GREAT BARRIER REEF
MARINE PARK AUTHORITY

RESEARCH PUBLICATION No. 55

Long-term Chlorophyll Monitoring in the Great Barrier Reef Lagoon: Status Report 1, 1993–1995

A D L Steven,
L Trott, F Pantus
and D Brooks

Reef

RESEARCH PUBLICATION No. 55

Long-term Chlorophyll Monitoring in the Great Barrier Reef Lagoon: Status Report 1, 1993–1995

A D L Steven, F Pantus, D Brooks
Great Barrier Reef Marine Park Authority

L Trott
Australian Institute of Marine Science

A REPORT TO THE GREAT BARRIER REEF MARINE PARK AUTHORITY

ISSN 1037-1508
ISBN 0 642 23056 0

Published October 1998
by the Great Barrier Reef Marine Park Authority

The opinions expressed in this document are not necessarily those of the Great Barrier Reef Marine Park Authority.

National Library of Australia Cataloguing-in-Publication data:

Long-term chlorophyll monitoring in the Great Barrier Reef Lagoon : status report 1, 1993-1995.

Bibliography.
ISBN 0 642 23056 0.

1. Chlorophyll - Queensland - Great Barrier Reef - Analysis. 2. Water - Sampling - Queensland - Great Barrier Reef. 3. Environmental monitoring - Queensland - Great Barrier Reef. I. Steven, A. D. L. (Andrew David Leslie), 1962- . II. Great Barrier Reef Marine Park Authority (Australia). (Series : Research publication (Great Barrier Reef Marine Park Authority (Australia)) ; no. 55).

363.73940943

GREAT BARRIER REEF
MARINE PARK AUTHORITY

PO Box 1379
Townsville Qld 4810
Telephone (07) 4750 0700

CONTENTS

SUMMARY

In 1992 the Great Barrier Reef Marine Park Authority initiated the Great Barrier Reef Nutrient Status Monitoring Network (hereafter the Network). The broad objectives of the Network are to document the nutrient status of regional waters within the Great Barrier Reef lagoon using chlorophyll *a* concentration as a proxy nutrient bioindicator. Chlorophyll *a* is used in preference to routine nutrient analysis because (a) chlorophyll *a* integrates change in nutrient availability over time; (b) samples are comparatively simple to collect; and (c) chlorophyll *a* is comparatively inexpensive to analyse. The Network was conceived to be ongoing, and to complement and collaborate with a number of other existing monitoring programs to ensure comprehensive reporting of the status of the Great Barrier Reef (GBR).

The purpose of this status report is twofold: (1) to detail the objectives, the design and sampling protocols of the Network, and (2) to describe the results from the first three and one-half years of data collection, and identify the major spatial and temporal trends in chlorophyll *a* concentrations. The report is descriptive, but provides a basis for further analysis of the data and reconsideration of the efficacy of the current Network design.

The Network initially commenced in late 1992 with five regional (quasi-latitudinal) clusters: Lizard Island (14°S), Port Douglas (15°S), Cairns (16°S), Keppel Bay and Capricorn (23°S). Monitoring of further clusters of stations commenced off Townsville (18°S) in 1995, and off the Whitsundays (21°S) and in the Far Northern Section (13°S) in 1996. These clusters are not interconnected, nor spatially representative; some extend from close to the coast to the shelf-break, while others are confined to either inshore (< 20 km from the coast) or offshore waters. The choice of clusters was primarily dictated by the availability of personnel who were contracted to undertake routine, long-term sampling.

Within each cluster, five to eight GPS fixed stations are sampled at approximately monthly intervals. Two water samples are collected from near-surface waters for chlorophyll *a* determination. Concurrent near-bottom samples were also collected until mid-1994, but discontinued on the basis of initial data analysis and increased operating costs. At each station, temperature, salinity and Secchi depth measurements are made and weather conditions noted.

The results presented in this report cover the period January 1993 to July 1996, except for the Townsville cluster. To identify cross-shelf patterns, stations were nominally divided into inshore and offshore groups. Chlorophyll *a* concentrations at inshore stations were ~twofold higher than offshore, but also much more variable. Inshore, median chlorophyll *a* concentrations in Keppel Bay and off Townsville were greater than 0.5 $\mu g\ L^{-1}$ and often exceeded 1 $\mu g\ L^{-1}$ at stations within 2 km off the coast. Offshore, median chlorophyll *a* concentrations varied between 0.17 $\mu g\ L^{-1}$ at Cairns and 0.36 $\mu g\ L^{-1}$ in the Capricorn cluster.

