differences in natural tolerance in coral species are likely to play an important role in the predicted effects of dredging activities on a coral community and would help to explain some of the apparently opposing results obtained by different workers.

1.2 Reactive Monitoring

Previous dredging surveys worldwide have tended to focus only on the longer-term changes in community structure of corals. A more effective management strategy would include repeated surveys of community variables which might detect impacts as they occur so that *reactive management* can take place to modify the impact and minimise any effects - this would be especially useful in areas of particular sensitivity (e.g. for tourism, adjacent to protected areas or in areas including rare or endangered species). Reactive Monitoring was first applied to the Magnetic Quays Development program in 1989-1990 based on predetermined levels of sedimentation, turbidity and coral condition (GBRMPA, 1989). This approach has been further refined for coral condition variables in the present study by the introduction of predetermined Decision Thresholds for partial mortality and bleaching of tagged corals.

1.3 Decision Criteria

Before measurements of coral health (or condition) could be used in the routine management of the TPA dredging operations, it was necessary to place limits on the amounts of coral damage that would be tolerated. Two measurements of coral condition were used. The first of these was a measure of the partial mortality of coral colonies; that is, the cumulative percentage of the original tissue area of individual colonies which died during the project. The worst-case scenario of partial mortality extended to the death of entire coral colonies. The second criterion was the percent of tissue area of each colony which had become (often reversibly) bleached. Bleaching was scaled in intensity: slight *vs* moderate *vs* white bleaching (*slight*, tissues were paler than normal; *moderate*, tissues were almost white but still showed some colour; and *white*, tissues were completely white). Thresholds were implemented only for the most intense level, white bleaching.

Because no precedent for acceptable levels of damage to corals existed, a series of scenarios perceived to be of increasing concern were derived by experienced coral experts and the management bodies (GBRMPA and QDEH) and described graphically in the form of decision thresholds. These were recommended to, and ratified by, the Expert Scientific Panel on 15 December 1992 before forming the basis of an agreement for dredge management between QDEH, GBRMPA and TPA to satisfy Clause 13c of the permit issued to the TPA under Section 86 of the Harbours Act 1955.

The decision thresholds describe, then, the percentage of damage allowable per colony in relation to the percentage of colonies affected. Three separate thresholds were defined for each of the two variables, each calling for increasing attention as the level of damage to corals intensified (see also Figure 1):

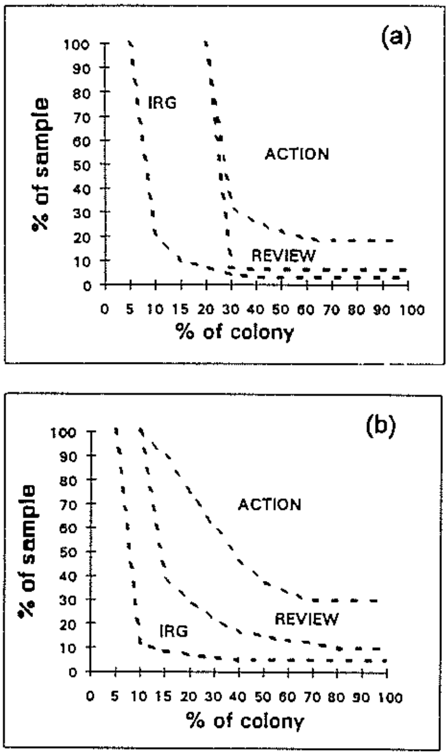
Increasing severity of coral damage

1. Decision by Immediate Response Group (IRG)
2. Review Panel
3. Immedate Action

Generally, the amount of damage permitted per colony decreased as the number of colonies affected increased. That is, one or two colonies with 80% white bleaching would not exceed any thresholds, while seven colonies (out of the 20 sampled) showing only 25% white bleaching would exceed both the IRG and Review Panel thresholds (Figure 1).

Decision thresholds were taken further to reflect the understanding that it was coral mortality and white bleaching above-and-beyond that occurring naturally (as estimated at control locations) that was of concern. To this end, additional weekly plots of coral condition in relation to the thresholds were produced after values at the two worst impact locations were subtracted from the two control locations.

Figure 1. Decision Thresholds for coral condition. (a) Decision Thresholds for partial mortality; (b) Decision Thresholds for white bleaching



1.4 Dredge Activity

A majority of all the material removed from the channel was dredged by a 4600 tonne trailer suction dredge, the 'WH *Resolution*', which began work on 19 January 1993. The WH *Resolution* worked 24 hours a day from this date until late March when it had mechanical problems and movement of material was slowed down. The WH *Resolution* finished work on 6 April leaving some high spots to be removed by a heavy duty grab dredge, the 'WH *Goomai*'. The WH *Goomai* was on site between 27 May to 21 June. In addition to these primary dredging vessels, there was some disturbance of the substrate by a smaller vessel pushing a 'sweep-bar' between 27 February and 14 April, and again between 7 and 24 June.

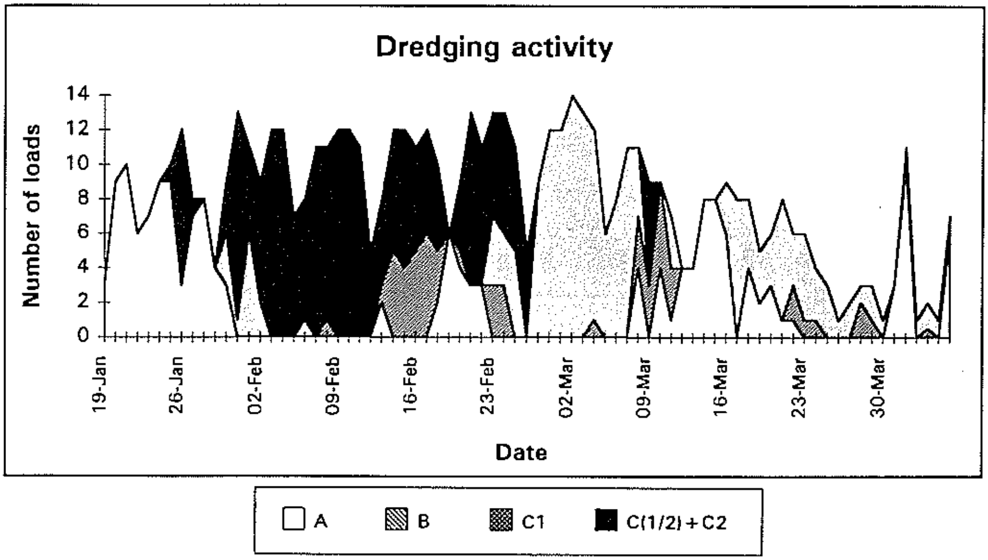
For ease of management of dredging operations, the channel was divided into three sections based on criteria likely to affect dredge productivity and dredging methods (distance from the Port, surrounding water depth and underlying geology): Section A, from the harbour entrance to 3.6km along Platypus Channel; Section B, from this point to 5km from the harbour mouth; and Section C, encompassing the last 1.5km of Platypus Channel, all of the Sea Channel, and all of the extension area. For the purposes of this report, section C has been further divided into C1: to the end of the Sea Channel: and C2: the channel extension (which also encompasses the area closest to Magnetic Island reefs).

Figure 2 summarises the number of dredge hopper loads removed from each region (A-C), cumulatively giving the total number of hopper loads dumped at the spoil site, during the course of the primary dredging period from 19 January to 6 April 1993. In Section C, effort was concentrated on the new extension before the Sea Channel was deepened.

1.5 Aims

The aims of this program were to provide reactive monitoring information for communities of corals adjacent to major dredging works undertaken in Cleveland Bay during 1993 (see Section 1.1 for background) with the purpose of preventing significant damage to corals at Magnetic Island, Townsville.

Figure 2. Number of loads of dredged material removed from the channel to the spoil dump. Area A: up to 3.6km from the harbour entrance; Area B: 3.6-5km from the harbour entrance; Area C1: 5km from the harbour entrance to the end of Sea Channel; Area C2: from the channel extension; and C(1/2): loads which spanned both areas C1 and C2. The graphed category "C(1+2)+C2" thus identifies all periods that dredging was taking place in Area C2. *Data courtesy Westham Dredging Company Pty Ltd*



2. METHODS

Assessments of the direct biological impact of dredging on coral communities and coral health were encapsulated in two studies. Contract 62376-02 *Assessment of Environmental Impact on Coral Communities* (Chapter 4 of this book) focussed on short to medium term effects. That study involved three surveys based on video transects of community composition just prior to, at the end of, and several months following the completion of dredging. Contract 62376-09 *Reactive Monitoring of Corals* was designed to meet the need for immediate management *reaction* to observed environmental impact and was particularly intensive during the course of dredging.

In December 1992, the Department of Marine Biology, James Cook University, Townsville, (MBJCU) successfully tendered for the Reactive Monitoring (RM) component of the Environmental Monitoring Program. Although the primary focus of the RM program was on short term changes in coral health, the frequent presence of the RM team at potential impact locations made it the most appropriate group to collect regular environmental data where this required frequent on-site sampling or maintenance. This included weekly collection and redeployment of sediment traps and measures of turbidity. Specifically, the goal of the Reactive Monitoring of Corals was defined in the contract specification as follows:

Section D9.1: Goal. To document stress levels and impacts experienced by corals as a result of dredging, and dredging-related stressors, for use in the day-to-day management of dredging activities.

Five potential impact locations and three control locations were proposed for the Reactive Monitoring program. Management, logistic and legal constraints led to a consensus that the principal focus should be on 'Control-versus-Impact' comparisons between three impact locations and two control locations. A further two impact locations would be set up but only monitored on the direction of the Environmental Supervisor of the Queensland Department of Environment and Heritage (QDEH).

A preliminary survey of the corals at all seven control and potential impact locations was undertaken between 6-11 December 1992 by Drs Veron and Stafford-Smith. The principal purpose of the survey was to provide information on the presence and abundance of coral species from which four species could be selected as targets for the Reactive Monitoring program (Appendix 2 of original report).

The final site and species selections were made by an Expert Scientific Panel on 15 December 1992. Locations were selected based on their perceived scientific and management significance while species selections were based on abundance, practical suitability, and known or expected sensitivity and range of response.

☐ **Control locations**
Rattlesnake Island
Bay Rock

☐ **Potential impact locations**
Principal:
Florence Bay
Geoffrey Bay
Middle Reef
Subsidiary:
Arthur Bay
Nelly Bay

☐ **Species of corals**
Acropora latistella
Merulina ampliata
Montipora aequituberculata
Pocillopora damicornis

2.1 Locations and Sampling Schedule
Monitoring sites were set up at each of the 7 designated principal locations (Rattlesnake Is, Bay Rock, Middle Reef, Nelly Bay, Geoffrey Bay, Arthur Bay and Florence Bay) between 17 December 1992 and 8 January 1993 (Table 1 and Figure 3). At each location, a 4 mm line was laid along a depth contour approximately 4-6 m below mean low water springs (MLWS) for a distance varying from 200 to 400 m depending on the frequency of target corals encountered (Table 1). The line was secured by star pickets at the beginning and end, and by various means along its course. Sediment traps and logging light meters were deployed at each location and either marked by buoys or linked to the reference line by additional lines so that they could be serviced in zero visibility as necessary (Figure 4).

Monitoring was carried out weekly between 11 January and 16 April, with an additional survey during 28 June to 1 July, 1993 (weekly summaries in original report). Three of the locations, Middle Reef, Geoffrey Bay and Florence Bay, were designated locations of potential impact to be monitored twice weekly. An additional two locations of potential impact, Arthur Bay and Nelly Bay, were monitored twice during the dredging program and were included to evaluate the extent of any observed impact. Locations at each of Rattlesnake Island

Table 1 Characteristics of each Location

Location	Rattle-snake Island	Bay Rk	Middle Reef	Geoffrey Bay	Florence Bay	Nelly Bay	Arthur Bay
Latitude	19°94.9'S	19°85.9'S	19°77.4'S	19°81.9'S	19°85.6'S	19°80.7'S	19°84.8'S
Longitude	147°59.7'E	147°74.0'E	147°80.1'E	147°85.4'E	147°87.4'	147°84.4'E	147°87.1'E
Control or Impact	Control	Control	Impact	Impact	Impact	Impact	Impact
Principal or subsidiary	Principal	Principal	Principal	Principal	Principal	Subsidiary	Subsidiary
Transect length	350m	250m	250m	400m	200m	250m	300m
Number of corals	80	80	64	80	80	80	80
A. latistella	20	20	4	20	20	20	20
M.aequituberculata	20	20	20	20	20	20	20
M. ampliata	20	20	20	20	20	20	20
P. damicornis	20	20	20	20	20	20	20
Sediment traps	16	16	16	16	16	0	0
Depth (shallow/ deep)	3/6	3/6	0.75/3	3/6	3/6		
Logging light meters	1 pair	1 pair	1 pair	1 pair	1 pair	None	None
Number of visits	2/week	2/week	2/week	2/week	2/week	2	2

and Bay Rock were considered controls, not likely to be affected by dredging.

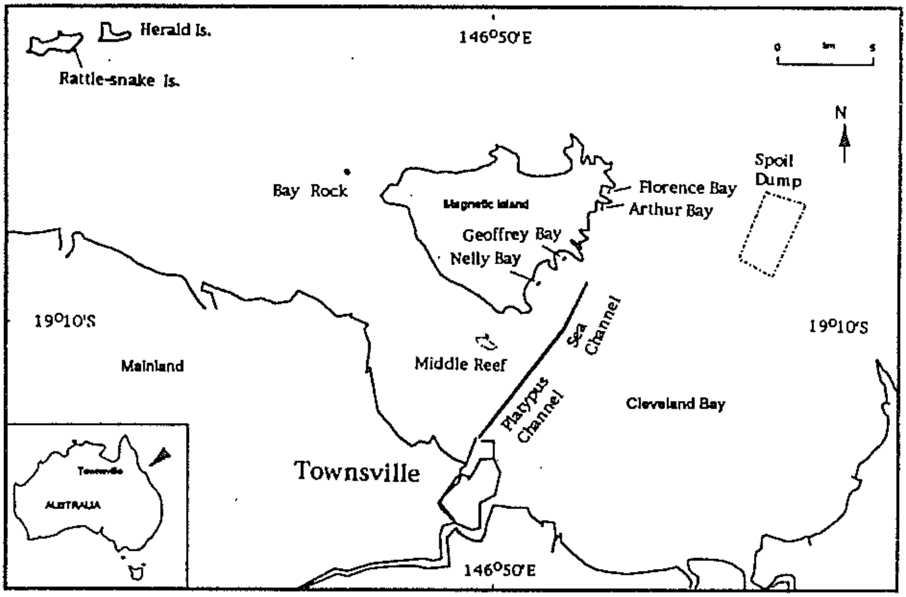
Corals at control locations were visited twice weekly but were quantitatively surveyed only once per week. This monitoring of controls provided background information on natural coral condition against which the behaviour of corals at impact locations could be compared.

2.2 Coral Health Variables

20 colonies of each of the four target species, *Acropora latistella, Montipora aequituberculata, Merulina ampliata and Pocillopora damicornis*, were located along the reference transect line at all locations other than Middle Reef where low incidence of *Acropora latistella* reduced the number of tagged colonies of this species to four. A tag was placed close to each target colony and all tags further than 0.75 m from the reference line were joined to it by sidelines. Sections of the target coral were selected randomly and photographed from approximately 30 cm vertical distance onto 100ASA Fuji colour print film using a Nikonos V camera, 15 mm lens and SB102 flashgun. Photographs were taken in the direction the diver would be swimming to the target and included significant features of the coral or its position so as to minimise relocation and orientation time during later monitoring.

No attempt was made to photograph entire colonies unless these were of a suitable size to fit into the frame.

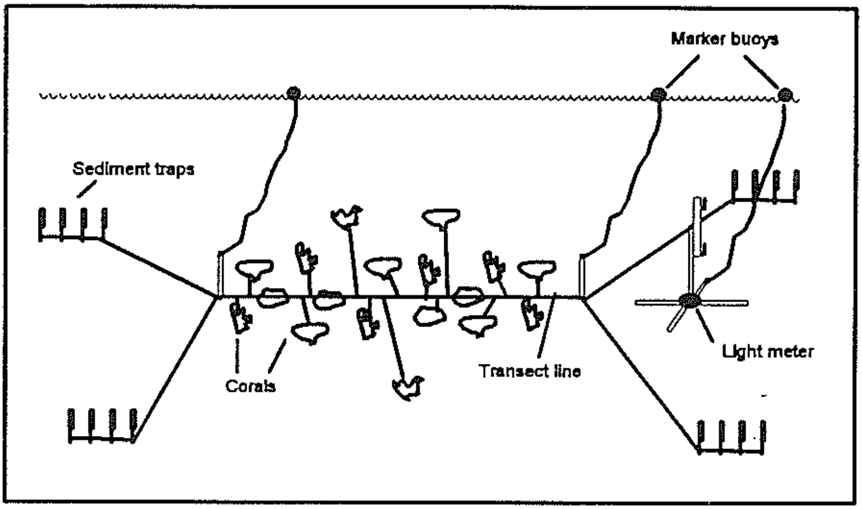
Figure 3 Locality and Site Map



Films were developed and two prints of each frame made at a size of 12.5 x 17.5 cm. On each photograph, coloured indelible pens were used to outline the target coral, as well as any areas already dead or strongly bleached. The total coral area (TCA), total initial mortality (TIM), and total initial bleaching (TIB) were digitised for each photograph and the initial living tissue (ILT=TCA-TIM) was calculated. Each print was then laminated between two sheets of A5 80 µm transparent plastic, leaving a wider top border. Two holes were punched at the top and 40 photographs bound together with plastic rings in the order in which they would be encountered along the reference line. One set of photographs was used as the primary set, the second was updated regularly as a backup in case of loss.

At each scheduled monitoring time, trained observers swam to each of the target corals and recorded both biological and physical changes in the state of the coral. Changes to the tissues were marked directly onto the laminated photograph with a red chinagraph pencil. At the end of each dive, the areas marked on the photograph were measured and recorded using a 2x2 mm grid of squares printed on transparent plastic. As each area was measured, the chinagraph was replaced by indelible black pen and coded according to the type of effect (mortality, bleaching, broken, etc.). Bleaching was recorded in three categories: *white*, tissues were completely white; *moderate*, tissues were almost white but still showed some colour; and *slight*, tissues were paler than normal. Observations of other potential signs of stress such as unusual polyp behaviour or tissue expansion, unusual mucus production or diseases, and overgrowth by other species were also recorded. Breakage of parts of colonies was common. Sections which were cracked were marked on the photograph but continued to be included in assessments.

Figure 4. Transect design



Some completely broken sections were lost and their fate is unknown, while others were still present but relocated with respect to the photograph. The latter normally showed little or no mortality. For consistency, all complete breakages were marked on the photograph and treated as a separate category (broken). The area of the coral covered by sediment was estimated in 20% categories.

In addition to detailed surveys of target corals, a minimum period of 20 minutes was spent in a general survey of corals in the surrounding reef area and the reef flat zone. This period was extended to up to 3 field hours when it was necessary to evaluate the extent of an effect.

2.3 Environmental Variables

2.3.1 Sedimentation Rates

Four sediment traps were deployed at each of two depths at either end of the reference transect line at all principal locations (16 per location in total). Traps were not deployed at subsidiary locations. With the exception of Middle Reef, 'shallow' traps were located at 3 m and 'deep' traps were located at 6 m (MLWS). At Middle Reef the maximum depth of reef was approximately 4 m (MLWS) and traps were located at 0.75 and 3.5 m (MLWS) respectively. The traps were of the same dimensions as those used during the Magnetic Quays (Mapstone *et al*, 1989), Trial Dredging (Sinclair Knight, 1992) studies and Sediment Data Collection (Chapter 7, this volume) with a diameter of 50 mm and height of 150 mm.

Traps were left *in situ* for 7-day deployments on a regular weekly schedule. Control location traps were replaced on Mondays and impact locations on Tuesdays. It should be noted that this logistic constraint led to a one-day asynchrony of sampling effort. The control locations were inaccessible on Monday 15 March (the collection date for traps sampling Week 8) and all sampling and deployments for this date took place on Sunday 14 March. In all cases, sedimentation has been standardised to rates per day.

Following collection, saltwater and sediment from each trap was decanted through a numbered and tared Whatman No. 1 filter paper. Traps were thoroughly cleaned to capture all sediment and filters were rinsed twice with distilled water to remove salt. Tests indicated that loss of fine sediments in the filtrate was negligible. Filters were placed in a 60°C oven overnight and reweighed.

The presence of fish eggs or dead fish in the traps was recorded and data from these traps were excluded from the analysis.

2.3.2 Turbidity

Turbidity at each principal location was continuously measured *in situ* from 11/12 January to 15/16 April 1993. A pair of cosine-corrected 2π light sensors (PRD-02, Monitor Sensors) were deployed at each principal location adjacent to the transect line at approximately 6 m depth (MLWS). The two light meters were securely fixed to the datalogger housing at a vertical separation of 1 m. For the first four weeks of deployment, the base of the light meter pair was positioned such that the upper meter was 2 m off the substrate. It became clear that light levels at the lower meter during periods of high turbidity were too low for confidence in calculated light attenuation values. The light meter stands were therefore modified so that, from Week 4, the upper sensor was 3 m off the substrate. Surface light levels were monitored by logging light sensors on Rattlesnake Island and Magnetic Island (Dataflow Systems) and on the mainland (LICor).

Sensors were cleaned and loggers downloaded twice per week at all locations. The down-welling light reaching each sensor was averaged and logged every 6-minutes along with a time stamp.

Profiles of suspended solids and light attenuation through the water column were carried out at principal locations on each visit (i.e. twice per week). Light and suspended solids profiles were carried out simultaneously, both instruments being attached to the same frame.

Light attenuation coefficients were estimated by comparison between two cross-calibrated LICor sensors, one measuring surface light and the other, down-welling light reaching points at 1 m intervals on the underwater profile.

A minimum of three measurements were recorded by an Analite nephelometer (McVann Instruments) at each of the 1 m intervals through the water column. Replicate 1-litre water samples were collected simultaneously at each depth for calibration, and for spot checks. Water samples were filtered through tared Whatman GF/C filters, washed with distilled water, dried at 60°C, and reweighed. Nephelometer turbidity units (NTU) values were converted to corresponding values in mg/litre.

3. RESULTS

3.1 Overview

Table 2 contains a brief summary of coral health during the dredging program. Attention is drawn to two notes pertaining to reporting procedures.

1. During the first few weeks of the dredging program the IRG made several requests for reporting format changes to bring the Weekly Reports more in line with the intention of the management agreement. It was clarified in Week 4, that management thresholds for bleaching should be based on white bleaching rather than all levels of bleaching as had been reported up to Week 3. In Week 5, graphs specifically illustrating control-versus-impact effects were

Table 2 Summary of coral health during the dredging program. **Week,** Week code; **Info type,** IRG requests or information, Coral health; **Thresholds: CvsI**=Control versus impact thresholds exceeded ; **S**=Single bay thresholds exceeded (does not constitute threshold exceedance in terms of the permit agreement); **M/B**=Exceeded for M:mortality or B:white bleaching. Brackets indicate that the exceedence was at Controls rather than Impact locations. References in this table refer to the original report (eg R2:F1a-b refers to Report Week 2 Figures 1(a-b).

Week	Info type	Description	Thresholds		
			Cvsl	S	M/B
0		No dredging. Coral health baseline confirmed underwater.			
1	❖	Clarification from IRG concerning format for reporting coral health data graphically on threshold graphs. Dredging began 19 January.			
	⌦	Only minor changes in coral condition variables.			
2	⌦	Some paling of colonies, particularly *Pocillopora damicornis* at Florence Bay (R2:F2b). NB: No exceedence of thresholds based on 'white' bleaching definition (see Week 4)			
3	⌦	Continuation of slight to moderate bleaching of *Pocillopora damicornis* (R3:F2b). Some bleaching of same species at control locations. NB: No exceedence of thresholds based on 'white' bleaching definition (see Week 4).			
4	❖	Clarification from IRG that bleaching thresholds refer only to white bleaching. From Week 4 onwards Reports (see Appendix 3) do not include moderate or slight bleaching.			
	⌦	Mortality showed only very minor changes (R4:F1a-c). However, significant increases in white bleaching were recorded at Geoffrey Bay where *Acropora latistella* reached the IRG threshold (R4:F2b). Moderate and slight levels of bleaching in this species also increased. Bleaching was recorded in a number of non-transect species in Geoffrey Bay and, to a lesser extent, at Florence Bay. Similar bleaching was not recorded at Control locations, nor at Middle Reef.		*	B
5	❖	On request from the IRG, the reporting format was altered to include threshold graphs specifically showing control-versus-impact comparisons. From this week onwards, the summary page thresholds box refers to control-versus-impact thresholds.			
	⌦	Partial mortality showed only minor changes (R5:F1a-e). However, white bleaching continued to increase at Geoffrey Bay (R5:F2c) and triggered the control-versus-impact IRG threshold (R5:F2d). The levels of bleaching were much greater in *Acropora latistella* than the other three transect species. At Geoffrey Bay, in addition to those colonies showing white bleaching, 90% (18) of all *A. latistella* were moderately bleached over more than 90% of their tissues. The degree of bleaching at Florence Bay was not as strong. Several non-transect species continued to show white bleaching at both Bays. Similar levels of bleaching were not apparent at the Control locations, nor at Middle Reef.	*	*	B
6	⌦	Partial mortality showed only minor changes (R6:F1a-e). White bleaching increased at Geoffrey and Florence Bays (R6:F2c). Levels of moderate bleaching at these bays also continued to increase significantly with most transect colonies of *Acropora latistella* at both Bays showing bleaching of >90% of their tissues. Elevated levels of white bleaching in *Montipora aequituberculata* were also apparent at Geoffrey Bay. Increases in white bleaching at Bay Rock were attributable to a single colony of *Merulina ampliata.* A number of non-transect species continued to show bleaching in Geoffrey and Florence Bays. Similar levels of white and moderate bleaching in these other species were not apparent at the Control locations, nor at Middle Reef. Additional surveys covered more than 1500m^2 of reef at each of Florence Bay, Geoffrey Bay and Middle Reef on 23 February 1993. In regions adjacent to and away from the transects, *A. latistella* was showing recent mortality of up to 25% of colonies, as well as moderate bleaching and other signs of ill-health (see Section *2.3.2.1 Bleaching).* More than 90% of all colonies of this species at depths greater than 2m (MLWS) were showing abnormal symptoms over >50% of their tissues. Similar abnormalities were observed in several of colonies of *Acropora valida* and in one colony of a third *Acropora* species. In contrast, shallow water colonies showed no symptoms, nor did colonies at Middle Reef or control locations.		*	B
7	⌦	Partial mortality continued to show only minor changes (R7:F1a-e). Levels of white bleaching in *Acropora latistella* at Geoffrey and Florence Bays relative to Control locations exceeded the IRG threshold (R7:F2d). Nevertheless, there was evidence of some recovery of colonies in lower levels of bleaching at Geoffrey Bay and the spatial extent of ill-health in this species at both Geoffrey and Florence Bays showed some decrease. There were small increases in white bleaching of *Montipora aequituberculata* at Geoffrey Bay and Bay Rock (Figure 6). Other changes at Controls and Middle Reef in mortality and bleaching were minor. Bleaching in non-transect species continued at similar levels. Independent observations raised concerns about the level of bleaching in *Montipora aequituberculata* at Arthur Bay, and bleaching and apparent mortality in *Porites* species at Geoffrey Bay.	*	*	B

Table 2 - continued

8	⌦ ❖ ⌦	Changes in partial mortality were minor (R8:F1a-e). However, the control-versus-impact IRG threshold continued to be exceeded for *Acropora latistella* with small increases in white bleaching (R8:F2d). Levels of moderate bleaching for this species continued to reduce. White bleaching in *Montipora aequituberculata* decreased at Geoffrey Bay but showed increases at Control locations (Figure 6). *Porites* species were found to have produced an abnormally high level of mucus on which turf algae and sediment had become embedded. It was now clear that mortality had not occurred as colonies started shedding up to 2mm thick layers of mucus and turf algae As a result of continuing exceedence of IRG thresholds and concern about the potential effects on other reefs around Magnetic Island, the IRG requested surveys of Arthur and Nelly Bays. Partial mortality and bleaching at Arthur and Nelly Bays, when combined with data from other impact locations, did not exceed the threshold levels (Add.R8:1b,2b). Substantial white bleaching had been observed in *Acropora latistella* and *Montipora aequituberculata* during independent survey work at the end of February but this was no longer clearly in evidence, probably reflecting the same improvement seen at other Bays during Weeks 7 and 8. In general, the levels of mortality and bleaching in these two Bays were within the range of the principal impact locations.	*	*	B
9	⌦	Changes in partial mortality continued to be minor (R9:F1a-e). White and moderate bleaching in *Acropora latistella* decreased during the week to a level where the control-versus-impact threshold was no longer exceeded (R9:F2d). There was continued improvement in lower levels of bleaching. *Montipora aequituberculata* was continuing to bleach at Bay Rock. This was largely due to abrasion from *Sargassum*. One colony of *Merulina ampliata* at Bay Rock was white bleaching over >25% of it's surface.		*	B
10	⌦	Changes in partial mortality continued to be minor (R10:F1a-e). White bleaching of *Acropora latistella* remained the same at Geoffrey and Florence Bays (Figure 6) but lower level bleaching decreased.		*	B
11	⌦	Changes in partial mortality continued to be minor (R11:F1a-e). White bleaching of *Acropora latistella* at Geoffrey and Florence Bays no longer showed individual exceedence of the IRG threshold (R11:F2c) although bleaching of *Montipora aequituberculata* at Geoffrey Bay was still marginal. Moderate bleaching at Geoffrey Bay was back to Week 3 levels.		*	B
12	⌦	Changes in partial mortality continued to be minor (R12:F1a-e) although there was some evidence of small increases in mean partial mortality at Rattlesnake and Florence Bay (Figure 5). All bleaching and mortality at potential impact locations was below threshold levels (R12:F1c&e,2b&d).			
13	⌦	Changes in partial mortality at Bay Rock, Middle Reef and Florence Bay were minor (R13:F1a-e). Partial mortality of *Merulina ampliata* increased at Geoffrey Bay. This was due to one colony located in sand, which had become buried under coarse grained sediment. The mortality, extending to 30% of its tissues, was not considered to be dredge related. Partial mortality showed greatest changes at Rattlesnake Island, where many *Montipora* species, including *M. aequituberculata* , were showing signs of a 'black band' disease. Infection was spreading across whole colonies in a line with a distinct black edge. Some of the transect colonies were affected causing an increase in partial mortality of this species (Figure 5a). *Acropora latistella* was also showing increased mortality. The cause of this mortality was not clear but may also have been a result of disease. Prior to mortality, the colonies were not showing similar symptoms of bleaching and ill-health as seen previously in Geoffrey and Florence Bays. Since this control site was located almost 20 nautical miles from the region of dredging, this disease was not considered dredge-related.		(*)	(M)
24	❖ ⌦	Dredging by the primary dredger '*Resolution*' ended on 6 April but the channel was not fully completed. The IRG requested that a further survey be carried out after the final, more minor, dredging works were finished. One survey would take place at each principal and subsidiary location. Changes in partial mortality at Bay Rock, Middle Reef, Arthur Bay and Florence Bay were minor (R24:F1a-e; AddR24:F1a-c). At Geoffrey Bay, the affected colony of *Merulina ampliata* had almost completely died increasing the mean partial mortality for this species. Small changes were noted in *Montipora aequituberculata* at Nelly Bay, which individually exceeded the IRG threshold (AddR24:F1c). This was due to mortality in a single colony. As in Week 13, the greatest changes in partial mortality were at Rattlesnake Island where further mortality of *Montipora aequituberculata* and *Acropora latistella* were observed. Disease was still present but there was less evidence of ongoing mortality, most affected areas of colonies having died or recovered since Week 13.		(*)	(M)

requested and from this week onwards the summary 'exceedence' box on the cover page of each Weekly Report referred exclusively to control-versus-impact exceedences. Coral condition variables were on the border in Week 6. In line with the management agreement's emphasis on 'exceedence' of the threshold criteria, the IRG requested borderline cases to be formally reported as non-exceedence. Verbal reports indicating that thresholds were met but not exceeded could still trigger management action if deemed necessary.

2. In this report the reader should distinguish between (a) control-versus-impact threshold exceedences (which refer to instances where the *difference* between control and impact sites exceeds the threshold), and (b) individual exceedence of thresholds (which refers to instances where coral condition variables for a species exceeded the thresholds prior to comparison with controls). Formal management action was based only on control-versus-impact threshold exceedences, but informal evaluation of data examined both control-versus-impact and individual species exceedence of thresholds to look for trends which might be of future importance.

3.1.1 Thresholds

☐ At no time did either mortality or white bleaching criteria for any species or Bay exceed the highest threshold and precipitate suspension of dredging.

☐ Neither mortality nor white bleaching criteria reached the Review Panel threshold in potential impact locations. Mortality of *Montipora aequituberculata* at Rattlesnake Island (Control) did individually reach this threshold due to disease.

☐ The control-versus-impact IRG threshold was not exceeded for mortality at potential impact locations. However, it was exceeded for white bleaching in the three Weeks 5, 7 and 8 and was on the threshold in Week 6.

3.1.2 Other Key Results

☐ No complete colonies died at principal or subsidiary impact locations with the exception of one colony of *Merulina ampliata* at Geoffrey Bay. Mortality of this colony was considered unrelated to dredging.

☐ Observed deterioration in coral condition potentially linked to dredging principally occurred in Geoffrey and Florence Bays. Adverse changes were at their greatest during Weeks 5-8 (15 February - 15 March). Of transect species the most significant deterioration was in *Acropora latistella* although minor changes were also observed in *Montipora aequituberculata*. Of the transect corals at Geoffrey and Florence Bays, more than 70% of *Acropora latistella* showed moderate bleaching over more than 90% of their tissues.

☐ During surveys of more than 1500 m^2 of reef on 23 February 1993, at Geoffrey and Florence Bays *A. latistella* was showing widespread moderate bleaching and additional signs of ill-health typical of corals prior to death. More than 90% of colonies were affected at depths greater than 2 m (MLWS) and several colonies were showing significant recent mortality of up to 25%. Mortality was occurring from the base upwards (Stafford-Smith, *pers.obs.)*. Although surveys were undertaken at Middle Reef and Control locations, similar stress was not observed.

- ☐ Despite the concerns associated with significant bleaching of *Acropora latistella*, this did not lead to subsequent mortality of colonies.
- ☐ Independent observations suggest that Arthur Bay may also have been showing deterioration during Week 6, particularly in *Montipora aequituberculata*. The status of Nelly Bay during Week 6 is not known. However, by Week 8, when full surveys of Arthur and Nelly were undertaken, neither mortality and white bleaching showed significant deviation from patterns at Controls. These observations support the original site selection which focussed greater monitoring effort on Florence and Geoffrey Bays.
- ☐ Many non-transect species showed significant white bleaching during Weeks 4 to 7.
- ☐ Trends in physical variables were apparent across all locations. Relatively high levels of sedimentation (Week 3) and turbidity (Weeks 4 & 5) were recorded in weeks leading up to adverse changes in coral health. Trends were less apparent in levels of sediment on coral tissues.

3.2 Temporal Patterns

3.2.1 Coral Health

Mortality

Figure 5a-e shows mean mortality over time for each species at each principal location.

One colony (*Merulina ampliata*) died at Geoffrey Bay but this mortality was not considered to be dredge-related. Partial mortality did not exceed any threshold criteria at potential impact locations. In general, partial mortality at impact locations was less than 10% for all colonies although this was exceeded by three colonies at Florence Bay, two at Geoffrey Bay, one at Middle Reef and one at Nelly Bay.

Over all locations, partial mortality was highest at Rattlesnake Island where disease caused significant mortality in a number of species both on and off the transect. This control location was almost 20 nautical miles from the region of dredging and the disease was therefore considered unrelated to dredging. There was no evidence of similar disease at any other location.

Bleaching

Figure 6a-e shows mean white bleaching over time for each species at each principal location.

White bleaching levels showed no increase at any location until Week 4. From Week 4, white bleaching in *Acropora latistella* increased at Geoffrey Bay, and from Week 5 at Florence Bay. There were also noticeable changes in *Montipora aequituberculata* at Geoffrey Bay. Only minor white bleaching was observed at Rattlesnake Island. With one main exception, bleaching of *M. aequituberculata* at Bay Rock was patchy and located on knolls which were constantly swept by *Sargassum*. The species showed recovery as the *Sargassum* died back towards the end of the program. One colony of *Merulina ampliata* showing >25% white bleaching at Bay Rock was responsible for the change in mean white bleaching in this species. Almost no changes took place at Middle Reef.

As a result of concerns about increased white bleaching levels in *Acropora latistella* and a number of non-

Figure 5. Mean partial mortality per species at each location over the dredging period. Locations (± mean standard error, ± max standard error, n=20 for samples on which standard errors are based): (a) Rattlesnake Island (0.6%, 3.7%), (b) Bay Rock (0.1%, 0.4%), (c) Middle Reef (0.3%, 0.7%), (d) Geoffrey Bay (0.5%, 4.6%), (e) Florence Bay (0.4%, 0.8%).

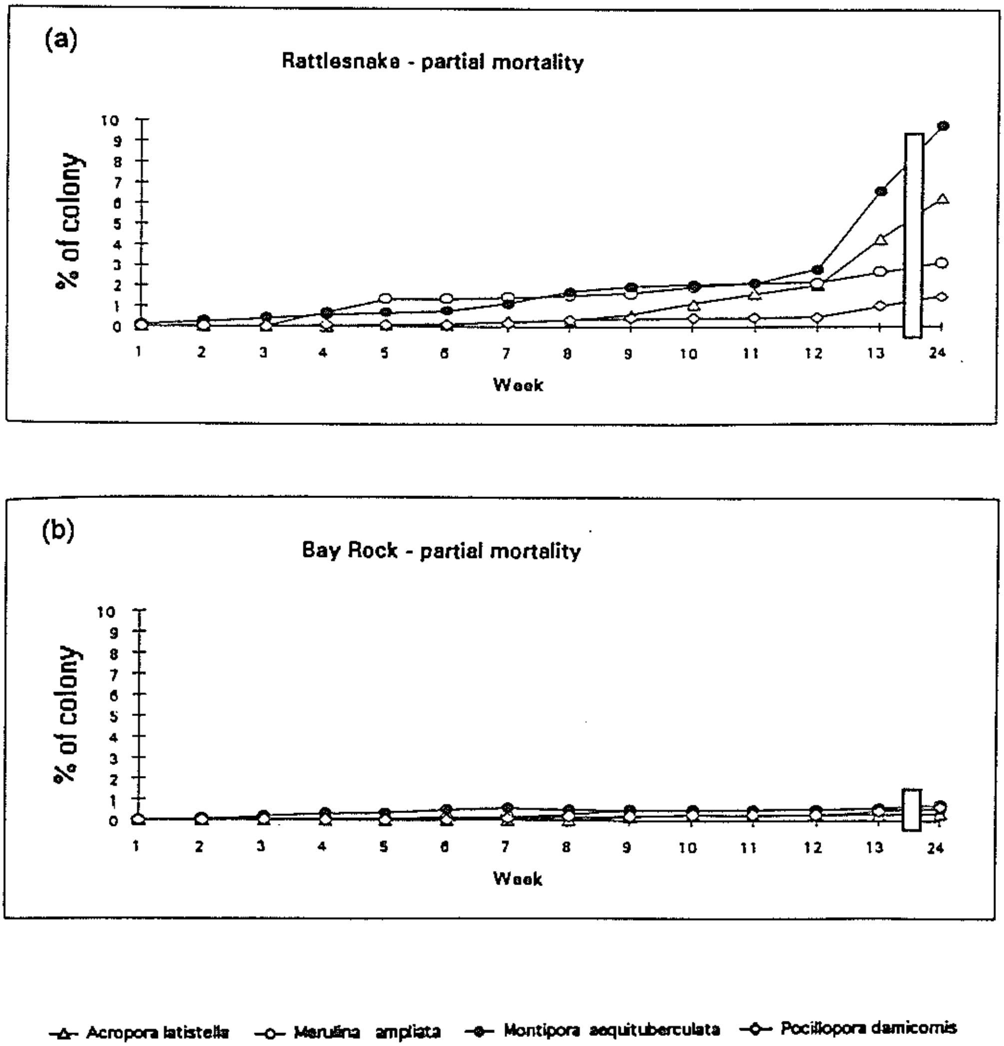
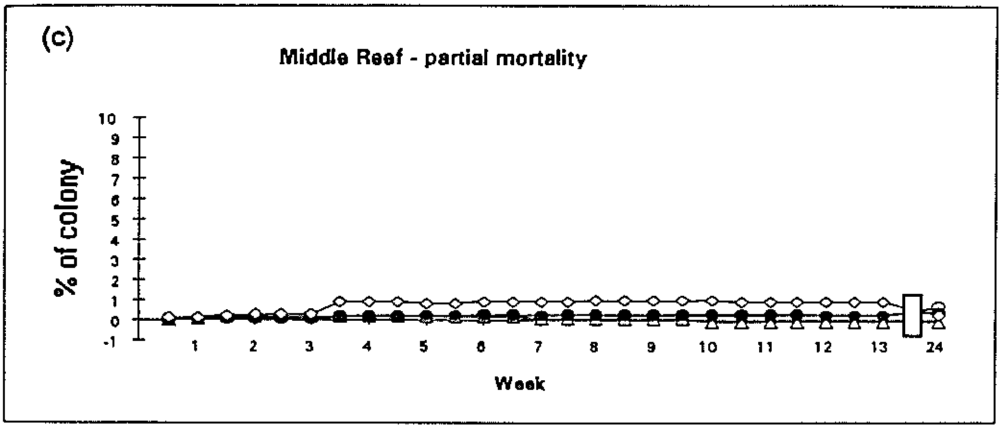
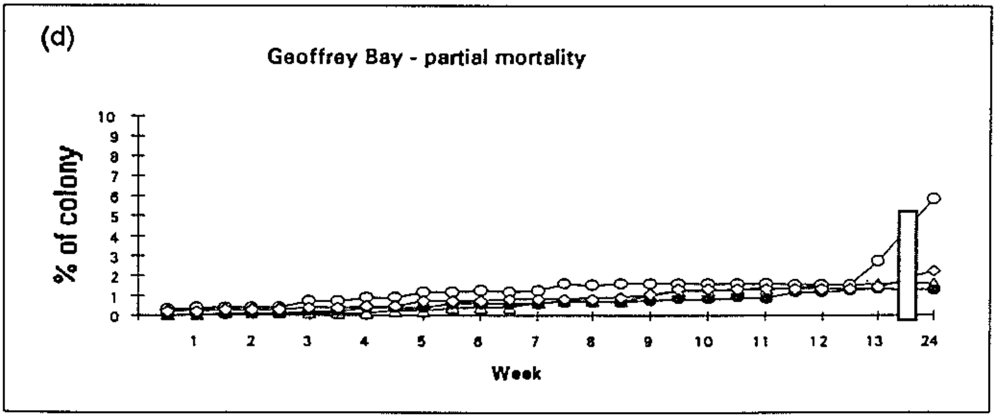


Figure 5 - continued





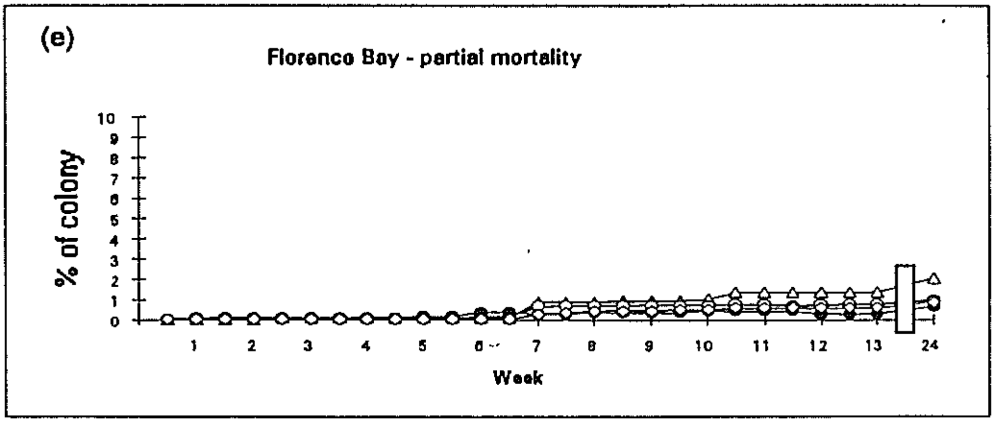


Figure 6. Mean white bleaching per species at each location over the dredging period. Locations (± mean standard error, ± max standard error, n=20 for samples on which standard errors are based): (a) Rattlesnake Island (0.7%, 2.0%), (b) Bay Rock (0.9%, 3.5%), (c) Middle Reef (0.3%, 1.3%), (d) Geoffrey Bay (0.9%, 1.3%), (e) Florence Bay (0.5%, 2.2%).

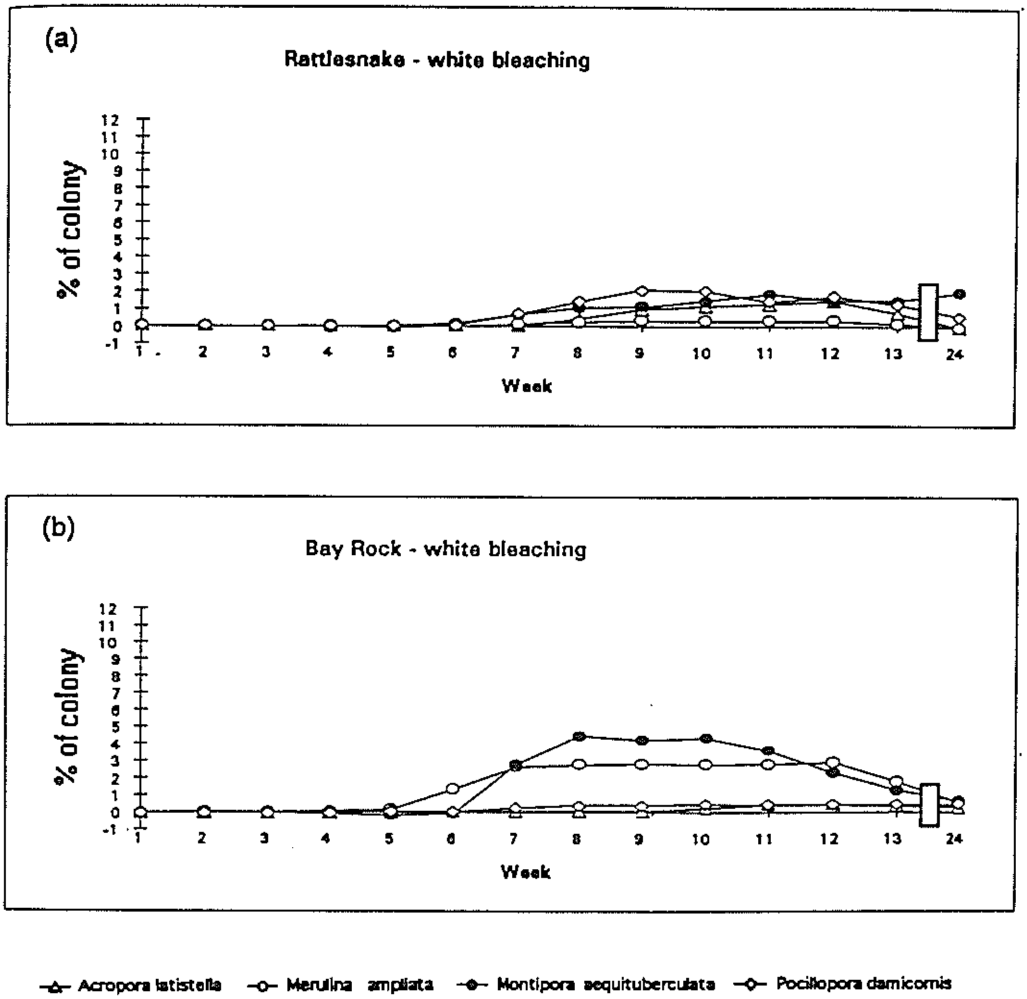
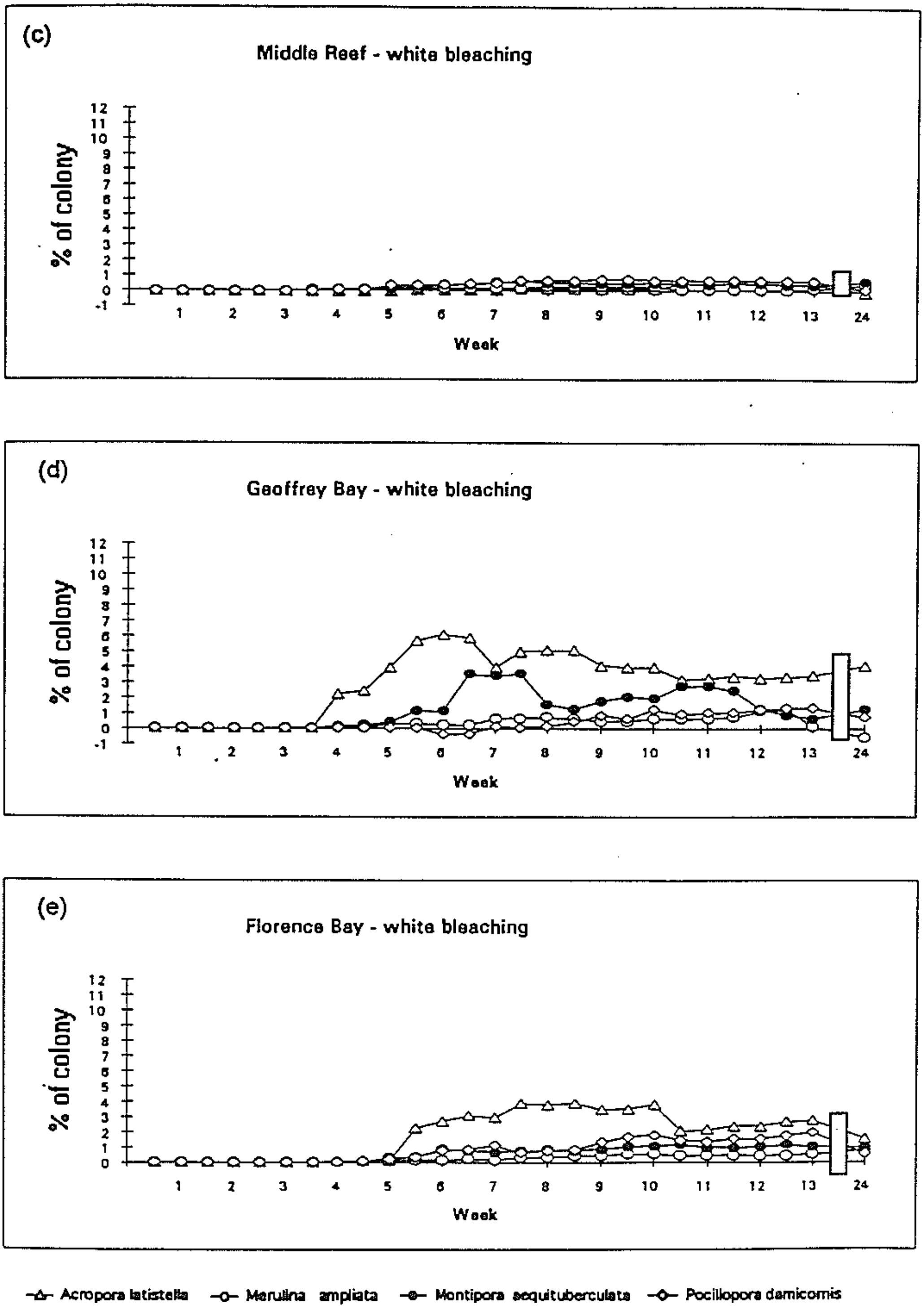


Figure 6 - continued



transect species, further observations were made on 23 February 1993 at each principal impact location over areas of more than 1500m². More than 90% of all colonies of this species at depths greater than 2m (MLWS) were showing symptoms of stress. Adverse symptoms included abnormal colouration and texture, dullness of tissue and tissue necrosis, and were associated with moderate rather than white bleaching of tissues. In several colonies there was evidence of recent mortality of areas representing up to 25% of the tissue. Mortality was taking place from the base of the colony branches upwards. In gradations of stress seen in different colonies, white bleaching was only a minor component, areas of colonies tending to be either moderately bleached in conjunction with other symptoms or dead. Similar abnormalities were observed in <5% of colonies of *Acropora valida* and in one colony of a third *Acropora* species. In contrast, shallow water colonies showed no symptoms, nor did colonies at Middle Reef or control locations. Of the transect corals at Geoffrey and Florence Bays, more than 70% of *Acropora latistella* showed moderate bleaching over more than 90% of their tissues.

Overlying sediment
High levels of overlying sediment were rarely recorded for the branching species *Acropora latistella* or *Pocillopora damicornis* and were largely restricted to *Merulina ampliata* and *Montipora aequituberculata* (encrusting to plating species). Highest mean levels at principal impact locations were recorded at Florence Bay in Week 4 and Geoffrey Bay in Week 4-6.

Non-transect species
Considerable changes in white bleaching of non-transect species were observed from Week 4. With the exception of the *Acroporas* noted above, there were no observations of widespread mortality. It should be noted, however, that partial mortality of untagged colonies is hard to evaluate unless it covers large areas, is very recent, or colonies are individually known by the observer.

3.2.2 Environmental Variables

Sedimentation rates
Sedimentation rates at each sampled depth are shown in Figure 7. Locations generally followed similar patterns to one another although Florence Bay showed some deviations from the common trend in Weeks 8 and 11 at the deeper locations. Deep traps showed consistently higher sedimentation rates at all locations than shallow traps.

Turbidity
Many problems were encountered with logging light meters resulting in considerable gaps in the data.

Highest turbidities generally occurred at Bay Rock and Middle Reef. These locations showed trends which were not always apparent at Rattlesnake, Geoffrey Bay or Florence Bay. All locations showed higher than average turbidities in Weeks 4 and 5. Short term temporal variations were high, particularly during wind changes or spring tides, and light attenuation coefficients could vary by >0.3 over a few hours.

4. DISCUSSION

Dredging operations in the vicinity of coral reefs have historically caused damage and environmental degradation in many regions (e.g. Brock *et al*, 1966; Grigg *et al*, 1972; Marsh & Gordon, 1974; Chansang *et al*, 1981; Brown *et al*, 1990). Effects can generally be described as 'acute' or 'chronic', the former being short-term and resulting in clearly visible death, the latter being long-term and resulting in slow change in community structure and viability.

There is photographic (Endean, 1976; Kinsey, *pers.comm.*) and anecdotal evidence (e.g. Klumpp, *pers.comm.*; Veron, *pers.comm.*) of reef degradation at Magnetic Island during the past 40 years. Recent studies have confirmed that dredging causes significant disturbance of sediment and subsequent movement of sediment close to the substrate (Wolanski & Gibbs, 1992) and that dredge plumes can reach vulnerable reefs of Magnetic Island (Sinclair Knight, 1992; aerial photographs during this dredging program, Raaymakers, *pers.comm.*). Thus, the potential for chronic effects from dredging activities exists and is a plausible explanation for the observed reef degradation. However, it is also possible that the reefs have reached a degree of equilibrium with their new sedimentary environment.

This report examines *acute* impacts that may have been correlated with the *recent* dredging of Platypus and Sea Channels; chronic impacts are outside the scope of this study.

All studies of acute impact events must seek to separate natural or 'background' changes from impacts of that event. Magnetic Island has a sediment-stressed environment, the stress being either direct (through smothering), or indirect (through many causes, of which light attenuation is the most important). In this study, two coral health variables, mortality and bleaching, were studied in four species of corals. It is emphasised that, consistent with all studies of this kind, practical constraints forced compromises between ideal and viable experimental designs. The compromises described below were discussed and the implications accepted by the Technical Advisory Committee prior to their approval:

(1) Logistic constraints limited the number of species that could be examined in detail. Although the four target species were selected on the basis of potential susceptibilityto changes in sediment regime, they represent only a small sample of the common species present in each Bay. Observations of other species were made during the course of the program, but mortality of unmarked colonies is very hard to evaluate unless it is widespread, very recent, or colonies are individually known by the observer.

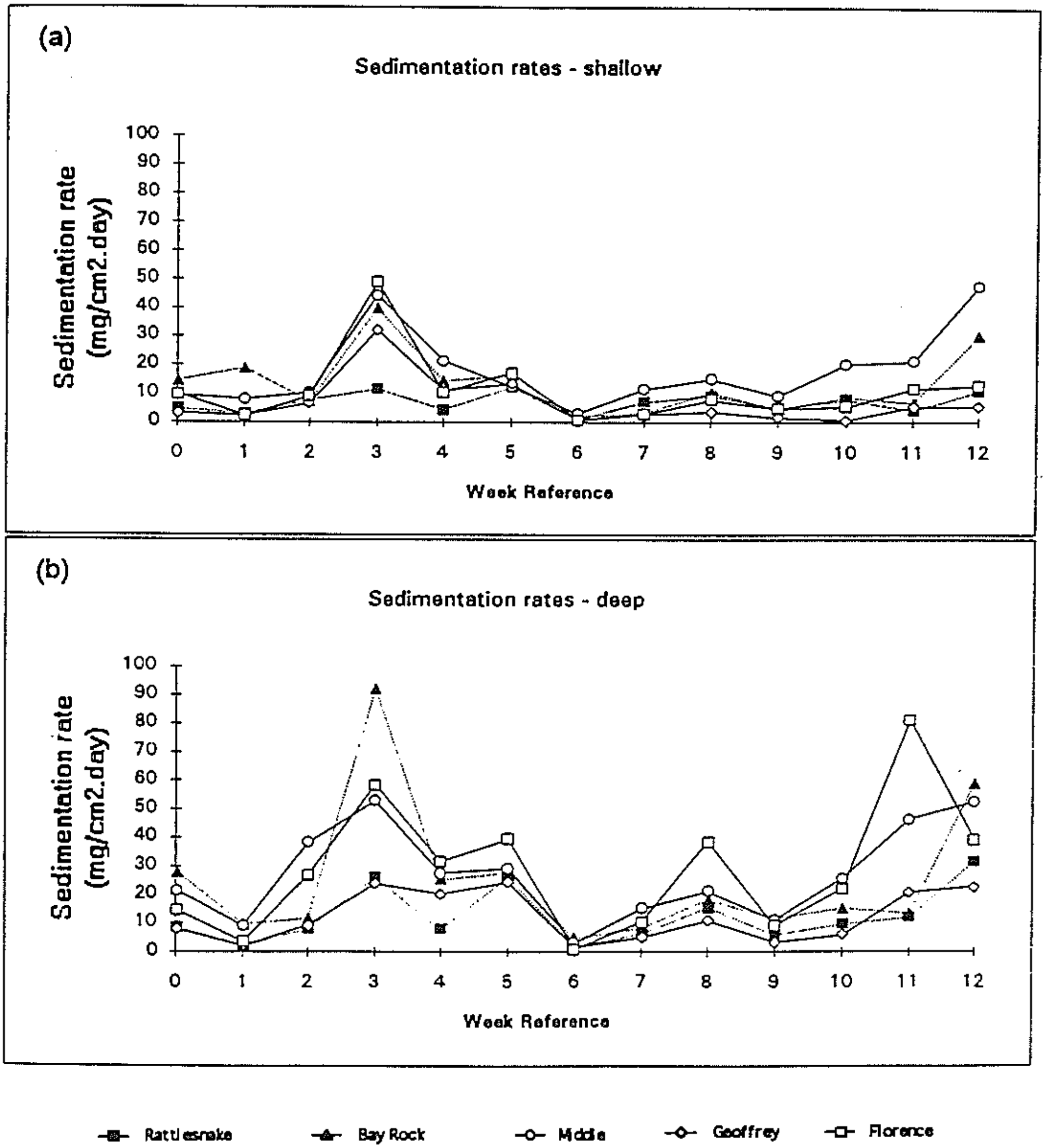
(2) Similar logistic constraints applied to transects which necessarily covered only a small proportion of the reef area in each location. Although supplementary observations were made over wider areas, these were restricted and they suffer from subjectivity.

4.1 Locations and Impacts

No colony died from dredge-related causes at principal impact locations and partial mortality was generally less than 10%. The highest rate of mortality was at Rattlesnake Island (a control location) in the last few weeks of the dredging program and was largely due to a disease which was, again, unrelated to dredging. General reconnaissance revealed that significant areas of colonies of several species died at that time. Since the level of mortality at impact locations was below threshold levels, the occurrence of the disease only mildly affected the interpretation of the control-versus-impact threshold exceedences.

Of all the principal and subsidiary impact locations, corals at the Middle Reef transect showed the least mean change in any health characteristic. Middle Reef has a maximum depth of approximately 4 m (MLWS) and its transect was therefore shallower than those of other locations. Turbidity at this location was relatively high, and the visibility poor,

Figure 7. Sedimentation rates at (a) shallow and (b) deep traps. Rattlesnake, 1.0/1.9; Bay Rock, 2.3/5.7; Middle Reef, 3.1/3.9; Geoffrey Bay, 1.9/2.0; Florence Bay, 2.4/5.3 (Locations, ± mean SE shallow/± mean SE deep, n=13).



suggesting either that the corals are well-adapted to high sedimentation and turbidity, and/or that their shallower location ensures that light is always sufficient for their metabolic requirements. Sediment plumes were regularly observed at Middle Reef but dredge plumes were not normally distinguishable from general turbidity due to other causes.

Corals under stress do not necessarily pass through a white stage prior to mortality, but there are usually noticeable changes in colouration, texture, and other less definable, visual cues. The levels of white bleaching during dredging increased at Geoffrey and Florence Bays during the dredging period and these were significant with respect to the threshold criteria for *Acropora latistella*, triggering more detailed assessment. The spatial extent of the stress in the case of this species was greater than the white bleaching data suggested. Adverse symptoms of abnormal colouration, dullness of tissue and/or tissue necrosis were present in most colonies deeper than 2m but were largely associated with conspicuous moderate rather than white bleaching of tissues. This link to moderate bleaching suggests that future management thresholds for developments involving modifications to sediment regimes may need to incorporate lower levels of bleaching.

