Cleveland Bay, Townsville Queensland Australia

Status Report - 2002

Compiled by

Caryn Anderson & Mick Roche

on behalf of the

Cleveland Bay Consortium

Contributing Authors

C. Anderson[1], C. Battershill[2], R.M. Carter[3], J. Cruz[3], G. Doherty[3], G. Ericson[2], E. Evansillidge[2], D. Haynes[4], A. Hesse[5], G.B. Jones[3], P. Larcombe[3], J. Lough[2], K. Neil[3], A. Orpin[3], A.J. Reichelt-Brushett[6], P. Ridd[3], M. Roche[7],V. Veitch[8].

[1] formerly Townsville Port Authority; [2] Australian Institute of Marine Science; [3] James Cook University; [4] Great Barrier Reef Marine Park Authority; [5] Townsville City Council / Environmental Protection Agency; [6] Southern Cross University; [7] BHP Billiton - Cannington; [8] Sunfish.

The level to which we can manage Cleveland Bay is directly proportional to our understanding of Cleveland Bay.

The more we know, the better we can manage.

The better we can manage, the more sustainable is our use.

Executive Summary

Cleveland Bay is located within the GreatBarrier Reef World Heritage Area and has recently been designated as a dugong protected area. These issues of environmental sensitivity, combined with the rapid expansion and development of the Port of Townsville over the past decade has meant that port operations and development need to be undertaken with due regard for the environment.

Increasingly as the world's population demands action in response to environmental degradation, governments are placed under pressure to respond through the introduction of legislative restrictions on activities and operations. These requirements have often been developed in an ad hoc fashion and often represent overlapping requirements which may not always reflect complimentary requirements.

The northeast coast of Australia is complicated in its regulatory regimes through the management and active jurisdiction of both the Commonwealth and the State of Queensland. Based on area, 97% of the Great Barrier Reef Marine Park is under the jurisdiction of the Commonwealth with the remaining 3% being subject to the laws of the State being within the internal waters of the State of Queensland[1].

In response to this multi-jurisdictional approach there is a comprehensive system of management and regulation of maritime activities within the GBR. Queensland has recently experienced considerable change in the legislative framework that manages development, planning and the environment. These changes have heightened community and industry awareness to both environmental and planning issues. Residential land developments, particularly in the area of South Townsville and Railway Estate, continue to encroach on Port lands

[1] White, M. 1999. "Sensitive Marine Environments and the Regulation of Shipping: The Great Barrier Reef Experience". *Asia Pacific Journal of Environmental Law*, Vol. 4, Issue 3(1999), 219:242.

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Chapter 1 – Introduction to the Cleveland Bay Consortium and the Cleveland Bay Status Report

The Cleveland Bay Consortium is an informal industry/research forum for the discussion of the sustainable use of the environments of Cleveland Bay. Industry and regulatory agencies in the Cleveland Bay region have identified a need for comprehensive information about water, sediment, flora and fauna of the Bay for environmental license applications and future planning for sustainable use of the region. Information from past research is often difficult to find, of variable quality, and is sometimes difficult to apply to current problems and applications. Business, industry, regulatory authorities, and research agencies identified a need for a focus or forum to exchange information, priorities, information needs, and expertise.

The first Cleveland Bay Consortium workshop was held in January 1998. The founding members of the CBC included, BHP Cannington, the Australian Institute of Marine Science, MIM Copper Refineries, Northern Shipping and Stevedoring, the Great Barrier Reef Marine Park Authority, Sun Metals, Townsville Port Authority, James Cook University, QNI.

All participants agreed that, it is often difficult to determine environmental monitoring requirements, licensing and discharge criteria when there appears to be a general lack of baseline data. The fact of the matter however, is that Cleveland Bay has been extensively studied and there is significant data available on the natural resources and processes of the region. The challenge however has been in identifying these research initiatives, where the data is held and coordinating these initiatives to ensure that the data is available in a single location, or at least to initiate this process. It was important from the outset to recognise the benefits to industry, research organisations and regulatory agencies a like ensuring data availability, efficiencies in research initiatives and improved environmental understanding.

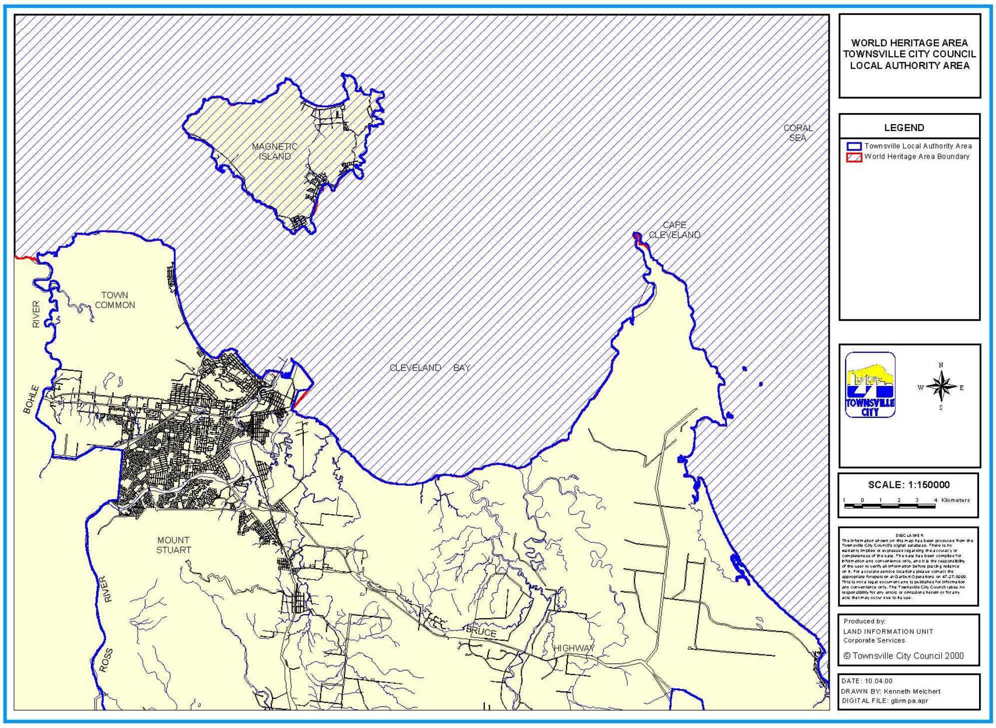

Figure 1.1 Location plan of Cleveland Bay showing the Cities of Townsville and Thuringowa located on the western shores, and the boundaries of the World Heritage Area.

This Cleveland Bay Status Report is the first step in providing the information and understanding of all the stakeholders of Cleveland Bay. An exercise of this complexity requires the input from a range of groups and individuals. The commitment by the contributors demonstrates a desire to ensure the sustainable use of Cleveland Bay.

This report is not intended to pass judgement on the quality of Cleveland Bay nor is it intended to comment on the quality of the available data. Rather, the Report is a compilation of all the available research data relevant to Cleveland Bay and the region. The report itself has been compiled through the voluntary contributions of individuals and organisations representing researchers, industry and regulatory authorities. To minimise the burden on participating agencies the forum has been established electronically, allowing anyone with a relevant interest to contribute and participate.

The Cleveland Bay Sustainability Cycle

The Cleveland Bay Sustainability Cycle, represented in figure 1, depicts the journey to the bsustainable use of Cleveland Bay.

By sustainable use, we mean, that the things that we do in Cleveland Bay today will not have a detrimental impact on the Cleveland Bay such that futures generations will be unable to do the things in Cleveland Bay that they want to do.

In 1996 a group of people representing industry, research and regulators got together to talk about our vision for Cleveland Bay. This group also discussed their interest and activity in the Bay. What was lacking previously in Cleveland Bay was a coherent vision and understanding of the links between the different values of Cleveland Bay.

What are the links between the air, the water, the sediment, the plants and the animals of Cleveland Bay? And what are the relationships between these internal contributors (ie nature) to Cleveland Bay and the external factors eg people and their activities?

The group then formed the Cleveland Bay Consortium and set out to answer some of these questions.

The journey of understanding has only just begun and this status report is a tangible contributor to the Cleveland Bay Sustainability Cycle .

The symbolism of the circle sizes in figure 1, at the entry point of the Cleveland Bay Consortium into the Cleveland Bay Sustainability Cycle reflects the 'steps' that are needed for our journey. They represent the incremental increase in knowledge, understanding, acceptance, contribution, commitment, honesty and integrity as we journey to our next milestone of the "Gap analysis". All the journeys in the Cleveland Bay Sustainability Cycle reflect the same stepping-stones. On completion of the Gap analysis, further research or understanding will need to be conducted to increase our knowledge of the environmental, social and economic vales of Cleveland Bay. This is often referred to as the triple bottom line of sustainable development – of people, planet and profit or earth, earthlings and earnings.

As we increase our knowledge we move on to the next stage of the journey. That is to adopt principle, practices and standards (or if necessary, regulation/legislation) that reflect our new knowledge.

That is not the end of the journey – the Cleveland Bay Sustainability Cycle is an endless cycle.

Sustainable development, we believe, means different things to different people, in different times. The vision of sustainable use however, should not change – it just gets its values redefined.

Hence the next step in this never-ending journey is to conduct another status report and start the cycle again.

The level to which we can manage Cleveland Bay is directly proportional to our understanding of Cleveland Bay. The more we know, the better we can manage. The better we can manage, the more sustainable is our use.

Figure 1.2 Flow chart demonstrating how the Cleveland Bay Consortium and Cleveland Bay Status Report, interact with environmental pressures and the objective of sustainable use of Cleveland Bay.

Table 1.1 Structure of the Cleveland Bay Status Report

	Chapter Subject	Title	Authors
1	Introduction	Introduction to the Cleveland Bay Consortium and the Cleveland Bay Status Report	C. Anderson & M. Roche
2	The Physical Environment	Weather and Climate of Cleveland Bay	J. Lough
		Water and Sediment Movement in Cleveland Bay	P. Ridd & A. Orpin
		Geological and sedimentary characteristics of Cleveland Bay	R. M. Carter & P. Larcombe
3	Marine Biodiversity	Cleveland Bay Biodiversity	C. Battershill, G. Ericson & E. Evansillidge
4	Industry	Industries and the environment in the Townsville Region	Greg Doherty, Vern Vietch, Mick Roche, Caryn Anderson
5	Regulatory	Environmental laws and regulations applicable to Cleveland Bay	A. Hesse
6	Toxicology	Chemical Contaminants in Cleveland Bay: Water Quality and Ecotoxicological Issues	G.B. Jones, A. J. Reichelt-Brushett, A. Muslim, P. Mercurio, G. Doherty & D. Haynes
7	Environmental Quality	Summary of investigations into marine environmental quality and air quality of Cleveland Bay	G. Doherty, J. Cruz, K. Neil & D. Haynes
8	Conclusions and Recommendations		C. Anderson & M. Roche

Web Address and
email contact

Table of email and web addresses of contributors

Chapter 2 - The physical environment

2.1 Weather and Climate of Cleveland Bay

Janice Lough

Australian Institute of Marine Science

2.1.1 Introduction – some definitions

Weather is how we experience the atmosphere around us at a given time and place (eg the wind speed, the amount of cloud, the air temperature and humidity etc). Climate is what we expect the weather to be like at that particular time and place. To define the climate of a region requires many years of weather observations to determine average statistics (30 years is typically taken as a standard by the World Meteorological Organisation; http://www.wmo.ch/). Climate also encompasses the range of variability (or observed extremes) about average conditions. Climate varies naturally from year to year and often departures from average (anomalies) are experienced. El Niño-Southern Oscillation (ENSO) is the major source of inter-annual tropical climate variability that causes climate anomalies in many parts of the tropics (including Queensland and adjacent waters) and extra-tropical latitudes (http://www.pmel.noaa.gov/toga-tao/el-nino/nino-home.html). A climate change occurs when there is a significant change in the average climate and/or its variability so that our expectation of weather also changes.

2.1.2 Sources of data

To describe and monitor variations and changes in climate requires long, high-quality, homogeneous observations of weather elements. What we can say about weather, climate, climate variability and change is highly dependent on the quality of these observational data sets. There is a range of data available to describe weather and climate of Cleveland Bay, each with their respective strengths and weaknesses. Factors to consider when selecting data for a particular application include: length of record, spatial and temporal resolution, spatial and temporal representativeness, instrument or site changes, etc. Some useful sources of information are:

2.1.2.1 Current weather

- Current observations, charts, satellite maps, forecasts etc from Townsville office of Bureau of Meteorology http://www.bom.gov.au/weather/qld/townsville/

- Colour-enhanced satellite maps of Australia, Queensland and any significant current weather events provided by Prof C.J. Kikkert, Dept of Electrical & Computing Engineering, JCU http://www.ece.jcu.edu.au/JCUMetSat/web/metsat.html

- Near real-time half-hourly measurements of sea water temperature, air temperature, wind speed and direction, air pressure and light levels from Australian Institute of Marine Science Automatic Weather Station (AWS) Network. The nearest stations are the recently installed AWS in Cleveland Bay and the land-based AWS at Cape Bowling Green. http://www.aims.gov.au/pages/facilities/weather-stations/weather-index.html

- Glossary of weather and climate terminology: http://www.bom.gov.au/climate/glossary/index.shtml/

2.1.2.2 Climate averages

- Monthly climate statistics (eg maximum, minimum temperatures, rainfall, number of rain days) for Townsville AMO (Bureau of Meteorology Station Number 32040) operating since 1940 at Townsville Airport http://www.bom.gov.au/climate/averages/tables/cw_032040.shtml Similar statistics for original Townsville weather station located near hospital (operated till 1941) http://www.bom.gov.au/climate/averages/tables/cw_032071.shtml

- Graphs of average monthly temperature and rainfall for Townsville AMO station http://www.bom.gov.au/cgi-bin/climate/cgi_bin_scripts/map_script_new.cgi?32040

- Overview of climate information available for Australia http://www.bom.gov.au/climate

2.1.2.3 Sea water temperatures

- Daily, weekly and monthly from data loggers deployed by the Great Barrier Reef Marine Park Authority at Middle Reef, Nelly, Geoffrey and Florence Bays of Magnetic Island http://www.gbrmpa.gov.au/seatemp/index.html. These data are downloaded every 3-6 months. See also AIMS AWS.

- Weekly and monthly sea-surface temperatures and anomalies from blended satellite data for 1^{o} latitude by longitude squares, 1981 to date IGOSS Data Products Bulletin of the IRI/LDEO Climate Data Library http://ingrid.ldgo.columbia.edu/

2.1.2.4 Climate outlooks and El Niño-Southern Oscillation

- Queensland Department of Primary Industries provide a range of information about current conditions and seasonal outlooks (see especially their Long Paddock pages) http://www.dpi.qld.gov.au/climate/Welcome.html

- A similar range of information with the Bureau of Meteorology's seasonal outlooks is provided on the SILO pages http://www.bom.gov.au

2.1.2.5 Past and possible future climate change in Australia

- The Bureau of Meteorology Research Centre have been developing high-quality rainfall and temperature data sets necessary to describe climate variation and change http://www.bom.gov.au/bmrc, see especially the pages from the Climate Group.

- Climate scenarios for Australia projected due to the enhanced Greenhouse effect are developed by the Atmospheric Research division of the CSIRO http://www.dar.csiro.au

2.1.2.6 Summaries of recent weather and climate

- A review of monthly weather in Queensland (including rainfall and temperature data for selected stations, evaporation and sunshine, water storage capacities, daily weather charts and a description of synoptic situation and weather events) can be found in the *Monthly Weather Review Queensland* published monthly by the Bureau of Meteorology.

- A review of monthly climate for the Australian region and globally (including up-to-date indices such as the Southern Oscillation Index) can be found in the *Climate Monitoring Bulletin Australia*, published monthly by the Bureau of Meteorology.

- A weekly summary of global climate highlights is provided by the US National Oceanographic and Atmospheric Administration http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/GLOB_CLIM/

- Another useful summary of weather events around the world is the World Weather pages of US Today http://www.usatoday.com/weather/

2.1.2.7 Climate data

- For applications requiring long records of climate elements (eg temperature, rainfall, wind speed, sea-level pressure), data (from 3-hourly up to monthly averages and totals) can be obtained for Bureau of Meteorology weather stations http://www.bom.gov.au/climate/how/sitedat.shtml on application to the Bureau. Care should be used with these data as there may be missing observations or inhomogeneities eg due to site or instrument changes. Townsville AMO records, in addition to standard weather elements: evaporation, incoming solar radiation, sunshine duration, cloud amount, upper air temperature and wind, rainfall intensity and maximum wind gusts. Townsville AMO is the most useful station for Cleveland Bay and is one of the Bureau's Reference Climate Stations. A station was also operated at Cleveland Bay Lighthouse from 1927 through 1987 for which historical data can be obtained from the Bureau.

- Daily and monthly river flows for rivers in the vicinity of Cleveland Bay, eg Burdekin (back to 1922) and Haughton (back to 1970) can be obtained on application to regional hydrographers of the Queensland Department of Natural Resources (DNR). The DNR office for the region is located in Ayr.

- Systematic recording of weather at sea by "ships of opportunity" dates back to the mid-19th century. Long-term records of sea-surface temperatures (SSTs) can be extracted from compilations of global SSTs. These monthly data are averages of all observations for a particular month and box made by "ships of opportunity", supplemented in recent years by Automatic Weather Stations and buoys (see Bottomley *et al.*, 1990). Monthly SST data are available for the vicinity of Cleveland Bay from:

a) the GOSTAPlus GISST2.2 dataset produced by the United Kingdom Meteorological Office in collaboration with the Massachusetts Institute of Technology and the Physical Oceanography Distributed Active Archive Center (see Rayner *et al.*, 1996; data freely available on CD-ROM on application to the UKMO). SSTs are presently available for the period 1903-1994. This is an interpolated data set and there are no missing values.

b) the Comprehensive Ocean-Atmosphere Data Set (COADS Release 1a/1b/1c 1999; http://www.scd.ucar.edu/dss/pub/COADS_intro.html; Woodruff *et al.*, 1993) provides monthly data at 2^o latitude by longitude resolution for SSTs and additional climate elements eg sea-level pressure, wind speeds, cloud amount. This data set is not interpolated so there may be many missing months of data for a particular box.

2.1.2.8 Tropical cyclones

- Tracks and details of tropical cyclones for the Australian region for the period 1909 to 1980 are provided by Lourensz (1981). It has, however, only been since the advent of satellite observations that we can be sure that all tropical cyclones have been recorded and correctly tracked. The best available information about tropical cyclones on the Great Barrier Reef and in the vicinity of Cleveland Bay for the period 1969-1997 is provided by Puotinen *et al.* (1997). For more recent summer seasons, tracks and details of tropical cyclones affecting the Australian region can be obtained from the seasonal climate summaries published regularly in the *Australian Meteorological Magazine*, a quarterly publication of the Australian Bureau of Meteorology.

2.1.3 Average climate

Climate of the region is defined as hot, humid and tropical with a summer rainfall maximum (more than 80% of rainfall occurs between October and March) associated with the Australian summer monsoon (Suppiah, 1992; Sturman & Tapper, 1996). Climate averages for the Townsville AMO station are provided in Table 1. Note that for rainfall, which tends not to be normally distributed, the average is not a good measure of what to expect. Better measures of "average" rainfall (and river flow) are obtained from the median and percentiles of the observations (50% of observations will have values above or below the median or 50th percentile; 90% of observations will be at or below the 90th percentile or there is a 10% probability that values will exceed the 90th percentile etc). The rainfall regime of Cleveland Bay is characterized by very high inter-annual variability – the driest year on record (and also for Queensland) was 1901-1902 when only 80 mm of rainfall was recorded. In the wettest year, 1939-1940, 2646 mm was recorded.

Table 2.1 Some average monthly and annual statistics for Cleveland Bay. Monthly and annual averages for Townsville AMO apart from sea surface temperature which are for 1^o latitude by longitude box closest to Cleveland Bay from historical data sets (see text).

Variable	Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Daily maximum temp ^{o}C	1940-96	31.3	31.0	30.6	29.5	27.5	25.5	24.9	25.9	27.6	29.3	31.3	28.7	28.7
Highest maximum ^{o}C	1940-96	44.3	42.7	37.6	35.8	32.0	31.6	33.3	35.9	37.1	41.0	42.1	44.3	44.3
Daily Minimum temp ^{o}C	1940-96	24.2	23.9	22.8	20.5	17.6	14.4	13.6	14.7	17.2	20.6	22.8	23.9	19.7
Lowest minimum ^{o}C	1940-96	18.7	17.9	16.7	10.9	6.2	4.4	0.1	1.1	7.7	8.2	14.1	18.7	0.1
Median rainfall mm	1940-00	198	221	155	32	19	10	3	5	3	13	35	75	1080
Mean no. raindays	1940-96	14	16	13	8	6	4	3	3	2	5	7	10	91
Highest monthly rainfall mm	1940-00	1142	1396	683	406	181	107	174	241	81	253	333	458	
Lowest monthly rainfall mm	1940-00	9	4	7	<1	0	0	0	0	0	0	<1	4	
Highest daily rainfall mm	1940-00	549	318	367	226	96	93	51	120	50	89	133	160	549
Daily hours of sunshine	1940-96	7.9	7.2	7.5	7.8	7.3	7.9	8.4	9.0	9.5	9.8	9.5	9.0	8.4
Solar radiation MJ.m^2	1971-92	21.3	20.1	19.4	16.5	15.2	14.7	15.7	18.3	22.0	24.3	24.6	23.3	19.6
Cloud amount oktas	1941-99	5.0	5.3	4.7	4.1	4.0	3.3	3.1	2.8	2.7	3.1	3.6	4.2	3.8
Daily evaporation mm	1940-96	8.4	7.4	7.0	6.6	5.6	5.1	5.5	6.4	8.0	9.1	9.4	9.2	7.3
Rel. humidity 3pm %*	1940-96	65	67	64	60	57	51	51	51	52	55	57	60	57
SLP 3pm mb	1941-99	1007	1007	1009	1012	1013	1015	1016	1015	1014	1012	1010	1008	1011
Wind 3pm m/s	1941-99	5.3	4.9	5.2	5.5	5.2	4.8	5.3	5.9	6.4	6.4	6.2	6.0	5.6
U-wd 3pm m/s†	1941-99	3.6	3.3	3.7	4.3	3.8	3.2	3.6	4.1	4.4	4.2	3.7	3.6	3.8
V-wd 3pm m/s‡	1941-99	2.4	1.9	1.6	1.8	1.4	1.0	1.6	2.5	3.3	3.7	3.8	3.4	2.4
Sea temperature ^{o}C	1940-96	28.3	28.5	27.9	26.6	25.2	23.3	22.5	22.7	23.7	25.3	26.8	27.6	25.7

* Averages for relative humidity, pressure and winds are for 3pm observations. Relative humidity at 3pm is ~10% less than at 9am; sea -level pressure is ~4mb lower than at 9am; wind speeds are ~3m/s higher than at 9a m; wind components are more easterly and southerly than at 9am.

† U-wind is the zonal or east-west wind component, calculated as wind speed x sin (wind direction).

‡ V-wind is the meridional or north -south wind component, calculated as wind speed x cos (wind direction).

Over the period 1969-1997 there were 18 tropical cyclones[2] within about 100-150 km of Cleveland Bay (ie about 6 per decade or 1 every 1-2 years). Of these 18 TCs, 3 occurred in December, 6 in January, 3 in February, 5 in March and 1 in April. Five were Category 0 (average wind speeds at least 17 m/s), 9 were Category 1 (average wind speeds 17-25 m/s, central pressure 1000-985 mb), 1 was Category 2 (average wind speeds 25-33 m/s, central pressure 985-970mb) and 3 were Category 3 (average wind speeds 33-44 m/s, central pressure 970-945). Category 3 tropical cyclones were Althea in December 1971, Charlie in February 1988 and Aivu in April 1989. Over this record period no Category 4 (44-56 m/s, 945-920 mb) or Category 5 (> 56 m/s, < 920 mb) were recorded in the Cleveland Bay area (information taken from Puotinen *et al.*, 1997).

2.1.4 Variability of climate and El Niño-Southern Oscillation (ENSO) events

Climate of Cleveland Bay varies naturally on a range of timescales – from year-to-year, to decadal and longer. The major source of global year-to-year climate variability is the El Niño-Southern Oscillation (ENSO). ENSO is the term used to describe large-scale fluctuations of the ocean-atmosphere climate of the tropical Pacific (see Allan *et al.* 1996 for a detailed description and history of our understanding of ENSO). The strength of ENSO is commonly monitored by the Southern Oscillation Index (SOI) - the difference in sea-level pressure between Tahiti and Darwin ENSO has two opposite phases, both of which can result in significant climate anomalies in Cleveland Bay: 1) ENSO, El Niño, negative SOI or "warm" events - when the eastern equatorial Pacific is warmer than normal and 2) anti-ENSO, La Niña, positive SOI or "cool" events - when the eastern equatorial Pacific is cooler than normal.

During ENSO events the summer monsoon of north Queensland tends to be weaker than during anti-ENSO events which gives rise to substantial differences in surface climate conditions between these sets of years. By averaging climate conditions over several ENSO events and over several anti-ENSO events we gain a picture of climate anomalies typical of ENSO and anti-ENSO events in the region. It should be noted, however,

[2] Defined by the Australian Bureau of Meteorology as a "non-frontal synoptic-scale cyclonic rotational low pressure system of tropical origin, in which 10 minute mean winds of at least 17.5 m/s occur, the belt of maximum winds being in the vicinity of the system's center."

that no two ENSO or anti-ENSO events are alike and climate conditions in any given ENSO and anti-ENSO year may differ from the following average or “composite” pictures.