Chlorophyll *a* concentrations, averaged over all stations within a cluster, were greatest in Keppel Bay (0.76 $\mu g\ L^{-1}$) and the Capricorn (0.62 $\mu g\ L^{-1}$) clusters. High chlorophyll *a* concentrations were very patchy even between replicate samples; they probably result from *Trichodesmium* aggregations which were present in over 30% of observations. In all other clusters, mean chlorophyll *a* concentrations were 0.26–0.42 $\mu g\ L^{-1}$, and *Trichodesmium* was observed in less than 8% of sampling events. Why these blooms are more frequent in southern GBR lagoon waters is unknown. Given the paucity of oceanographic data in this region, this finding is significant.

Chlorophyll *a* concentrations were generally greater in summer (October–April inclusive) than winter (May–September). Seasonal differences were discernible at offshore stations, but were obscured by high temporal variability inshore. Chlorophyll *a* concentrations in the Lizard, Port Douglas, Cairns and Capricorn clusters were greatest in 1993 and decreased in the following two years. In contrast, chlorophyll *a* concentrations in the Keppel Bay cluster were greatest in 1995. Preliminary trend analyses found no significant changes in mean chlorophyll *a* concentration for any cluster. Consistent with the observed interannual patterns described above, a negative slope estimate at offshore stations indicated a decline in chlorophyll *a* concentration from 1993 to 1995. A drought persisted through 1991–95 and regional run-off was considerably below the long-term average. This may have contributed to the

observed temporal trends. However, it must be noted that several more years of data will need to be collected before trends can be reliably estimated.

Lack of reliable hydrographic instrumentation and regular calibration prevented examination of the relationship of these observed spatial and temporal patterns in chlorophyll *a* concentration with temperature and salinity changes. Generally, short-term phytoplankton blooms rapidly followed changes in salinity resulting either from rainfall or riverine discharge, or from intrusions of upwelled water masses. No significant relationship between chlorophyll *a* concentration and Secchi depth was identified in any cluster.

In summary, the routine collection of chlorophyll *a* data over such a large and important geographic area is an invaluable dataset. The data collected in the first three and one-half years demonstrate persistent cross-shelf and regional differences in chlorophyll concentration. Seasonal and interannual trends are generally consistent between regions. The nutrient status of GBR waters cannot, however, be inferred from these data, as clusters are not explicitly linked to regional nutrient input data. The spatial and temporal patterns identified do, however, provide a basis for redesign of the Network and reallocation of sampling effort. This is essential if the Network is to infer long-term changes in the nutrient status of the GBR lagoon. Specific recommendations include:

- Clear, explicit objectives are needed before any redesign takes place. These should include both broad strategic objectives for the maintenance of 'water quality' within the GBR lagoon, as well as specific technical objectives for the measurement of chlorophyll and inference of nutrient status.
- Explicit links to putative nutrient sources should be made. Monitoring stations should be linked to other ongoing catchment and river monitoring (e.g. Queensland Department of Environment and Heritage, Queensland Department of Natural Resources, Australian Institute of Marine Science).
- Techniques linking chlorophyll *a* concentrations to nutrient status have not been defined. This has been a major hindrance to the interpretation of the data. Technical expertise should be sought in developing these relationships and models.
- Other bioindicator techniques such as primary productivity estimates should be considered as part of the Network. These measurements could be carried out most routinely by research station staff.
- Size fractionation of samples into picoplankton (< 2 μm) and phytoplankton (> 2 μm) would provide greater inference as to which species respond most readily to changes in nutrient availability.
- Remote sensing has the capacity to greatly extend the inferences made about spatial dynamics of regional chlorophyll *a* patterns. Both SEAWIFS and AIDOS will provide high-frequency coverage of the GBR region. The integration of this technology into the Network is recommended.
- Several specific changes to the clusters are recommended: (1) within the Lizard cluster, additional stations closer to the coast and to the shelf-break are needed; (2) Keppel Bay and Capricorn clusters should be linked with fewer stations concentrated around Keppel Bay and more between Keppel Bay and the Capricorn stations; and (3) initiation of a sampling cluster adjacent to the Johnstone and Russell–Mulgrave rivers should be considered. Intensive agriculture occurs on these catchments which are also the focus for a number of pilot land-use and run-off studies.