Abnormal symptoms in *Acropora latistella* in Geoffrey and Florence Bays, other than bleaching, had largely faded by the end of Week 7. White and moderate bleaching persisted for some weeks longer. Similar indications of abnormal stress were only observed in a few colonies of two other species of *Acropora*. No similar increases in white or moderate bleaching, or other abnormalities were recorded in these species at Middle Reef nor at Control locations during this period. Nevertheless, the levels of moderate bleaching did *not* lead to correspondingly elevated mortality in transect colonies at Geoffrey and Florence Bays. Despite evidence of partial mortality (generally 0-10% but up to 25%) of colonies of this species off the transect, it is estimated that mortality with respect to its total surface area across the surveyed reef region was less than than 5%. The evidence suggests that this species was close to its tolerance limits but that conditions improved in time for the immediate impact to be relatively slight.

Increased levels of white and moderate bleaching were observed in many non-transect species at Geoffrey and Florence Bays from Week 4. This level of bleaching was not observed at Middle Reef nor at Controls during the same period. Focus on these other species was outside the scope of the Reactive Monitoring program and it is not possible to make conclusive statements about their survival or mortality. What evidence is available, however, does not support the view that there has been substantial dredge-related mortality of non-transect species. No observations of substantial recent mortality were made by the Reactive Monitoring team. A simultaneous research project comparing the seven Reactive Monitoring locations (five impact with two controls) examined the fate of a total of more than 500 additional colonies at impact locations encompassing more than 20 additional species. Mortality was evaluated by the same quantitative photographic technique as described above. No colonies died and partial mortality was less than 5% with five exceptions (4 less than 27% and one at 50%, Stafford-Smith, unpubl. data).

White bleaching of *Montipora aequituberculata* at Bay Rock was mostly attributable to abrasion by *Sargassum* and recovery occurred when the *Sargassum* died back seasonally. White bleaching of *Merulina ampliata* was due to a single colony and its cause was not clear. White bleaching levels at Rattlesnake Island remained low throughout the program.

These observations suggest that there were influences affecting the health of corals in the south-east Bays of Magnetic Island during February which were absent or less pronounced at Control locations. However, the influences were not at a high enough level, or did not persist for long enough to cause mortality in the short term.

4.2 Potential Causes of Stress

Control-versus-impact threshold criteria for coral condition in potential impact bays were exceeded or reached during Weeks 5-8. This discussion therefore focuses on the period prior to and including these weeks in seeking a cause.

4.2.1 Temperature and Salinity

Both temperature and salinity can cause bleaching and mortality in corals (Brown & Howard, 1985). Data on water temperatures available for Magnetic Island sites suggested no abnormalities (Oliver, *pers.comm.*). Rainfall was generally low during the course of the study, but a short period of stormy weather occurred during Week 5. The rain was unlikely to have created salinity problems for corals at the depth of the transect. Had high temperatures or low salinities been a primary cause of stress, they would have been expected to cause greater effects in shallow water colonies than in those at depth. This was specifically not the case since corals at less than 2m showed no signs of stress.

4.2.2 Light and Sedimentation

Light is essential to photosynthesis by the symbiotic zooxanthellae present in the tissues of reef corals. Reductions in light reaching the coral can therefore affect photosynthesis and thereby reduce the energy available for a coral's normal activities. Light levels reaching the coral can be reduced in three principal ways: (a) if surface light levels decrease because of cloud cover or storms, (b) if the amount of light attenuated in the water column increases (e.g. as a result of increased suspended solids), and (c) if some obstruction occurs between the coral tissues and the light source such as a sediment layer on the tissues. In addition to light attenuation, sediment lying on the coral's tissues can also cause abrasion or result in a diffusion barrier (Stafford-Smith & Ormond, 1992). It may also foster proliferation of bacteria and lead to disease (Ducklow & Mitchell, 1979; Hodgson, 1990). Corals employ a variety of mechanisms to reject sediments on their tissues and minimise adverse effects. However, these mechanisms (largely behavioural activities and mucus production) have an energetic cost which, like light reduction, can lead to stress and ultimately to mortality.

In general, surface light was high during the dredging program. However, surface light was relatively low between 29 January to 1 February (Weeks 2/3), and between 14 to 18 February (Weeks 4/5).

There is evidence that aspects of the sediment regime became less favourable to corals during the weeks leading up to observed coral stress (Chapter 8 of this book). The present study showed that sedimentation rates at the transect depth at Geoffrey and Florence Bays were close to or higher than each Bay's average during Weeks 3-5 (Figure 7b) Turbidities at these two locations were higher than each Bay's average from the beginning of Week 4 to the beginning of Week 6 (approximately 8-24 February), with the exception of 13-15 February. Underwater visibility on the 9 and 16 February was near-zero at Geoffrey and Florence Bays. Near-zero visibility was not encountered in these bays on monitoring days at other times.

Dredge

In the period leading up to observed episodes of coral stress the dredge was active in the extension to the channel, working relatively close to Nelly and Geoffrey Bays (Figure 2), while tidal and wind driven circulation in Cleveland Bay tended to carry dredge and dump plume material towards Florence and Arthur Bays. Sediment plumes were recorded entering both Geoffrey and Florence Bays in Week 3, but by Week 4 any plumes were indistinguishable as the entire region became turbid.

Tide, wind and swell

Chapter 7 (Oceanographic Data Collection) provides general background on tides and on wind strengths, two potential influences on turbidity and sedimentation. Maximum daily tidal range provides a proxy indicator of the currents likely to be generated by tides, which in turn generate turbidity. Aerial photographs taken during the spring tide early in February showed significant sediment eddies around headlands along Magnetic Island's coast. These sediment plumes and eddies were also well-developed in Bowling Green Bay (to the south of Cleveland Bay) and Halifax Bay (to the north) (Raaymakers, *pers. comm.*).

Relatively strong winds coincided with the spring tide but then dropped off until the beginning of Week 5 (15 February), at which time a weaker spring tide was developing. Data collected in a concurrent program to study the concentration and movement of sediment around the Bay show an increase in the wind-wave heights and swell leading up to the 9 February, and again over the period encompassing 16 February (Chapter 8 of this book).

4.3 Cause of Stress in Geoffrey and Florence Bays

Plumes of sediment surrounding the dredge and leading from the spoil dump towards the northern tip of Magnetic Island were recorded in aerial photographs on several occasions during the course of the dredging program (Raaymakers, *pers. comm.*). The dredge was working predominantly in a high risk area for Florence and Geoffrey Bays during the critical period leading up to observed stress in *Acropora latistella*. Thus, the potential for increased turbidity and sedimentation from the dredge was present at this time.

It is not clear whether the absolute levels of sedimentation and turbidity in Florence and Geoffrey Bays during the period leading up to stress were significantly higher in the presence of the dredge than they would have been in its absence. However, with the exception of Florence Bay deep sites in Weeks 8 and 11 (Figure 7b), there were similar trends in sedimentation rates at potential impact locations and at control locations. The same general comment can be made of turbidity. This suggests that, although the dredge may have enhanced the absolute levels of sedimentation and turbidity experienced by the impact bays, there were other influences acting on the sediment regime throughout the region. These are likely to be the result of the coincident wind-wave and swell heights (Ridd, *pers. comm.*) and spring tides. The concurrent sediment studies suggest that swell may be one of the most important processes affecting sediment mobility. Thus the coincidence of swell may have been a significant contributor to the variable and elevated sediment levels observed at all locations around this time.

The co-occurrence of spring tide, wind-waves, ground swell and low surface light may all have affected coral health during the critical period in February by causing adverse sediment and light regimes. However, since coral stress was not observed at control locations at this time, it is concluded that dredging activities also contributed to the observed stress in corals at Geoffrey and Florence Bays.

This study focussed on short-term effects of dredging activities on specified target corals. Quantitative data for these corals showed no evidence of significant dredge-related mortality. However, enhanced levels of coral stress (particularly as measured by moderate bleaching levels) at Geoffrey and Florence Bays during February, support the contention that at least one species was close to its tolerance limits during this period. It is therefore recommended that major dredging within close proximity of Magnetic Island reefs be avoided or closely monitored when adverse natural conditions (such as spring tides, strong winds, ground swell and/or persistent low light) coincide.

4.4 Additional Notes

(1) The coincident occurrence of other potential influences on coral condition early in the dredging program have obscured any easy conclusions about the discrete effects of dredging on coral health. Combined spring tides and strong winds in early April were not correlated with increased bleaching. Further periods of ground swell were not recorded (Ridd, *pers. comm.)* so that discrete effects of ground swell cannot be evaluated. The effects of dredging in Cleveland Bay may become significant in the short-term only when other, natural, events are coincident. It is not yet clear what the long-term effects of this dredging program may be. Evaluation of medium-term effects of the dredging program has been made by the simultaneous study on corals (Chapter 4).

(2) It is possible that much of the damage likely to occur from dredging has already occurred in the past and that only long-term enhancements of sediment loads will affect a population of corals already adapted to high sediment regimes. The results of this study should not be generalised to other parts of the Great Barrier Reef which have different historical sediment regimes.

(3) There is some indication from the sedimentation rates in Weeks 8 and 11 (both coincident with spring tides) that Florence Bay was experiencing anomalous levels at deep sites relative to Geoffrey Bay and the Controls. This may represent an influence from the spoil site, enhanced at spring tides. Whilst it is not clear how long such influences may persist following cessation of dumping due to unknowns such as retention times of imported sediments in the bays, changes in the periodicity of suspended solids or sedimentation loads at critical threshold levels will be an important factor driving chronic impacts on corals in the longer term.

(4) Following their study of the dispersion of dredge material during 1989, Wolanski and Gibbs (1992) suggested dredging modifications such as releasing *'muddy overflow near the bottom instead of at the surface'* to minimise plume development. The WH *Resolution* was a dredge of this type, discharging its overflow approximately 7m below the waterline. This vessel's method of dredging may have an advantage over other vessels which discharge at the waterline.

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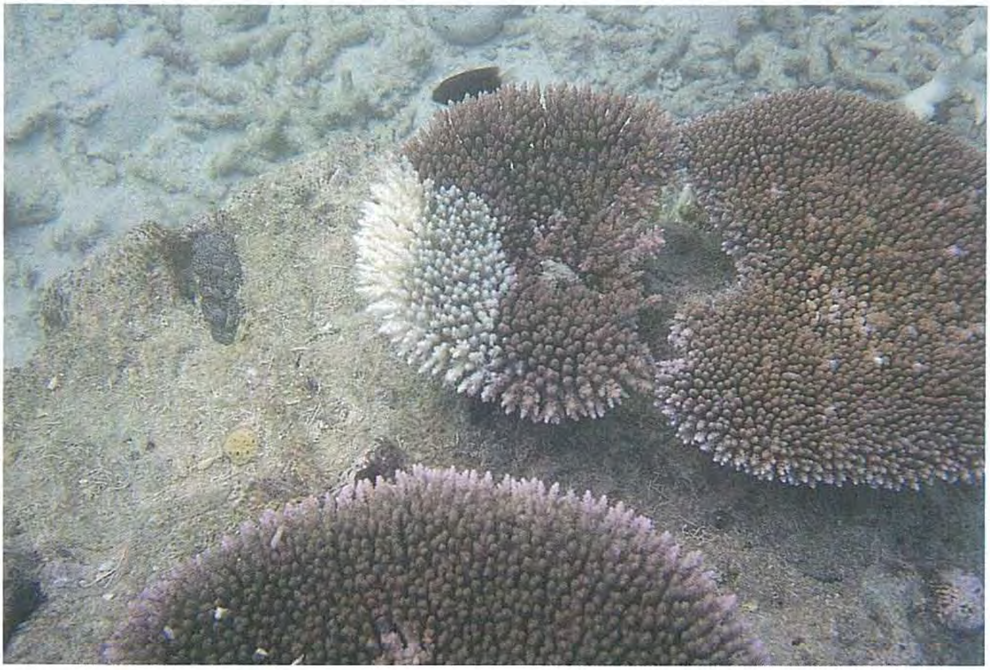
Plate I - Diver taking notes on coral health

Plate II - Coral colony showing the effect of bleaching. Coral bleaching was used as a measure of community stress.



CORAL COMMUNITIES

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EXECUTIVE SUMMARY

This report summarises the results obtained in a study of ecological impacts on corals of dredging in Platypus Channel (Cleveland Bay, Townsville) undertaken by the Townsville Port Authority in early 1993. It formed part of a larger environmental monitoring program being undertaken to monitor effects of dredging on surrounding marine physical, floral and faunal conditions in Cleveland Bay.

The assessment of impacts of the dredging on coral abundance was mainly focused on Magnetic Island ('Impact Locations'). These were the areas considered most likely to be affected by turbidity generated by the dredging of the nearby shipping channel, and the dumping of spoil in Cleveland Bay. Coral communities at six Sites at each of the 'Impact Locations' were compared with a similar number of Sites at 'Control' Locations (e.g. Rattlesnake Island) and repeatedly surveyed three times using a video transect technique: (i) once prior to the beginning of dredging (survey during late December 1992, start date of dredging 18/1/93); (ii) once towards the end of the dredging works (April 1993); and (iii) once several months after the completion of dredging (late August 1993). The survey design, known as a BACI (Before-After-Control-Impact) comparison, was designed with a view to detecting changes of around 20% in cover by corals in response to dredging impacts.

This final report details the results obtained during all three surveys. The aims of the work were to:
(a) describe and quantify the existing abundances of, and any changes in, the abundance of corals at Magnetic Island, Middle Reef and Rattlesnake Island prior to, during and after dredging; (b) determine whether any changes observed might have been dredging impact-related; and (c) examine the results obtained in these surveys (termed TPA1-3) in relation to a longer-term data set obtained during an earlier survey (as part of the Magnetic Quay Development) at some of the same Locations between January 1989 and June 1990 (MQ1-3).

Few impacts of dredging on percentage cover by corals and algae were detected during this study. Of ten taxonomic groups examined (Table 2), only the Faviid corals and Soft Corals showed significant declines in abundance consistent with an impact of dredging. Other apparent changes in abundance detected in the coral *Montipora* and total Hard Corals were not attributable to the effects of dredging because most of the losses of cover occurred at the primary control location, while abundances at the impact locations remained steady or declined at a lower rate. The two groupings of algae, *Sargassum* and All Algae, showed greater seasonal declines in abundance at impact locations as compared with controls. This result must, however, be interpreted with caution because the historical abundance at controls for these taxa was low prior to impact and therefore had less capacity to decline.

1. INTRODUCTION

1.1 Background Studies

Coral biologists have argued that corals are susceptible to turbidity and light attenuation in their environment. Some species appear to be more tolerant of sedimentation and tend to occupy continental near-shore reefs where clear waters are rare (Bull, 1982; see review by Craik & Dutton, 1987), and others are found only in areas with very little turbidity. Within that apparent partitioning of species between silt-tolerant and clear-water taxa, it has also been suggested that any activities which would further increase the local background siltation levels (human development, cyclones, etc) would lead to damage to the corals normally found within any one area (Fisk, 1983; Cortes & Risk, 1985). The effects of development on coral reefs is of increasing concern on the Great Barrier Reef where human developments are being balanced with the conservation of the coral reef systems. It is clear that studies on the effects of particular developments, such as this dredging operation, on reef communities are of great importance for coral reef management.

Although studies which examine the overall changes in coral communities in response to environmental impacts are relatively common (e.g. Brown & Howard, 1985; Carpenter & Maragos, 1989) only a small proportion of these have focussed on the effects of dredging or the dumping of sediments (Pastorok & Bilyard, 1985; Rogers, 1990). A few studies which focus on other forms of development, such as increasing run-off adjacent to island and continental farming communities and other activities which disrupt the natural coastal and hinterland vegetation, are also of relevance here. The shortage of literature on dredge-related projects is probably largely because most major ports around the world have tended in the past to be concentrated in temperate and cooler climes, with large-scale port developments only recently expanding to the tropics.

Early studies on the effects of dredging on adjacent coral communities were often approached only qualitatively or semi quantitatively with little opportunity for accurate descriptions of the effects. Brock, *et al.*, (1966) reported on the effects of large-scale dredging on Johnston Atoll (700 acres dredged). Declines due to sedimentation of up to 40% loss in biotic cover affected 1,100 acres of coral reef. More recent quantitative studies have come up with opposing results. In some areas, or types of operations, impacts are great, leading to large losses in coral cover (e.g. Dodge & Vaisnys, 1977; Chansang, *et al.*, 1981). In other dredging assessments very few impacts on coral communities were detected (Mapstone, 1990; Stafford Smith *et. al.*, 1993). In one study, the turbidity associated with dredging was considered small in relation to that observed during natural disturbance events (Zolan & Clayshulte, 1981). The presence of regular periods of natural turbidity (e.g. cyclones) and/or differences in natural tolerance in coral species are likely to play an important role in the predicted effects of dredging activities for any particular coral reef community and would help to explain some of the apparently opposing results obtained by different workers.

1.2 Aims

This study was undertaken as part of a larger Environmental Monitoring Program designed to assess the impacts of dredging undertaken by Townsville Port Authority (hereafter, "TPA") in Cleveland Bay during the early part of 1993. Platypus Channel and its extension, Sea Channel, is the major shipping passage traversing Cleveland

Bay providing access to the Port of Townsville. Dredging works required to upgrade and extend the channel by several kilometres involved the relocation of approximately 0.75 million m^3 of Recent and Pleistocene sediments. These sediments were removed by suction dredge, collected into a sub-surface-draining hopper barge, and dumped in approximately 10 m of water at a site approximately half way between Magnetic Island and Cape Cleveland.

In December 1992, The Department of Marine Biology, James Cook University (hereafter "MBJCU"), successfully tendered for the assessment of impacts of dredging on coral communities around Magnetic Island. This report encompasses the results obtained during three surveys of coral communities (including results previously released in three earlier reports: Kaly *et al*, 1993a,b,c) done:

(i) prior to the commencement of dredging (during December 1992 - start date of dredging was 18/1/93);
(ii) towards the end of dredging (late April 1993); and
(iii) several months after the conclusion of dredging (late August 1993).

In addition to this study of coral communities, a large database, collected during an earlier Environmental Impact Study of coral communities around Magnetic Island, was used to augment the assessment of impact-related trends in changes in abundance of corals. The earlier data set was collected in relation to the Magnetic Quay Development (MQ Study) during 1989-90 by MBJCU (Mapstone, *et al.*, 1989, 1992; Mapstone, 1990).

The central aims of this project were to:

1. assess whether any impacts on the abundance of corals (and other biota) occurred around Magnetic Island and possibly Middle Reef in response to the TPA Dredging Program;
2. quantify the magnitude and direction (i.e. increases or decreases) of any changes in coral abundances which might be associated with dredging; and
3. if possible, relate any changes in the abundance of corals (and other biota) to longer term records collected during the earlier Magnetic Quay development.

2. METHODS

2.1 Locations and Sites Surveyed

Five "Locations" were selected for the study (Figure 1). The Locations originally included a single Control at Rattlesnake Island, which is believed to be remote enough to be beyond any potential for effects of the dredging, and four at which a potential for impacts of dredging existed. The Locations were:

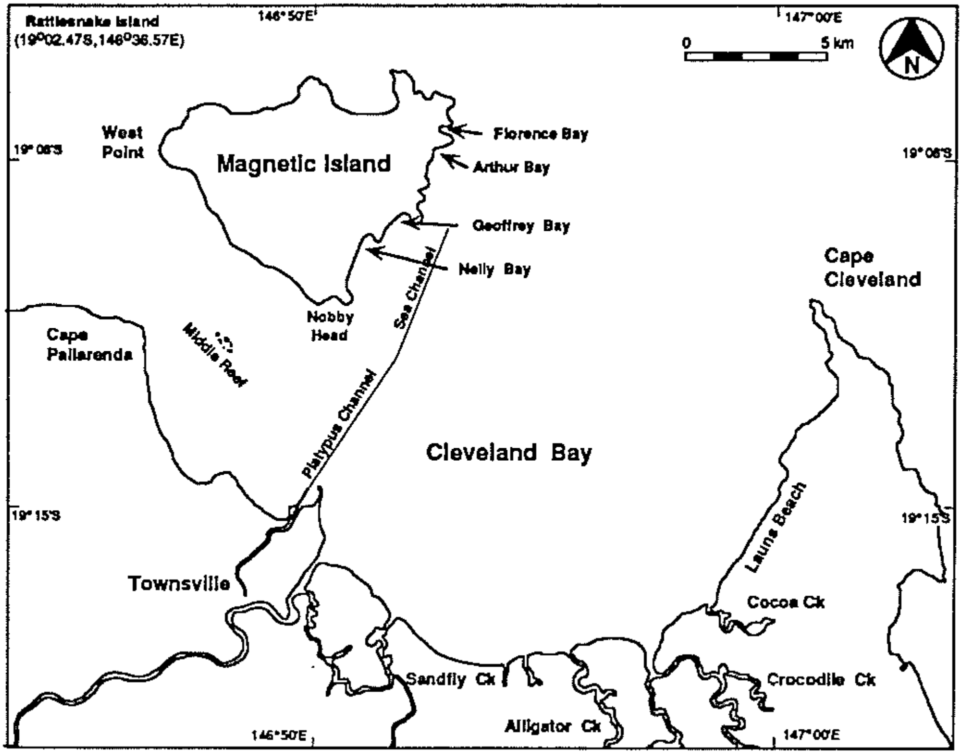
Control:
Rattlesnake Island

Potential Impact Locations:
Middle Reef
Nelly Bay
Geoffrey Bay
Florence and Arthur Bays

Note that in an earlier report (Kaly *et al*, 1993b) we considered Middle Reef to be the least likely location to be impacted (apart from Rattlesnake Island) and calculated the expected power of tests to detect impact if Middle Reef was assigned as a control, rather than a location of potential impact. This division was maintained in this report for the purposes of power analysis, a decision which appears to have been borne out by the apparent lack of impact at Middle Reef.

Each Location was sub-sampled at six "Sites" (Figures 1 & 2). All Sites were

Figure 1 Locality Map Showing Study Sites



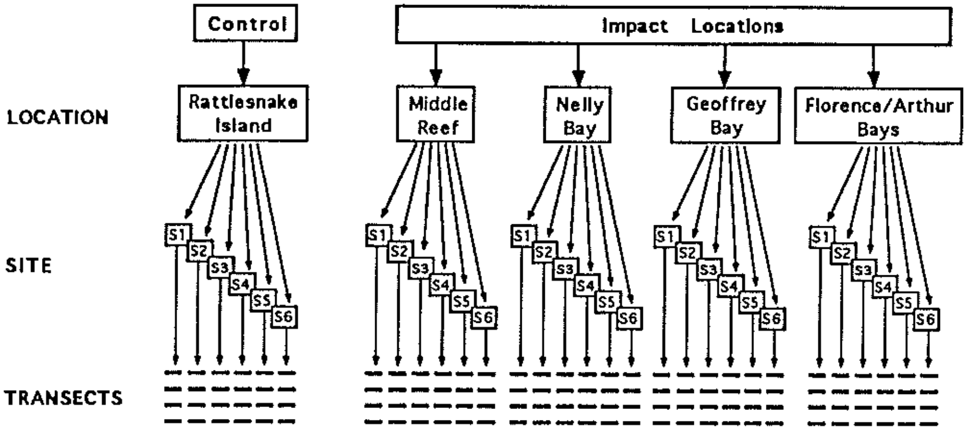
located in a more-or-less equidistant row within each Bay or along each reef forming a Location. The sites are generally, but not exclusively, referred to by their position in this series beginning from North to South, or East to West at any Location. Note that only three sites were surveyed at each of Florence and Arthur Bays which taken together form the full complement required for a Location. The sites (and their transects) re-used from the Magnetic Quay study are identified in Table 1.

2.2 Field Methods

Each Site at each Location was sampled using four replicate fixed transects. Transects were either resurrected from the previous Magnetic Quay study (Mapstone *et al.*, 1989, 1992; Mapstone, 1990), or newly defined, as required. All of the original Magnetic Quay transects were relocated, very few of these having lost any of their markers. In all cases, where Magnetic Quay transects were available at a TPA Study Location, they were used.

Transects were 20 m long and defined by steel reinforcing stakes hammered into the substratum at 5 m intervals. These were aligned parallel to the shore in each Bay or adjacent to each reef and placed at a depth of between 2 and 8 m (below MLWS). For sampling, a fibreglass measuring tape was strung tightly between each stake and the substratum in a strip 30 cm wide along the seaward

Figure 2: Design Tree showing relationship among factors Location and Site surveyed during this study. Note that this same design was repeated through time in a Repeated Measures ANOVA design applied to four fixed transects at each Location and Site combination.

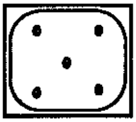


side of the tape recorded on video using a Hi8 camera.

2.3 Laboratory Methods

Video recordings made of each transect at each Site and Location were backed-up onto new Hi8 tapes in the laboratory. copies were titled at the beginning of each tape with the survey number, and then at the beginning of each transect with the transect number, Site, Location and the date on which the transect was recorded.

Tapes were played back through a Hi8 video player, an editor (Sony RM E-300) and high-resolution Trinitron screen. The video screen's surface was marked with five points for analysis, arranged as follows:



Each transect was paused via the editor at six second intervals and the taxa under each of the five screen points recorded. A total of 30 video frames was analysed for each transect, yielding 150 points under which coral and other taxa were recorded. Screen points were assessed for a total of 46 possible categories (later pooled), including hard corals of 13 families, soft corals, algae and sponges (Table 2).

Table 1: Comparison of Sites and Locations used in all TPA surveys with those used in Magnetic Quay Surveys. Those sites which were in common with Magnetic Quay Surveys are marked in bold with an asterisk.

Location	Site					
Rattlesnake Is	S1	S2	S3	S4	S5	S6
Middle Reef	S1	S2	S3	S4	S5	S6
Nelly Bay	**S1***	**S2***	**S3***	**S4***	**S5***	**S6***
Geoffrey Bay	**S1***	**S2***	**S3***	**S4***	**S5***	**S6***
Florence Bay	**S1***	**S2***	S3			
Arthur Bay				**S4***	**S5***	S6

2.4 Statistical Analyses

2.4.1 General Statistical Methods

All raw data on percent cover by groups of corals were aggregated on taxonomic bases (Table 2). Only these higher taxonomic groupings were analysed because it was impossible to reliably identify many corals to species level from video images, and most species or genera that could be reliably identified from video occurred at abundances too low or were distributed too patchily for separate analysis. *Montipora* spp, *Turbinaria* spp, and *Sargassum* spp were the only exceptions.

Three sets of analyses were done:

1. comparisons among the five locations sampled in this study of changes in coral cover that occurred during the period of dredging and which might have been caused by impacts from that dredging;
2. comparisons of the status of coral cover in January 1989, June 1989, July 1990, December 1992, April 1993, and August 1993 at sites surveyed in both the impact assessment program for the Magnetic Quay development (1989-1990 data) and for this study (1992-1993 data);and
3. estimation of the statistical power of tests which failed to reject the null hypotheses of no impact of the current dredging program, and estimation of the magnitude of change that we would have expected to detect with nominal statistical power of 80%.

The emphasis of this project was to assess whether dredging activities in the Platypus and Sea Channels had 'important' deleterious impacts on the biota, especially corals, of the fringing reefs of Magnetic Island. Hence, the major interest in the analyses that follow was in assessing whether changes (declines) in coral coverage occurred at Nelly and/or Geoffrey and/or Florence-Arthur Bays during the period of dredging whilst coral coverage at Rattlesnake Island (and potentially Middle Reef) remained constant or increased. The key terms of interest in the analyses which follow, therefore, are the interactions between Locations and Time.

For the remainder of the report, the data from the three surveys for the

Table 2: Taxonomic groupings used for analyses of percent cover across both Magnetic Quay and Townsville Port Authority Surveys.

ACROPORID POCILLOPORID GROUP

Pocilloporidae
Seriatopora
Pocillopora damicornis
Stylophora
Acroporidae
Bottlebrush
Corymbose
Plates
Staghorns
Astreopora

FUNGIIDS

Siderastreidae
Agaricidae
Pachyseris
Fungiidae
Fungia
Heliofungia
Podobacia
Pectiniidae
Echinophyllia
Oxypora
Mycedium
Pectinia
Mussidae

TURBINARIA

Dendrophyllidae
Turbinaria

HARD CORALS

All Hard Corals
All above
Oculinidae
Caryophyllidae
Unidentified hard corals

SPONGES

All Sponges

MONTIPORA

Montipora

PORITIDS

Poritidae
Porites
Goniopora
Alveopora

FAVIIDS

Faviidae
Favia
Favites
Cyphastrea
Platygyra
Echinopora
Caulastrea
Goniastrea
Montastrea
Plesiastrea
Leptastrea
Moseleya
Merulinidae
Merulina
Hydnophora

SOFT CORALS

Soft Corals
Sarcophyton
Lobophyton
Encrusting soft corals
Zooanthids
Sinularia

ALL ALGAE

SARGASSUM

Magnetic Quay program will be referred to as MQ1, MQ2, and MQ3 for the January 1989, June 1989, and June 1990 data respectively. Data from this study will be referred to as TPA1, TPA2, and TPA3 for the data from December 1992, April 1993, and August 1993 respectively.

All analyses were done with raw data (% coverage) or direct derivatives of them (*e.g.,* differences between successive surveys), and no 'normalising' transformations were applied. Throughout this work we use 0.1 as the critical significance level by which to reject null hypotheses. *A posteriori* comparisons among means were by the Ryan-Einot-Gabriel-Welsch procedure, hereafter 'Ryan's test'. All analyses were done using the SAS ™ (©) system.

2.4.2 Comparisons Among Locations Between December 1992 and August 1993 (TPA1, TPA2 and TPA3)

Data for each taxonomic group were analysed by a repeated measures analysis of variance (RMANOVA) comprising two hierarchical spatial factors [Locations and Sites(Locations)], with four replicate transects at each site being repeatedly measured on the above three occasions [the repeated factor, Time]. Sites(L) was considered a random variable, whilst Location and Time were considered fixed effects, with their interaction being the term of most interest (see author for more details on the structures of analyses). When the probability of the observed Site or Site*Time variation arising under the relevant null hypotheses (α_0) exceeded 0.25 (Winer, 1971), the sums of squares (SS) and degrees of freedom (DF) of the Sites(L) and/or Sites(L)*Time term(s) were pooled with those of either the spatial or temporal residual variances respectively. Effects of Locations, Time, and Location*Time were then tested against the relevant pooled residual variance, resulting in more powerful tests of these effects. Non-significant fixed effects were never pooled in the analyses reported here. Note that data for coverage by sponges were not analysed for this report because a high proportion of the site means were zero at and following the first TPA survey. These data are presented as graphs only.

Sphericity tests for homogeneity of the variances & covariances were done for all repeated measures analyses, and Huyne-Feldt corrections to the degrees of freedom of F-ratios for Time effects were applied when the variance-covariance structure was considered likely to be non-homogeneous ($\alpha_0 \leq 0.1$). This was the case for only three groups. The Huyne-Feldt correction results in more conservative tests of effects involving Time, taking into account the apparent heterogeneity of correlations between repeated measurements.

When Time*Location effects were non-significant in the RMANOVAs, no further analyses were done, since the absence of such an interaction would not be consistent with an impact of dredging. Examination of 'non-impact' changes in cover were not considered important for this report. When Time*Location effects were statistically significant, possibly indicating an impact of dredging, the profiles of coverage between successive surveys were examined to identify when such effects arose. Profiles were constructed by taking the arithmetic differences between (the same) transects surveyed on successive field trips. For example, the cover at TPA1 was subtracted from that at TPA2 for each transect to construct the profile of change between TPA1 and TPA2. These differences were analysed by two factor nested ANOVA (Locations, Sites(L)), with the overall mean change also being tested for difference from zero. A significant effect of the overall mean would indicate that the percent coverage of the indicated taxon changed significantly when averaged over all Locations. Such an effect, in the absence of significant

'Location' effects, would not indicate an impact since in this case all Locations would be deemed to have changed by approximately the same amount. A significant effect of Location would mean that changes in percent coverage by the indicated taxon were not consistent among Locations. This would be a necessary, though not sufficient, precursor to the inference of an impact. Significant effects of Locations in these analyses were resolved by Ryan's tests.

2.4.3 Comparisons Using MQ and TPA Data

Data from MQ1, MQ2 and MQ3, and TPA1, TPA2 and TPA3 were compared for four of the six Sites sampled in the present study at each of Nelly, Geoffrey, and Florence-Arthur Bays. These sites were common to both the Magnetic Quay and current studies, and the transects sampled at each were the same throughout. Although the remaining sites (3 and 6, Figure 2) in Nelly and Geoffrey Bays were also sampled in the Magnetic Quay study, they were dropped from the analyses in order to maintain balance in the analytical models.

Data were analysed by RMANOVA, with each transect being surveyed on each occasion. Because of the lengthy interval between MQ3 and TPA1 (~18 months) and because there was a noticeable change in the measured cover of some groups during this interval (Kaly, *et al* 1993b), the temporal sequence of six repeated measurements were analysed in two factors: Period (either Magnetic Quay or this study) and Times nested within periods. Both factors were considered fixed effects because of their specific relations to events in the development of the two projects. The spatial factors in these analyses were Locations, Sites(L), and replicate transects, arranged as described earlier (see author for more details of structures of analytical models).

As above, when terms of interest in the analyses were tested against terms other than the residual mean square (*eg.* Location tested against Site(Location)), a more powerful test for those terms was constructed by using a pooled residual mean square as denominator only when $\alpha_0 > 0.25$ for the higher order denominator (*ie* Site (Location) in the above example) and pooling of SS & DF seemed justified. Tests of sphericity of the variance-covariance matrices and corrections to degrees of freedom for tests of 'repeated' factors were done as described in 2.4.2.

The principal interest in these analyses was whether the changes between MQ3 and TPA1 noted previously persisted for the duration of the present study, and whether cover at the three 'impact' Bays on Magnetic Island changed during this study. Note that since all three Bays were considered potential impact Locations, a significant Time(Period) effect would be a precursor to the inference of an impact at all of them. Significant Time(Period)*Location effects might have resulted from an impact at only one or two of Nelly, Geoffrey, and Arthur-Florence Bays.

2.4.4 Power of Tests and Minimum Detectable Differences Where No Impact Was Detected

For non-significant Time and Time*Location effects in the RMANOVAs discussed in 2.4.2 and 2.4.3, we calculated the expected statistical power to detect a nominated impact when the hypothesis test was conducted against a critical Type I error rate of 0.1. For the purposes of these estimates, an impact was defined as a decline in coverage between TPA1 and TPA3 at Nelly, Geoffrey, and Florence-Arthur Bays equivalent to 20% of the cover observed at TPA1. It was assumed that no change in coverage occurred at Rattlesnake Island and Middle Reef. The impact was cast as a constant linear change in cover over the period TPA1-TPA3. The error variance used in deriving the non-centrality parameter for these calculations was whichever error variance was used in the relevant F-ratio when the real data were analysed. For example, if the Time*Location term was tested against a pooled error(Time) variance for a taxon, then that pooled error(Time) mean square was used as the denominator of the non-centrality parameter for the estimation of statistical power. The numerator of the non-centrality parameter was the sum of squares calculated from the hypothetical means expected under the above impact scenario. Thus, for a Time*Location term, the non-centrality parameter, λ_{T*L}, was:

$$\lambda_{T*L} = \frac{sn\sum_{t}\sum_{l}(\mu_{tl}-\mu_{t.}-\mu_{.l}+\mu_{..})^2}{MS_{T*S(L)}}$$

where:
s = number of sites per location (6);
n = number of transects per site (4);
μ_{tl} = the means hypothesised under α_o;
$MS_{T*S(L)}$ = the mean square used in the denominator of the F-test on the data, in this case the Time*Site(L) mean square. This would be the pooled error(Time) MS if the Time*Site(L) term was non-significant and $\alpha > 0.25$.

In addition to calculating the statistical power to detect an impact of 20% at three of the five Locations, we also estimated the magnitude of change at those Locations that we would have expected to detect with a statistical power of 80%, given a critical Type I error rate of $\alpha_c = 0.1$. This was done by iteratively adjusting a hypothetical non-centrality parameter and calculating statistical power until power equalled 80%. The non-centrality parameter at that point was then multiplied by the MS used in the denominator of the F-test for the term of interest, and divided by the appropriate coefficient (*sn* in the above example) to leave a raw sum of squares, SS1. From the percentage cover observed at TPA1, coverages at TPA2 and TPA3 at the three notionally impacted Locations were then iteratively calculated assuming varying levels of impact (*e.g.*, 10%, 20% 30% etc) until the resulting sums of squares equalled SS1. The percentage change that precipitated this SS was, therefore, that which would have been detected with a power of 80%. Coverages at Rattlesnake Island and Middle Reef were held constant at TPA1 level during these calculations.

3. RESULTS AND DISCUSSION

3.1 Comparisons Among Locations Between December 1992 and August 1993 (TPA1, TPA2 and TPA3)

3.1.1 Detecting Impacts

Changes in cover of all groups except the Acroporids proved significant when averaged over all locations (significant Time effects in Table 3). For four of the taxonomic groups (Acroporids, Fungiids, Poritids and *Turbinaria*), the important Location*Time interactions were demonstrably non-significant (Table 3) and no impact would be inferred for these groups (Figure 3). A significant Location*Time interaction term, potentially indicating impacts due to dredging, was detected in the remaining 6 of the 10 groups analysed by RMANOVA (Table 3). These groups were: Faviids, *Montipora* , Hard Corals, Soft Corals, *Sargassum* and All Algae.

Analyses of the profiles TPA1-TPA2 and TPA2-TPA3 revealed that change in coverage varied significantly among Locations mostly in the period TPA1-TPA2. Coverage by total Hard Corals, total Soft Coral, *Montipora*, the Faviids, and *Sargassum* spp all varied between TPA1 and TPA2 in a Location dependent way (Table 4). Only *Sargassum* spp. and

All Algae showed significant Location-dependent change during the TPA2-TPA3 interval.

During the period TPA1-TPA2, patterns in change in coverage by total Hard Corals and *Montipora* could not be considered consistent with a deleterious impact of dredging. In both cases, coverage decreased most at Rattlesnake Island and increased most at Middle Reef (Table 5, Figure 3). Coverage by *Montipora* changed very little at Nelly, Geoffrey, or Florence-Arthur Bays during the period (Table 5, Figure 3). Although total coral cover apparently declined over the period at the three Bays, such declines were exceeded by decline in cover at the single unambiguous control Location, Rattlesnake Island (Table 5, Figure 3). It would be difficult to substantiate an inference of impact on either group caused by dredging under these circumstances.

Changes in coverage by the Faviids and soft corals, however, did vary among Locations in a pattern consistent with localised impacts of dredging. Faviids either did not change or declined in coverage at all Locations, but declines were substantially greater at Nelly and Florence-Arthur Bays than at all other Locations (Table 5, Figure 3). Although relatively small in absolute terms (1.31% & 2.68%, Table 5), coverage declined by approximately 42.4% & 31.8% of pre-dredging coverage respectively at the two Bays. For soft corals, there was strong evidence of an impact at Florence-Arthur Bay, where coverage declined significantly (Table 5, Figure 3). This decline (2.61% coverage) represented loss of 43.3% of the initial crop. Coverage did not change at the other four Locations during the same period, and it seems likely that there may have been an impact of dredging activities which was localised at Florence-Arthur Bays. This possibility might be investigated further with reference to records of turbidity and visible plume behaviour during the period TPA1-TPA2.

For both algal groups, changes in cover between TPA2 and TPA3 were zero or more positive at Rattlesnake Island and Middle Reef, and tended to be negative at the other three Locations, although the locations were not clearly delineated into distinct groups by the Ryan's tests (Table 5). The apparent opposite directions of changes at the impact and control (or potential control, Middle Reef) Locations might be suggestive of an impact of dredging on the normal seasonality of these algae. It should be noted, however, that the abundance of *Sargassum* would be expected to decline during the winter months (TPA2-TPA3) and so declines at Nelly, Geoffrey, and Florence-Arthur Bays are not surprising. The relatively little change at Middle Reef and Rattlesnake Island probably resulted from the relative scarcity of *Sargassum* at those Locations (Figure 3). The result for total algal coverage, however, is less clear-cut because the normal seasonality of species other than *Sargassum* is not so well understood. The relative dominance of *Sargassum* on the fringing reefs of Magnetic Island (Figure 3) inevitably mean that the perceived responses of the total algal assemblage there will be dominated by the seasonality of *Sargassum*, hence apparently declining in winter months. At Middle Reef and Rattlesnake Island, however, Sargassum formed a minor part of the algal assemblage (Figure 3).and changes in the total assemblage were less likely to be dominated by *Sargassum* seasonality. Clearly, at least some algae at those Locations increase in abundance during winter, (Figure 3) but we are unable to determine whether those components were either present at the three impact Locations or failed to increase in abundance. This ambiguity, added to the clear increases in coverage by algae at the impact Locations during TPA1-TPA2, again consistent with the known seasonality in *Sargassum* growth, leaves any inference of impact on algal assemblage ambiguous.

3.1.2 Other Patterns

When time-averaged means were considered, variation among Sites within at least some Locations was high for all groups (Table 3). In all cases it was highly unlikely that such variation would have arisen under the null hypothesis (α_0 <0.01). Sites differed considerably at all Locations for some groups although Sites were relatively homogenous in each Location for at least one group (see author for more details). Averaged over Times, Locations would not be considered statistically significantly different (α_0 > 0.1) for five of the 10 groups (Acroporids, Faviids, Poritids, Soft Corals, and All Algae), but differed significantly for the remaining five groups (Table 3, Figure 3). These patterns in abundance are not of major interest here, relating only peripherally to our assessment of impacts of dredging. We will discuss them only briefly.

In general, algae tended to be most abundant at Magnetic Island, with very low cover being recorded at Rattlesnake and Middle Reef (Figure 3). Further, as already discussed, the assemblage composition seemed to differ between Magnetic Island and the other Locations, rendering any inference of impacts on algae ambiguous.

The total cover by hard corals was highest at Rattlesnake Island, Middle Reef and Florence/Arthur Bays (between 55 and 66%) with measurably lower cover at Nelly and Geoffrey Bays (up to 40%). Coral cover tended to be less for most groups at Nelly and Geoffrey Bays than at Florence-Arthur Bays, the notable exceptions being Poritids (greatest at Geoffrey Bay) and *Turbinaria* spp (most abundant by far at Nelly Bay) (Figure 3). Middle Reef and Rattlesnake Island coral fauna were dominated by *Montipora* spp far more than at the remaining three Locations (Figure 3), with all other groups being fairly similar to abundances at at least two of the bays on Magnetic Island. Faviids and Fungiids were most abundant at Florence and Arthur Bays (Figure 3). Acroporid/Pocilloporid corals varied in abundance slightly among Locations (Figure 3), but there were no statistically significant differences among the Locations (Table 3).

3.2 Comparisons of Coral Cover MQ and TPA Surveys 1989 - 1993

Several of the eleven taxonomic groups apparently experienced relatively marked changes in coverage between MQ3 and TPA1. Such changes would be unrelated to impacts of dredging, although reference to the previous patterns in abundances of corals may aid in the interpretation of putative impacts. The results of RMANOVAs for 10 groups are presented in Table 6 and the data are plotted in Figure 4.

Figure 3 Graphs of mean percentage cover by the 11 taxa examined at each location during all surveys in this study (TPA1, TPA2, TPA3). Sites at each location were pooled for these graphs. Values are means +/- SE; RI = Rattlesnake Island, MR = Middle Reef, NB = Nelly Bay, GB = Geoffrey Bay, FAB = Florence/Arthur Bays.

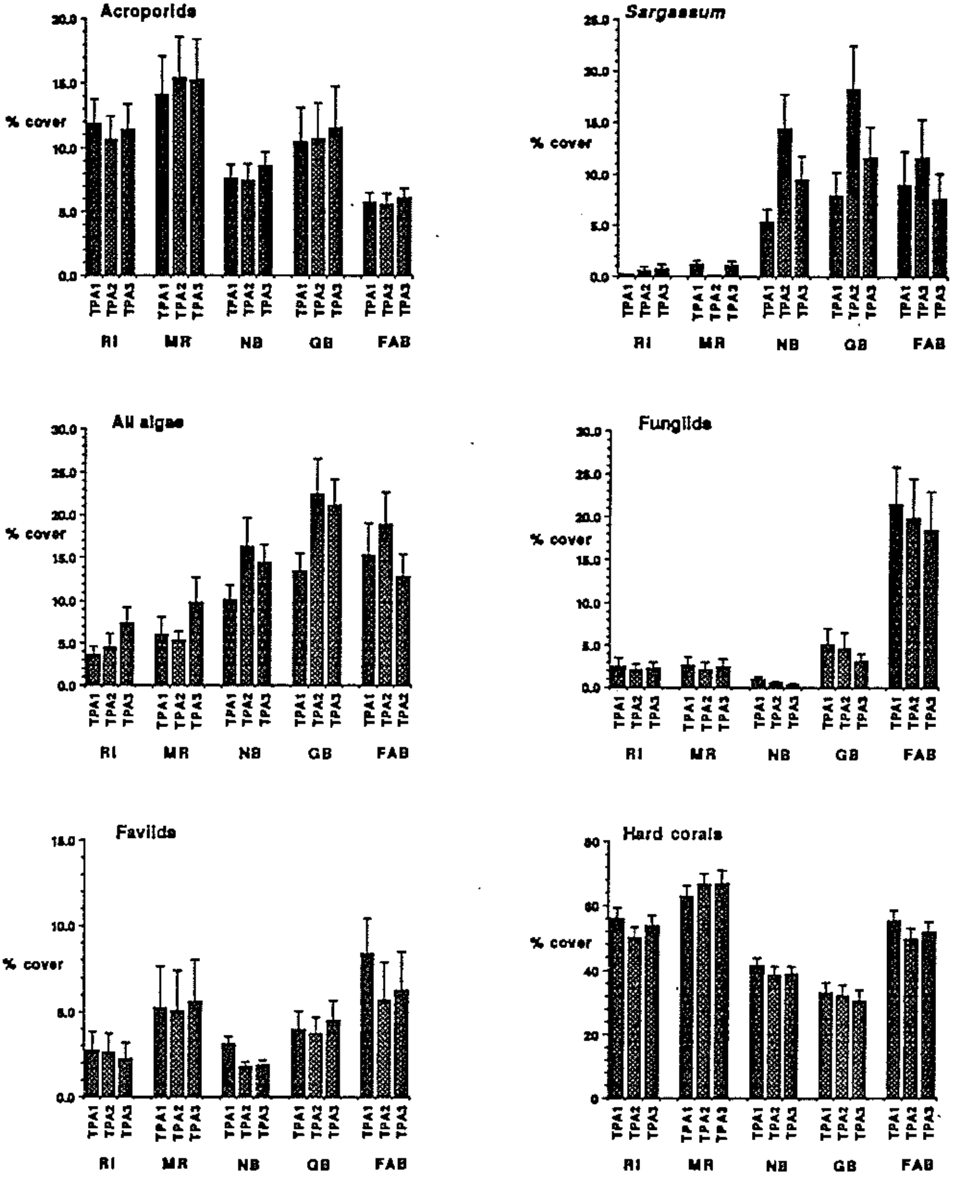


Figure 3 - continued

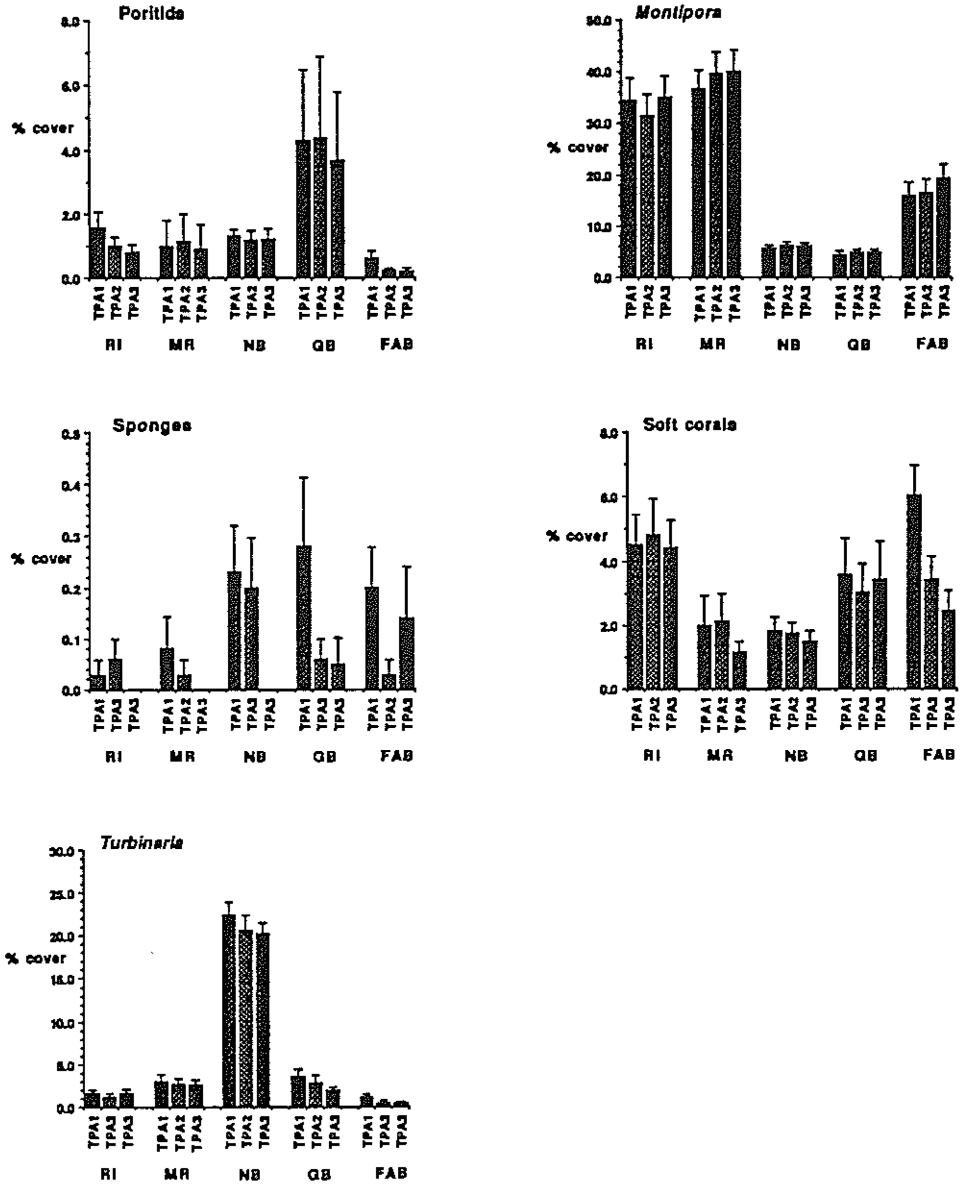


Table 3 Results of RMANOVA for data from TPA1, TPA2 and TPA3 for each of the taxa considered (excluding sponges - see text). All terms in the model are listed, but no F-ratios or values are given for those that were subsequently pooled with the error term below them. The DF for these terms are parenthesised to indicate that these DF were added to the error DF below, and it is the sums of these additions that are shown in the tables where appropriate. Where the denominator for an F-ratio is indicated as "*P-error* x", that (source) term was tested against the relevant error MS after random Site terms had been pooled if appropriate. The structure of the full (no pooling) models can be seen for the Acroporids. Critical level of $\alpha = 0.1$.

Taxon	SOURCE	F-Denom	DF	F	α	
Acroporids	Location	Site(L)	4	0.92	0.47	NS
	Site(L) error(s)	error(s)	25	5.73	0.00	*
			90			
	Time	S*T(L)	2	1.54	0.22	NS
	L*T	S*T(L)	8	0.69	0.70	NS
	S*T(L)	error(T)	50	1.41	0.05	*
	error(T)		180			
Favilds	Location	Site(L)	4	0.49	0.74	NS
	Site(L)	error(s)	25	6.06	0.00	*
	error(s)		90			
	Time	P-*error*(T)	2	7.22	0.00	*
	L*T	P-*error*(T)	8	2.99	0.00	*
	S*T(L)	error(T)	(50)	Pooled		
	error(T)		230			
Fungiids	Location	S(L)	4	4.06	0.01	*
	Site(L)	error(s)	25	6.91	0.00	*
	error(s)		90			
	Time	P-*error*(T)	2	6.08	0.00	*
	L*T	P-*error*(T)	8	1.34	0.22	NS
	S*T(L)	error(T)	(50)	Pooled		
	error(T)		230			
***Montipora* sp**	Location	Site(L)	4	8.42	0.00	*
	S(L)	error(s)	25	7.00	0.00	*
	error(s)		90			
	Time	S*T(L)	2	4.98	0.01	*
	L*T	S*T(L)	8	2.32	0.03	*
	S*T(L)	error(T)	50	1.37	0.07	*
	error(T)		180			
Poritids	Location	Site(L)	4	1.0982	0.38	NS
	Site(L)	error(s)	25	1.9579	0.00	*
	error(s)		90			
	Time	S*T(L)	2	3.43	0.04	*
	L*T	S*T(L)	8	0.80	0.61	NS
	S*T(L)	error(T)	50	1.25	0.15	NS
	error(T)		180			

Table 3 - continued

Taxon	SOURCE	F-Denom	DF	F	α	
***Turbinaria* sp**	Location	S(L)	4	4.85	0.00	*
	Site(L)	error(s)	25	5.79	0.00	*
	error(s)		90			
	Time	P-*error*(T)	2	5.92	0.00	*
	L*T	P-*error*(T)	8	1.15	0.33	NS
	S*T(L)	error(T)	(50)	Pooled		
	error(T)		230			
Hard Corals	Location	S(L)	4	4.85	0.00	*
	Site(L)	error(s)	25	5.79	0.00	*
	error(s)		90			
	Time	P-error(T)	2	8.49	0.00	*
	L*T	P-error(T)	8	5.51	0.00	*
	S*T(L)	error(T)	(50)	Pooled		
	error(T)		230			
Soft Corals	Location	Site(L)	4	1.62	0.20	NS
	Site(L)	error(s)	25	2.49	0.00	*
	error(s)		90			
	Time	S*T(L)	2	5.66	0.01	*
	L*T	S*T(L)	8	2.86	0.01	*
	S*T(L)	error(T)	50	1.50	0.03	*
	error(T)		180			
***Sargassum* sp**	Location	Site(L)	4	2.43	0.07	*
	Site(L)	error(s)	25	4.56	0.00	*
	error(s)		90			
	Time	S*T(L)	2	13.3	0.00	*
	L*T	S*T(L)	8	4.05	0.00	*
	S*T	error(T)	50	2.94	0.00	*
	error(T)		180			
All Algae	Location	Site(L)	4	1.4	0.15	NS
	S(L)	error(s)	25	5.31	0.00	*
	error(s)		90			
	Time	S*T(L)	2	6.72	0.00	*
	L*T	S*T(L)	8	2.43	0.03	*
	S*T(L)	error(T)	50	3.37	0.00	*
	error(T)		180			

Table 3 - continued

Table 4 Analyses of variances of differences in cover ('Profiles') between successive surveys in the TPA study. Only these groups for which a significant Time*Location effect was evident in the RMANOVAs are shown.

A) Analyses for the interval TPA1-TPA2.

TAXON	SOURCE	SS	DF	F	α	
Favids	Mean	99.55	1	16.48	0.00	•
	Location	116.45	4	4.61	0.01	•
	Site(L)	157.77	25	1.04	0.42	NS
	Error	543.72	90	.	.	
Montipora	Mean	8.91	1	0.53	0.47	NS
	Location	406.89	4	2.84787	0.05	•
	Site(L)	892.97	25	2.13907	0.00	•
	Error	1502.85	90	.		
All Algae	Mean	1687.50	1	35.95	0.00	•
	Location	1453.38	4	1.82	0.16	NS
	Site(L)	4990.92	25	4.25	0.00	•
	Error	4225.14	90	.		
Hard Coral	Mean	725.21	1	16.93	0.00	•
	Location	1524.67	4	7.72	0.00	•
	Site(L)	1233.88	25	1.15	0.31	NS
	Error	3855.25	90	.	.	
Soft Coral	Mean	37.97	1	5.84	0.02	•
	Location	135.33	4	3.73194	0.02	•
	Site(L)	226.64	25	1.39442	0.12998	NS
	Error	585.13	90	.	.	
Sargassum	Mean	2213.64	1	62.71	0.00	•
	Location	2579.29	4	4.26	0.01	•
	Site(L)	3788.39	25	4.29	0.00	•
	Error	3177.16	90	.	.	

B) Analyses for the interval TPA2-TPA3

TAXONS	SOURCE	SS	DF	F	α	
Favids	Mean	11.53	1	1.62	0.2066	NS
	Location	18.52	4	0.72448	0.58350	NS
	Site(L)	159.75	25	0.89660	0.60859	NS
	Error	641.41	90	.	.	

Table 4 - Continued

TAXONS	SOURCE	SS	DF	F	α	
Montipora	Mean	196.35	1	8.86	0.0037	*
	Location	262.58	4	2.17793	0.10077	NS
	Site(L)	735.54	25	1.36056	0.14789	NS
	Error	1993.84	90	.	.	
All Algae	Mean	14.77	1	0.29	0.5887	NS
	Location	1674.73	4	2.28663	0.08825	*
	Site(L)	4577.50	25	3.65017	0.00000	*
	Error	4514.59	90	.	.	
Hard Coral	Mean	113.49	1	2.97	0.0885	*
	Location	367.09	4	1.89251	0.14311	NS
	Site(L)	1212.33	25	1.26726	0.20795	*
	Error	3443.94	90	.	.	
Soft Coral	Mean	23.94	1	4.04	0.0473	*
	Location	29.67	4	0.75595	0.56364	NS
	Site(L)	245.31	25	1.65759	0.04414	*
	Error	532.78	90	.		
Sargassum	Mean	1016.17	1	27.78	0.0001	*
	Location	1040.51	4	4.43389	0.00860	*
	Site(L)	1466.69	25	1.60360	0.05562	*
	Error	3292.65	90	.	.	

Table 5 Results of Ryan's tests for differences among Locations in changes of percent coverage by nominated taxonomic groups between successive surveys in the TPA study. The data for each analysis were differences between the second survey and the first survey in each pair, indicated by TPA1-TPA2 and TPA2-TPA3. Thus, a positive mean indicates that the cover of a group increased between surveys, whilst a negative mean indicates a decrease in cover. Means that could not be distinguished by the Ryan's test share the same letter in the 'Group' column. Impacts would be indicated where coverage at any or all of Middle Reef, Nelly Bay, Geoffrey Bay, and Florence-Arthur Bays declined whilst coverage at Rattlesnake Island and/or Middle Reef remained constant or increased. The status of Middle Reef with respect to potential impacts of dredging is here considered uncertain. Ryan's tests are only shown for significant Location effects in Table 4.

	Group	Location	Mean Change	Conclusion
Favids				
TPA1 - TPA2	A	Rattlesnake Is	-0.1417	Potential
	A	Middle Reef	-0.2083	Impact
	A	Geoffrey Bay	-0.2167	
	BA	Nelly Bay	-1.3083	
	B	Florence-Arthur	-2.6792	
Montipora				

Table 5 - continued

	Group	Location	Mean Change	Conclusion
TPA1 - TPA2	A	Middle Reef	2.846	**No Impact**
	BA	Florence-Arthur	0.638	
	BA	Nelly Bay	0.554	
	BA	Geoffrey Bay	0.233	
	B	Rattlesnake Is	-2.908	
All Algae				
TPA2 - TPA3	A	Middle Reef	4.417	**Potential**
	BA	Rattlesnake Is	2.917	**Impact**
	BA	Geoffrey Bay	-1.46	
	BA	Nelly Bay	-1.788	
	B	Florence-Arthur	-6.514	
Hard Coral				
TPA1 - TPA2	A	Middle Reef	3.750	**No Impact**
	B	Geoffrey Bay	-1.250	
	B	Nelly Bay	-3.083	
	B	Florence-Arthur	-5.667	
	B	Rattlesnake Is	-6.042	
Soft Coral				
TPA1 - TPA2	A	Rattlesnake Is	0.3000	**Likely Impact**
	A	Middle Reef	0.1083	
	A	Nelly Bay	-0.0708	
	A	Geoffrey Bay	-0.5375	
	B	Florence-Arthur	-2.6125	
Sargassum				
TPA1 - TPA2	A	Geoffrey Bay	10.417	**Impact**
	A	Nelly Bay	9.117	**Unlikely**
	BA	Florence-Arthur	2.654	
	B	Rattlesnake Is	0.271	
	B	Middle Reef	-0.983	

Table 5 - continued

	Group	Location	Mean Change	Conclusion
Sargassum				
TPA2 - TPA3	A	Middle Reef	0.850	Impact
	BA	Rattlesnake Is	0.242	Unlikely
	CBA	Florence-Arthur	-4.046	
	CB	Nelly Bay	-4.988	
	C	Geoffrey Bay	-6.608	

3.2.1 Spatial Variation

All groups except Poritids showed significant variation among sites within at least one of Nelly, Geoffrey, or Florence / Arthur Bays when data were averaged over surveys (Table 6). Poritids were apparently relatively homogeneous among sites within all Bays (α=0.13). Differences among the Bays were significant only for *Montipora* spp and *Turbinaria* spp. *Montipora* spp were significantly more abundant at Florence-Arthur Bays than at either Nelly or Geoffrey Bays, which differed little (Figure 4). *Turbinaria* spp were clearly most abundant at Nelly Bay, of low abundance at Geoffrey Bay, and scarce at Florence-Arthur Bays (Figure 4). The absence of a significant Location effects for the Fungiids, given such apparently stark contrasts in average abundances among Locations (Figure 4), is probably attributable to great site variation in abundances and the relatively low power of the test (see Table 7). The more powerful test based on the TPA data alone (above), when six sites were sampled at each Location, clearly detected the differences between Florence-Arthur and the other Locations.