In ENSO years, SSTs tend to be cooler in winter and warmer in late summer compared to anti-ENSO years in the vicinity of Cleveland Bay (Figure 1). The weaker summer monsoon typical of ENSO years leads to below average rainfall at Townsville compared to anti-ENSO years (Figure 2). The median total annual rainfall (over the water year October-September) for ENSO years is 796 mm compared with 1,350 mm for anti-ENSO years. ENSO years are also characterised by substantially reduced river flows and tropical cyclone activity compared with anti-ENSO years when the summer monsoon tends to be more vigorous (see Lough, 1994; in press).

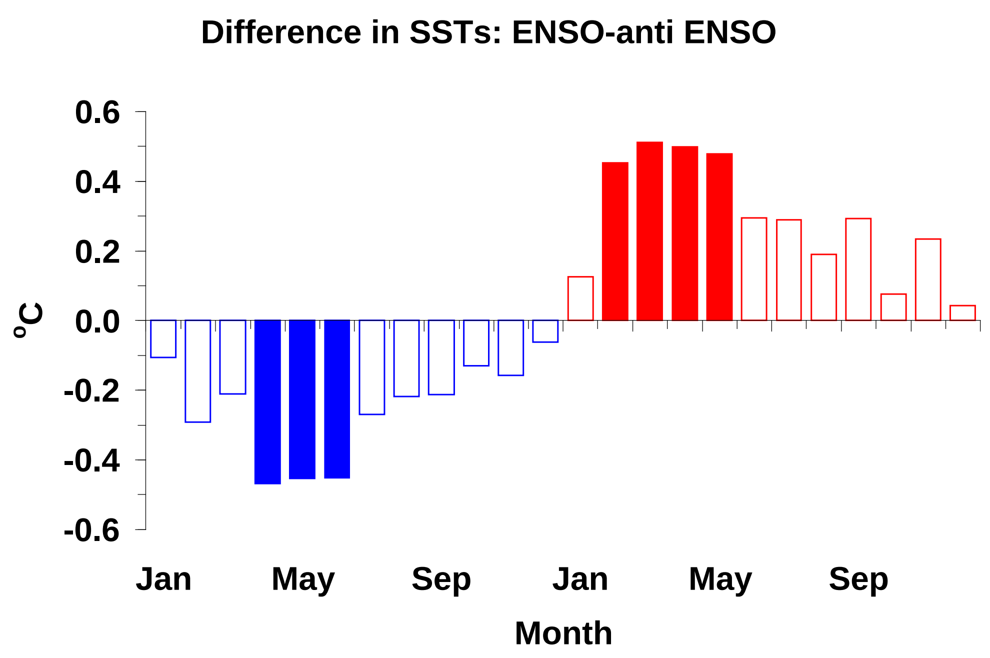

Figure 2.1 Average differences in monthly sea-surface temperatures at 19.5^{o}S, 147.5^{o}E between years of ENSO and anti-ENSO[†] events over the two-year period typical of evolution of such events. Solid blue bars indicate months when SSTs are significantly cooler and red bars significantly warmer during ENSO events compared to anti-ENSO events.

[†] Years used to produce Figures 1 and 2 were: ENSO events 1951-52, 1957-58, 1963-64, 1965-66, 1968-69, 1969-70, 1972-73, 1976-77, 1977-78, 1979-80, 1982-83, 1986-87, 1987-88, 1991-92, 1994-95 & 1997-98; anti-ENSO events 1950-51, 1954-55, 1955-56, 1964-65, 1970-71, 1973-74, 1975-76, 1984-85, 1988-89, 1995-96 & 1998-99.

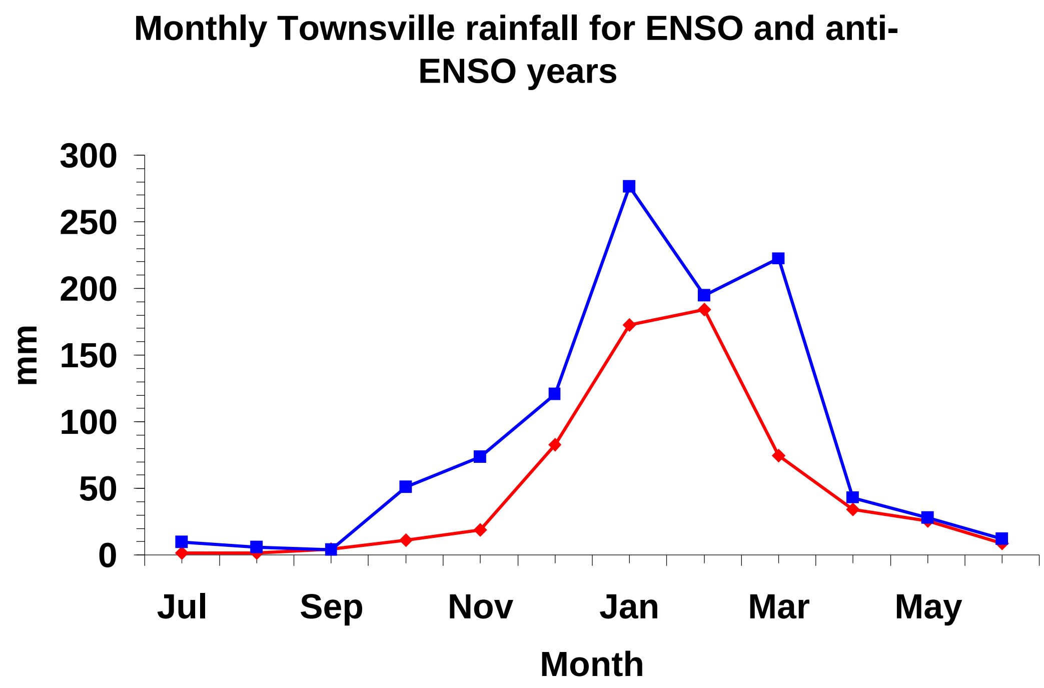

Figure 2.2 Median monthly rainfall for Townsville from July to June for ENSO years (red line) and anti-ENSO years (blue line).

2.1.5 Climate of the past century

SSTs around Cleveland Bay have, in keeping with the rest of the GBR (Lough 1999), significantly warmed over the past century (Figure 3). Annual average SSTs are 0.6°C warmer in the last 30 years of the 20th century compared with the first 30 years of the century. As has been occurring in Queensland (Lough, 1997), air temperatures in Townsville have also been rising (Figure 4). Annual average temperatures for the most recent 20 years of record (1979-98) are 0.5^{o}C warmer than in the first 20 years of record (1941-60). Warming has been slightly greater for minimum (nighttime) temperatures which have increased by 0.9^{o}C over the same time period. Rainfall in Townsville is characterized by considerable inter-annual and inter-decadal variability (eg wetter 1950s and 1970s) and shows (similar to Queensland, see Lough, 1991, 1997) no significant trend over the past century towards wetter or drier conditions (Figure 5).

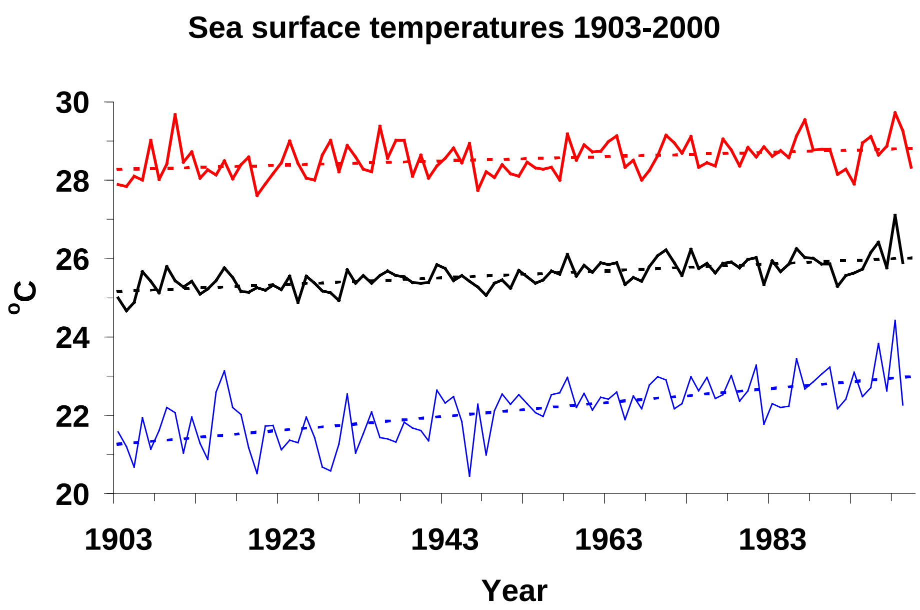

Figure 2.3 Average annual (black), maximum (red) and minimum (blue) sea-surface temperatures at 19.5°S, 147.5°E from 1903-2000. Dashed lines are linear trend lines.

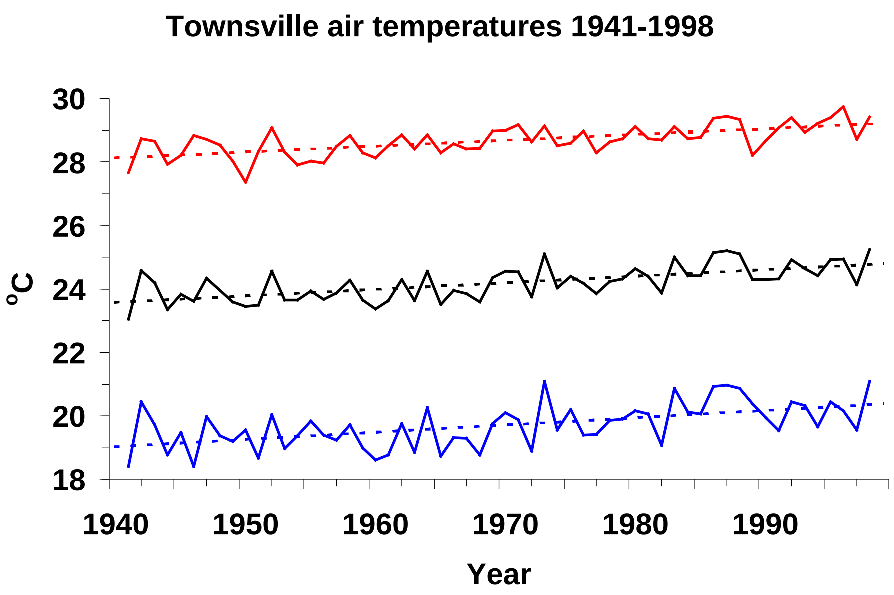

Figure 2.4 Townsville AMO annual average (black line), annual maximum (red line) and annual minimum (blue line) air temperatures, 1941-1998. Dashed lines are linear trend lines.

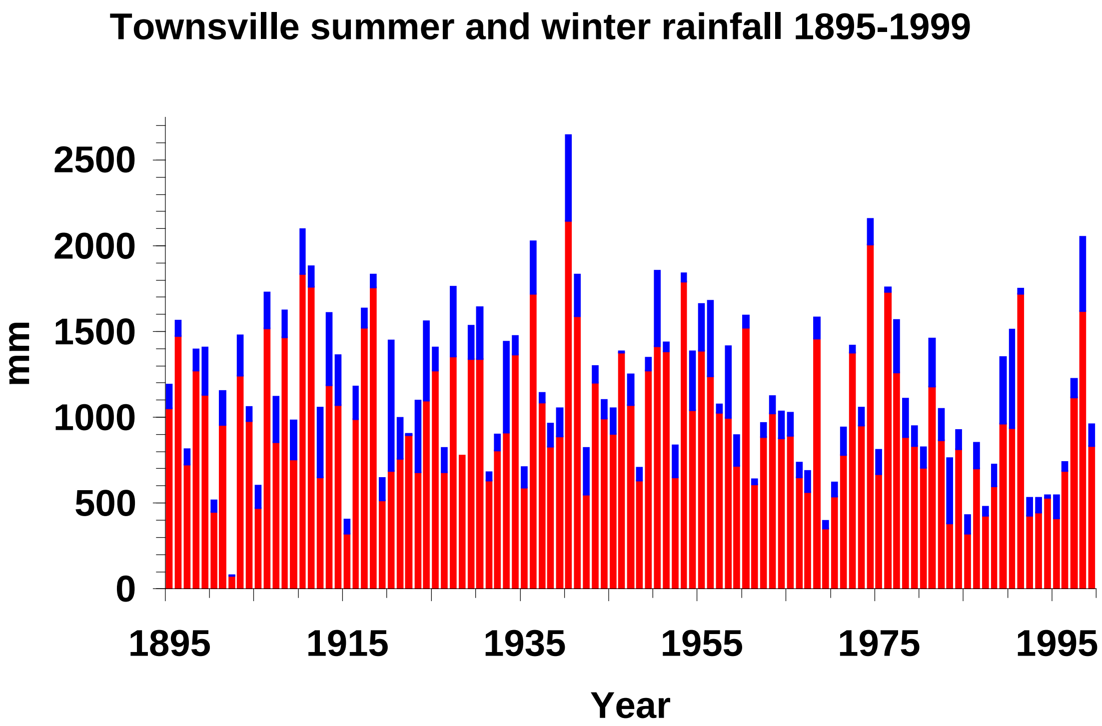

Figure 2.5 Townsville total summer (red bar) and winter (blue bar) rainfall, 1895-1999. Total height of bars give annual total rainfall for water year (October-September).

2.1.6 Climate of the past several centuries

Instrumental records of weather for Queensland are of a high quality due to the foresight and tenacity of the first Government Meteorologist, Clement Wragge, working in the late 19th century. These records extend back little more than a century which is a relatively short time to assess the long-term natural variability of climate. To examine variations of climate before the mid-19th century proxy climate records are required eg tree rings, ice cores. For shallow-water tropical ocean regions a wealth of proxy climate and environmental information is locked away in the annual bands of certain massive coral skeletons which can live to be 700-800 years old (Barnes & Lough, 1996). A reconstruction of Burdekin River runoff from luminescent bands in corals from Havannah and Pandora Reefs (see Isdale *et al.* 1998) shows much greater variations of river flow than have been experienced in the 20th century (Figure 6). A reconstruction of sea-surface temperature from the calcification rates of corals along the GBR (Lough & Barnes, 1997) also shows larger excursions of temperature than experienced in the 20th century (Figure 7). These proxy records contain many sources of error and more records are required to refine the climate histories they suggest.

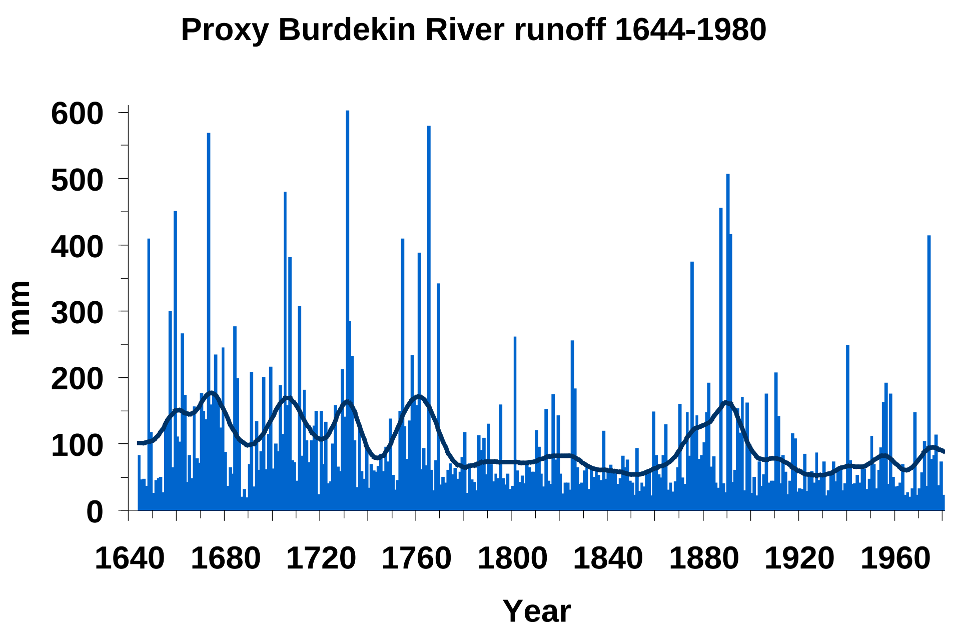

Figure 2.6 Reconstructed Burdekin River runoff, 1644-1980, from luminescence in coral skeletons. Thick line is 30-year gaussian filter to emphasize multi-decadal variability (from Isdale *et al.* 1998).

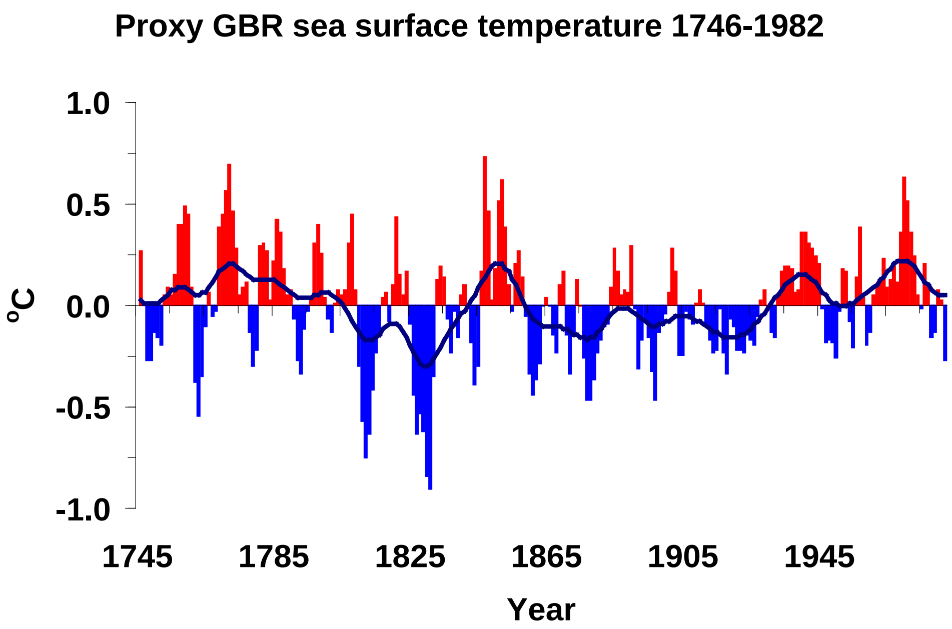

Figure 2.7 Reconstructed sea surface temperature anomalies for the Great Barrier Reef from calcification rates in 10 corals. Thick blue line is 30-year gaussian filter to emphasise multi-decadal variability (from Lough & Barnes, 1997).

2.1.7 Future climate

Climate of Cleveland Bay will vary naturally as it has done in the past. Human activities since the 19th century have, however, superimposed a source of global climate change - the enhanced Greenhouse effect (Houghton *et al.* 1996). Global temperatures are projected to rise over the next century and early reports from the latest Intergovernmental Panel on Climate Change third assessment due to be published in 2001 suggest that there has already been "a discernible human influence on global climate" (Kerr, 2000). Associated with global warming will be changes in atmospheric circulation patterns, rainfall etc. The regional consequences of climate change due to global warming are, however, less reliably projected than global or hemispherical changes. Land and sea temperatures in Cleveland Bay have been warming but there is no evidence, as yet, of significant changes in the rainfall regime. The biggest unknown for future climate in this area is what may happen to ENSO which is not as yet reliably modeled in the global climate models used to provide scenarios of future climate (Hulme & Sheard, 1999; Walsh *et al.* 2000).

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2.2 Water and Sediment Movement in Cleveland Bay

Peter Ridd & Alan Orpin

Marine Geophysical Laboratory, James Cook University, Townsville Q4811

2.2.1 Tidal currents

Tidal currents in Cleveland Bay have been well documented by several authors (Lou & Ridd, 1997) using numerical models and current meter deployments. Flood tide currents enter the bay between Cape Cleveland and Magnetic Island and flow southwest (Figure 2.8). Ebb tides are generally in the opposite direction. In West Passage, flood tides are directed southeast close to Pallarenda, and in a westerly direction close to Townsville. There is a zone in West Passage where there is very little tidal current caused by the convergence of the tidal propagation from either end of the channel. Tidal currents on spring tides generally do not exceed *ca.* 50 cm/s.

2.2.2 Wind-driven currents

Southeasterly trade winds are the predominant cause of wind-driven circulation in the region. Southeasterly trade winds dominate for the dry season months of April to November, and produce a northward longshore current and associated wind waves (e.g., Wolanski, 1994). The Townsville region is influenced more strongly by northeasterly afternoon sea breezes which reach wind speeds between 15-25 km/h throughout the year. Southeasterly winds generate northeast-directed currents along the Great Barrier Reef coast, and Cleveland Bay is no exception. Modelling results indicate that wind-driven currents during a continuous 15 knot southeasterly wind are approximately 5 cm/s. These currents enter the bay close to Cape Cleveland and exit either close to Magnetic Island, or through West Passage. Under these conditions the flushing time of the bay is estimated to be *ca.* 5 days.

Orpin *et al.* (1999) estimated the long-shore sediment flux in the Burdekin region from SSC data, and predicted a potential annual sediment export from Bowling Green Bay into Cleveland Bay of 3×10^8 kg/yr. This figure is smaller, but comparable, to that estimated by Belperio (1978) of 8×10^8 kg/yr using relative sediment accumulation rates. By difference from the estimated suspended sediment output from the Burdekin River, Orpin (1999) estimated that Cleveland and Bowling Green bays trap ca. 10% and 80% of the annual riverine output respectively (ignoring small northward transport into Halifax Bay).

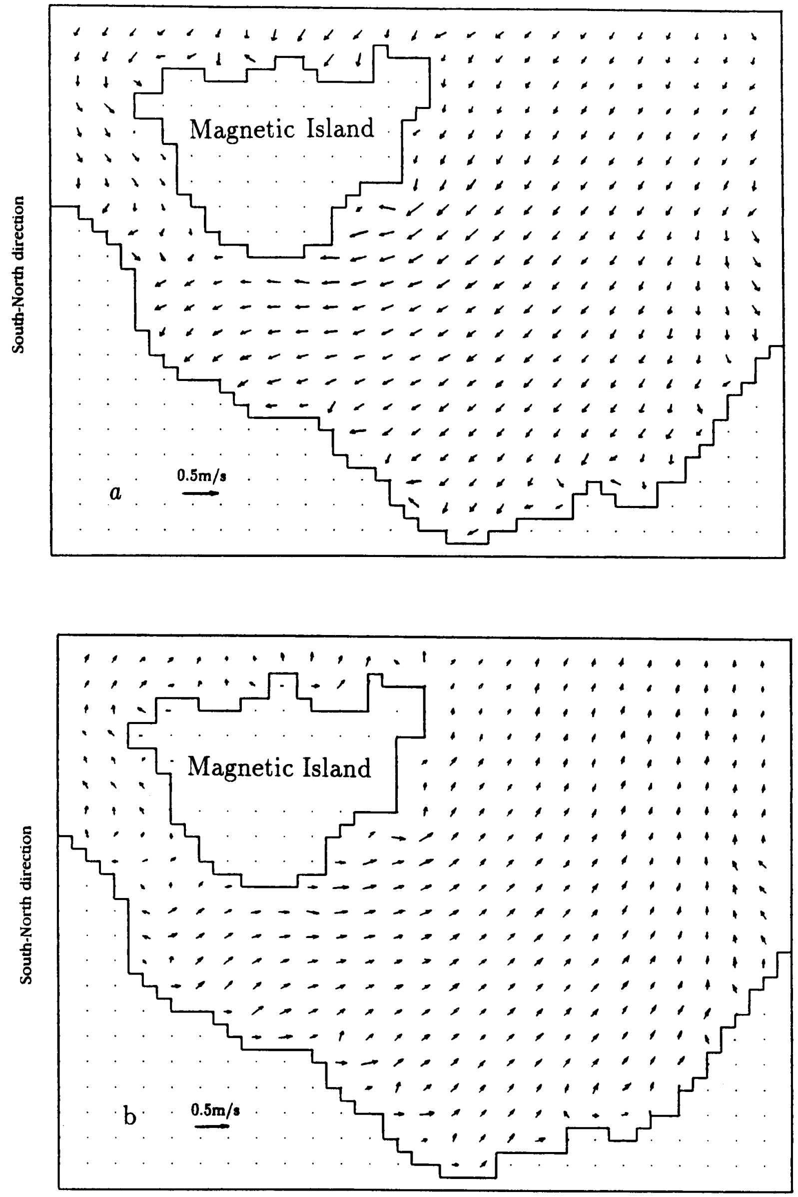
South-North direction
Magnetic Island
0.5m/s
a
South-North direction
Magnetic Island
0.5m/s
b

Figure 2.8 Typical tidal currents in Cleveland Bay during (a) maximum flood tide, and (b) maximum ebb tide (after Lou, 1995).

Lou (1995) calculated the magnitude of the offshore (northward) three-dimensional bottom return current within Cleveland Bay using a three dimensional finite difference model. The results suggest that a bottom return flow developed when the northeasterly sea breeze exceeds 7 m/s, and winds of 10 m/s (36 km/h) may generate a northward (seaward) bottom current up to 0.1 m/s. An average current speed of approximately 0.05 m/s was predicted to extend up to 2 m above the bed. An assessment of how far offshore these currents persist is problematic due to a lack of near-bed current and SSC time-series measurements away from embayments, but would probably be restricted to the inner shelf.