A number of operational protocols need to be improved to ensure the integrity of the data collected and the continued participation of stakeholders. Specifically:

- All clusters need to be provided with reliable equipment for the routine measurement of temperature and salinity. Regular recalibration is essential to ensure data integrity.
- Samples should be transferred by collectors to AIMS for analysis more frequently. Samples should not be left any longer than one to two months before transfer.
- Although publication of data and reports on the World Wide Web may be desirable, more rigorous quality assurance procedures need to be developed beforehand to ensure the integrity of the data; in particular the temperature and salinity data collected to date.
- Future results need to be more readily available. Annual summaries of spatial and temporal patterns and quinnenium status reporting are recommended.

1. INTRODUCTION

1.1 PROGRAM OVERVIEW

In 1992 the Great Barrier Reef Marine Park Authority (GBRMPA) initiated a water quality monitoring program for the Great Barrier Reef – the Great Barrier Reef Nutrient Status Monitoring Network. The broad objectives of the Network are to document the nutrient status of regional waters within the Great Barrier Reef (GBR) lagoon, and in the long-term, identify any significant trends which may result from adjacent land-use patterns. Chlorophyll *a* concentration was chosen as a proxy nutrient bioindicator because it integrates change in nutrient availability through time and is comparatively inexpensive and simple to collect. It was recognised that several years of data would need to be gathered before any long-term trends could be reliably distinguished. The Network was conceived to ideally expand as resources became available, and priority coastal areas are identified. It was to complement and collaborate with a number of other existing monitoring programs to ensure comprehensive status reporting of the GBR.

The Network initially commenced with five clusters: Lizard Island (14°S), Port Douglas (15°S), Cairns (16°S), Keppel Bay and Capricorn (23°S). Additional clusters of stations commenced off Townsville (18°S) in 1995, and off the Whitsundays (21°S) and in the Far Northern Section (13°S) in 1996. The choice of stations was primarily dictated by the availability of personnel who could be contracted to undertake routine, long-term sampling in a reliable cost-effective manner. Within each cluster, between five and eight fixed sampling stations are sampled at approximately monthly intervals. Table 1.1 summarises the overall design of the program.

Table 1.1 Summary of the Great Barrier Reef Nutrient Status Monitoring Network objectives and framework

Management Goal:	Status and trend detection of changes in nutrient status of Great Barrier Reef lagoon waters
Objectives:	To quantify regional and cross-shelf patterns of phytoplankton biomass (as chlorophyll *a*) and relate these to nutrient input and availability; and to examine temporal variability in phytoplankton biomass which may reflect changing episodic nutrient inputs to Great Barrier Reef shelf waters.
Environmental context:	Regionally and temporally heterogenous water mass affected by a variety of nutrient inputs and changing land-use patterns
Nutrient Indicator:	Chlorophyll *a* as an integrator of nutrient inputs and availability
Spatial scale:	Regional network. Initially, five latitudinal clusters (14–23°S) with a total of 41 fixed sampling stations
Temporal scale:	Monthly, ongoing
Participants:	Great Barrier Reef Marine Park Authority, Australian Institute of Marine Science, Queensland Department of Environment and Heritage, Lizard Island and Heron Island Research Stations, Reef Biosearch Pty Ltd

1.2 REPORT SCOPE

As this is the first report of the Network, its purpose is twofold: (1) to detail the existing monitoring program design, and (2) to summarise the results for the first three and one-half years of sampling (1993–1996). Accordingly, the report is presented in two parts. In Part 1, the logic and design of the Network are detailed. Sampling protocols, data handling and interpretation are documented. Part 2 describes the hydrographic conditions and chlorophyll *a* concentrations from 1993 to 1996 in the Lizard Island, Port Douglas, Cairns, Townsville, Keppel Bay and Capricorn clusters. Spatial and temporal trends in chlorophyll *a* concentration are summarised. The analysis is necessarily descriptive, and does not attempt to infer nutrient status of the GBR. These results do, however, provide a basis for consideration of the efficacy of the current experimental design.

PART 1

DESIGN CRITERIA AND SAMPLING PROTOCOLS

FOR THE

GREAT BARRIER REEF NUTRIENT STATUS

MONITORING NETWORK

Part 1 of the report summarises the rationale, design and sampling protocols of the Network. Chapter 2 (Network Definition) considers the management concerns for the potential of land-based sources to effect nearshore waters of the Great Barrier Reef. It describes the experimental and operational criteria which underpin the design of the Network. The choice of chlorophyll *a* as an integrative nutrient bioindicator and the expected responses to changing patterns of nutrient input are discussed. Chapter 3 (Network Design) details the Network design: objectives; roles and responsibilities; sampling frequency; sampling locations. It discusses the limitations of the existing design and collaboration with other concurrent monitoring programs. Sample collection and data handling protocols are detailed in Chapter 4 (Sampling and Data Protocols).