3.2.2 Temporal Variation

3.2.2.1 Contrasts Between Magnetic Quay Surveys and TPA Surveys

Only the *Montipora* spp showed no significant variation through time at any of the three Magnetic Island Locations (Table 6, Figure 4). Soft corals showed no significant effect of Period (Table 6), though they varied among times within periods. Fungiids, Poritids, *Sargassum* spp, and all algae showed significant contrasts between the average of all MQ data and the average of all TPA data (significant Period effects, Table 6), and these contrasts were relatively consistent across the three Bays (non-significant Locations*Period terms in Table 6). Both Fungiids and Poritids appeared slightly less abundant in the TPA surveys than in the MQ surveys, whilst the two algal groups generally were apparently substantially more abundant in the latter surveys (Figure 4). It is unclear whether such differences were real or artefacts of the different methods used in the two projects. Methodological considerations will be discussed later.

Acroporids, Faviids, *Turbinaria* spp, and total hard corals also showed significant Period effects, but these were Location-specific, as indicated by the significant interaction of Location and Period (Table 6). Acroporids seem to have been steadily increasing in abundance at Nelly Bay, approximately stable at Florence-Arthur Bay, but dropped substantially in abundance between MQ3 and TPA1 at Geoffrey Bay (Figure 4). A similar pattern was evident also for total hard coral cover, although the drop in cover at Geoffrey Bay seemed more gradual

(Figure 4). *Turbinaria* spp appear to have undergone the opposite trends to Acroporids in Nelly and Geoffrey Bays, but have remained relatively constant in Florence-Arthur Bays (Figure 4). None of these corals were implicated in impacts of the dredging activities, and these patterns would not change that conclusion.

This is not the case for Faviids, however. Faviids were implicated in impacts of the dredging activities at Florence-Arthur and Nelly Bays (see above). Whilst the MQ data do not counter the inference of impacts on Faviids at Nelly and Florence-Arthur Bays, they do help contextualise the impacts. Even after the decline, the apparent coverage of Faviids at Florence-Arthur Bays was only slightly less than it had appeared throughout the Magnetic Quays project. This occurred because of an apparent substantial increase in cover between MQ3 and TPA1. At Nelly Bay, however, the inferred impact of dredging resulted in the lowest abundances of Faviids recorded since 1989.

3.2.2.2 Variations Within Period

There were no significant variations among surveys within either the MQ or TPA surveys at any of the three Magnetic Island Bays for Acroporids, Fungiids, *Montipora* spp, or Poritids (Table 6, Figure 4).

Sargassum spp varied significantly among times within the MQ and TPA surveys, and that variation was apparently homogeneous among the three Bays (Location*Time(P) non-significant, Table 6, Figure 4). The considerable temporal variation within Periods in coverage by *Sargassum* spp probably reflects seasonal life-history characteristics of these algae. It is noteworthy, however, that the algae were either more abundant or perceived to be more abundant in all seasons during the TPA study than during the MQ surveys.

The remaining taxonomic groups (Faviids, *Turbinaria* spp, total Hard Corals, Soft Corals, and total Algae) showed Location specific temporal variations within Periods (Table 6). Variations among times in the TPA data have already been discussed with respect to their potential relevance to impacts from dredging of the channel. Since variations among time during the Magnetic Quay study are of little relevance here, these results will not be discussed further, except to note that, as for the Faviids, the putative impact of dredging on soft corals at Florence-Arthur Bays resulted in decreases only to about those levels apparent during the 1989-1990 MQ surveys (Figure 4).

3.3 Power of Tests and Minimum Detectable Differences Where no Impact was Detected

Results of estimates of statistical power to detect 20% change in cover at Nelly Bay, Geoffrey Bay, and Florence-Arthur Bay, given no change at Middle Reef and Rattlesnake Island, are given in Table 7 for non-significant Time and Time*Location effects in the analyses present in Tables 3 and 6. The main effects of interest are the Time* Location effects for the full data set from TPA surveys, and the Time and Time*Location effects for the restricted data set from MQ and TPA Surveys at the three Magnetic Island Locations. In the latter case, a significant Time(Period) effect would be consistent with an impact at all three Locations, whereas a Location*Time(Period) effect would arise if an impact occurred at only one or two of the three Bays.

For the TPA data alone, we clearly had good power to detect impacts of 20% or more for Fungiids and *Turbinaria* spp, and we are reasonably confident that the non-significant results for these taxa did not merely reflect Type II errors. Statistical power was relatively poor for

Table 6 Results of RMANOVA for data from MQ1-MQ3 and TPA1-TPA3 for each of the taxa examined (excluding sponges - see text). All terms in the model are listed, but no F-ratios or values are given for those that were subsequently pooled with the error term below them. The DF for these terms are parenthesised to indicate that these DF were added to the error DF below, and it is the sums of these additions that are shown in the tables where appropriate. Where the denominator for an F-ratio is indicated as "*P-error* x", that (source) term was tested against the relevant error MS after random Site terms had been pooled if appropriate. The structure of the full (no pooling) models can be seen for *Sargassum* sp. Critical α = 0.1.

Taxon	SOURCE	SS	DF	F	α	
Acroporids	Location	Site(L)	2	0.30	0.75	NS
	Site(L)	error(s)	9	3.69	0.00	*
	error(s)		36			
	Period	S*P(L)	1	1.17	0.31	NS
	L*P	Site*P(L)	2	4.19	0.05	*
	S*P(L)	error(P)	9	1.95	0.08	*
	error(P)		36			
	Time(P)	*P-error*(TP)	4	1.41	0.23	NS
	L*T(P)	*P-error*(TP)	8	0.46	0.88	NS
	S*T(L*P)	error(TP)	(36)	Pooled		
	error(TP)		180			
Favids	Location	Site(L)	2	0.40	0.68	NS
	Site(L)	error(s)	9	2.61	0.02	*
	error(s)		36			
	Period	*P-error*(P)	1	11.10	0.00	*
	L*P	*P-error*(P)	2	4.08	0.02	*
	S*P(L)	error(P)	(9)	Pooled		
	error(P)		45			
	Time(P)	*P-error*(TP)	4	5.34	0.00	*
	L*T(P)	*P-error*(TP)	8	2.49	0.01	*
	S*T(L*P)	error(TP)	(36)	Pooled		
	error(TP)		180			
Fungiids	Location	Site(L)	2	2.24	0.16	NS
	Site(L)	error(s)	9	7.99	0.00	*
	error(s)		36			
	Period	*P-error*(P)	1	3.80	0.06	*
	L*P	*P-error*(P)	2	0.82	0.45	NS
	S*P(L)	error(P)	(9)	Pooled		
	error(P)		45			
	Time(P)	*P-error*(TP)	4	1.81	0.13	NS
	L*T(P)	*P-error*(TP)	8	0.45	0.89	NS
	S*T(L*P)	error(TP)	(36)	Pooled		
	error(TP)		180			

Table 6 - continued

Taxon	SOURCE	SS	DF	F	α	
Montipora spp	Location	Site(L)	2	3.66	0.07	*
	S(L)	error(s)	9	5.26	0.00	*
	error(s)		36			
	Period	*P-error*(P)	1	0.31	0.58	NS
	L*P	*P-error*(P)	2	0.13	0.88	NS
	S*P(L)	error(P)	(9)	Pooled		
	error(P)		45			
	Time(P)	*P-error*(TP)	4	1.01	0.40	NS
	T(P)	*P-error*(TP)	8	0.67	0.72	NS
	S*T(L*P)	error(TP)	(36)	Pooled		
	error(TP)		180			
Poritids	Location	S(L)	2	1.67	0.24	NS
	Site(L)	error(s)	9	1.69	0.13	NS
	error(s)		36			
	Period	*P-error*(P)	1	10.02	0.00	*
	L*P	*P-error*(P)	2	2.15	0.13	NS
	S*P(L)	error(P)	(9)	Pooled		
	error(P)		45			
	T(P)	*P-error*(TP)	4	0.71	0.58	NS
	L*T(P)	*P-error*(TP)	8	1.25	0.27	NS
	S*T(L*P)	error(TP)	(36)	Pooled		
	error(TP)		180			
Turbinaria	Location	S(L)	2	28.14	0.00	*
	Site(L)	error(s)	9	5.75	0.00	*
	error(s)		36			
	Period	*P-error*(P)	1	17.45	0.00	*
	L*P	*P-error*(P)	2	6.62	0.00	*
	S*P(L)	error(P)	(9)	Pooled		
	error(P)		45			
	T(P)	*P-error*(TP)	4	3.78	0.00	*
	L*T(P)	*P-error*(TP)	8	2.51	0.01	*
	S*T(L*P)	error(TP)	(36)	Pooled		
	error(TP)		180			
Hard Corals	Location	S(L)	2	1.30	0.32	NS
	Site(L)	error(s)	9	3.03	0.01	*
	error(s)		36			
	Period	*P-error*(P)	1	3.27	0.08	*
	L*P	*P-error*(P)	2	12.50	0.00	*
	S*P(L)	error(P)	(9)	Pooled		
	error(P)		45			
	T(P)	*P-error*(TP)	4	4.71	0.00	*
	L*T(P)	*P-error*(TP)	8	2.52	0.01	*
	S*T(L*P)	error(TP)	(36)	Pooled		
	error(TP)		180			

Table 6 - continued

Taxon	SOURCE	SS	DF	F	α	
Soft Corals	Location	S(L)	2	0.81	0.48	NS
	Site(L)	error(s)	9	2.02	0.07	*
	error(s)		36			
	Period	*P-error*(P)	1	0.65	0.42	NS
	L*P	*P-error*(P)	2	1.19	0.31	NS
	S*P(L)	error(P)	(9)	Pooled		
	error(P)		45			
	Time(P)	*P-error*(TP)	4	3.24	0.01	*
	L*T(P)	*P-error*(TP)	8	4.55	0.00	*
	S*T(L*P)	error(TP)	(36)	Pooled		
	error(TP)		180			
Sargassum spp	Location	S(L)	2	0.10	0.90	NS
	Site(L)	error(s)	9			
	error(s)		36	2.59	0.02	*
	Period	*P-error*(P)	1	13.37	0.01	*
	L*P	*P-error*(P)	2	0.23	0.80	NS
	S*P(L)	error(P)	9	2.96	0.01	*
	error(P)		36			
	Time(P)	*P-error*(TP)	4	10.16	0.00	*
	L*T(P)	*P-error*(TP)	8	0.85	0.54	NS
	S*T(L*P)	error(TP)	36	2.42	0.00	*
	error(TP)		144			
All Algae	Location	S(L)	2	0.07	0.93	NS
	Site(L)	error(s)	9	2.96	0.01	*
	error(s)		36			
	Period	*P-error*(P)	1	19.52	0.00	*
	L*P	*P-error*(P)	2	0.51	0.62	NS
	S*P(L)	error(P)	9	3.66	0.00	*
	error(P)		36			
	Time(P)	*P-error*(TP)	4	12.25	0.00	*
	L*T(P)	*P-error*(TP)	8	3.71	0.01	*
	S*T(L*P)	error(TP)	36	1.43	0.07	*
	error(TP)		144			

Figure 4 Graphs of changes in percentage cover by the 11 taxa examined during the Magnetic Quay (MQ1, MQ2 & MQ#) and TPA Surveys (TPA1, TPA2 & TPA3) at Nelly Bay, Geoffrey Bay and Florence/Arthur Bays. Sites a each location were pooled for these graphs. Values are means +/- SE; NB = Nelly Bay, GB = Geoffrey Bay, FAB = Florence/Arthur Bays.

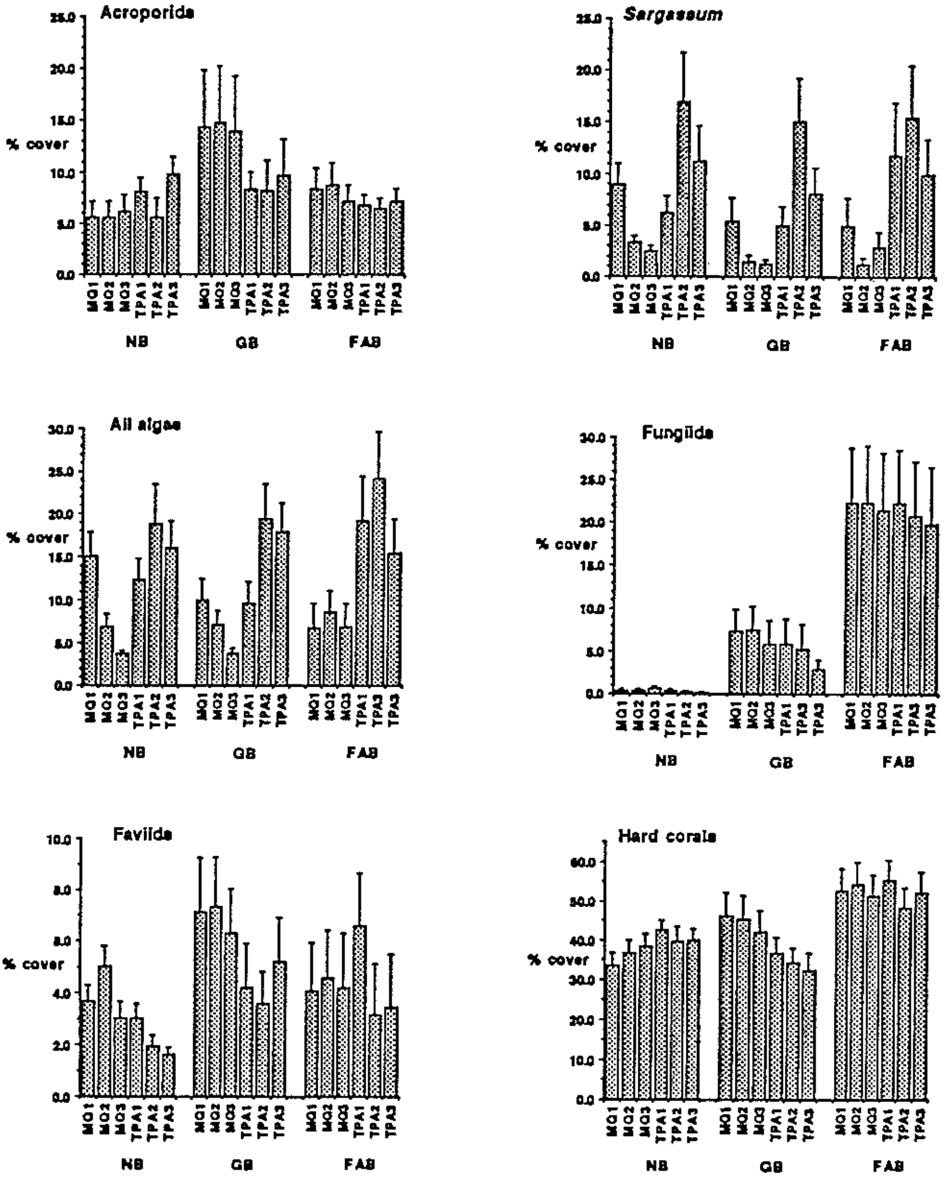


Figure 4 - continued

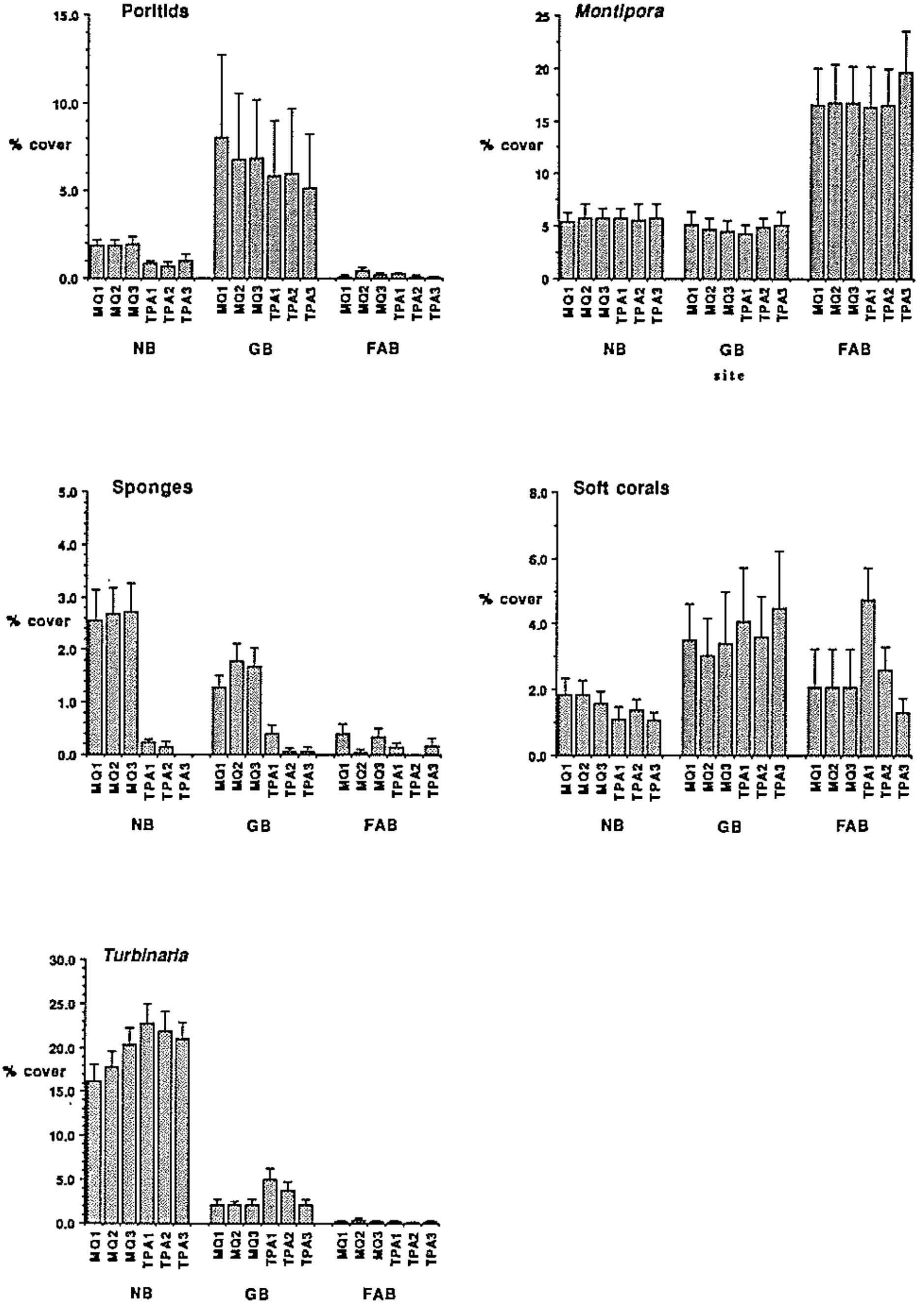


Table 7 Estimates of the statistical power and detectable effect sizes for **non-significant tests** of interest. Statistical power was calculated for the detection (α_c=0.10) of a change in cover between TPA1 and TPA3 at nominal impacted Locations equivalent to 20% of the cover present at each at TPA1. The "Change @ p=0.8" is the change in cover between TPA1 and TPA3 at those locations, as a proportion of the cover at TPA1, that might have been detected with statistical power 80%, given α_c=0.10. In both cases, where data from the Magnetic Quays study were present, their observed status was taken as their status under the alternative hypothesis. In A) and B), no change was postulated for Middle and Rattlesnake Reefs for either the Time or Time*Location calculations. In C) and D), estimates for the Time effects under Ha were calculated assuming that all three Bays (Nelly, Geoffrey, and Florence-Arthur) had suffered a 20% decline between TPA1 and TPA3. For the Location*Time interaction, it was assumed that one of the Bays (nominally Florence-Arthur) had escaped impact and remained unchanged between TPA1 and TPA3, whilst the other two had suffered a 20% decline in cover over the same period. In all cases, the impact was assumed to be in the form of a constant linear effect which had reached 20% accumulated change by TPA3.

A) Source = Loc*Time, data from TPA1-TPA3 only

Taxon	F Denominator	Power	Change @ p=0.8
Acroporids	Site*Time(Loc)	34%	36%
Fungiids	*P-error(T)*	97%	15%
Poritids	Site*Time(Loc)	35%	35%
Turbinaria spp	*P-error(T)*	99%	12%

B) Source = Time, data from TPA1-TPA3 only

Taxon	F Denominator	Power	Change @ p=0.8
Acroporids	Site*Time(Loc)	>99%	11%

C) Source = Loc*Time(Period), data from MQ1-MQ3 and TPA1-TPA3

Taxon	F Denominator	Power	Change @ p=0.8
Acroporids	*P-error(TP)*	37%	49%
Fungiids	*P-error(TP)*	15%	115%
Montipora spp	*P-error(TP)*	15%	120%
Poritids	*P-error(TP)*	42%	48%
Sargassum spp	Site*Time(Loc*Period)	14%	281%

Table 7 - continued

D) Source = Time(Period), data from MQ1-MQ# and TPA1-TPA3

Taxon	F Denominator	Power	Change@p=0.8
Acroporids	*P-error*(TP)	57%	26%
Fungiids	*P-error*(TP)	49%	29%
Montipora spp	*P-error*(TP)	46%	31%
Poritids	*P-error*(TP)	28%	49%

detecting changes of 20% in Acroporids and Poritids, however, and we would be moderately confident that we had not erroneously missed impacts of only about 35% or greater for these taxa.

For the MQ and TPA data, we would have little confidence that we would have detected even substantial impacts at only one or two of the three bays with these analyses (Table 7c). We were relatively certain (power = 80%) of detecting impacts of about 30% for all groups except Poritids, however, if those impacts occurred at all three bays.

4. CONCLUSIONS

Few impacts of dredging on percentage cover by corals and algae were detected during this study. Of the ten taxa examined, only the Faviids and Soft Corals showed changes in abundance likely to be attributable to the effects of dredging in Cleveland Bay (Table 8). Those potential impacts detected in the two algal categories were probably more attributable to pre-existing patterns of abundance - algal cover was found to be intrinsically lower at the control locations when compared with the impact locations. This form of pre-existing condition would tend to dampen our detection of natural declines at those locations where algae were already low before dredging and result in relative changes of abundance among locations which would be interpreted as impact.

We conclude that, at least in the short term, the dredging works undertaken by the Townsville Port Authority in Cleveland Bay during the early part of 1993 did not result in major changes in community composition of corals at the Magnetic Island Reefs examined. Even though two taxa, the Faviids and Soft Corals did show declines consistent with impacts of up to a 43% loss in original standing cover, their original densities were low (<6% cover of the substratum).

Data for the TPA and the MQ surveys were collected by different techniques. The MQ estimates of percentage cover by all of the same taxa were collected using benthic line transects (BLTs) which appear to better estimate the cover by hard corals, soft corals and sponges than the video transects used here. Using the video method, we found that it was very difficult to distinguish encrusting and brown-coloured sponges from some turfing algae and soft corals (and *visa versa*). It is also likely that *Sargassum* sp. and other macroalgae are estimated differently by the video technique because they often overlie corals. That is, the video technique appears to best estimate secondary cover, while the BLT's better estimate primary cover by organisms. Such biases could have resulted in the marked differences between the MQ1-3

Table 8 Summary of impact status of the 10 formally-analysed taxa and the power of the RMANOVA used (to detect 20% decline, $\alpha=0.1$) associated with any non-significant results.

Taxon	Potential Impact Detected?	Interpretation	Power	Change detectable with 80% Power
Acroporids	No		34%	36%
Faviids	Yes	Decline of 42% Nelly Boy Decline of 32% at Florence/Arthur Bays	N/A	N/A
Fungiids	No		97%	15%
Montipora	Yes	Not dredge-related	N/A	N/A
Paritids	No		35%	35%
Turbinaria	No		>99%	12%
Hard Corals	Yes	Not dredge-related	N/A	N/A
Soft Corals	Yes	Decline of 43% at Florence/Arthur Bays	N/A	N/A
Sargassum	Yes	Possible impact but likely to be driven by pre-existing patterns	N/A	N/A
All Algae	Yes	Possible impact but likely to be driven by pre-existing patterns	N/A	N/A

and TPA1-3 surveys observed in several taxa, without there having been any true change in abundance over time (between the two studies). We currently have no mechanism for separating true from methodological changes in percentage cover by corals and algae between the two surveys. In future surveys of coral cover which might benefit from the long-term data sets presented here, it will be necessary for both methods to be simultaneously employed to calibrate the two techniques and quantify the potential biases we have identified.

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Plate III - Underwater videography was used to monitor changes in coral cover.

SEAGRASSES

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

This study was undertaken as part of a larger environmental monitoring program conducted to assess impacts resulting from the dredging works for Townsville Port Authority's port expansion.

Seagrass monitoring involved: a review of historical changes in seagrass community distribution within Cleveland Bay, Townsville; baseline mapping of two major seagrass communities within Cleveland Bay using colour and infra-red aerial photography; ground truthing verification of seagrass density and diversity; aerial photographic survey of the same two seagrass communities after eight weeks of dredging activity; and a final aerial photographic survey with ground truthing verification four weeks after completion of channel dredging works.

The historical review revealed that the distribution of seagrass communities in Cleveland Bay has changed over the period 1961 - 1991. The distribution and extent of seagrasses in Cleveland Bay was notably low around 1974, possibly as a result of severe climatic conditions and/or extensive dredging operations undertaken by Townsville Port Authority at that time. Seagrass distribution and extent has since increased.

Extensive aerial surveys and ground truthing by Sinclair Knight did not reveal any major changes in seagrass distribution or densities in the period from December 1992 to May 1993.

The majority of sites surveyed showed increases in distribution and abundance of seagrasses. Local decreases in density were also found. These variations could not be attributed to the adverse effects of sediment movement resulting from dredging and dredge spoil disposal.

No evidence for increased sedimentation of seagrass communities was found anywhere within the study areas along the shores of Cape Cleveland and South-west Magnetic Island.

The dredging operations for the Port of Townsville had no major effects upon the seagrass communities in the area, that were detectable using the aerial survey method.

1. INTRODUCTION

Seagrasses are flowering plants (Angiosperms) which grow worldwide in intertidal and shallow subtidal zones along tropical and temperate coasts. Their distribution is generally restricted to areas of low wave energy where unconsolidated sediments predominate. Depth distributions vary but are related to water clarity in order to provide sufficient light for photosynthesis.

The importance of seagrasses to coastal ecology is well accepted (Coles *et al*, 1987, 1993; Bell and Pollard, 1989). As a food source for dugong and green turtles, an important habitat for juvenile and adult fish and crustaceans and in the stabilisation of coastal sediments, seagrasses play a vital role in coastal ecosystems.

Coastal development has the potential to affect the growth and distribution of seagrass communities. Larkum and West (1983) list the most common causes of human-induced impacts on seagrass communities as: increased turbidity associated with eutrophication or dredging; physical removal and/or smothering during dredging and filling; sewage effluent; hot water effluents; salinity changes; oil pollution; physical disturbance by boats; and industrial effluents.

Townsville Port Authority (TPA) recognised the potential for impacts on seagrasses occurring as a result of the lengthening and deepening of the Port of Townsville access route - Platypus Channel and its extension, the Sea Channel (Figure 1). TPA contracted Sinclair Knight (SK) to undertake monitoring of two major seagrass communities in Cleveland Bay (Figure 1) throughout the dredging period.

The design of the seagrass monitoring strategy was undertaken in consultation with the Technical Advisory Committee (TAC) which had been established to coordinate scientific and commercial inputs to the overall environmental monitoring program (see Chapter 2).

It was decided by the TAC that, due to the lack of suitable control sites of similar seagrass communities in the immediate area, the more common monitoring design of impact versus control sites would not be accommodated in this study. Since the main aim of the seagrass monitoring was to determine whether seagrass health and distribution was affected by dredging activities, the TAC decided that monitoring of these changes (if any) could be undertaken on the basis of baseline seagrass distribution patterns, density and diversity, recorded prior to commencement of dredging operations. Aerial photography (colour and infra-red) and ground-truthing surveys were used to map seagrass communities within the two study areas and to determine whether dredge-related changes had occurred.

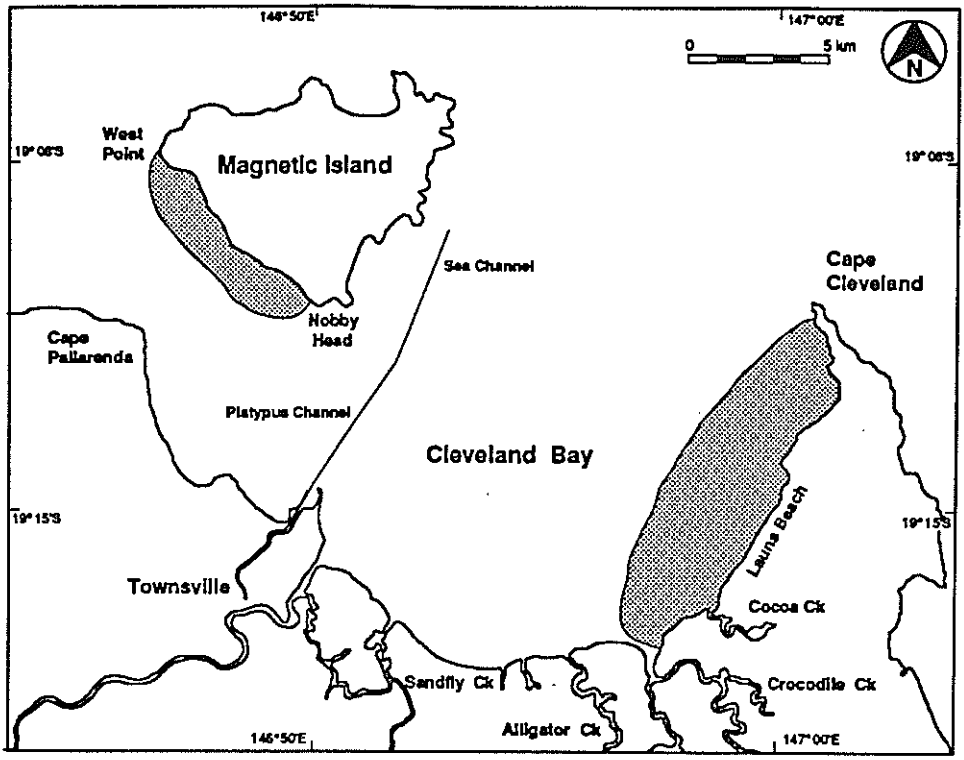
Previous studies of seagrass distribution in Cleveland Bay consisted of ground surveys (Coles *et al*, 1992) and a review of historical aerial photographs to determine changing distribution patterns over time (Pringle, 1989). This current monitoring study aimed to use ground survey verification of aerial photography to determine distributional changes.

2. METHODS

2.1 Historical Review of Aerial Photographs

Pringle (1989) extensively reviewed the history of dredging operations and coastal change within Cleveland Bay. Aerial photographs from 1941 to 1988 were analysed by Pringle to determine the

Figure 1 Locality Map Showing Seagrass Monitoring Areas (Shaded)



extent of coastal change and where possible the dynamics of mangrove, coral reef and seagrass communities throughout this period of time.

In order to determine change in seagrass communities since the Pringle report, all available aerial photographs taken after 1988 were scrutinised at the commencement of this current study. In addition to the Beach Protection Authority (BPA) aerial photographs flown in September 1991, aerial photographs taken by D Hopley and P Catt of James Cook University in June 1988 were studied. The latter photographs are held at the Great Barrier Reef Marine Park Authority library and were kindly made available for study.

2.2 Aerial Photography and Ground Truthing

To assess the potential effects of the proposed dredging operation on the seagrass communities of Cleveland Bay, it was necessary to determine the pre-dredging distribution patterns.

An aerial photographic survey of the area between Crocodile Creek and the Cape Cleveland lighthouse and West Point and Nobby Head, Magnetic Island was conducted on 10 December 1992 (Figure 1 Locality Map). The results of that survey formed the basis for identifying future changes in seagrass distribution patterns during the dredging operations.

Aerial photographs were taken from a Partenavia aircraft fitted with an aiming periscope and photographic port. Using a Hasselblad 70 mm format camera with an 80 mm lens, photographic runs were flown across the required coastlines at a height of 10 000 feet. Both colour and infra-red images were taken. The aerial photography was timed to coincide with spring low tides in order to maximise the exposed intertidal zone and therefore limit the area of seagrass submerged and possibly obscured by turbid water.

The distribution of seagrass communities identified from the aerial photographs was plotted on navigation charts and then the species composition, density and the location of boundaries were determined during ground-truthing surveys.

In order to map the actual boundaries of the seagrass beds, divers conducted "spot-dives" along transect lines that crossed the width of the seagrass bed. At each "spot-dive" a GPS (Global Positioning System) was used to obtain an accurate location fix and then divers estimated the percent cover of seagrass and assessed the species composition. Identification of the seagrass species was conducted *in-situ* using taxonomic features detailed in Lanyon (1986). The outer boundary was determined by divers recording a zero seagrass cover estimate. When possible, intertidal seagrass was assessed by walking across the mudflats but in many instances this was not possible due to difficulties associated with soft sediment and/or access to the intertidal zone. However, the intertidal distribution of seagrasses is well documented in the aerial photographs.

An interim aerial photographic survey of the seagrass communities in the two monitoring areas was conducted on 10 March 1993. Both colour and infra-red photographs were compared to baseline photographs (December 1992) to determine whether changes had occurred in broad seagrass distribution patterns over the first eight weeks of dredging activity. Aerial survey methodology was the same as for the baseline study. No ground-truthing was conducted.

A final post-dredging aerial photographic survey of the seagrass communities was conducted on 5 May 1993. The aerial photographic survey was timed to coincide with spring low tides of approximately 0.1 m AHD. Aerial survey methodology was the same as for the previous aerial surveys.

A detailed visual comparison of the most recent aerial photographs (May 1993) with both the baseline aerial photographs (December 1992) and the interim aerial photographs (March 1993) was conducted to determine changes in seagrass distribution or density.

In addition, due to the inability to detect subtidal seagrass communities by aerial photography (refer to 3.3.1), selected sites visited during the baseline ground truthing surveys in January 1993 were revisited on 11 May 1993. The sites to be revisited were relocated using the original GPS fixes recorded for each site in January 1993. The accuracy of the GPS fixes is in the order of 30-50 metres and consequently broad swims were conducted in the vicinity of each GPS fix to compensate for potential errors in site relocation.

At each site revisited, seagrass density was estimated by divers and species composition was determined *in-situ*. It is recognised that the estimation of percentage cover of seagrass leaves may overestimate densities if, for example, water currents flatten leaves across bare substrate. Shoot densities are a more accurate means of seagrass estimation but require an increased level of fieldwork. Since the purpose of this monitoring program was a comparison of pre-dredging and post-dredging seagrass cover, the use of the same estimation method at both times is sufficient to provide an indication of large scale community changes if they occur. Of particular interest was the possibility of seagrass smothering by resuspension and settlement of dredge spoil. Therefore, evidence of sedimentation on seagrasses was specifically targeted during the surveys.

Not all sites originally surveyed in the baseline study were revisited, however representative sites were chosen (in terms of spatial separation and varying seagrass densities) to provide an indication of seagrass community changes throughout the two areas of study.

3. RESULTS

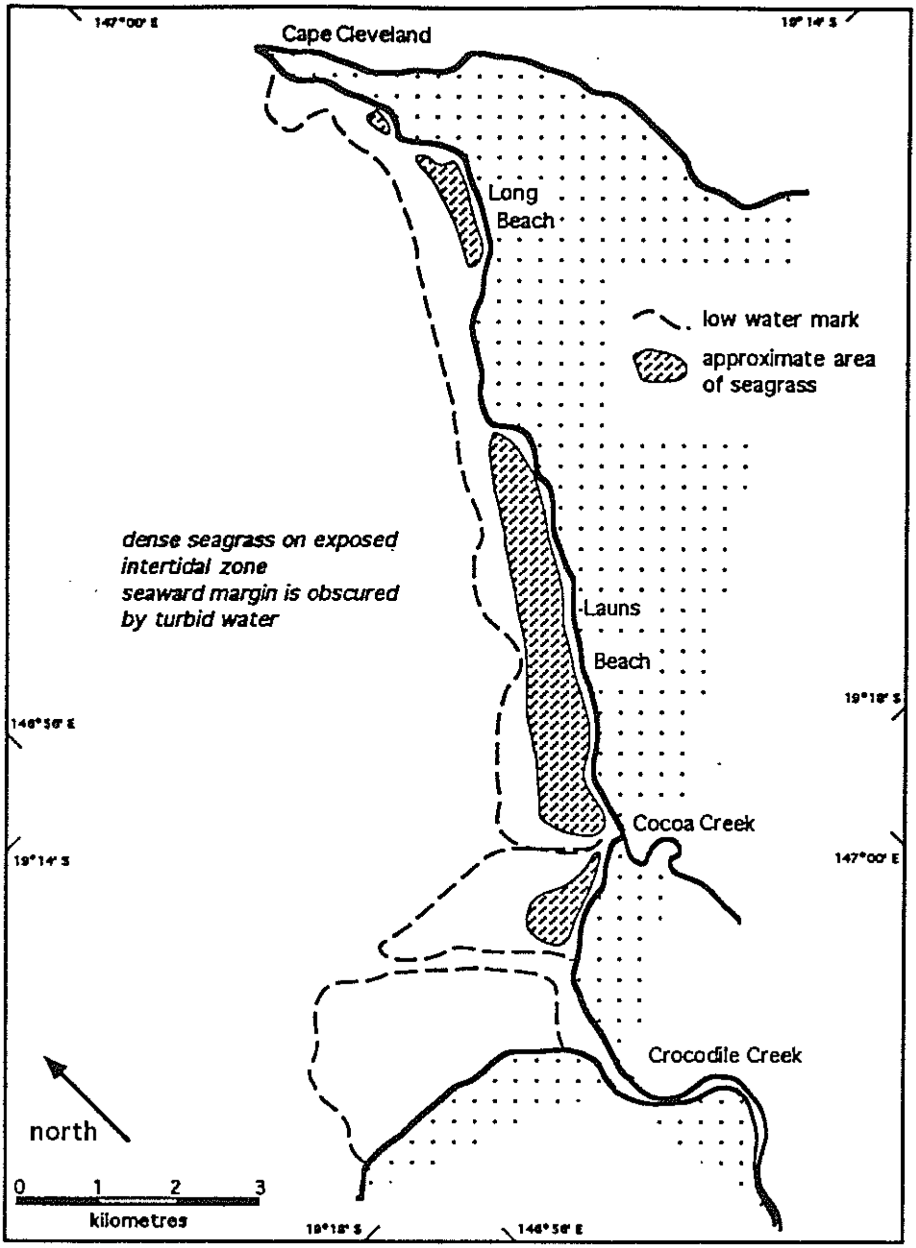
3.1 Historical Review

3.1.1 Crocodile Creek to Cape Cleveland

This area of coast consists of an extensive intertidal zone of fine silty sand with a narrow strip of mangroves between Crocodile Creek and Cocoa Creek and between Cocoa Creek and the northern end of Laun's Beach (Figure 2). Further north along the coast, mangroves are less frequent and sandy beaches separated by rocky headlands predominate. The broad intertidal zone, up to 1 kilometre wide, is protected from direct wave action by Cape Cleveland and thus provides a low energy environment ideal for seagrass colonisation. Consequently, extensive seagrass beds are located in the intertidal and subtidal zones along the coast south-west from the Cape Cleveland lighthouse. Pringle (1989) reported that the distribution of seagrass communities in this area had changed dramatically over the years and her summary is provided below:

1961	"Seagrass was visible below LWM seaward of the north-east end of Laun's Beach and Long Beach".
1973	"No seagrass visible above or below LWM".
1974	"No seagrass was visible along this coast ". (West of Cocoa Creek).
	"Seagrass was visible only below LWM immediately east of Cocoa Creek channel. From Cape Cleveland south to Long Beach the water was very turbid with large southward pointing plumes of sediment in suspension".
1978	"Seagrass below LWM was visible immediately west of Crocodile Creek channel and north-eastwards from there parallel to the coast".
	"Seagrass was visible below LWM north-east of Cocoa Creek in two bands parallel to the coast, with a strip of sediment between. Along the rocky coast, seagrass was visible below LWM only intermittently due to highlights on the photographs where the sun was reflected from the sea surface".
1981	"Seagrass above and below LWM extended from immediately west of Crocodile Creek channel north-eastwards parallel to the coast".

Figure 2 Seagrass Beds, Cape Cleveland, September 1991



"North-east of Cocoa Creek seagrass was visible above and below LWM in the troughs between oblique bars of sediment (the south end of the bars, lying closest to the coast). There was thicker, more continuous seagrass seaward. Along the rocky coast, a large area of seagrass was visible above and below LWM extending from the first rock headland south of Cape Cleveland to Long Beach".

1985 "Seagrass below LWM extended parallel to the whole section of coast" (Sandfly Creek to Cocoa Creek), "and appeared relatively dense east and west of the Cocoa Creek channel".

"North-east of Cocoa Creek seagrass was visible again in troughs between oblique sediment ridges, and opposite the first rock headland north of Laun's Beach, in troughs between sediment ridges parallel to the coast. Northwards to the first rock headland south of Cape Cleveland seagrass was visible below LWM, in patches interspersed with sediment nearer the coast, but with dense growth seawards".

The Hoply/Catt photographs of June 1988 showed seagrass in the intertidal zone as a continuous mottling running the entire length of the photo run from Alligator Creek to Laun's Beach. This pattern suggests low density, patchy seagrass cover. Unfortunately, as with all other aerial photographs taken in this area, turbid water below the intertidal zone prevent identification of seagrass distribution patterns below low water mark.

The BPA aerial photographs of this area from September 1991 showed a moderately dense cover of seagrass in the intertidal zone between Crocodile Creek and Cocoa Creek (Figure 2). However, large patches of this area (approximately 50%) showed very little, if any, seagrass cover. Unfortunately, the entire subtidal zone of this region was obscured by turbid water and as such no idea of the extent of subtidal seagrass beds was obtained.

The intertidal zone parallel to Laun's Beach from Cocoa Creek to the first rocky headland north consisted of a dense seagrass band extending from near the mangrove margins out to the limit of vision at the edge of the turbid water in the subtidal zone. The "oblique sediment ridges" described by Pringle in the 1985 photographs were not apparent in the 1991 photographs.

Further north along the coast, seagrass was visible as a relatively dense band within the bay of Long Beach. Although not as dense as the seagrass along Laun's Beach, the seaward margin of the intertidal zone consisted of reasonably dense seagrass communities which became more patchy towards the coast and, particularly in the north of the bay, diminished to a band of sparse or negligible seagrass cover between the mangroves and the seagrass along the intertidal subtidal margin.

Between Long Beach and the tip of Cape Cleveland, seagrasses were only visible as very patchy cover in Red Rock Bay. The problem of turbid water obscuring the subtidal zone was again evident here.

3.1.2 South-West Coast of Magnetic Island

This part of the Magnetic Island coast lies between West Point and Nobby Head. The main feature is the extensive reef flat which stretches along more than half of this coastline and is up to 1 kilometre wide (Figure 3). Towards the north, the reef flat diminishes and is replaced by a sandy silty intertidal zone offshore from Bolger and Young Bays. Mangroves extend along most of the length of the coast highlighting the sheltered nature of this area.

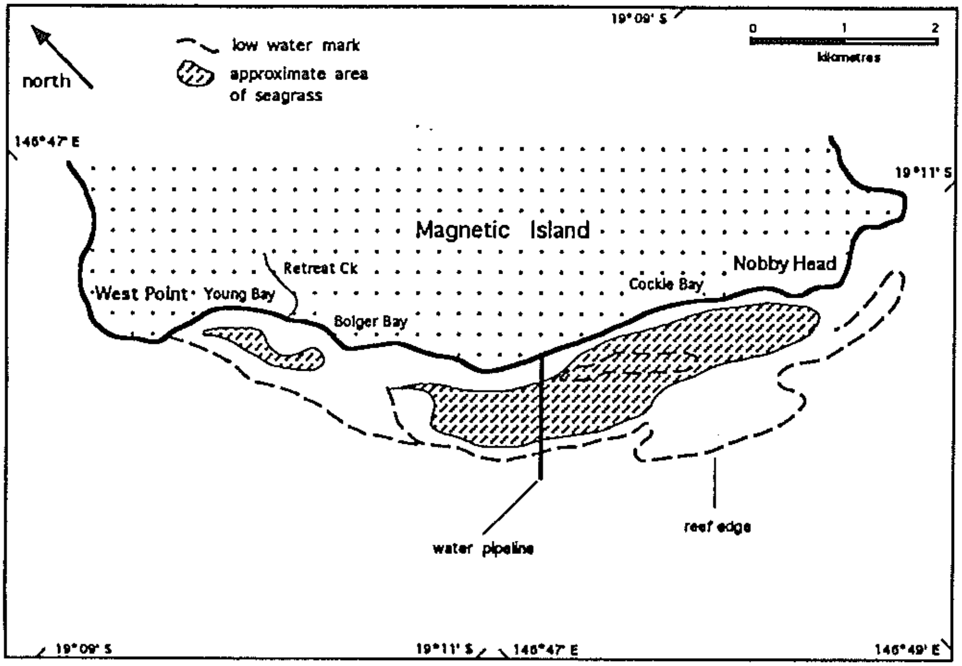
Pringle (1989) discussed the dynamics of seagrass distribution along this coastline over the period 1959 to 1985. A summary of her findings is given below:

1959	"patches of seagrass and sediment were visible under water extending between Bolger and Young Bays. Further south areas of seagrass were growing in the channels near the landward side of the coral reef flat north-west of Cockle Bay and seaward, interspersed with sediment, on reef flat off Bolger Bay. Patches of seagrass and sediment were visible also in the belt off Cockle Bay and extending along the shore to near Nobby Head".
1961	"seagrass distribution pattern broadly similar".
1974	"no seagrass despite clear underwater visibility".
1978	"small area visible in the channel landward of the reef flat south of Bolger Bay, more extensive areas were seen underwater off Young Bay and there were possibly small patches interspersed with sediment south-east of Cockle Bay".
1981	"dense seagrass growing in the channel landward of the reef flat south of Bolger Bay and seagrass patches growing extensively in the sediment on the reef flat seawards. Dense seagrass was also seen growing underwater off the north end of the reef, southward of Bolger Bay.
1985	"dense seagrass patches in the channel landward of the reef, north-west of Cockle Bay and on the northern end of the reef flat. Seagrass interspersed with sediment is also extensive on the reef flat north-west of the water pipeline which was installed between 1981 - 1985 (a marked contrast existed between the two sides of the pipeline, with no seagrass identifiable to the south-east). Some seagrass was growing above LWM in the fine sediment seaward of Young and Bolger Bays".

Unfortunately, the Hopley/Catt photographs of June 1988 showed very little of the southern reef flat area. However, seagrass patches were visible along low water mark in Young Bay and isolated patches were identifiable in the region on the northern end of the reef flat where Pringle identified "dense seagrass patches" in 1985. Comparing 1985 and 1988 photographs, these dense patches were smaller and more widespread in 1988.

The BPA aerial photographs from September 1991 showed seagrass cover over most of the reef flat but of a low density and patchy nature. (Figure 3). The dense cover identified by Pringle in the channels landward of the reef flat was not apparent in 1991 and there was no apparent difference in the cover of seagrass on the reef flat north and south of the water pipeline. The patchiness of seagrass at the northern end of the reef flat (noted by Pringle) was again

Figure 3 Seagrass Beds, Magnetic Island, September 1991



identifiable and seagrass was also visible growing in the sediment above low water mark adjacent to Bolger and Young Bays. No seagrass was visible underwater in any of the 1991 photographs, although fringing reef was visible underwater in the south.

3.2 Baseline Survey

3.2.1 Crocodile Creek to Cape Cleveland

Twenty-five sites were assessed for seagrasses along five main transect lines. Due to the turbid nature of the subtidal water in the aerial photographs, no clear indication of the approximate extent of seagrasses was available to base the transects on. The only available data was the results of the ground surveys conducted by the Queensland Department of Primary Industry (DPI) during October and November 1987 (Coles *et al* 1992). The DPI report identified a large wedge-shaped seagrass distribution running the length of the area from Cape Cleveland to Crocodile Creek.

The results of the ground-truthing surveys are provided in Table 1 and Figure 4. The distribution of seagrasses roughly approximated that determined by the DPI and showed that the nearshore margins had the greatest density of seagrass. The seagrass areas identified from the December 1992 aerial photographs were those along the intertidal zone and, judging from the results of the ground-truthing survey, were the most dense sections of the entire seagrass bed.

The extent of seagrasses in this region were substantial with most of the identified distribution containing an estimated 10-50% cover. The intertidal zone contained seagrass cover between 50% and 60%.

Table 1 Ground Truthing - Cape Cleveland

Site	Position	Depth (m)	Species	% cover	Comments
1	19°11.45' S 147°00.48' E	5	Ho ; Cs	20	patchy
2	19°11.23' S 147°00.30' E	5	nil	0	too far out
3	19°11.27' S 147°00.69' E	4	nil	0	close to beach
4	19°11.59' S 147°00.78' E	4	Ho ; Cs	30	Ho patchy
5	19°12.00' S 147°00.00' E	5	nil	0	too far out
6	19°12.05' S 147°00.52' E	3	Ho ; Cs	10	patchy
7	19°12.14' S 147°00.78' E	3	Ho ; Cs ; Hs	60	dugong feeding scars / *Halimeda sp.*
8	19°12.91' S 146°59.39' E	3	Cs ; Ho	10	outer edge of bed
9	19°13.23' S 146°59.22' E	4	nil	0	fine sand
10	19°13.50' S 147°00.13' E	2	Ho ; Cs	30	fine silt
11	19°14.32' S 146°58.52' E	3	Ho	5	sparse cover
12	19°14.23' S 146°57.91' E	3	nil	0	too far out
13	19°14.56' S 146°59.15' E	2	Ho ; Cs	10	fine sand
14	19°15.39' S 146°58.03' E	2.5	Ho ; Hu	30	mainly Ho
15	19°15.51' S 146°58.35' E	1.9	Ho ; Hu	30	patchy
16	19°15.53' S 146°58.32' E	1.9	Ho ; Hu	35	less patchy than site 15
17	19°15.73' S 146°58.61' E	1.9	Ho ; Hu	40	
18	19°15.73' S 146°58.87' E	1.1	Ho ; Hu	50-60	fouled by Cyanophytes
19	19°15.75' S 146°57.32' E	1.9	Ho ; Cs	10	
20	19°15.52' S 146°57.26' E	2.2	Hu ; Hs	<5	very sparse and patchy
21	19°15.41' S 146°56.99' E	2.5	Hu	<5	sparse
22	19°15.24' S 146°56.67' E	2.8	nil	0	fine sand/silt
23	19°15.30' S 146°56.80' E	2.8	nil	0	fine sand
24	19°15.77' S 146°56.74' E	2.6	nil	0	silt/mud
25	19°16.00' S 146°56.61' E	2.6	nil	0	mud

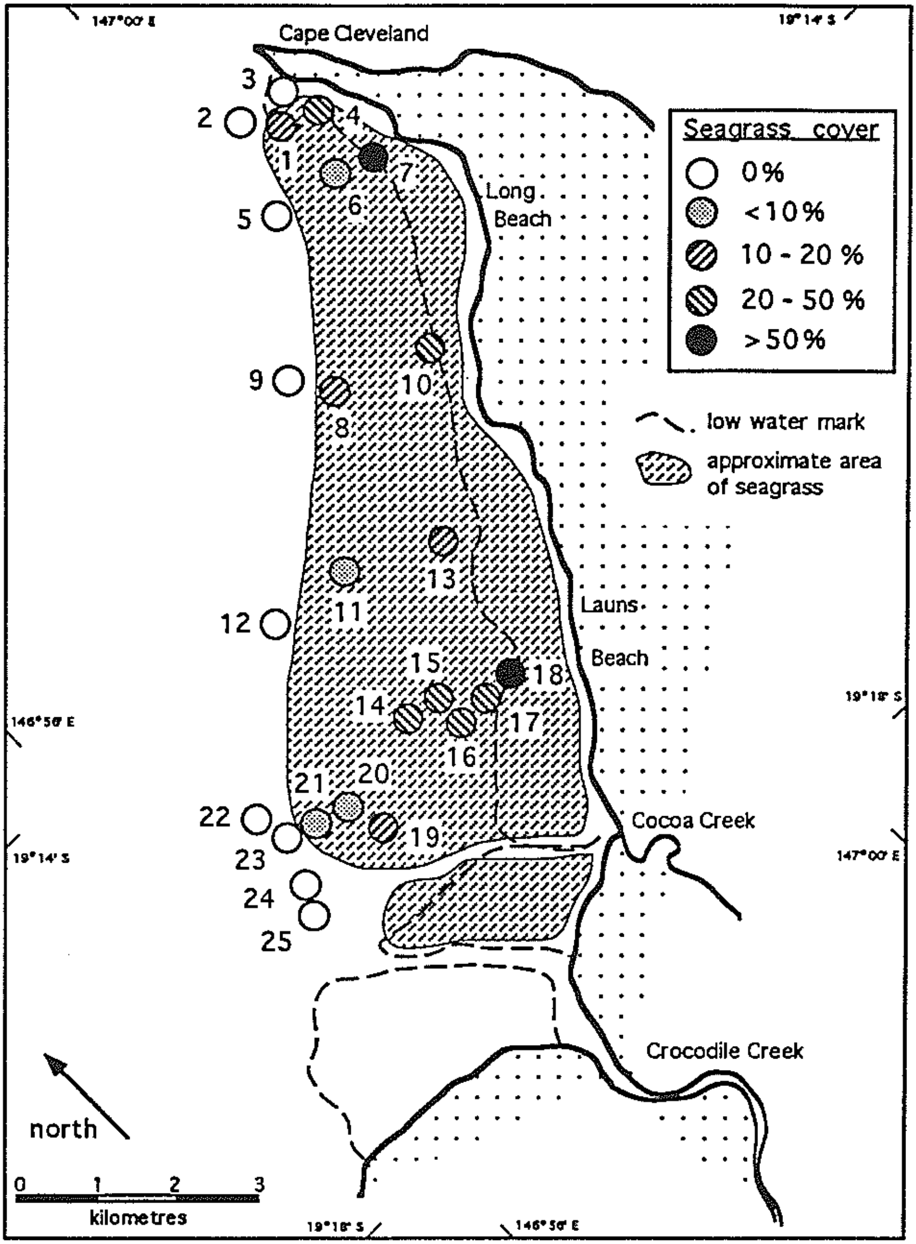
Ho = *Halophila ovalis* and *H.ovata*

Hs = *Halophila spinulosa*

Hu = *Halodule uninervis*

Cs = *Cymodocea serrulata*

Figure 4 Seagrass Distribution, Cape Cleveland, January 1993



The estimated area of seagrass cover in this region was approximately 2600 hectares.

Seagrass beds consisted largely of *Halophila ovalis* and *Cymodocea serrulata* although *Halodule uninervis* became more common toward the intertidal zone. *Cymodocea rotundata* was also occasionally observed but generally as scattered individuals. The seagrasses in the intertidal zone were heavily fouled with cyanophytes.

Many dugong feeding scars were observed, particularly in the areas closest to Cape Cleveland.

3.2.2 South-West Coast of Magnetic Island

The aerial photographs taken in December 1992 provided a good basis for ground-truthing surveys in this area. Nineteen sites were assessed for seagrasses and all of the seagrass areas identified on the aerial photographs were visited.

The results of the ground-truthing survey and the 1992 aerial photographs are provided in Table 2 and Figure 5. The coral reef flat was covered by patchy seagrass which was generally 40-60% cover. In the drainage channels that cross the reef flat, the seagrass was most dense and may have approached 80% cover. On the northern section of the reef flat very dense areas of seagrass were found in channels between areas of bare sediment. The seagrass extended from the edge of the reef flat shoreward to the edge of a band of very soft mud which borders the mangrove shore.

A large area of subtidal seagrass bed lay offshore from Bolger and Young Bays extending up into the intertidal zone of Young Bay and Bolger Bay but intersected by a sediment wedge from the mouth of Retreat Creek. This distribution generally agrees with the results of the DPI surveys in 1987 (Coles *et al*, 1992). The species composition of these seagrass beds was mainly *Halophila ovalis* and *Halodule uninervis* although small patches of *Cymodocea serrulata* were observed on the reef flat.

The estimated area of seagrass cover in this region was approximately 600 hectares.

3.3 Interim Aerial Survey

3.3.1 Crocodile Creek to Cape Cleveland

The March aerial photographs provided a much clearer indication of the seagrass distribution in the intertidal and upper subtidal region. The water, at the time of photography, was less turbid than during the initial aerial photography in December. Despite the clarity of the water, much of the subtidal zone was covered by water that was too deep to adequately photograph through and as such these areas provided no indication of seagrass distribution.

Seagrass distribution (where visible) appeared to be consistent with the ground truthing results described in the Baseline report. That is, a band of dense seagrass cover along the lower intertidal zone which generally decreased in density with increasing distance offshore (Figure 6).

The most recent photographs highlighted the patchy nature of seagrass distribution throughout the region with areas of seagrass amongst sediment bars that appeared to be covered with little or no seagrass. These sediment bars were described by Pringle (1989) from the 1981 and 1985 BPA photographs but were not visible due to turbid water in the 1991 BPA photographs and the photographs taken by Sinclair Knight in December 1992. These bare sediment bars were clearly a "natural" occurrence, not a result of the recent dredging operations.

Table 2 Ground Truthing - Magnetic Island

Site	Position	Depth (m)	Species	% cover	Comments
1	19°10.64' S 146°48.09' E	5.2	nil	nil	silt
2	19°10.15' S 146°47.67' E	3	nil	nil	sand/mud
3	19°10.00' S 146°47.82' E	0	Ho ; Cs	45	patchy distribution; some 80 % cover
4	19°09.79' S 146°47.67' E	0	Ho ; Cs	40	patchy distribution; some 80 % cover
5	19°10.03' S 146°48.00' E	0	Ho ; Cs	45	patchy distribution; some 80 % cover
6	19°10.21' S 146°48.06' E	0	Ho ; Cs	45	patchy distribution; some 80 % cover
7	19°10.39' S 146°48.40' E	0	Ho ; Cs	40	patchy distribution; some 80 % cover
8	19°09.82' S 146°47.27' E	3.1	nil	nil	fine mud
9	19°09.73' S 146°47.43' E	2	Ho ; Hu	40-50	fine mud
10	19°08.64' S 147°46.67' E	2.8	nil	nil	fine mud
11	19°08.66' S 146°47.00' E	2.7	Ho ; Hu	40	large plants
12	19°08.66' S 146°47.13' E	2	Ho ; Hu	40	smaller plants
13	19°08.42' S 146°47.06' E	1.8	Ho ; Hu	45	gritty mud; consistant cover
14	19°08.58' S 146°47.26' E	1.5	Ho ; Hu	45-50	closer to mangroves
15	19°09.20' S 146°47.00' E	5.3	nil	nil	fine silt along edge of channel
16	19°09.13' S 146°47.07' E	3.6	Ho	20	
17	19°19.01' S 146°47.25' E	2.4	Ho ; Hu	40	
18	19°08.95' S 146°47.35' E	1.9	Ho ; Hu	45	filamentous Cyanophytes
19	19°09.61' S 146°47.91' E	0	Ho ; Cs	70	within drainage channel

Ho = *Halophila ovalis* and *H.ovata*
Hu = *Halodule uninervis*
Hs = *Halophila spinulosa*
Cs = *Cymodocea serrulata*

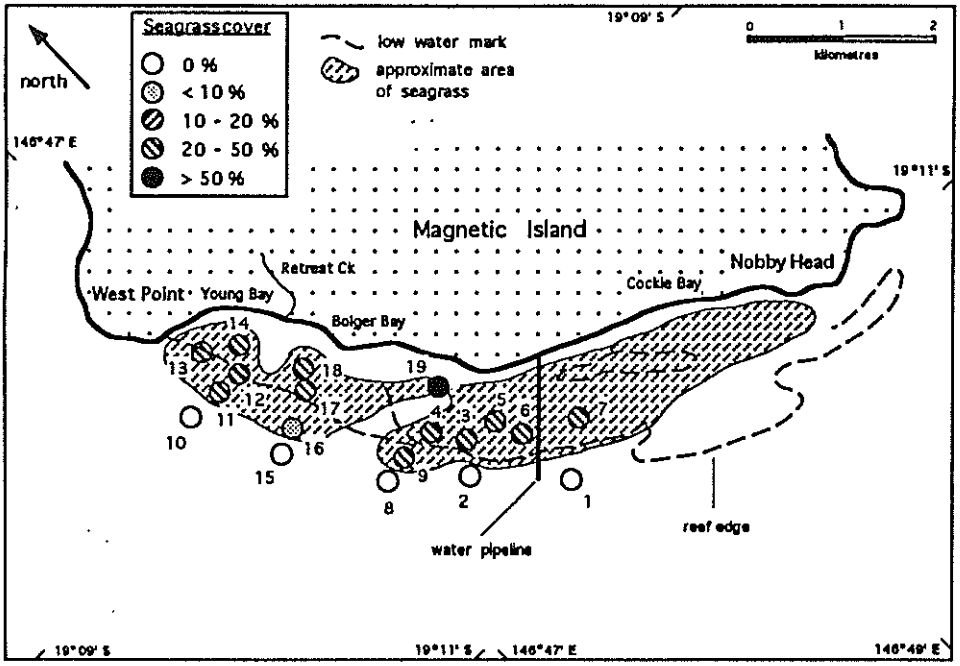
Possible seasonally-related changes in seagrass distribution (as described for Magnetic Island below) cannot be adequately addressed for this region as the poor visual quality of the baseline photographs prevents a clear picture of pre-summer patterns. However, it is assumed that the general trends of increasing seagrass distribution into the upper intertidal zones identified for Magnetic Island also apply for the Cape Cleveland region.

3.3.2 South-West Coast of Magnetic Island

As for the Cape Cleveland region described above, the most recent aerial photographs provide a clear indication of intertidal and upper subtidal seagrass distribution but, due to water depth, provided little indication of lower subtidal distribution.

A good comparison of aerial photographs before and during the dredging operations could be made for this area as the

Figure 5 Seagrass Distribution, Magnetic Island, January 1993



December photographs were reasonably clear. For ease of discussion, the entire region has been divided into three sub-sections:

- West Point to the east point of Bolger Bay;
- east point of Bolger Bay to the water pipeline;
- water pipeline to Nobby Head.

West Point to the East Point of Bolger Bay

Previous clear delineation between lower intertidal and upper intertidal seagrass cover was not as apparent in the most recent photographs. An increased seagrass cover spreading up towards the mangrove margins was apparent (Figure 7). The entire intertidal zone appeared to have an almost uniform cover of seagrass from the limit of visibility below LWM up to the level of the mangroves and sandy beaches.