2.2.3 Sediment resuspension

The major cause of sediment resuspension in the bay are waves (Larcombe *et al.*, 1995; Orpin *et al.*, 1999). Waves typically have a short period of 3.6-5.8 s with mean significant wave heights (Hsig) between 0.53-0.66 m. Larcombe *et al.* (1995) and Lou & Ridd (1996) suggest that these waves are locally generated. The dominant orientation of the waves is east-southeast, concordant with the prevailing wind direction (Department of Environment, 1986). Within the central Great Barrier Reef lagoon, swell waves typically have periods in excess of 7 s and Hsig <0.4 m (Patterson, 1994). Longer period (Tp >7 s) and higher (Hsig > 1.4 m) waves are more predominant in southern regions such as Mackay, and reflect increased fetch and exposure. Low amplitude swell waves alone are probably incapable of generating bed stresses above the critical threshold, and Orpin *et al.* (1999) suggest that the superposition of short-period, high amplitude, wind waves and currents are essential for the initiation of significant resuspension.

Tidal currents alone are not usually capable of resuspending sediment though Orpin *et al.* (1999) suggest they may augment resuspension when occurring with high energy waves. Using OBS measurements, Larcombe *et al.* (1995) found that near bed Suspended Sediment Concentrations (SSC) peaked at *ca* 300 mg/L in water depths ranging from 3-15 m (Figure 2.9). Lou (1995) calculated that within Cleveland Bay, a mean near-bed SSC of 100 mg/L occurs on *ca.* 20 days per year, and Larcombe *et al.* (1995) suggest rough weather produces a uniformly mixed water column an SSC of 50 mg/L or higher. A typical threshold shear stress for sediment resuspension is *ca.* 1 N/m^2 (Orpin *et al.*, 1999). The highest SSC occurred in water depths between 5-10 m. Lou *et al.* (1996) explain this phenomenon in terms of the changes in the induced wave surge velocities as a wave propagates into the bay. The change in bathymetry of the bay in conjunction with frictional effects causes the maximum benthic wave surge velocities in the 5-10 m depth range thus causing higher SSC. Hydrodynamic studies by Larcombe *et al.* (1995), Lou & Ridd (1996), and Woolfe & Larcombe (1998) suggest that the exposed portion of Cleveland Bay is regularly subjected to sediment resuspension, winnowing, and transportation by wave-induced bed stress and tides. Using published wave data for the Townsville region, Orpin *et al.* (1999) suggest that muddy sediment at 20 m water depth is resuspended on only a few days per year, but sediment at water depths <10 m is resuspended on more than 110 days per year (Figure 2.10).

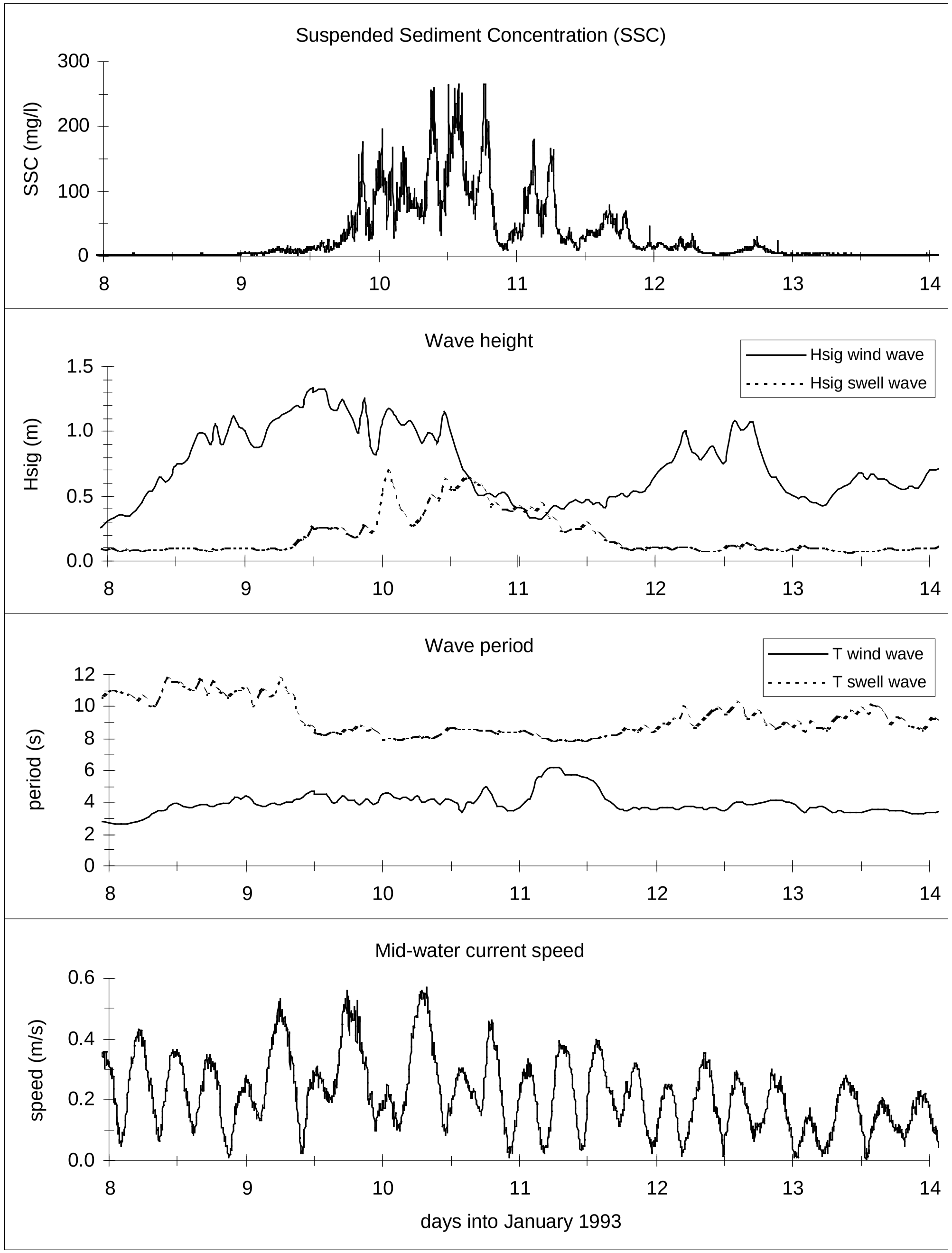
Suspended Sediment Concentration (SSC)
SSC (mg/l)
300
200
100
0
8
9
10
11
12
13
14
Wave height
Hsig (m)
Hsig wind wave
Hsig swell wave
1.5
1.0
0.5
0.0
Wave period
period (s)
T wind wave
T swell wave
12
10
8
6
4
2
0
Mid-water current speed
speed (m/s)
0.6
0.4
0.2
0.0
days into January 1993

Figure 2.9 Summary of oceanographic data during a period of high suspended sediment concentration January 1993, in 10 m of water, outer Cleveland Bay (after Orpin *et al.*, 1999; data from CoMarine, 1993). The SSC data were measured using a nephelometer 0.3 m above bed at 10 m water depth, recording 10 s averages every 5 minutes. Currents were determined using an INTEROCEAN S4 current meter, deployed at mid-water depth (5 m), recording 1 minute averages every 10 minutes. Wave data were measured using a WAVERIDER buoy over a 26 minute period every hour, and data were modelled using spectral analysis that applied a 7 s second cut off to separate swell and wind waves. A full description of the data collection and instrumentation is summarised in CoMarine (1993) and Larcombe *et al.* (1994, 1995).

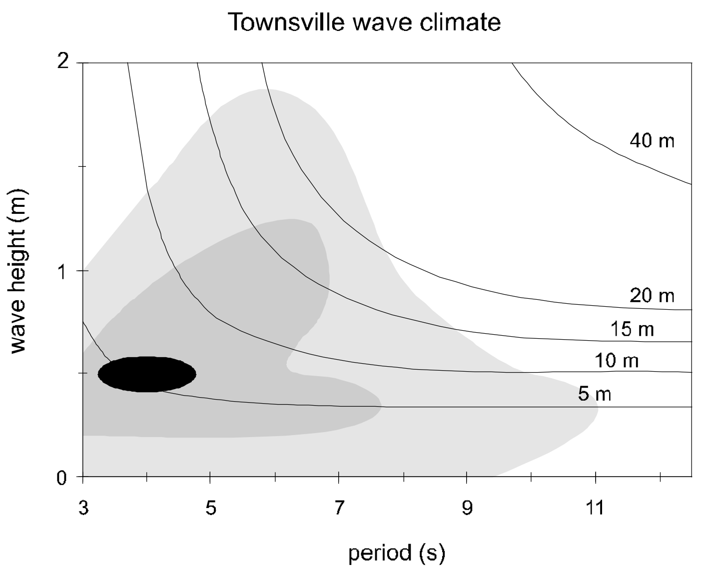

Figure 2.10 Variation of critical bed stress for sediment resuspension with water depth and wave regime Cleveland Bay (modified after Orpin *et al.*, 1997). Each of the curves represents values of wave height and period where $\tau_{b,max}$ equals 1 N/m^2. The values are derived assuming a current of 0.35 m/s at 0.2 m above bed. The inner shelf extends to 20 m water depth. Published wave climate data for Townsville are summarised by the shaded areas

(Department of Environment, 1997). Contours enclosing the shaded areas represent lines of equal probability of a wave with period and height centred in a band of width of 2 s and height 0.2 m. The wave class “band” with the highest frequency of occurrence is centred on the black ellipse. Individual wave class bands falling in the dark grey area are associated with a frequency of occurrence >20 days/yr. The cumulative frequency of wave class bands occurring within this area is approximately 345 days/yr. Similarly, the cumulative frequency of wave class bands occurring within the light grey area is approximately 20 days/yr (excluding dark grey area). The wave class bands falling within the white outer region have a cumulative frequency of approximately 1 day/yr.

A twenty four day record of time-series measurements of wave climate, tidal height, and near-bed (0.3 m above bed) SSC’s from 21 m depth off Cape Cleveland suggests little or no significant resuspension (Orpin *et al.*, 1999). The bottom sediment was a sandy mud (51% mud), and had a carbonate sand content of 14%. This bottom sediment is typical of the deeper regions of Cleveland Bay where significant resuspension of the mud fraction occurs.

SSC’s close to Magnetic Island and Middle Reef are typically an order of magnitude less than close to the bed in the middle of the bay. This is probably due to the lack of easily suspendable material close to Magnetic Island, and less energetic wave climate close to Middle Reef. SSC close to the mangrove forests have been measured by Bunt and Halide (pers. comm.) to be highly variable, with very high values occurring in the exposed sections of the coast close to Townsville (300 mg/L) and much lower SSC occurring in the sheltered regions close to the mouth of Cocoa Creek.

Regionally, the wave-exposed portions of Upstart, Bowling Green, and Cleveland bays typically show sediment accumulation rates of < 0.5 mm/yr. The eastern portion of Cleveland Bay is accumulating sediment more rapidly, and ^{210}Pb-derived sediment core profiles indicate vertical accumulation rates around 1.3 mm/yr (G. Brunskill, unpubl. data). Data summarised by Woolfe and Larcombe (1998) indicates that the three embayments north of the Burdekin River (Bowling Green, Cleveland, and Halifax bays) show successively decreasing rates of terrigenous infill.

A trend of seaward-coarsening sand has been described in Cleveland Bay by McIntyre (1996a). Size modes up to approximately 400 µm diameter occur at the seaward margin of Cleveland Bay in 15 m water depth, and progressively fine to <100 µm at 5 m water depth in the western portion of the bay. McIntyre (1996a) attributed this trend to a shoreward reduction in wave energy, and thus entrainment velocity. Similar trends were described by Orpin (1999) in the western portion of Bowling Green Bay.

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2.3 Geological and sedimentary characteristics of Cleveland Bay

R.M. Carter & P. Larcombe

Marine Geophysical Laboratory, School of Earth Sciences, James Cook University

2.3.1 Introduction

Cleveland Bay is a tropical embayment located at 19°S and about 325 sq km in area, with the port of Townsville located in its southwestern corner (Figure 2.11). The bay is landlocked around its southern and eastern margins by the mainland; Magnetic Island shields most of the northwestern margin. An aggradational coastal plain up to 7 km wide occurs along the southern shoreline, and connects eastwards through to the coastal plain of Bowling Green Bay further south. Otherwise, Cleveland Bay is fringed by rocky headlands which rise to 495 m on Magnetic Island, 557 m on Cape Cleveland and 581 m on Mt Stuart. The hinterland hills, which provide sediment to the bay, comprise granitic intrusions of late Paleozoic age which intrude older Paleozoic volcanic and volcanoclastic rocks (Wyatt *et al.*, 1970; Tresize *et al.*, 1986; Bain & Draper, 1997).

Cleveland Bay is located about 50 km north of the Burdekin River, and is also about halfway between the Burdekin and Herbert rivers which provide the dominant sediment supply to the central Great Barrier Reef coast (Belperio, 1983; Moss *et al.*, 1993). At the coast, bedload sediment (sand) from these rivers, and from the much smaller Houghton and Ross rivers, comes under the influence of longshore drift, and is passed northwards along the shoreline. During summer floods, suspended load muds, and some finer sand, are jetted directly onto the inner shelf, where they either accumulate at depths out to c.20 m, or are advected back into the tidal mangrove systems which fringe the coastal plain (Belperio, 1978, 1983; Larcombe & Ridd, 1994, 1995; Bryce *et al.*, *accepted*; Bunt, *in prep*.). During cyclones, coarse material at the coast may be formed into sandy beach ridges (e.g. along Cape Pallarenda) or, in the southern and eastern protected areas of the bay, deposited as shelly chenier ridges (Miller, 1982; Larcombe *et al.*, 1999; Harvey, *in prep*.).

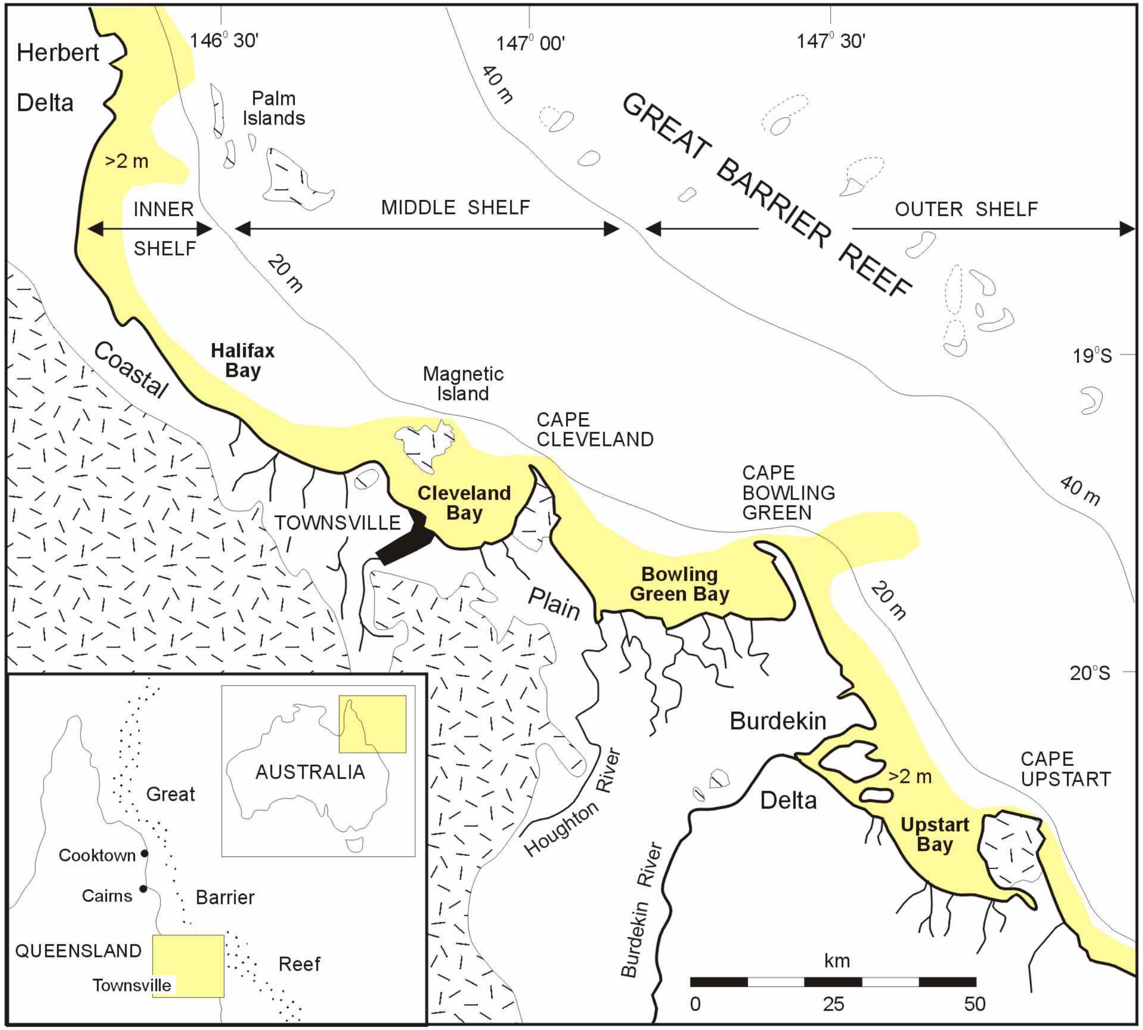

Figure 2.11 Locality map, showing location of Cleveland Bay, North Queensland, Australia.

2.3.2 Bathymetry

Cleveland Bay is shallow, reaching a maximum depth of 15 m at its seaward edge (Figure 2.11). The coastal plain around the south and east sides of the bay passes into a 1-2 km wide mangrove-fringed intertidal sandflat, seawards of which lies a wide subtidal sand platform on which the 2 m isobath is located up to 2.5 km offshore. A shallow bottom gradient of less than 1 m/km continues across the embayment plain out to a depth of c.10 m. The 10 m isobath corresponds to the seaward lip of the main bay sediment-fill, the foreslope of which passes offshore at a steeper angle (c.2 m/km) to merge with the general surface of the open-shelf near the 20 m isobath.

Exceptions to this simple bathymetry occur adjacent to Cape Cleveland and 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 and 13 m, lapping down onto a distinct terrace seawards of the shallow bar which runs southwestwards from Cape Cleveland. The seaward edge of the Cleveland Terrace has a relatively short and steep slope (10-12 m/km) down to the shelf surface.

In the west, Cleveland Bay connects 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. Further north, at the northeastern corner of the island, a natural tidally-scoured channel (named Orchard Channel by Carter *et al.*, 1993) 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 prism of shoreface sand that surrounds the island.

2.3.3 Circulation

Cleveland Bay is protected from the dominant southeasterly trade wind by Cape Cleveland, but lies open to northerly and northeasterly weather, and to the effects of seasonal tropical cyclones. Water motions just outside the bay are dominated by the effects of refracted southeasterly-generated swell waves (mostly 0.5-1.5 m high, 5-8 s period; Beach Protection Authority, 1979; Patterson, 1994). A maximum wave height of 4.7 m was reached during cyclone Peter in January, 1979, and other measured wave heights over 1.75 m were also associated with nearby cyclones. Carter *et al.* (1993, their Table 1) showed that wave conditions within the bay could be expected to cause widespread mud resuspension for much of the time, and that particles up to medium sand size would commonly be stirred within the inner bay (see also Orpin *et al.*, 1999). This is consistent with more recent instrumented datasets which show that suspended sediment concentrations (SSCs) of 30 mg/l are common under the influence of swell induced by trade winds (Larcombe *et al.*, 1995), and that higher values up to 250 mg/l occur spasmodically.

Earlier observations (Easton 1970; Belperio 1978a; Walker 1981; Heron *et al.*, 1985), together with more recent recording current meter observations (Carter *et al.*, 1993; Larcombe *et al.*, 1995a, b), show that water motions in Cleveland Bay are dominated by semi-diurnal tidal currents which reach velocities of 15-45 cm/s during spring tides. The tide floods into the bay in a south to southsoutheasterly (170^o-230^o) direction, rotating anticlockwise to ebb northnortheast to northeast (030^o-050^o). At the eastern end of West Passage, the flood is more westerly (240^o-250^o) and the ebb more easterly (050^o-080^o); further, during neap periods the weak tide both floods and ebbs northeast between Magnetic Island and the mainland, leading (in the absence of wind-forcing) to several day periods of uniform 5-10 cm/s northeasterly current through West Passage. Overall, the measured tidal asymmetry indicates that net sediment transport should be into the bay, a conclusion consistent with the sediment budget and other calculations (Carter *et al.*, 1993; Orpin *et al.*, 1999). Wind-driven currents commonly reinforce the anticlockwise tidal current motion within Cleveland Bay (Belperio, 1978a), and augment sediment transport towards the southeast of the bay in the east, and northwest through West Channel on the west.

In summary, the normal weather, tidal and wave regime in Cleveland Bay results in the maintenance of a well mixed isothermal, isohaline and turbid water column throughout most of the year. Bay waters are affected by flood events of the Burdekin River, 75 km to the southeast, as Walker

(1981) has shown a close correlation exists between salinity variations within the bay and the weekly-averaged discharge of the Burdekin River. Mud and fine sand are stirred into suspension over much of the bay for significant periods of the year. Those parts of the bay lying under tidal current streams are subjected regularly to currents capable of entraining fine-medium sand. During exceptional storm events, such as cyclones, currents may reach 150 cm/s or higher and the bay-floor is subjected to widespread sublevation.

2.3.4 Sediment Sources

The regional distribution of sediments along the Great Barrier Reef shelf is described by Maxwell (1968), Johnson *et al.* (1986) and Larcombe *et al.* (1996). Estimates of sediment flux to the coastline have been provided by Belperio (1983) and Moss *et al.* (1993), and reviewed by Wasson (1997). Rates of sediment transport and sedimentation on the shelf are not well documented, but those of the inner shelf have been noted and interpreted by Woolfe & Larcombe (1998) and Larcombe & Woolfe (1999).

In historic times the main local contributor of sediment to Cleveland Bay was the Ross River with an estimated annual load of 0.33 Mt (Belperio, 1983). The construction of a number of weirs and the Ross River Dam, for Townsville's water supply, had by the late 1970's cut-off the bulk of this sediment supply. Other minor local sources include a number of small catchments on Magnetic Island and Cape Cleveland, which feed sediment to local bay-beaches, and the tidal Alligator and Crocodile Creeks in the southeast corner of Cleveland Bay. Flood events from the Burdekin River, the mouth of which lies about 50 km to the south, have also provided a major supply of mud-sized sediment to the bay from its seaward side. Carter *et al.* (1993) estimated that around 1500 Mt of Holocene sediment is preserved in and around the bay.

Sediment supply to and accumulation in the inner-shelf wedge of Cleveland Bay is controlled by coast-parallel transport (Belperio 1983; Woolfe *et al.* 1998) and is therefore ultimately controlled by winds, waves, and tides. Given this pattern of along-shelf sediment dispersal, an important concept is the ‘trapping efficiency’ of coastal embayments. As used here, an embayment with a trapping efficiency of 10% would trap 10% of sediment introduced into the bay itself (in the long-term) and allow transfer of the remaining 90% downdrift along the coast. Woolfe and Larcombe

(1998) have compared sediment accumulation rates for Holocene cores from Cleveland Bay (Belperio 1978, 1983; Carter *et al.* 1993; Larcombe & Carter 1998) with accumulation rates inferred by modern measures of sedimentation (time-series oceanographic, turbidity and sediment trap data; Larcombe *et al.*, 1994; Larcombe *et al.*, 1995; Lou & Ridd 1997). The results indicate that Cleveland Bay has a trapping efficiency of only 0.2 %, so that the modern bay acts as a zone of sediment transfer far more than a zone of accumulation.

2.3.5 Modern sedimentary facies

Five major seafloor sediment facies occur in Cleveland Bay, as characterised by Carter *et al.* (1993).

Facies 1: terrigenous bay mud (with seagrass in the southeast)

The main part of the bay is occupied by an acoustically uniform facies of muddy sand with scattered molluscan shells and shell debris. Bioturbation is ubiquitous and primary sedimentary bedforms are generally absent. On the more distal parts of the main bay sediment fill, as across the mouth of the bay and adjacent to Orchard Channel, the muddy sands grade into more homogeneous mud and sandy mud. A wide area in the shallow southeastern bay gives rise to a "piebald" sidescan sonar reflection, indicating the presence of extensive beds of seagrass. McIntyre (1996) later termed these sediments the muddy intertidal-inner shelf facies.

Facies 2: intertidal and subtidal muddy sand

The southern and eastern sides of the bay are fringed by a subtidal platform of slightly muddy fine sand with scattered shells. The seaward edge of this platform corresponds broadly with the 2 m isobath and with a 70% sand content (Miller 1982, p.73). Landwards, a 1-2 km wide intertidal sandflat occurs, fed with sediment from Ross River and the mangrove-fringed Alligator and Crocodile Creeks. Shore-parallel, crescentic, low-angle sand-bars up to several hundred metres long characterize the intertidal sandflat east of the mouth of Ross River.

Facies 3: Magnetic Island sediments

Sandy beaches along the eastern and north-eastern parts of Magnetic Island pass offshore into a subtidal platform of fine sand and muddy sand at depths of 7-10 m (Davidson 1985), the seaward edge of which descends rapidly to the level of the 11-13 m terrace or to the adjacent Orchard Channel. The only significant near-island depocentre of mud is within Horseshoe Bay, the eastern side of which is well protected from the predominant easterly and southeasterly seas.