---

2. NETWORK DEFINITION

Maintenance of water quality is now one of the most critical goals challenging long-term management of the Great Barrier Reef Marine Park (GBRMP). The principal concern is the potentially negative effects of land-based sources of pollution on adjacent coastal mangrove, seagrass and coral reef communities. Increased loads of sediment and nutrient resulting from inappropriate or poorly managed land-use activities have the greatest potential to invoke regional degradation of these coastal ecosystems. Other persistent contaminants such as agricultural pesticides and herbicides, heavy metals, hydrocarbons and litter are of local concern.

The increased supply to coastal waters of the essential nutrients nitrogen and phosphorus is perhaps the most insidious and controversial of these pollutants. There is widespread community and scientific concern that rapid development of the adjacent Queensland coast has substantially increased land-based nutrient inputs to near-shore waters. Biological demand for nitrogen and phosphorus by autotrophic communities is high, ensuring water column concentrations remain low (oligotrophic). Increases in nitrogen and phosphorus availability, either through 'new' inputs of nutrients or recycling, stimulate the primary productivity of benthic and nektonic communities. Sustained increased organic production resulting from enhanced nutrient supply is known as eutrophication. One of the first signs of the onset of eutrophication is an increase in the biomass of phytoplankton which are better able to assimilate higher loadings of nutrient than benthic primary producers. If increased water column production persists it can compromise the functioning of underlying benthic autotrophic communities by attenuating light levels and favouring the dominance of filter-feeding species.

Thus the reasons for maintaining or improving existing water quality of the Great Barrier Reef (GBR) water include:

- maintaining water clarity for the functioning of phototrophic communities such as seagrasses and corals;
- limiting the potential for overgrowth of corals by macroalgae and filter-feeders;
- preventing excessive sedimentation which can smother benthic fauna incapable of removing unwanted particulate matter;
- ensuring healthy functioning fisheries which can otherwise be deleteriously affected by changes in primary production; and
- maintaining visual amenity, essential for the tourist industry.

In 1992 the Great Barrier Reef Marine Park Authority (GBRMPA) initiated, with federal appropriations, a reef-wide 'nutrient status' monitoring program. Regular reporting on the nutrient status of the GBR was seen as an essential component in formulating environmental management strategies. As planktonic communities respond quickly to nutrient availability, they were considered a sentinel indicator of nutrient status. Such a program was consistent with recommendations by 'The Coastal Zone Inquiry' (Resource Assessment Commission 1994), and 'The Marine Environment Conference' (Johnson and Neil 1996) which called for the establishment of a national coordinated system of monitoring programs for the Australian marine environment. The following three sections (2.1–2.3) examine the rationale and conceptual criteria for the design of such a monitoring program.

2.1 RATIONALE: IS THE GREAT BARRIER REEF AT RISK?

In assessing the risk of land-based sources of marine pollution to the integrity of the GBR, one must carefully consider the scale of the perceived problem in relation to commercial, cultural and recreational interests within and adjacent to the GBR. The Great Barrier Reef Marine Park Authority's approach to the issue of land-based pollution is precautionary. It is based upon: (1) its national and international responsibilities; (2) the great uncertainty regarding the GBR's resilience to continued anthropogenic inputs and demand for extractive resources; (3) this century's unprecedented change in land use of the adjacent catchment and the expected strong population growth into the new millennium; and (4) the known risks of eutrophication in other areas of the world. These issues are discussed below.

2.1.1 Responsibilities, agreements and costs

The natural beauty and rich biological diversity of the GBR is the basis for the proclamation of the Marine Park in 1975 and its inscription as a World Heritage Area in 1981. The Marine Park Authority is responsible for ensuring the GBR is afforded the best possible protection while allowing fair and reasonable use of this resource (Section 7 of the *Great Barrier Reef Marine Park Act 1975*). The minimisation of land-based sources of nutrients and sediments entering the Marine Park is one of three guiding outcomes for the Marine Park Authority's Corporate Plan (1994a) and the 25-year Strategic Plan for the Great Barrier Reef World Heritage Area (1994b).