Subtidal areas of seagrass which were clearly visible in the December photographs were less visible in the latest photographs, however, the general distribution patterns subtidally appeared to be consistent between the two aerial surveys.

The area along the seaward margin of the sediment wedge at the mouth of Retreat Creek, showed a greater cover of seagrass than previously, including patches of high density cover.

Generally, the seagrasses within this area appeared to have increased their distribution particularly into the upper intertidal zone.

East Point of Bolger Bay to the Water Pipeline

As in 3.3.2 above, the clear delineation of dense lower intertidal seagrass areas from sparsely covered upper intertidal areas was less apparent in the latest aerial photographs. Almost the entire intertidal zone in the northern section of the reef flat appeared to be covered by a relatively uniform seagrass distribution (see again Figure 7).

Some areas of dense seagrass cover identified from the December photographs, had increased in size with a general pattern of increase towards the upper intertidal zone. Some of these patches of dense cover had almost doubled in size since the December aerial survey. Some other areas of dense cover appeared to have decreased in density, thereby adding to the overall effect of a more uniform but greater, seagrass distribution pattern.

Water Pipeline to Nobby Head
This sub-section appeared to be largely unchanged in terms of seagrass distribution although upper intertidal areas exhibited slightly more seagrass cover than in earlier photographs (as described for the above two sub-sections).

3.4 Final (Post-Dredging) Survey

3.4.1 Aerial Photographic Interpretation - Cape Cleveland to Crocodile Creek

The May aerial photographs clearly showed the distribution of seagrass communities in the intertidal and upper subtidal areas along this coastline. (Figure 8). These photographs were taken at a tidal height of approximately 0.1 m AHD thus showing more intertidal seagrass than previously recorded in earlier photographs (which were taken at a tidal height of ~0.5 and 1.0 m AHD). Turbid water was less of a problem than with previous aerial photographs but the depth of water over the subtidal seagrass communities was still too great to permit photographic interpretation of subtidal areas. Hence, the need for the second ground survey of baseline sites.

Cape Cleveland Lighthouse to Red Rock Point
This area did not appear to show any changes in seagrass distribution or density. Seagrass was evident throughout the intertidal zone as a consistent mottling in the aerial photographs. Subtidal seagrass distribution was difficult to ascertain although some patches of seagrass were evident subtidally offshore from the rocky points immediately south from the lighthouse access beach. These seagrass communities represented the northern-most margin of seagrass distribution along this coastline.

Within Red Rock Bay, seagrass distribution was restricted to the lower intertidal and subtidal regions. A wide band of sparse or nil seagrass cover was evident throughout most of the bay.

Red Rock Point to White Rock Bay
The mid to lower intertidal region along this section of coast consisted of a good cover of seagrass amongst sand ridges that ran either parallel or obliquely to the coastline.

Large patches of very sparse or nil seagrass cover within this band of seagrass were evident in the March 1993 photographs. These bare patches had since been covered by seagrass to such an extent that many previously bare patches were not discernible from the surrounding seagrass community in the May 1993 photographs. The bare patches were not visible in the baseline aerial photographs of December 1992 due to turbid water. Therefore, it was not possible to determine whether these patches were a pre-dredging phenomena or appeared during dredging operations. In either case seagrass colonisation of these bare patches suggests that adverse conditions for seagrass growth in this area if they were present as a result of dredging operations and/or resuspension of dredge spoil from the offshore dump

Figure 6 Seagrass Distribution, Cape Cleveland, March 1993

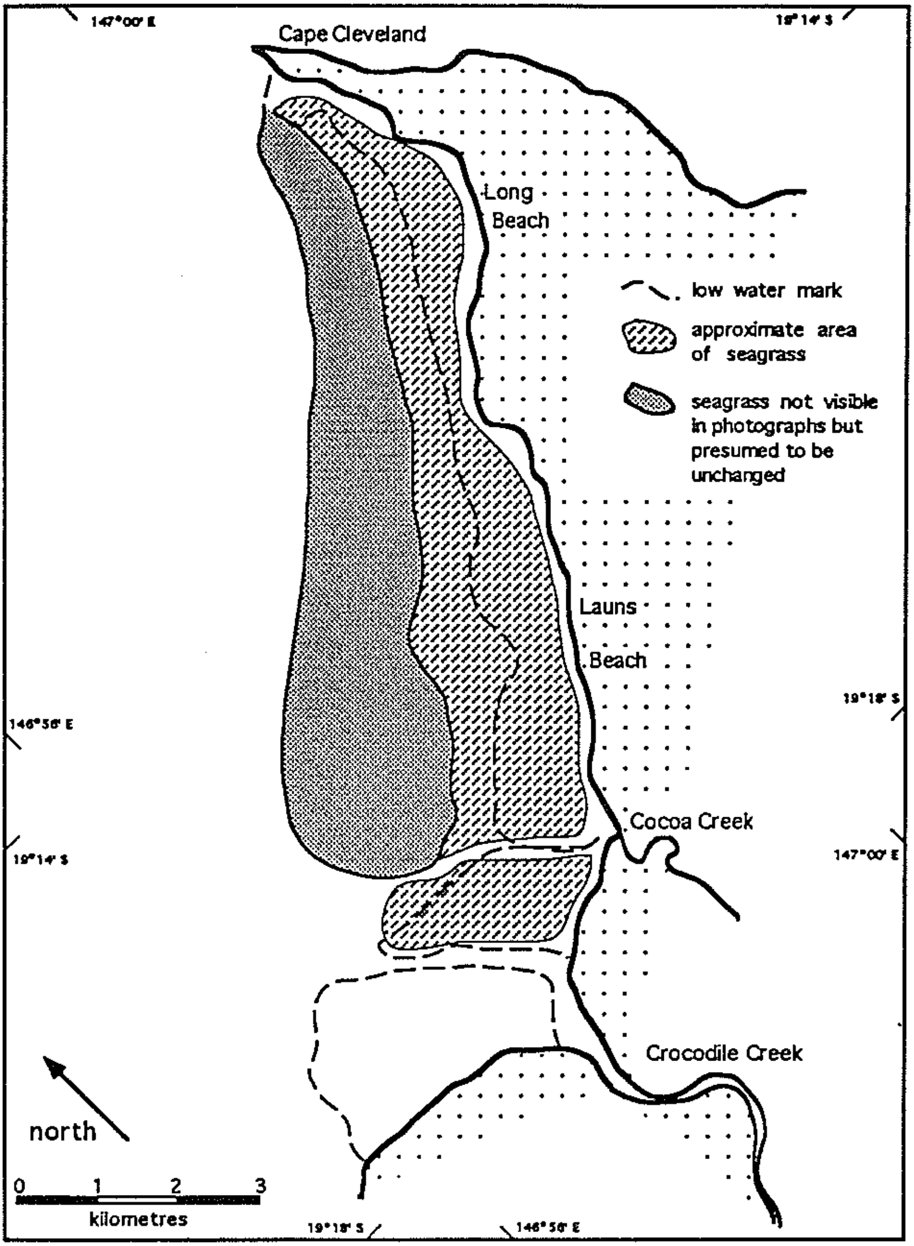
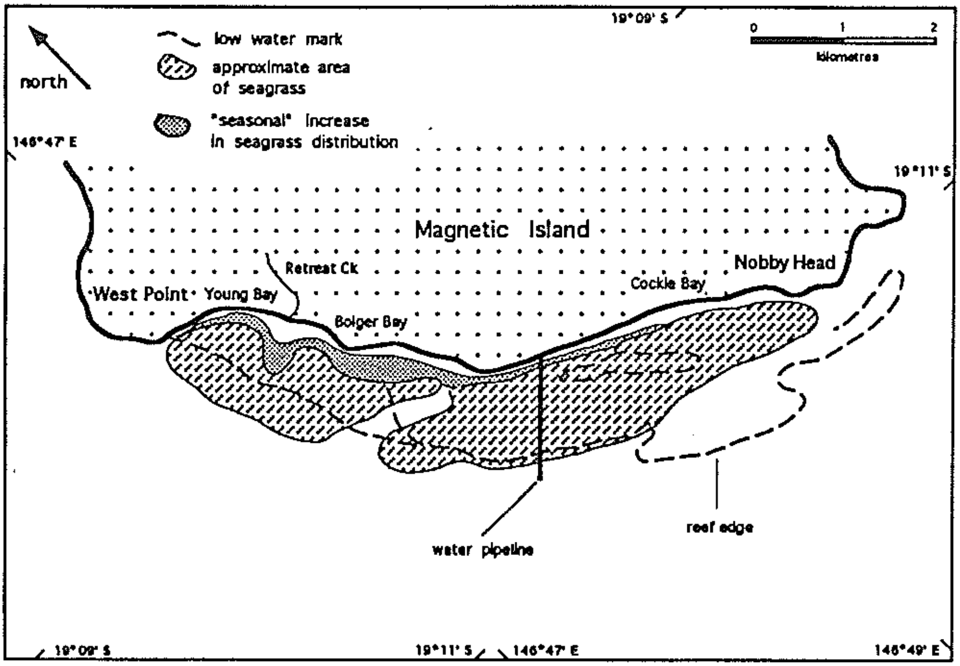


Figure 7 Seagrass Distribution, Magnetic Island, March 1993



ground, were not present at a sufficient level to halt a high rate of seagrass growth.
It is not possible to comment whether it was new growth from old rhizomes or new colonisations between March and May 1993.

Subtidal seagrass distribution was not discernible due to the limitations of aerial photography in areas of deeper water.

White Rock Bay to Cocoa Creek

The area of seagrass communities directly off Laun's Beach consisted of a dense band of seagrass in the intertidal zone amongst oblique sand ridges. These ridges appeared to be more pronounced in the latest aerial photographs although this may merely have been a result of different photographic quality, and/or time of day and shadow effect. These oblique sand ridges were described as a prominent feature by Pringle (1989) who noted their presence in aerial photographs from July 1981 and June 1985.

Seagrass growth was most prominent in the swales between the ridges but also covered many of the ridges. Further along the coast towards Cocoa Creek, the oblique sand ridges became more perpendicular to the shore and smaller in size. Seagrass cover was still very high in this area with no observable change in either distribution or density between March and May 1993.

Cocoa Creek to Crocodile Creek

The intertidal region between these two creeks appeared to be unchanged compared to earlier aerial photographs. Seagrass distribution was reasonably uniform across the intertidal area and presumably was similar in the subtidal areas although water clarity and depth prevented interpretation of aerial photographs. No obvious changes occurred between March and May.

Resurvey of Ground Truthing Sites - Cape Cleveland

The May resurvey of 11 selected sites that were originally assessed for seagrass cover in January 1993 prior to commencement of dredging operations, revealed that estimates of seagrass cover were largely similar (Table 3). At most sites, seagrass cover was estimated to be the same or within 5% of the cover recorded in January (refer Figure 8 Seagrass Beds, Cape Cleveland, May 1993). Given that percentage cover estimates were made by eye in both cases, it is clear that there is negligible change between most sites.

Three sites (#1, 17, 18) had seagrass estimates that were 10 to 20% less than their January equivalents. These variations may be a reflection of seasonal fluctuations and/or due to the patchy nature of the seagrass communities. It must be noted that the level of accuracy of GPS fixes (in the order of 30-50 metres) may result in slight variations in site relocations which, together with the patchy nature of many of the seagrass communities, may wrongly document changing patterns of seagrass cover. This may account for the apparent decrease in seagrass cover estimates at Site 1 where the distribution was patchy, however at Sites 17 and 18 seagrass cover was relatively uniform. At these two sites, the observed decrease in seagrass density must be related to some other factor. Of particular interest with respect to these sites is that there was no indication of an increase in sediment on or around the seagrass plants. Therefore, it is unlikely that the recorded decrease in seagrass cover is related to increased sedimentation resulting from dredging operations.

3.4.2 Aerial Photographic Interpretation - South-West Coast of Magnetic Island

As for the Cape Cleveland region discussed above, the May 1993 aerial photographs of the south-west coast of Magnetic Island between West Point and Nobby Head provide a good indication of seagrass distribution in the intertidal and upper subtidal areas (Figure 9).

The distribution of seagrass communities along this coastline had little changed from the March 1993 patterns. There were no obvious increases or decreases in the overall distribution although there may have been marginally less dense seagrass in some areas. In particular, the area adjacent to the water pipeline (both sides) appeared to have seagrass cover that was less dense than previously. However, it must be noted that this conclusion is based upon differences in colour shades on the aerial photography which may be an artefact of the photography rather than an actual change in the seagrass community, although infra-red photographs exhibited similar features suggesting observed changes were real.

Elsewhere, seagrass densities appeared unchanged with no evidence for large scale sediment settlement anywhere along this coastline.

Resurvey of Ground Truthing Sites - Magnetic Island

Four sites were resurveyed for seagrass changes and evidence of sedimentation (refer Figure 9). One site (#9) was unchanged, two sites (#13 and 18) Figure 8 exhibited a cover of seagrass greater than 20% more than originally recorded, and one site (#16) exhibited 15% less seagrass than previously (Table 3).

Table 3 Ground Truthing Sites - Resurvey

Cape Cleveland

Site	Depth(m)	Species	% cover	Baseline % cover	Comments
1	3.5	Hu ; Cs	5-10	20 (patchy)	patchy; rhizomes exposed no siltation evident
5	3	nil	0	0	bare, coarse sand *Halimeda* sp.
7	2	Hu ; Cs	60	60	heavily fouled with anenomes
10	2	Hu ; Cs	30	30	no sign of siltation healthy plants
11	3.5	Ho ; Hu	25	5	uniform cover
13	3	Ho ; Hu	30-35	10	no sign of siltation uniform, healthy cover
15	2.5	Hu ; Ho	25-30	30 (patchy)	no siltation/fouling dugong feeding scars
17	2	Hu ; Ho	25-30	40	uniform cover
18	1.5	Ho ; Hu	40-45	50-60	good cover; no siltation
21	2.5	Ho	5	<5	very patchy; largely bare
23	4	nil	0	0	fine silt/sand

Magnetic Island

9	1.5	Ho ; Hu	40	40-50	very patchy no sign of siltation
13	2.3	Ho ; Hu ; Cs	60-70	45	patchy but healthy and clean much *Caulerpa* sp.
16	4.5	Ho ; Hs	<5	20	very fine silt overlaying leaves sediment 0.5 m deep; no buried seagrass
18	1.9	Hu ; Hs ; Ho	90	45	very dense cover no siltation

Ho = *Halophila ovalis* and *H.ovata*
Hs = *Halophila spinulosa*
Hu = *Halodule uninervis*
Cs = *Cymodocea serrulata*

The patchy nature of the seagrass communities means that these variations in seagrass cover may merely be a reflection of slight differences in the actual locations surveyed each time. Therefore, of more importance than small differences in seagrass cover is the presence or absence of large scale sediment settlement on and around the seagrass plants.

Three of the four sites resurveyed exhibited no sign of sedimentation of the plants themselves nor recent accumulation of sediment around the plants. The one exception was site 16 which consisted of a very heavily sedimented environment (with very high water turbidity). At this site, sparse seagrass cover was evident on very soft sediment and the leaves of the plants were heavily silted. However, subsurface evidence for buried seagrass communities could not be found, even to a sediment depth of 50 cm. Therefore, it appears as if the site surveyed consisted of a "naturally" sedimented area with sparse seagrass colonisation rather than a seagrass community smothered by resuspended sediment. The conditions at this site were not similar to the conditions of water visibility and

Figure 8 Seagrass Beds, Cape Cleveland, May 1993

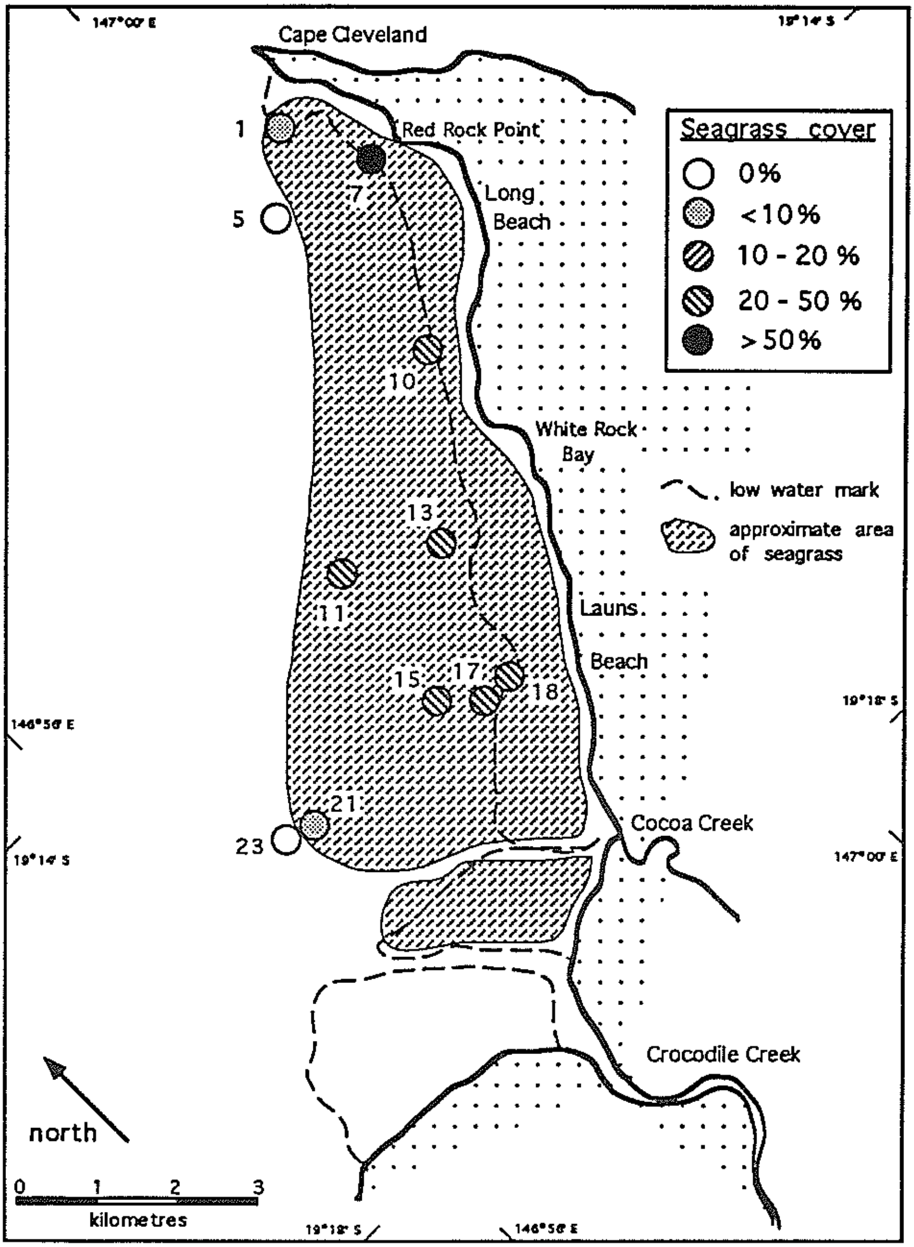
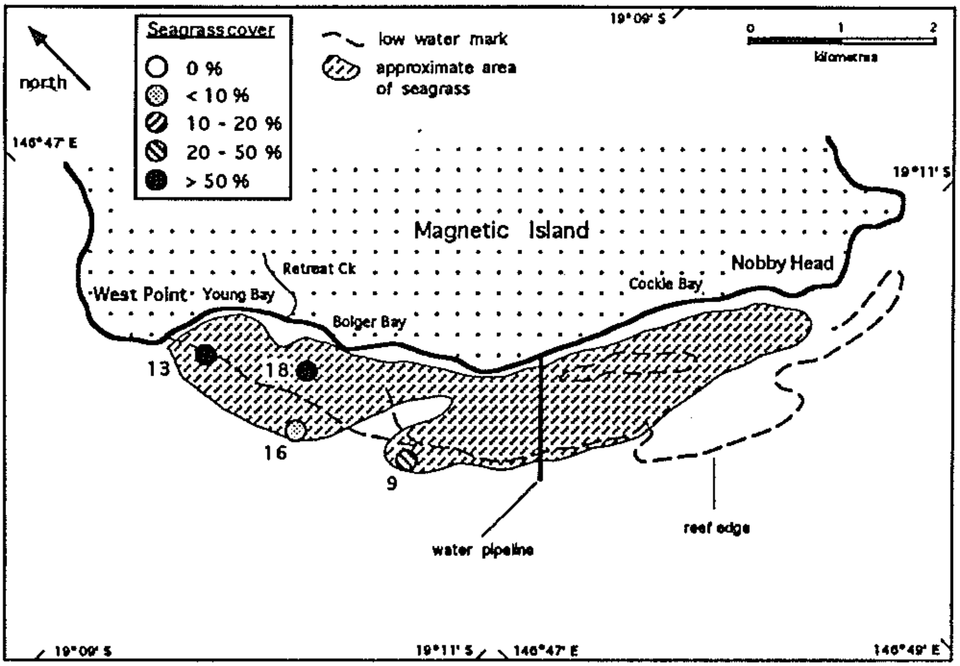


Figure 9 Seagrass Beds, Magnetic Island



substrate type found at Site 16 during the first ground truthing survey. Therefore, it appears as if the GPS fix was incorrect and Site 16 was not relocated.

4. DISCUSSION

4.1 Historical Review

Temporal Changes in Seagrass Distribution

Pringle (1989) concluded that "the overall sequence of change in seagrass cover in the Cleveland Bay and Magnetic Island area was from a moderate cover in 1959 and 1961, to almost none in 1974, followed by a steady increase in cover again from 1978 to 1985". She attributed the non-existence of seagrass in 1974 to a combined effect of a major dredging operation undertaken for the Port of Townsville in 1972 and extreme climatic conditions between 1971 and 1974, consisting of three tropical cyclones and long periods of heavy rainfall which created massive flooding and resulted in a huge input of fresh water and terrigenous sediment into the nearshore zone.

Pringle stated that as a result of the redistribution of fine sediment around Cleveland Bay "it is possible that much of the seagrass was buried or was so adversely affected by the high turbidity and/or high levels of freshwater that much of it died".

The steady increase in seagrass distribution since 1974 appears to have continued through to 1991 although difficulties in interpretation associated with possible seasonal fluctuations in seagrass cover must not be overlooked. Most of the aerial photographs were taken between late May and early September and should therefore show the general winter pattern of seagrass distribution. Coles *et al* (1992) noted that "seagrass beds between Cairns and Cape York, north of this region, has recorded marked seasonal decreases in seagrass biomass from summer to winter" and it is likely that seagrasses in Cleveland Bay also exhibit seasonal biomass changes. Difficulties arise when aerial photographs taken during the summer months are compared to these historical photographs and allowances for seasonal effects must feature highly in their interpretation.

The temporal variation in seagrass distribution is difficult to assess based on the available historical photographs. Clearly, the distribution of seagrasses has changed between each successive aerial survey and although periodic fluctuations cannot be identified from the thirty year photographic record, the apparent increase in seagrass cover since 1974 suggests that conditions in Cleveland Bay are currently well suited to growth of seagrass communities.

4.2 Monitoring Study

The aerial photographic survey of the major seagrass communities of Cleveland Bay conducted one month after dredging operations had ceased, revealed that very little change had occurred in the seagrass distribution and density throughout the dredging period.

Whilst some aspects of the methodology have proven difficult (adequate water penetration for photos in subtidal areas, relocating survey sites closely), the overall results of photo interpretation should be taken as indicative of a relatively stable seagrass community. Previous studies using a similar methodology have succeeded at detecting very large changes in seagrass distribution (Pringle 1989), and have suggested a possible link between dredging activities and seagrass mortality. Even amidst any ambiguity over small-scale effects, in this study, it is clear that there has been none of the substantial seagrass mortality previously attributed to dredging activities.

Seagrass distribution has remained largely static except for minor increases into the upper intertidal zone during the summer months (between December and March). Additionally, some small areas of sparse seagrass cover or bare sediment within the overall seagrass distribution pattern has exhibited increased seagrass growth between March and May. Areas of moderate to high seagrass cover adjacent to the water pipeline in Cockle Bay, Magnetic Island have exhibited a slight decrease in seagrass cover during the same period although this phenomena is very localised and does not suggest large scale smothering of seagrass plants by resuspended sediment.

Despite careful observations, no evidence for smothering of seagrass communities was found during ground surveys. All seagrasses, whether in areas of apparent density decreases or not, appeared healthy and free from adverse sedimentation.

The apparent fluctuations in seagrass distribution and/or density may be attributed to one or more factors. Firstly, variations in the clarity of aerial photographs and exposure levels resulted in difficulties in density interpretation based on degrees of shading in the photographs. In general, only broad distribution patterns and large scale density estimates were possible from the aerial photographs. These differences between photographs may have resulted in minor changes to seagrass communities being overlooked, or in artefacts of the photographic technique being wrongly attributed to actual variations in seagrass communities. Infra-red photography assisted in the determination of actual seagrass variation although the problems of clarity and exposure levels are also applicable.

Secondly, during ground surveys the subjective diver estimate of percent seagrass cover may has introduced a bias due to observer error. To limit the extent of this error, the same observer was used for both the initial baseline ground survey and the final resurvey events. Even so, slight variations would be expected from site to site, and would simply reflect the diver's ability to reclassify precisely on this subjective basis.

Thirdly, the study period extended through Summer and Autumn and hence the observations of seagrass changes may be related to seasonal growth periods. The widespread increase in seagrass distribution in the upper intertidal zone between December and March (Sinclair Knight, 1993b) is most likely a result of a seasonal growth episode.

Additionally, the patchy nature of many of the seagrass communities in the study area means that minor differences in the relocation of ground survey sites may influence the survey results. Minimisation of site location errors by using GPS fixes does not eliminate the problem since GPS accuracy is in the order of 30 - 50 metres. Seagrass densities and distribution patterns can vary extensively across areas of this scale, hence identifying apparent temporal changes in seagrasses that may not be real.

Finally, the observed changes in seagrass distribution and density may be related to environmental conditions. The most relevant environmental condition related to dredging and dredge spoil disposal is the potential increase in water turbidity due to resuspension of sediment and the subsequent smothering of seagrass communities as this sediment settles.

To effectively determine dredging related changes in the seagrass communities the seagrass must first be shown to have declined in either distribution or density.

Alternatively, impact status would be inferred from a different degree of change at control and impact sites. The latter approach is not possible in the present study, because there are no comparable seagrass beds in the Townsville region that are not potentially affected by dredging activities, and that might have served as adequate "control" sites for this study. In approving this study the TPA and Technical Advisory Committee made a conscious decision that the control impact methodology was of limited value given the remoteness of other comparable seagrass sites.

In this study, minor decreases in seagrass densities have been identified but with no decrease in distribution patterns.

Areas exhibiting decreases in seagrass distribution and/or seagrass density must also exhibit a corresponding increase in sedimentation. Increased sedimentation on and around the seagrass plants will occur as dredge spoil in suspension settles. Sedimentation on seagrass plants will result in a lowering of the photosynthetic ability thus resulting in declining seagrass health. No evidence for sedimentation on seagrass communities was found anywhere throughout the study area. Seagrass plants appeared healthy and free from sediment fouling at all stages of this monitoring program.

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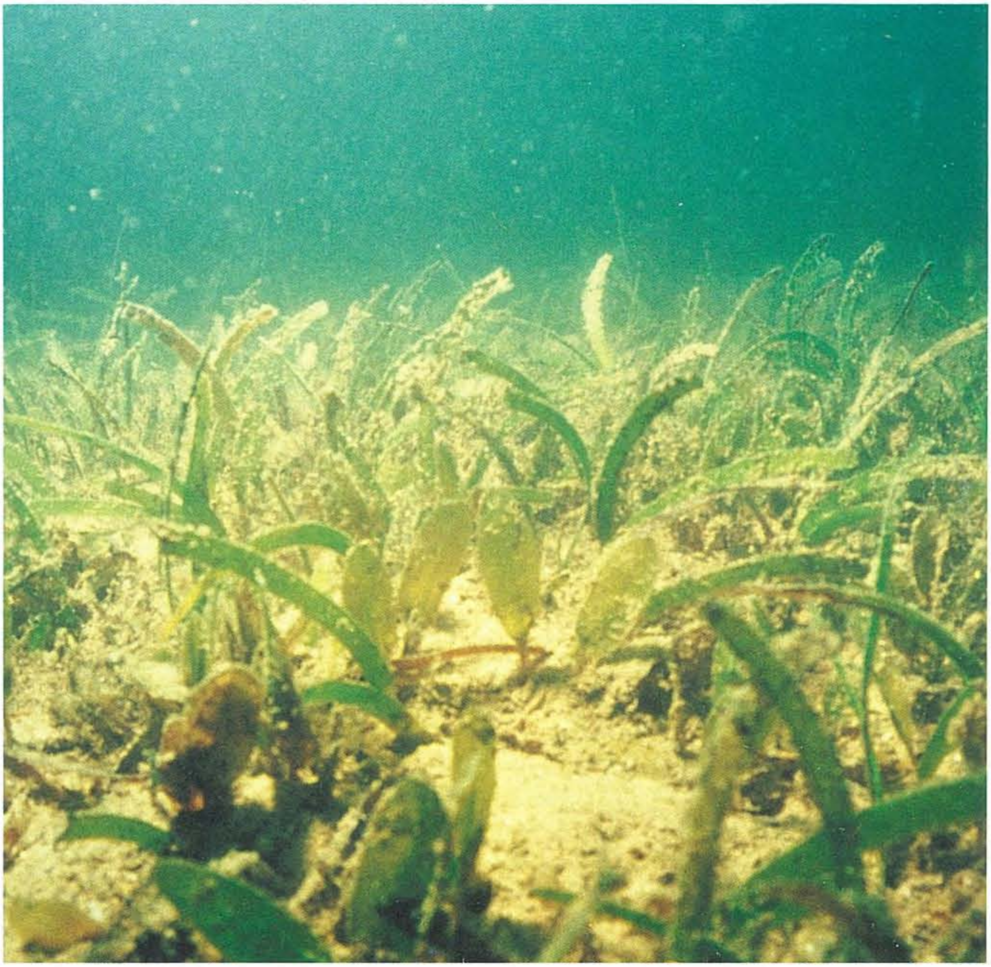
Plate IV - Seagrasses at one of the Cleveland Bay monitoring sites.



REMOTE IMAGERY

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1. INTRODUCTION

Port dredging has been a requirement of the shipping industry for many years. Given the dynamics of the coastal marine environment, the increase in industrial output and the subsequent increase in the size of transport vessels, channel maintenance by way of port dredging has become a routine task. For some Port Authorities, the task needs to be conducted annually or biennially.

The recent rapid growth of human settlements along the coastal zone has resulted in coastal ecosystems being removed, irrevocably damaged or seriously threatened. Consequently, in recent years there has been a conscious effort by national and international governments to preserve those coastal zone environments which have survived this rapid increase in growth.

Port Authorities have therefore implemented environmental monitoring programs co-incident with their dredging activities. Traditionally these monitoring programs are carried out using a spot-site sampling method and consequently they have been labour and equipment intensive.

The Townsville Port Authority conducted an environmental monitoring program to co-incide with channel dredging activities between January and May, 1993. Satellite image technology combined with aerial photography were used to significantly reduce the cost of the monitoring program and to provide a 100 percent sampling strategy.

2. METHODOLOGY

A two-tiered remote sensing approach was designed to allow the collection of local and regional images over the Townsville Port study site. These images were interpreted to extract information on the distribution of suspended sediments which was needed by project managers in their risk assessment decision making process.

The remote sensing design consisted of an "on-call" photographic record; a weekly photographic record of the local environment directly around the dredging event; and a monthly satellite image record of the regional environment encompassing the port and the bay.

Aerial photography was used to collect "on-call" and "quick delivery" local information at different path widths depending on the variable being monitored. The high versatility of having a small aircraft as a platform meant that photographic evidence of environmental disturbances could be acquired within an hours notice. A small aircraft and a photo developing laboratory were on stand-by throughout the monitoring period. The "on-call" demand was controlled by the project manager who requested photographs in response to environmental alerts from field workers. An environmental alert for example, may be when the field workers sight sediment laden waters approaching sensitive habitats.

A weekly photographic aerial record of the near-dredging environments was built into the monitoring program design to ensure a broad scale pictorial record was available. This strategy ensured that the sediment regime created by the dredging activities was assessed independently of relying on field worker alerts. A pre-determined flight path (Figure 1) was followed each week to allow the comparison of conditions at the same site. The flight path was designed to optimise information collection for sensitive environmental habitats.

Both the "on-call" and weekly aerial photographic records were assembled

Figure 1 The Standard Flight Path for the Weekly Aerial Photography Recordings

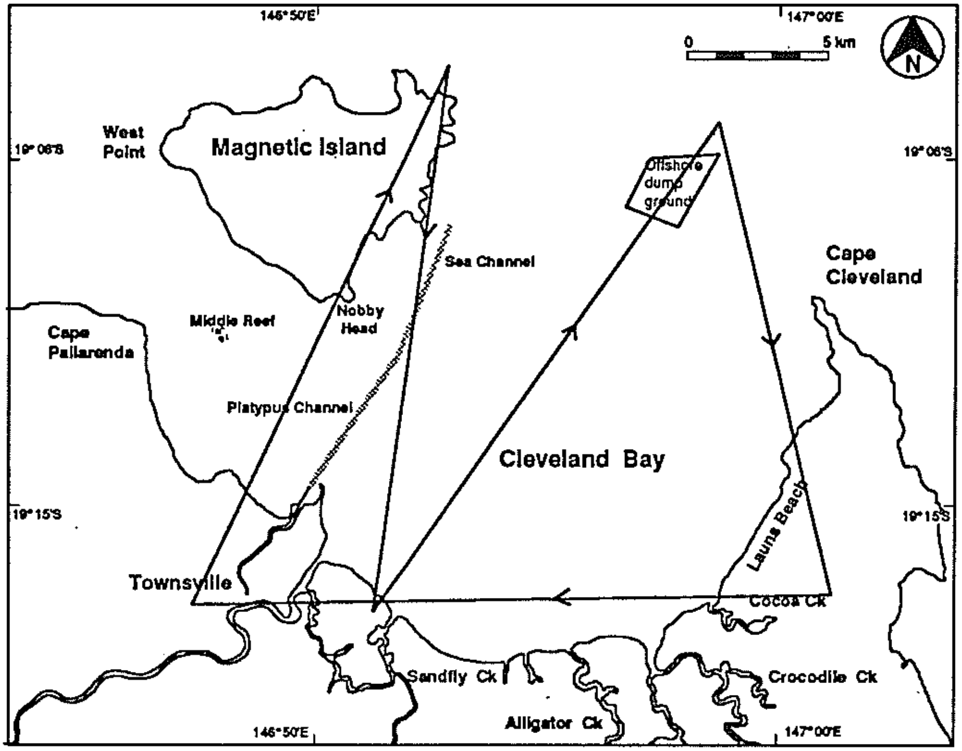
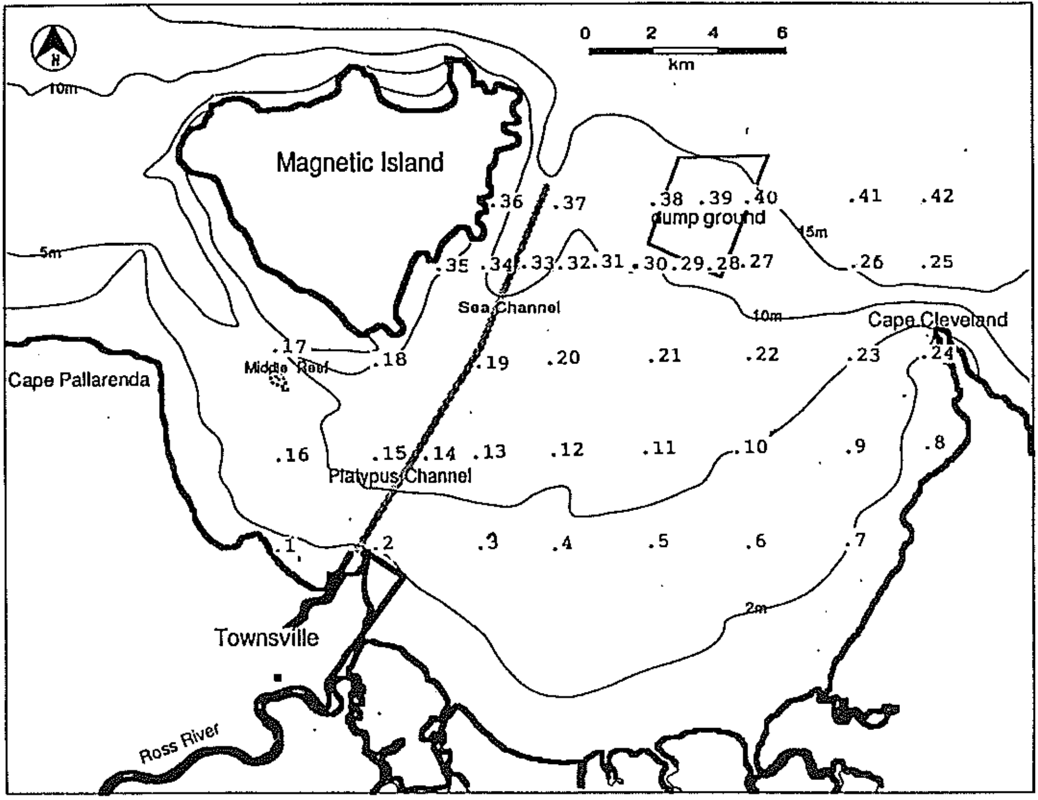


Figure 2 Forty-two Sample Sites Were Used in Attempts to Calibrate the Satellite Imagery for Suspended Sediments



into mosaics and qualitatively interpreted for sediment movements and characteristics within the local area of the dredging and dumping activity. A written report was then made available to the project manager.

It was also planned that satellite imagery be acquired on a monthly basis for the regional area including the waters around Cape Cleveland and Magnetic Island and all of Cleveland Bay. The purpose of using satellite imagery was to provide an assessment of the total Cleveland Bay environment and to quantify the sediment load. Both Landsat TM and SPOT HRV cloud-free imagery were available to the project.

An additional satellite image was acquired prior to commencement of dredging to use as a standard to establish the pre-dredging suspended sediment environment.

In order to calibrate the satellite imagery for suspended sediment load, field measurements of suspended sediments were acquired during the first overpass in January, 1993. The field measurement collection was the responsibility of Comarine Consulting. The suspended sediment data were collected following the sampling strategy diagrammed in Figure 2.

3. RESULTS

In response to field workers alerts, two "on-call" aerial photographic records of the eastern coastline of Magnetic Island were made. From the information provided by the aerial view, it was possible to conclude that sediment laden waters were not encroaching on the fringing coral reefs.

The weekly recording of aerial photographic information was perused for a period of six weeks following the commencement of dredging. During this time there were no adverse conditions recorded and the dredging activities were shown to be maintained within tolerable environmental limits.

Extensive efforts were made to calibrate the satellite image data for suspended sediment concentrations. This was done by attempting to correlate the range of satellite image values with the suspended sediment field data values, but unfortunately, no correlation could be found. The field data samples were not retained, so it was impossible to work back to find the source and rectify the problem. At this point, the project manager decided to abandon the use of satellite imagery as a monitoring tool. However, there were eighteen cloud-free images which were available for potential use during the dredging period. Though the calibration problem could not be identified this should not deter attempted use of this technique in future.

The satellite image that was obtained during the dredging allowed (28 February 1993 - Figure 3) the pattern and extent of the sediment plume to be mapped and the different load densities be qualitatively assessed.

4. DISCUSSION

Aerial surveillance allowed management personnel to obtain an overall visual assessment of near-surface sediment disposal in Cleveland Bay and the photographic mosaic provided an historical record of plume development. Satellite images give the same general result but in one frame. The unfortunate and unexplained lack of calibration of the satellite image with water samples should not deter use of the technique in future monitoring programs.

Figure 3 February 28 SPOT Satellite Image Clearly Shows the Sediment Plumes Associated with Dredging and the Off-shore Dump Ground

Plate V - Aerial photographic reconnaissance allowed virtually instantaneous · visual assessment of plume movements

OCEANOGRAPHIC DATA COLLECTION

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EXECUTIVE SUMMARY

Oceanographic data collection for the dredge monitoring was undertaken by WBM Oceanics Australia jointly with Comarine Consulting, James Cook University.

The oceanographic data collection program implemented as part of the dredge monitoring successfully provided comprehensive data to be used for both interpretation of the observed patterns of spoil behaviour and validation of hydrodynamic models. This component of the monitoring is aimed primarily to collate and present that data for use by others. Interpretation of the significance of these processes for spoil movement and utilisation for modelling are part of other related study components.

The dredging period extended over several months in the cyclone season which included relatively large spring tides. One cyclone (Oliver) affected the region, but remained some 500 kilometres offshore as it passed down the Queensland coast over the period 5th - 10th February, 1993.

Winds in the region were typically east to southeast ranging from 5-25 knots over the dredging period. Only one period of stronger winds to 30 knots at Davies Reef occurred around 10th January 1993. Typically, the seabreeze/land breeze effect shows up in the nearshore data as significant fluctuations in direction while the offshore directions are more consistent.

Significant wave heights in Cleveland Bay ranged generally from about 0.3 metres to 1.3 metres over the period. Waves at the offshore Cape Cleveland site were typically somewhat higher to about 1.75 metres.

The sea/swell component analysis showed a dominance of the local sea both during the dredging and in the longer term. Analysis results for the full year April 1992 - March 1993 are presented in the principal summary report (WBM Oceanics Australia 1993) and show swell heights ranging up to about 0.5 metres and very rarely dominating the sea. The influence of cyclone Oliver in February is evident in the form of an underlying swell of period about 10-12 seconds peaking to a height of about 0.7 metres in Cleveland Bay. This may have had a significant influence on spoil resuspension at that time.

Peak ebb and flood tide currents near the spoil ground range typically from about 0.2 m/s to 0.6 m/s. Current directions shift during the tidal cycle and are influenced by the wind. The data shows that the peak flows are predominantly at about 220° - 240° on the flood tide and 30° - 50° on the ebb. Typically, the mid-depth and near-bed flows were similar in direction, but with lower speed near the bed as would be expected.

Currents at Middle Reef and in the southern Bay area are also presented. These indicate a general dominance of the tide, particularly at Middle Reef, but with significant wind influence on directions, particularly in the shallower southern Bay area. Drogue and dye tracks are consistent with the current meter data, but indicate a slight net drift towards the east, consistent with the occurrence of light to moderate northerly winds at the time.

1. INTRODUCTION

Oceanographic data collection for the dredge monitoring was undertaken by WBM Oceanics Australia jointly with Comarine Consulting, James Cook University.

The objectives and deliverable outcomes of this work were targeted at understanding the nature and behaviour of the spoil plume movement and at providing a firm basis for numerical modelling of spoil and seabed sediment processes at the spoil ground. This included model boundary and other forcing data, tides, waves and currents to be used for validating the hydrodynamic model(s), establishing and confirming wave models and assessing conditions affecting the short and long term movement of dumped spoil.

The oceanographic data contract provided for the collection of the following physical and oceanographic variables for the Cleveland Bay region.

- ☐ tide levels;
- ☐ water currents (speed and direction);
- ☐ wave height and period;
- ☐ wind speed and direction; and
- ☐ barometric pressure.

Detailed data on these phenomena were accurately and reliably recorded for the project. This involved both deployment of special-purpose equipment where needed and sourcing of information from existing long term data acquisition systems. All data obtained is stored in digital time-series format supplied to the Townsville Port Authority and documented in summary report form (WBM Oceanics Australia 1993).

2. METHODS

2.1 Equipment Deployment

A deployment proposal describing the schedule for equipment installation associated with the oceanographic data collection contract was initially prepared and approved. The schedule lists the following equipment required for installation in January 1993, prior to the beginning of dredging:

- ☐ datawell wave recording buoy - spoil ground;
- ☐ interOcean S4 current meter - spoil ground;
- ☐ Aanderra WLR 5 tide gauge - John Brewer Reef.

The 'spoil ground' wave recording buoy and current meter were deployed on Tuesday January 5, 1993 (1500 - 1540 hrs) on separate moorings at a location 1.50 km south east of the active spoil ground area. The mooring location was not ideal in that it was not immediately at the spoil ground, but was chosen as the most suitable compromise to avoid hazard to the dredge and the equipment itself at the direction of the Townsville Harbourmaster and Townsville Port Authority consultants (Sinclair Knight). The mooring location (19° 10' 06.4"S, 146° 57' 38.1" E) has an approximate depth of water of 10.5m at low water datum, which is similar to that at the location originally selected for the mooring at the southern boundary of the spoil ground.

On Monday February 8, 1993, an additional three Inter Ocean S4 current meters were deployed at sites around Cleveland Bay, at the spoil ground (near bed - suspended from the same mooring described above), Middle Reef (19°12'08.05"S, 146°49'12.0"E) and in southern Cleveland Bay (19°09'35.0"S, 146°56'55.0"E). The location of instruments deployed in Cleveland Bay is illustrated in Figure 1.

Equipment already in place as part of longer term recording programs operated by other organisations and used in this project included:

- BPA Datawell wave recording buoy off Cape Cleveland;
- AIMS weather stations located at Davies Reef and Myrmidon Reef;
- BPA water level recorders at Cape Ferguson, Lucinda and Townsville;
- Townsville Port Authority wind recorder at the Port;
- Bureau of Meteorology weather stations at Townsville and Lucinda.

All equipment was subject to appropriate quality assurance and calibration checks. All field work was undertaken with properly accredited field staff (divers) and survey boats.

2.2 Data Collection Program

Oceanographic data collected during January, February, March and April 1993 covered the dredging period and includes:

Data from Existing Recording Systems:

- wave data for the Cape Cleveland recorder site;
- tidal data for Townsville, Lucinda and Cape Ferguson;
- wind data for Townsville Airport, Townsville Port Authority Tower, Davies Reef, and Lucinda; and
- atmospheric pressure recordings for Townsville Airport, Myrmidon Reef Davies Reef, and Lucinda.

Data from Deployed Equipment:

- current speed and direction measured near the spoil ground at Site 1 (mid-depth, and near-bed), Middle Reef, and southern Cleveland Bay;
- waves measured near the spoil ground (Site 1);
- tide levels recorded at John Brewer Reef; and
- tide levels recorded at Site 1 near the spoil ground.

2.3 Other Measurements

- drogue tracking over a period of 36 hours from the spoil ground in Cleveland Bay;
- dye plume dispersion measurements at the spoil ground in Cleveland Bay.

2.4 Data Retrieval

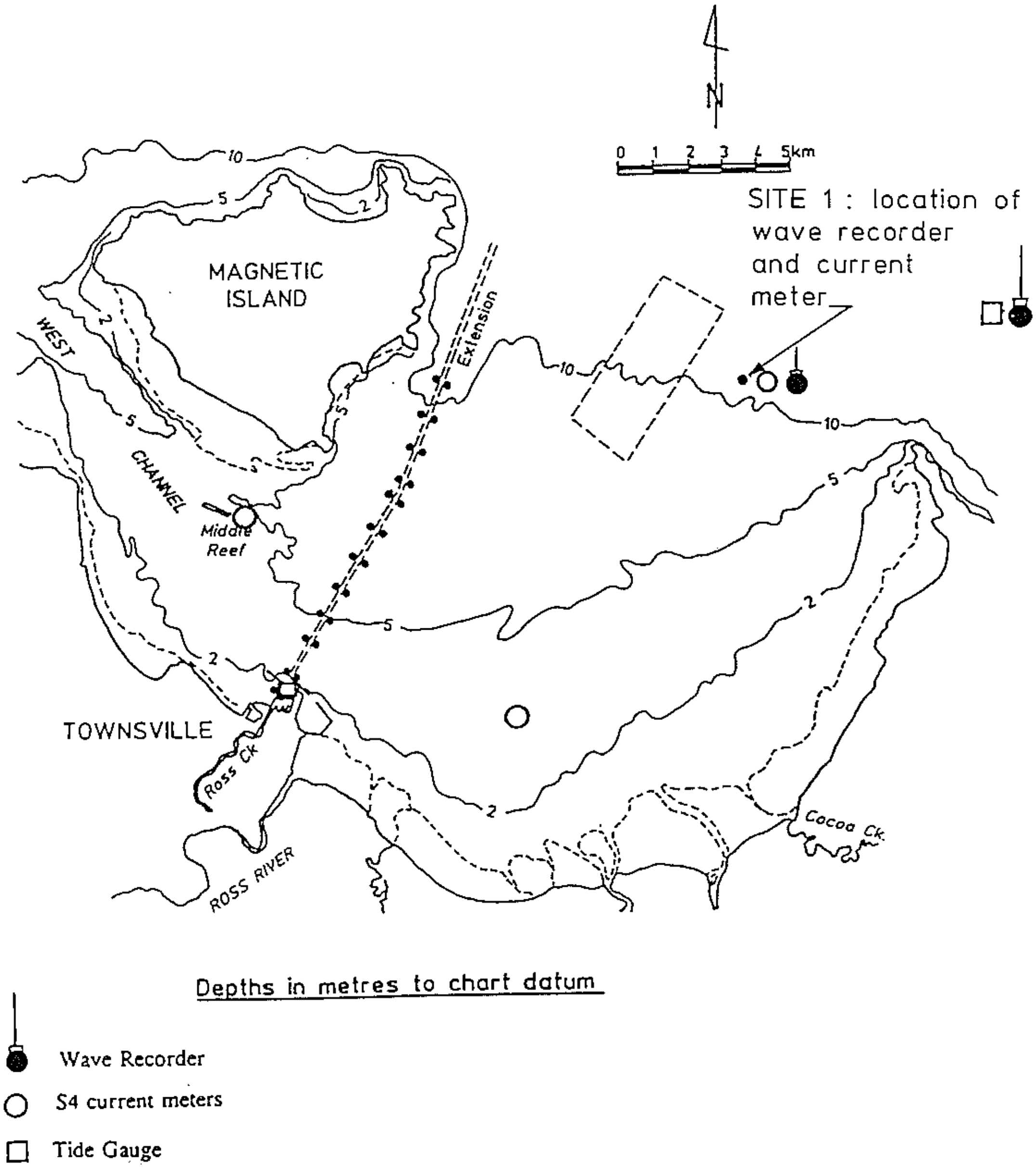
The following data was obtained directly in digital format as either downloaded from the recording equipment or output from primary analysis computer programs:

- wave data including both spectral ordinates and parameter results for Cape Cleveland and the spoil ground;
- current speed and direction components at the spoil ground (mid-depth and near bed), Middle Reef and southern Cleveland Bay;
- tidal data from Townsville, Lucinda and Cape Cleveland, being water surface levels from a stilling well recorded;
- tidal data from John Brewer Reef and Cape Cleveland, being sub-surface pressure data;
- wind speed and direction from Davies Reef and Cleveland Bay; and
- atmospheric pressure data from Davies Reef.

The following data was obtained in either chart or manually recorded format:

- atmospheric pressure at Lucinda and Townsville; and

Figure 1 Instrument Deployment in Cleveland Bay



☐ wind speed and direction at Townsville Airport and at Lucinda.

All data was stored on computer at the office of WBM Oceanics Australia, Brisbane. Where necessary, chart format data was digitised and manual recordings keyed in to computer files.

All data was checked in both its tabulated form and as time series plots in order to identify any lost or anomalous recordings. Some data losses occurred as follows:

☐ frequent record losses from the Cape Cleveland wave recorder were caused by interference associated with transmissions from a tide recorder operated by the dredging contractor. This problem continued throughout the deployment period and would have required complete shut down of the tide recorder to prevent interference. After discussions in February, the dredging contractor agreed to minimise transmissions, so as to limit data losses from the recorder; and

☐ the wind and barometric pressure recorder at Davies Reef failed during February. Data from Myrmidon Reef was substituted for this period to represent offshore wind and barometric pressure conditions.

2.5 Data Analyses

Data from each of the recording devices was stored on computer files and processed as required to common user parameters. Data listings of those parameters are also stored on computer files, tabulated and plotted graphically for use in validation and interpretation.

The data sets acquired and the processing undertaken are outlined below.

2.5.1 Waves

Hourly wave data from both the Cape Cleveland and spoil ground recorders was obtained in the form of:

☐ primary analysis results of the key wave parameters derived from both the time domain and the spectral analyses; and

☐ individual wave spectra.

The primary analysis results were stored on computer files and plotted.

The spectral wave data was analysed in terms of component "sea" and "swell" wave trains. Locally generated sea waves are generated within the immediate region of Townsville. Swell waves are generated outside the local region and propagate to the site over longer distances from either within the Great Barrier Reef lagoon waters or the deep ocean beyond the continental shelf.

Sea waves are typically steep, with a height to length ratio in the range of 0.025 to 0.05 depending on their state of development or decay. Swell waves are of low height relative to their length.

The recorded data shows wave periods (spectral peak period Tp) are spread over a range from 2.5 to 10 seconds, with distinct sea and swell populations. There is a cut-off at around 6.5 seconds which typically separates the locally generated wave population from the swell. Sea waves may have higher period when they exceed about 2.0 m height.

A computer analysis procedure was developed, incorporating some smoothing of the spectra together with identification of individual sea and swell peak frequencies (f_p) and the energy density (M_o) within each of the sea and swell parts of the spectra. The spectral peak period (T_p) for each component is given as the inverse of f_p, while the component significant wave heights are derived as:

$$H_s = 4\sqrt{M_o}$$

The total significant wave height resulting from the coexisting sea and swell corresponds to the total energy density for the whole spectrum, and can be expressed as:

$$H^2_{s\ TOTAL} = H^2_{s\ SEA} + H^2_{s\ SWELL}$$

The key steps in the procedure to isolate the sea and swell components from the spectra involved:

- identification of the primary wave train corresponding to the spectral peak as sea or swell, based on both wave steepness and period criteria appropriate to the site;
- estimation of the primary wave train spectral shape, based on the Pierson-Moskowitz spectrum modified to best fit the recorded spectrum for each record;
- determination of the secondary wave train spectrum by subtraction of the total spectrum; and
- determination of the component sea and swell significant wave heights and spectral peak periods for each record.

This form of analysis was undertaken for both the dredge period data and for a whole year for Cape Cleveland data. This provides a basis for comparison of the conditions with those occurring over the longer term.

2.5.2 Tide Levels

Data on tides was obtained from a range of recorders. The existing Department of Environment and Heritage (DEH) gauges trace the movement of the water surface to an established datum (Townsville, Lucinda, Cape Ferguson). The John Brewer Reef and Cape Cleveland recorders record the pressure of the water column plus atmospheric pressure.

All pressure tide data has been analysed to compensate for atmospheric pressure changes to produce compatible results in the form of water surface recordings based on measured water salinity temperature and meteorological data.

2.5.3 Currents

The S4 current meters were located at mid-depth and one metre above the bed at Site 1 near the spoil ground and at Middle Reef and South Cleveland Bay.

Due to a failure in the S4 current meter at Middle Reef during February, additional data was collected from this station as well as from South Cleveland Bay and the spoil ground through March and into early April to satisfy contractual requirements for data collection.

The downloaded current data was in the form of east-west and north-south current components. These were processed via the standard WBM Oceanics Australia computer analysis system to provide files of current speed and direction.

The data from each instrument was recorded at 6 minute (0.1 hour) intervals, each recording being half-second samples averaged over one minute. The directions as recorded were relative to magnetic north. Those directions plotted herein are relative to true north.

2.5.4 Wind

Wind data for the onshore, nearshore and offshore sites at Lucinda, Townsville Airport, Townsville Port Authority Tower, Davies Reef and Myrmidon Reef were acquired, stored and presented as speed and direction vector components.

Available wind data was processed to calculate percentage wind occurrence of wind speed and direction. The analysis has been done on a site-by-site and month-to-month basis, except for data collected from Davies Reef during February due to instrument failure. Data for that period has been assessed in terms of each sub-period of February. The results of these analyses are presented in the principal data summary report (WBM Oceanics Australia 1993).

2.6 Drogue Tracking and Dye Release

Three current drogues were deployed at slack water (low tide) at 0500 hrs from a location near to the south-east corner of the spoil ground. The drogues were deployed with an initial spatial separation of approximately 80 - 100m. The location of each of the drogues was routinely fixed by GPS receiver at half hourly to hourly intervals over the next 36 hours.

In combination with the drogue tracking exercise, a dye release and tracking program was also undertaken. This commenced at the central drogue location at approximately 0730hrs on Wednesday 10/2/93 and coincided with the peak of the spring tide flood velocity. The behaviour of the dye plume was monitored for several hours using fluorometric dye tracing equipment operated from a survey vessel. Aerial photography of the dye plume was also undertaken by officers of the Department of Environment and Heritage.

The results yielded direct data on the dispersion, diffusion and advection processes of flows at the spoil ground for the given tidal and climatic conditions which prevailed at the time.

Drogue locations were recorded using a 3 channel TRIMBLE Pathfinder Basic GPS which generally provided a position fixing accuracy of better than ± 30m.

Concentrations of Rhodamine B dye were determined in the field using a TURNER DESIGNS Model 10-005 field fluorometer. This instrument measures the quantity of light emitted from excitation of a fluorescent dye on a relative scale. The use of an appropriate light source and filter in the instrument enabled Rhodamine B dye to be detected in concentrations as low as 1.0 part per billion.

Following its release the dye plume was allowed to propagate, without disturbance from boat propulsion, for a period of 20 minutes. After this time, the plume was intersected by a series of measurement transects. The transects followed the progression of the visible centroid of the dye plume with the flooding tide. Measurement transects were conducted at 2 depths (1 m) and (3 m) through the plume.

3. RESULTS

Results of the wave recording and sea/swell analyses are presented as time series of heights and periods for sea and swell in Figure 2.

The results indicate that both sea and swell commonly coexist, while the local sea waves dominate most of the time. The longer period swell reached about 0.7 metres in height and up to 12 seconds period during early February when cyclone 'Oliver' passed down the Queensland coast some 500 kilometres offshore. Figure 3 illustrates the percentage exceedence for sea and swell waves.

Water level variations at Lucinda, Cape Cleveland, Townsville, Cape Ferguson and John Brewer Reef for the study period are shown in Figure 4.