Coral reefs occur at Middle Reef and as fringing reefs adjacent to the southern shore of Magnetic Island, and to a minor extent in Nelly Bay and further north. Carbonate debris shed from these reefs forms a forereef talus deposit of poorly sorted calcareous gravel and sand. Usually restricted to within a few tens of metres of the reef front, sidescan sonar images show that these sediments reach further offshore off Nelly Bay.

Facies 4: West Channel sand banks

The eastern end of West Channel encompasses a field of low sediment mounds, up to 1.2 m thick, several tens of metres wide and oriented parallel to the prevailing currents. Carter *et al.* (1993) report the occurrence of moderately well-sorted, orange-brown, silty, medium to coarse quartzose shelly sand in a core from the edge of one of these features. This sediment may in part be derived from dredge spoil which was dumped off Cockle Bay during the 1970's (Pringle, 1989; Townsville Harbour Board records), and which is being redistributed by present-day currents.

Facies 5: palimpsest pre-transgressive surface

Wide areas of the North Queensland continental shelf comprise a slightly modified, pre-transgressive, coastal plain land surface, termed Reflector A where it passes beneath younger sediment (e.g. Orme *et al.*, 1978). A similar surface is exposed offshore from Cleveland Bay, seaward of the edge of the bay-fill sediment prism (Ohlenbusch, 1988; Larcombe & Carter, 1998), cutting in to occur close to shore off Cape Cleveland, and passing under the Holocene bay-fill.

The pre-transgressive surface also forms the seabed in a narrow strip down the west side of Cleveland Bay, between the Magnetic Island sediment prisms and the main bay-fill. The pre-transgressive surface is characterised by a strong, slightly irregular acoustic return on seismic profiles and sidescan images. Core and grab samples confirm that the surface is developed on tough, weathered Pleistocene clay which often contains caliche nodules, and is locally armoured with a lag deposit of Holocene shell-gravel with a matrix of poorly sorted sandy mud. Sonographs within Orchard Channel show trains of 1.5m wavelength megaripples associated with the lag gravels. A slight megaripple asymmetry suggests southward current flow, i.e. flood tide dominance.

McIntyre (1996) studied these sedimentary facies in more detail, analysing both their granulometry and their foraminiferal biofacies. In part building on the work of Miller (1982), McIntyre also characterised three additional facies, namely *mangrove muds*, *chenier sands*, and *salt flat muds*. Foraminiferal faunas from mangrove-related sediments are dominated by two species of *Ammonia*, whereas the inner shelf (bay) sandy muds assemblage is characterised by *Pararotalia venusta* (<50%), *Quinqueloculina* sp. (<35%), and *Planispirinella exigua* (<15%).

Baseline geochemical and mineralogical data from the sediments of Cleveland Bay have recently been published by Ward *et al.* (1995). Geochemically, surface sediments of the main bay are broadly homogenous, with some indications of high trace metals related to spillage of material near the harbour itself. In the main bay, the clay minerals are mostly kaolinite, illite and smectite, with higher levels of smectite occurring in mangrove muds.

2.3.6 Stratigraphy

Cleveland Bay contains three main post-glacial stratigraphic units (units A-C), which together comprise a shore-connected, terrigenous sediment prism up to c.10 m thick which rests on the weathered late Pleistocene clay of reflector A (Figure 2.12). The Pleistocene land surface represented by Reflector A is planar, dips seaward at 0.8 m/km, and is incised by a major complex of early Holocene fluvial and/or tidal channels.

Three main seismic units were recognized within the Cleveland Bay sediment prism by Carter *et al.* (1993). Seismic unit C encompasses cross-bedded or draped fluvial and estuarine fill of the early Holocene channel system. Seismic unit B, occurring laterally to C, comprises massive or bedded grey mud up to 4 m thick with mangrove roots. Unit A is the main Holocene bay fill, comprising mostly bioturbated muddy sand and sandy mud of offshore bay origin. In places, the base of unit A consists of well-sorted beach sand, and the unit A sediment prism therefore represents rapid transgression, followed by coastal and bay progradation since the c.5.5 ka mid-Holocene sea-level maximum (Belperio, 1979; Hopley, 1983; Beaman *et al.*, 1994; Higley, 1999).

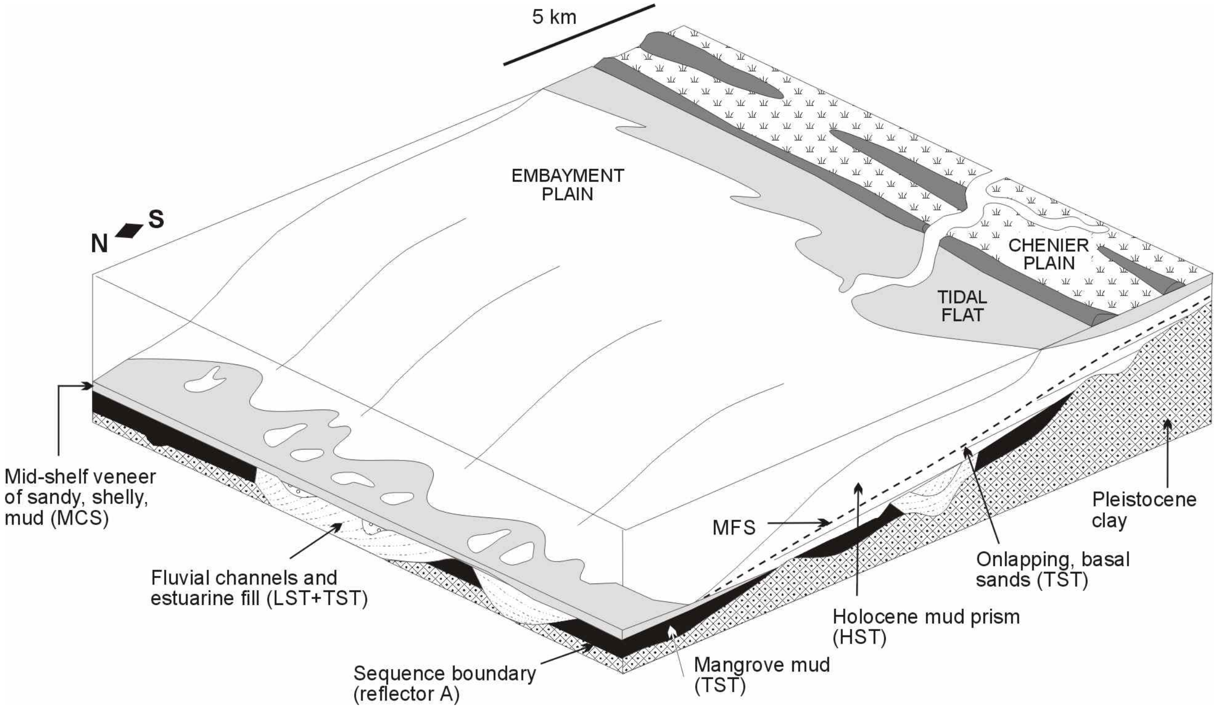

Figure 2.12 Three-dimensional reconstruction of the Holocene sedimentary fill of Cleveland Bay (after Carter *et al.*, 1993).

The unit A-C stratigraphy exists throughout Cleveland Bay and onto the inner shelf at all depths down to c.25 m. As stressed in a sequence stratigraphic study by Larcombe & Carter (1998), however, the stratigraphic relations of these units are those of homotaxy - and not age equivalence - in sections at different depths. Unit A-C lithofacies do not correspond to continuous transgressive sediment blankets, nor, on their own, to seismic parasequences. Rather, different occurrences of each unit onlap at different depths across the bay in close association with other contemporary facies within particular parasequences.

2.3.7 Sea-level change and the Holocene development of Cleveland Bay

The modern configuration of Cleveland Bay, and the disposition of its sedimentary fill, has been shaped during the last stages of the post-glacial sea-level rise. Conflicting evidence exists for the precise nature of the sea-level change; in particular, whether it was continuous (Hopley, 1983; Harris *et al.*, 1990) or episodic (Carter *et al.*, 1986; Larcombe & Carter, 1988), and whether a mid-Holocene high was attained (Beaman *et al.*, 1994; Higley, 1999) or not (Belperio, 1979).

In a recent comprehensive summary of radiocarbon and stratigraphic data, Larcombe *et al.* (1995) concluded that the late rise was indeed probably episodic, with a marked early Holocene minor fall at c. 8.5 kybp, and a mid-Holocene sea-level high at c. 5.5 kybp. However, in a detailed stratigraphic analysis of the sediments which comprise the Cleveland Bay Holocene sediment prism, Larcombe & Carter (1998, p. 118) also concluded that "even with close control upon seismic stratigraphy, well understood sedimentary facies, and with many cores and radiocarbon dates, it is still not possible to derive a unique and fully accurate interpretation of the palaeogeographic and environmental history of the Cleveland Bay area". Bearing this caveat in mind, and utilising the model sea-level curve of Larcombe *et al.* (1995), an outline Holocene history for the bay is given below and depicted on Figure 2.12.

About 10 kybp the shoreline was situated 30 km seaward of the present mouth of Cleveland Bay, at depths around 28-30 m. Magnetic Island and Cape Cleveland were isolated hills rising through a widespread coastal plain, and a major fluvial drainage system passed through the eastern and central parts of the bay, probably the predecessor of the Ross and Houghton-Burdekin Rivers (cf. Carter *et al.*, 1993, their Figure 14), although sediment transport through this system was, like today, probably intermittent rather than continuous.

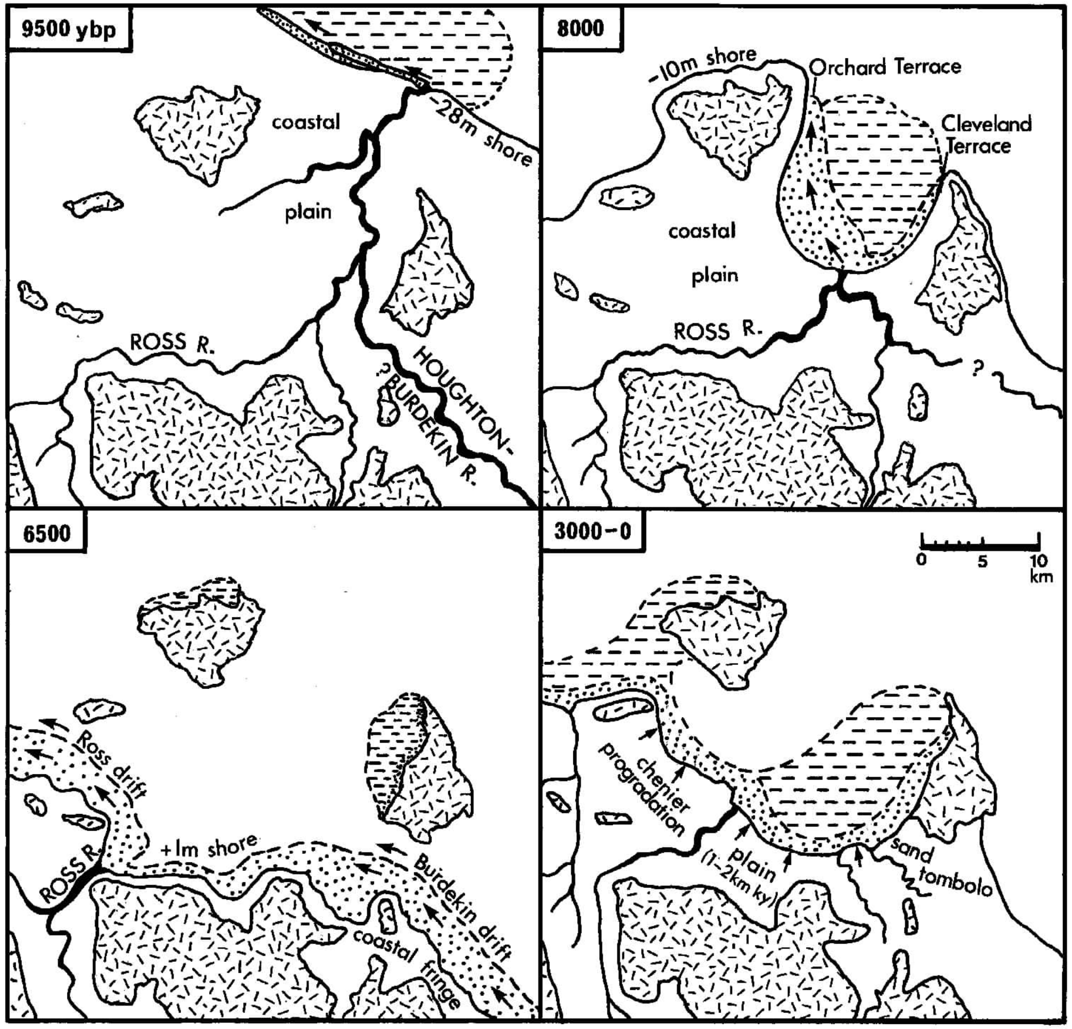
9500 ybp
coastal
plain
ROSS R.
-28m shore
HOUGHTON-
?BURDEKIN R.
8000
-10m shore
Orchard Terrace
Cleveland Terrace
coastal
plain
ROSS R.
?
6500
Ross drift
ROSS R.
+1m shore
Burdekin drift
coastal fringe
3000-0
0
5
10
km
chenier progradation
plain
(1-2km ky)
sand
tombolo

Figure 2.13 Palaeogeographic reconstructions showing the inferred history of development of Cleveland Bay over the last 10,000 years (after Carter *et al.*, 1993).

After abandoning the -28 m level, sea-level rose rapidly across the coastal plain, the shoreline reaching depths of 17 m at the entrance to Cleveland Bay around 9.5 kybp. An ancient barrier sand of similar age and depth, associated with estuarine muds, has been described by Pye & Rhodes (1985) from Hinchinbrook Island, 100 km north of Cleveland Bay. Between about 9.0 and 8.3 kybp rapid aggradation occurred within the bay in response to a short pause or reversal of the sea-level rise, causing a widespread development of estuarine mangrove forests. After a short period of rapid sea-level rise between c. 8.2-7.9 kybp, either a slowing of the rise or a major input of sediment (or both) resulted in the development of a quasi-stable sandy shoreline at depths around 10-12 m within Cleveland Bay. The bay-wide mangrove forest of the preceding stage was largely drowned at this time, but limited (younger) mangrove development continued landwards of the shoreline. Magnetic Island and Cape Cleveland remained isolated coastal hills, buttresses from which formed the western and eastern headlands of paleo-Cleveland Bay.

Tidal currents sweeping around these headlands, and wave activity, moulded the terraces which occur northeast of Magnetic Island, and projecting west from Cape Cleveland, and which have their seaward edges at depths of c. 10-12 m. Further within the bay, a gravelly beach on the more exposed western side passed eastwards into a more protected beach of fine to very fine quartz sand. Sediment was delivered to the bay by the Ross, and, possibly intermittently, the Haughton-Burdekin, river systems. Muddy sand and sandy mud accumulated in the shallow offshore bay.

After abandoning the -10 m level, the shoreline reached a height slightly above modern sea-level at c. 5.5 ky bp (Chappell *et al.*, 1983; Beaman *et al.*, 1994; Higley, 1999). Magnetic Island, Castle Hill, Cape Pallarenda and Cape Cleveland became, for the first time, offshore islands, opening Cleveland Bay to tidal and wind-driven flushing. As the coastal plain was transgressed, the mouth of the Haughton-Burdekin River system (which flowed northwards parallel to the coast prior to this last phase of transgression) was displaced southwards to near its present position. Northward longshore drift and advection delivered significant amounts of Houghton-Burdekin sediment to the Cleveland Bay region, building out a system of beach ridges towards the Cape Cleveland island at rates of c. 0.3-0.7 km/ky. Further west, sediment delivered by the Ross River caused similar but more rapid progradation of the Cape Pallarenda chenier complex at rates perhaps as high 2 km/ky. Though mud was trapped in part in the coastal mangrove fringe, little settled offshore in Cleveland Bay, which was constantly stirred by wave advection and tidal currents; bay sediments at this time are dominated by poorly sorted, slightly shelly, fine-medium sand.

About 3 kybp, coastal progradation resulted in the completion of the tombolo linking Cape Cleveland island with the mainland. The precise timing of bay closure by the tombolo is however not well dated, and more drilling and dating studies are necessary to refine our understanding. This notwithstanding, tombolo completion resulted in a significant reduction of energy levels within Cleveland Bay due to the suppression of inshore tidal currents and removal of direct wave activity. Since then, Cleveland Bay has evolved steadily towards its modern configuration, with continued slow progradation of the coastal plain and accumulation of bay-fill sediments offshore. Circulation patterns are still sufficiently vigorous to remove most of the finer grained sediment from the bay (Woolfe & Larcombe, 1998), bypassing it onto onshore tidal flats, or long-shelf to the north. The modern bay fill is dominated by poorly sorted muddy sand, which is bioturbated and periodically resuspended during cyclonic events. Some more homogeneous mud accumulates in the deeper offshore bay.

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Chapter 3 - Cleveland Bay Biodiversity

C. Battershill, G. Ericson & E. Evansillidge

Australian Institute of Marine Science

3.1 Introduction

Cleveland Bay is situated inshore of the central section of the Great Barrier Reef which is almost at its widest at this latitude. It hosts a wide diversity of marine and estuarine habitats supporting a highly biodiverse marine community. It is clearly influenced by the presence of Townsville, ts population and industry. It is also influenced by river borne runoff from the key catchments of Townsville and Thuringowa and to the north and south.

This chapter provides key contact details for link into metadatabases and databases holding information on the marine biodiversity of the Cleveland Bay region. In addition a CD ROM database derived from the Australian Institute of Marine Science Marine Biodiscovery research groups Australian collection program lists and identifies common species found in a variety of habitats in the Bay and around Magnetic Island. There are 300 specimens listed in the database together with *in situ* or deck top photographs. Taxonomic description, habitat description and other notes are provided. Most of the scientific literature for the Bay is found in what is known as ‘grey literature’. Unpublished reports and articles. The contacts listed below will provide first linkage to this resource.There are also key avenues for information gathering such as the University Library and AIMS Metadatabase. Web sites are also listed.

3.2 Meta Data

Australian Institute of Marine Science

AIMS scientists have been carrying out research in the Cleveland Bay area for over 25 years in a variety of disciplines ranging from effects of Human Impact to Taxonomy and Marine Biotechnology. The Institute provides a rich source of information and experience in the marine environment of the region. The location of sample sites within Cleveland Bay is presented as Figure 3.1. The CD ROM provided with this chapter (Appendix 1) is a subset of a database containing over 20,000 entires of organisms from around Australia. It is clear that the assemblages found within the bay represent a diverse array of organisms with affinities to other nearshore or neritic assemblages in the Mid Region of the Great Barrier Reef.

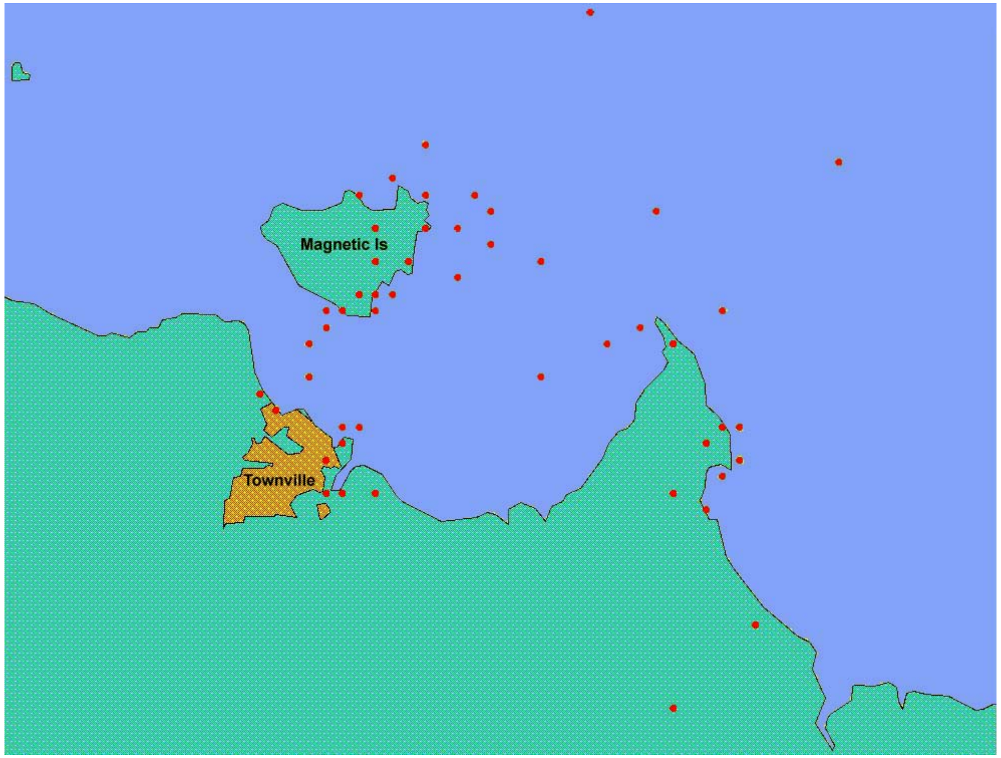

Figure 3.1 Location of AIMS sample sites in Cleveland Bay

Great Barrier Reef Marine Park Authority

Scientists and marine managers from GBRMPA have also bee working within the region for many years and are charged with review and research into issues pertaining to the management and protection of the reef. Currently GBRMPA is reviewing the network of marine protected areas in a revolutionary manner making full use of all available scientific information from the full field of disciplins (taxonomy, biogeography to geology and nearshore/oceanic current systems)

James Cook University

Staff and students from Townsville's University provide a wealth of knowledge and experience pertaining to marine resources and issues in the region. James Cook University is recognised as one of the finest marine research facilities globally. Research has been carried out on a wide range of topics from estuarine to offshore coastal ecology, biosystematics, physiology, chemistry and oceanography. Research papers, theses and articles can be sourced from the University Library and key contacts are summarised in Table 31.

Table 3.1 Sources of information on the biodiversity of Cleveland Bay

Organisation	Contact
Australian Institute of Marine Science PMB No 3 Townsville, Q 4810 www.aims.gov.au	Dr Steve Routley, Manager AIMS Metadatabase Ph (+61 7) 47534 370 s.routley@aims.gov.au Dr Andrew Heyward, Project Leader, Marine Biodiversity Ph (+61 8) 91831 122 a.heyward@aims.gov.au Dr Chris Battershill, Project Leader, Marine Biotechnology Ph (+61 7) 47534 431 c.battershill@aims.gov.au Ms Libby Evans Illidge, Leader Bioinformatics and Marine Biodiversity Policy, Marine Biotechnology Project Ph (+61 7) 47534 444 e.evansillidge@aims.gov.au Dr David McKinnon, Larval Fish Project Ph (+61 7) 47534 292 d.mckinnon@aims.gov.au Dr David Klumpp, Seagrass Project Ph (+61 7) 47534 232 d.klumpp@aims.gov.au
Great Barrier Marine Park Authority PO Box 1379, Townsville, Q 4810 www.gbrmpa.gov.au	TBA, Manager, Research and Monitoring Coordination Ph (+61 7) 47500 809 www.gbrmpa.gov.au

	Kim Lally Assistant Project Officer, Research and Monitoring Ph (+61 7) 47500 809 kimd@gbrmpa.gov.au
James Cook University Private Bag Townsville Q 4811 www.jcu.edu.au	Head Librarian James Cook University Ph (+61 7) 47815 500 Dr John Collins Ph (+61 7) 47814 122 John.Collins@jcu.edu.au
Museum of Tropical Queensland	Dr Peter Arnold Ph (+61 7) 47211 662 petera@mtq.qld.gov.au

The Museum of Tropical Queensland

The Townsville museum supports a number of key scientific staff with a wealth of knowledge in marine biosystematics, particularly groups such as corals, bryozoans, ascidians and sponges. The museum holds the globes most significant coral collection and is a source of biosystematic information for the region.

Other Sources

Other sources of information on the biodiversity of Cleveland Bay include the Port Authority and regional Environmental Consultants. Both these groups have a wealth of experience in the Bay and are likely to hold many reports and other material, some of which may be made available on request if not already in the public domain.

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Appendix 3.1 Australian Institute of Marine Science - Marine Biotechnology Project, Sample location and description databases:

Sample location AIMS Cleveland Bay Sample Location

AIMS Cleveland Bay Sample Description

Sample description

Appendix 3.2 Australian Institute of Marine Science - Marine Biotechnology Project, Sample image data base

Image database of organisms collected in and around Cleveland Bay:

(Insert Folder of images – memory exceeded!)

Chapter 4 - Industries and the environment in the Townsville Region

Greg Doherty[1], Vern Vietch[2], Mick Roche[3], Caryn Anderson[4]

[1]James Cook University, [2]Sunfish, [3]BHP Cannington, [4]Townsville Port Authority

4.1 Introduction

A major challenge facing the Townsville region is the need to manage economic development and population growth so that the regions environmental assets and lifestyle are maintained and enhanced (TTSP, 2000). The objective of this chapter is to summarise some of the information available that describes relationships between industry, the environment and Townsville, past, present and future. It is not the intention to make judgements about industries or the environment, rather it is to summarise the information available so that the challenges like that described above can be met.