While the *Great Barrier Reef Marine Park Act 1975* provides the GBRMP with the greatest degree of protection of any marine ecosystem in Australia, it cannot deal effectively with trans-boundary land-based pollution. Other instruments to achieving this goal include (1) collaboration with other agencies to manage across jurisdictional boundaries; (2) active extension and liaison with agricultural communities ranging from grass roots to peak bodies; and (3) endorsement of 'best available' technologies that lead to nutrient and soil loss reduction. At the same time the Authority, recognising the importance of understanding the processes controlling the loss, transport, fate and recycling of nutrients, has invested in targeted research and monitoring as a basis for improved decision making.

Australia is a signatory of the United Nations Convention on Law of the Sea (UNCLOS) and the Global Program of Action for the Protection of the Marine Environment from Land-based Activities (GPOA) which commits members to take actions to prevent, control and reduce degradation of the marine environment.

The GBR provides an estimated $1 billion in annual revenue to a diverse range of industries including fishing, tourism, shipping and research (Driml 1994). Any decline in the 'health' of the GBR could have serious repercussions for these industries. From overseas examples it is well known that the costs of remediation of marine areas can far outweigh the costs of mitigation. Plans to reduce nutrient loads from the top 100 'hot spots' in the Baltic will cost an estimated ECU$15 billion. In Australia, an estimated Aus$60 million is spent annually on remediating eutrophic areas (Brodie 1996). Apart from the potential impact on the marine environment, sediment and nutrient loss constitutes a significant economic cost to the agricultural community.

2.1.2 Scientific uncertainty

The processes governing the GBR's capacity to continue assimilating increased loads of terrestrially derived nutrient and sediment are poorly understood. Much of the evidence for eutrophication is speculative, and the correlation between nutrient input and the impact is not easily defensible – or disproved. Environmental factors operating at a variety of spatial and temporal scales, confound our ability to discriminate and set limits of acceptable change. Clear definitions of what constitutes a 'healthy' ecosystem, and what is considered 'good water quality' are lacking – and perhaps unrealistic.

In a series of publications, Bell and others (Bell 1992; Gabric and Bell 1993; Bell and Elmetri 1995) have advocated that the GBR is on the verge of widespread eutrophication. This conclusion is based on their studies at Low Isles which use the data from the 1928 British Royal Expedition (Marshall 1933) as a baseline. Significant increases in phytoplankton concentration, changes in phytoplankton class structure, and loss of hard corals on reef flats are claimed to be indicative of anthropogenic eutrophication, the most likely cause of which is run-off from agricultural development (Bell and Elmetri 1995). Others have taken the stand-point that there is as yet no evidence for regional eutrophication. Summarising a dataset of hydrographic conditions throughout the GBR spanning the last fifteen years, Furnas and Brodie (1996) concluded that dissolved and particulate nutrient concentrations are in general low and there is no evidence of regional eutrophication. Similarly, analysis of a 20-year dataset of chlorophyll *a* concentrations in the central GBR by Brodie et al. (1997) concluded there was no indication of any long-term increase in phytoplankton biomass.

This divergence of opinion reflects in part the fact that comprehensive research has only been undertaken on the GBR in the last 20 or so years. However, even in well-studied ecosystems, scientific consensus on the historical trends and causes of water quality degradation has been difficult to achieve. For example: Chesapeake Bay (D'Elia et al. 1992); Florida Bay (Lapointe and Clark 1992; Lapointe et al. 1994; Szmant and Forrester 1996); and the North Sea (Josefson 1990; Gray 1990).

Equally disparate are the views taken over the role science should play in marine resource management and protection (Gray 1990, 1996; Gray et al. 1991; Stebbing 1992; Peterman and M'Gonigle 1992; Buhl-Mortensen 1996). While most scientists maintain that science needs to remain objective, few would advocate that management should wait until further studies confirm with 'scientific certainty' that a 'problem' exists.

2.1.3 The known risks: Eutrophic case studies

The growing number of enclosed or semi-enclosed coastal waters throughout the world that have become 'culturally' eutrophic in recent decades are testimony to the risks of unmitigated terrestrial run-off (table 2.1). They provide clear examples of the types of impacts, and the costs of remediation. Perhaps the most obvious lesson learned from many of these studies is that little indication of change in nutrient status was detected before the rapid collapse of the ecosystem.