Figure 2 Sea and Swell Wave Data. January - March 1993

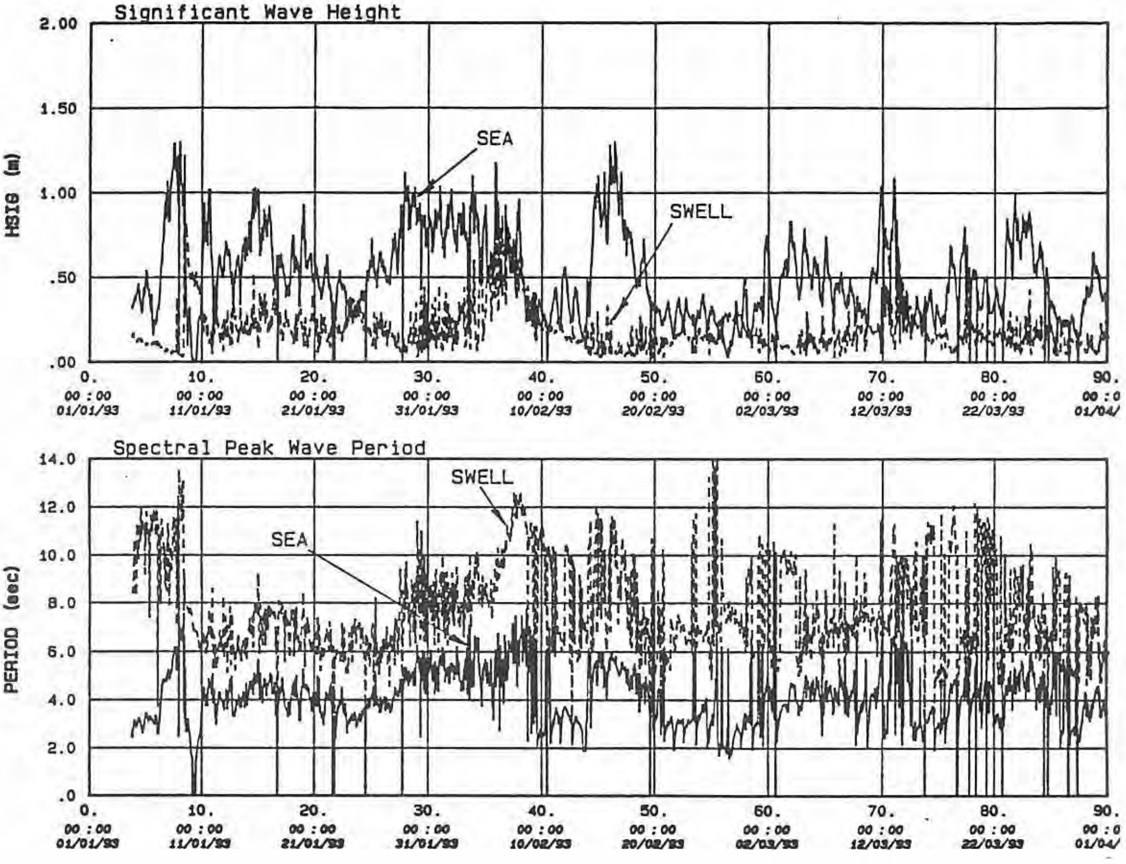


Figure 3 Sea and Swell Percentage Exceedance Cape Cleveland

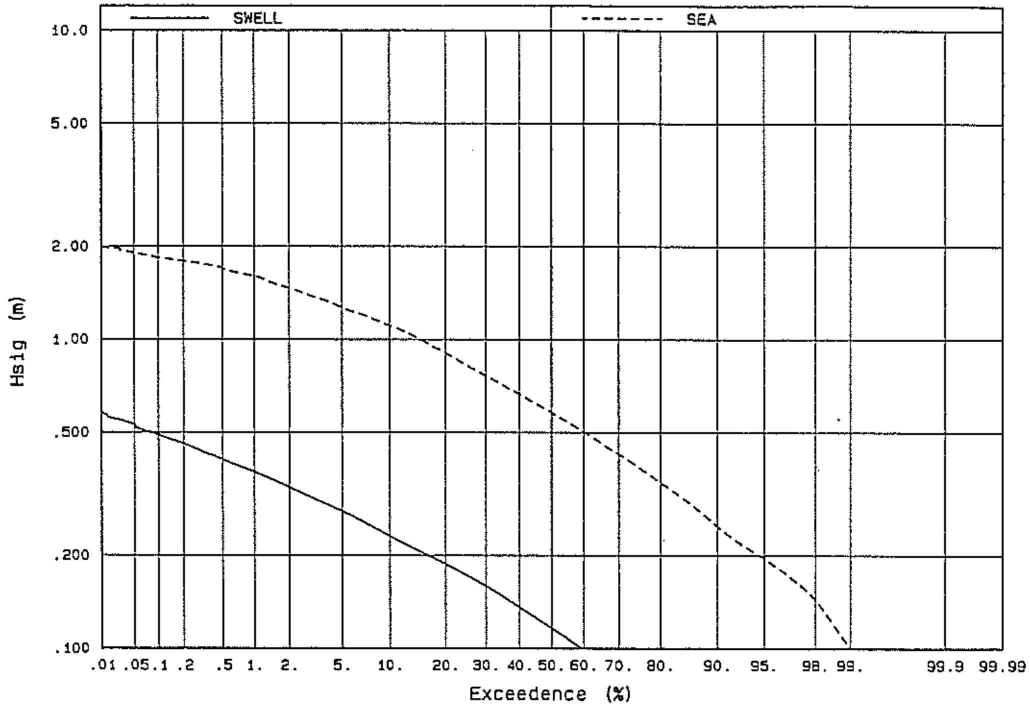
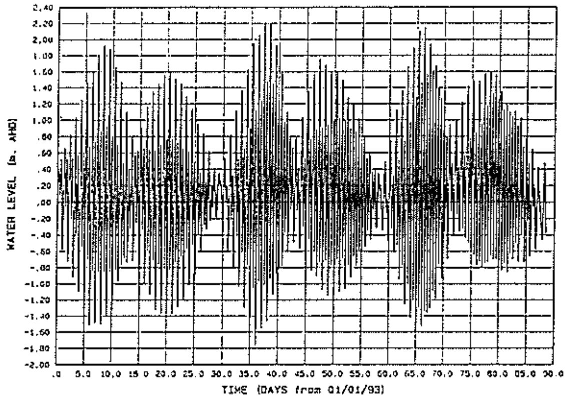
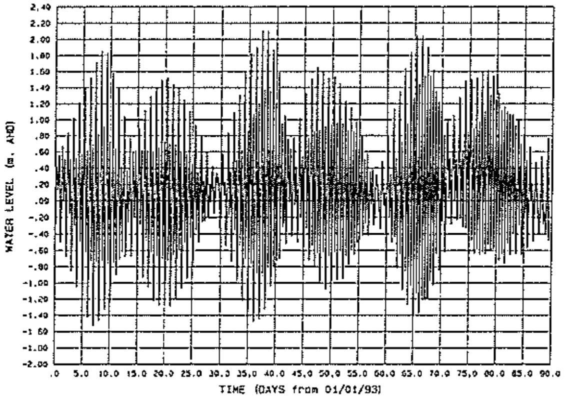


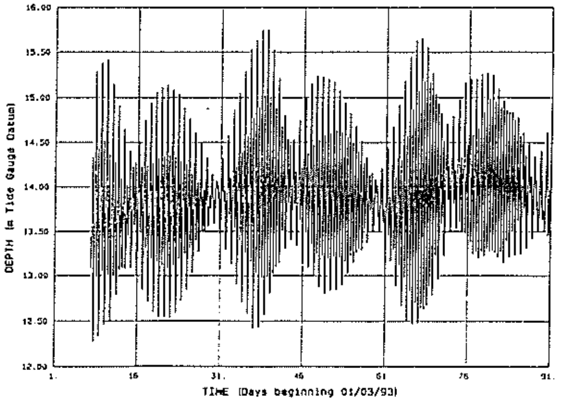
Figure 4 Tide Levels, January - March 1993



TOWNSVILLE



CAPE FERGUSON



JOHN BREWER REEF

The currents recorded at the spoil ground are illustrated on Figures 5a, b and c. Currents for each of the principal recorders are shown as plots of speed and direction for the deployment period in Figure 6.

The wind data collected at Cleveland Bay and Offshore is shown on Figures 7a, b and c. The results of the drogue tracking measurement are illustrated in Figure 8. Dye dispersion patterns in terms of transect concentrations and peak concentration change with time are shown in Figure 9.

4.DISCUSSION

4.1 General

The oceanographic data collection program implemented as part of the dredge monitoring successfully provided comprehensive data to be used for both interpretation of the observed patterns of spoil behaviour and validation of hydrodynamic models. This component of the monitoring is aimed primarily to collate and present that data for use by others. Interpretation of the significance of these processes for spoil movement and utilisation for modelling are part of other related study components.

The general nature of these oceanographic data and any notable features potentially affecting dredge spoil movement are discussed briefly below.

4.2 Discussion of Data

The dredging period extended over several months in the cyclone season which included relatively large spring tides. One cyclone (Oliver) affected the region, but remained some 500 kilometres offshore as it passed down the Queensland coast over the period 5th - 10th February, 1993.

Winds in the region were typically east to southeast ranging from 5-25 knots over the dredging period. Only one period of stronger winds to 30 knots at Davies Reef occurred around 10th January 1993. Typically, the seabreeze/land breeze effect shows up in the nearshore data as significant fluctuations in direction while the offshore directions are more consistent.

Significant wave heights in Cleveland Bay ranged generally from about 0.3 metres to 1.3 metres over the period. Waves at the offshore Cape Cleveland site were typically somewhat higher to about 1.75 metres.

The sea/swell component analysis showed a dominance of the local sea both during the dredging and in the longer term. Analysis results for the full year April 1992 - March 1993 are presented in the principal summary report (WBM Oceanics Australia 1993) and show swell heights ranging up to about 0.5 metres and very rarely dominating the sea. The influence of cyclone Oliver in February is evident in the form of an underlying swell of period about 10-12 seconds peaking to a height of about 0.7 metres in Cleveland Bay. This may have had a significant influence on spoil resuspension at that time.

Peak ebb and flood tide currents near the spoil ground range typically from about 0.2 m/s to 0.6 m/s. Current directions shift during the tidal cycle and are influenced by the wind. The data shows that the peak flows are predominantly at about 220° - 240° on the flood tide and 30° - 50° on the ebb. Typically, the mid-depth and near-bed flows were similar in direction, but with lower speed near the bed as would be expected.

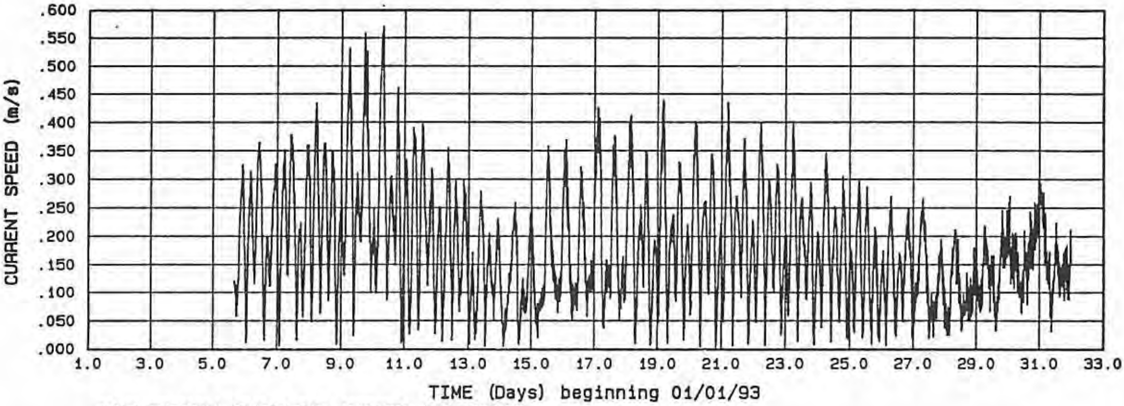
Currents at Middle Reef and in the southern Bay area are also presented. These indicate a general dominance of the tide, particularly at Middle Reef, but with significant wind influence on directions, particularly in the shallower southern Bay area.

Drogue and dye tracks are consistent with the current meter data, but indicate a slight net drift towards the east, consistent with the occurrence of light to moderate northerly winds at the time.

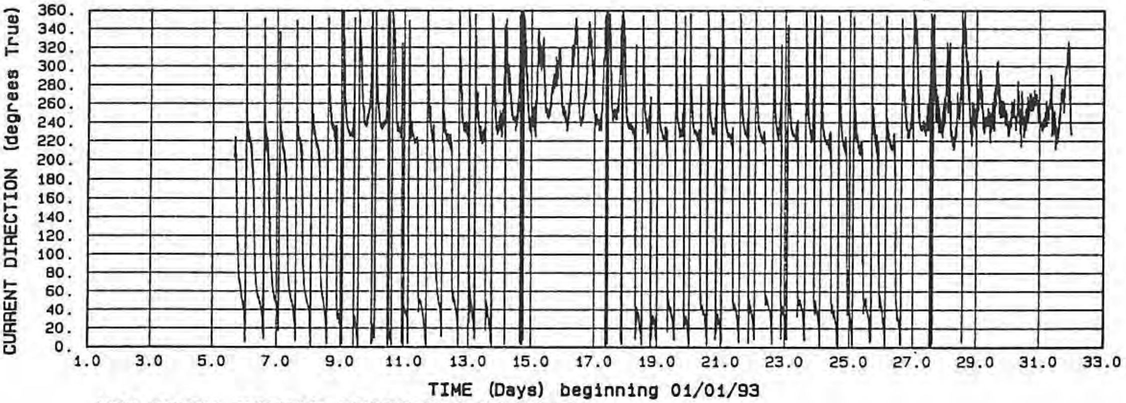
5. REFERENCES

WBM Oceanics Australia (1993) Contract No. 62376-12, Oceanographic Data - Final Report. Report for the Townsville Port Authority.

Figure 5a Spoil Ground Currents, January 1993

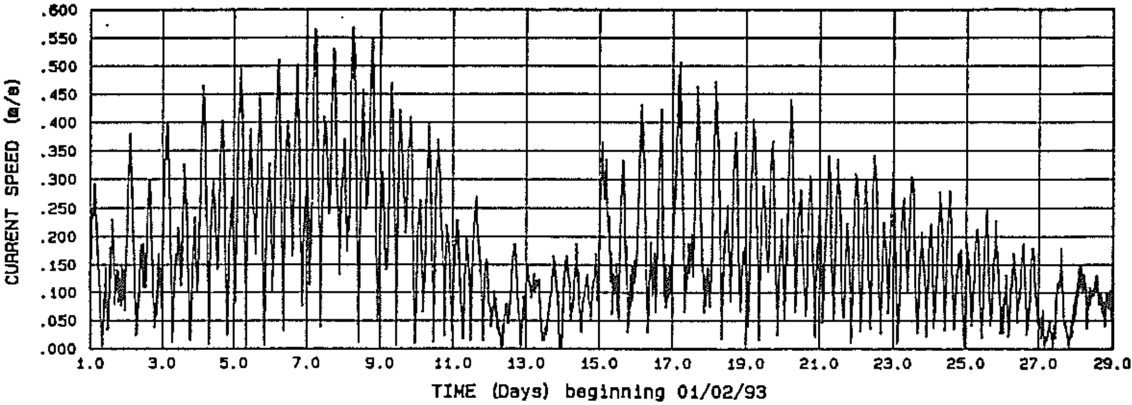


MID DEPTH CURRENT SPEED VS TIME

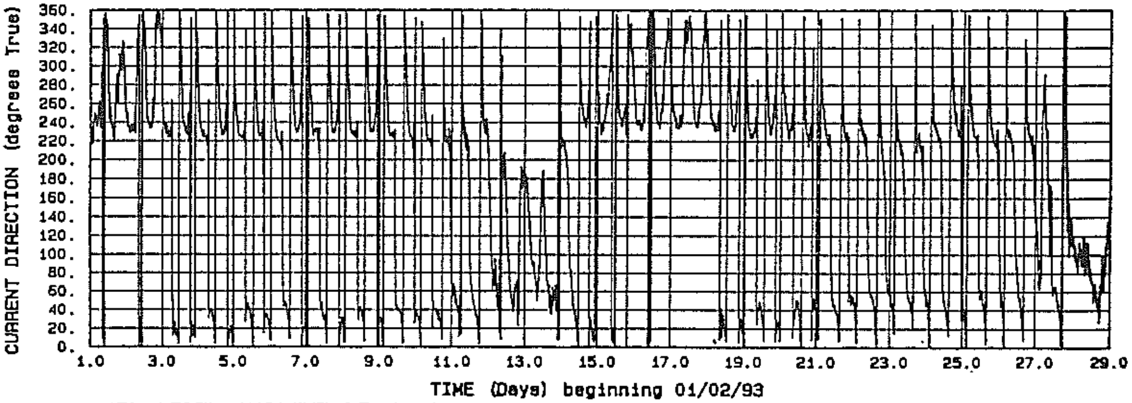


MID DEPTH CURRENT DIRECTION VS TIME

Figure 5b Spoil Ground Currents, February 1993

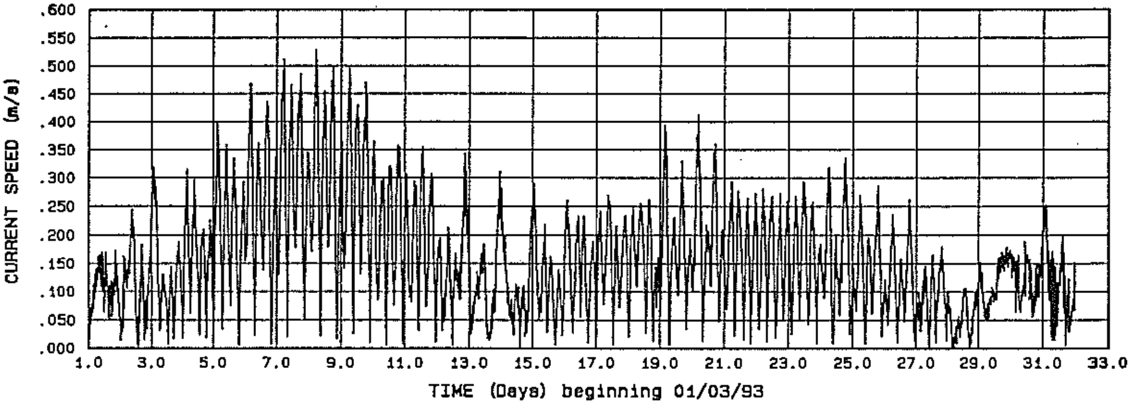


MID DEPTH CURRENT SPEED VS TIME

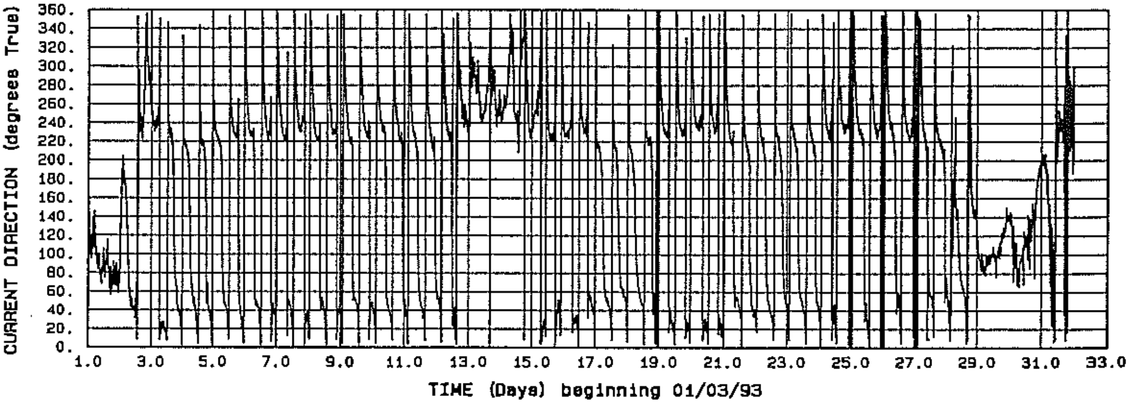


MID DEPTH CURRENT DIRECTION VS TIME

Figure 5c Spoil Ground Currents, March 1993

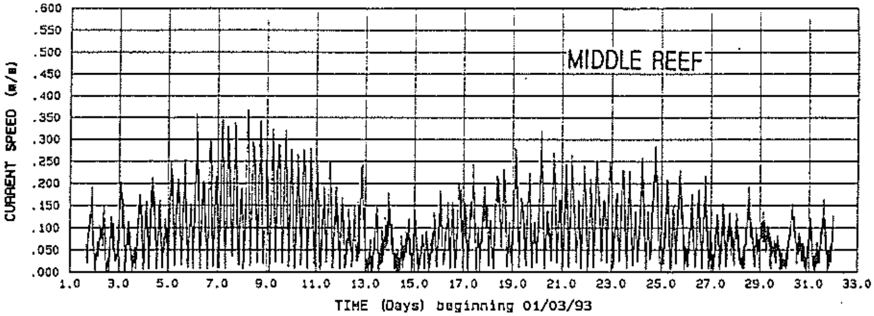


MID DEPTH CURRENT SPEED VS TIME

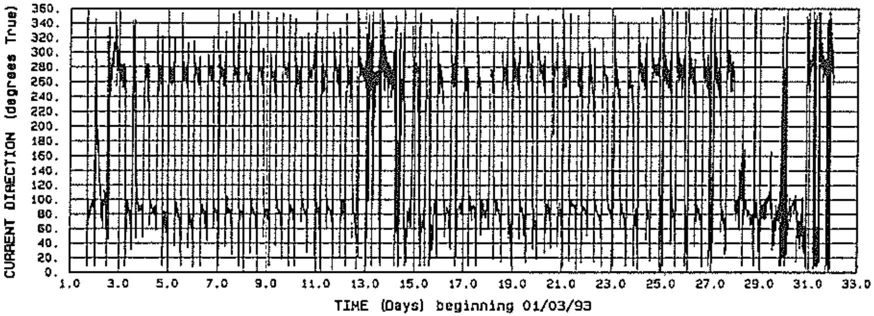


MID DEPTH CURRENT DIRECTION VS TIME

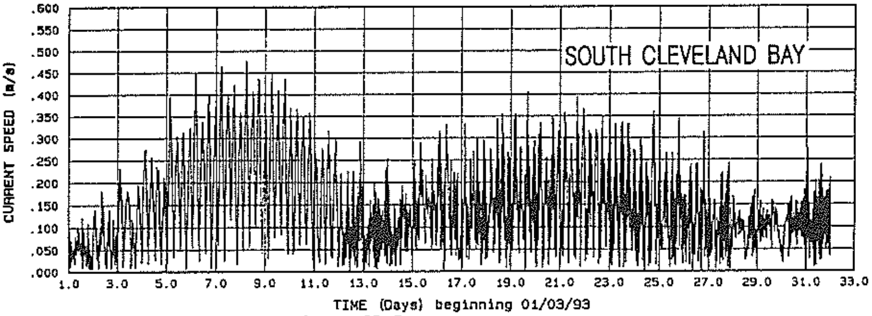
Figure 6 Currents at Middle Reef and South Cleveland Bay, March 1993



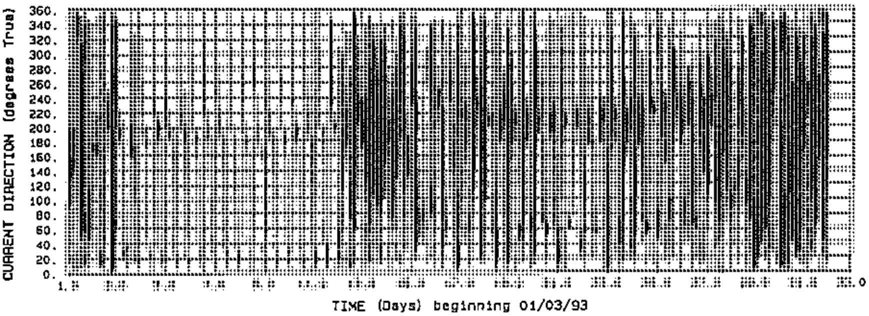
MID DEPTH CURRENT SPEED VS TIME



MID DEPTH CURRENT DIRECTION VS TIME



MID DEPTH CURRENT SPEED VS TIME



MID DEPTH CURRENT DIRECTION VS TIME

Figure 7a Wind Data - Cleveland Bay and Offshore, January

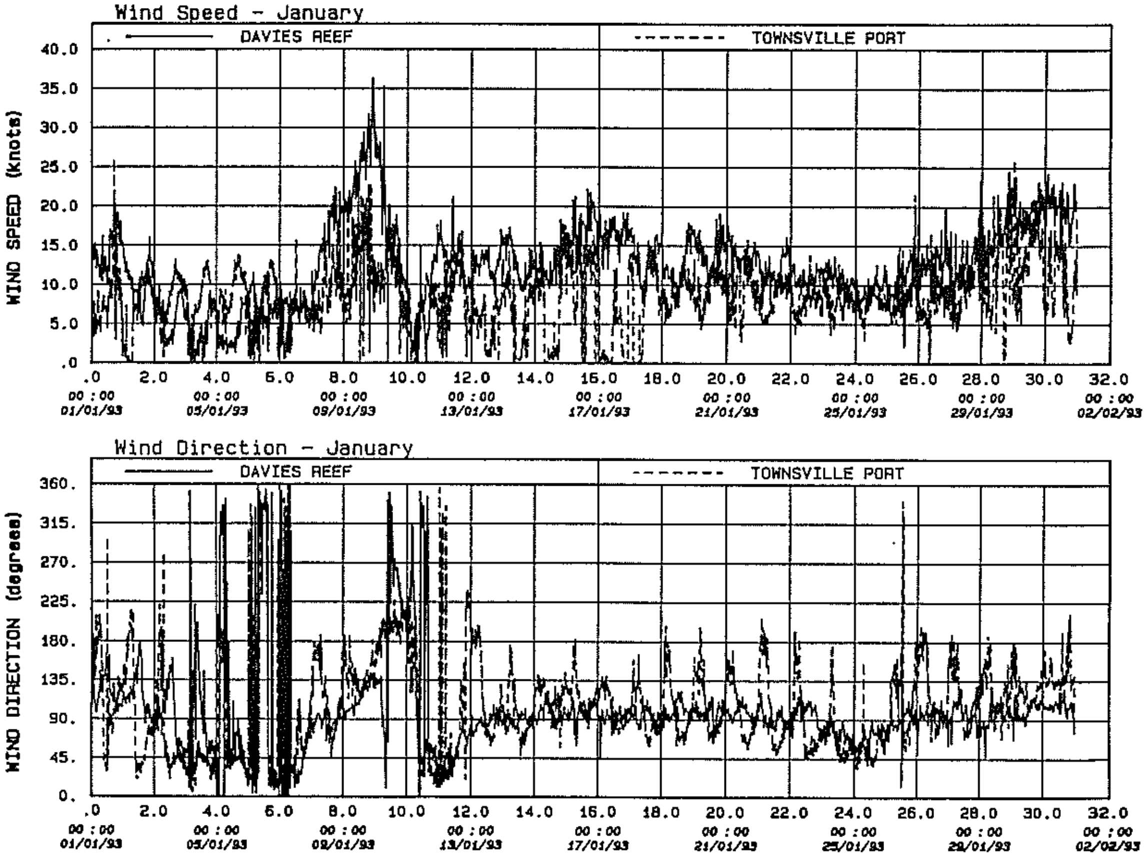


Figure 7b Wind Data - Cleveland Bay and Offshore, February

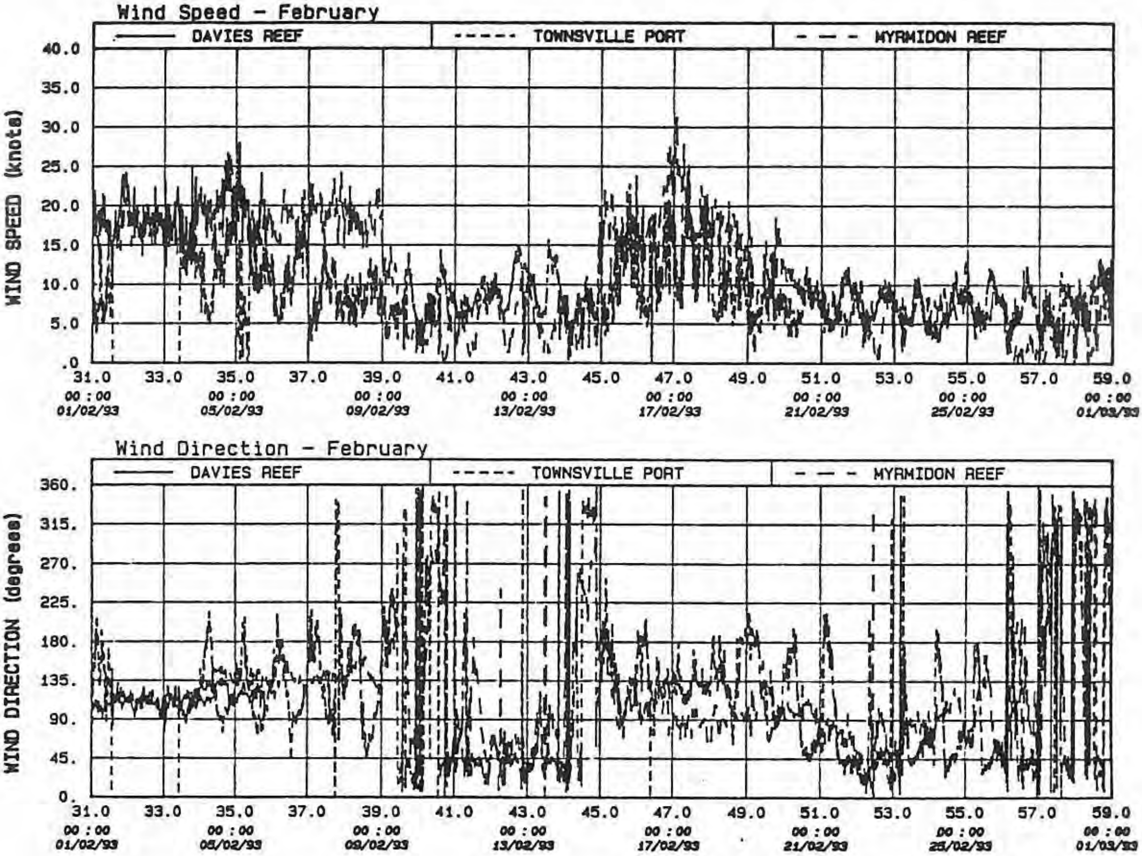


Figure 7c Wind Data - Cleveland Bay and Offshore, March

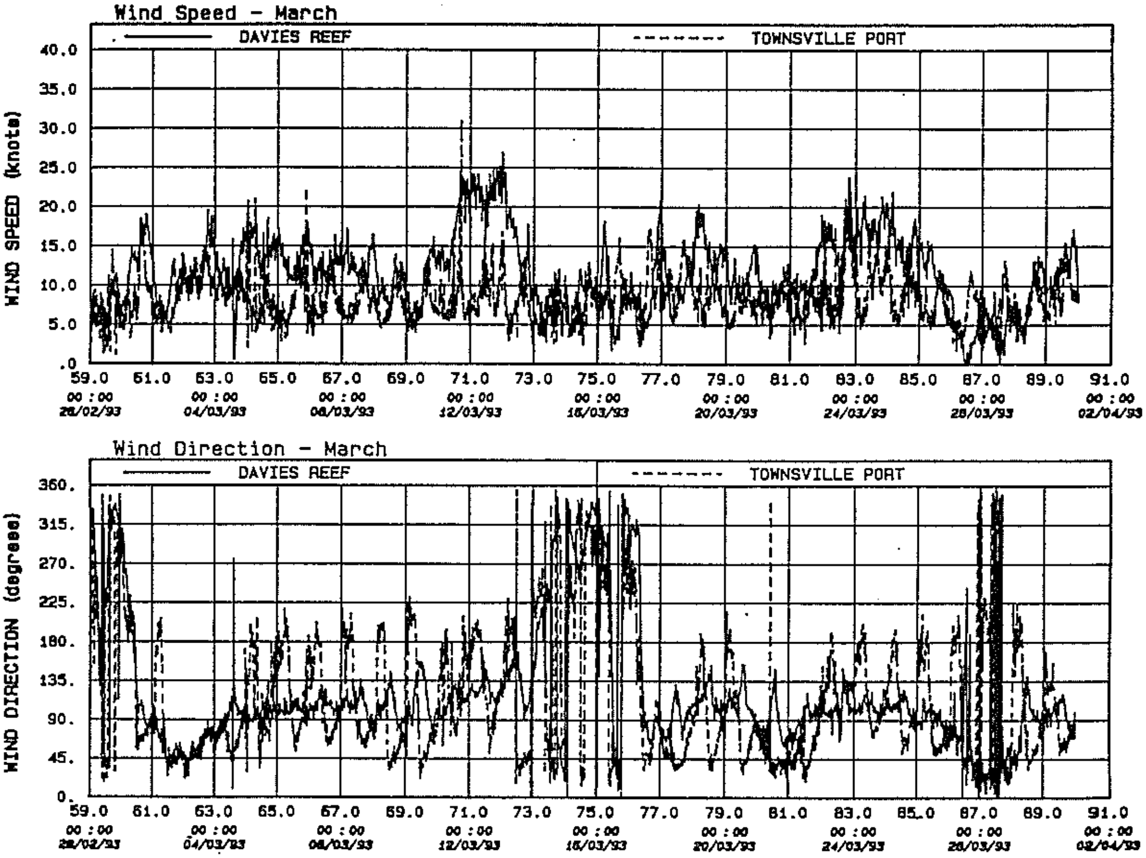


Figure 8 Drogue Tracking

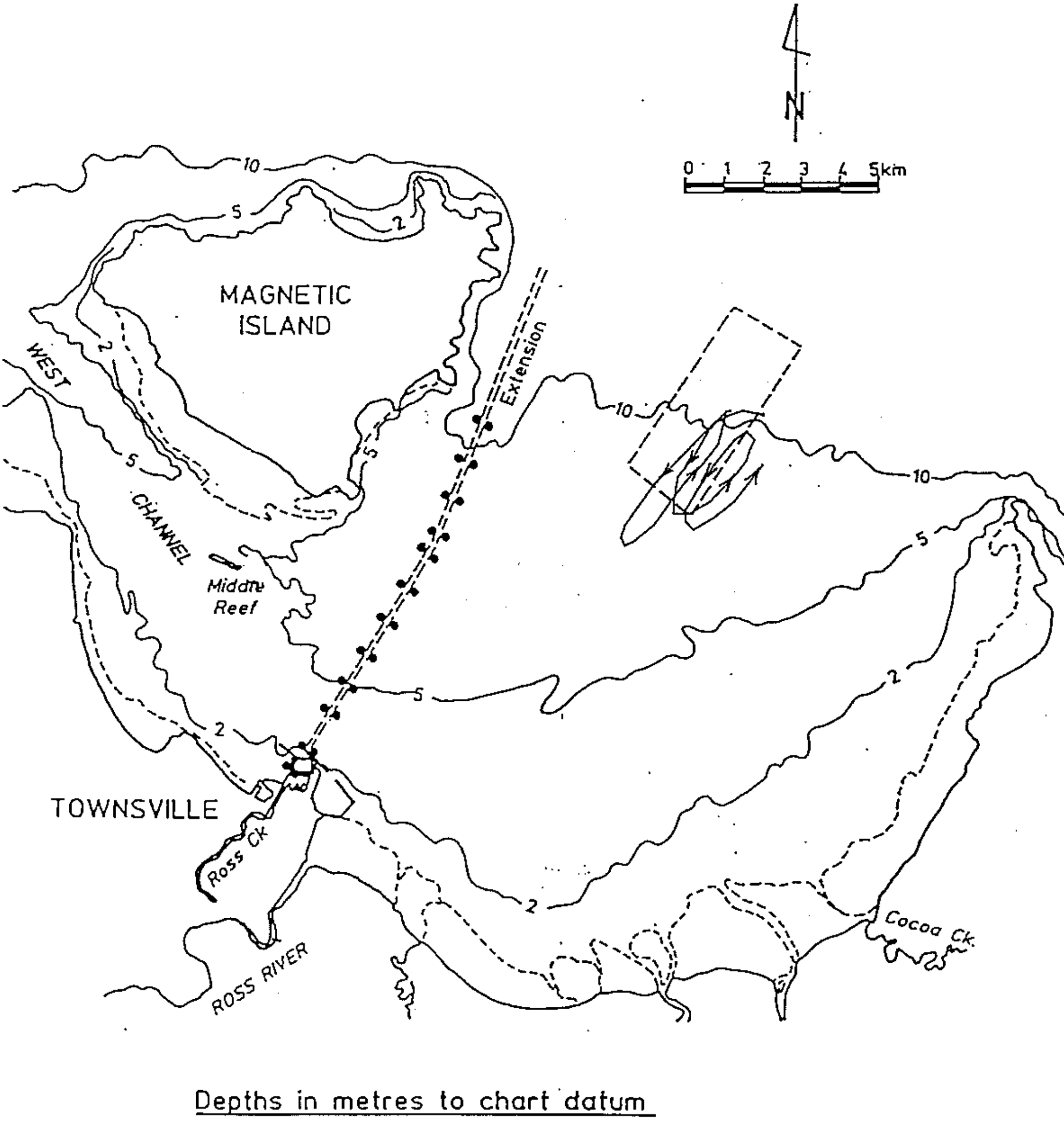
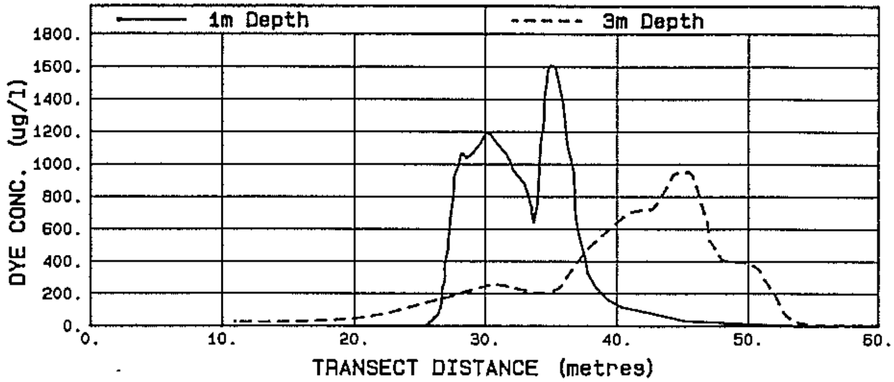
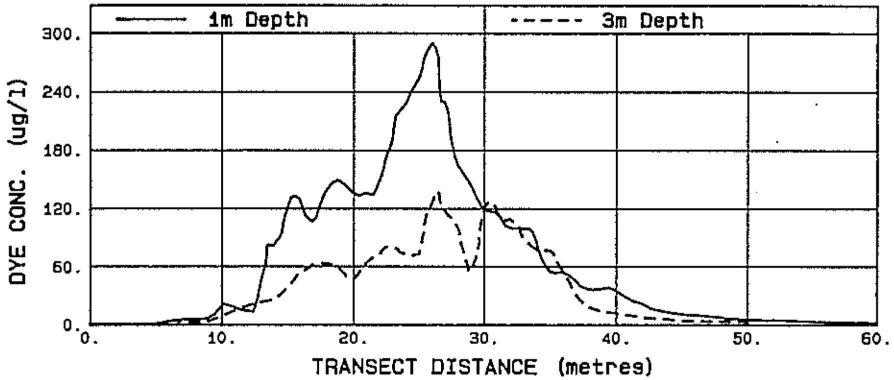


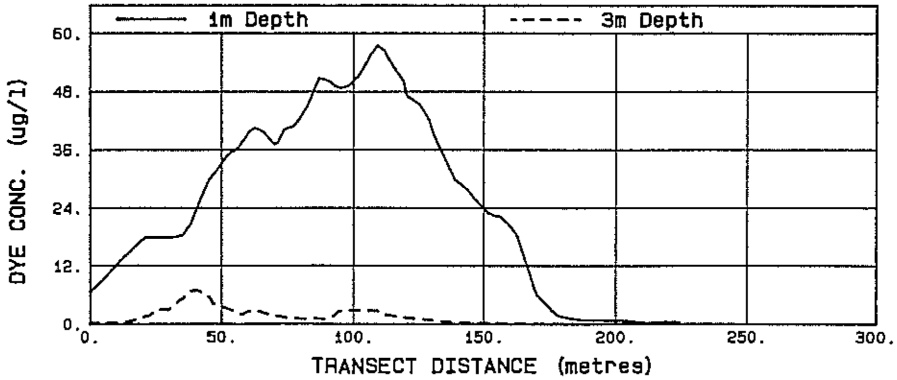
Figure 9 Dye Concentration Measurements



Transect times 0800 hrs



Transect times 0830 hrs to 0900 hrs



Transect times 0955 hrs to 1000 hrs

SEDIMENT DATA COLLECTION

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Townsville Qld 4811

TABLE OF CONTENTS

EXECUTIVE SUMMARY

This document describes the acquisition and processing of sediment data during monitoring of dredging operations in the Platypus and Sea Channels of the Port of Townsville. Data collection commenced on 30/12/92 and ceased on 30/4/93. A variety of data have been collected from soft-bed sites in Cleveland Bay and hard-bed sites adjacent to Magnetic and Rattlesnake Islands, for pre-, during and post-dredging sedimentary conditions.

The data comprise:

- Recordings, at five minute intervals, of near-bed suspended sediment concentration taken using logging nephelometers. Of 97 retrievals, 88 successfully gave data. After removal of invalid data, a total of 29865 nephelometer hours of useful data were collected, equivalent to over 80 % of the potential recovery. A realistic expected retrieval rate of data from unattended electronic marine instrumentation is 60-70 %, and the high retrieval rates attained in this work are testament to the reliability and high quality of the equipment deployed and field techniques used;

- Measures of suspended sediment concentration in the water column taken using Niskin water sampling bottles. A total of 356 samples were taken;

- Measures of gross sedimentation taken using sediment traps. Of 292 traps, 268 were successfully retrieved, a 92% retrieval rate;

- Samples of pre- and post-dredging bed sediments at the dump site, taken using cores. A total of 25 cores were taken.

Dredging operations commenced on the evening of 19/1/93 and ceased at ca. 8 pm on 6/4/93. The nephelometers therefore collected:

- up to 20 days of data for pre-dredging conditions;

- 77 days of data for dredging conditions;

- 24 days of data for post-dredging conditions.

Data presented graphically in this report is only a small proportion of that collected, for details please contact the authors.

1. INTRODUCTION

1.1 Scope

This documents reports on one of a suite of studies which together form the Townsville Port Authority Environmental Monitoring Program, which was emplaced to monitor the effects of the dredging and sea dumping components of the port expansion program.

This work was performed under Contract Number 62376-12, Oceanographic and Sediment Data, and was undertaken jointly by Comarine Consulting and WBM Oceanics Australia. This Sediment Data Collection report covers the Sediment Data part of this contract, and describes the acquisition and processing of sediment data from 30/12/92 to 30/4/93.

1.2 Goals

The goals of the work were to compile:

- ☐ Sufficient oceanographic data to permit confident modelling of processes likely to lead to resuspension and redistribution of dumped spoil from the existing offshore dump site at the mouth of Cleveland Bay.
- ☐ Sufficient suspended sediment and sedimentation data to permit a confident description of actual sediment dispersal from dredging activities and from the dump ground during the dumping period and against which to test sediment redistribution models.

2. METHODS

2.1 Sampling Design

Four main methods of investigation were used for this work:

- ☐ Bed-Mounted Nephelometers;
- ☐ Bed-Mounted Sediment Trap Arrays;
- ☐ Niskin Water Sampling Bottles;
- ☐ Short Cores.

2.1.1 Instrumentation

A. Nephelometers

Cleveland Bay, like many such sheltered tropical embayments, has high natural turbidity. In order to gauge the effect of water turbidity on marine life, the primary measurements must be of the spatial and temporal variations in turbidity. For this purpose, self-logging, self-cleaning nephelometers (Ridd & Larcombe, 1994) were deployed.

Nephelometers (sometimes called 'Optical Backscatterance Sensors', OBS) transmit light of a particular wavelength into the water column and measure the amount of that light reflected back from particles in the water column (backscattered light). For relatively low concentrations of suspended sediment, in simple terms, the more particles, the more backscattered light and the higher the nephelometer reading.

For this study, the nephelometers were calibrated with Cleveland Bay sediment obtained from sea-bed cores, and this calibration was assessed during the project under field conditions by taking simultaneous water samples. Overall, the nephelometers give a good measure of suspended sediment concentration.

B. Sediment Traps

Many studies of the marine environment have included sediment traps as part of assessing sedimentary conditions, due mostly to their simplicity. There is, however, much uncertainty of the precise meaning of the data obtained. Sediment traps give a very specific measure, unique to the type of tube, deployment site, and suite of hydrodynamic and sedimentary conditions over a given time period. This is not necessarily a measure of sedimentation. It is also important to note that the data do not indicate net sediment accumulation rates, or rates of erosion and resuspension. Even under erosive conditions, sediment traps collect sediment. Further, the volume of sediment collected by each set of sediment traps does not necessarily relate to water turbidity. Thus, interpretation of these data require a great deal of circumspection.

This study used sediment traps identical to those used by Mapstone *et al.* (1989), to permit a first order comparison with their baseline study of corals fringing the east coast of Magnetic Island.

C. Niskin Bottles

Niskin bottles are standard equipment for taking water samples in the marine environment. They are able to take water samples from a specific distance below the water surface, by use of a brass 'messenger' weight, which is dropped down the cable and triggers the sampler to close.

Water samples were taken for the following purposes:

1. routine sampling of the Cleveland Bay water column under a range of hydrodynamic conditions;

2. for sampling of specific dredge plumes;

3. for bay-wide sampling to coincide with satellite overpasses; and

4. for field comparison with nephelometer data.

Water samples were of 1 litre volume, and were taken at 0.5 m and 2 m above the bed. Samples for comparison with nephelometer data were taken at 0.5 m above the bed.

D. Short Cores

Samples of the sea-bed sediments were necessary to allow assessment of the potential for sediment transport and resuspension, and so aid interpretation of nephelometer and other turbidity data. For instance, with time the dumped material may have been 'winnowed' by waves and tidal currents, removing the finer component of the spoil which might have produced lower turbidity readings. Further, it was possible that the dumping of stiff cohesive Pleistocene material (which lies beneath the modern sandy muds, Larcombe, 1991) would potentially decrease resuspension from the dump site.

Cores of 12 - 50 cm length were taken by divers at 6 sites at the dump ground and also at the soft-bed nephelometer sites. A total of 25 cores were taken, comprising 13 pre-dredge cores and 12 post-dredge cores.

2.2 Deployment Details

At each site, a nephelometer and a sediment trap array were deployed together as part of the same mooring system. The locations of the sampling instrumentation are shown in **Figure 2.1** and positions of the diver driven short cores are shown in **Figure 2.2**. The nephelometer sensors pointed horizontally, to measure turbidity ca.30 cm above the bed. The top of each sediment trap was also ca. 30 cm above the bed.

Instruments were serviced by a team of divers, who:

- ☐ Retrieved the nephelometer and replaced it with a serviced unit. (Batteries were replaced monthly.)

Figure 2.1: Locations of Sampling Instrumentation

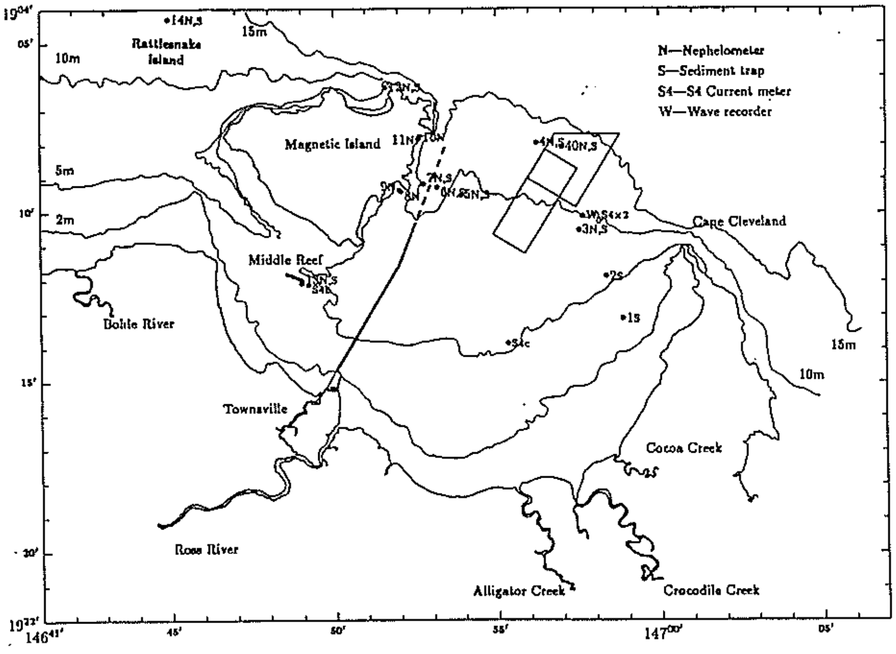
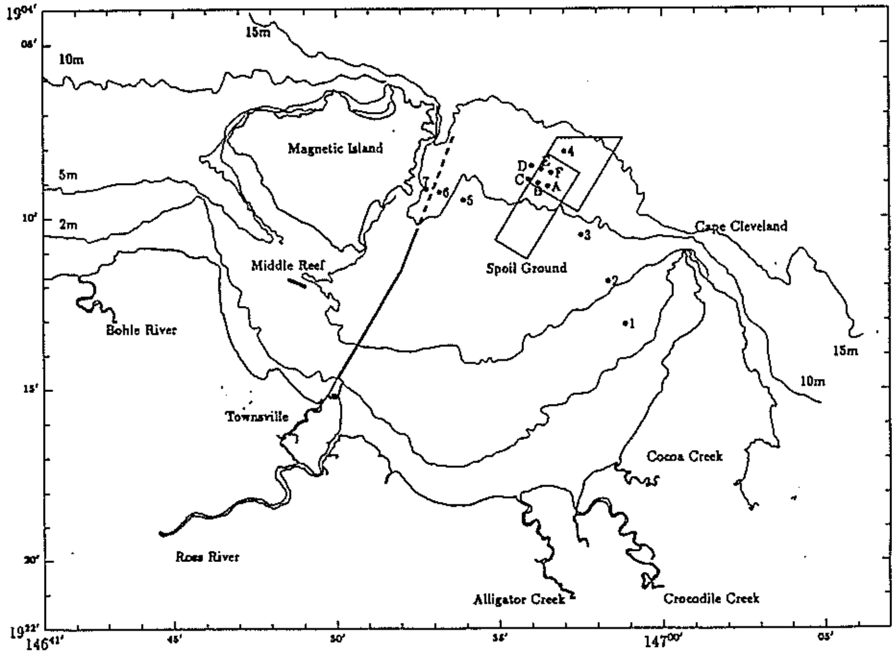


Figure 2.2: Positions of Diver Driven Short Cores



☐ Capped each sediment trap and returned it to the surface. Clean traps were then emplaced.

☐ Reported, where visibility permitted, on any biological interference with the instruments.

The Rattlesnake Island site was serviced monthly while the Cleveland Bay sites were serviced fortnightly.

During the course of the project, some instrument arrays were moved:

Site 4 - The mooring was found destroyed on 1/2/93. It was subsequently re-deployed at a new location on 13/2/93;

Site 6 - On 24/2/93 the mooring was found destroyed and the nephelometer was missing. The mooring was replaced on 26/2/93, and the nephelometer from Site 2 was moved to Site 6, based on predetermined data priority and a shortage of spare equipment.

All instruments and moorings were removed from Cleveland Bay and Rattlesnake Island after the completion of the study.

2.3 Software

Complex computational and graphics software was written to calibrate, archive and present the large amount of nephelometer data. The program proved highly efficient in dealing with the extensive datasets produced by the nephelometers.

3. RESULTS

3.1 Nephelometer Data

3.1.1 Data Retrieval

Nephelometer data was retrieved either at sea or, during rough weather, on land at Arcadia where saline moisture could not enter the electronic components of the nephelometers during servicing. This caused loss of some nephelometer data between 13/2/93 and 26/2/93. Data was downloaded onto portable computer, copied and later loaded onto computers at the Marine Geophysics Laboratory, James Cook University.

Of the 32600 nephelometer hours of collected data, approximately 2500 hours were assessed to be invalid (see Section 3.1.3).

3.1.2 Data Quality

Figures 3.1a, b and **3.2a, b** show examples of time series of 15 minute SSC averages, for the soft bed and hard bed sites respectively. **Figure a** in each case shows a spring tidal cycle pre-dredging while **b** shows a similar cycle during dredging. Note that the y-axis is logarithmic in character, with tick marks at 1, 2, 5, 10, 20, 50, 100, 200, and 500 mg/l. Hence variations in high suspended sediment concentrations appear far smaller than variations at low concentrations.

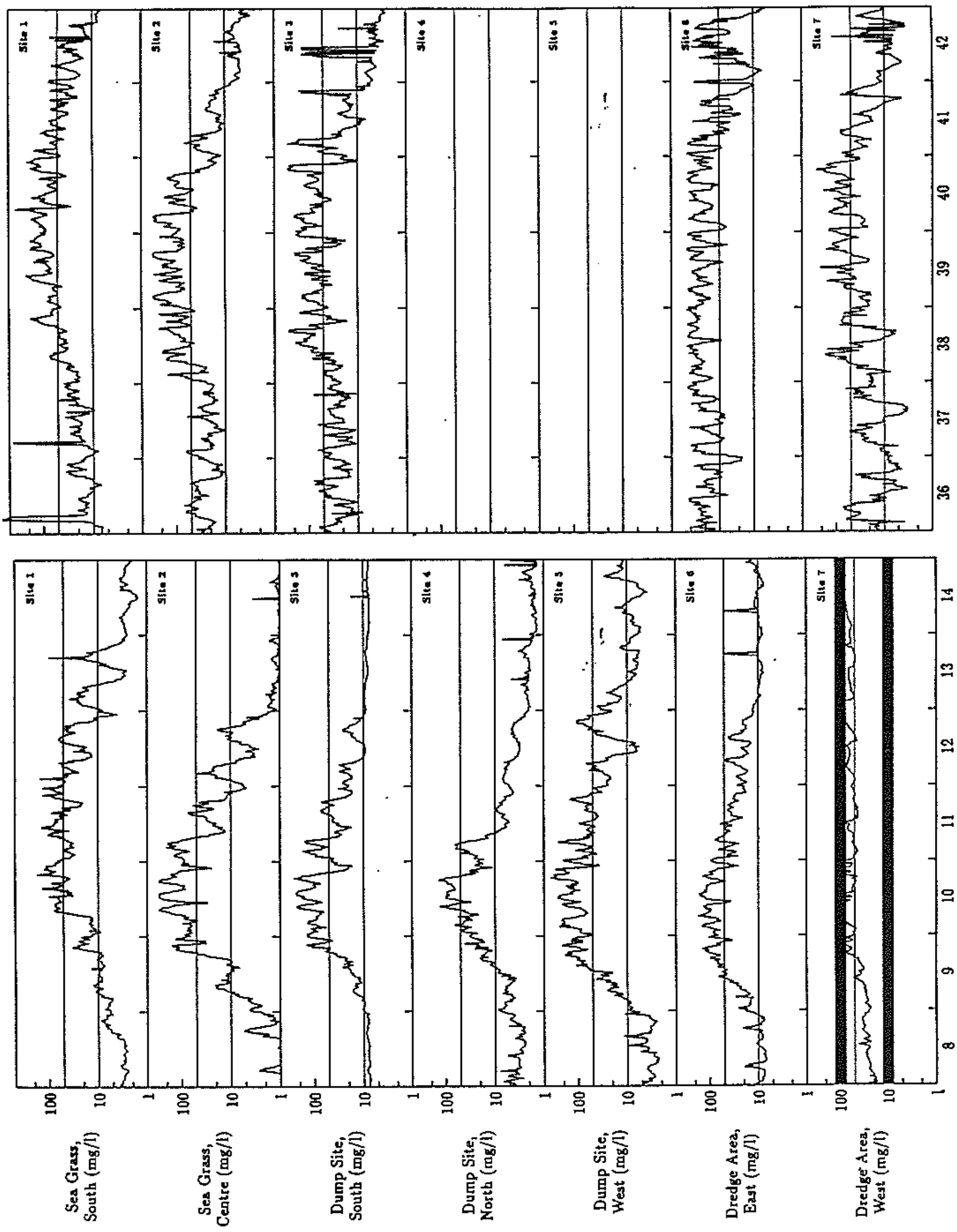
3.1.3 General Points

Effects of high value cutoff, sediment accumulation or biofouling affect the data quality. These are explained below. Where these affected data quality, two thick black lines overscore the data (eg **Figure 3.1a**).

A. High Value Cutoff

The working range of each nephelometer is limited. For the conditions in Cleveland Bay, a low range and consequent high sensitivity was appropriate. In conditions of very high suspended sediment concentration, the nephelometer indicates only its maximum value. Given the individual calibration of each nephelometer, this high cutoff may occur at different indicated values of suspended sediment concentration for

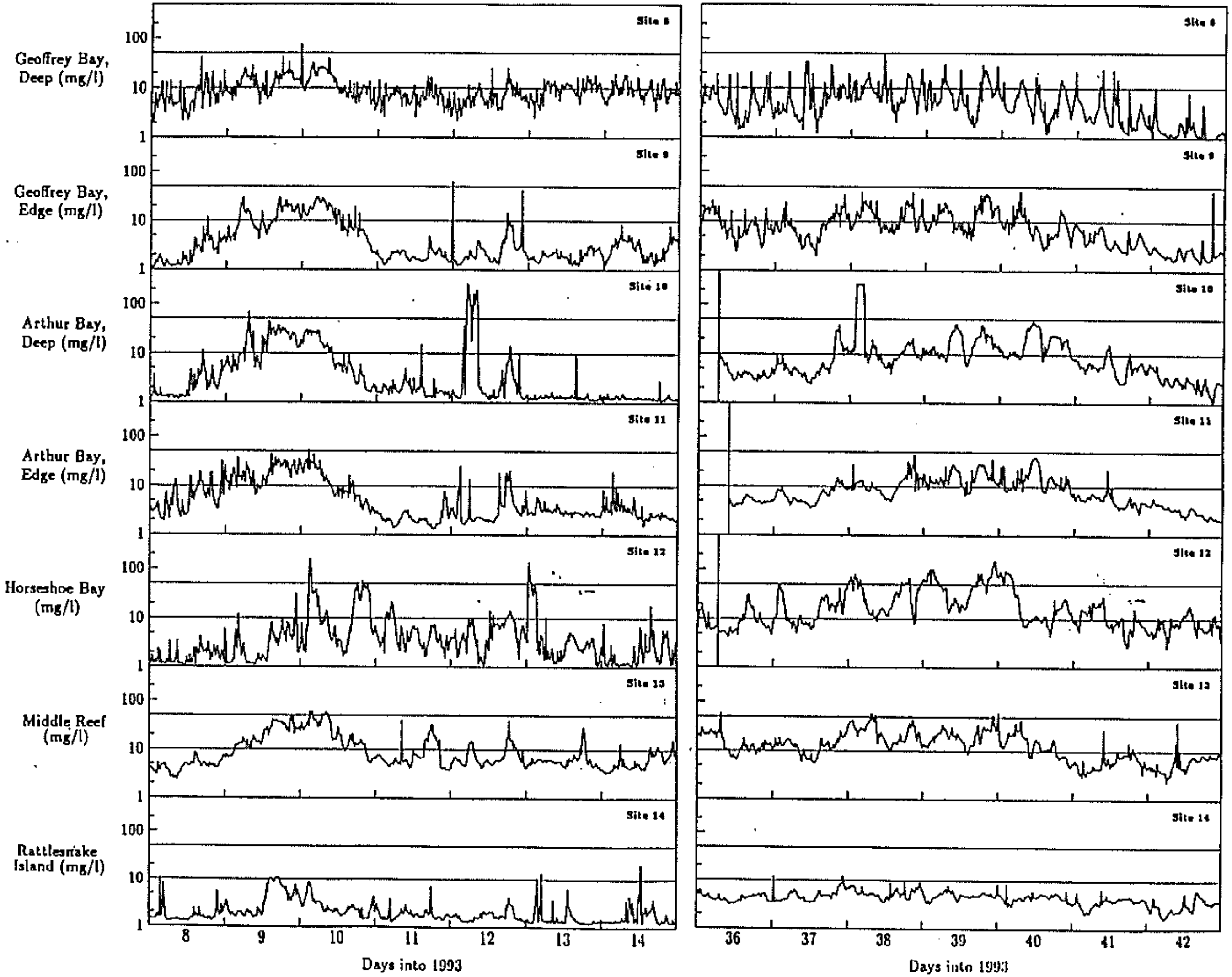
Figure 3.1 Soft Bed Nephelometer Plots



a: Days 8 - 14 1993

b: Days 36 - 42 1993

Figure 3.2 Hard Bed Nephelometer Plots


a: Days 8 - 14 1993

b: Days 36 - 42 1993

different nephelometers. In this study, high value cutoff occured at ca. 250 - 400 mg/l.

B. Sediment Accumulation

Sediment accumulation on the nephelometer lens can occur if the lens is inclined slightly upwards, even by a few degrees, and it has the effect of showing an apparent increase in suspended sediment concentration. In this case, with each wiper operating every 4 or 2 hours, the effect is that of a characteristic asymmetric saw tooth pattern with troughs at 4 or 2 hourly intervals, suggesting that sediment accretion occurred in the period between operation of the wiper. Beyond ensuring the units are level when deployed, ensuring the nephelometer mountings are secure, and nephelometer bases adequate, there is little control over this effect.

C. Biofouling

Biofouling may occur if the wiper is not able to remove all biological growth on the lens. This may be due to the wiper operating too infrequently, and/or with insufficient pressure. The trend produced in apparent suspended sediment concentration is long term and upwards.

Early in the work program, algal growth on some nephelometers was not being fully removed by the wiper. Not only does early algal growth rapidly increase, but it also increases the potential for sediment accumulation on the nephelometer lens. Thus, on 13/2/93 we:

☐ increased the wiper pressure;

☐ decreased the interval between wiping from of 4 hours to 2 hours;

☐ cleaned the whole nephelometer face thoroughly during servicing to help prevent algal build-up.

These changes proved effective.

3.2 Sediment Traps

3.2.1 Data Retrieval

A total of 268 of 292 individual sediment traps were successfully retrieved, i.e. a 92% recovery rate. Most data covered periods of ca. 14 days, except for Rattlesnake Island data which generally covered a month. All traps were not necessarily serviced on the same day, and the data therefore does not not always cover exactly the same time period. Examples of results for before, during and after dredging are presented in **Figures 3.3a, b, c.**

3.2.2 Data Quality

During the work program, all traps were gradually replaced by a new design which reduced loss from the traps. Occasional biological interference was noted by the divers who deployed and retrieved the traps (some traps contained small fish or crabs). Often, no observations were possible due to poor visibility. There were no clear effects of biological interference upon the results, with no systematic increases or decreases in the weight of sediment measured.

3.3 Water Samples

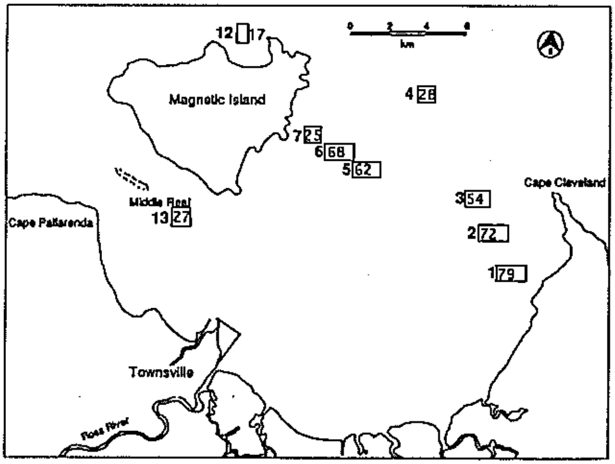
3.3.1 Data Retrieval

Examples of results for before, during and after dredging, are presented in **Figures 3.4a, b, c.** The comparison of nephelometric and water sample measurements of suspended solids is shown in **Figure 3.5.**

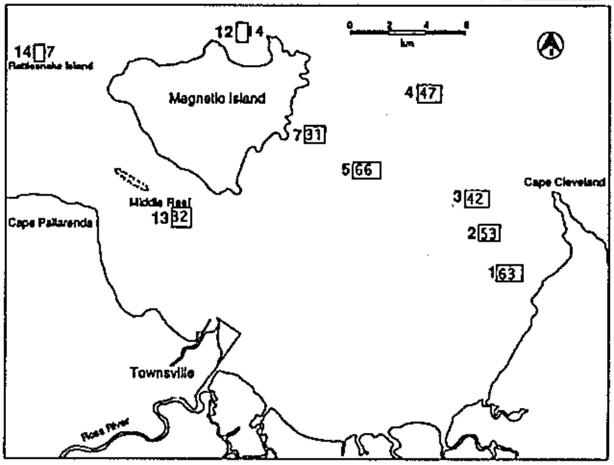
Obtaining high quality simultaneous data from 0.5-1.0 m above the sea-bed is difficult even when done in calm conditions. The high sea conditions under which these samples were taken undoubtedly were a major contributor to noise in the field data. Nonetheless, the majority of points are in good agreement, and confirm the use of these instruments in the field.