The term industry is used broadly herein to describe activities that can constitute an 'industry'. Therefore, education, health services and recreational fishing manifest as industries as much as metal refining or agriculture. This is because each of these activities can be rationalised to have a value to the region, and may also have an effect upon the environment.

4.2 Industry and Townsville

Townsville is Australia's largest tropical city (NQN, 2000), and combined with Thuringowa they form the largest urban area in the state outside of south east Queensland (TTSP, 1998). It has a regional economy of over $5.7 Billion, that is forecast to double by 2017 and is growing in line with the Australian economy, which exceeds other regions of Queensland (AEC, 1999).

The key to this economic growth is stability and diversity across a range of industry sectors (TTSP, 2000; AEC, 1999; TEL, 1999), including; agriculture; public administration; defence; finance; transport; tourism, recreation; health services; fishing; mining; trade; construction; manufacturing and research. The relative contribution of these sectors to the regional economy is presented in Figure 1. Not all of the previously mentioned industries are isolated in these statistics, e.g., mining is distinct from mineral processing which is included in manufacturing , and defence or health services are not separated from administration (public).

These activities are underpinned by attributes that include: Strong international trade links; strong local labour force; established industries; established air, sea, road and rail infrastructure; proximity to suppliers and markets; centres for excellence in research, education and health (NQN, 2000).

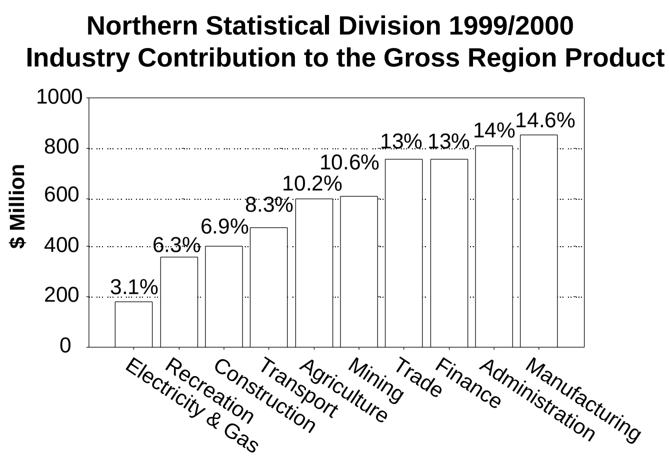

Figure 4.1 Contribution of different industry types to the economy of the Townsville region (after Ramm, 2000)

4.3 Changes in industry over time

Two decades ago economic growth in the region was limited by regional factors (AEC, 1999), which influenced local industries. In the recent past there has been a closure of a cement manufacturing plant, meatworks, rail work shops, contraction of the some parts of the public sector and loss of international flights (NQN, 2000). Today, economic growth is a function of international factors (AEC, 1999), and these changes are led by the development of export markets, primarily by mining and sugar (NQN, 2000).

Progressive changes to industries in the Townsville region over time have occurred in response to these influences since establishment of a Port in 1864. Some of these changes are demonstrated by the rends in the proportion of the labour force employed in each industry over time (Figure 2).

The port was initially established to service predominantly pastoral holdings (wool and beef) located in the hinterland, and subsequently boiling down works, meatworks and freezer works were established in the region to treat produce (TMI, 1999; TPA, 1998; Taylor, 1980). Later agriculture located along the coastal region to the north and south of Townsville, primarily sugar production, provided a strong regional industry base, that continues to present. The discovery of mineral resources in the Charters Towers, Cloncurry and Mount Isa Mining Districts resulted in the construction of rail links with western Queensland by 1915 (Taylor, 1980).

Since 1945, the establishment of heavy industries has stimulated population growth in Townsville (TTSP, 2000). These industries support predominantly mining and rural activities in regional areas of North Queensland and include; the copper refinery in 1957; sugar terminal in 1959; Yabulu nickel refinery in 1974; Ni laterite imports in 1986; and a zinc refinery in 1999.

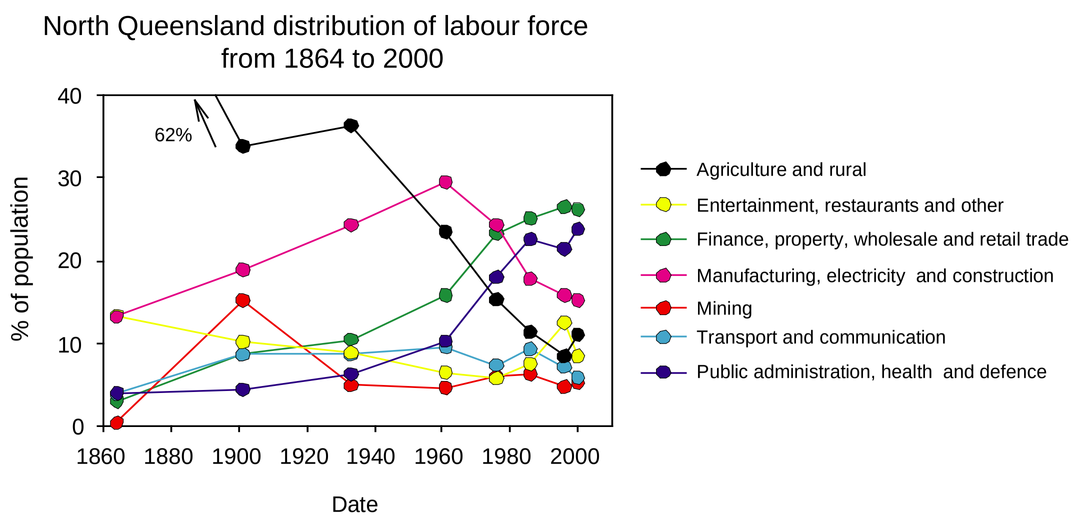

Figure 4.2 Changes to labour force distribution over time between 1864 and 200 in North Queensland. Data from QGSO (1998) and AEC (1999).

The majority of these heavy industries are closely linked to the Port of Townsville, where over $200 Million has been spent in the last 5 years to upgrade mineral and fertiliser handling facilities. The Port has recently been identified to contribute over 10% of the Gross Region Product presented in Figure 1 (TPA, 2000).

At the same time there has also been growth of public administration, education, health and defence industries. This includes the establishment of Lavarack Barracks in 1966, which is now the largest army base in Australia; James Cook University and the Australian Institute of Marine Science during the 1970s; and location state and commonwealth regional offices during the 1980s (NQN, 2000; TTSP, 2000).

4.4 Industries and the environment

In other regions of the world parallel trends of increasing economic growth and population growth are significant in respect of environmental quality. This is because some aspects of environmental quality have been found to decline with economic growth (e.g., Huh & Chen, 1999) urbanisation (Callender & Rice, 1999) or the commencement of specific industries or human activities (Bother *et al.*, 1998). However, these trends often show an improvement in response to increased environmental awareness and legislation introduced to protect the environment (e.g., Bricker, 1993; Launstein & Daskalakis, 1998).

Increasing economic growth and population growth are predicted for Townsville (Figure 3). The near parallel growth of port throughput and population indicate links between productivity of industries and population growth. To make this rate of population growth ecologically sustainable is a challenge to be met by the community. During the period 1993 to 2000 and average of 29 000 Megalitres of water was consumed annually in Townsville, which over 60% was used for garden watering (TCC pers comm). Water consumption over this period was determined by weather conditions and not by population growth (TCC pers comm). Daily sewage treatment rates are 11-13 mega litres and 18 megalitres for the Mount St John and Cleveland Bay Wastewater Purification Plants respectively. Key environmental issues identified by the TTSP (2000) to accommodate population growth in the region include storm water, waste water and solid waste management strategies.

Importantly, declining terrestrial run off quality, resulting in an increase in sediment and nutrient loadings, is considered to be the most significant effect of human activities upon the environmental quality of the Great Barrier Reef lagoon (Brodie, 1997). However, the significance of these apparent changes upon the greater lagoon have been the subject of public scientific debate since at least 1985 (e.g., Pringle, 1986; Brodie, 1990; Bell & Gabric, 1991; Hopley *et al.*, 1991; Johnson, 1996; Furnas & Brodie, 1996; Wasson, 1996; Larcombe & Woolfe, 1999).

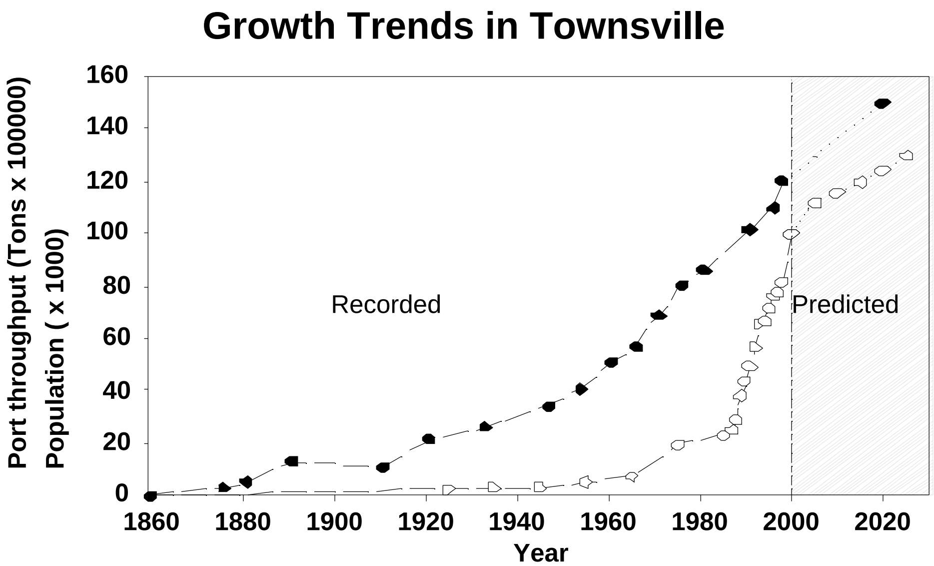

Figure 4.3 Historical and predicted growth of Port throughput and population of Townsville. Population ( ), throughput ( ).Recorded data from QGSO (1998), Taylor (1980), Hoyle (1978); TPA (1996), TMI (1999). Predictions from TTSP (1998), TPA (1999), SKM (2000).

Regardless of this debate, it is *accepted* the parts of the lagoon that are threatened by declining quality of terrestrial run off are characteristically near the coast, are close to a source (e.g., urban areas or areas of habitat destruction) and, are limited in spatial extent (Kelleher, 1987; Botto *et al.*, 1987; Baldwin *et al.*, 1987; Cosser, 1987; Wallace, 1992; Brodie, 1997).

Potentially detrimental increased levels of metals, organic substances and nutrients in sediments, water and biota (e.g., Wallace, 1992; Gibbs, 1993, Jones, 1992, Cavanagh *et al.*, 1999; Ingliss & Kross, 1999; TPA-IAS, 2000), and the detrimental effects of increased sediment loads have been found in the bay (e.g., Pringle, 1989; Carter *et al.*, 1993). Many of these effects are a legacy of past activities suchas waste disposal, when the consequences of such activities upon the environment were not known, or were perceived as an acceptable trade off between development and the environment.

These effects are coupled with a perception in the community that in general industries do effect run off quality and pose a risk to the lagoon (Brown, 1973; Stark *et al.*, 1975; Knauer, 1977; Wallace, 1992; Ludescher, 1997; Ormsby, 1996). These threats whether real or publicly perceived constitute issues (e.g., Kinsey, 1991) that need to be addressed by science, management and the community.

4.5 Industry and environmental management

The concepts of ecologically sustainable development (ESD) add significant scope to the interaction between industries and the environment. The objectives of ESD are now established in the community by their incorporation into guidelines such as the Draft Australia and New Zealand Environment and Conservation Council Guidelines for Fresh and Marine Water Quality (http://www.affa.gov.au/nwqms/ publist.html), and regional development strategies such as; the Townsville-Thuringowa Strategy Plan (TTSP, 2000), and the Draft Community Plan for Natural Resource Management and Environmental Conservation compiled by the Townsville-Thuringowa Landcare Association (TTLA, 2000).

The onset of increased environmental awareness has created a new culture for many industries in the Townsville region. Integrated or whole of catchment management approaches are recognised to be required to improve terrestrial run off quality (e.g., Zann, 1995). Environmental performance of some industries is now measured against contribution to global warming (e.g., NQCGBHP, 2000),

Some local businesses in Townsville are leaders in worlds best practise standards, which include transparent and innovative environmental strategies to stop negative environmental consequences. This is typified by the ISO 14000 certification at Queensland Nickels Yabulu operations that is a worlds first for a nickel refinery, and a ‘pioneering’ appraisal of BHPs environmental performance by the North Queensland Conservation Council (www.bhp.com.au/ minerals/ commodities/cannington/bhphome.htm).

Other actions by industries in the local region to improve their environmental performance include; Innovative management solutions to water management (Minchan *et al.*, 1999) and community based conservation management (Chirgwin & Melzer, 1999) at the Yabulu refinery; Engineering, design, environmental and communication awards to BHP Cannington for mine site and port site achievements (NQN, 2000); A policy of no waste water discharge from the refinery to the marine environment at the new Sun Metals Corporation zinc refinery (Boggiano, 1999); Integrated and scientifically rigorous monitoring and management practices undertaken at the Port of Townsville (Anderson & Roche, 1999; Benson *et al.*, 1994); Support of the River Group involvement in environmental monitoring of the Ross Island Barracks by the Defence Estate Organisation.

In the commercial fishing industry, over 370 boats record catches in the local area during 1999, and the value of the catch between Bowen and Tully is estimated to be at least $26 million based on whole sale prices of major catch species (Ludescher, 1997). By catch reduction devices and turtle exclusion devices are now compulsory. Cleveland Bay is designated as a dugong sanctuary and gill netting is now banned in the bay.

In the recreational fishing industry, there are several local tagging projects are running, and the value of the industry is currently being assessed. Preliminary results indicate that are over 8200 registered recreational boats, over 40% of the local population fish, and combined with associated businesses and visitor expenditure the value is expected to exceed $50 million (Sunfish pers comm). This type of information is essential if the industry to be managed appropriately.

To address sediment and nutrient loss from rural industries and the consequent effects upon terrestrial run off quality there are several projects coordinated through a variety of agencies including AIMS, CSIRO, GBRMPA, DPI, DNR, JCU, CRC Reef and CRC Sugar. These projects are not focussed within Cleveland Bay. They are focussed in the adjacent Burdekin and Herbert catchment areas, but are relevant in respect of local industries and the effect of declining quality of terrestrial run off entering the lagoon.

Industries in the Townsville region are actively monitoring their activities that may effect the environment, and providing funding for research to help understand the natural environment and the effects human activities have upon it. A summary of monitoring and research currently being completed by local industries is presented in (Appendix 1 database attachment). Where available, attached to this table is more detailed descriptions of business operations and their environmental activities. This table is not complete, and represents a summary of the available information at the time of this report.

4.6 Industry, the environment and the future

Economic growth is predicted to be predominantly export driven, and potential new heavy industries have been identified as; value adding to mineral and agricultural products (TTSP, 2000). Other emerging industries include; live cattle exports; rice exports; feed pellet export; electricity generation; chemical manufacturing (AEC, 1999; SKM, 2000).

Opportunities for growth are not restricted to heavy industries, and other growth areas are envisaged as; ecotourism and events management, the development of technologies related to marine science, mining, agriculture and medicine (TTSP, 2000).

Unless properly managed the continued economic growth, with consequent growth of industries and population, represents a potential to have increased environmental effects in the Townsville region. Activities such as agriculture, combustion of fossil fuels, dredging, metal refining, sewage treatment, transport operations, urban development, and damming for water supplies, will continue to occur, and pose a challenge to the community to manage any consequent effects to acceptable levels.

In this respect the responsibility for managing and protecting the environment is a challenge to the community. To address this, and articulate concerns and priorities concerning the environment across the community, a Draft Community Plan for Natural Resource Management and Environmental Conservation (TTLA, 2000), and the Townsville-Thuringowa Strategic (TTSP, 2000) plan have been formulated.

While new standards for environmental best practice are being set by local businesses, which are in line with these plans, the positive effects of such practices can be diminished by persistent problems that are a legacy of past activities, or lesser management practices by other industries.

Perhaps the greatest challenge for those leading the way in protecting and managing the environment is probably translating these plans and the concepts of ecologically sustainable development (NQCGBHP, 2000) to ensure that they and others see the benefits and have the direction and motivation necessary to achieve the desired outcomes.

The attached database (Appendix 1) of monitoring and research activities is a step towards adopting and implementing such plans, and can be used to identify current monitoring and research activities that are relevant to the local area, as well as points of contact should further information be required. Additonal information of indutry operations and environmental management are also provided in Appendix 2.

Acknowledgements

The authors would like to acknowledge the assistance of numerous organisations that provided information to support this chpater.

Appendix 4.1 Research and monitoring database

Database of industry monitoring and research in the Cleveland Bay region

Research & monitoring database

Appendix 4.2 Description of industry operations and environmental programmes

BHP Port Operations

BHP Cannington Port operations

QNI Port Operations

QNI description of Port operations

Townville Port Authority dust monitorong program.

Port dust monitoring

Townville Port Authority sediment baselione study

Port sediment baseline study

Townville Port Authority sediment monitorong program.

Port sediment monitoring

Townville Port Authority storm water monitorong program.

Port storm water monitoring

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Chapter 5 – Environmental laws and regulations applicable to Cleveland Bay

Laws regulating environmental issues in Australia have increased considerably during the past decade in unison with rapid urban and industrial development along the coastal zone. The rise in environmental legislation can be attributed to a growing recognition that environmental protection and conservation of natural resources is essential for sustainable economic and social development.

Cleveland Bay, its coastline and Magnetic Island have significant environmental and natural resource values. Accordingly, there are a substantial number of environmental laws, policies and regulations applicable to the area (Table 5.1). A summary of the applicable legislation is contained within Appendix 1.

As elsewhere in Australia, legislation relevant to Cleveland Bay and the wider Townsville-Thuringowa region is established and administered at Commonwealth, State and local government levels. The major responsibility for environmental planning matters rests with the State and local governments. The Commonwealth Government is the primary regulator of activities within the Great Barrier Reef Marine Park.

The Great Barrier Reef Marine Park, Magnetic Island and the waters of Cleveland Bay to the Low Water Mark are contained in the Great Barrier Reef World Heritage Area (GBRWHA), which was inscribed on the World Heritage list in 1981 for its unique natural values. The Commonwealth, State and local governments all have a role in the regulation of environmental issues within the GBRWHA.

The Townsville City Council, often in conjunction with State Government agencies, is the primary regulator for land-based development on Magnetic Island and the mainland adjacent to Cleveland Bay. A summary of environmentally relvant acticities and licenses in the Townsville region is presented in Appendix 2. Regulatory responsibility for Cleveland Bay itself is shared between the Townsville Port Authority (Appendix 3), the Great

Barrier Reef Marine Park Authority for the Commonwealth Government, and the Environmental Protection Agency and Queensland Parks and Wildlife Service for the Queensland Government..

Regulatory responsibilities and jurisdictions often overlap within Cleveland Bay and the adjacent coastal zone. The boundaries to jurisdictions and environmental regions are presented in Appendix 4. The overlap necessitates a number of approvals, licences or permits from regulators at all levels before a particular development or activity can proceed. This chapter of the State of Cleveland Bay Report aims to identify all major environmental legislation relevant to development activities in Cleveland Bay.

Appendix 5.1 Summary of relevant environmental legislation

Summary of legislation

Appendix 5.2 Summary of environmentally relevant activities and licences issued in the Townsville region.

Environmentally relevant activities

Appendix 5.3 Legal framework of the Port of Townsville

Port legal framework

Appendix 5.4 Maps of jurisdiction boundaries in the Townsville region.

Jurisdiction maps

Table 5.1 Legislation requiring permits or approvals

Legislation	Applicable to Development & Works within	Requirements
Queensland Fisheries Act 1994 & Fisheries Regulations 1995	Tidal or inter-tidal Marine Plant lands & Fish Habitat areas below the level of Highest Astronomical Tide Ephemeral and permanent flowing open drains and waterways if fish movement is impaired	1. Section 51 permit required to remove, or damage marine plants including mangroves, salt marsh and other vegetation on tidal or inter-tidal lands 2. Section 113 permit is required for major installations (GPT's etc.) only
Great Barrier Reef Marine Park Act 1975 (Cwth) & Great Barrier Reef Marine Park Regulations (Cwth)	Great Barrier Reef Marine Park (Commonwealth) to low water mark	Permits/approvals required for activities or development within, or directly adjacent to, the Marine Park including: all drainage maintenance, construction or runnelling works commercial watersport or tourism activities

		development with the potential to impact on the Marine Park or World Heritage area
Marine Parks Act 1982 (Q) & **Marine Parks Regulations 1990**	**Intertidal zone (to MHW) within the Townsville/ Whitsunday Marine Park ie: all tidal & intertidal areas around:** **Magnetic Island,** **northern end of Pallarenda &** **parts of Cape Cleveland**	**Permits required for activities or development within the Townsville/Whitsunday Marine Park including:** **sediment & debris removal,** **maintenance of access ramps, bank reshaping or stabilisation, vegetation pruning or removal, channelisation of creek beds** **commercial watersport, scientific research or tourism activities**
Beach Protection Act 1968	**Tidal and inter-tidal regions and erosion prone areas within 40 metres of Highest Astronomical Tide**	**Approval required for sediment & debris removal, interference with sand & gravel, dredging, maintenance of access ramps, bank reshaping or stabilisation, channelisation of creek beds**
Nature Conservation Act 1992	**Protected areas such as the Magnetic Island or Cape Bowling Green NP**	**Permit is required for all activities in protected areas, including maintenance works, ecotourism ventures or other developments.**
Water Resources Act 1989	**Freshwater watercourses with continuing flow**	**A "Riverine Protection Permit" is required for vegetation removal, excavation and creek filling** **Permit is required to extract groundwater, install wells or bore infra structure in identified area (ie.Bohle area)**
Harbours Act 1955 **(as far as the repealed Act's provisions have been saved in Part 3 of the**	**In/on tidal lands or waters adjacent or within costal shipping activities**	**Section 86 approval is required for all works in, on, under, through or across tidal land or waters, inc:**

Transport Infrastructure Act, 1994)		**new or major modification drain construction or initial runnelling works** **construction of pontoons, marina's or infrastructure** **Section 91-93 approval is required for removal of materials from the seabed.**

Table 5.1 Legislation requiring permits or approvals, continued.

Legislation	Applicable to Development & Works within	Requirements
Environmental Protection Act 1994, its Amendments, Regulations & Policies inc: **Environmental Protection Regulations 1998** **Environmental Protection Amendment Regulation (No.2) 1999** **The Environmental Protection (Water) Policy 1997** **The EP (Air) Policy 1997 & Environmental Protection (Air) Amendment Policy (No.2) 1999** **The EP (Noise) Policy 1997 & Environmental Protection (Noise) Amendment Policy (No.1)1999** **Environmental Protection (Interim**	**All lands and waterways (natural or man made) in Queensland**	**All <u>“Environmentally Relevant Activities”</u> listed in Schedule 1 of the EP Regulations 1998 require a licence or approval.** **Section 37 of EPA, 1994 requires the notification of all environmental incidents that may or have caused environmental harm.** **Contaminant releases, including sediment and litter, within or adjacen t to the stormwater drainage system or waterways constitute an offence. (s 31 & 32 EPP(Water))** **Site works involving the excavation or removal of contaminated soils or materials from lands listed on the EMR (Environmental Management Register) or CSR (Contaminated Site Register) requires EPA approval under section 118ZZF of the EPA 1994.**

Waste) Regulation 1996		
Integrated Planning Act 1997	**All land under Townsville or Thuringowa City jurisdiction & subject to the Townplanning Scheme**	**Council permits or approvals are necessary for all development works including:** **Material change of use and reconfiguration of a lot** **Operational works** **Building works inc. drainage & plumbing** **IPA's single approval process, the Integrated Development Approval System (IDAS), unify's development approvals across all levels of government.**
Queensland Heritage Act 1992	**All structures, places, natural areas or vegetation listed on the register (inc. Parks or the stormwater drainage system)**	**Permit is necessary for all maintenance work on heritage listed property** **Prohibits the removal of trees from drainage banks if covered by a Vegetation Protection order**
Native Title (Qld.) Act 1993 **Native Title Act (Cwth)** **Native Title Amendment Bill 1996 (Cwth)** **Native Title Amendment Act 1998 (Cwth)**	**All land in Queensland where Native title rights have not been extinguished (ie. Freehold or granting of certain leasehold tenures).** **May also apply over Waterways, Reefs and Sea.** **Can co-exist with other statutory rights and interests in or on land or waters.**	**All native title work procedures have to be complied with including the legislation's** **notification requirements and** **consultation or negotiation processes**

Canals Act 1958	**The Act's application is proposed for the Nelly Bay Safe Harbour residential canal development**	**Council Permit is required for dredging within areas designated "Canal development"** **Obliges Council to maintain the access channel and drainage system leading into the Canal estate**
Sewerage and Water Supply Act 1949	**The stormwater drainage system and sewerage ifrastructure**	**Requires a Council permit for grey-water discharges to Sewerage infrastructure** **Section 17a prohibits discharge of prohibited materials such as sediment & litter to the drainage and sewage system**

Table 5.1 Legislation requiring permits or approvals, continued.