Table 2.1 Effects of cultural eutrophication on benthic and nektonic communities in large coastal seas

	Area 10^3 km^2	Nutrient load* g m^{-2} yr^{-1} N	P	Putative marine impacts
Europe				
Northern Adriatic	19.0	70.0	7.8	noxious algal blooms (Degobbis 1989); benthic anoxia and mortality (Justic 1987)
Baltic	373.0	4.3	0.3	increased benthic biomass (Josefson 1990); anoxia (Koop et al. 1990); decreased DIN:DSi (Rahm et al. 1996)
North Sea	575.0	4.2	0.9	increase in phytoplankton biomass and composition, (Cadee 1986; Zevenboom et al. 1991); toxic algal blooms (Underdal et al. 1989)
Black Sea	420.0	–	–	blooms of introduced phytoplankton and algae species anoxia; loss of fisheries (Mee 1992)
Asia				
Seto Inland Sea	2.3	8.2	0.8	red tides, loss of fisheries (Goda 1992, Nakanishi et al. 1992);
Hong Kong		–	–	loss of benthic fauna (Morton 1985)
America				
New York Bight		–	–	increase in phytoplankton biomass, benthic anoxia and fisheries collapse (Stoddard et al. 1986)
Chesapeake Bay	6.5	–	–	3–5 fold increase in phytoplankton abundance over 40 years (Harding 1994); loss of fisheries and benthic fauna and anoxia
Florida Bay and Keys		–	–	loss of coral, seagrass, mangroves and sponges, fish and shrimp catch (Lapointe and Clark 1992)

* Vollenweider 1992

The only regions comparable in size to the GBR (344 000 km^2) are temperate – the North Sea (575 000 km^2) and the adjoining Baltic (373 000 km^2). Increases in phytoplankton biomass (Cadee 1986; Zevenboom et al. 1991), changes in class structure and blooms of noxious algae (Underdal et al. 1989) are some of the first documented signs of the onset of eutrophic conditions. In Chesapeake Bay, synthesis of a 40-year dataset of phytoplankton abundance demonstrated significant long-term increases in surface chlorophyll *a* concentrations of up to 500%. Nutrient concentrations and ratios changed significantly from the 1960s as DIN concentrations ~doubled and orthophosphate concentrations declined (Harding 1994). Similarly, synthesis of a range of monitoring programs off the coast of New

Jersey from 1948 to the present concluded that increased anthropogenic nitrogen loading had resulted in an increase in annual phytoplankton production of ~ 30% (Stoddard et al. 1986).

Secondary effects, resulting from increased production include increases in benthic biomass, particularly of large macrophytes and filter feeding organisms. Chronic eutrophication can result in benthic anoxia (Justic 1987; Koop et al. 1990) and fisheries collapse (Lee and Jones 1991).

In tropical waters, small island nations with confined coastal embayments or lagoons are the most susceptible to increased nutrient and sediment loads. Examples include: the Caribbean (Barbados, Tomascik and Sander 1985; Belize, Lapointe et al. 1992; Bermuda, Lapointe and O'Connell 1989; Jamaica, Lapointe 1997), Florida Keys (Lapointe and Clarke 1992; Lapointe and Matzie 1996; Lapointe et al. 1994; 1997), Pacific Ocean (Kaneohe Bay Hawaii, Smith et al. 1981; Jakarta Bay, Tomascik et al. 1994) and the Indian Ocean (Le Reunion, Montaggionni et al. 1994, Naim 1993; Seychelles, Littler et al. 1991). There is some evidence that nutrients can directly impinge on coral growth (e.g. Kinsey and Davies 1979; Tomascik and Sander 1985, 1987a) and reproduction (e.g. Tomascik and Sander 1987b; Tomascik 1991; Ward and Harrison 1997), but more commonly reefs are overgrown by filamentous and macro-algae and filter-feeders, leading to profound changes in the community structure and functioning of reefs (e.g. Smith et al. 1981; Kinsey 1988).

2.1.4 Historical and future changes in adjacent land use

A number of studies provide evidence that present levels of nutrients and sediments entering the GBR lagoon are cause for concern (e.g. Gourlay and Hacker 1986; Valentine 1988; Moss et al. 1992; Neil and Yu 1995). The desktop study of Moss et al. (1992) estimated that in 1990, 15 million tonnes of sediment, 77 thousand tonnes of nitrogen and 11 thousand tonnes of phosphorus were exported to coastal Queensland waters via river discharge. Present levels of nutrient and sediment discharge were estimated to be three to five times greater than prior to European settlement – the last 130 years. Much of the increase occurred in the last 40 years, when extensive deforestation of coastal catchments occurred and fertiliser use increased dramatically (figure 2.1). Fertiliser use has declined since the early 1990s, but significant areas of the coast are still being cleared for crops, particularly sugar cane (Pulsford 1993).