Figure 3.3: Sediment Trap Data (mg/cm²/d)

a: Before Dredging
(30-12-92 to 17-01-93)



b: During Dredging
(13-02-93 to 26-02-93)



c: After Dredging
(13-04-93 to 30-4-93)

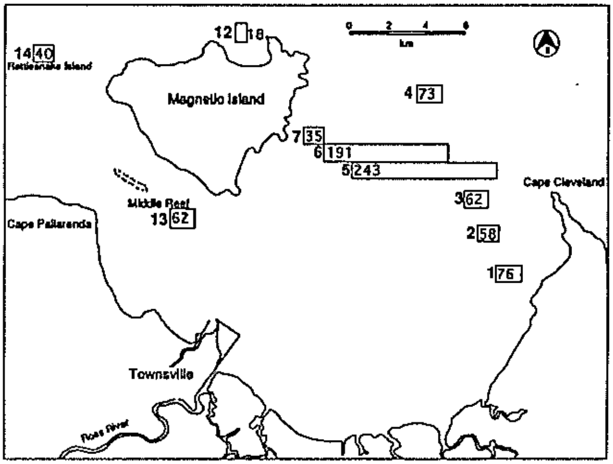
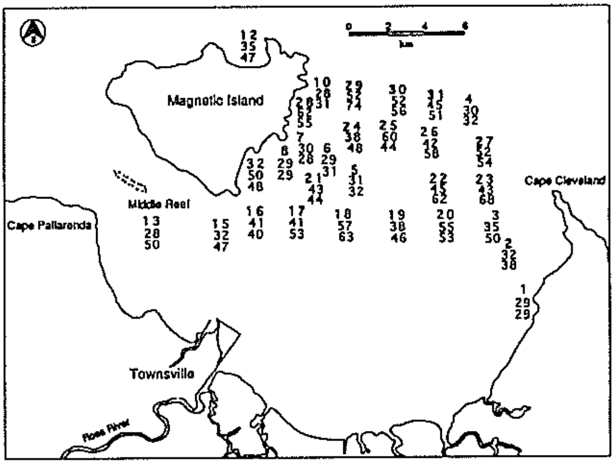
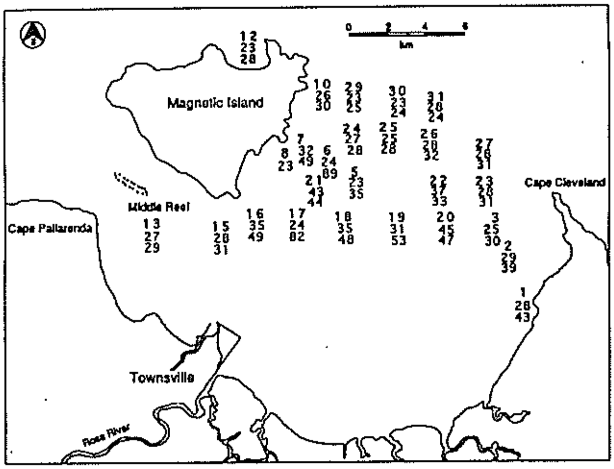


Figure 3.4: Suspended Solids from Niskin Bottle Samples
(Numbers represent, from top to bottom: site number; sample collected 2 m above bottom; sample collected 0.5 m above bottom)

a: Before Dredging
(04-01-93 and 18-01-93)



b: During Dredging
(10-02-93)



c: After Dredging
(16-04-93)

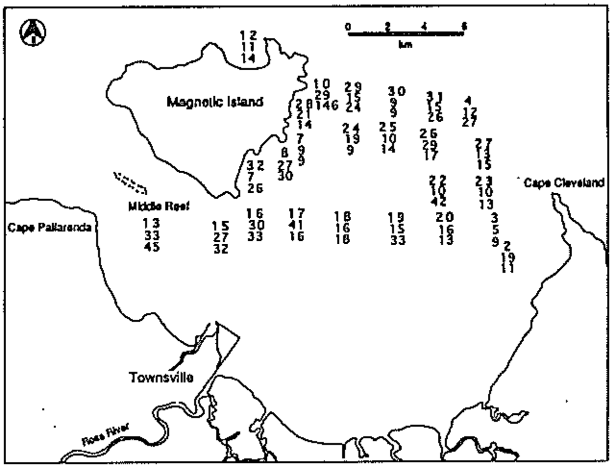
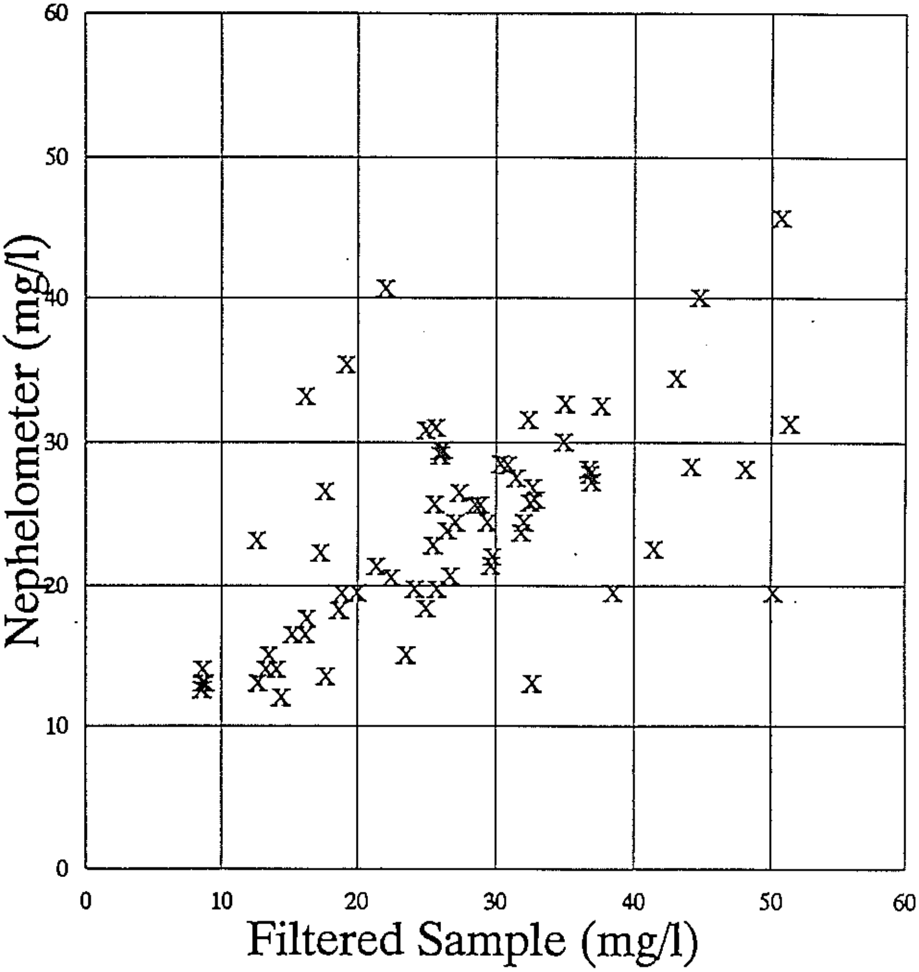


Figure 3.5: Comparison of Nephelometer and Water Sample Measurements of Suspended Solids



3.4 Diver-Driven Short Cores

3.4.1 Data Retrieval

Cores were taken by divers at 6 sites at the dump ground and at the soft-bed nephelometer sites, for pre-dredge and post-dredge conditions. A total of 25 cores were taken, comprising 13 pre-dredge cores and 12 post-dredge cores. We summarise the core material below.

3.4.2 Data Description

A. Pre-Dredging Cores

On 4/1/93, 13 short cores were obtained from Cleveland Bay. Core lengths retrieved ranged between 12 cm and 50cm. All samples taken from the cores had a significant amount of fine-grained sediment, with 7% to 40% (by weight) finer than 38 um (coarse silt). The majority of samples were muddy fine-medium sands, typical of the surficial sediments of Cleveland Bay (Carter *et al.*, 1993). The silt and sand fractions were dominantly terrigenous in origin, whereas coarser material tended to be biogenic.

East of the dredged channel, the modal grain size was either fine or medium sand, but in one case (Site 6) this was dominated by the fraction less than 38 µm, ie coarse silt. West of the dredge channel (Site 7) the samples were comprised of a bimodal sediment; a muddy mixed terrigenous-carbonate gravel. Samples from the dump site cores were very similar, with 11% to 25% of sediment finer than 38 µm. Most samples had a median grain size of ca. 2.5 ϕ (180µm).

B. Post-Dredging Cores

On 13/4/93, 12 short cores were obtained from Cleveland Bay. A core at Site F was not taken due to rapidly deteriorating weather conditions. Core lengths retrieved ranged between 16 cm and 50 cm.

Strong evidence for the presence of dredged material occured in Core E2. Three distinct sediment types were present, occurring as irregular lenses throughout the length of the core, and there was strong evidence for the presence of Pleistocene clays, probably derived from the base of the dredged channel.

C. Conclusions

All sampled sea-bed sediments contained between 7% and 40% of material finer than coarse silt (ca. 4.7 ϕ or 38 µm), and there is thus ample sediment within Cleveland Bay for resuspension. Dredging has clearly changed the surficial sediments at some sites at the dump site (e.g. compare cores A & A2, E & E2) and has produced a mixed array of sediment types in a small area. At other core sites at the dump site the sediments in pre- and post-dredging cores were little different.

4. DISCUSSION

A variety of sediment data have been collected for pre-, during and post-dredging sedimentary conditions in Cleveland Bay. The field methods and equipment adopted for collection of sediment data were highly effective. Data has been collected from soft-bed sites in Cleveland Bay and hard-bed sites adjacent to Magnetic and Rattlesnake Islands. The data represent:

- ☐ Up to 20 days of data for pre-dredging conditions;
- ☐ 77 days of data for dredging conditions;
- ☐ 24 days of data for post-dredging conditions.

The data comprise:

- ☐ Measures of near-bed suspended sediment concentration taken using bed-mounted logging nephelometers. A total of 29865 hours of useful nephelometer data were collected, equivalent to over 80% of the potential recovery;

☐ Measures of suspended sediment concentration in the water column taken using Niskin water sampling bottles. A total of 356 samples were taken;

☐ Measures of gross sedimentation taken using sediment traps. A retrieval rate of 92% was achieved;

☐ Samples of pre- and post-dredging bed sediments at the dump site were taken using cores. A total of 25 cores were taken.

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DATA INTERPRETATION

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EXECUTIVE SUMMARY

A - Issue

At the time of writing, Townsville Port Authority is upgrading port facilities to allow the entry of larger vessels. A major aspect of this work is deepening and extension of the dredged channel to the port in Cleveland Bay. Concern exists over the short and long-term effects of dredging operations upon nearby areas of environmental sensitivity including:

- ☐ The coast of Magnetic Island, which harbours fringing coral reefs and a variety of other marine life;
- ☐ Extensive seagrass beds in southern Cleveland Bay, within which dugongs have been observed;
- ☐ Middle Reef, which contains a range of coral species.

An experimental dredging study in November 1992 suggested that "the planned dredging had the potential to create sediment plumes that would impact to some extent on the fringing reefs of Magnetic Island" (Sinclair Knight, 1992). Further, spoil dumping had been observed to form a mobile, 1 m thick, high concentration suspension near the sea-bed (Wolanski & Gibbs, 1992; Wolanski et al., 1992), which could have the potential to be carried by currents into sensitive areas.

B - Research

An Environmental Monitoring Programme was undertaken of which this document describes the interpretation of a suite of environmental datasets collected from sites in Cleveland Bay and from the region. Sedimentary and oceanographic data were collected from sites in Cleveland Bay, adjacent to the coast of Magnetic Island and other sites. This interpretation chapter describes the currents, waves, sedimentation and turbidity regimes during dredging, and assesses 'natural' and 'dredging-related' sedimentary processes.

C - Summary

Dredge-related effects were identified in outer Cleveland Bay, as dump event turbid underflows which reached 50 mg/l and lasted over periods of hours, and as swell-induced raised suspended sediment concentrations which lasted periods of hours-days.

At the Magnetic Island reefs:

- ☐ Natural turbidity is spatially and temporally very variable;
- ☐ The bays are periodically flushed through exchange of water with offshore waters;
- ☐ Wind-waves generate turbidity in the bays themselves.

We are confident that no extreme suspended sediment concentration occurred at any of the Magnetic Island bay sites as a direct result of dredging. Given the available data, dredge-related effects appear to lie within normal variation at seagrass sites in SE Cleveland Bay and the coral systems at Middle Reef.

1. INTRODUCTION

1.1 Objectives

The objectives of this study were:

- ☐ To receive data reports on oceanographic conditions, sedimentary conditions and remote imagery, and to interpret these in terms of sediment dispersal rate and concentrations from dredging and dumping sites;
- ☐ To base interpretations upon actual data, without additional modelling exercises;
- ☐ To provide an interpretation of 'natural' versus 'dredge-related' sediment dispersal within Cleveland Bay;
- ☐ To interpret measured levels of suspended sediment and sedimentation in the context of other studies that have examined biological effects of these stressors.

1.2 Scope

The study concerns interpretation of data from Cleveland Bay, Townsville, North Queensland. Carter et al. (1993) have summarised the location, local climate and bathymetry, and this forms the main source for the following sections.

1.2.1 Location

Cleveland Bay lies immediately offshore from Townsville, Australia's largest tropical city, and encompasses a port facility in its southwestern corner. The bay is approximately 18 km square and landlocked around its southern and eastern margins by the mainland; Magnetic Island shields most of the north western margin. A progradational coastal plain 7 km wide occurs along the southern shoreline, and connects eastwards through to the coastal plain of Bowling Green Bay. Otherwise, Cleveland Bay is fringed by rocky headlands and hinterland rising to 495 m on Magnetic Island, 557 km on Cape Cleveland and 581 m on Mt Stuart.

1.2.2 Climate

Though located in the tropics, at latitude 19° S, the Townsville region has an average annual rainfall of only 1163 mm (46 inches). The rainfall is strongly seasonal, mostly falling in the summer months, December to March. Tropical cyclones are also dominantly summer phenomena. In the 30 year period 1940-1969, 22 tropical cyclones passed within 167 km of Townsville (Oliver, 1978). Winds blow from the east or southeast for 60% of the time, and at wind strengths greater than 7.5 m/s for 25% of the time. The fetches for the major wind directions are:

NW	60 km
N	65 km
NE	60 km
E	120 km

Wind-driven currents created by winds from the SE quadrant, will mostly reinforce the anticlockwise tidal current motions within Cleveland Bay, and augment sediment transport towards the southeast of the bay on the east, and northwest through West Channel on the west.

1.2.3 Bathymetry

Cleveland Bay is shallow, reaching a maximum depth of 15 m at its seaward edge. The embayment plain has a low bottom gradient of <0.7 m/km out to a depth of ca.10 m. The 10 m isobath corresponds to the seaward edge of the main bay sediment-fill, the foreslope of which passes offshore at a slightly steeper angle (1.25 m/km) to merge with the general surface of the mid-shelf near the 20 m isobath.

Exceptions to this simple bathymetry occur adjacent to Cape Cleveland. At three locations on the western edge of the Bay for a distance of about 2 km southwest of Cape Cleveland, the seaward edge of the bay sediment-fill lies at depths between 12 m and 13 m, forming a distinct terrace seawards of the shallow bar which runs southwestwards from Cape Cleveland. The seaward edge of the Cleveland Terrace has a relatively narrow, steep slope (up to 12.5 m/km) down to the shelf surface.

In the west, Cleveland Bay connects to Halifax Bay through the shallow West Channel, which separates Magnetic Island from the mainland and has a maximum depth of 4 m. The access channel to the port of Townsville (Platypus Channel), dredged to a depth of 12-13 m, passes along the northwestern side of the bay, about 2 km off Magnetic Island (Figure 1.1). Further north, at the northeastern corner of the island, a natural channel (here named Orchard Channel) exists at depths of 15-20 m, between the eastern edge of the fringing sediment prism of Magnetic Island and the western edge of the main Cleveland Bay sediment fill. The seaward parts of individual bay sediment wedges off Magnetic Island are similar to Cleveland Terrace, i.e. they comprise constructional platforms at 11-14 m depth, overlapped on their landward side by the more steeply sloping shoreface sediment prism that surrounds the island.

The tidal cycle is dominantly semi-diurnal, with a maximum range at springs of 3.8 m. There is a close linear correlation between tidal range and the bottom currents (Mason *et al.*, 1991). During neaps (range 0.5-0.8 m) currents are of irregular direction and generally less than 5 cm/s velocity; during springs (2.3-3.6 m) currents vary between 15-30 cm/s with minor asymmetry (the flood tide being slightly stronger) but regular orientation. During extreme spring tides, currents may exceed 70 cm/s (Belperio, 1978). The measured tidal asymmetry indicates that net sediment transport should be into the bay.

Belperio (1978) measured wind generated currents off Cape Cleveland and reported: (1) that a 7-10 m/s E or SE wind (ca. 13-19 knots) was sufficient to obliterate the southerly-directed flood tide component; and (2) that wind-drift currents set anticlockwise around Cape Cleveland, and northwesterly through West Channel.

2. METHODS

The data interpretation process was performed in a series of stages:

A. Computer Processing - The great volume and range of data necessitated management, analysis and presentation by computer programs.

B. Graphical Data Assessment - Graphical datasets were produced by instruments at sites within 5 geographical areas. The area names, with their adopted site numbers, are:

Dump Site	Sites 3, 4, 5
Dredge Area	Sites 5, 6, 7
Magnetic Island	Sites 8, 9, 10, 11
Seagrass	Sites 1, 2, 3
Other sites	Sites 12, 13, 14

See Figure 2.1 for location of sites.

Initial data interpretation gauged 'background' data levels and recognised distinct 'data events'.

C. Data Event Grouping - The data allowed limited grouping of individual 'data events' on a scale relating to the degree of

Figure 1.1 - Bathymetry of Cleveland Bay

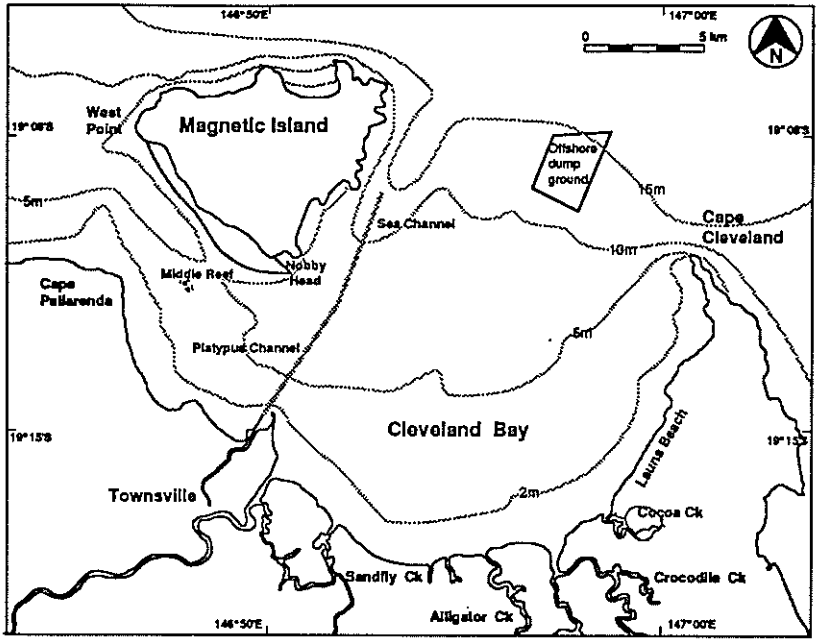
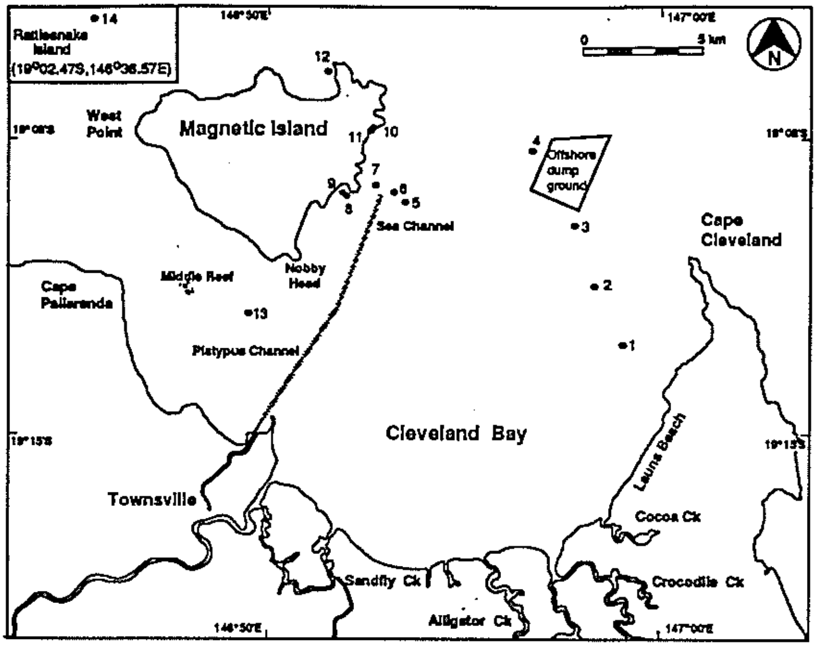


Figure 2.1 - Location of Sites



relationship with dredging and dumping operations. The set of physical, hydrodynamic, spatial and temporal characteristics of each 'data event' allowed an interpretation of its likely cause.

D. Quantitative Interpretation - Data processing allowed some quantitative data interpretations, particularly on the major controls on near-bed SSC at each study site, and a comparison between pre-dredge and syn/post-dredge data.

E. Biological Context - Interpretation of sedimentation impact status was achieved by reference to published studies, and consultation with recognised experts.

In this report, data is discussed in terms of Julian Days, i.e.

1/1/93 = day 1
31/1/93 = day 31
1/2/93 = day 32 etc.

The data received for interpretation consisted of:

Nephelometer Data;
Sediment Trap Data;
Water Sample Data;
Diver-Driven Core Data;
Wave Data;
Current Meter Data;
Tide Gauge Data;
Wind Data;
Aerial Photographs;
Satellite Images;
Track Plots of Dredge ;
Logs of Dredge Loads and Times;
Log of Port Shipping Movement.;

Some datasets received were not integral to achieving the objectives of this study, having been collected primarily to allow oceanographic modelling. The relevant datasets are considered in turn:

Firstly, we describe the datasets representing the forcing processes which drive sediment transport;

Secondly, we describe the datasets which represent the sedimentary 'products' of the forcing processes. These are discussed in a more interpretative way, drawing on the process datasets, and some sediment datasets collected during the study. The nephelometer dataset is discussed separately and in detail, by virtue of its importance, size and complexity.

Not all datasets cover the entire January - April period, and discussion is largely restricted to the time periods covered by each dataset received. Generally, the greater number of simultaneous datasets, the higher the quality of interpretation, which therefore was variable over the 4 month study period in question. In particular, there is little wind, wave and tide data for April, and the interpretation for this month is severely compromised.

For each section, the data is discussed broadly in order of occurrence.

3. RESULTS

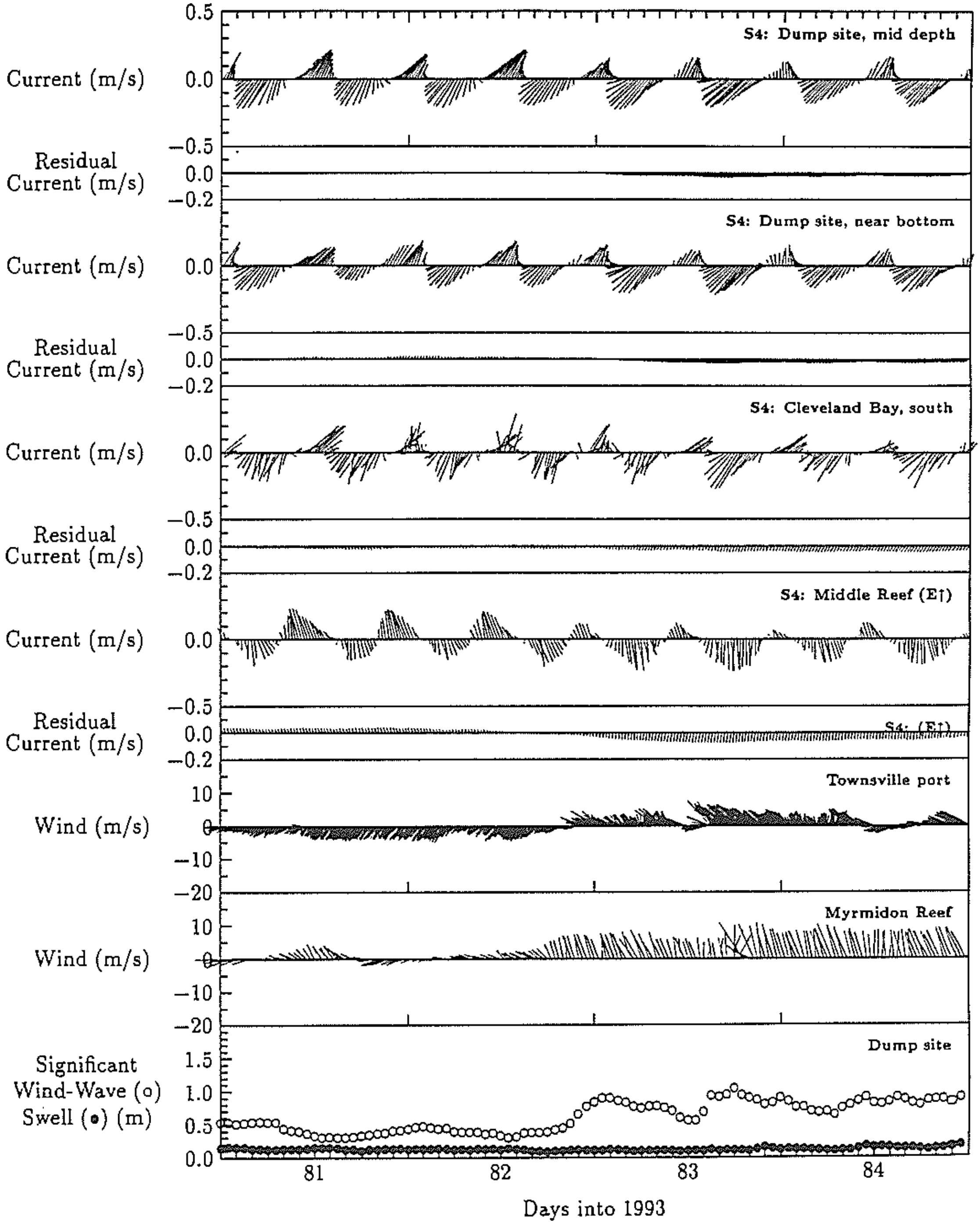
3.1 Forcing Datasets

Examples of the plotted forcing datasets are shown in Figure 3.1. Detailed examinations will require viewing the original report.

3.1.1 Wind

Wind speeds, as 6 minute averages, are presented in their correct SI units of m/s, but for familiarity are discussed in knots (10 m/s = 18.5 knots). Wind directions are PLOTTED in the oceanographic convention i.e. the direction towards which the wind moves, to be consistent with the tidal-current data, but for familiarity are DISCUSSED in conventional terms.

Figure 3.1 Example of Plotted Forcing Datasets



The sea-breeze effect was sometimes prominent at Townsville Port, whereby winds were strongest during the late afternoons (e.g. 10-15 knots rather than 5-10 knots), and were more shore-normal (e.g. NE rather than SE). Winds at Townsville Port and Airport were more variable in speed and direction than offshore at Davies and Myrmidon Reefs. At these reefs, the winds also tended to be stronger. There is thus a clear distinction between the local and regional wind fields.

JANUARY - Wind speeds measured at the Port Authority Tower, usually showed a strong sea-breeze effect. Winds exceeded 20 knots on 4 main occasions (days 1, 9-10, 27, & 29-30). The major wind event was on days 9 & 10, where winds were SE at 20 knots, and a weaker event occurred on days 16 & 17 with winds generally above 15 knots and from the SE. Instantaneous wind speeds at Davies Reef were generally higher than at the coast, and peaked at over 35 knots from the SE during the major wind event of day 9. This is significant as much swell is generated well off the coast.

FEBRUARY - The major wind event was on days 46-48, where winds at Townsville Port were dominantly SE at 15-25 knots. A smaller event at the coast occurred early in the month when Cyclone 'Oliver' passed south parallel with the coast, ca. 500 km offshore, causing continuous winds over 15-20 knots at Davies and Myrmidon Reefs (ca. days 30-39). Winds during the last 9 days of February at Townsville were light and variable.

MARCH - At Townsville Port, the light winds continued, with no major wind events in March. Winds reached 20 knots briefly on only 4 occasions. Wind directions were dominantly from the NE to SE quadrant, but occasionally were more variable, and with the absence of major wind events, the sea-breeze effect was present for most of the month.

APRIL - At Townsville Port, winds peaked at ca. 20 knots on day 95, having increased since day 92. The stronger winds were generally from the SE quadrant. There was a sea-breeze effect evident on days 89-93. Winds were strong later in the month for an extended period, but no datasets were received for this period.

3.1.2 Waves

'Wind-waves' and 'swell' were arbitrarily separated at a period of 7 seconds, i.e. swell is that portion of the wave spectrum with periods greater than 7 seconds. The data were plotted showing the significant wind-wave and swell heights, defined by 2 √2 times the root mean square of the amplitudes.

The height of wind-waves rise and fall quicker than swell, partly because much of the wind-wave spectrum is relatively local. In contrast, the swell component would have travelled some distance from its original source. With refraction around Cape Cleveland, the fetch from the SE is large as waves can potentially travel along the Great Barrier Reef lagoon for hundreds of kilometres. It is these long-travelled long period waves that are most important in controlling sedimentary processes in outer Cleveland Bay.

The major periods of swell waves occurred with periods of a strong SE regional wind field (generally of a few days). Increased wind-waves also accompanied these periods, but were also generated relatively locally in short periods of time (hours).

The wave signature measured at the Waverider Site in Cleveland Bay was generally similar to that measured by the Waverider off Cape Cleveland. There is a sporadic tendency for the wind-wave component to be stronger off Cape Cleveland, and generally, the swell is also slightly larger.

JANUARY - The major period of wind-wave and swell activity at the Cleveland Bay Waverider site occurred on days 9 - 11, when the significant swell component rose above 0.5 m in height and the significant height of the wind-waves was above 1.5 m. The wind-waves preceded the swell component, and later, the swell was the dominant component of the wave spectrum for at least 24 hours.

FEBRUARY - At the Cleveland Bay site, there were two periods of significant wind-wave activity. The first extended until day 40, being a continuation of winds late in January related to Cyclone Oliver, and on days 36 to 40 the swell component of the wave spectrum rose to above 0.5 m in significant height. The second period of wave activity comprised wind-waves with virtually no swell waves (days 46-50), and the wind-waves were probably generated relatively locally.

With S to SE winds, the wind-waves were up to 0.5 m larger at the Cape Cleveland Waverider site (days 37-39) than at the dump site, because of the decreased local fetch within Cleveland Bay to southerly winds caused by the presence of Cape Cleveland. In contrast, the swell components at the two Waverider sites were very similar for the whole of February, which would be expected due to refraction around Cape Cleveland. Wind-waves and swell were minimal during the period of NE winds (days 41-44 and 52-60), and it would appear that their limited fetch resulted in little swell being created.

MARCH - In general terms, March in Cleveland Bay was fairly calm. At the Cleveland Bay dump site, the swell height peaked at 0.5 m on day 72, but otherwise was below 0.3 m. The wind-waves had a greater signigicant height, exceeding 1 m in significant height on days 71 & 72, and exceeding 0.5 m for a number of periods during the month.

APRIL - Recorded conditions were similar to March. The wind-waves exceeded 1 m in significant height on days 94 & 95. No data was received covering mid and late April, but it is likely that the swell and wind-wave components were relatively great in significant height due to the extended period of strong winds.

3.1.3 Tidal and Wind-Driven Currents

The datasets include data from the Dump Site (mid-depth and near-bed), southern Cleveland Bay (mid-depth), and Middle Reef (mid-depth) for parts of February to March. Tidal residuals at the S4 site were calculated by averaging over 24.8 hours (i.e. 2 tidal cycles, one before and one after the plotted data point).

Tidal currents in Cleveland Bay are generally weakly anticlockwise in nature, i.e. the movement of a particular parcel of water will, over time, describe a series of ellipses each in an anticlockwise direction. Of the survey stations, the exception to this rule is Middle Reef, where the tendency towards an elliptical form for the tide is heavily suppressed by the local bathymetry, producing rectilinear currents. In West Channel, the tidal wave which has travelled through Cleveland Bay meets that part of the same tidal wave which has travelled around Magnetic Island and SE through West Channel (Mason *et al.*, 1991). The data below suggests that this meeting point is further west into West Channel than Middle Reef.

In outer Cleveland Bay, the flood tide generally enters the bay towards the SW at speeds up to 0.55 m/s and the ebb flows towards the NE at up to 0.45 m/s. In southern Cleveland Bay currents peaked at ca. 0.48 m/s on spring flood tides which flow southward, and at Middle Reef, flood tides attain 0.4 m/s and flow towards the WSW.

3.1.3.1 Current Meter Station Near The Dump Site

The flood tide generally enters the bay towards 220-250 degrees (true), and the ebb flows towards 20-50 degrees. Peak spring tidal mid-depth currents were attained in February of 0.55 m/s on flood tides and 0.45 m/s on ebb tides.

Mid-depth currents were highly dependent upon winds. In the presence of medium-strong S-SE winds (e.g. 15-20 knots) flood currents are enhanced and ebb currents are reduced, resulting in a residual current towards the WSW, which can attain 0.15 m/s (e.g. days 46-48). With similar winds and neap tides, the ebb tide is deflected to flow towards the west (days 30-31). In the absence of strong winds, residuals appear below 0.05 m/s.

As expected at the S4 site, vertical profiles of tidal currents in inner shelf waters showed near-bed currents of similar direction and generally weaker strength than higher up the water column. The shear between near-bed and mid-depth currents varies up to 0.15 m/s (e.g. days 48-51).

Winds at Davies Reef have a correlation with the residual current with a time lag of ca.12-24 hours. Periods of strong southeasterly winds (e.g. days 71-72) tend to be followed by a strong WSW current residual into Cleveland Bay.

In April, the combination of light regional winds and neap tides corresponded to the occurrence of a strong southward residual of up to 0.15 m/s (days 89 & 90), and there was a strong vertical shear (ca. 0.2 m/s) between mid-depth and near-bed currents.

A complex current structure occurred on day 45, between 0830 to 1030 hrs. The data show the mid-depth current was 0.25 m/s towards the northeast, whereas near-bed the current was of similar magnitude but in the opposite direction. The data appear reliable, and show that there are sporadic significant differences in the velocity vector of near- bed water and water further up the water column. No temperature data are available. We speculate that this phenomenon was caused by temperature induced stratification, the formation of which was favoured by the combination of warm weather, light winds, calm conditions and neap tides. Days 43-45 had daily maxima of 32.8, 33 & 33 Celsius, and overnight minima of 26.5, 26.5 & 25.6 Celsius.

3.1.3.2 Southern Cleveland Bay

Measured currents peaked at ca. 0.48 m/s on spring tides in March & April. Tides flood towards the S-SSW and ebb towards the N-NNE. At neap tides and with weak winds peak currents are below 0.1 m/s. Currents display a weak anticlockwise rotary nature, and weak residual currents occur towards the south. Current vectors were more variable than those of the Dump Site station or Middle Reef, as may be expected in a relatively shallow water site. However, the strongest residual currents were driven by strong S-SE regional winds, rather than the local wind-field.

3.1.3.3 Middle Reef

The tidal currents are rectilinear, controlled by the local bathymetry. The spring flood tide peaks at 0.4 m/s towards the WSW and the ebb slightly less towards the ENE. Westerly residuals tend to occur in reponse to strong regional SE winds (days 82-84), and even on spring tides (days 94-95). The significance of these residuals is discussed later in this chapter.

3.1.4 Dredge, Dump and Shipping Activities

These datasets were used in determining the likely origin of turbidity events around the dredge area and dump site.

These datasets were of limited use because the track plots of the dredge were not marked to distinguish the position of each specific dump event. We were able to define the suite of positions used in each 24 hour period, but this was insufficient to allow confident identification of some likely dump events, or confident description of their dispersal characteristics.

The dump site is 2.5 km wide and 3 km to 5 km long, thus it was pertinent exactly where within the dump site a particular dump event took place, for example; in January, the position of dump events varied by over 3 km in some 24 hour periods, thus a particular plume could have arrived at a nearby nephelometer at any time within a broad time window. A plume would take up to ca.4 hours to travel 3 km with a current of 0.2 m/s, thus a potential dump event might reach a nearby nephelometer within a time window of 4 hours. This made it more difficult to confidently distinguish a medium to low concentration near-bed turbidity event from natural events. Identification and interpretations of the characteristics of individual dump events would have been more confident with identification of the positions of each specific dump event.

The logs of shipping movements in and out of Townsville Port had insufficient detail of the timing of ship movements through the channel, and it was not possible to make a judgement on the contribution of shipping to water turbidity in Cleveland Bay.

3.2 Nature of the Sediments in Cleveland Bay

The nature of surficial sediments were assessed from a suite of Diver Driven Cores taken before dredging operations began and late in the dredging program.

3.2.1 Pre-Dredge Cores

'Seagrass' - Sites 1 - 3.

All sediments were heavily bioturbated. The sand fractions are comprised of equal proportions of carbonate and terrigenous grains and have a median size of medium to fine sand. There is a secondary grain-size mode of material finer than coarse-silt. The surface sediments at Sites 1 & 2 are firmer than at Site 3, possibly due to the action of waves influencing the bottom in shallower water. The soft, silty nature of the upper 12 cm of Core 3 implies that this may have been a relatively recent deposit.

'Dredging Area' - sites 5 - 7.

Sites 5 & 6 are east of the dredged channel. Surficial sediments are very soft at both locations. Site 6 is situated on the flank of the seaward end of Orchard Channel (a natural bathymetric feature) and the silty sediment probably reflected deposition in relatively quiescent conditions at the base of the channel. This is probably removed during spring tides and/or storms, conditions which produce the more shelly deposit beneath.

West of the dredge channel (Site 7) the sediment is strongly bimodal, formed of a very coarse sand to granule sized material, mixed with ca. 15% of material finer than coarse silt. The coarse fraction is dominated by terrigenous material (lithic fragments and quartz) probably derived from either Magnetic Island and/or erosion of the underlying pre-Holocene (> 10,000 yrs B.P.) and Holocene sediments. Around 15% of the coarse fraction is carbonate fragments, presumably representing material removed from the island's coastline and fringing reefs. This sediment is equivalent to the 'gravelly-mud platform' described by Davidson (1985) which fringes the lower reef slope around eastern Magnetic Island.

'Dump Site' - Site 4 and Sites A - F. Generally, these cores are similar, with 11-25 % of sediment finer than coarse silt, and comprised generally of a median grain size of ca.2.5 phi (180 µm). They are soft to firm poorly-sorted sediments, silty sands to sandy muds, the coarse fraction of which comprises 60-95 % carbonate fragments.

Variation in the grain size distributions is concentrated in the medium and coarse sand fraction, probably influenced largely by fragments of the shelly infauna. Site 4, towards the seaward end of the dump site, is compositionally similar but slighty softer, possibly due to having been deposited in deeper water, and thus less often stirred by waves.

3.2.2 Post-Dredge Cores

In places, dredging clearly changed the surficial sediments eg at the dump site (core E2). The dumping of dredged material produced a mixed array of sediment types in a small area, to a depth of at least 0.45 m, far different to the uniform or weakly-bedded stratigraphy of the natural surface sediments (Ohlenbusch, 1991; Carter *et al.*, 1993; Larcombe & Carter, unpublished data). Further, the presence of firm to hard sandy gravelly clay with lithic gravel in core E2 is strong evidence for the presence of Pleistocene sediments (ca. 18,000 yr B.P.). Away from the Sea Channel in outer Cleveland Bay, Pleistocene sediments are buried beneath between 1 m and >5 m of younger sediments (Larcombe, 1991, Carter *et al.*, 1993), and the dredging program required dredging to 13 m, involving the removal of up to 2 m of stiff Pleistocene sediment (Larcombe, 1991). Thus, the presence of Pleistocene material as clasts in non-bedded mixed type surficial sediments is strongly indicative of derivation from the dredge. At other core sites at the dump site the sediments in pre- and post-dredging cores are little different. Although taken at identical sites (fixed by G.P.S.) a difference of ca. 20 m is possible, thus our ability to comment in detail upon apparent changes between the nature of sediments at each site is limited, as there is no information upon small-scale spatial variation on bed sediments. However, the apparent variation in the sediments at these sites (away from the dump site) is of a nature not unexpected in shallow marine environments.

3.2.3 Conclusion

Sediments with a bimodal grain size distribution are common in Cleveland Bay, and are interpreted as representing the result of mixing (by bioturbation) of a layered stratigraphy, of sandy beds deposited during high energy periods (cyclones and storms) and more muddy beds deposited during calmer periods (Ohlenbusch, 1991; Carter *et al.*, 1993).

All sampled sea-bed sediments contained between 7 % and 40 % of material finer than coarse silt (ca. 4.7 ϕ or 38 µm). There is thus ample sediment within Cleveland Bay for resuspension. These observations are consistent with the samples described by Davidson (1985), Carter & Johnson (1987), Carter *et al.* (1993) and with unpublished data of Larcombe & Carter.

The bed material close to the bays of Magnetic Island contains less fine sediment, and in the bays themselves amongst the coral heads, there is very little muddy sediment available for resuspension. It would be expected that suspended sediment concentrations would be lower in these bays than in most of Cleveland Bay.

3.3 Product Datasets

3.3.1 Satellite Images

The satellite images provided of pre-dredging conditions (2/1/93) and dredging conditions (28/2/93) were draft versions only, and not calibrated for SSC (**Section 6 Remote Imagery**). However, we can note the widespread presence of linear features in the outer bay, which we interpret as *Trichodesmium* plumes, and the images have been referred to in interpreting data.

3.3.2 Aerial Photographs

Aerial photographs have been used to aid description and interpretation of natural and dredge-related conditions in Cleveland Bay. Some photos from Mapping and Monitoring Technology (MMT) were unable to be easily located within Cleveland Bay, and some photos were not easily related to the dredge or dump plumes. There was a general lack of photographs which combined the dump area with the coastlines. Low flight elevations (due to a low cloud base) are a cause of many of these problems. Additional photos were received from Queensland Department of Environment and Heritage (QDEH).

Aerial photographs were received for the following times and conditions:

MMT Photographs

Julian Day	Date Time	Tidal Range, Elevation & Condition
2	02/1/93 0900-1000	Neaps, ca. 1.7m (Port Datum), mid ebb
20	20/1/93 0900-1000	Springs, ca. 2.7m, early ebb
28	28/1/93 0900-1000	Intermediate, ca. 2 m, late flood
34	03/2/93 1100-1200	Intermediate, ca 2.4 m, mid-ebb
40	09/2/93 1200-1300	Springs, ca. 2.7 m, early-ebb
46	15/2/93 0900-1000	Intermediate, ca. 1.9 m, mid-ebb

QDEH Photographs

Julian Day	Date Time	Tidal Range, Elevation & Condition
36	05/2/93 0800-0830	Springs, 3.5 m, high water
36	05/2/93 1445-1530	Springs, 0.8 m, low water
40	09/2/93 1215-1245	Springs, ca. 2.7 m, early ebb
41	03/2/93 1100-1200	Intermediate, ca 2.4 m, mid-ebb
46	15/2/93 0930-1000	Intermediate, ca. 1.9 m, mid ebb
59	28/2/93 1100-1130	Neaps, ca. 1.6 m, mid ebb
76	17/3/93 1100-1300	Springs, ca. 1.7 m, mid ebb
85	26/3/93 1000-1030	Neaps, ca. 1.6 m, mid ebb
90	31/3/93 1000-1030	Intermediate, ca. 1.5 m, late ebb

3.3.3 Sediment Trap Data

This dataset was formed from the analysis of sediment trap array measurements. As emphasised in Chapter 8, sediment data traps give a very specific measure of sedimentation, unique to the type of tube, deployment site, and suite of hydrodynamic conditions which occur over a given deployment period. The tubes do not give any indication of the rates of sediment fallout from the water column, or any information on rates of resuspension. Even in net erosive conditions, sediment will fall into the sediment traps.

JANUARY - From sediment trap data, there was no measured effect of dredging operations on the rates of gross sedimentation at the sample sites in January. Data variation remained within 'natural' levels. However, the hydrodynamics and sediment dynamics of the water near the dredged channel and between the channel and Magnetic Island appears highly complex and this study has insufficient high density data to fully explain these data.

FEBRUARY - We interpret raised values at Sites 6 & 7 in early February as being in part 'dredge-related'. Sediment stirred and released by dredging near the nephelometer sites and during passage to the dump site probably contributed to the sediment load of the water in the area.

MARCH - No clear effects of dredging or dumping were present in the datasets of March, despite the intensity of dumping activities. Tidal currents alone appear to be relatively ineffective in creating high levels of SSC in Cleveland Bay (see below). However, the relatively calm seas which occurred during March appeared to cause relatively little sediment redistribution in Cleveland Bay.

APRIL - The rough weather in April was thus the first substantial period of swell to act upon a relatively large volume of dumped material. This combination may have been responsible for the pattern of widespread elevated SSCs shown by the nephelometers during the extended period of strong winds. We conclude that in April there was evidence for effects from dredging and dumping operations.

3.3.4 Intensive Water Sampling Data
The datasets of SSC from water samples taken in Cleveland Bay are shown in Chapter 8. Water samples were taken at mid-depth and at 0.5-1.0 m above bed using Niskin Bottles.

The calm conditions in March allowed an interpretation of SSC values and distributions with very low height swell, and generally small wind-waves:

- ☐ On high spring tides (9/3/93, day 68), which were just 3 cm below the highest astronomical tide for Townsville, the data allow the conclusion that mid-depth and near-bed SSCs created by tides alone rarely exceed 40 mg/l and mostly do not exceed 30 mg/l. The water column is vertically mixed by the spring tide currents;
- ☐ On extreme neap tides (30/3/93, day 89) mid-depth and near-bed SSCs in western Cleveland Bay did not exceed 8 mg/l. This finding is important in demonstrating that very low turbidities exist in Cleveland Bay under suitable conditions.

These conclusions are also supported by the nephelometer data below. They are also subject to the limitations noted below regarding organic and inorganic components of suspended sediment (Section 4.2).

3.4 Nephelometer Data - Variation in Near-Bed Turbidity

Data assessment comprised viewing graphical datasets produced by instruments at sites within 5 geographical areas (refer to Methods). There are a number of general points regarding these sites:

- ☐ The significant height of the swell component of the wave spectrum (wave period > 7 seconds) is the most important factor in controlling SSCs at the deeper water sites (Sites 3,4,5,6,7). The direction, speed and duration of the regional wind field is thus very important because, for example; strong persistent SE regional winds generate coast-parallel swell waves which refract into Cleveland Bay and cause resuspension of bed sediment over large areas.
- ☐ The significant height of the wind-wave component of the wave spectrum (wave period < 7 seconds) is the most important in controlling SSCs at the shallow water sites (Sites 8,9,10,11). Whether the bays of the southeast coast of Magnetic Island are exposed to or sheltered from the local wind direction is thus a major control in determining SSCs in these areas, for example; periods of NW winds tend to correspond to very low SSCs at all these sites.

- Tidal currents tend to enhance swell-induced SSCs in Cleveland Bay rather than cause widespread high SSCs by themselves.

- The controls upon SSCs at Dredge Area West (Site 7) ca. 1 km off Alma Bay are more complex, and appear to be influenced by processes of flushing of Geoffrey Bay and eddying at Bremner Point and adjacent headlands. Spring tides are likely to enhance these flushing processes (see Section 4.5). The identification of dredge-related turbidity events, such as the occurrence of coast-parallel 'tongues' of turbid water, was complicated by these natural processes. Processes within 500 m to 1 km of the coastline all along the southeast coast of Magnetic Island are likely to be similarly complex.

- The controls upon SSCs at Middle Reef (Site 13) are less clear, but appear heavily influenced by the presence of westerly residual currents through West Channel. These currents are induced by strong SE regional winds and advect turbid water from Cleveland Bay past Middle Reef.

- Dredge-related effects were identified in the nephelometer datasets, including underflows resulting from individual dump events, and entrainment and/or resuspension events from the sea-bed near the dump site and dredge area.

- No direct effects of dredging were clearly identified in any nephelometer datasets from the Magnetic Island sites (see also below).

- The nephelometer data were plotted on a logarithmic scale so that extremely wide ranges of SSC could always be plotted on the same scale. It was thus possible for example to view data from Rattlesnake Island (SSC <10 mg/l) on the same scale as data from close to the dump site where SSC's were often two orders of magnitude higher. Unfortunately, the logarithmic scale can be extremely deceptive. For example, a rise in SSC from 50 mg/l to 300 mg/l appears the same as a rise from 0.5 mg/l to 3 mg/l.

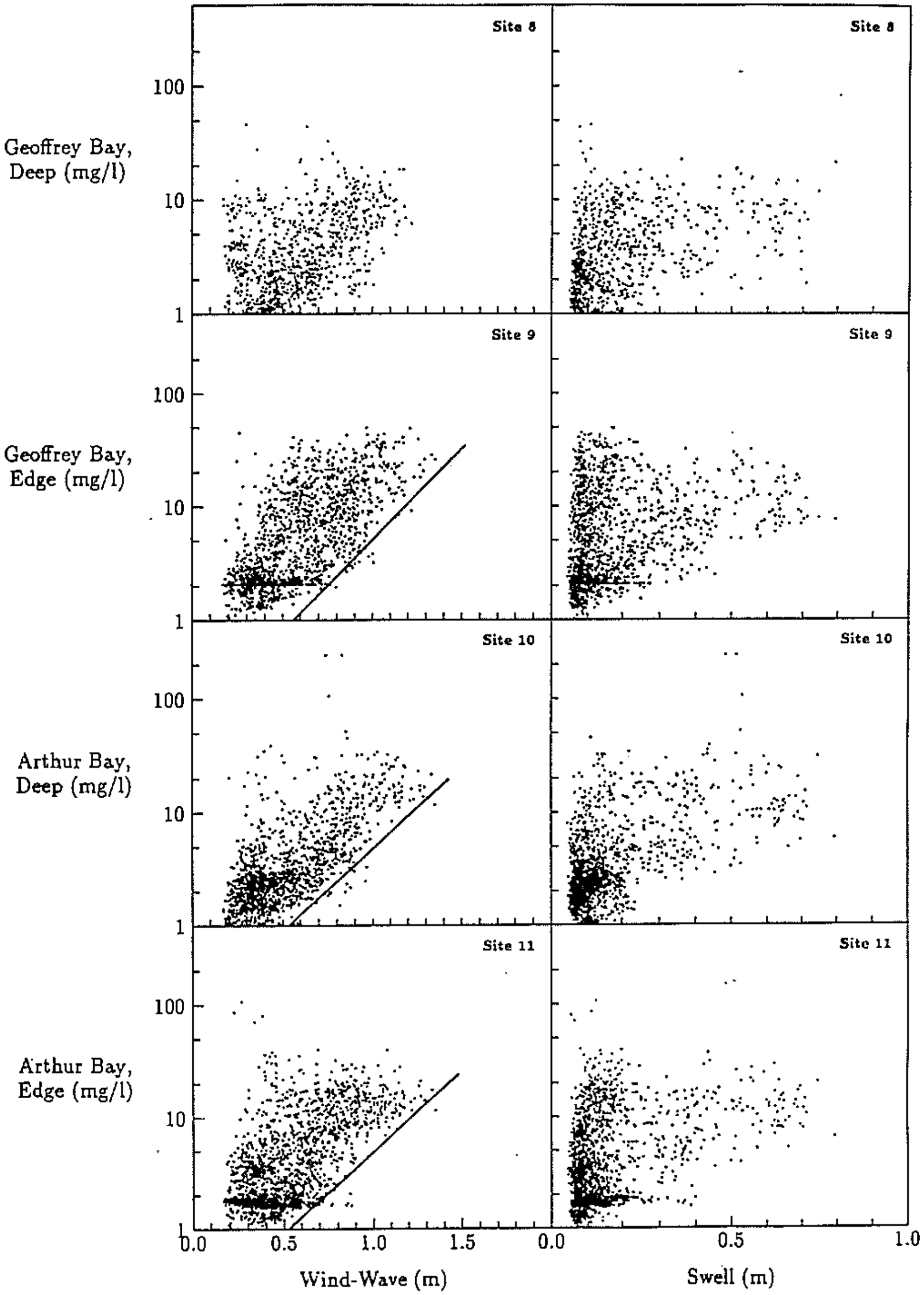
In order to determine the importance of various physical mechanisms in producing elevated SSC levels, scattergrams were plotted, for Pre-Dredge and Syn/Post-Dredge conditions, of various hydrodynamic parameters against SSC. Each plot for Pre-Dredge plots has up to ca. 500 data points, and each Syn/Post-Dredge plot has up to ca. 2500 points. Each point represents one hour, comprising the mean of one hour of nephelometer data with the hourly wave data from the Cleveland Bay Waverider site. Examples of the scatter plots are shown in Figure 3.2.

We believe that, on the basis of these data, there were no major widespread differences between the pre-dredge and syn/post-dredge conditions.

3.5 High Turbidity Events

Distinction of turbidity 'events' in the nephelometer datasets was been achieved by viewing time series data, noting spikes in the record (generally a few hours long) or more extended periods (1 day to a week or longer). In distinguishing events, we have assessed their likely cause. The near-bed nephelometers near the dredge area and dump site were most likely to record the passage of near-bed underflows and/or entrained suspended sediment. Potential dump event underflows were investigated noting the direction of the current, the likely time

Figure 3.2 - Examples of Scatterplots Showing Relationships Between Suspended Sediment Concentration and Wind-Wave and Swell



delay between the dump site and the nephelometer site (given the magnitudes of the current in the area), the rate of rise of SSC (very rapid compared to pre-dredging tidal signatures) and rate of decay, and the timing of the dump events. We were greatly hindered in assessing this information because the track plots of the dredge were not marked to allow distinction of the position of each specific dump event. Extra doubt was thus introduced in our interpretation of natural and dredge-related turbidity events.

3.5.1 Potential 'Dredge-Related' Turbidity Events

Below we briefly describe some turbidity events which may have been related to dredging activities. We have varying degrees of confidence in our interpretation of these events, and include some events that are more illustrative of 'natural' sediment dynamics. We used a set of subjective groups to denote the degree of confidence that the event or events were 'dredge-related'. The groups were:

NOT RELATED - We were certain that the turbidity event was not dredge-related;

VERY UNLIKELY TO BE RELATED - We were confident that the turbidity event was not dredge- related;

UNLIKELY TO BE RELATED - We judged that the turbidity event was not dredge-related;

INDETERMINATE - We could not judge that the turbidity event was dredge-related or not;

POSSIBLY RELATED - We judged that the turbidity event was dredge-related;

PROBABLY RELATED - We were confident that the turbidity event was dredge-related.

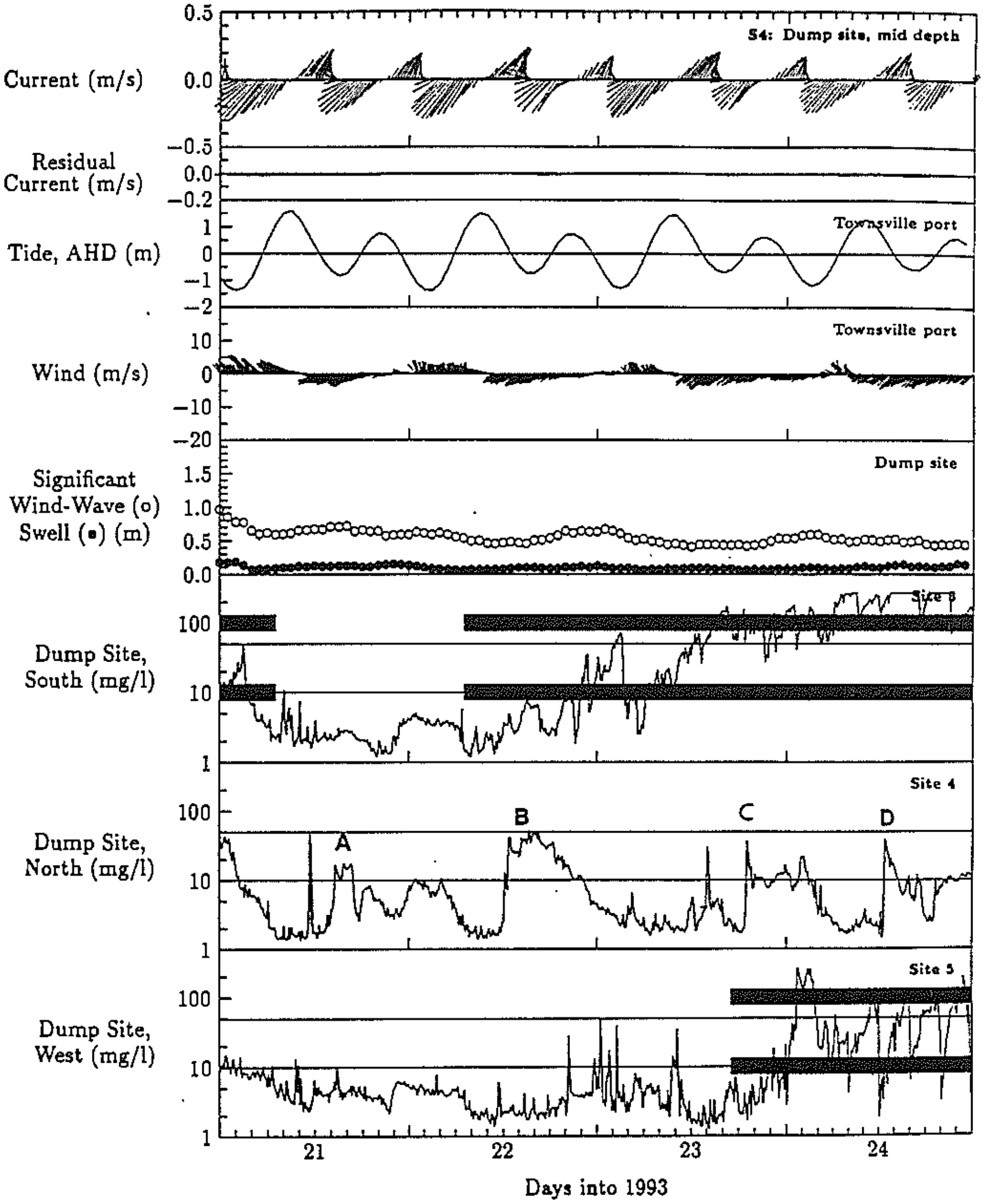
RELATED - We were certain that the turbidity event was dredge-related.

3.5.2 Examples of Events

January - Dump Site North (Site 4)
From days 20 to 27, fifteen turbidity events were potentially related to dredging activities (Figure 3.3). (These are selected examples only, for detailed examinations of other sites, please refer to the final report). These were approximately 20% of the 70 dump events for that period recorded in the dredge log. For half the time, tidal currents would carry plume events landward, away from the nephelometer, so this represented well over a third of the potential events that might be measured. Further, given the time period for which some events persisted, some were likely to be compound events, representing the product of two or more adjacent dump events. The turbidity events covered time periods of ca.30 minutes up to ca. 10 hours, and show peak SSCs of generally ca.50 mg/l. These concentrations were ca. 10 times that expected for similar hydrodynamic conditions at that site. Status - RELATED.

Middle Reef (Site 13)
SSCs were generally limited in variability, but showed sporadic short-lived peaks, generally less than 60 minutes in duration and up to over 100 mg/l in concentration, some of which could have been due to dredge or widely-dispersed dump plumes flowing westwards into West Channel. One potential dredge-related event was on day 26, of ca. 200 mg/l, which apparently flowed past Middle Reef for about 2 hours up to high water, and then flowed back again into Cleveland Bay. Separate events on day 23 were consistent with movement of a plume produced by dredging activities in the inner channel area, but two similar events on day 24 do not appear consistent with the timing and position of dredging activities.

Figure 3.3 - Nephelometer Readings for the Dump Site Showing Plumes Related to Dumping Events (Labelled A, B, C and D). Thick black lines represent data possibly affected by high value cut-off, sediment accumulation or biofouling.



Whilst this type of event was not exclusive to the post-dredging period, and may have resulted from the advection of plumes from the Picnic Bay area, it remains a possibility that dredging operations produced plumes which impinged upon Middle Reef. Status - INDETERMINATE.

February - Dump Site South (Site 3)
Short-lived spikes in the data (day 41-43) may have been real, but may also have been due to small animals moving across the lens of the nephelometer. Status - VERY UNLIKELY.

Some more gradual rises in SSC (e.g. day 33,) occured on ebb tides, which flow NE out of the bay, and were thus unlikely to be directly related to dumping events. Status - UNLIKELY.

March - Dump Site North (Site 4)
For the first 2 weeks of March, the pattern of variation in near-bed turbidity at this site was generally similar to that of Site 3, however, even on the spring tides the tidal signal was less clear, and daily minimal SSCs were raised. Some peaks on days 64-67 were probably non-hydrodynamic in nature, as were very spiky peaks on days 74-78. The troughs between spikes were not at 2 hour intervals indicating these data were not related to wiper operation. (Current evidence suggests these events had a good chance of being dredge-related). Status - POSSIBLY RELATED.

An overall rise and sustained period of high turbidity from days 79-84 was difficult to explain in terms of natural hydrodynamics. Levels of well over 100 mg/l were present for a period of 5 days where the hydrodynamics suggested that levels below 10 mg/l were present. Although instrument malfunction was a possibility, such an explanation was unlikely for three reasons:

1. There was a strong tidal signature on days 80 & 81, where turbidity lows occurred midway through the ebb tide and turbidity rose on the ebb tide;

2. There was a gradual return of SSCs to lower levels over a period of 12-18 hours on day 84, and;

3. There was negligible difference in the final reading of this unit with the first of a different unit emplaced on the 30/3/93.

Given the direction of the tide in the area, the nephelometer data is consistent with remobilisation of near-bed sediment from near the dredged channel and the path of the dredge to and from the dump site. Status - PROBABLY RELATED.

4. DISCUSSION

4.1 Amount of Suspended Sediment in Cleveland Bay

Water sample data on 21/4/93 indicated that the general SSCs in Cleveland Bay were ca. 50 mg/l. Estimating the area of the bay as 200 km², with an average depth of 5 m, a 50 mg/l SSC throughout the bay results in a total mass of sediment in suspension of 50,000 tonnes. Given that near-bed turbidities are likely to be higher, this figure is a low estimate.