Legislation	Applicable to Development & Works within	Requirements
Transport Operations (Marine Pollution) Act 1995	Applies to all shipping activities in Queensland's marine and coastal waters: Coastal waters subject to the ebb and flow of the tide and Marine waters to the first 3 nautical miles of the (Qld) territorial sea	The Act regulates for the protection of marine/coastal waters from ship-sourced pollutants. The Act: Prohibits the discharge of sewage into coastal waters unless exemption approval has been obtained. [(s 47. (1) (2) (3) (4); s 48. (a), (b) & s 49] Prohibits the disposal of garbage into coastal waters [s 55.(1)] Requires the fitting of a toilet connected to a holding tank to all ships larger than 10m in overall length unless exemption has been obtained from the CEO of a port authority. [s50.(1) & (2)] Requires the owner and/or ship's master to report incidents pursuant to section 67. (1) "Duty to report incidents". (ie. Discharges of oil or jettisoning of harmful substances. Requires approval for night transfer operations. [s 63.(1)]
Recreation Areas Management Act 1988	Queensland coastal waters and lands.	The Act provides for the setting apart of land and waters for recreational activities and the appropriate management declared recreational areas. Approval permits may be necessary to gain access or use public facilities in declared

		recreational areas. [S 27. (1), (2) & (2A)] **Permits are required to conduct commercial activities (inc. tour operations) in declared recreational areas. [s 26]**
State Development and Public Works Organisations Act (1971-81)	**Environmental sensitive areas and/or regions of high conservation value**	**Obliges persons performing works to assess environmental effects of the works on wetlands, estuaries or areas with native vegetation communities (including rare or protected flora and fauna)**
Workplace Health and Safety Act	**All workplaces in Queensland (including out-door sites)**	**A management plan must outline details of measures taken to safeguard employee's health.**
Coastal Protection and Management Act 1995	**Coastal Zone. The Act defines the coastal zone as *"Coastal waters and all areas landward side of coastal waters in which there are physical features, ecological or natural processes or human activities that effect, or potentially affect, the coast or coastal resources"***	**TheCPM Act describes how coastal management is to be achieved by coordinated and integrated planning and decision making, involving for example the preparation of a Management Plan and declaration of control district. The State Coastal Management Plan, prepared under Section 5 of the Coastal Act, is currently available in Draft form.**

Table 5.2Proposed Legislation

Proposed Legislation	Proposed date of commencement and application	Aims & Obligations
Environmental Protection and Biodiversity Conservation Act 1999 (Cwth) **The EPBCAct will replace the following legislation:** **Environment Protection (Impact Proposals) Act 1974** **Endangered Species Protection Act 1992** **National Parks and Wildlife Conservation Act 1975** **World Heritage Properties Conservation Act 1983** **Whale Protection Act 1980**	**16.July 2000** **Great Barrie Reef Marine Park World Heritage Area (Magnetic Island & to MLW Cleveland Bay)** **RAMSAR Wetland (the Cape Bowling Green Ramsar Wetland)** **Also applicable to:** **Migratory Species** **Nationally threatened species & ecological communities** **Commonwealth marine areas** **Nuclear actions (inc. uranium mining)**	**The Act aims to legislate for environmental protection and biodiversity conservation within areas of "national environmental significance" which are Commonwealth responsibilities.** **All actions which are likely to have significant impact on World Heritage properties or Ramsar sites will be subject to an environmental assessment and Commonwealth (or Cwth approved State) approval regime.** **The unlawful taking of an action that has a significant impact on a matter of national environmental significance may attract a civil penalty of up to $ 5.5 million or a criminal penalty of up to 7 years imprisonment** **The legislation is NOT retrospective**

Chapter 6 - Chemical Contaminants in Cleveland Bay: Water Quality and Ecotoxicological Issues

G.B. Jones, A. J. Reichelt-Brushett*[1], A. Muslim*[2], P. Mercurio*, G. Doherty[*] & D. Haynes[3]*

**Department of Chemistry, James Cook University, Townsville, Queensland 4811.*

[1]*Centre for Coastal Management, Southern Cross University, Lismore, NSW 2480.*

[2]*Faculty of Fisheries & Marine Science, University of Diponegoro, Semarang, Central Java, Indonesia.*

[3]*Great Barrier Reef Marine Park Authority, PO Box 1379, Townsville, Qld 4810.*

6.1 Introduction

Despite the wealth of information carried out over the years on water quality in Cleveland Bay, few investigators have made any serious attempt to use this information to actually derive relevant water quality criteria for the bay. Water quality not only encompasses the water column, but also is affected by the quality of sediments, the quality of air, and the human and natural activities in the catchments. Deteriorating water quality significantly affects the biodiversity of marine organisms. The overall water quality of Cleveland Bay is therefore a function of all these interlinked areas. The main objective of the recent ANZECC (2000) water quality guidelines is to provide an authoritative guide for setting water quality objectives required to sustain current, or likely future, environmental values for natural and semi-natural water resources in Australia and New Zealand. The guidelines are intended to provide Government, industry, consultants and community groups with a sound set of tools for assessing and managing ambient water quality, according to designated environmental values. They are not mandatory standards, and should not be used as such, but they provide a framework for recognizing, and protecting water quality (ANZECC, 2000). Whether ambient water quality is above or below the guideline values, the philosophy of continual improvement is promoted. Long-term management aims should be to continually improve water quality to levels that are better than those defined by the guidelines (ANZECC, 2000). The objective of this chapter is to review past research that has been carried out on micronutrients, metals and toxic organic chemicals in Cleveland Bay, and to compare this data with the most recent ANZECC water quality guidelines for these substances in coastal and estuarine waters, sediments, and marine organisms. Recent work on the toxicity of metals to a variety of marine organisms in the bay is also reviewed, and illustrates the paucity of data in this area. Finally the chapter concludes with an attempt to highlight the main water quality and ecotoxicological issues for Cleveland Bay, and a need to fund such activities in a sustainable way, so that a higher level of understanding of the main issues affecting water quality in Cleveland Bay is obtained.

6.2 Water Quality

6.2.1 Micronutrients

Coastal eutrophication is recognized worldwide as a growing problem in areas affected by the discharge of sewage, agricultural and urban run-off (GESAMP 1990). Some of the problems in Australian fresh and marine waters have been summarized in recent publications (e.g. Brodie, 1995; Brodie *et al.,* 1990; AEC 1987; Cullen 1986). The principal micronutrients associated with eutrophication are nitrogen (N) and phosphorus (P), but others such as organic carbon, silicon, iron, molybdenum, and manganese may play a supplementary role (Brodie, 1995). On a global scale, it is now estimated that the input of nutrients to the oceans from human sources via rivers is equal to, or greater than, the natural input (Windom, 1992). In Cleveland Bay a number of nutrient studies have been carried out over the years (Walker, 1981; Walker and O'Donnell, 1981; Brodie *et al.,* 1988; Muslim, 1995; Muslim &Jones, 2000).

During 1993-94, one of the driest years on record, the effect of phytoplankton blooms on dissolved nutrients and chlorophyll a was studied in Cleveland Bay (Muslim 1995; Muslim and Jones, 2000). Chlorophyll a, dissolved ammonium, dissolved nitrate, dissolved organic nitrogen (DON), and total nitrogen (TN) levels (Table 1) were far higher than concentrations reported for many inshore sites within the Great Barrier Reef (Muslim and Jones, 2000). Chlorophyll a, TN, and dissolved nitrate and nitrite levels were well above ANZECC water quality guidelines for the protection of coastal and marine waters. Although the mean dissolved inorganic phosphate concentration (0.20 µM) was close to the guideline value, on occasion's concentrations have reached as high as 0.30-0.40 µM (Muslim and Jones, 2000). The high levels of DON imply a large source of nitrogen is entering Cleveland Bay, which most probably stimulates intense bacterial nitrification.

Table 6.1 Dissolved nutrients (µM) and chlorophyll a (µg/l) in Cleveland Bay, compared with the ANZECC (2000) nutrient water quality guideline values for coastal and marine waters. Source: Muslim & Jones (2000)

Nutrient	**Cleveland Bay**	**Guideline Values**
H_2PO_4	0.20	0.19
$NO_2 + NO_3$	0.70	0.56
NH_4^+	0.84	2.22
TN	8.59	2.78
DON	7.10	-
Chl-a	1.35	0.30

In Cleveland Bay Muslim and Jones (2000) established that chlorophyll a was significantly correlated with dissolved inorganic phosphorus ($r = 0.47$. $P<0.001$)(Figure 1), with no significant correlations occurring between chlorophyll a and any nitrogen species measured.

Figure 6.1 Correlation of dissolved inorganic phosphate and chlorophyll a in Cleveland Bay.

Chlorophyll a levels in the bay were double those determined in 1988 (Brodie *et al*,. 1989), and the mid to late-seventies (Walker, 1981), and were significantly correlated with *Trichodesmium's* abundance, a cyanobacteria, or blue-green algae which often blooms in the bay, and along the Queensland coast (Jones *et al.,* 1982). In the central GBR, blooms of this organism occur throughout the year (Jones, 1981; Revelante & Gilmartin, 1982; Jones *et al.,* 1982; Jones, 1988; Jones & Thomas, 1988). In Cleveland Bay (Figure 1), *Trichodesmium* is a conspicuous member of the phytoplankton assemblage (Jones, 1981; Jones *et al.*, 1982; Jones, 1992). In Townville’s coastal waters *Trichodesmium erythraeum* (Ehr.ex Gomont Geitler) is the dominant species, but *T. thiebauti* (Gomont ex Gomont) is also present (Revelante & Gilmartin, 1982). During *Trichodesmium* blooms, filaments are aggregated by the wind to form dense slicks, which accumulate at the air/sea interface (Jones *et al.*, 1982). From August to November, prior to the summer monsoons, these surface slicks are borne landward by the prevailing winds where these malodorous aggregations decompose in shallow bays and estuaries along the tropical east Queensland coast (Jones *et al.,* 1982; Jones *et al.,* 1986). On occasions blooms can stretch along a major portion of the Queensland coast, extending from the shoreline to the outer barrier, occupying up to 150 000 km^2 of sea surface (Wood, 1965, Revelante & Gilmartin, 1982; Kuchler & Arnold, 1986). It is possible that these large-scale events are fuelled by the nutrient-rich intrusions of the East Australian Current (Andrews, 1983;

Andrews & Gentian, 1982), but inshore these blooms could be responding to elevated levels of N and P. As *Trichodesmium* is positively buoyant large aggregations of this organism are transported inshore by the NE trade winds (sea breeze effect), often during the afternoon.

There is now increasing concern and evidence that *Trichodesmium* blooms are toxic to fish (Chako, 1942) and phytoplankton (Revelante & Gilmartin, 1982), cause neurotoxicity in mammals (Hawser *et al.*, 1991; Hawser & Codd, 1992), and respiratory problems in humans (Sato *et al.*, 1966). In the GBR, *Trichodesmium* blooms affect trace metals such as cadmium, copper, iron, zinc, and lead (Jones *et al.*, 1982; Jones *et al.*, 1986), and also affect nutrient levels (Jones, 1992). Endean *et al.* (1993) have identified a polypeptide and an alkaloid that may be responsible for the toxic nature of water-soluble material from *T. erythraeum* from Hervey Bay in New South Wales. Despite *Trichodesmium* being such a conspicuous member of the planktonic community in GBR waters, we still do not understand the factors that cause it to accumulate in inshore waters. Abundance data suggests that *Trichodesmium* blooms more frequently in Cleveland Bay in recent years and fixes twelve times the amount of nitrogen brought into the bay by sewage input (Muslim & Jones, 2000). Such a situation would explain the high levels of DON in Cleveland Bay (Table 1).

Proxy records of phosphorus input into Cleveland Bay over 131 years have been obtained from a coral core collected from Geoffrey Bay (Jones & Tirendi, 1989). Phosphorus was measured in annual fluorescent bands covering wet and dry periods from 1955-1986, and 1855-1886. From 1855-1875 and 1982-86 the fluorescent record indicated a severe drought in the region spanning 21 and 5 years, respectively. From 1855-1875 phosphorus levels ranged from 4-53 ppm (mean 27 ppm), with levels from 1982-86 ranging from 22-31 ppm (mean 26 ppm). During wet years levels of phosphorus were much lower. The coral record indicates that phosphorus levels seem to build up in Cleveland Bay during drought years, a situation that has also been found for trace metals in the bay (Jones, 1981). It is now clear that marine and freshwater phytoplankton can access particle-bound phosphorus. Consequently not too much reliance should be placed on the ANZECC guideline for dissolved inorganic phosphorus in Cleveland Bay.

For example, Chiswell *et al.* (1997) studied the speciation of phosphorus in Cleveland Bay and the Herbert Estuary. These authors used iron strips to access dissolved inorganic phosphate, and a fraction of the colloidal-bound phosphorus present in seawater, which phytoplankton may access. Measurements of dissolved phosphorus, particulate phosphorus and dissolved organic phosphorus were also made. The iron strips are made of filter paper impregnated with iron oxyhydroxide (FeO(OH)). When placed in seawater they act as a "phosphorus sink" and adsorb dissolved phosphorus from solution, disrupting the equilibrium between dissolved and particulate phosphorus. Part of the particulate phosphorus desorbs into solution and is taken up by the iron strip. The phosphorus recovered from the strips is a measure of the 'bioavailable' phosphorus present in seawater. In Cleveland Bay 'bioavailable' phosphorus was generally higher than dissolved inorganic phosphorus, but this was reversed in the Herbert Estuary. This was thought to reflect differences in the amount of dissolved and particulate organic matter in the two catchments. In Cleveland Bay elevated levels of 'bioavailable' phosphorus, dissolved organic phosphorus, and particulate phosphorus occurred in close proximity to sewage discharge at Sandfly Creek.

6.2.2 Trace metals

During 1976-1979 trace metal studies (i.e. Fe, Mn, Zn, Cu, Ni, Cd, Pb) were carried out in Cleveland Bay and the Ross Estuary. Water, sediment, and marine organisms were screened in order to determine the baseline and seasonal variation of these metals (Burdon-Jones *et al.,* 1975; 1977; 1982; Jones, 1981). The mean dissolved trace metal concentrations in Cleveland Bay and the Ross Estuary are reported below (Table 2), and are compared with ANZECC guidelines for marine waters. In the most recent guidelines (ANZECC, 2000), the level 1-guideline trigger levels, the highest grade, were derived from multiple species data or chronic 'no observable effect concentration' (NOEC) data.

Of all the metals measured in Cleveland Bay, the mean copper concentrations are close to the guideline trigger value. On occasions however 'bioavailable' copper levels in the bay (0.49 µg/l) were above the guideline value (Jones and Thomas, 1988). In the Ross Estuary the mean bioavailable copper concentration was close to the guideline value, with some values (0.89 µg/l) well over the guideline values during the dry season (Jones & Thomas, 1988). Mean dissolved zinc levels in the estuary (2.1 µg/l) were close to the guideline value. On several occasions dissolved zinc levels at the Bundi Creek boat ramp reached 14 µg/l, over five times the guideline values. Mean dissolved manganese levels in the estuary were close to the interim guideline value, with some values (100-400 µg/l) during the dry season well over the guideline levels (Jones, 1981). All other metals were well below the guideline values.

The recent "guideline" values are considered as "trigger" levels to initiate further investigation and subsequent refinement to regional, local, or site-specific conditions. The appropriate state or regional authority should provide guidance and direction in this process. Site-specific variation of dissolved copper in the Ross Estuary indicates that at all six estuarine sites studied, at certain times in the dry season, total dissolved copper can reach levels as high as 4-5 µg/l (Jones & Thomas, 1988). Copper speciation measurements at the Harbour Breakwater suggested that ‘bioavailable’ copper concentrations increased to three times the guideline values (0.83-1.0 µg/l) during *Trichodesmium* blooms from August-December (Jones *et al.*, 1982). It seems that this also occurs at other sites in the Ross Estuary as the algae is swept into the estuary (Jones & Thomas, 1988).

Table 6.2 Dissolved metals in Cleveland Bay and the Ross Estuary (µg/l), compared with the ANZECC (2000) water quality guideline values. Source: Jones (1981), Jones and Thomas (1988); * Level 1 Guideline values; ** Interim value

Metal	Cleveland Bay	Ross Estuary	Guideline Levels*
Cu	0.27	0.24	0.32
Pb	0.15	0.11	0.80
Cd	0.07	0.07	1.70
Zn	1.02	2.10	2.7
Ni	0.13	0.30	32.6
Fe	0.83	1.80	-
Mn	0.63	35	47**

Elevated cadmium levels have also been found in offshore waters in this region during *Trichodesmium* blooms (Jones *et al.*, 1986), although levels were much lower than the guideline values. Jones *et al.* (1982) provide evidence that decomposition of *Trichodesmium* inshore causes dissolution of particulate-bound metal, which raises the 'bioavailable' fraction of some metals such as copper, zinc, lead, and nickel. This strongly suggests a link between eutrophication of coastal waters and metal uptake in marine organisms in this region, and needs to be investigated further.

6.3 Sediment Quality

The distribution of surface and subsurface sediment facies, description of their composition, and models of sedimentary evolution in Cleveland Bay have been described by Miller (1982), Carter *et al.* (1993), Larcombe & Ridd (1994), Ward (1994), and McIntyre (1996). The geomorphological features and soil types of the different catchment areas of the bay has been undertaken by aerial photography (Townsville City Council). The distribution of sediment facies is controlled by proximity to a source of sediment and exposure to wind and wave energy. Hence, calcium carbonate rich sediments occur in the western bay close to coral reef colonies formed on the fringes of Magnetic Island and Middle Reef, while the central bay is characterised by a terrigenous muddy sand. Sources of terrigenous sediment to the bay includes discharges of sediments from local creeks and rivers as well as sediment from the Burdekin River (75km south east), which is transported north by along shore processes (Belperio, 1983). Fine-grained sediment accumulates in areas of low energy, such as the lee of bays and headlands (Larcombe & Woolfe 1999).

Published marine chemical and geochemical surveys of metals in sediments in Cleveland Bay include Reichelt & Jones (1994), Ward & Larcombe (1996), Haynes (2001) and Doherty *et al.* (in prep). In the work reported by Reichelt and Jones (1994) concentrations of Zn, Cu, Pb, Ni in Cleveland Bay sediments were between those in average shale's and carbonates (Turekian & Wedepohl 1961). The recent ANZECC interim sediment quality guideline (ISQG) values leads to a definition of three levels of contamination, based on the setting of both a low set of values below which there is a low probability that there would be effects on benthic biota (ISQG-LOW), and a high set above which there is a high probability that there will be toxic effects (ISQG-HIGH). Values falling below these sets had an intermediate probability of effects on benthic biota.

Table 6.3 Copper, lead, zinc, and nickel in Cleveland Bay sediments, compared with the recent ANZECC sediment quality guidelines for metals (µg/g) in sediments Source: Reichelt & Jones (1994).

Metal	Cleveland Bay	ISQG-LOW	ISQG-HIGH
Cu	32	65	270
Pb	15	50	220
Zn	40	200	410
Ni	30	21	52

Total lead concentrations (<5 -31 µg/g; mean 15 µg/g) were closely comparable to values found for Cockburn Sound in Western Australia (Talbot and Chegwedden 1983), and were considerably less than the ANZECC sediment quality guideline value (Table 2). In the mid-1990's lead in Port sediments (53-330 µg/g; mean 128 µg/g)(Reichelt, 1993) was mid-way between the low and high guideline values (Table 2), and similar to levels in the Mersey Estuary, a busy port area in the UK (Langston, 1986). Total copper in Cleveland Bay sediments (2-50 µg/g; mean 32 µg/g) was well below the recent guideline values (Table 2) and similar to North Sea coastal sediments (Taylor, 1979), which were classified as natural and subject to effluents from mixed industries (Moore and Ramamoorthy 1984). In the Port sediments copper concentrations (30-460 µg/g; mean 142 µg/g) were mid-way between the low and high guidelinevalues, and comparable to those in Southampton Port (Armannsson *et al.*, 1985), and along the coast of Bermuda (Jickells & Knap, 1984). Total zinc concentrations in Cleveland Bay sediments (5-86 µg/g; mean 40 µg/g) were well below the recent low-level guideline values (Table 2) and similar to values in Mediterranean sediments (Moore & Ramamoorthy, 1984). Zinc in Port sediments (160-3680 µg/g; mean 739 µg/g) was well above the 'high level' guideline value (Table 2). In Platypus Channel, zinc concentrations (60-110 µg/g) were also elevated. Concentrations of zinc in sediments collected off the sewage outfall were only moderately elevated (54-58 µg/g). Nickel in Cleveland Bay sediments ranged from 3-178 µg/g; mean 49 µg/g) and were close to the high guideline value (see Table 2 in Reichelt & Jones, 1994). On close examination of the data the highest values occurred at Radical Bay, Middle Reef, and the dredge spoil Dump Site (115-178 µg/g), all sites affected by dredging. When these values are deleted the mean nickel level is 30 µg/g, between the guideline values. Exceptionally high levels of iron and nickel (30.8% and 11, 800 µg/g) were detected in Port sediments (Anon, 1991), possibly reflecting spillage of nickel ore. Since the study by Reichelt & Jones (1994) considerable environmental improvements have been made to Port activities and metal levels in sediments from the Port may be lower. The most recent work by Doherty *et al.* (in prep) reports levels of cadmium, copper, nickel, lead, and zinc in Cleveland Bay, Cocoa Creek, Sandfly Creek, Ross Creek, and Ross River sediments. This analytical database forms part of a sediment sample archive containing over 2000 sediment samples from North Queensland, which is held at the Australian Institute of Marine Science. Metal concentrations are compared with the recent ANZECC (1999) interim sediment quality guidelines (Table 3).

Table 6.4 Copper, lead, zinc, and nickel in Cleveland Bay & Ross Creek sediments, compared with the recent ANZECC sediment quality guidelines for metals (µg/g) in sediments. Source: Doherty (PhD thesis)

Metal	Cleveland Bay	Ross Creek	ISQG-LOW	ISQG-HIGH
Cu	6	39	65	270
Pb	10	49	50	220
Zn	26	168	200	410
Ni	9	17	21	52

This recent work suggests that levels of copper, nickel, and zinc in Cleveland Bay are lower than levels reported in Reichelt & Jones (1994), whilst lead levels are comparable in the two studies. These differences may reflect the different areas studied, sample pretreatment, and different sediment digestion procedures (Reichelt, 1993). For example, Reichelt & Jones (1994) determined total metals using a lithium meta-borate fusion at 1100 ^{o}C, dissolution in 5 M nitric acid, and graphite furnace atomic absorption, whilst Doherty *et al.* (in prep.) used a concentrated nitric acid-perchloric acid digestion followed by ICP-AES. The data by Doherty *et al.* is therefore likely to underestimate total metal concentrations for some metals. The data by Doherty *et al.* does however show than the upper ranges of copper, lead, and zinc in Ross Creek are above the maximum ANZECC guideline values for metals in sediments, whilst the upper ranges of nickel in Sandfly Creek, Ross Creek, and Ross Estuary sediments are either close to, or just over the minimum guideline values.

Nickel could therefore be a more widespread contaminant in Cleveland Bay, or a more significant component of mineralized sediments in the region.

ANZECC sediment quality guidelines recommend that acid-soluble metals rather than total metal analysis be reported. It is recognized that the analysis of total trace metals in sediments often generates data that can mask pollution trends (see Reichelt & Jones (1994), although this fraction can be useful for comparison purposes. Reichelt & Jones (1993) describe a technique for monitoring pollutant levels of metals in Cleveland Bay sediments by determining the bioavailable (labile) metal fraction. The technique distinguishes between lattice-held (residual) and non-lattice-held (non-residual) metals. Dilute hydrochloric acid leaches have been shown to cause the clay mineral lattice to break down. Trace metals are commonly bound to clay minerals. According to several researchers (see Reichelt & Jones 1994) dilute hydrochloric acid will release the bioavailable trace metal fraction from sediments. Another novel feature of this work was the correlation of the bioavailable metal fraction in the sediments with iron, an index of detrital input from river discharge and resuspension. With this treatment polluted sites stand out for Zn, Cu, Pb and Ni against their background concentrations.

These authors went onto show that bioavailable Cu, Pb, and Zn in sediment transects across the mouths of Sandfly Creek, Ross River, and towards the Port all increased in concentrations towards the port area (Figure 2). The research by Gibbs (1993), Reichelt & Jones (1994), Esselmont (1997) and Doherty (in prep) all indicate that trace metals are enhanced in Ross Creek relative to other regions of the bay, and in some cases exceed the ANZECC interim sediment quality guideline screening levels.

Figure 6.2 (a) Inshore and (b) offshore transects of acid-soluble metals in sediments from Cape Ferguson to the Port area.

6.2.3.1 Organochlorine Pesticides in sediments

Sediments collected from Cleveland Bay have been analysed for organochlorines and pesticides (atrazine, diuron, chlorpyrifos, heptachlor, aldrin, endosulfan, lindane, dieldrin, DDT, DDD, and DDE) by Haynes *et al.* (2000). No organochlorine or pesticides were detected in sub-tidal samples from the bay. Some inter-tidal sediment samples collected from Cape Pallaranda contained a range of dioxin congeners (Müller *et al.*, 1999), and data on dioxin concentrations in other sediment sample sites is not yet available. Other published analyses of organic compounds in sediments include Pringle (1989), Cavanagh *et al.* (1999) and Inglis & Kross (1999). The work by Ingliss & Kross (1999) and Cavanagh *et al.* (1999) indicate that organisms in Ross Creek may be responding to the presence of increased levels of organic contaminants.