Strong population growth and development is expected to continue along the adjacent north-east Queensland coast. By 2006, it is estimated Townsville, Cairns, the Whitsundays and Hervey Bay populations will have increased by more than 140% from 1986 census figures (Tarte et al. 1996).

2.2 ENVIRONMENTAL CONTEXT: THE GREAT BARRIER REEF REGION

No single location typifies the GBR as a whole. Rather, nutrient status must be assessed and monitored on a variety of scales. The following section overviews some of the spatial and temporal characteristics of the GBR. Recognition of this variability is essential, both in selecting sites for monitoring, and determining the frequency at which samples are collected. If not taken into account, these scaling effects can bias or confound the interpretation of data.

2.2.1 Spatial diversity

The 344 000 km^2 of the GBRMP extends 2000 km from Lady Elliot Island (24°30′S) to the tip of Cape York Peninsula (10°41′S). The Park encompasses some 2900 catalogued reefs most of which lie on the outer continental shelf (Hopley et al. 1989). Significant latitudinal variation in reef type and the degree of regional aggregation of reefs occurs.

Between the reef matrix and the coastline lies a contiguous north–south body of open water commonly referred to as the GBR lagoon. The width of this open water increases from 18 km near Cape Tribulation (16°S) to 150 km at the entrance to Capricorn Passage (23°S). The lagoon has an estimated area of 128 530 km^2, or 36% of the Marine Park. It contains approximately 758 fringing reefs, many incipient reefs around high islands, and extensive seagrass beds (Poiner and Peterken 1995). Mangrove forests along the coast provide an important buffer to adjacent seagrass beds and coral reefs by trapping sediment, nutrients and other chemical contaminants.