4.2 The Nature of the Suspended Material

The organic and inorganic components of suspended sediments have different optical properties. Their relative proportions in the water column are known to be spatially and temporally variable. The organic matter content of surface waters in Cleveland Bay varies between 10% and 80% (Belperio, 1978). In central Cleveland Bay, under 'smooth and smooth to slight' sea conditions, the organic matter content is 30-50%, and under 'rough' seas 20-30%. These proportions may vary seasonally and with depth. Walker (1981) suggested that phytoplankton chlorophyll "a" concentrations are dependent on intermittent resuspension of bottom sediment, resulting from the enrichment of the water column with bottom interstitial nutrients (Walker & O'Donnell, 1981) and from resuspension of benthic microalgae. These effects may also alter the optical properties of the water column.

The nature of the suspended material in Cleveland Bay was not determined, which placed a degree of uncertainty upon the interpretations made.

4.3 The Value of Measurements

It is important to acknowledge the value of scientific measurements of the natural environment as contrasted to human perceptions. The human eye, photography and satellite images can be highly sensitive to subtle contrasts in suspended sediment concentrations. A true change in SSC of only 5 or 10 mg/l may appear as a clear contrast in most visual, photographic and satellite observations of sediment plumes etc. Similarly, a viewer on a nearby hill may 'see' a well-defined area of apparently very turbid water, when measurements prove little variation in turbidity and or low turbidities.

Remote optical methods of assessing water turbidity (visual observations, aerial photographs and satellite observations) tend to 'see' an integrated response from a few metres of water, and enhance tonal contrasts, thus a small quantity of sediment in the water can cause an apparent major discolouration. There were instances during this program where anecdotal evidence has suggested the presence of turbid plumes impinging on the reefs. It is quite likely that in these instances the 'turbid plume' contained SSCs of not more than a few mg/l.

Photography, satellite images and aerial observation only give information on the top few metres of water where suspended sediment concentrations may be considerably lower than close to the sea-bed (where sediment transport fluxes may be at their highest). Thus, one should not expect visual and aerial observations to necessarily correlate with near-bed measurements of SSC. In fact, there is generally minimal correlation.

4.4 Flushing of Cleveland Bay

The regional SE wind pattern drives residual movements of water at all three stations in Cleveland Bay. This is consistent with the study of Belperio (1978) who concluded that the entire water column in Cleveland Bay was 'essentially wind driven when the wind speed exceeds 7-10 m/s' (ca.13-19 knots)'. However, it should be noted that residual currents are controlled by both the regional wind field and the interaction of the currents with coastal morphology. Hence strong S-SE regional winds are capable of producing the following different residual current movements:

☐ At the dump Site current meter station - WSW;

☐ At the Southern Cleveland Bay station - S;

☐ At the Middle Reef station - WSW, through West Channel.

These directions are all consistent with the likely regional movement of mid-shelf waters driven northwards along the Great Barrier Reef lagoon by regional SE winds. The residual currents also move around Cape Cleveland and into Cleveland Bay, and within the bay, are consistent with a current parting aligned N-S in Cleveland Bay (as inferred by Carter et al. 1993). We conclude that the regional SE wind field drives large-scale along-shelf movements of water, which induces movement through Cleveland Bay. (Unfortunately, there were no long periods of strong regional northerly winds for comparison in the datasets collected for this project).

The residual currents present may flush Cleveland Bay quite effectively. The flushing time of the bay is estimated at ca. 4 days, using a residual current of 0.1 m/s. Residual currents may therefore have the useful effect of flushing the bay of suspended sediment, but, equally, may also cause sediment in the outer bay to be transported back into the bay in the long term. Flushing of sediment as a consequence of these currents is likely only for the finer particles which remain suspended sufficiently long, or which undergo repeated deposition and resuspension. The seasonal variation in winds may therefore be important in terms of sediment redistribution. In the winter, under the influence of the dominant southeasterly winds, sediment suspended in outer Cleveland Bay (e.g. from the area of the dump site) may move into the bay, whereas in the summer, which has more variable winds, suspended sediment may be flushed less quickly or even deposited within the bay at times. Sediment resuspension in the bay is probably increased in winter, due to the larger swell, and residual currents would tend to move the suspended sediment onshore, especially in southern Cleveland Bay. Ultimately it is likely to be deposited on the subtidal flats and mangrove swamps of southern Cleveland Bay, and the shallow relatively quiescent water of West Channel.

4.5 Flushing of Magnetic Island Bays

The rough outline of Magnetic Island may be a major contributory factor to the sediment dynamics of the bays and nearby waters. In response to strong tidal currents, the promontories shed eddies a few hundred metres to a kilometre out from the coastline. These eddies constitute a significant mechanism for the bays to be flushed of sediment, since, if wind-waves have resuspended material, the eddies are able to advect this turbid water offshore.

Under conditions of high swell and/or spring tides, the whole of Cleveland Bay is highly turbid. Later, when the swell reduces, deep water sites will tend to become less turbid, however, wind-waves (which are often present in the absence of swell) can maintain sediment in suspension in shallow water close to the islands. With a smooth coastline, a well-developed turbid coastal boundary layer may form, which has limited mixing with offshore waters (Wolanski & Ridd, 1990). However, with the presence of headlands, as on Magentic Island, the boundary is rapidly broken down into patches and increases flushing of the turbid coastal water offshore (Wolanski, *et al.*, 1984; see also Parnell, 1988). Thus, without these headlands, water turbidity close to the island might tend to be higher, as there would be fewer mechanisms to move fine sediment offshore out of the bays of Magnetic Island. Eddy generation may therefore be a mechanism by which bays are kept relatively clean.

4.6 Suspended Sediment Levels - A Biological Context

Here we address aspects of the physical regime of Cleveland Bay, and assess the potential impacts upon corals using other studies for comparison.

4.6.1 Local Studies

There are a set of established data regarding sedimentation and water turbidity around corals (Hopley & Van

Woesik, 1988). Those of greatest relevance in this study are listed below, with additional comments on this study where appropriate:

- Fringing reef corals appear to be adapted to moderate to high rates of turbidity and sedimentation. The data collected for this study, and geological considerations (see Section 4.6.4 below) would support this;

- Acceptable rates of sedimentation should be based on Australian data rather than from the Caribbean.

  The data from this study will contribute towards reassessment of these rates;

- Distinction should be made between chronic and acute turbidity stress on biological organisms.

  This is now less difficult given time series SSC data recorded over long periods;

- Prolonged SSCs of up to 30 mg/l appear to be acceptable in most fringing reef situations.
  The new data suggests this occurs regularly at Magnetic Island, but not at Rattlesnake Island;

- Acute levels of over 1000 mg/l may cause no permanent damage if maintained for no more than one or two tidal cycles and if not accompanied by high rates of sediment settlement.

  It is important that the actual level of SSC is considered in concert with the time period for which the organisms are subjected to it. The processes able to resuspend sediment (e.g. wind-waves, tides) and move the turbid water away from the coastal zone (e.g. wind-driven residual currents, tidal currents, headland eddies) are very important factors here. Levels of 1000 mg/l have not been measured at Magnetic Island in this study, even under rough conditions;

- Australian fringing reefs appear to flourish in areas where gross sedimentation rates over short periods may reach 200 mg/cm^2/day and may have chronic figures of 130 mg/cm^2/day. A threshold for chronic stress may exist at 150 mg/cm^2/day.

  Levels near these have only been recorded offshore, between the dredged channel and the dump site in February, although these are averages of ca. 14 days and it is likely that rates were higher in the short-term. There are no data within the Magnetic Island bays.

- Magnetic Island fringing reefs already withstand high sediment loadings. Suspended sediment levels of 115 mg/l and settlement rates of 120 mg/cm^2/day have been recorded.

Hopley & van Woesik (1988) reviewed local, regional and global data, and also measured turbidity levels in Nelly Bay. They found SSCs were dependent upon wind speed (their Table 2). In winds between calm conditions and 20 knots, at 1 m off the sea-bed, they measured:

- At south central Nelly Bay:
  50 m off the reef front, SSCs of 39.6 -58.0 mg/l
  20 m off the reef front, 42.0 - 68.7

- At north Nelly Bay:
  50 m off the reef front, 36.7 - 53.3
  20 m off the reef front, 40.3 - 71.6

- Off Bright Point:
  44.1 - 115.6

- At the southern end of Geoffrey Bay:
  44.3 - 76.9 mg/l

They also measured SSC at the water surface, which were very similar to the near bed data. Their data indicate that even under low wind speeds, water close to the reef can have relatively high turbidity (i.e. > 30 mg/l), consistent with values obtained in this study. They are even a little higher, for example; in March, SSCs just seaward of Magnetic Island ranged up to 42 mg/l, and 46 mg/l in Horseshoe Bay.

Due to the small quantity of data that can economically be taken using water samples, no clear pattern resulted from the data of Hopley & van Woesik (1988). The new nephelometer data presented in this study show that this was probably due to the naturally high temporal variability of SSC.

Collins (in McIntyre & Associates, 1986) reported sediment trap data on the upper reef slope at Nelly Bay of 30-120 mg/cm²/day, averaging 80 mg/cm²/day, and similar figures were found for Geoffrey Bay. Sediment trap data close to Magnetic Island appears to range from 2.6 to 360 mg/cm²/day and are generally less than 80 mg/cm²/day (Hopley and Choat, 1990). The reef slopes generally have higher sedimentation rates than the reef flat.

These data are consistent with data recorded in this study, which ranged between 9 and 62 mg/cm²/day at Middle Reef and Horseshoe Bay. These rates would imply little or no impact on corals at these sites. Data from within Cleveland Bay found in this study are also consistent with the conclusions of Hopley & Choat (1990).

The control site at Rattlesnake Island recorded 6 & 7 mg/cm²/day throughout the period January-April, suggesting no significant change in regional conditions.

4.6.2 Other Aspects

Dredging activities have been found to be detrimental to coral reefs. Bak (1978) studied a coral reef at 12-14 m depth in the Caribbean and noted decreased calcification rates on some corals, and whole or partial death of colonies. This was related to light levels reduced to less than 1% of surface illumination, and was simultaneous with the stimulation of sediment rejection behaviour by coral polyps.

Evidence for long term changes to coral communities as a result of dredging was presented by Dodge & Vaisnys (1977), who studied a series of shallow (2-5 m) coral reefs in Bermuda. From analysis of growth patterns in 100 living and 51 dead corals, they found a striking difference in the age structures of corals living in the dredged harbour: (1) with their older counterparts, and (2) with living communities away from the dredged area. They also found decreased coral skeletal densities and decreased proportions of living to dead coral skeletals in the harbour. The change in coral community age structure was related to the commencement of dredging in 1941-43. This interpretation was supported by a change in species distribution, where species more capable of removing sand-sized grains are now dominant in the harbour.

Historical records of sedimentation on coral reefs are few, and although useful conclusions have been drawn from measurements of terrigenous sediments and fulvic acids (Cortes & Risk, 1985; Isdale, 1984) regarding historical sedimentation events, apparently severe sedimentation events which may be caused by dredging operations may not be recorded in the coral skeleton. Brown *et al.* (1990) found that after a 9 month dredging operation, reef corals showed as much as a 30% reduction in living coral cover 12 months after the start of dredging. The reef recovered after a further 10 months. No evidence of the event was detected in cores of *Porites lutea* in terms of their growth rate, skeletal density or calcification rate. However, a major problem with this study was that no measurements of SSC were taken, and the implication of high community resilience to sedimentary events must be tempered.

Recently, Rogers (1990) reviewed the responses of coral reefs and other organisms to sedimentation and concluded that we are still unable to predict the responses of coral reefs and reef organisms to excessive sedimentation. Significantly, she noted that:

A. Measures of physical processes such as sediment transport are required to complement organism and ecosystem responses;

B. Long-term datasets are critical.

This project has provided excellent data on the first and it is to be hoped that similar studies will occur for which some dtasets are extended for a period of years following dredging.

4.6.3 Significance of New Technology

The technology to take frequent recordings of suspended sediment data over long periods has only just been developed (Ridd and Larcombe, 1994), and all previous data recorded in Cleveland Bay taken together forms only a tiny fraction of the data recorded for this project. Only now is there sufficient data to begin the description of the suspended sediment dynamics of Cleveland Bay; which is required to understand the data gained from sediment traps and water samples.

The large variations in SSC found by this project in the Magnetic Island bays mean that conclusions made by previous workers on the basis of spot water samples and sediment traps require reconsideration. The empirical 'thresholds' by which stress on biological organisms have previously been measured must now be replaced by data which incorporate time series measurements of water turbidity. Previously poorly known factors such as the duration for which certain SSC levels are exceeded can now be accurately quantified, and the controls of water turbidity and hence the controls upon the biological responses can be better assessed. This study is a pioneer in this field.

4.6.4 A Geological Perspective

Intertidal *Porites* corals have been growing in Nelly and Picnic Bays for over 5000 years (Chappell, *et al.*, 1983). The geological evidence clearly indicates the presence of extensive mangrove swamps in the area which now forms Cleveland Bay over the period 8500 to 5000 years B.P. (Carter & Johnson, 1987; Tye, 1992; Carter *et al.*, 1993; Larcombe & Carter, unpublished data). Mangrove systems now fringe Cocoa, Crocodile, Alligator, Sandfly and Ross Creeks, and the Ross River. In the last 5000 years, up to 5 m of muddy sands and sandy muds have accumulated within Cleveland Bay, in a similar style of sedimentation to that in Upstart Bay, Bowling Green Bay, and Halifax Bay. Both the general coastal geology and the muddy nature of the last 5000 years of sedimentation are regional features.

We conclude that in the last 5000 years, the turbidity of water in Cleveland Bay has probably been similar to modern levels, and the corals which live around Magnetic Island have historically lived in such conditions. It is also important to note that there are no data on the large-scale natural changes which may have occurred in coral communities in the geological past, and which may be occurring at present, thus distinction of 'natural' variation versus 'dredge-related' variation is complex and difficult.

The nephelometer datasets show that even when large waves and spring tides are present in Cleveland Bay, and presumably similar conditions exist in Halifax Bay, SSC levels at Rattlesnake Island remain very low, below 10 mg/l. This may partly be due to the southerly aspect of this site, but is also probably related to the nature of the sediment nearby. The surface sediments of Cleveland Bay thin out at the mouth of the bay (Carter *et al.*, 1993) beyond which the surface sediments are formed of a shelly gravel which characterises the mid-shelf of the central Great Barrier Reef shelf (Harris *et al.*, 1990; Ohlenbusch, 1992). A similar coast-attached prism of muddy sand is present in Halifax Bay, but thins out near Rattlesnake and Herald Islands, and at the Rattlesnake Island study site, the bed was formed of coral rubble. Thus, near Rattlesnake Island, there is limited fine sediment available for resuspension and it is thus not surprising that it has lower turbidity water than Cleveland Bay. This has almost certainly been the case for several thousand years.

4.6.5 Conclusions

On the basis of the data received, suspended sediment concentrations and apparent gross sedimentation rates are consistent with data collected by other workers in Cleveland Bay. None of the recommended limits of sedimentation and turbidity of Hopley & Van Woesik (1988) for reef flat and reef front locations at Magnetic Quay were exceeded at any nephelometer sites in this study. The nature of the data collected in this study are of the type which will allow better definition of such "limits" in the future.

4.7 Summary of Impact Status

4.7.1 Status During Dredging

In January, north of the dump site, dump event underflows produced near-bed suspended sediment concentrations up to 10 times that expected for non-dredging conditions. This is likely to have been the situation throughout the dredging program. In February, March and April, we are confident that SSCs in the area between the dump site and the dredging area were raised as a consequence of dredging activities to levels not likely to be obtained under similar hydrodynamic conditions without dredging. The time scale of these impacts were in the order of hours to days.

Our judgement is that there was no major impact in terms of near-bed SSC, either generally in Cleveland Bay, or at Middle Reef, Geoffrey Bay and Arthur Bay.

4.7.2 Future Status

The most likely future impacts will result from remobilisation of dumped material from the dump site. This may take place either as chronic leakage under low to medium-level hydrodynamic conditions, or as events under major storms or cyclones. In the area at the dump site and for some distance to its SW, SSCs are likely to be raised above natural levels for a considerable period of time (weeks to years).

In some situations, sediment deposits which are not in equilibrium with the hydrodynamic regime have the potential to remain over long periods of time due to 'armouring' of the surface. In brief, this process operates on sediments with a variety of grain sizes, whereby the extant hydrodynamic processes remove finer grains from the sediment surface, leaving a layer of coarser grains which are less likely to be remobilised; this layer 'armours' the remainder of the deposit and reduces the potential for further erosion.

However, post-dredging cores taken at the dump site suggest that no armouring of the dumped material had occurred probably because the dumped material contains little coarse-grained material. Further, the natural infauna of Cleveland Bay thoroughly mixes the surficial sediments to depths of ca. 0.3 m. There is thus the likelihood of chronic leakage of sediment from the dump site for a period of years, and for more intense erosion events by the large swell generated by cyclones.

The potential consequences of chronic leakages and intense erosion events are unknown. Some sediment is likely to be flushed from the bay, but some may be deposited in environmentally sensitive areas. Subtidal flats containing seagrass and mangrove swamps are the major areas of sediment accumulation in Cleveland Bay.

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HYDRODYNAMIC MODELLING

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EXECUTIVE SUMMARY

The Marine Modelling Unit (MMU) of the Department of Civil and Systems Engineering, James Cook University of North Queensland, has been involved in four separate studies relating to various aspects of dredging and spoil dumping by the Townsville Port Authority (TPA). This work has concentrated on the modelling of hydrodynamic effects, and has mainly been directed towards a better understanding of the processes affecting the transport of suspended sediments by the movement of water within Cleveland Bay.

The first study modelled the tidal and wind-driven circulation of Cleveland Bay under a number of specified wind forcing scenarios. These techniques were then applied to the flushing of Cleveland Bay in the second study, via modelling of the trajectories of neutrally buoyant particles released in the dredged channel. The third study, required the development of new numerical forecasting tools for predicting possible problems associated with the movement of suspended sediment during dredging operations. The final work was a three-dimensional modelling study of the movement of suspended sediment from the dump site.

The hydrodynamic models for Cleveland Bay are driven by astronomical tide, direct forcing by wind stress at the sea surface, and by influences of the East Australian Current. Nonlinear interactions, through bottom friction, have a significant influence on the currents and hence on the extent of particle movement. In the third study, attention was given to methods for representing actual (as opposed to pre-specified) synoptic-scale winds, as well as the influence of the sea breeze. To avoid the problems commonly associated with open boundary conditions, the fine-scale model of Cleveland Bay is nested within two successively coarser-scale models.

In the 2D simulations, the released particles are moved essentially along the isobaths by wind-induced currents. Movement of particles occurs in an anti-clockwise sense around Magnetic Island, except when the wind direction is from the north or northwest. Although this general description applies during the weaker neap tides, three additional effects are noted during spring tides. Nonlinearities associated with the larger spring tidal currents diminish the strength of the wind-induced currents and hence reduce the nett movement of particles. Secondly, the larger excursions associated with spring tidal currents can move particles into different current regimes of the bay, and hence their ultimate destinations can be altered significantly. Thirdly, spring tides cause increased shore-normal transport of water. This can bring particles closer to sensitive areas on Magnetic Island.

Comparisons of the results of the forecast model with those of the later hindcast emphasised the importance of accurate wind field specification. This part of the modelling process remains an area where more reliable inputs are essential. The wind field in the forecast model consisted of two components – a spatially uniform but time dependent synoptic-scale wind, and a sea breeze model based on harmonic analysis of nearshore wind data.

In the final study, a 3D model of Cleveland Bay is used to determine the sensitivity of particle transport to the location of dredge spoil dumping. This model indicates that three-dimensional effects can be important in an area such as Cleveland Bay, where both tidal and wind-driven currents are significant. The sensitivity study showed that particles released in the deeper waters at the outer edge of the dump site have significantly less impact on Magnetic Island than those released closer to shore.

1. INTRODUCTION

The Marine Modelling Unit (MMU) of the Department of Civil and Systems Engineering, James Cook University of North Queensland, has been involved in four separate studies, each relating to various aspects of the harbour dredging and spoil dumping program of the Townsville Port Authority (TPA). This work has concentrated on the modelling of hydrodynamic effects, and has mainly been directed towards a better understanding of the processes affecting the transport of suspended sediments by the movement of water within Cleveland Bay.

During the planning stages for the TPA dredging program, attention was drawn to the possible deleterious effects of the dredging on coral colonies within certain of the bays on Magnetic Island. The possibility was raised that suspended fine sediments, released by the dredging operations, could lead to increased turbidity levels in these bays over substantial periods of time. The consequent decrease in light levels available to the corals may stress them significantly, especially since the dredging was scheduled for summer, when stress levels in the coral could be already high. An additional concern was also raised that seagrass beds in the southeast of the bay might also be affected by sediment.

The first work, the report by Mason *et al.* (1991), hereafter MBH1, studied the tidal and wind-driven circulation of Cleveland Bay, under a number of specified wind forcing scenarios. The techniques in this report were extended to a study of the flushing of Cleveland Bay in Mason *et al.* (1992 – MBH2) via modelling of the trajectories of neutrally buoyant particles released in the dredged channel. The third component, Mason (1993), involved the development of new numerical forecasting tools for predicting possible problems associated with the movement of suspended sediment during dredging operations. All of the above used two-dimensional (2D) modelling techniques, as discussed in Section 2.1. The final work, Mason and Bode (1993), was a three-dimensional (3D) modelling study of the movement of suspended sediment from the dump site. The sensitivity of particle trajectories to variations in the location of dumping *within* the confines of the designated dump site formed the major focus of this component. A summary of some of the above work was also provided in Bode *et al.* (1993). Since a number of the modelling techniques used are common to all these reports, the discussion naturally tends to cover essential aspects of all four studies.

The hydrodynamic models are driven by various combinations of the astronomical tide, direct forcing by wind stress at the sea surface, and by the nearshore influences of the East Australian Current. In the third study, Mason (1993), attention was also given to methods for representing actual (as opposed to pre-specified) synoptic-scale winds, as well as the influence of the sea breeze. In order to avoid the problems commonly associated with open boundary conditions, the fine-scale model of Cleveland Bay is nested within two successively coarser-scale models. The outer grid encompasses the entire width of the continental shelf; the intermediate scale model covers Halifax, Cleveland and Bowling Green Bays.

2. METHODOLOGY

Only the essential details of the numerical models and model grids will be presented in this section. Further details may be found in the references cited above. The boundaries of the innermost grid described here were used in all studies except the first. However, the differences, which involve only minor increases in the extent of the grid, will not be covered further.

2.1 Hydrodynamic Model

Except for the final (3D) study, the equations of motion that are solved numerically are the conventional two-dimensional (2D), depth-integrated, nonlinear long wave equations, describing conservation of momentum and mass, in a Cartesian coordinate system rotating with the earth. The prognostic variables are the free surface elevation η, and the two components (U,V) of horizontal transport or depth-integrated velocity. These are specified on a square, spatially staggered finite difference grid (the Arakawa 'C' scheme), as described for example in Sobey *et al.* (1977). The equations are solved by a fully implicit splitting procedure, similar to that of Wilders *et al.* (1988), but incorporating a number of significant differences and improvements (Bode & Mason 1994). A pre-conditioned conjugate gradient-squared method is used to solve the difference equations. This has led to a fast, efficient and stable scheme, which can be used successfully and economically over a wide range of spatial scales. Accepted 2D modelling practice is used to parameterise bottom stress and surface wind stress by quadratic friction laws. Tidal forcing (see Section 2.4.1) is imposed by specifying a time series of η along the outermost open boundary. Differences between the 2D and 3D model formulations are discussed briefly in Section 2.1.3.

2.1.1 Nested Grids

The main rationale behind the use of nested grids is the need to overcome open boundary condition problems, which are commonly encountered in limited area, fine-scale modelling. By means of nesting, the fine-scale Cleveland Bay grid is linked to the dynamics of the continental shelf, so that open boundary problems are largely transferred further afield, where: (i) they tend to have negligible influence on the evolution of model solutions in the region of interest, as is the case when the alongshore open boundary is located in deep water off the continental shelf; (ii) the nearshore region is linked by a *dynamic* coupling with the waters of the outer shelf, which play a major role in the dynamics of low frequency wind-driven motions (periods of the order of several days), rather than the alternative, which involves the imposition of largely artificial open boundary conditions close to the area of interest; and (iii) the extensive range of tidal data from the shelf region can be utilised, either for boundary conditions or model verification.

The coarsest resolution model, Grid A, is shown in Figure 2.1. It extends approximately from Mackay to Cardwell, and seawards past the edge of the continental shelf, with a spatial resolution of $\Delta s = 5$ nautical miles (nm). Figure 2.2 shows the intermediate Grid B (Halifax, Cleveland and Bowling Green Bays), which has a spatial resolution of $\Delta s = 1$ nm.

The innermost Grid C is centred on Cleveland Bay, with a resolution of $\Delta s = 1/5$ nm (370m) – see Figure 2.3. All grids are orientated at 50 degrees anticlockwise to true north. Figure 2.3 also shows features such as coastal boundaries, bathymetric contours (in metres), the original extent of the dredged Platypus and Sea Channels, and 'Site 1', where field data have previously been collected for model calibration purposes, as discussed by Nielsen (1990).

Figure 2.4 shows the computational grid outline and includes model boundaries, the area of the shipping channel from which particles were released in the second study (MBH2), as well as the eight areas around Magnetic Island in which model particle numbers were monitored in MBH2.

Figure 2.1 Grid A, with resolution of 5 nm. Also shown are the boundaries of the nested grids B and C, with respective grid spacings of 1 nm and 1/5 nm.

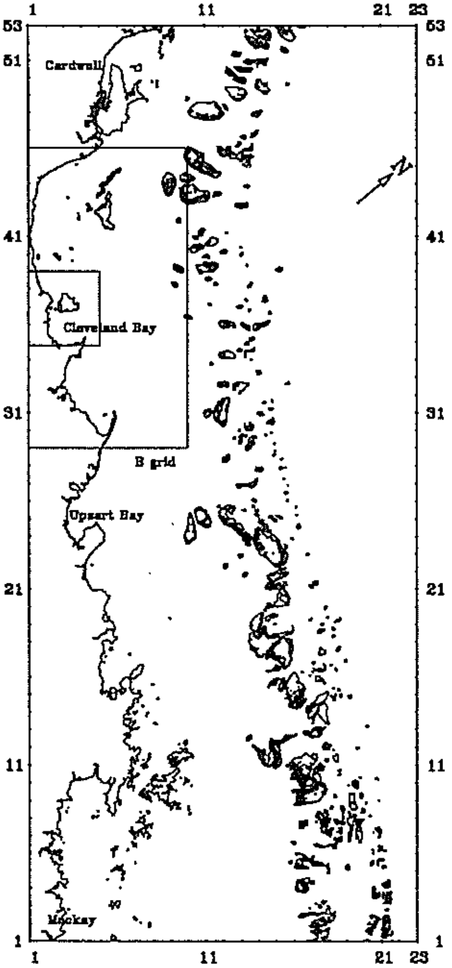


Figure 2.2 Grid B, with resolution of 1 nm. Also shown is the boundary of the nested grid C, with a grid spacing of 1/5 nm.

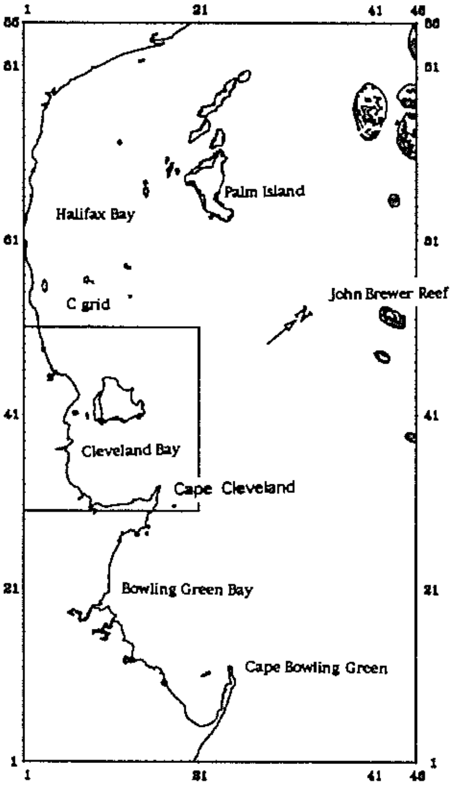


Figure 2.3 Grid C, with resolution of 1/5 nm. Also shown are bathymetric contours (metres) and the shipping channel.

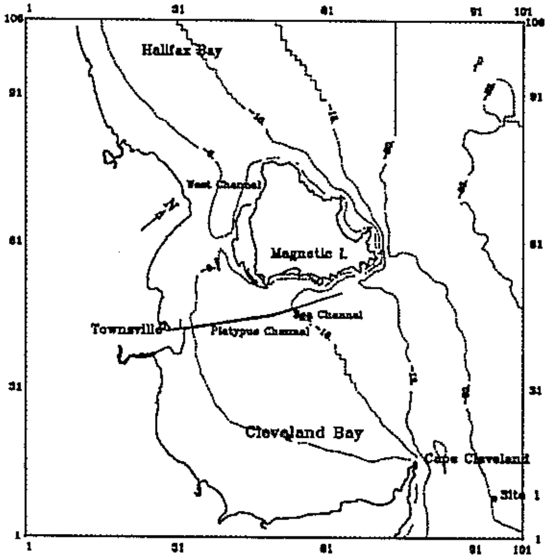
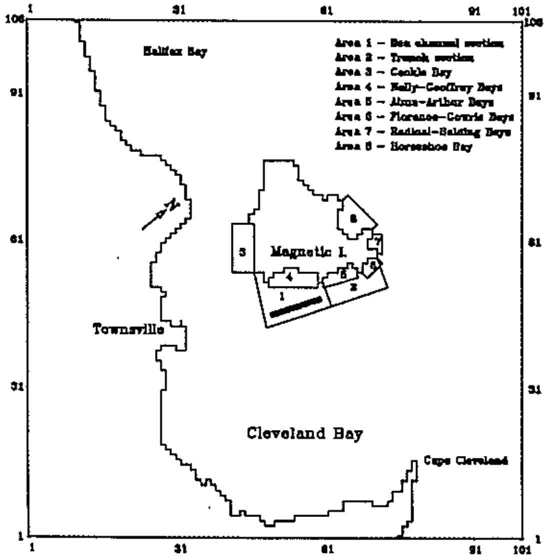


Figure 2.4 Computational boundaries for Grid C Also shown are the eight regions around Magnetic Island where particle numbers are monitored.



An additional advantage of the nested formulation is that the continental shelf scale (A) grid has permitted the inclusion of a simulated East Australian Current (EAC) on the shelf. This work, which was first implemented in MBH2, is discussed further in Section 2.4.2. As a result, it has been possible to model the spatial variations of this current system in the vicinity of Cleveland Bay and Magnetic Island with more confidence.

2.2 Particle Tracking Model

All studies except the first were set up to determine the likely destinations of the suspended *fine* sediment released into the water column by dredging or dumping operations. Under normal conditions this sediment should remain suspended for a number of days before being advected out of the region or else settling to the bottom. The precise duration of this intervening period will, of course, depend on many factors, chief among which are the size distribution of the sediment particles, as well as the strength of the prevailing winds and consequent surface wave activity. It is this very fine sediment (not bed load) that will tend to be advected passively by water currents, and which could cause problems for the local reefs, through the diminution of sunlight reaching the live corals. The suspended sediment was modelled as neutrally buoyant particles, released at specified times and locations, and advected passively by the computed currents. The effects of turbulent diffusion associated with the three-dimensional nature of the currents (thus leading to shear dispersion) is treated by a random walk procedure in the 2D hydrodynamic models. In the 3D models, however, the full velocity field is explicitly calculated and no such procedures are required. The instantaneous positions of each particle were obtained by numerical integration of a pair of ordinary differential equations, as detailed in MBH2.

The main areas of concern in MBH2 were the bays of Magnetic Island, adjacent to the dredged channel. It was decided in that study to delineate eight sub-regions, most of which were close to the release area – see Figure 2.4. The scope of that study specified that particle releases were to be performed at both neap and spring tides.

2.3 Three Dimensional Modelling

Unlike the first three studies (MBH1; MBH2; Mason, 1993), the work described in Mason and Bode (1993) used a three dimensional hydrodynamic model. That is, the horizontal velocity components, responsible for the passive advection of the particles, can also vary with depth. The 3D model requires the solution of a much more complex and computationally expensive set of equations, even in the case of homogeneous (constant density) water, the situation modelled in Mason and Bode (1993). Ten levels in the vertical were specified in an equally-spaced sigma-coordinate system. This involves a mathematical transformation of the total depth of the water column onto a layer of constant thickness, using a new vertical coordinate, σ. Hence these models follow the sea bed terrain. Note also that the vertical velocity component is computed in the 3D model.

An integral part of the 3D computations is that horizontal shear stress is calculated through the depth of the water column. This contrasts with the case of the 2D model, where stress terms are applied only at the surface (specified wind stress) and the sea bed (bottom friction). To compute shear stress, the *vertical eddy viscosity, K*, is required. In Mason and Bode (1993), a simple constant K model was used, with $K = 0.005$ m²/sec. This value is at the lower end of the range typically suggested in the literature for this type of environment (Fischer *et al.*, 1979; Csanady, 1982).

2.4 Model Forcing

Three modes of forcing are used in the various studies: astronomical tide, wind stress, and the EAC. Tidal and EAC forcing are introduced by specifying water levels at the open boundaries of the outermost (A) grid. Wind stress is applied to all three grids as a direct forcing term in the horizontal momentum equations. As well as the wind stress term, the solutions in the nested inner grids B and C are forced via the values of η, which are transferred to their open boundaries from the respective outer grids, A and B. The model forcing is fully nonlinear (all three forcing functions are applied *simultaneously*, rather than using linear superposition of the individual solutions). This leads to a more realistic representation of the dynamics, particularly for effects that arise from the quadratic bottom friction.

2.4.1 Astronomical Tide

The tidal model uses a total of ten diurnal and semi-diurnal tidal constituents. In order of increasing frequency, these are: O_1, P_1, K_1, ${}_2N_2$, m_2, N_2, n_2, M_2, S_2 and K_2. At Townsville, these constituent amplitudes range from 0.0427 m (n_2) to 0.7357 m (M_2). We estimate that these ten frequencies constitute approximately 95% of the total tidal variance in the region of Cleveland Bay. Excellent agreement has been obtained between the model results and field data, for both tidal elevations and tidal currents. More detail can be found in MBH1 and MBH2.

2.4.2 East Australian Current

The EAC is a poleward flowing western boundary current, which runs principally along the edge of the continental shelf, but can also influence near-coastal currents (Middleton, 1987). The strength of the EAC varies over very long time scales, being influenced by large-scale seasonal and inter-annual forcing, chiefly via the winds on a scale at least as extensive as the south-west Pacific Ocean. It can therefore be treated as an essentially steady current for the present purposes. Although its effects are relatively weak near the coast off Townsville, the current is essentially uni-directional, and may be important in the net transport of matter suspended in the water column. Such low frequency currents are essentially geostrophic, and thus flow parallel to the isobaths (Pedlosky, 1987).

Data on the EAC near the coast are not readily available, as such ultra-low frequency signals can only be analysed adequately from long-term current meter records. Andrews (1983) reported on low frequency currents in the mid-shelf region near John Brewer Reef, based on a 12-month mooring. He found currents of approximately 5 cm/sec in winter and 8 cm/sec in summer. Some indirect evidence of a uni-directional and essentially steady current in the region of Cleveland Bay, was found by comparing model output and current meter data at Site 1 (Figure 2.3). However, records were not of sufficient duration to permit any definitive conclusions to be made about the strength of this current. In this study the EAC has been modelled by applying constant alongshore and cross-shelf pressure gradients (variations in η) to the boundaries of the A-grid. The model was then calibrated to obtain peak current speeds at Site 1 of approximately 9 cm/sec. Since the current is relatively weak, its strength is modulated tidally through the effects of quadratic bottom friction (see Section 3.2.1).

2.4.3 Wind Stress

Prevailing winds through most of the year tend to blow from the southeast. Winds from the north and northeast are more common in summer months, when there is also greater variability in wind strength and direction. In the first two studies, six different wind fields were used. Directions ranged clockwise from north-westerly to southerly, and a constant wind speed was specified for each simulation. Space limitations mean that only limited results of the wind-forced modelling are presented here. In MBH1, MBH2 and the 3D modelling (Mason and Bode, 1993), a number of simplifying assumptions are made about the specification of the wind field: (i) no sea breeze or land breeze is modelled; and (ii) a constant wind stress (spatially and temporally) is used for each simulation, so that topographic and synoptic influences are excluded.

These are obviously major simplifications, but given the lack of data and basic knowledge on small-scale and mesoscale meteorological phenomena in the Townsville region, it is a challenging exercise to incorporate these additional effects into the modelling. Clearly, a major research effort would be needed to provide accurate and reliable information on meteorological forcing. A recent study (Brink *et al.*, 1994) finds that deficiencies in the specification of wind forcing at small spatial scales constitute perhaps the major cause of inaccuracies in coastal and shelf circulation models. Nevertheless, the third study (Mason, 1993) set out to address some of these questions. This work was completely different in concept and design from the others. Its aim was to *forecast* particle trajectories during the actual dredging operations. We have already identified the synoptic-scale wind fields and the sea breeze as the major time-varying forcing factors which needs to be specified. This is particularly so in the case of a forecast model.

2.4.4 Synoptic Scale Winds

To obtain realistic wind fields on the scale of hundreds of km, use was made of data and predictions supplied by the Bureau of Meteorology, Townsville. The Bureau supplied six-hourly synoptic-scale winds for a period of four days prior to commencement of the simulation. A forecast for a further four days was also supplied. Although time-varying, these winds were still spatially uniform.

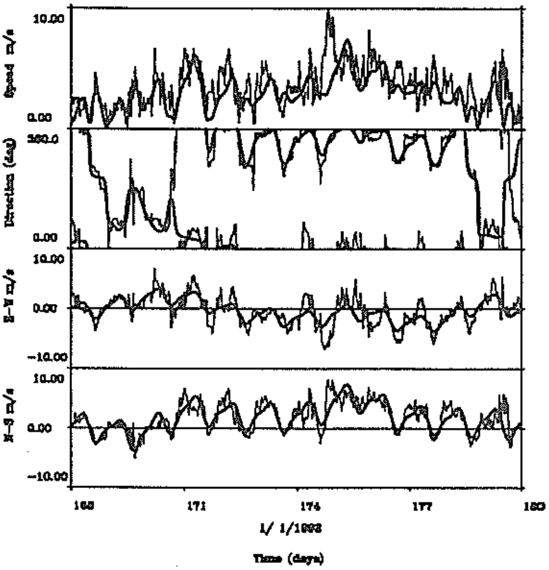
2.4.5 Sea Breeze Modelling

Even the minimum amount of observation will show that the mesoscale wind field in Cleveland Bay and around Townsville and Magnetic Island is complex, due to the topography and geometry of the coastline. To obtain a realistic representation of the spatial and temporal structure of the local winds would require, at least, the construction of a mesoscale atmospheric model. For the present work, a simple but reasonably effective model was conceived to describe, in an average sense, the major temporal structure of the sea breeze.

The sea breeze cell is dominated by a 24-hour signal, along with higher harmonics. The existence of this type of temporal structure made it seem logical to apply harmonic analysis to the wind data, which is given in vector form. The aim is to extract the magnitude and phase of both directional components (north-south and east-west), for the major (diurnal) sea breeze signal and its higher harmonics. A tidal analysis package with redefined tidal frequencies (e.g. periods of 24, 12, 8, 6 hours, etc.) allowed the analysis of six months of Cleveland Bay wind data. This resulting sea breeze constituent information can then be applied to a tidal prediction package to predict a modelled sea breeze. As with tidal currents, any sea breeze constituent in this model can thus be represented in the form of an ellipse. For example, the diurnal constituent has the following properties: magnitude of major axis is 2.43 m/sec; magnitude of minor axis is 0.04 m/sec; orientation of major axis is 211° clockwise from north; phase is 267° (i.e. peak diurnal signal at 1750h).

Figure 2.5 provides a comparison of this sea breeze model against data. The sea breeze model was constructed by firstly applying a low pass filter (50 hour cutoff) to the data and then adding vectorially the predicted sea breeze. Note that the harmonic content of this sea breeze model is assumed to be constant over any period, in a time-averaged sense. As seen in Figure 2.5, the sea breeze model (heavy curve) produces a surprisingly good fit to the raw data. Although there are obviously exceptions to this broad statement, both the wind speed and the major directional changes are represented well.

Figure 2.5 Comparison of raw wind data (light curve) with that provided by the vector sum of the low-passed measured winds (50h cutoff) and those from the sea breeze model (heavy curve).



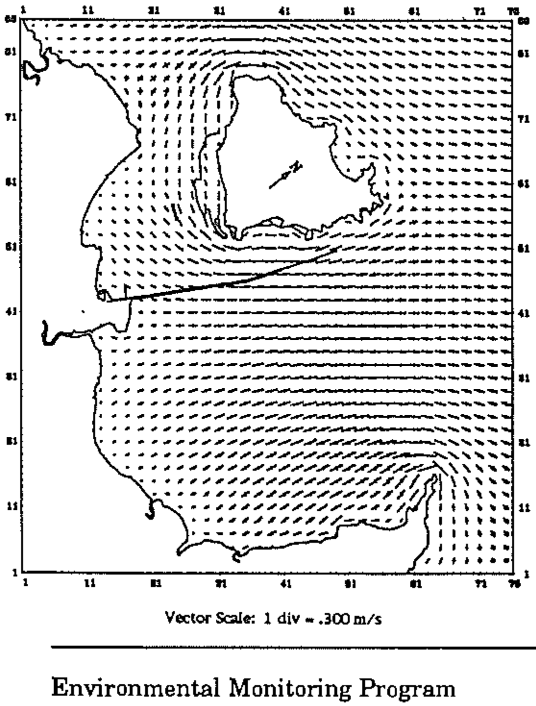
3. RESULTS

3.1 Tidal and Wind-drive Circulation in Cleveland Bay

This part presents a brief summary of some of the modelling results from the first of the four studies (MBH1). As well as tidal forcing, only constant wind speed scenarios were modelled. The EAC was not included and no particle tracking was performed. Although combined wind and tidal modelling was performed in MBH1, only separate tidal and wind-driven results are presented here, in order to delineate the major structure of the circulation patterns in Cleveland Bay, associated with each of these two components.

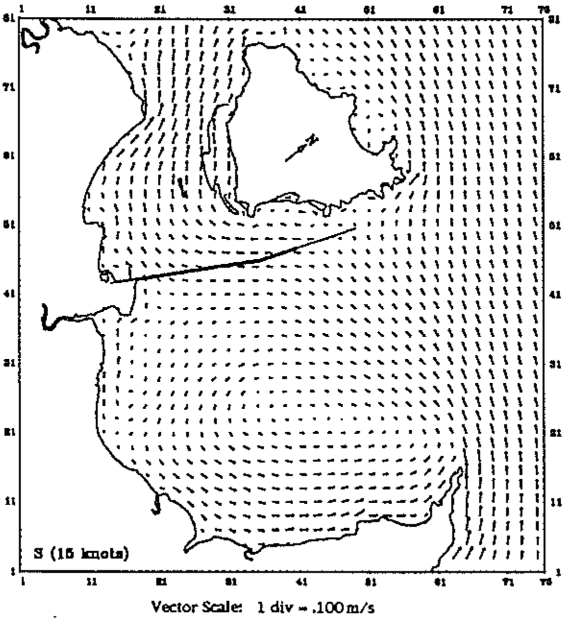
Figure 3.1 shows tidal ellipses for the M_2 constituent over the C grid. The length of the semi-major axis of the ellipse gives the maximum M_2 current. The directions of the major tidal streams can be clearly seen. Over most of Cleveland Bay, tidal ellipses are highly eccentric. That is, the currents tend to flow directly into and out of the bay, with little tendency towards rotation. As a general rule for Cleveland Bay, peak currents for spring tides can be obtained by doubling the M_2 values. The spatial pattern for the M_2 tide is also closely representative of that for the full tidal signal.

Figure 3.1 M_2 tidal ellipses for the C grid, drawn at every second grid point in each direction.



In accord with the scope of the project in MBH1, five different wind-driven cases were modelled, using a uniform wind speed of 15 knots: southerly, south-easterly, easterly, north-easterly and northerly. For each case, the model was run on Grids A, B and C in succession, until a steady state was reached. Figures 3.2 to 3.6 show the current patterns on the C grid, for all five cases.

Figure 3.2. Steady-state C grid currents for constant southerly wind speed of 15 knots. Vectors are drawn at every second grid point in each direction.



Certain properties of the wind-driven currents are immediately apparent. In all cases except northerly winds, the basic direction of the flow is towards the north-west. The southerly wind case (Figure 3.2) is characterised by a large eddy in Cleveland Bay. Figure 3.3 shows currents for the dominant south-easterlies case. There is a basic north-westward movement of water, both through West Channel and past the north-easterly tip of Magnetic Island. A

Figure 3.3 Steady-state C grid currents for constant south-easterly wind speed of 15 knots. Vectors are drawn at every second grid point in each direction.

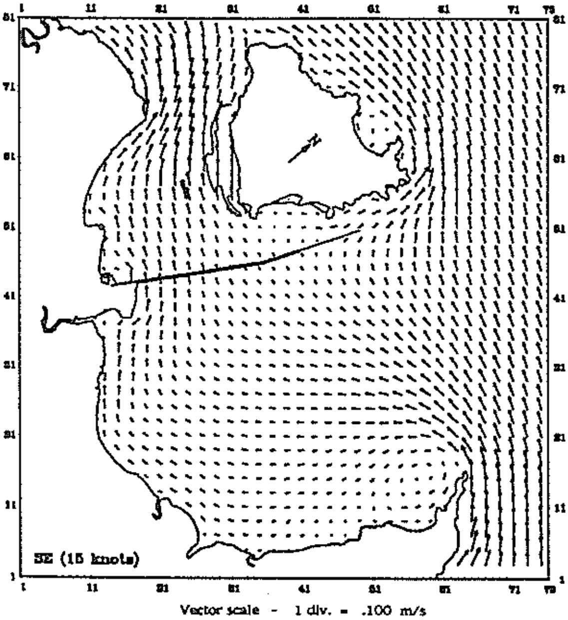


Figure 3.4 Steady-state C grid currents for constant easterly wind speed of 15 knots. Vectors are drawn at every second grid point in each direction.

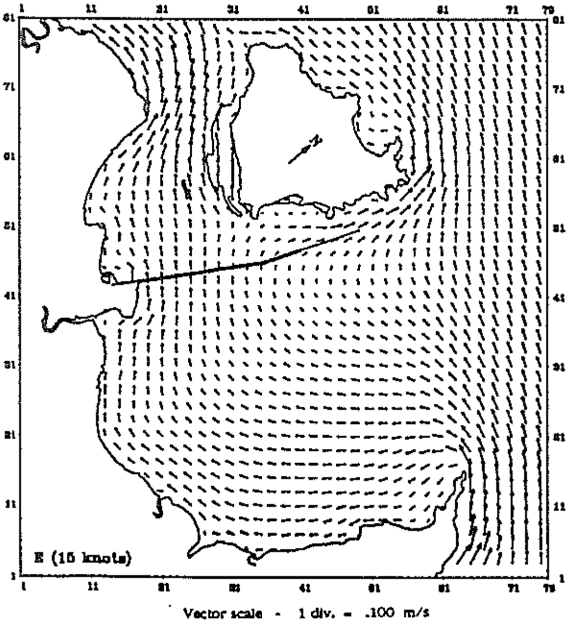


Figure 3.5 Steady-state C grid currents for constant north-easterly wind speed of 15 knots. Vectors are drawn at every second grid point in each direction.

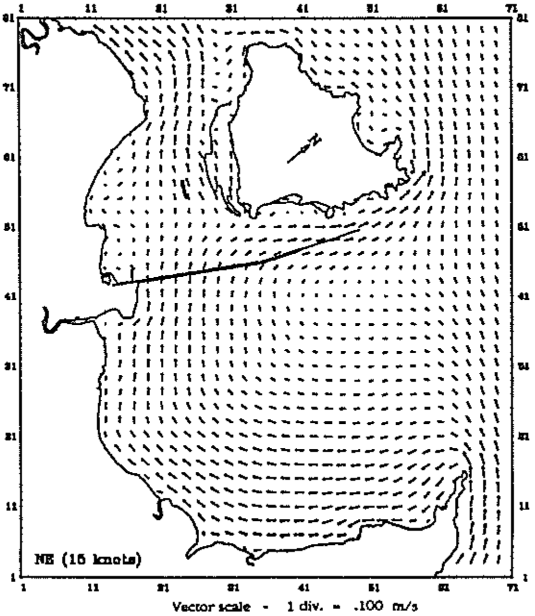
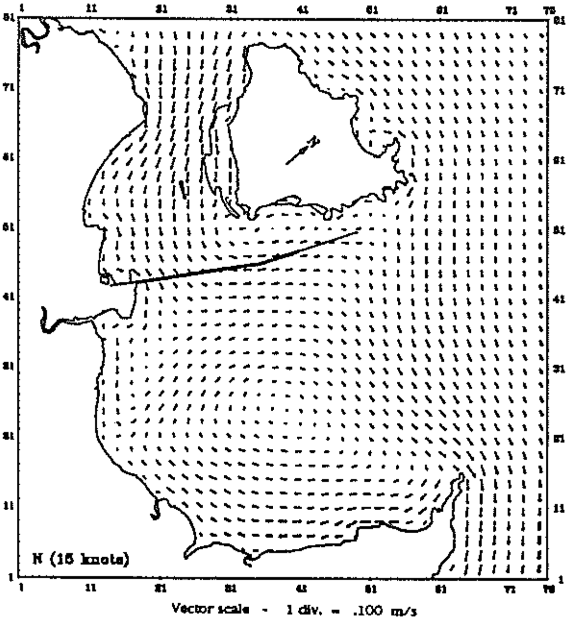


Figure 3.6 Steady-state C grid currents for constant northerly wind speed of 15 knots. Vectors are drawn at every second grid point in each direction.



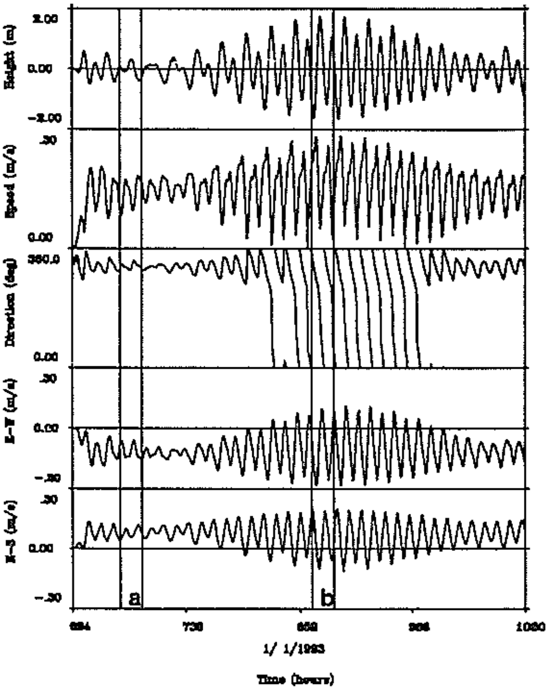
smaller gyre is now present in Cleveland Bay, up against Cape Cleveland. It is also apparent that there is a line of bifurcation for the water which flows around Magnetic Island. This line separates water which flows out through West Channel from that which exits past Orchard Rocks. In the present case, it can be seen to extend from Cape Cleveland to a (stagnation) point coinciding roughly with Hawkings Point on Magnetic Island. This is near the line of the extended channel. For the easterly and north-easterly winds (Figures 3.4 and 3.5), the direction of the wind stress acts to push the flow more directly into the bay, giving a distinct U-shaped circulation pattern. Northerly winds (Figure 3.6) provide the only one of the five cases in which the flow through Cleveland Bay is directed towards the south. As already discussed, results for this direction are almost the same as those for southerly case, but with the directions reversed.

3.2 Tidal and Wind-driven Circulation in Cleveland Bay

The scope of the MBH2 study specified that particles were to be released over 24-hour periods, during both neap and spring tides. The period chosen, during January and February 1993, contained a representative fortnightly spring-neap cycle that exhibited a relatively large tidal range, and also corresponded to the expected time of dredging.

Computed surface elevations and currents at Site 1 off Cape Cleveland (see Figure 2.3) are shown for a 16 knot south-easterly wind in Figure 3.7. This also shows the release periods, denoted by 'a' (neap) and 'b' (spring tide). Each particle release was tracked for 120 hours from time of release of the first group of particles.

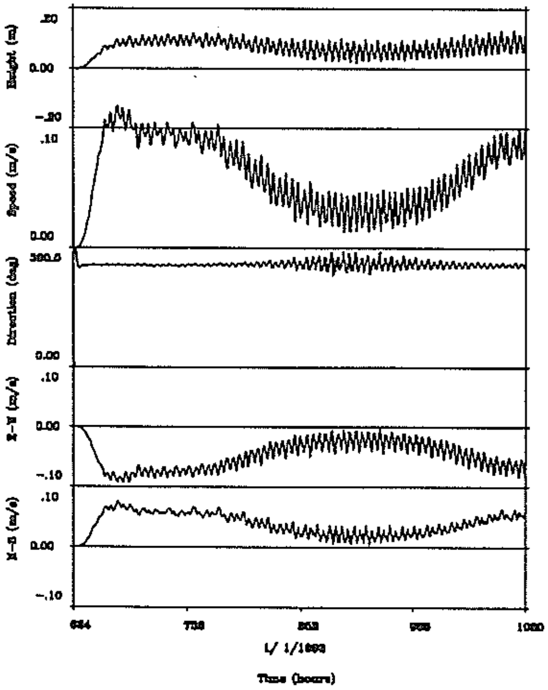
Figure 3.7 Time series of modelled surface elevations and currents at Site 1 for a 16 knot south-easterly wind. The time axis denotes hours in 1993 (624h = 0000h, 27/1/93). The 24-hour periods **a** and **b** show the two releases detailed in MBH2.



3.2.1 EAC Modelling

As stated in Section 2.3, the aim of the EAC modelling was to achieve a current speed of approximately 9 cm/sec near Site 1. Since the EAC is relatively weak, compared with average tidal currents, it will be affected significantly by the state of the tide, through the action of quadratic bottom friction. This is borne out by numerical experiments, outlined here. These results show the effects of the state of the tide at Site 1 on the modelled EAC. If the model is run with EAC forcing alone, it simply settles down after initial transients are dissipated by bottom friction to produce a steady current at each grid point. In this experiment, the model was run in two configurations, firstly with tidal plus EAC forcing, and then with tides alone. The *differences* between the results are shown in Figure 3.8. It can be seen that the nett strength of the EAC is strongly modulated by the tide, both over the spring-neap cycle, and also within each semi-diurnal oscillation. At Site 1, the EAC varies in strength from approximately 9 cm/sec at neap conditions, to as low as 3 cm/sec during peak springs. This result emphasises the difficulties involved in isolating the EAC from other currents, since a significant proportion of this low frequency current would be "seen", in conventional analyses, as being of tidal origin.

Figure 3.8 Time series showing the dependence on tidal state of the nett strength of modelled EAC currents at Site 1.



3.2.2 Wind-forced Scenarios

A total of six different wind directions (S, SE, E, NE, N and NW) were used with a constant wind speed of 8 knots. For two of these (SE and N) the model was also run with a 16 knot wind. All particles were released using the initial configuration shown in Figure 2.4. Only the south-easterly case is considered here. Individual simulations are identified by an alphanumeric identifier. For example, SE16a indicates a 16 knot wind speed from the South-East, with the time corresponding to release period a (neap tides). Of the total of twenty different scenarios modelled, four are reported here: SE8a, SE8b, SE16a, SE16b. More details can be found in MBH2. The results show snapshots of the positions of all particles at 2 and 4 days after the start of a given release sequence.

SE8a: South-easterly winds cause particles released in Area 1 to be transported in an anti-clockwise direction around the island, as seen in Figure 3.9, which is a 'window' from the full C grid. The particle pattern is consistent with the directions of current vectors calculated in the earlier hydrodynamic modelling study, MBH1. The majority of particles remain grouped within Area 1 over the 5-day period, although tidal currents tend to move roughly 10% through Area 2. Towards the end of the run, some also move closer to the coast into Area 4.

SE8b: The corresponding spring tide release shows a different pattern of particle movements (Figure 3.10). The larger tidal excursions move the particles into different zones of the wind-induced circulation, and particles are thus re-distributed into the north-eastern and northern bays of the island, as well as closer to Townsville Harbour. The snapshots also show how the larger spring tidal currents (which tend to flow perpendicular to the isobaths near Magnetic Island, and hence perpendicular

Figure 3.9 Snapshots of the positions of all particles at 2 and 4 days after the start of release SE8a.

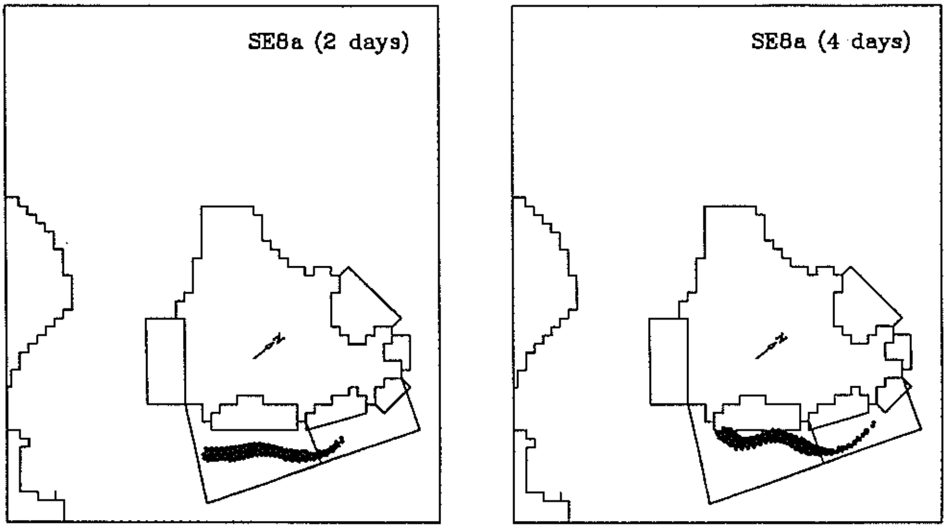
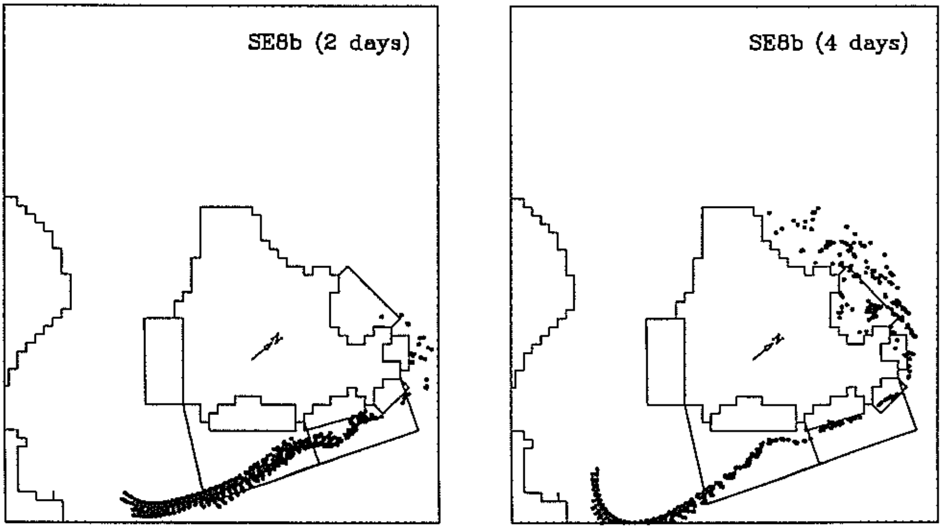


Figure 3.10 Snapshots of the positions of all particles at 2 and 4 days after the start of release SE8b.



to what could be identified as the purely wind-induced streamlines), transport particles into the bays. Initially, there is some tidal exchange between Areas 1 and 2. However, by the end of about the second day, there are also significant numbers of particles in Areas 5 to 8.

SE16a: Wind-driven effects dominate the particle distribution in this case (Figure 3.11). Most particles move

Figure 3.11 Snapshots of the positions of all particles at 2 and 4 days after the start of release SE16a.