6.3 Marine Organisms- Biological Indicators

6.3.1 Metals

Although dissolved metal levels may be close to water quality guidelines, in some cases it may be desirable to proceed to field biological monitoring to supplement the water column studies. OECD (1992) provide guidance on when a water manager might proceed to complex ecosystem studies to evaluate a guideline under site-specific conditions, and what parameters these studies should include. The studies by Burdon-Jones *et al.* (1975) and (1977) provide a wealth of baseline data on metals in marine organisms from Cleveland Bay, Halifax Bay and Bowling Green Bay, which can be used in this context. In these studies ten metals (Fe, Mn, Zn, Cu, Ni, Cd, Cr, Co, Pb and Ag) were analysed in representative samples of angiosperms, macroalgae, molluscs (bivalvia, gastropoda, and cephalopoda), crustacea, fish and dugong. Several organisms (fish, crab, oyster, beach pipi, scallop, sand snail, macroalgae) were also screened for any seasonal variation (Burdon-Jones *et al.*, 1977).

Macroalgae

Macroalgae concentrate metal ions from water and thus reflect metal concentrations in their surroundings A seasonal study of the ten metals in *Padina tenuis* and *P. tetrastromatica* from Rattlesnake Island, Magnetic Island, Townsville Harbour, and Ticklebelly Bay (Burdon-Jones *et al.*, 1982) found that the highest copper, lead, and zinc concentrations occurred in brown algae from Townsville Harbour.

Oysters

Of the other organisms screened, oysters were found to be a good bioindicator of zinc, copper, and cadmium pollution in Cleveland Bay (Jones 1992). In this later work the upper range of zinc in *Saccostrea echinata* (black lip oyster) collected from the eastern Harbour breakwater (seaward side) was half the highest ever recorded concentration of zinc in oysters (38,700 ppm dry wt) reported for the Derwent Estuary, Tasmania, one of the most polluted areas of the world (Bloom & Ayling, 1977). Copper levels were even higher than reported for the Tamar Estuary (Ayling, 1974), and cadmium levels were also high. In contrast, nickel concentrations in oysters were comparable to concentrations reported in many species of oysters from various parts of the world (Forstner & Wittmann, 1981), supporting the view that the bioaccumulation of this element is usually quite low. Recent studies on zinc in black lip oysters collected from the western Harbour Breakwater in 1999 suggest that levels of zinc in oysters in the vicinity of the Port have decreased, although levels are still higher than the recent ANZECC guidelines (Jones *et al.*, in press). However, zinc in oysters collected from Orpheus Island and Rattlesnake Island were also higher than the guideline values. The eastern Harbour Breakwater in the 1979 studies was selected because *Trichodesmium* blooms affected this site. Although the high levels of Zn, Cd, and Cu in black lip oysters from the eastern Harbour Breakwater may have reflected metal shipments through the port at that time, urban and industrial activity, sewage discharge, algal blooms, boating and dredging activities cannot be discounted as possible sources of these metals (Jones, 1992; Reichelt & Jones, 1994; Jones *et al.*, 2000).

Fish, crabs, sharks, rays,

Zinc, cadmium, lead, nickel,and copper measurements have been in muscle tissue from 28 species of fish, 3 species of sharks and rays, 2 species of squid and cuttlefish, and 3 species of crustacea collected from Cleveland Bay in 1999 (Mercurio, 1999; Jones *et al.*, 2000). Of the all the metals analysed only a good data analysis has so far been made on zinc. In the fish species the mean Zn concentration in muscle tissue was 4.83 ± 2.82 µg/g wet weight, slightly lower than zinc measurements (7 µg/g wet weight) made in 14 fish species collected from the bay in 1975. Zinc in sharks and rays ranged from 3.5-7.2 µg/g wet wt, in squid and cuttlefish 13-16 µg/g wet wt, and in crustacea levels ranged from 14-18 µg/g wet wt (Mercurio, 1999; Jones *et al.,* 2000). Zinc levels in fish varied between species with concentrations well below the ANZECC Maximum Residue Limit of zinc in seafood (150 µg/g wet wt.).

Mangrove flora and fauna

A few trace metal analysis have been made on mangrove flora and fauna in the bay (Jones *et al.*, 2000). Highest concentrations of zinc in mangrove leaves (30-65 µg/g dry wt.) occurred in *Osbornia octodonta, Exocaria agalocha,* and *Aegialitus annulata*, compared with *Ceriops tagal*, and *Avicennia marina* (5-10 µg/g dry wt.). No significant difference in zinc concentration occurred between leaves and litter fall for most of these species, with the sole exception of *Exocaria,* which showed almost a twofold increase in concentration. In seven species of mangrove fauna levels of zinc were very uniform and close to 50 µg/g (dry wt.) *Telescopium telescopium* from the mouth of the Ross Estuary was the exception with levels at 400 µg/g (dry wt.).

Marine mammals

Seven stranded dugong (Dugong dugon) carcasses have been retrieved from the Townsville region (Cleveland Bay, Magnetic Island and Halifax Bay) between 1996-1999. Tissue samples collected from these animals were analysed for heavy metals and organochlorines including dioxins (Haynes 2001). Dugong fat contained unexpectedly high concentrations of dioxins, particularly the octa-substituted PCDDs (Haynes *et al.,* 1999; Caroline Gaus (NRCET), unpublished data). Low levels of dieldrin and DDE were present in liver and fat tissues (Haynes et al 2001). Metal concentrations of mercury, lead and nickel were elevated in dugong carcasses collected from Magnetic Island and Halifax Bay (Haynes et al, 2001).

6.3.2 Stress indicators in corals

Many species of marine algae contain dimethylsulphonium compounds, the most important being dimethylsulphoniopropionate (DMSP), a compound believed to be involved in the osmoregulation of certain species of algae (Kirst, 1989). Enzymatic cleavage of this substance yields dimethylsulphide (DMS) and acrylic acid. Levels of DMS and DMSP are very variable in the oceans, both temporarily and spatially, being dependant on the species composition as well as the total biomass of phytoplankton (Keller *et al.,* 1989). Under normal conditions algae release only very small quantities of DMS (Andreae, 1979; Dacey & Wakeham, 1986; Varavamurthy *et al.*, 1985). Release of DMS from algae can be a result of osmoregulation, enzyme action, grazing by zooplankton, or other forms of stress such as salinity changes and physical disturbance (Challenger and Simpson 1948). The physiological state of phytoplankton also appears to influence the rate of DMS emission, with highest amounts emitted during senescence (Nguyen *et al.,* 1988).

Large amounts of DMS have been observed to be released from the coral, *Acropora cervicornis* in the laboratory, and during exposure to the air (Andreae *et al.*, 1983). Symbiotic zooxanthellae in corals and clams from the GBR have been found to contain very high levels of DMSP, the precursor compound to DMS (Broadbent, 1993; Jones *et al.*, 1994; Broadbent, 1997). In *Acropora formosa*, from Magnetic Island, DMSP levels of 0.15-0.27 pmoles per cell have been measured (Broadbent, 1993). Compared with most other classes of phytoplankton, the Dinophyceae are significant sources of DMSP.

Recent work suggests that the concentration of DMSP in certain species of algae may be an adaptation to a low nutrient environment (Liss & Galloway, 1993), and this may be true of corals. Nitrogen has been suggested as the most energy-efficient preference for the synthesis of osmolytes. During nitrogen limitation, it has been suggested that sulphur can replace some nitrogen-containing osmolytes of similar structure, so that nitrogen can be utilised for the more important process of amino acid and protein synthesis. An increase in the DMSP contents of the phytoplankton, *Emiliana huxleyi* , under N limiting conditions, was explained as the substitution of the nitrogen-containing osmolyte glycine betaine by DMSP (Turner *et al.,* 1988). In contrast, when subjected to increased nitrogen the level of DMSP within cells should decrease.

In 1992 it was suggested that DMS and DMSP could be possible indicators of stress (Jones, 1992a), and an opportunity to test this hypothesis was made available in the ENCORE experiment (Enriched Nutrient Coral Reef Experiment) at One Tree Island (Jones *et al.,* 1995; Larkum & Steven, 1994), and at Nelly Bay Reef, Orpheus Island Reef, and Kelso Reef.

Table 6.5 The variation in the DMSP/chlorophyll a ratios, and chlorophyll a for different locations. * µg/L

Location	DMSP/Chl-a	Chl-a*	Source
GBR Waters	27	0.18	Curran & Jones (1996)
Kelso Reef	24	0.23	Jones *et al.,* (1996)
Magnetic Island	3	1.1	Muslim (1995)
Orpheus Island	8	-	Curran (1996)
European Shelf waters	6	-	Turner *et al.,* (1995)

6.4 DMSPp/ chlorophyll a ratios in the water column

Whilst we did not have the time to investigate algal speciation at these reef sites, the variation in DMSP/Chl a ratio can be considered an estimate of the proportion of DMSP producers in the total phytoplankton assemblage (Turner *et al.,* 1995; Curran, 1996). A comparison of the mean ratio determined at the various sites is shown in Table 2, together with the chlorophyll a levels, and has been sourced from Curran (1996). It can be seen that the average ratio for Kelso Reef (24) is close to the average ratio for the wider GBR (27). However, at Nelly Bay, Magnetic Island, and Orpheus Island the ratios are very low (3 and 8), reflecting the much higher levels of chlorophyll a, high proportion of diatoms (Walker, unpublished) and low levels of DMSP producers at these sites (Curran, 1996). Ratios of 6 have been recorded in European waters, when 50% or more of the algal assemblage was composed of diatoms, and nuisance algae such as flagellates (Turner *et al.,* 1995; Curran, 1996).Measurements of DMSP have also been made in coral tissue at Nelly Bay, Kelso Reef, and One Tree Reef (Broadbent, 1996).

6.5 Fate of contaminants in Cleveland Bay

There have been very few studies carried out on the fate of contaminants in Cleveland Bay. One study however has investigated the fate of metals during dredging operations in Cleveland Bay (Reichelt & Jones, 1994). Dredging operations in Queensland waters are controlled by State environmental authorities through Section 86 of the Queensland Harbour Act 1955. Sea dumping of dredge spoil is controlled by the Commonwealth Environmental Protection (Sea Dumping) Act 1981 (Reichelt, 1993; Reichelt & Jones 1993; Reichelt & Jones, 1994). Before permits are issued, the impact of pollutant release at the dredge site must be fully assessed, as must the dredge spoil dumping (Batley 1988). Platypus Channel, the main Townsville shipping channel is usually dredged once or twice a year. Dredge spoil is dumped in Cleveland Bay towards Cape Cleveland. Because the port has expanded, dredging and dumping of sediment has been more critically examined in recent years. Environmental concerns have focused primarily on the effects of sediment plumes produced by dredging and dumping on the fringing reefs of Magnetic Island and the sea grass beds in Cleveland Bay (Pringle, 1989; Anon. 1991; Wolanski *et al.,* 1992). Reichelt & Jones (1994).carried out the first detailed study of the fate of metals associated with dredged sediments in Cleveland Bay. This study determined (1) trace metal concentrations in Cleveland Bay and Port sediments. (2) the most significant carrier phases of trace metals during a simulated dredging disturbance in the laboratory, and (3) assessed the fate of dredged sediments at selected fringing coral reefs surrounding Magnetic Island.

Using a laboratory simulation experiment to mimic the dredging activities, Reichelt & Jones (1994) showed that during resuspension of sediments the dominant carrier phases of all four metals was the carbonate phase for lead, the organic phase for zinc and copper, the iron oxide phase for lead and zinc. It is the organic forms of copper and zinc that are more bioavailable, than the carbonate or iron oxide phases. One general feature of the lab experiments was the fact that the fluid mud layer contained consistently higher concentrations of all four metals, than the settled sediments. This new technique yielded useful information on the fate of dredged sediments in Cleveland Bay, especially with respect to the transport of this material to the fringing coral reefs of Magnetic Island. The fringing reefs that were most affected using this tracer technique were Middle Reef, Florence and Radical Bay, all sites that were shown by aerial photography to be affected by sediment plumes from the dredging activities. Tracer studies with phosphorus have shown a similar result (Muslim and Jones, in prepn.).

6.6 Ecotoxicology

One of the earliest ecotoxicological studies of the effect of metals on marine organisms in the region was that carried out by Burdon-Jones & Denton (1979). In this study the effect of temperature and salinity changes on the toxicity and bioaccumulation of selected metals in commercially important species was investigated. Changes in salinity and temperature were selected that would be experienced during very dry and wet seasons in the tropics. The study also included a comparative evaluation of the affinity of different tissues and organs for various metals. Such data are fundamental to the understanding of the possible long-term effects of these pollutants on the survival, reproduction, growth and development of marine organisms. Acute toxicity studies were carried out on oysters, prawns, and fish (Denton & Burdon-Jones, 1986). The rank order of metal toxicity was different for each species examined and varied according to the temperature and salinity regime adopted. Mercury and copper were generally the most toxic elements tested, followed by cadmium and zinc, then nickel, and then lead. Oysters and juvenile banana prawns showed increased susceptibility to heavy metals with increased temperature, whilst among the fish tested, glass perchlets were seemingly unaffected. Salinity did not affect the survival time of oysters in solutions of heavy metals, whereas prawns and fish were frequently more susceptible to certain metals in low salinity water. Prawns were more sensitive to mercury, copper, zinc, nickel, and lead than any other species tested. They were particularly sensitive to zinc at elevated temperatures. In contrast glass perchlets were the most tolerant species tested with zinc at 30^{o}C, and also displayed the greatest resistance to copper, cadmium, and nickel at this temperature. Oysters were the least sensitive to mercury, zinc, and lead in all treatments, but were highly sensitive to copper.

When this original work was carried out in the region the maximum acceptable toxicant concentrations (MATC) for pollutants released into the aquatic environment were calculated for any species by multiplying the 96-h LC-50 value by an 'application factor'. Application factors of 0.01 (Hg, Cu, Cd, Zn), and 0.02 (Ni, Pb) were advocated by the NAS/NAE (1973). Using this information the calculated safe levels for copper, cadmium, zinc, nickel and lead for prawns exposed to these metals at 35^{o}C/36 salinity were 0.20, 3.7, 5.7, 5.6 and 620 µg/l, respectively. Clearly the calculated safe copper levels for prawns (0.20 µg/l) is lower than the overall mean level reported for Cleveland Bay and the Ross Estuary in Table 1, but during the dry season levels of dissolved copper in the estuary, and inshore waters during *Trichodesmium* blooms, can be as high as 1 µg/l, five times these safe levels. Dissolved zinc levels in the Ross Estuary were only slightly lower than the safe zinc level (3.7 µg/l), and clearly there were occasions in the estuary in the late seventies when dissolved copper and zinc levels were higher than the safe levels for prawns.

As part of a study of the effects of urban runoff in coastal estuaries, Inglis & Kross (1999) demonstrated that there was a measurable effect upon the benthic fauna of Ross Creek that was spatially associated with enhancement concentrations of metals and hydrocarbons. Importantly, other than the work of Ingliss & Kross (1999), no other published local ecotoxicological work is available to demonstrate atwhat concentrat-ions metals in sediments will have a measurable effect upon the environment.

Other recent ecotoxicological studies include the assessment of trace metal effects on different life stages of scleractinian corals. These studies have shown that copper concentrations of 20 µg/l significantly reduce fertilization success of gametes from the coral species *Goniastrea aspera*, collected from the reef flat around Magnetic Island, Cleveland Bay (Reichelt-Brushett & Harrison, 1999). Cadmium and zinc concentrat-ions in waters did not significantly reduce fertilization success of *Goniastrea aspera* gametes at concentrations up to 200 µg/l and 500 µg/l respectively (Reichelt-Brushett & Harrison, 1999).

The survival of coral larvae is also inhibited by trace metals. Larvae were grown up from numerous *Goniastra aspera* colonies from Nelly Bay, Magnetic Island. Dosage experiments have shown that copper of 500 µg/l caused 100% mortality after 6 hours of exposure (Reichelt-Brushett, 1998). Lead was not as toxic as copper to coral larval survival, with concentrations of 20 000 µg/l causing 100 mortality after only 6 hours exposure (Reichelt-Brushett, 1998). The 72 hour LC – 50 values for copper effect on 5-day old larvae was 34µg/l (95% confidence limits 19-62µg/l) and for 6 day old larvae was 82µg/l (54-123µg/l). These results suggest that younger larvae may be more sensitive to copper than older larvae (Reichelt–Brushett, 1998). The 72 hour LC –50 value for the effect of lead on 6 day old larvae was 9890µg/l (5730-17080µg/l), which is considerable higher than for copper (Reichelt-Brushett, 1998).

The effect of copper on the settlement success of from *Acropora tenuis*, a common coral species that occurs around Magnetic Island, was also investigated (Reichelt-Brushett & Harrison, 2000). Settlement success represents a critically important stage in the coral life cycle and results in major morphological and physiological changes in the coral. Measured copper concentrations of 42 µg/l and above significantly reduced larval settlement and the 48 hour EC–50 value was calculated to be 35 µg/l (95% confidence limits 32–37 µg/l) (Reichelt-Brushett & Harrison, 2000).

These results are some of the first EC –50 and LC -50 values for the effects of trace metals on scleractinian corals and show that copper is highly toxic to critical life stages of scleractinian corals. Although dissolved copper and lead concentrations that are harmful to corals do not occur in waters in Cleveland Bay under natural conditions (Jones, 1981), the effect of metals that are associated with sediments at much higher concentrations is not known. Sediment mobilization and subsequent metal desorption from sediments during dredging activities (Reichelt & Jones, 1994) may affect critical life-stages of local coral species and should not be conducted during coral spawning events. Corals usually spawn from 2 to 10 nights after the 10th or 11th full moon of each year.

6.7 Water Quality and Ecotoxicological Issues In Cleveland Bay

If we are to clearly distinguish between anthropogenic and natural effects of chemical contaminants in Cleveland Bay it is essential that we focus on establishing reliable data sets in order to critically evaluate man-made effects, as well as gaining an understanding of the major factors affecting the behavior of contaminants. This will involve gaining an in-depth understanding of how contaminants cycle in Cleveland Bay between the different reservoirs of seawater, sediment, and organisms, and understanding how these contaminants are transported around the bay, and in what chemical form. From the information already obtained it would seem that of the metals investigated so far copper would seem to be the most toxic, and on occasions levels in the water column have reached their guideline value. There is evidence that Ross Creek, Ross Estuary and the Port regions are elevated in zinc, lead, copper, and nickel. There is no good evidence concering the major sources of metals to the bay. Clearly metal input from urban run-off could be expected to be high, but it is only in recent years that this source is being quantified. There is good evidence that the nutrient status of the bay has changed in recent years. This may reflect an increase in population growth in the region, the continual discharge of treated sewage to the bay, and the severity of droughts in the region. There is some evidence that *Trichodesmium* blooms more frequently in the bay in recent years. As this is a nitrogen-fixing organism this is hardly surprising. Evidence suggests that phosphorus may be the cause. More research needs to be carried out on establishing whether *Trichodesmium* blooms are toxic to fish and other organisms such as Dugong, and the chemical and biochemical factors that lead to this organism accumulating toxins. Whilst a reasonable amount of research has been carried out on metal and organic pollutants, lack of long-term funding has failed to produce a detailed understanding of how contaminants affect marine organisms in the bay. Furthermore there is little knowledge of how biological diversity has changed within the bay, with respect to specific contaminants, and very little information exists on the effect of contaminants on corals in the bay. In this regard the recent ANZECC guidelines can be questioned since they take no account of what acceptable concentrations of contaminants should be in fringing coral reef waters such as Cleveland Bay. Lack of funds for the development of these protocols will continue to hinder our understanding of the effect of contaminants in GBR waters, and will continue to produce controversy.

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Chapter 7 - Summary of investigations into marine environmental quality and air quality of Cleveland Bay

G. Doherty[1], J. Cruz[2], K. Neil[2] & D. Haynes[3]
[1] School of Biomedical and Molecular Science, James Cook University
[2] School of Biological Science, James Cook University
[3] Great Barrier Reef Marine Park Authority

7.1 Introduction

The objective of this chapter is to summarise previous work that describe some aspects of the qualities of sediment, water, biota and air in Cleveland Bay. It is not an attempt to specify desirable qualities, because in most instances insufficient information is available to determine meaningful local guidelines.

7.2 Sediment Quality

7.2.1 Sediment facies distribution

Maxwell (1968), Orme & Flood (1980) and Belperio (1983) have described the regional distribution of sediment facies of the Great Barrier Reef lagoon, including Cleveland Bay. A comprehensive digital database of sediment sample data from the region and other Australian sites (auSEABED database) can be accessed at "http://www.usyd.edu.au/su/geosciences/geology/centres/osi/auseabed/au7_web.html" .

The detailed distribution of surface and subsurface sediment facies, description of their composition and models of sedimentary evolution of Cleveland Bay have been described by JCU (1975), Miller (1982), Davidson (1985), Carter *et al.* (1993), Larcombe & Ridd (1994), Ward (1994), Ward *et al.* (1995); and McIntyre (1996). Aerial photographic interpretation and mapping of geomorphological features and soil types has been completed by the Townsville City Council in the catchment areas of the bay.

7.2.2 Sediment sources

Natural sources of terrigenous sediment to the bay include; discharges of sediments from local creeks and rivers; discharges form the Burdekin River (75km south east) that is transported north by along-shore processes (Belperio 1983; Carter *et al.* 1993; Orpin & Ridd 1996); and reworking of sediment in the bay (Orpin & Woolfe 1999). Gauging of local streams and measurement of dissolved, suspended and bed load materials under high flow and ambient conditions has not been done to determine current flux of materials from local sources.

Since 1998, after a period of inclement weather, variations in the distribution of some near shore sediment facies has occurred, and resulted in sand renourishment programs along the foreshore of the western bay. Dredging activities in the bay result in the periodic redistribution of sediment, and have been described by Pringle (1989).

7.2.3 Metals

Sediment geochemical surveys completed in Cleveland Bay include JCU (1975), Knauer (1977), Reichelt & Jones (1994), Ward & Larcombe (1996), Ward *et al*, (1995), Moss & Costanzo (1998), Haynes (in prep) and Doherty *et al.* (in prep). The most recent work by Doherty *et al.* (in prep), forms part of an analytical database and sediment sample archive containing over 2000 sediment samples from North Queensland, which is held at the Australian Institute of Marine Science (http://www.aims.gov.au/pages/ research). Summary of cadmium, copper, nickel, lead and zinc concentrations from 4 regions in Cleveland Bay are presented in Table 1. The analyses have been determined by methods that are consistent to the Draft Australia and New Zealand Environment and Conservation Council (ANZECC) interim sediment quality guidelines (http://www.affa.gov.au/nwqms/ publist.html).

Work by Gibbs (1993), Reichelt & Jones (1994), Esselmont (1997) and Doherty (in prep) indicate that weak acid soluble ('bioavailable') metals are enhanced in Ross Creek relative to other regions of the bay, and are associated with total metal concentrations that exceed the ANZECC interim sediment quality guideline screening level.

Table 7.1 Summary of metal concentrations in sediments from Cleveland Bay and its estuaries.

		Cadmium (µg/kg)				Copper (mg/kg)				Nickel (mg/kg)				Lead (mg/kg)				Zinc (mg/kg)			
	N	Min.	Max.	Av.	S.D.	Min.	Max.	Av.	S.D.	Min.	Max.	Av.	S.D.	Min.	Max.	Av.	S.D.	Min.	Max.	Av.	S.D.
Cleveland Bay	41	0	68	21	16	1	21	6	4	1	24	9	5	3	19	10	4	6	67	26	14
Cocoa Creek	47	0	19	4	6	5	22	9	4	8	29	13	5	8	23	12	4	26	78	38	10
Sandfly Creek	33	0	61	18	22	3	25	18	7	2	19	15	4	4	18	15	3	7	65	48	14
Ross Creek	37	0	838	68	189	9	366	39	63	6	27	17	5	16	325	49	67	39	1532	168	273
Ross River	59	0	143	23	29	6	25	16	4	5	22	14	3	9	32	18	4	24	94	58	15
ANZECC ISQG		Screening level – 1 500 Maximum level – 10 000				Screening level – 65 Maximum level – 270				Screening level – 21 Maximum level – 52				Screening level – 50 Maximum level – 200				Screening level – 200 Maximum level – 410			

As part of a study of the effects of urban runoff in coastal estuaries, Inglis & Kross (1999) found that changes in benthic fauna of urbanised creeks (including Ross Creek) were different to non urbanised creeks, and the changes correlated with enhanced concentrations of metals and hydrocarbons.

Monitoring of metals in sediments is conducted quarterly by the Townsville Port Authority (TPA) at over 200 grab sample sites located in Ross Creek, Shipping Channel and Ross River (Anderson & Roche, 1999). Periodic sampling and analysis of metals in sediment is completed by the Townsville City Council (TCC) at sites around Townsville.

7.2.4 Organic contaminants

Sediments collected from Cleveland Bay have been analysed for organochlorines and pesticides (atrazine, diuron, chlorpyrifos, heptachlor, aldrin, endosulfan, lindane, dieldrin, DDT, DDD, and DDE) by Haynes *et al.* (2000). No organochlorine or pesticides were detected in subtidal samples from the bay. Intertidal sediment samples collected from Pallarenda contained a range of dioxin congeners (Müller *et al.*, 1999), and data on dioxin concentrations in other sediment sample sites is not yet available (Gaus, pers comm.). Other published analyses of organic compounds in sediments include Pringle (1989), Cavanagh *et al.* (1999) and Inglis & Kross (1999). The work by Ingliss & Kross (1999) and Cavanagh *et al.* (1999) indicate that organisms in Ross Creek may be responding to the stress of increased levels of organic contaminants.

7.3 Water Quality

7.3.1 Temperature

Water temperature variations in Cleveland Bay have been described by Kenny (1974) and Walker (1981c). The effects of water temperature upon bleaching of corals in the bay have been described by Berkelmans *et al.* (1997). The Great Barrier Reef Marine Park Authority monitors seas surface temperature at 4 sites in the bay as part of a larger monitoring program. Details of this program can be viewed at - http://www.gbrmpa.gov.au/seatemp/index.html.

7.3.2 Salinity

Over a 3 year period from 1977-1979 a salinity maximum (36‰ - October) occurred in Cleveland Bay during the dry season and a salinity minimum (27‰ - February) occurred during the wet season (Walker 1981). The salinity maximum was generated by evaporative concentration, where as the salinity minimum was variable between years, and was dependent upon discharges from the local rivers and the Burdekin River. The effects of discharges from the Burdekin River upon water quality in Cleveland Bay are described by Wolanski & Jones (1981) and Wolanksi *et al.* (1981).

Salinity variations at the margins of the bay are also influenced by the presence of hypersaline flats within the supra tidal zone. Subsurface brines from these regions have been described by Pomeroy (1987) and Ridd & Sam (1996). The interaction between these hypersaline brines, groundwaters and surface waters of the bay is described for a site in eastern Cleveland Bay by Ridd *et al.* (in prep) (salt and nutrient flux), Sam (1996) (salinity variations) and Ridd (1999) (burrowing organisms).

While total ground water resources in the Townsville region were considered to be under used Hausler (1991), salinisation of smaller freshwater aquifers has occurred due to overuse. Little information is available on the extent and consequences of this impact.

7.3.3 Suspended sediment concentrations

The shallow depth of the bay, coupled with the muddy terrigenous nature of the central bay facies and its exposure to south east wind-wave events can result in naturally high suspended sediment concentrations in Cleveland Bay (JCU 1975; Belperio 1978; Carter *et al.* 1993; Larcombe & Ridd 1994; Larcombe & Woolfe 1999a). Under moderate to rough sea conditions the entire bay is characterised by suspended sediment concentration between 5 to 20 mg//L (Belperio 1978), with near bottom suspended sediment concentrations up to 200 mg/L (Larcombe *et al.*, 1995).

The principal mechanism for resuspending sediment in the bay is wind induced waves, and has been described by Lou & Ridd (1997), Larcombe *et al* (1995) and Orpin *et al.* (1999). Once suspended, the sediment is available for redistribution by currents.

Measurement of suspended sediment concentrations has been undertaken in conjunction with several projects in the bay and is reported in Mapstone *et al.* (1989), Reichelt & Jones (1994) and Kettle (1999).

7.3.4 Metals

Dissolved metals in seawater have been described by JCU (1975), Burdon Jones *et al.* (1984), Jones (1981), Jones *et al.* (1986), Jones & Thomas (1988), Jones (1992), Esslemont (1997) and Jones (1999). Concentrations of metals in sea and estuarine waters of Cleveland Bay are influenced by seasonal variations in salinity, suspended sediment and nutrient levels. The concentrations of labile Cd were found to increase during periods of *Trichodesmium* blooms (Jones 1981).

The concentration of metals in sediment pore waters have been described by Ward (1994) and Doherty (in prep). Monitoring of ground water occurs at the Sun Metals Zinc Refinery (Boggiano, 1999).

7.3.5 Nutrients

Nutrient concentrations in surface waters in Cleveland Bay and surrounding regions have been measured by JCU (1975), Walker & O Donnell (1981) and Mitchell *et al.* (1991) and Chiswell *et al.* (1997). Historical nutrient fluctuations where investigated by Jones & Tirendi (1989). Monitoring of nutrient levels, colliforms and salinity is completed by the TCC at sites in the Townsville region. Chlorophyll *a* has been measured as a surrogate nutrient measure in the bay by GBRMPA since the mid1990s (Haynes *et al.,* 1998; Steven *et al.,* 1998; Devlin *et al.,* 1999). The impact of flood plumes on Cleveland Bay water quality has also been investigated and mapped (Devlin et al 2001).

7.4 Marine biota

The biota inhabiting marine, freshwater and terrestrial habitats associated with Cleveland Bay have been the focus of numerous investigations, the majority of which have been conducted within the Biological Sciences Departments of James Cook University. These investigations include; population dynamics and ecology of taxa of commercial, recreational and ecological significance including squid, mullets, anchovies, sharks, various crustaceans, algae and seagrasses. Studies have been initiated for a variety of purposes including; monitoring specific anthropogenic activities in the bay; investigations of commercial fisheries; and more general investigations of scientific issues.

7.4.1 Marine flora

7.4.1.1 Marine algae/plankton

Qualitative description of algae communities in the Townsville region are described by JCU (1975). Vakamoce (1987) studied the algal communities associated with the fringing reefs of Magnetic Island. Jayasinghe (1982) and Martin-Smith (1994) studied more specific aspects of algal communities associated with the fringing reefs of Magnetic Island. The former study focussed on interactions between algae and crustaceans (mainly crabs), while the second study was focused on the taxonomy of the Corallinacea family. Ngan & Price (1979, 1980a, 1980b) and Price (1989) intensively studied the intertidal algal communities of Cleveland Bay; focusing their research on the ecology, distribution and temporal changes of these communities.

Ecotoxicology studies and measurement of metal concentrations in different algae species have been conducted by Burdon-Jones *et al.* (1982) Burdon-Jones & Denton (1984) and Denton & Burdon Jones (1986). Brown algae had several favourable characteristics that would lend them to be usefull sentinel organisms to monitor changes of metals in the environment.

A qualitative inventory of phytoplankton and zooplankton in Cleveland Bay is described by JCU (1975). The marine blue green algae *Trichodesmium* has been studied in more detail in the bay because of its association with potentially deleterious eutrophocation events in the waters of the Great Barrier Reef Jones (1992) and Saker (in prep).

7.4.1.2 Sea grasses

Studies of spatial distribution and temporal distribution of sea grass population ecology in Cleveland Bay have been undertaken by Abel (1982), Birch & Birch (1984), Coles *et al.* (1987), Pringle (1989), Goldsworthy (1994) and Lanyon & Marsh (1995), Fisher (in prep); and McKenzie (in prep). Ludvianto (1992) examined, particularly, the foraminiferan community associated with the sea grass beds in the Townsville region.

Lanyon & Marsh (1995) indicted that abundance and diversity of sea grasses fluctuated between seasons by a factor between two and four. The minimum abundance of sea grasses occurred during the dry season (August to September) with consequent recovery of seagrass during the wet season (November to March).

Mauger (1997) and Haynes (2001) have investigated metal and metal, organochlorine and dioxin concentrations respectively of common seagrasses of Cleveland Bay and Halifax Bay.

Research on local seagrasses is currently being undertaken by the School of Tropical Environment Studies and Geography (TESAG) at James Cook University. Topics include the effects of shading and recovery from disturbance; heavy metal accumulation; the effects of nutrients on growth; the effects of dugong and turtle grazing; and population genetics (Ingliss *et al.,* 1998). Monitoring of sea grass populations in the Townsville region is currently in progress along the Townsville Strand by Sinclair Knight Merz and JCU (Kettle 1999).

7.4.1.3 Mangroves

Zonation patterns and the controls to zonation within mangrove colonies located to the east of Townsville have been described by Macnae (196X) and Spenceley (1977), while Hendrarto (1992) has studied the diatoms associated with the mangroves of Cleveland Bay. The effects that mangrove forests may have upon wave attenuation has been investigated by Brinkman *et al.* (1997) at a site in eastern Cleveland Bay.

Pringle (1989) described recent changes to mangrove colonies along fringes of the eastern bay to examine the effects of dredging. Impacts upon mangrove communities as a result of dredging could not be detected.

Mangrove leaf longevity, leaf litter trapping and production of a saltmarsh/mangrove herbarium has been monitored by the RIVER group at sites along Ross River (River 1999).

7.4.2 Marine fauna

7.4.2.1 Invertebrates

Coral Communities

Smith (1978), Bull (1981) and Mapstone *et al.* (1989) have provided general descriptions of the fringing coral reefs of Magnetic Island and their associated fauna. The effects of dredging upon coral communities have been investigated by Pringle (1989), Kaly *et al.* (1994) and Stafford-Smith *et al.* (1994). The effects of water temperature upon coral bleaching was studied by Berkelmans *et al.* (1997).

Reichelt & Jones (1994) investigated the supply of trace metals to coral colonies of Cleveland Bay in response to increased levels of suspended sediment caused by dredging. Esselmont (1998) determined the optimum method to measure metal concentrations in coral colonies, which included analysis of metals in corals from several sites in Cleveland Bay.

Reichelt-Brushett & Harrison (1999) have investigated the effects of heavy metals upon the fertilisation of corals that were collected from Cleveland Bay.

Crustaceans

Johnston (1995), Johnston & Yellowlees (1998), Johnston et al (1998) and Johnston & Alexander (1999) studied several aspects of the ecophysiology of the slipper lobster (*Thenus orientalis*). Perez (1985) and Perez & Bellwood (1988) described the ecology of the sandy shore crab (*Matuta lunaris).* Neipp (1979*)* undertook investigations into the ecology of *Decapoda Palaemondiae.*

Special attention was given to the study of the Banana prawn (*Penaeus merguiensis)* in Cleveland Bay. Studies by Haywood & Alexander (1982) and Longmuir (1983) have been concentrated in the physiology of this species, while studies by Robertson (1988) have concentrated on autoecology.

Other invertebrate communities and populations

Three recent surveys of invertebrate communities have assessed effects on benthic communities from anthropogenic activities. Cruz (1998) investigated the sensitivity of soft bottom benthic communities to the effects of dredging in Cleveland Bay, and Neil (1998) has investigated intertidal rocky shore communities in the western bay. Both these surveys suggest that identification of specific events that make an impact upon the community is complicated by large natural spatial and temporal variations. However, a third study by Ingliss & Kross (1999) identified measurable differences between Ross Creek and control sites which were spatially associated with metals and hydrocarbons.

Analysis of metal concentrations in a range of invertebrates has been completed by Burdon-Jones & Denton (1984) and Jones (1992). Uptake of metals by marine invertebrates has been investigated by Olivier (in prep) and Allison (1982). The effects of the influences of oil, oil dispersants on the growth, reproduction and eco-physiology of invertebrates has been investigated by Monfils (1998).

A general survey of the soft bottom benthic community in the intertidal zone of Cleveland Bay have been conducted by Muffley (1981), which presented a list of species of this kind of community in the Townsville region. Intertidal 'hard bottom' populations have been studied by Adisendjaja (1994) (intertidal rocky gastropods), Ibrahim (1981) (shipworms) and Tzioumis (1994) (Bryozoans). Specific ecological studies on particular populations of invertebrate fauna of Cleveland Bay, have been done by Hammond (1980, 1982) (Brachiopods) Crossland *et al.* (1991) (Gastropods), Lemmens *et al.* (1995) (Seastars), Zeidler (1981) (distribution of Amphipods), Uneputty (in prep) (Benthic community structure), Horpet (in prep) (Gastropods), RIVER (1999) (Most Common Macro Gastropods).

7.4.2.2 Icthyofauna

Several components of the ichthyofauna of Cleveland Bay have been studied by JCU (1975), Cabanban (1991) (Leiognathidae), Fogg (1993) (Carangids), McCormick (1992) (Mullidae), Molony (1993) (Chandidae), Mosse (1991) (clupeiod fishes), Gunn (1978) and Gunn & Milward (1985) (Sillaginidae), Hoedt (1984, 1994) (Engraulidae), Yap (1993) (Scianidae), Sondita (1997) (community structure), Sheaves (1995) (Lutjanid and Serranid) and Nursall (1981) (Mudskippers). Intensive studies, have been done on sharks (Carcharhinidae & Sphyrnidae) of Cleveland Bay by Simpferdorfer (1986, 1992, 1993a, 1993b, 1993c, 1998) and Simpferdofer & Mildward (1993), which have been mainly concentrated in the biology, taxonomy, ecology and ecophysiology of the group. Changes in fish populations encountered by people using cast and seine nets over time and per unit effort in the Ross and Bohle Rivers are being investigated by the RIVER Group (RIVER 1999). In addition, Moltschaniwskyj (1995) and Jackson (1991, 1995) have studied several species of squids of Cleveland Bay.

Analysis of metals in several species of fish has been completed by Burdon-Jones & Denton (1984) as part of a larger program that determined baseline concentrations of metals in organisms in North Queensland. This work has been extended recently by G. Jones and students at the School of Biochemical and Molecular Science at James Cook University, by repeating the analysis of metals in identical species of fish from the same regions (Strate *et al.*, 1998).

7.4.2.3 Mammals

Cleveland Bay is a designated dugong (*Dugong dugon)* sanctuary ([http://www.gbrmpa. gov.au](http://www.gbrmpa.gov.au)). Population studies have been conducted by Anderson & Birtles

(1978) on dugongs in Cleveland Bay, and they are the subject of monitoring by the GBRMPA. Seven stranded dugong carcasses have been retrieved from the Townsville region (Cleveland Bay, Magnetic Island and Halifax Bay) between 1996-1999. Tissue samples collected from these animals were analysed for heavy metals and organochlorines including dioxins. Dugong fat contained unexpectedly high concentrations of dioxins, particularly the octa-substituted PCDDs (Haynes *et al.*, 1999; Caroline Gaus, unpublished data). Low levels of dieldrin and DDE were present in liver and fat tissues (Haynes et al 2001). Metal concentrations of mercury, lead and nickel were elevated in dugong carcasses collected from Magnetic Island and Halifax Bay (Haynes et al 2001).

7.5 Air Quality

Information describing natural and ambient air quality in the Townsville region is limited relative to the information available in each of the categories previously described. Ma (1997) has completed an investigation into the modelling of sea breezes over Cleveland Bay.

Monitoring of air quality at the windward side of Cape Bowling Green by AIMS/CSIRO is conducted as part of a global program that monitors green house gas emission (http://www.dar.csiro.au/res/gac/default. htms). This monitoring includes CO_2, CO_2 isotopes, CH_4, N_2O, CO, H_2, but does not include particulate materials or SO_2.

Monitoring of air quality in Townsville by the Environmental Protection Agency includes two hi-vol PM10 samplers (located in South Townsville and in Garbutt), which have been in operation for several years).

Air quality monitoring is also undertaken on a monthly basis by the Townsville Port Authority Anderson & Roche (1999). Mobile monitoring stations are proposed to be used to measure air quality by Sun Metals refinery (Boggiano 1999), and mobile monitoring equipment is also used by the Townsville City Council to monitor periodic events.

The current standard of monitoring is not compliant with the National Environmental Protection Measure. Under this agreement (between all states), ambient air quality is to be monitored in communities greater than 25,000 in population, in a standardised way.

7.6 Summary

From the information presented here it is apparent that there are gaps in the knowledge of marine environmental quality in Cleveland Bay. These gaps include;

- Ecotoxicological studies that integrate physical, chemical and biological investigations, and that are directed towards developing meaningful local guidelines for pollutants (e.g. nutrients, sediment, metals, organics etc.);
- Quantitative flux measurements of sediments, nutrients and pollutants from local streams under 'first flush', highflow and ambient conditions;
- Groundwater quality – domestic use, salinisation and contamination; and
- Air quality monitoring in the Townsville region compliant with the National Environmental Protection Measure.

These gaps are created by the need to address emerging issues, and are important because they can provide direction for future investigations. The first point recognises that there is an abundance of survey information covering a wide range of topics, but that there is little multidisciplinary study that could lead to a greater understanding of the environment. For example, there is evidence for localised increases in pollutants in estuaries of suburban Townsville. However, there is a corresponding dearth of more specific ecotoxicological data to determine if, and how pollutants are having an impact upon the local estuaries.

In such circumstances the identified increases in pollutant levels are relegated to being simply a diagnostic of a deterioration in environmental quality, and alone the information does little to provide meaningful local guidelines for specific pollutants.

Multidisciplinary ecotoxicological studies are required to determine how, and at what concentrations specific pollutants impact upon the local environment in order to develop meaningful local guidelines for levels of pollutants.

The second, third and fourth points recognise that there is no quantitative measurements of the natural or anthropogenic inputs to the environment (fluxes). This is a fundamental gap in understanding the effects of human activities upon the environment, and restricts the effectiveness of environmental management and amelioration of potential pollutant sources.

Potentially the most significant gap in the understanding of marine environmental quality in Cleveland Bay does not relate to knowledge, but it relates to the management and culture of work being undertaken in the region.

Information that can contribute to understanding environmental quality is often collected by research, regulatory, community and industrial organisations that may be undertaking environmental research, monitoring, restoration or preservation, but it is rarely harnessed or made available in a way that it can be integrated with other investigations.

A possible reason for this lack of integration is that there exists no protocol for reporting or registration of environmental work being undertaken in the region More often the role of these organisations, the work that they have completed and its quality are generally ambiguous. Attempting to recover previous survey data or obtain up to date information is generally inefficient.

This situation demands greater collaboration between groups to ensure optimum use of resources, and to provide support and direction for future work that may lead to a greater understanding of marine environmental quality.

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Chapter 8 - Further Work and Future Directions

M Roche (BHP Billiton) and C Anderson (formerly Townsville Port Authority; currently Technical Adviser, The International Tanker Owners Pollution Federation Limited)

In response to a general perception of a lack of baseline data on the status of Cleveland Bay, the Cleveland Bay Consortium has sought to compile a report of existing data and research initiatives. The contents of this report represent voluntary contributions from researchers in the region and, whilst every effort has been made to compile a comprehensive account of existing research initiatives, it is recognised that some work or studies may not have been included within this report. In light of the above, the Cleveland Bay Status report should be viewed as an evolving framework through which to encourage improved communications between research organisations, industry and government.

This chapter attempts to summarise the current state of research initiatives in Cleveland Bay and, to identify, based on available information, any potential gaps in the knowledge base. However, it should be recognised that the primary objective for future initiatives in this field should be the development of multi disciplinary communications amongst research organisations and individuals, industry and government.

In an effort to better facilitate achievement of objectives of the Cleveland Bay Consortium, this Chapter has been divided into two components. The first addresses management and administrative opportunities that exist to improve the interaction and communication between individuals and organisations. The second component addresses potential opportunities for future research. These opportunities have been identified on the basis of the contributions received and a basic working knowledge of the natural environment in Townsville and Cleveland Bay. Finally, a number of aims and objectives have been identified for the future direction of the

Cleveland Bay Consortium and its constituent individuals and organisations.

Management & Administration

One of the fundamental issues to emerge from the production of this report is the wealth of information that currently exists on isolated aspects of the Cleveland Bay environment. However, it has also been acknowledged by several of the contributing authors that existing data is often difficult to access in any useful means. Whilst access to information may be available through reference to published reports summarising the collected data, such reports are often limited in their scope and coverage of the wealth of information that has been considered and collected. It appears that whilst there is a lot of information in published form, a significant amount of information appears to be in what has been termed "grey literature" such as unpublished reports and articles. This has often lead to duplication of effort and the collection of data that may potentially add value to existing knowledge but that can not be used to its full potentially due to variations in methodology.

There is an urgent need to promote a more integrated and collaborative approach to the collection and dissemination of research and monitoring data if the conclusions and objectives outlined in this chapter are to be fully realised. Potentially, this may require the development of data management protocols and intellectual property rights agreements in an effort to promote data and resource sharing amongst individuals and funding organisations.

Overall it appears that there is a significant amount of research on various aspects of Cleveland Bay, there is a need to develop a more integrated and consistent approach to research and monitoring. There is a need to take advantage of the wealth of knowledge that already exists by building on existing research and adopting consistent methodologies in an effort to allow existing data to be used comparatively and in an ongoing manner. It is also necessary at this stage to emphasise the need for improved communications between researchers and funding organisations to minimise duplication of effort to ensure that future research adds value to the existing knowledge base by focusing on areas where further research is required.

Research

Whilst there is a wealth of information currently available on the natural environment of Cleveland Bay, the compilation of this report has allowed the identification of particular gaps in the existing knowledge base. This section of the report attempts to identify these knowledge gaps and identify future research opportunities.

One of the outstanding factors to emerge from the compilation of the Cleveland Bay Status Report is the need for improved integration of existing research initiatives and the standardisation of research methodologies. Whilst these issues have been addressed in the previous section, Data Management and Administration , it is important that the following issues be considered within this context.

There appears to be a wealth of information on specific aspects of the natural environment of Cleveland Bay, particularly in the field of pure research. However, there appears to be limited emphasis placed on the integration and practical application of such data for natural resource management. Generally, there appears to be a general lack of information in relation to specific areas along with a lack of integration of existing information, holistic interpretation and the compilation and understanding of the specific research projects.

On reviewing the existing information available, there seems to be a general lack of information in regard to general biological monitoring and particular biological thresholds. Based on this lack of information, there is a need to develop integrated, quantitative biological effect parameters. This is particularly important in light of the development of regionally relevant water quality criteria under the draft ANZACC water quality Guidelines.

Building on this lack of integration, the following research opportunities have been identified:

1. Isolation of natural and anthropogenic impacts

There appears to be further opportunities to differentiate between natural and anthropogenic effects of chemical contaminants in Cleveland Bay, for example:

- Critically evaluate human induced effects on ecology of Cleveland Bay.
- Improve understanding of the factors affecting behaviour of contaminants in Cleveland Bay.
- Consideration of the influence of variables on benthic fauna and fouling organisms. Do natural variation and physical disturbances or human induced contaminant concentrations drive these communities?
- Develop studies that may be used to improve the understanding of the source and sink and natural fluctuations of pollutant inputs to the environment.

2. Integration & standardisation of research data

- Establish reliable data sets on different sources of contaminants.
- Contaminant cycling and contaminant transport pathways (see page 85)
- Patterns and causes of trichodesmium blooms and the influence on fixation of chemical contaminants and the subsequent influence on fauna.
- Review of long term data sets related to metal concentrations.
- A study of the various types of sediment loads / metal/ nutrient concentrations in discharges to the Bay.
- Comprehensive sediment budget for Cleveland Bay.
- Impact of changing metal concentrations on biological diversity of Cleveland Bay.

- Current flux of sediment material into Cleveland Bay.
- Use of groundwater in the Townsville catchment area and effect of groundwater use on salinity.
- Improved understanding of water quality and ecotoxicological issues. Look at relations between anthropogenic sources of contaminants and improve understanding of source/sink pathways.

- Contaminant impacts on corals
- The information gaps identified in Chapter 7. ie

- Ecotoxicological studies that integrate physical, chemical and biological investigations, and that are directed towards developing meaningful local guidelines for pollutants (e.g. nutrients, sediment, metals, organics etc.);

- Quantitative flux measurements of sediments, nutrients and pollutants from local streams under 'first flush', highflow and ambient conditions;

- Groundwater quality – domestic use, salinisation and contamination; and

- Air quality monitoring in the Townsville region compliant with the National Environmental Protection Measure

The existing information indicates that comprehensive data is available on climatic conditions surrounding Townsville and Cleveland Bay area. However, it is implied that this data may be difficult to access in the necessary form in many circumstances. Tidal Currents appear well documented for Cleveland Bay. However, there seems to be a degree of uncertainty over sediment loads from the Burdekin particularly with respect to historical discrepancies in the available data and the interpretation of such data. Wave data appears to be well studied in terms of both actual and predicted. However, there is a need to look at dissemination and publication of data from the mangrove areas.

- Need further work on the closure of the Bay by the tombolo and connection of Cape Cleveland with mainland timing and process if this is not well understood.

Future Aims & Objectives

- Geographic information system showing monitoring sites, parameters considered and research and funding organisations involved (including contact details) along with any relevant published information.

- Increased voluntary contributions to existing databases, promote the concepts of information sharing and the benefits to be gained by industry, government, research bodies and the community.

- Need to identify at an early stage as a minimum what types of research are being undertaken, in an effort to promote co-ordinated and complimentary research without duplicating effort and resources.

- Use of existing data to develop management criteria for activities within the region.

Summary

- Need to address emerging issues, the CBC report will provide direction for future research.

- There is an urgent need for integration and collaboration which will result in the development of multi disciplinary studies that improve our understanding of the natural fluctuations in biological and physical parameters and the potential effects that the growth of Townsville may have on such interactions.

Closing comments

Different people, in different sectors of the community, place different values on aspects of the natural environment. Over time, these values will change with a changing society and our appreciation of the finiteness of natural resources. In this context it is important to realise that sustainable development is not a static concept, it is evolving across different sector and over time. The vision of sustainable development however, should not change – the values will just be redefined. In this context, it is important to recognise that this report and the concept of the Cleveland Bay Sustainability Cycle is a continuously evolving philosophy.

As discussed in the introductory chapter of this report, the journey of understanding of the natural envi ronment of Cleveland Bay has only just begun. This report represents one of the first tangible outcomes of improving our understanding and developing the Cleveland Bay Sustainability Cycle.

Considerable effort has been exerted both into discussions about, and in the development of, this Report. The community of Cleveland Bay must now work together to address the perceived needs and objectives identified by the Cleveland Bay Consortium and the suggestions of the contributing authors and participants of this report. The next step in this evolving process is to consider the recommendations, particularly those related to the administration and sharing of data, the need to coordinate and collaborate in research efforts and to work together to address these issues.

The level to which we can manage Cleveland Bay is directly proportional to our understanding of Cleveland Bay. The more we know, the better we can manage. The better we can manage, the more sustainable is our use.

Caryn Anderson and Mick Roche

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