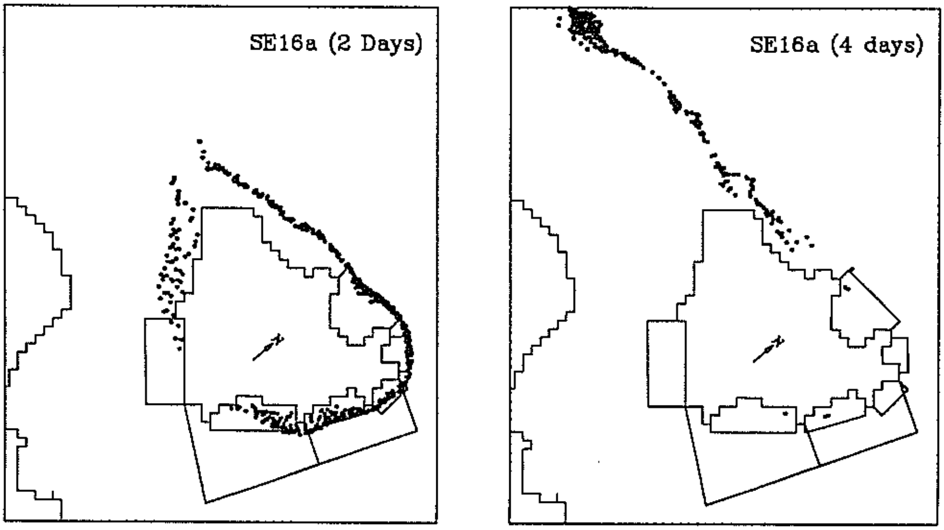
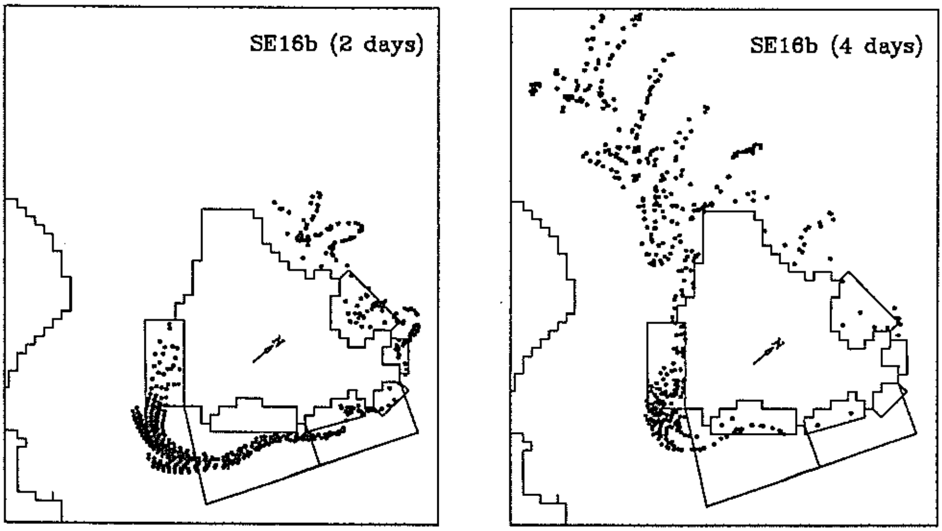


Figure 3.12. Snapshots of the positions of all particles at 2 and 4 days after the start of release SE16b.



relatively rapidly around the island in the anti-clockwise sense and ultimately out of the area altogether. A small proportion is influenced by the streams which flow through West Channel and hence these particles have a transitory impact on Area 3. The weaker tidal currents result in a reduced amount of particle exchange between the bays and surrounding waters.

SE16b: A more complex result is seen in Figure 3.12 for the corresponding spring tide case. Larger tidal excursions move a much greater proportion of particles towards West Channel and Area 3 (Cockle Bay). At the end of the 5-day simulation, there are still significant particle numbers in Areas 1, 3 and 4, in contrast to the previous cases, and considerable tidal exchange of particles still appears to be occurring across the boundaries of these three regions. The shore-normal transport induced by the large tidal currents is also evident in the snapshots. In this 2D modelling, the wind-induced currents tend to move particles along the isobaths. For all wind directions except for N and NW, particles move principally around Magnetic Island and ultimately into Halifax Bay. Most travel anti-clockwise around the island, although the details depend on the wind direction and tidal conditions. Flushing occurs more rapidly in the case of higher wind speeds. Discussion of the effects of the EAC was given in MBH2. This current tends to retard any northward movement of particles that are swept around Magnetic Island under the action of winds from the south and east. When both tidal and wind-driven currents are weak, however, the effects of the EAC then become significant.

Spring tides lead to a more shore-normal direction of particle transport, into the bays of Magnetic Island. Under neap tides, by contrast, the dominating effects of the wind-induced component of the motion tends to advect particles along the isobaths and hence past the island. It should be noted that only steady wind forcing has been applied and that the currents here have been calculated with a 2D (depth-integrated) model. Sections 3.3 and 3.4 discuss, respectively, the application of time-dependent winds and a 3D circulation model.

3.3 Operational Forecast Modelling

The predictive modelling proceeded as follows. Sinclair Knight and Partners requested that a predictive simulation be performed, given a specified initial distribution of particles. Also supplied was a time sequence of planned dredging and dumping operations, which were to be incorporated into the modelling sequence. Predictive simulations of particle distributions within Cleveland Bay were required for a number of days following the initialisation period. Results were required within 24 hours of any request.

Forcing for this model is provided by the tides, EAC and wind stress. The method of forcing for the first two of these is identical to that used in MBH2. The major uncertainty in such predictive modelling is associated with the specification of wind stress. As discussed above, we overcome some of these deficiencies by developing a simple model to provide time-dependent wind forcing to the hydrodynamic model.

This model consists of two components. The first is due to the more slowly varying, synoptic-scale winds. The second is due to the sea breeze, which forms a major component of the wind field and its variability within Cleveland Bay, although these effects diminish with distance from shore. Results for the basic sea breeze model, described in Section 2.4.5, have been shown in Figure 2.5. These form the starting point for the work described in this section.

Figure 3.13 shows a comparison of the synoptic winds provided by the Bureau of Meteorology (heavy curve) with the 50-hour low-passed filtered wind data measured at the TPA Building. Approximately the first four days of the data supplied by the Bureau of Meteorology are based on existing

Figure 3.13 Time series of synoptic scale winds supplied by the Bureau of Meteorology (heavy line) for the period 10–18 February 1993, compared with filtered (50h low-passed) measured winds from the TPA Building.

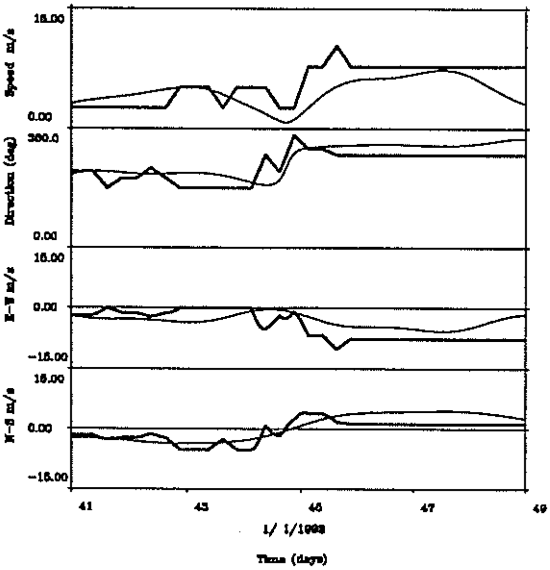
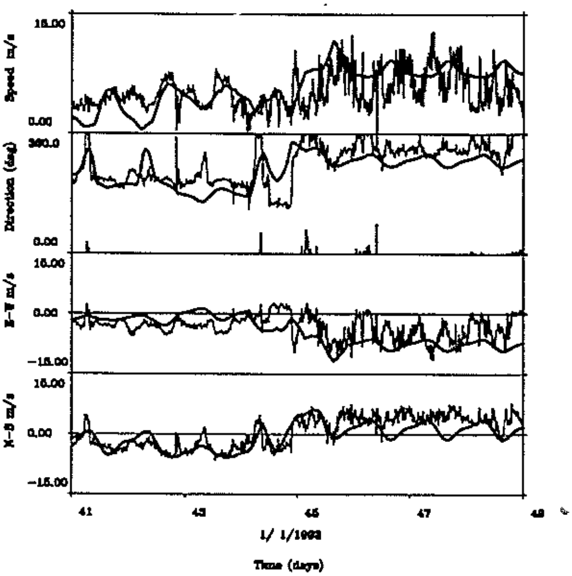


Figure 3.14 Time series of synoptic scale plus modelled sea breeze winds (heavy line) for the period 10–18 February 1993, compared with raw winds from the TPA Building.



measurements and analysis; the second four days constitute the Bureau's prediction. Results for the first half of the period are reasonable. In the predictive half, the supplied winds are considerably stronger than those measured. The time shown is from 10–18 February 1993. During this period, large spring tides were predicted. Based on the earlier results of MBH2, it was expected that there would be a stronger likelihood of suspended dredge spoil being advected into the bays of Magnetic Island under these conditions.

Figure 3.14 shows a comparison of the synthesised winds used in the predictive model (a vectorial combination of the data supplied by the Bureau of Meteorology and the sea breeze model) with the raw wind data measured at the TPA Building. It should be noted that the TPA wind data were not available until several days after the results of the forecast model were made available. The actual data then allowed the generation of hindcast model results – not previously presented.

Figure 3.15 shows the distribution of pre-existing particles for the predictive modelling. Three levels of initial particle density were required. Two levels are shown in this figure; a third (higher) value of particle density is specified within the dredged channel, according to the dredging schedule – see Mason (1993) for additional details.

Figures 3.16 and 3.17 show the forecast and hindcast particle distributions, three days after the initiation of the predictions. Particles can be seen to be moving from both the dredged channel as well as the outer dump site (where a

Figure 3.15 Pre-existing distribution of particles in Cleveland Bay.

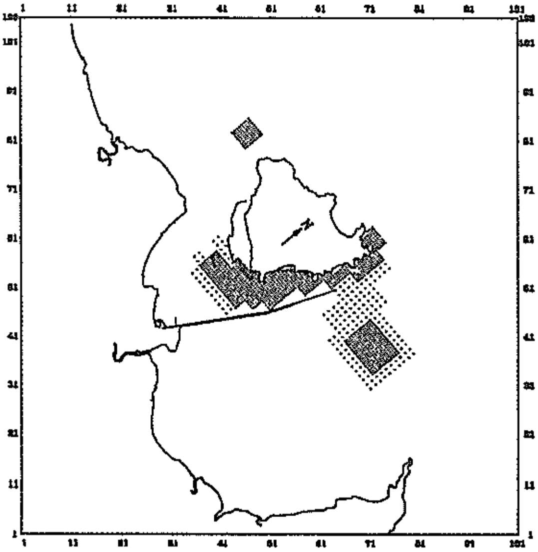


Figure 3.16 Forecast distribution of particles after three days.

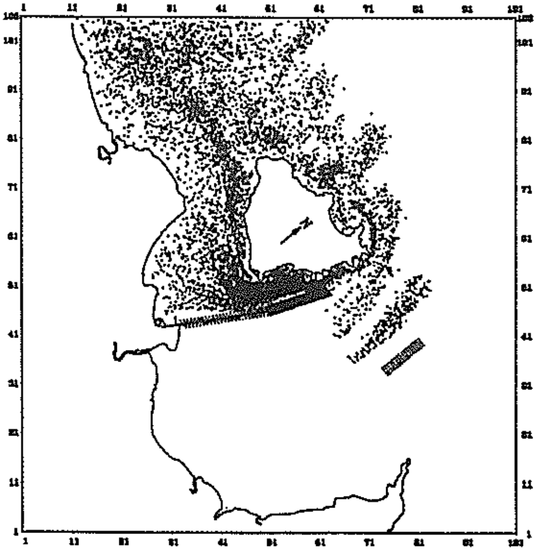
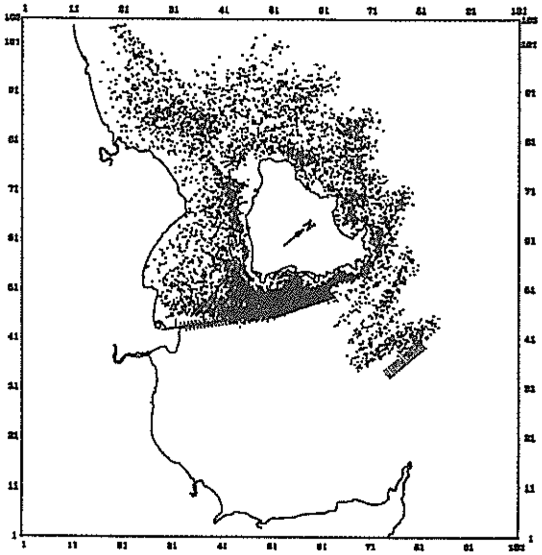


Figure 3.17 Hindcast distribution of particles after three days.



Level 2 particle density is specified). It is clear that particles are advected much larger distances in the predictive model (Figure 3.16) and also penetrate further into the bays on Magnetic Island. Figure 3.17 shows that, under the significantly lighter measured winds used in the hindcast study, the suspended material remains in more concentrated groupings.

Comparison of results from the forecast and hindcast particle distributions shows that wind strength and variability play an important part in sediment movement. The forecast indicates that there would be a strong likelihood of suspended material being forced into the bays. In the hindcast period, during which the imposed winds are weaker, the nett movement of material is much less than in the case of the forecast. Particles remain further from the bays of Magnetic Island, thus posing less of a problem than that indicated by the earlier forecast. This emphasises again the crucial importance of the availability of a reliable wind field model.

3.4 Dump-site Sensitivity Study - Three Dimensional Modelling

This study was initiated to determine whether it is suitable to continue the dumping of dredge spoil at the (then) site, closest to land, within the dumping ground, or whether it would be preferable to move dumping to the outermost extremity of this site. As background to this discussion, it was believed that dumped spoil material was being advected into the bays of Magnetic Island. Firstly, the modelling was to be used to determine if this was a possible scenario. Secondly, the model was to be used to investigate if particle trajectories were sensitive to the precise location of the dumping, within the designated area.

It was further decided that it was preferable to use the 3D hydrodynamic model. From the results of the first study (MBH1), it can be seen that the directions of the tidal and wind-driven streams tend to be perpendicular to each other. This is clearly illustrated by comparing Figures 3.1 and 3.2. The vertical structure of the tidal currents are expected to be largely depth-independent, except in the immediate vicinity of the sea bed. The wind-driven currents, by contrast, are likely to be significantly sheared in the vertical, particularly near the surface. It is therefore not immediately obvious which directions will be taken by particles released into the water column. Indeed, this is the type of complex spatial and temporally dependent question that can only really be addressed by numerical modelling.

Three wind-driven scenarios with constant wind fields were modelled: southerly, south-easterly and easterly, all with 16 knot winds. These were combined with our existing tidal and EAC open boundary forcing. The initial time of release was set at neap tides: it had been shown in MBH2 that the nett displacement of particles is increased under neap tidal conditions, due to the reduced influence of bottom friction. The two initial particle locations are shown in Figure 3.18. In this 3D modelling, particles are released at random vertical positions within the water column.

Figures 3.19 and 3.20 show particle distributions for the south-easterly wind, after two days, for the inner and outer locations, respectively. It is obvious that, under these conditions, particles released at the outer location are barely advected into Cleveland Bay proper. By contrast, those released from the inner location are advected much closer to Magnetic Island. Although there is a marked difference between the two releases in this south-easterly case, this distinction is not as obvious for the other two wind scenarios. However, in all cases, more material is advected closer to the bays of Magnetic Island when particles are released at the inner site – this can also be seen in the time histories presented in Mason and Bode (1993).

The effects of the three-dimensional nature of the flow can best be seen for the southerly wind scenario. Figure 3.2 shows the development of a large, anti-clockwise, wind-induced eddy in Cleveland Bay. It should be emphasised that this represents the *depth-averaged* description of the flow. Figure 3.21 shows that particles deeper in the water column move with this eddy. On the other hand, a significant proportion of the particles, higher in the water column, tends to be advected in the direction of the wind. This would not be the case if a 2D model were used: in this case, modelled particles would follow the depth-averaged flow and thus tend to remain within the eddy.

Figure 3.18 Model C grid showing outline of the dump ground and its inner and outer dumping locations.

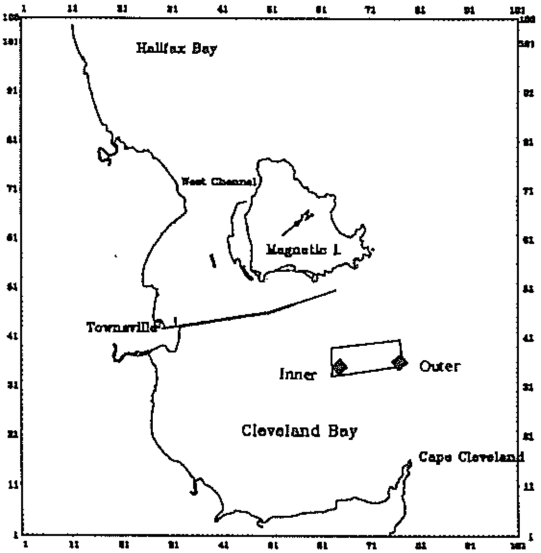


Figure 3.19 Particle distribution in the 3D model for the south-easterly wind, two days after release from the *inner* location.

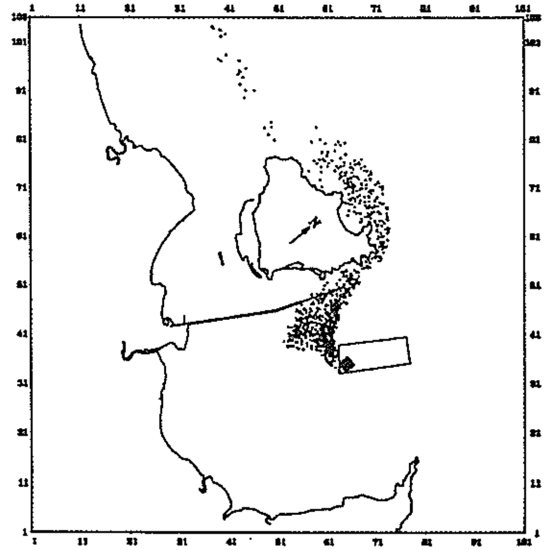


Figure 3.20 Particle distribution in the 3D model for the south-easterly wind, two days after release from the *outer* location.

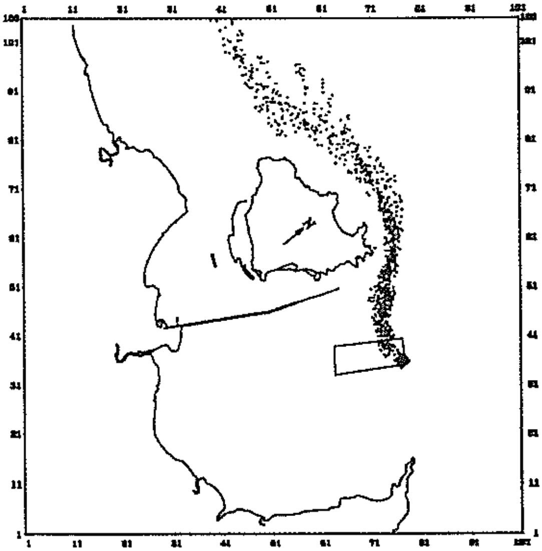
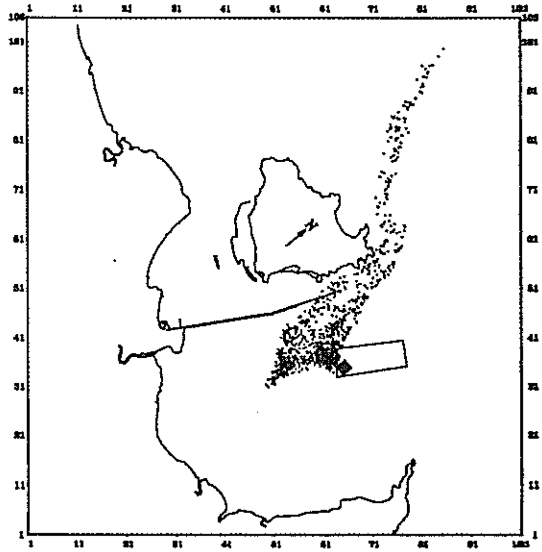


Figure 3.21 Particle distribution for southerly wind, two days after release from the *inner* location.



4. DISCUSSION

The results of four individual modelling studies in Cleveland Bay are outlined in this report. The work performed in these studies included: modelling of the circulation and transport of suspended fine particles under idealised forcing; forecasting the movement of suspended matter during dredging operations; and the application of a 3D hydrodynamic model to a sensitivity study of dump site locations.

The initial circulation study (MBH1) forms the basis of the particle transport modelling in MBH2. The models are forced by tides, surface wind stress and a simulated steady EAC. All modes of forcing are applied simultaneously. As a result, nonlinear interactions, through bottom friction, have a significant influence on the currents and hence on the extent of particle movement. In the 2D simulations, the released particles are moved essentially along the isobaths by wind-induced currents.

Except for the cases when wind stress is applied from the north or northwest, movement occurs in an anti-clockwise sense around Magnetic Island. Although this general description applies during the weaker neap tides, three additional effects are noted during spring tides. Nonlinearities associated with the larger spring tidal currents reduce the strength of the wind-induced currents and hence reduce the nett movement of particles. Secondly, the larger excursions associated with spring tides can move particles into different current regimes of the bay. Their ultimate destination can thus be altered significantly. Thirdly, spring tides cause increased shore-normal transport of water. This can bring particles closer to sensitive areas on Magnetic Island. In general, the effects of the EAC on particle transport are relatively minor, except during neap tidal conditions and weak winds.

Comparisons of the results of the forecast model with those of the later hindcast emphasise the importance of accurate wind field specification. This part of the modelling process remains an area where more reliable inputs are essential. The wind field in the forecast model consisted of two components – a spatially uniform but time dependent synoptic-scale wind, and a sea breeze model based on harmonic analysis of nearshore wind data.

In the final study, a 3D model of Cleveland Bay is used to determine the sensitivity of particle transport to the location of dredge spoil dumping. This model indicates that three-dimensional effects can be important in an area such as Cleveland Bay, where both tidal and wind-driven currents are significant. The sensitivity study showed that particles released in the deeper waters at the outer edge of the dump site have significantly less impact on Magnetic Island than those released closer to shore.

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THE ROLES AND RESPONSIBILITIES OF THE ENVIRONMENTAL MANAGEMENT AGENCIES

S Raaymakers

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EXECUTIVE SUMMARY

In 1993 the inner port and port approach channel at Townsville underwent major developmental dredging as part of an overall expansion of the port. The dredging and sea dumping of dredge spoil presented the potential for a number of environmental impacts; primarily turbidity and sedimentation effects on fringing coral reefs and seagrass beds.

The potential for impacts required the development and implementation of a sophisticated environmental management framework, including the most comprehensive and intensive monitoring program ever carried out in relation to a single development in the Great Barrier Reef Region.

The works required a dredging permit from the Queensland Department of Environment and Heritage under the Queensland *Harbours Act 1955* and a sea dumping permit from the Commonwealth Environment Protection Agency under the *Environment Protection (Sea Dumping) Act 1981*. Although none of the works took place within the Great Barrier Reef Marine Park or the adjoining State Marine Park, the potential for impacts on the marine parks required significant involvement of the Great Barrier Reef Marine Park Authority and Queensland Department of Environment and Heritage.

Because of the number of organisations involved, development of the environmental management framework relied very heavily on a multi-agency, multi-disciplinary approach, and has been hailed as a model of inter-agency cooperation for similar projects in the future. The program included the appointment of an Environmental Supervisor by the Queensland Department of Environment and Heritage, with overall responsibility for ensuring that the development works proceeded according to the environmental management framework.

The core of the management framework was a reactive monitoring program which allowed any impending environmental impacts to be detected and reacted to, through modifying or ceasing the dredge operation. This program allowed dredging to proceed without restrictions while ensuring that impacts could be managed. Throughout the project the reactive monitoring did not detect any impacts that warranted dredge management action. However, the possibility of long-term sub-lethal impacts has yet to be addressed.

The overall program was extremely successful, and made significant advances in reactive monitoring and real-time management of dredging operations in sensitive environments.

1. INTRODUCTION

In 1993 the inner port and port approach channel at Townsville underwent major developmental dredging as part of an overall expansion of the port.

The dredging presented the potential for a number of environmental impacts, primarily turbidity and sedimentation effects on fringing coral reefs at Magnetic Island and seagrass beds in Cleveland Bay.

The potential for impacts required the development and implementation of an environmental management framework, including the most comprehensive and intensive reactive monitoring program ever carried out in relation to a single development in the Great Barrier Reef Region.

Development of this program relied very heavily on a cooperative, multi-agency, multi-disciplinary approach.

2. LEGISLATION AND REGULATORY RESPONSIBILITIES

A number of pieces of State and Commonwealth legislation applied to the environmental aspects of the project.

2.1 Queensland

Queensland *Harbours Act 1955*

Under Section 86 of the Queensland *Harbours Act 1955* a permit is required for all marine and coastal development works, including developmental dredging and reclamation. Section 86 permits regulate the way in which the works are conducted, including environmental management and monitoring provisions. Assessment and management of these permits is conducted by the Coastal Management Branch of the Queensland Department of Environment and Heritage (QDEH). A Section 86 permit was issued to Townsville Port Authority (TPA) for the deepening and lengthening of the port entrance channel, and rehandling of dredge spoil in the harbour. This permit formed the basis for implementation of the environmental management framework and placed QDEH in the position of primary regulator.

Queensland *Marine Parks Act 1982*

The tidal lands and waters around Magnetic Island (generally 500m seaward of the low tide mark or fringing reef edge, and also West Channel between Magnetic Island and Cape Pallarenda) are part of the Townsville/Whitsunday State Marine Park. As none of the development works were carried out within the State Marine Park the Queensland *Marine Parks Act 1982* did not apply directly and the potential for impacts was managed consistent with the Great Barrier Reef Marine Park (see also Great Barrier Reef Marine Park Act below).

2.2 Commonwealth

Environment Protection (Sea Dumping) Act 1981

Under the *Environment Protection (Sea Dumping) Act 1981*, which implements the London Convention (LC) in Australia, a sea dumping permit is required for the disposal of dredge spoil at sea. Sea dumping permits provide a mechanism to ensure proper assessment, monitoring and management of sea dumping. Assessment and management of these permits is conducted by the Commonwealth Environment Protection Agency (CEPA). The TPA obtain annual sea dumping permits for the disposal of approximately 300 000 m^3 of spoil from routine maintenance dredging each year. In 1993 TPA were issued with a permit for the disposal of 940 000 m^3 of dredge spoil from the developmental dredging.

Great Barrier Reef Marine Park Act 1975

In addition to being within a Queensland State Marine Park, Magnetic Island is also surrounded by the Great Barrier Reef Marine Park (Figure 1). As none of the development works were carried out within the Great Barrier Reef Marine Park the *Great Barrier Reef Marine Park Act 1975* did not apply directly. However under section 66 (2)(e) of this Act the Governor-General of Australia is empowered to make regulations to control activities outside of the Marine Park that may pollute waters inside the Marine Park in a manner likely to harm plants and animals in the Marine Park.

As the dredging works were conducted adjacent to the Marine Park and the possibility of impacts to the Marine Park was the major environmental issue, GBRMPA proceeded with the drafting of special regulations, titled the *Great Barrier Reef Marine Park (Cleveland Bay Dredging) Regulations*, that would allow direct control of the dredging by GBRMPA should the necessity arise. Although it was not necessary to enact these regulations, this drafting process was a significant event as these powers have only ever been utilised once before, in the drafting of regulations to prohibit exploration for oil outside of the Marine Park but inside the Great Barrier Reef Region, and demonstrated GBRMPA's commitment to ensuring the project did not cause any impacts on the Marine Park.

While none of the dredging works took place in the marine parks, much of the environmental monitoring did, and the monitoring contractors were required to obtain permits under both the Queensland Marine Parks Act and the Great Barrier Reef Marine Park Act. In addition, one of the new navigation markers for the extended channel falls within the marine parks, therefore requiring a Marine Park Permit.

World Heritage Legislation

All subtidal areas of Cleveland Bay, including the area dredging as part of the 1993 port development, fall within the Great Barrier Reef World Heritage Area. As such the provisions of the *World Heritage Properties Conservation Act 1983* and the *Australian Heritage Commission Act 1975* applied to the development. While this placed no specific requirements for permits and approvals, it did add to the environmental significance of the project and the need to ensure that appropriate environmental management measures were implemented.

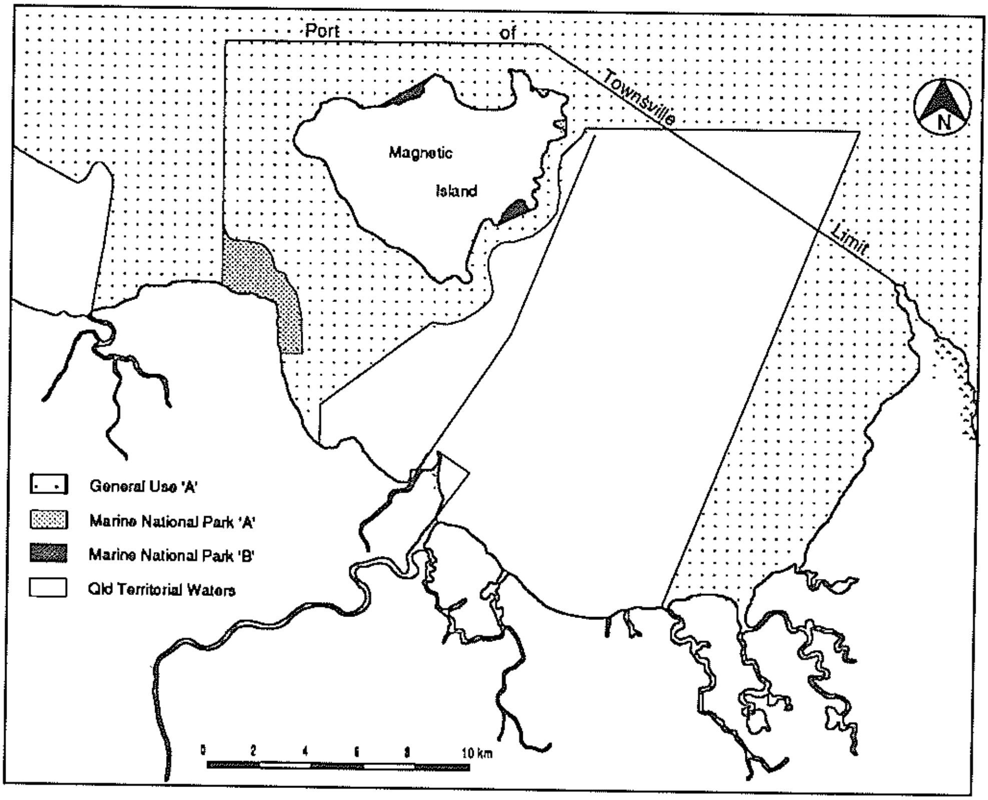
3. ENVIRONMENTAL CONCERNS & ASSESSMENT

QDEH, GBRMPA and CEPA began to receive information on the proposed development in 1990, with an Initial Advice Statement being received from TPA via the Queensland Department of Transport (QDoT) in July 1990. A number of potential environmental impacts were identified.

3.1 Dredging

Both routine annual maintenance dredging of the Townsville port approach channel and the developmental dredging utilise a "trailer-suction-hopper-dredge". This type of dredge is basically a ship with hoppers in the place of cargo holds, and two "arms" which trail down either side of the ship. These arms are equipped with toothed heads which drag along the bottom, dislodging material which is sucked up by powerful pumps

Figure 1 Magnetic Island Marine Park Zones



and deposited into the hoppers. As the material being dredged is actually a mixture of sediment and water, the sediment settles to the bottom of the hoppers and when the water level reaches the top of the hoppers the dredge is not necessarily carrying on optimum load. Dredging continues with sediment-laden water overflowing the hoppers until an optimum load is achieved. It has been estimated that in some cases up to forty percent of the total material dredged in one cycle is discharged in the overflow process (Sinclair Knight, Nov 1991). The sediment-laden overflow can generate substantial sediment plumes that can be carried away from the dredge by water movements. In addition the dredge heads cause resuspension and turbidity as they drag along the bottom.

Aerial photography of maintenance dredging of the Townsville port approach channel (Sinclair Knight, 1991) showed sediment plumes adjacent to Magnetic Island fringing reefs after three days of continuous overflow dredging. However no quantitative information was available on the concentration or vertical distribution of these plumes and therefore on their ecological significance.

The effects of increased sedimentation and light attenuation on coral reefs are well documented in the literature, and can range from mild coral stress and subtle changes in reef community structure, to outright coral mortality and even ecological collapse of the reef under severe sedimentation or light attenuation.

The dredging works planned for the Townsville port development were to be conducted over an extended period of some months, and in summer when corals are already at the upper levels of their stress tolerance limits.

Historical photographs and anecdotal evidence indicate an apparent degradation of the Magnetic Island fringing reefs in the last several decades, with some "old-timers" claiming this apparent degradation was related to historical dredging of Townsville port.

In addition, concerns were raised about the possibility of fine sediments from the dredging being carried into shallow waters adjacent to the Strand, Townsville's main city beach, causing impacts on amenity. There have been anecdotal claims that historical dredging has caused water clarity to be degraded at the Strand through deposition and subsequent resuspension of fine sediments, and that what used to be clean, coarse sand in the near-shore shallows has now become fine silt, making swimming less pleasant. Aerial observations have shown dredge plumes from the port area and Platypus Channel being transported onto the Strand under certain conditions (pers obs 1991, '92 & '93).

3.2 Dumping

Trailer-suction-hopper-dredges can discharge their load of dredge spoil in several ways, including pumping ashore or into adjacent waters via a pipeline, or dumping at sea by opening doors in the bottom of the hoppers.

Spoil from the annual routine maintenance dredging of the port entrance channel has been dumped at sea at an approved dump site for the last twenty years, with approximately 300 000 m^3 being dumped per year. It was proposed to dump approximately 1 000 000 ^{m3} of material from the deepening of the channel at the existing offshore spoil dump site.

Sea dumping of dredge spoil can cause a number of environmental impacts. If there are any contaminants in the spoil they may be released into the marine environment. The benthic ecosystem at the dump site can become physically smothered and therefore significantly altered. Chemical and Biological Oxygen Demand in the water column can be temporarily altered. The sediment released during dumping can be transported by waves, tides and currents onto nearby sensitive sites, and sediment that does settle onto the dump site may be resuspended and transported in the longer term.

The Townsville offshore dump site is located about 5 km from the nearest fringing reefs at Magnetic Island and about 7 km from seagrass beds in the south-east corner of Cleveland Bay. The possibility of both short and long-term sedimentation and turbidity impacts from the sea dumping of dredge spoil constituted a major consideration during the environmental assessment of the project.

3.3 The Impact Assessment Study (IAS)

In 1991 QDot, as part of its responsibility for coordinating development of transport infrastructure, established a multi-agency Steering Committee which included representation from QDEH, GBRMPA and CEPA, to oversee conduct of an Impact Assessment Study (IAS) for the project.

The Steering Committee drafted a Terms of Reference for the IAS and TPA engaged consultants Sinclair Knight to conduct the study. The IAS investigated all aspects of the development proposal, including onshore issues such as ore stockpiles and rail lines.

The IAS identified a number of potential impacts from dredging and dredge spoil disposal. It stated that dredging to deepen and lengthen the port approach channel had the potential to generate turbid surface plumes that could extend to the Magnetic Island coral reefs, and that impacts could result from light attenuation and settlement of fine sediments in conditions of light onshore winds.

The IAS also recommended a number of dredge management strategies that might mitigate these impacts. These included:

☐ use of a large dredge to minimise the time period of dredging,

☐ discharge of overflow water beneath the waterline to minimise dispersal of sediment,

☐ relocation of the dredge to areas of the channel furthest from the Magnetic Island reefs during unfavourable weather conditions,

☐ dredging adjacent to coral reef areas only at night to minimise shading effects, and

☐ dredging only during ebb tides to assist dispersal of plumes away from the reefs.

Once the IAS was completed the Steering Committee was disbanded.

3.4 The Trial Developmental Dredging Study

As a result of the findings of the IAS parties concluded that while there was a possibility of impacts from the developmental dredging on Magnetic Island reefs, there was insufficient scientific and technical information available to allow an accurate prediction of the likely nature and extent of such impacts, and more importantly the likely effectiveness of proposed dredge management techniques in preventing impacts.

As TPA were planning to conduct routine annual maintenance dredging in mid 1992, all parties agreed that it would be prudent to take the opportunity to also conduct some limited trial developmental dredging, with intensive monitoring, in order to gain a better understanding of the likely impacts from the full-scale developmental dredging. A small working group comprising GBRMPA, TPA and SK was formed to design the study, with SK being engaged by the TPA to conduct the study.

The dredge *Sir Thomas Hiley* arrived and commenced three days of intensive developmental dredging at the outer end of the channel, closest to the Magnetic Island fringing reefs, on 29 August 1993. The monitoring program including:

☐ data-logging light meters placed underwater at Geoffrey, Nelly, Arthur and Horseshoe Bay,

☐ arrays of sediment traps between the channel and Magnetic Island,

☐ turbidity profiling of dredge plumes, and

☐ aerial photography and satellite imagery.

This study concluded that the planned developmental dredging had the potential to create sediment plumes which could impact on the fringing reefs of Magnetic Island, but that effective dredge management strategies could also be developed.

4. THE TECHNICAL ADVISORY COMMITTEE AND THE MULTI-AGENCY APPROACH

In early 1992 a Technical Advisory Committee (TAC) was established, comprising a similar membership to the IAS Steering Committee, but this time chaired by QDEH as the primary regulatory agency. The TAC's main function was to coordinate assessment and issue of the relevant permits by the various agencies and facilitate a multi-agency approach to the development of an appropriate environmental management framework.

The multi-agency TAC approach had been used effectively with the Cairns port development in 1990, and proved effective again in the Townsville situation, ensuring that the interests of all relevant organisations were taken into account.

Ensuring coordination between various bodies and avoiding unnecessary delays in the assessment of development proposals is a worthy objective for all regulatory agencies, and the use of a multi-disciplinary steering committee proved useful to achieve this. It is vital that appropriate technical expertise is present on the committee to ensure proper environmental assessment and management is achieved.

In addition to the TAC, a number of other multi-agency groups were formed at various stages throughout the project to deal with specific issues, including:

☐ a scientific advisory group to assist with the design of the monitoring programs,

☐ a tender evaluation group to select consultants for the monitoring,

☐ an Initial Response Group (IRG) to undertake day-to-day management of the dredge in response to the findings of the reactive monitoring program, and

☐ an expert review panel to undertake independent review of the Reactive Monitoring Program and the IRG's conduct.

This degree of multi-agency cooperation, consultation and joint decision making at all levels of the project has been unprecedented in relation to development projects in the Great Barrier Reef Region, and was a major contributing factor to the successful management of the project.

5. PERMIT ASSESSMENTS

While the TAC had the overall role of coordinating assessment of the relevant permits by the regulatory agencies, it had no statutory powers itself. Responsibility for the actual assessment and issuing of permits rested with QDEH for the Section 86 dredging permit and with CEPA for the sea dumping permit.

Whilst GBRMPA had no direct jurisdiction, it was vital that GBRMPA had significant input to the permit assessment process as the dredging and dumping had the potential to cause impacts on the Great Barrier Reef Marine Park. The TAC mechanism ensured that GBRMPA had adequate representation and was able to contribute its expertise to the design of monitoring and management procedures.

5.1 Dredging (Section 86) Permit

After consideration of the findings of the IAS, the trial developmental dredging, and other relevant studies, it was concluded that dredging could proceed subject to a stringent environmental management framework that would allow the works to be modified or stopped should the possibility of impacts be detected.

A Section 86 dredging permit was issued to TPA by QDEH in November 1992, with conditions requiring an environmental management framework and monitoring program, including the specification of management criteria and the appointment of an Environmental Supervisor.

5.2 Sea Dumping Permit

Assessment of the sea dumping permit application was not as straightforward as the Section 86 dredging permit. Previous studies (Carter and Johnson 1987, Wolanski *et al.* 1991) had indicated that material moves away from the dump site under certain conditions, both in the short and long terms. It was not known whether the concentration, distance and rate of this transport was sufficient to cause impacts on the Magnetic Island fringing reefs or Cleveland Bay seagrass beds, although available evidence suggested that such impacts were unlikely.

These studies placed a question mark over the environmental suitability of the offshore dump site and this lead CEPA, in 1991 (before the port development was even proposed), to require the TPA to develop a Long Term Dredge Spoil Disposal Strategy. This Strategy would:

☐ investigate ways of minimising the need to dredge,

☐ seek productive uses for the dredge spoil, and

☐ determine the suitability of the offshore dump site in a comparative environmental risk assessment with other options such as terrestrial disposal.

The Long Term Strategy was slow getting off the ground, but eventually QDoT was contracted to commence Phase One (investigation of ways to minimise dredging, productive uses of dredge spoil and terrestrial disposal options) in 1992.

When TPA sought permission to dump up to 1 million m^3 of spoil from the 1993 developmental dredging, the initial response from CEPA, supported by GBRMPA, was to state that although data was incomplete, the available studies indicated that the offshore dump site must be considered an environmental risk until proven otherwise, that the Long Term Dredge Spoil Disposal Strategy must be completed and that in the meantime the material should be pumped ashore to the reclaim area. The adoption of this approach by CEPA and GBRMPA was consistent with the Precautionary Principle which, under the Australian National Strategy for Ecologically Sustainable Development (1992) is described as:

"Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation."

The North Queensland Conservation Council (NQCC), an umbrella environmental group, along with scientists at the Australian Institute of Marine Science (AIMS) and the Australian Coral Reef Society, expressed concerns about the proposed dumping. The NQCC made a submission to CEPA and the Commonwealth Environment Minister calling for a moratorium on dumping in Cleveland Bay until completion of the long-term strategy.

There were some major obstacles to such an approach. Completion of the Long Term Dredge Spoil Disposal Strategy, including full environmental impact assessment of possible alternative spoil disposal options, was likely to take another two or three years. The reliance on One Nation funding for the dredging, which required funds to be expended by 30 June 1993 in order to allow accounting against the Federal budget, meant that it was impossible to complete the required studies in time.

This timing constraint placed limitations on the ability to conduct adequate environmental assessment of possible alternatives and clearly exemplifies the inappropriateness of requiring environmental management activities to operate within the artificial context of the short-term political process and annual budgetary cycles.

When CEPA and GBRMPA further considered the preference of having all of the material pumped to reclaim they considered two separate economic studies which estimated an extra cost to the project of around $9 million. This cost was considered disproportionate to the total dredging cost. Therefore, unless an extra $9 million could be found to allow pumping to reclaim, or unless the time frame for One Nation funding could be extended for another two to three years to allow adequate environmental assessment of alternative spoil disposal sites, the offshore dump site was the only option available for spoil disposal if the project was going to proceed in 1993.

TPA contracted SK to carry out a study of the status of the offshore dump site, including a review of the findings of all previous studies, and to prepare a sea dumping permit application.

The SK studies suggested that the conditions that cause resuspension and transport of sediment from the dump site also cause resuspension and transport of sediment throughout the whole of Cleveland Bay. Calculations of the volume of material remaining in the dump mound indicated that over seventy percent of all material dumped there in the last twenty years had remained there. It appeared highly unlikely that the rate, concentration and distance of transport of sediment from the dump site, relative to natural sediment resuspension and transport in Cleveland Bay generally, would be sufficient to cause impacts to the Magnetic Island fringing reefs or Cleveland Bay seagrass beds.

CEPA and GBRMPA sought oceanographic advice from James Cook

University (JCU) and AIMS and concluded that by moving the dump site offshore beyond the 11 m contour, the chances of long term resuspension could be largely eliminated as wave induced resuspension in greatly reduced at depths below 10 m.

A sea dumping permit was issued to TPA by CEPA in November 1992 for the dumping of 940 000 m^3 of dredge spoil at a redefined dump site beyond the 11m contour, and requiring the same environmental monitoring program as the Section 86 dredging permit, in order to allow reactive management of the dumping in the short term and measurement of dump behaviour in the longer term.

6. THE ENVIRONMENTAL MANAGEMENT FRAMEWORK

The IAS identified a number of possible dredge management strategies that could minimise the risk of environmental impacts. The strategy that would have achieved the most, to the extent of virtually eliminating production of sediment plumes, would have been to dredge in non-overflow mode. This means that once the water level reaches the top of the hoppers dredging stops for that cycle and the dredge proceeds to the dump site to discharge its load before returning for another cycle. It should be noted that imposition of a non-overflow conditions was applied by New Zealand environmental authorities on the same dredge operating in Auckland Harbour in 1992, in order to protect snapper spawning grounds from sedimentation (Kettle, *pers comm.* 1992).

While non-overflow dredging would have considerably reduced the possibility of impacts to the magnetic island reefs, it would have increased costs by about a factor of four. As a result of funding constraints it was decided not to impose such a cost penalty when there was no certainty about the likelihood of impacts. Instead it was agreed by the TAC that the dredging should be allowed to proceed in a routine manner, with a reactive environmental monitoring program. It was agreed that the reactive monitoring program would form the basis for management of the dredge, ,linking measurement of physical and ecological parameters with a management framework that allowed the dredging operation to be modified, including changing to non-overflow mode or complete cessation of dredging, should predetermined management triggers be exceeded.

The task remained to determine what would constitute an adequate reactive monitoring program. Such a program would have to:

- ☐ ensure that impending impacts could be detected and responded to in time;
- ☐ determine what parameters should be measured and how;
- ☐ determine how to set the predetermined management triggers; and
- ☐ decide how to link the monitoring program with the legislative powers of the regulatory agencies to ensure action could be taken with regard to the dredge should it be necessary.

6.1 Design of the General Program

A number of options were considered for designing the monitoring program and building on the monitoring recommendations made by SK in the original IAS. It was suggested that the TAC call for proposals from the scientific and consulting community. However, it was argued that despite its title the TAC contained very little technical expertise and would have limited ability to adequately assess proposals received. Also, calling for proposals would be a slow process that could be likely to result in research-driven designs being put forward. Time constraints were a constant feature of the project, with all environmental management arrangements needing to be fully developed and in place by November 1992.

GBRMPA recommended that the significant expertise available locally from JCU and AIMS be used as much as possible in all aspects of the project. It was therefore decided to adopt a workshop approach to the design of the monitoring programs. Relevant scientific experts from a variety of disciplines and a number of institutions and consulting companies were invited to act as a scientific advisory group and attend workshops to design the monitoring program. This process worked very effectively, allowing much quicker progress to be made than if the standard process of calling for proposal had been followed. It also allowed for active, direct review of the programs to occur as they were designed, as many competing scientists were present at the workshops simultaneously. It also ensured the objectives of the program remained management-driven as opposed to research-driven. To achieve this it was vital to ensure the scientists were provided with a complete and thorough briefing on all aspects of the port development, the significance of the monitoring to the overall environmental management effort and the specific needs of the environmental management agencies.

The scientific advisory group recommended that a number of different monitoring packages from a number of disciplines would be necessary. To supplement the short-term reactive monitoring, it was recommended that monitoring of sediment movement and physical oceanographic processes, and traditional before/after monitoring of coral reefs and seagrasses be conducted.

No meaningful measures were taken to address the possibility of spoiling of Townsville beaches with fine dredge silts. This may have resulted from the absence of the Townsville City Council from the TAC and a preoccupation with the Magnetic Island fringing reefs on the part of the TAC.

6.2 The Tender Evaluation Process

Once the outline for the monitoring programs was developed by the scientific advisory group, a set of objectives, deliverables and indicative methodologies was developed for each program by SK. These formed the basis of tender documents. A tender evaluation group consisting of the TPA, their advisers, SK, GBRMPA and QDEH was established to assess the tenders received and select the preferred bids. The tendering process was conducted according to Queensland government legal requirements and tenders were evaluated using the Association of Consulting Engineers in Australia (ACEA) Value Selection scheme, a weighted point score system which allows both price and non-price attributes to be taken into account during selection of the most appropriate consultant.

The presence of environmental management agencies (GBRMPA and QDEH) on tender evaluation panels for such projects is unusual in Queensland, but was beneficial in ensuring that adequate consideration was give to the requirements of all parties. Several tenders were awarded to more expensive bidders whom it was judged could do the best job.

6.3 The Reactive Monitoring Program

Details of the design and implementation of the Reactive Monitoring Program can be found in the Reactive Monitoring section.

6.3.1 The Management Response Procedure

Three management trigger levels were determined for each of the two parameters measured by the Reactive Monitoring Program (coral bleaching and mortality). If coral bleaching or mortality remained below the first level then no impact was implied and dredging continued unhindered. If the first level was exceeded the Initial Response Group (IRG), comprising QDEH Environmental Supervisor, the SK Project Manager, the leader of the Reactive Monitoring team and a representative each from TPA and GBRMPA, would meet to consider the significance of the observations, likely causes and an appropriate response. If the second level was exceeded then an independent Review Panel, comprising coral experts, the leader of the Data Interpretation team and any other necessary experts would be called in to provide the IRG with advice on appropriate action. If the third level was exceeded then action would be taken immediately to modify or stop the dredging. Management of this process was carried out according to a Management Decision Flow Chart (Figure 2) and a signed written agreement between TPA, QDEH and GBRMPA specifying decision criteria and procedures for modifying or halting the dredge.

This worked very effectively and ensured all parties involved were fully aware of the process that would take place should management triggers be exceeded. A key factor in the success of this approach was a very clear linkage between the data generated from the reactive monitoring, the roles and responsibilities of the Environmental Supervisor and the regulatory requirements of the Section 86 dredging permit and relevant legislation.

Full written reports were submitted to the IRG on a weekly basis and verbal reports were made to the QDEH Environmental Supervisor after each field survey.

The Environmental Supervisor participated directly in many of the reactive monitoring trips, which was useful for gaining familiarity with the program and the trends at the reef sites, therefore allowing a better understanding of the significance of the data being presented in the reports. A high level of rapport between the Environmental Supervisor and the reactive monitoring team, and the direct line of reporting to the Environmental Supervisor were vital in ensuring the management agencies were in a position to react promptly should the need arise.

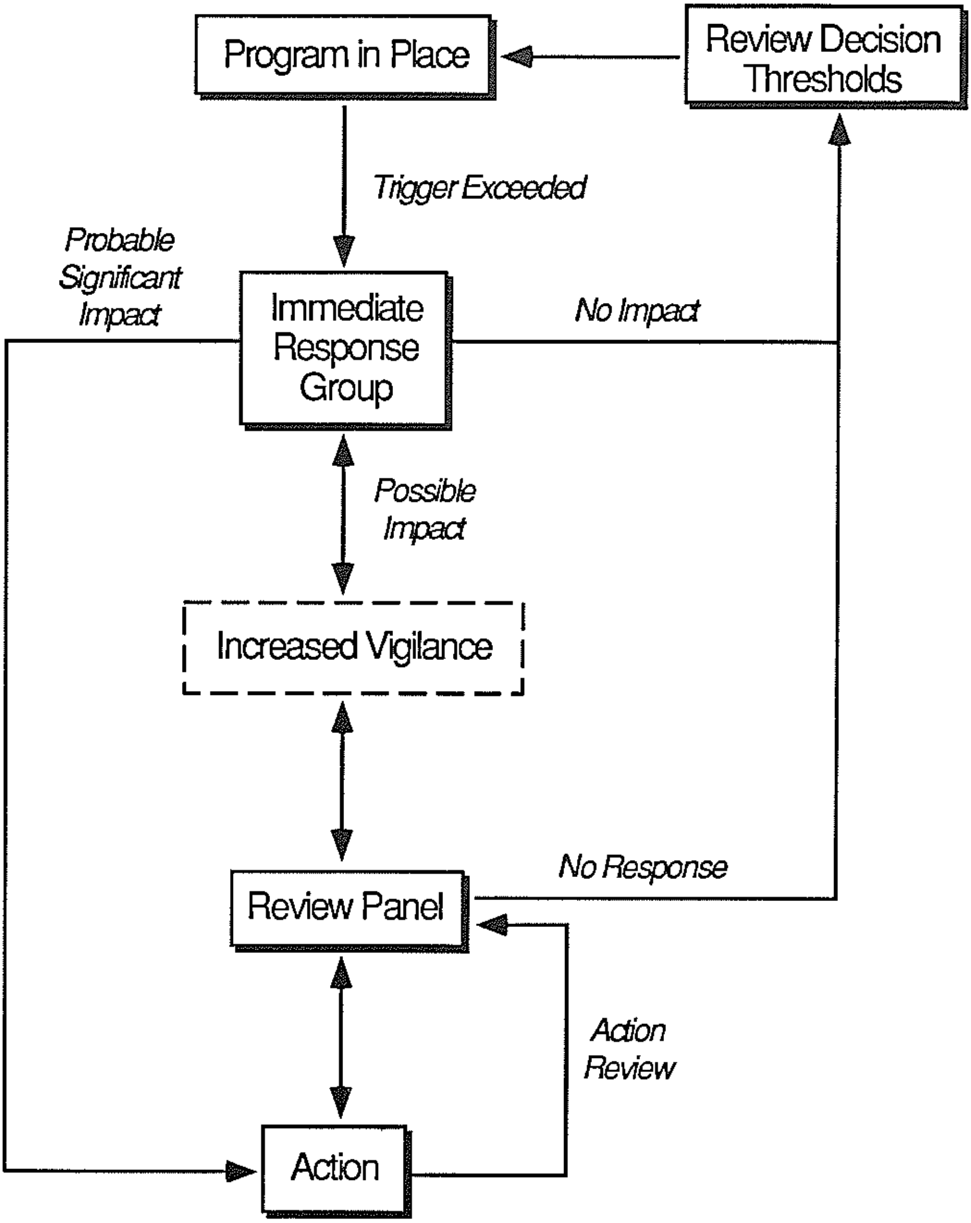
6.4 The Other Monitoring Programs

In addition to the reactive monitoring a number of other monitoring packages were conducted to assist with the differentiation of dredge related and naturally caused events. These included:

- ☐ Remote Imagery
- ☐ Sediment Monitoring
- ☐ Oceanographic Monitoring
- ☐ Hydrodynamic Modelling
- ☐ Before/After Coral Community Monitoring
- ☐ Before/After Seagrass Monitoring

Details of these programs can be found in other sections.

Figure 2 Management Decision Flow Chart



7. COST CONSIDERATIONS

Environmental management is an essential, integral component of modern port management that must be allowed for in all aspects of port planning, budgeting and operations.

Environmental agencies are often criticised for not having due regard for costs and having little appreciation of commercial realities. An analysis of the Townsville port project clearly demonstrates that the whole process was characterised by a genuine attempt on behalf of all parties to keep cots to a minimum, while ensuring that the integrity and rigour of the program were maintained.

In both the IAS and the report on the trial developmental dredging, TPA's consultants agreed with the environmental agencies that the dredging presented the potential for significant impacts to the Magnetic Island fringing reefs, and that dredge management strategies would be necessary. A dredge management strategy, non-overflow dredging, was available that would substantially reduce the risks to the Magnetic Island reefs.

However, in direct recognition of the constraints on funding available to TPA and the need for the port to remain competitive, the environmental agencies agreed not to impose a non-overflow condition and allowed the dredge to operate unrestricted, subject to a comparatively less expensive reactive monitoring program.

When assessing the proposal to dump the dredge spoil at sea, the environmental agencies considered submissions from conservationists and the local scientific community, including the NQCC and staff from AIMS, seeking a moratorium on sea dumping. However, in direct recognition of the disproportionate costs of the alternative to sea dumping, and after considering the likely environmental impacts from sea dumping, the environmental agencies agreed not to impose such a moratorium and allowed sea dumping to go ahead.

The need to minimise the costs of monitoring was a constant feature in the design of the monitoring programs. However all parties agreed that as the monitoring was going to form the basis of the dredge management framework, with no restrictions being placed on the dredge unless management triggers were exceeded, then sufficient funds had to be allocated to ensure the monitoring was scientifically rigorous and capable of providing the level and quality of information required.

Other cost saving measures included deleting some monitoring packages that were not considered essential or useful, (such as monitoring of reef fish populations), reducing the scope and/or the design of other programs, and the provision of direct staff and resource support by QDEH and GBRMPA, including aircraft, photographic equipment and staff time for seagrass monitoring.

8. PROJECT MANAGEMENT

Within the TAC, QDEH, through the Environmental Supervisor, was responsible for regulating the dredging through the Section 86 permit, ensuring TPA complied with the permit conditions, including those relating to environmental monitoring and management of the dredge.

Under the QDEH permit system, monitoring programs that are required as a permit condition are carried out either by the permittee or by consultant(s) on contract direct to the permittee. Monitoring data and draft reports are submitted to the permittee for editing and approval before being passed to the regulatory agencies.

In the case of the 1993 Townsville port development use of the multi-agency consultative approach and an agreement that at least the Reactive monitoring reports would be submitted from the consultants direct to QDEH, GBRMPA and TPA simultaneously introduced an extra level of credibility to this system.

TPA appointed SK as Project Managers for the environmental monitoring program. Under this system the monitoring consultants were contracted direct to the TPA but managed by SK with all communications between TPA and the monitoring consultants, and between the regulatory agencies and the monitoring consultants, being directed through SK. The Project Managers were also responsible for coordinating activities between the various separate components of the monitoring program. For details of project management refer to the Project Design and Management section.

9. MEDIA MANAGEMENT

A major consideration in any controversial large-scale development project with the potential for significant environmental implications is media and public information management. This consideration was compounded in relation to this project by the fact that the development was taking place immediately adjacent to a major population centre in a high profile area. Previous development projects are still causing controversial media attention in Townsville (eg Magnetic Quays and Halifax Bay Nickel Ore Facility), and a proportion of the local population are world leaders in marine science and environmental management with a critical interest in events in their local bay.

Regardless of how well managed the technical aspects of a project may be, the "power without responsibility" nature of the news media means that it is possible for inaccurate and/or ill managed media coverage to cause major problems for all parties involved, potentially taking up valuable time that can be better spent on the management of the project itself.

A proactive media and public contact strategy is vital. Once again a multi-disciplinary, consultative consensus approach was adopted. The basic principles of the media strategy were:

- stick to the facts, whether favourable or not;
- ensure coordination between all agencies to avoid contradictory releases and opportunities for the media to exploit apparent differences between organisations;
- pre-empt unexpected media attention by maintaining a flow of high quality information on a regular basis, therefore removing the novelty factor and opportunities for a "scoop" or an "exclusive".

This strategy was put in place by developing a set of media guidelines (Appendix 1) by which TPA, SK, QDEH and GBRMPA agreed to abide. All parties agreed that a press release, titled an Environmental Update, would be released by the Environmental Supervisor every two weeks or whenever a significant result was picked up by the monitoring program. These updates were reviewed by all four organisations prior to release and bore the logos of all four organisations. This joint approach to media contact ensured objectivity and consistency in the information released and enhanced the cooperative spirit that was so vital to the practical day-to-day management of the project.

To facilitate consistency in releases it was agreed that the number of individuals dealing directly with the media for interviews would be kept to a minimum, with all initial enquiries being directed to either the QDEH Environmental Supervisor or the SK Project Manager.

In addition, field-days were organised for the media by SK and TPA, with reporters and camera crews being taken up in aircraft and out on boats to observe and film the dredge operating and monitoring teams in action. Interpretive talks and interviews were provided by the SK Project Manager and the Environmental Supervisor. This ensured that the media were getting scientifically and technically correct information which might not have occurred if they had organised their field observations independently.

In addition to the media dealings, efforts were also made by TPA to take information direct to the public. A public meeting was held before the port development commenced, in conjunction with a meeting of the NQCC, at which SK presented the results of the trial developmental dredging and outlined the proposed port development, likely impacts and possible management strategies. In addition, speakers from AIMS and other bodies were invited to present their views at the meeting.

Overall the project received considerable media coverage, with newspaper, radio and television interviews being conducted virtually every week during the fifteen week project. The vast majority of the coverage was positive, with most stories emphasising the comprehensiveness of the monitoring program and the commitment of all parties to ensuring dredging would not cause any impacts.

At no stage during the project did a media crisis evolve and apart from attending to the routine media procedures, which were planned into the overall work program of the Environmental Supervisor, no staff time was wasted dealing reactively with media issues.

The general public and special interest groups such as NQCC and Island Voice were satisfied with the program (although Island Voice made some minor negative comments in local newspapers towards the very end of the dredging). NQCC publicly stated that they were completely satisfied with the arrangements that had been put in place, believing that it was a "win-win situation for the port and the environment". When NQCC were approached by TPA and SK at the end of the project with an offer of conducting a presentation on the results of the monitoring at their next meeting, their response was that they felt there was not enough concern to warrant it.

In addition to media and public contact another very important part of information management was to ensure relevant staff within QDEH, GBRMPA and CEPA were kept up-to-date via seminars and briefings. Of course it was necessary to keep Ministers informed as well.

10. CONCLUSION

The environmental management program comprised the most intensive and comprehensive program ever conducted in relation to a single development in the Great Barrier Reef Region. It made substantial advances in linking reactive environmental monitoring with preventative environmental impact management, allowing environmental impacts of development projects to be controlled rather than just measured. It also provided an extremely large data base on the physical and biological conditions in Cleveland Bay that are of immense value to both sustainable management of the Bay and pure research.

The appointment of an Environmental Supervisor, with the express role of ensuring all environmental requirements are adhered to during a development project, proved to be an effective component of the environmental management arrangements. However, such a person should ideally represent all of the environmental agencies involved and have the appropriate delegations/appointments under all of the applicable environmental legislation.

While no immediate, short-term impacts on the Magnetic Island fringing reefs or Cleveland Bay seagrass beds were measured, the possibility of long-term sub-lethal impacts has not been addressed, nor has the possibility of degradation of water clarity and bottom composition at the Strand swimming beach.

A full analysis and critical review of all of the data from all of the monitoring packages is needed in order to:

- ☐ summarise the major pertinent facts now established regarding the biological, physical and chemical environments of Cleveland Bay;
- ☐ summarise the major pertinent facts now established regarding the short-term, medium-term and long-term impacts of dredging and dredge spoil disposal in Cleveland Bay;
- ☐ formulate recommendations to management regarding what management measures should, if any, be applied to dredging and dumping in Cleveland Bay, based on the above knowledge;
- ☐ identify gaps in the above knowledge and recommend priority areas for future research and monitoring; and
- ☐ determine to what extent the above knowledge can be applied to similar projects elsewhere.

11. REFERENCES

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APPENDIX 1 - COPY OF MEDIA GUIDELINES

Townsville Port Development Media Guidelines for TPA, SK, QDEH, GBRMPA and Monitoring Contractors.

1. Press Releases

The QDEH Environmental Supervisor will draft fortnightly press releases, to be called "Environmental Updates", which will report on the status of the dredging and monitoring results. These will bear the logos of TPA, SK, QDEH and GBRMPA and will be reviewed and approved by all parties before release.

TPA, SK, QDEH and GBRMPA will retain the prerogative to make press releases at their discretion. However all parties agree to utilise the joint Environmental Updates as the preferred method of making press releases, and any additional unilateral releases will be faxed to the other three parties prior to release.

Monitoring contractors will not make press releases.

2. TV, Radio and Newspaper Interviews

TPA, SK, QDEH and GBRMPA are free to conduct such interviews at their discretion. However, all parties are to communicate prior to any interview to ensure consensus and consistency with regard to the line being taken. It is preferred that such interviews be directed to either the SK Project Manager or the QDEH Environmental Supervisor.

Monitoring contractors may only by interviewed in relation to the monitoring program if permission is given by the SK Project Manager. Any media enquiries to monitoring contractors should be directed to the SK Project Manager or the QDEH Environmental Supervisor.