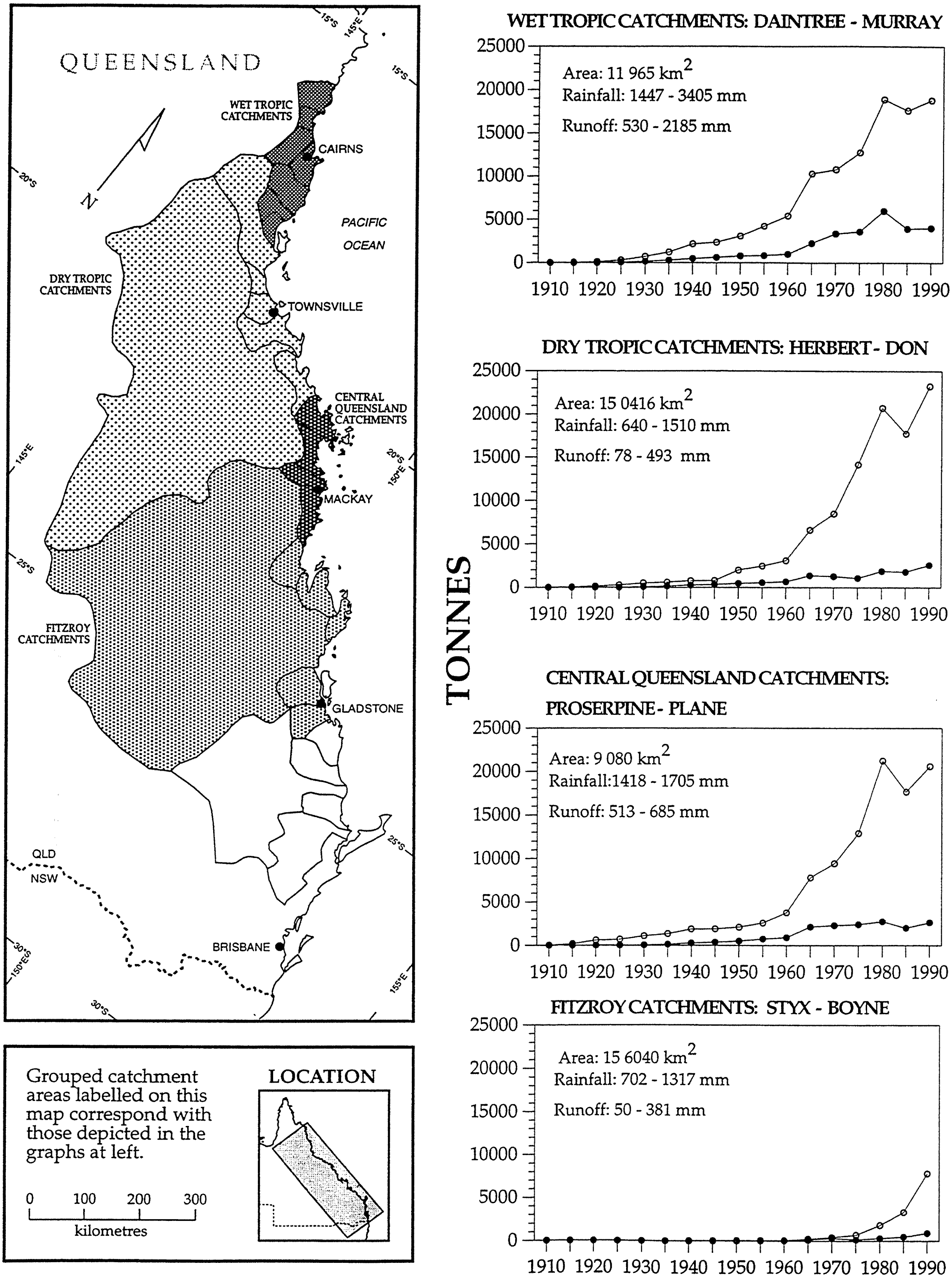

Figure 2.1 Application rates of nitrogenous and phosphatic fertiliser to catchments adjacent to the Great Barrier Reef from 1910–1990

Cross-shelf gradients in population structure and abundance have been defined for hard (Done 1982) and soft (Dinesen 1983) corals, sponges (Wilkinson and Cheshire 1989), infauna (Alongi 1989) and fish (Williams 1982). These population gradients relate in part to cross-shelf changes in water quality visibility and nutritional status (e.g. Wilkinson and Cheshire 1988). Whereas oceanic influences predominate at the shelf-break, terrestrial processes result in turbid inshore waters.

Studies of the cross-shelf distribution of terrestrially derived sediments (Belperio 1983; Alongi 1989; Gagan et al. 1990; Pailles et al. 1993), stable isotopes (Gagan et al. 1987; Risk et al. 1994) and other chemical markers (Currie and Johns 1989) indicate that sediments and other particulate material derived from the land are retained in a narrow (10–15 km) coastal band. Hydrodynamic studies confirm that nearshore waters are at least episodically constrained in a coastal boundary layer by a dynamic front that results from surface coastal waters running counter to the geostrophic flow of the East Australian Current (King and Wolanski 1991). Water exchange with offshore water masses is limited, except in regions where the main reef matrix lies close to the coast, or during exceptionally large river discharge events (e.g. Wolanski and van Senden 1983) or during cyclonic resuspension events (Gagan et al. 1990).

Regional differences in water quality have been identified (e.g. Furnas and Brodie 1996) and persist because of the diverse geographic structure of the reef and the multiplicity of marine, atmospheric and terrestrial nutrient sources (table 2.2).

Table 2.2 Annual mean (± S.E.) salinity and concentrations of nutrients, chlorophyll and suspended solids sampled between 1979 and 1994, and grouped by region and shelf position. Inner refers to coastal waters < 20 m depth and outer > 20 m depth. Data modified from Furnas and Brodie (1996).

		Cooktown	Cairns	Innisfail	Townsville
Salinity	Inner	33.55 ± 0.56	34.38 ± 0.11	33.57 ± 0.32	34.96 ± 0.49
(‰)	Outer	34.83 ± 0.76	34.71 ± 0.06	34.81 ± 0.12	35.2 ± 0.03
NH_4-N	Inner		0.02 ± 0.01	0.15 ± 0.03	
(μM)	Outer	0.02 ± < 0.005	0.05 ± 0.01	0.07 ± 0.01	0.17 ± 0.01
NO_2-N	Inner	0.04 ± 0.01	0.01 ± < 0.005	0.03 ± 0.01	0.02 ± 0.01
(μM)	Outer	< 0.005 ±	0.01 ± < 0.005	0.02 ± < 0.005	0.02 ± < 0.005
NO_3-N	Inner	0.04 ± 0.01	0.03 ± < 0.005	0.23 ± 0.11	0.03 ± 0.01
(μM)	Outer	0.03 ± 0.01	0.07 ± 0.01	0.06 ± 0.01	0.09 ± 0.02
DON-N	Inner	4.8 ± 0.4	5.7 ± 0.2	6.1 ± 0.5	7 ± 1.3
(μM)	Outer	4.4 ± 0.4	5.5 ± 0.1	5.5 ± 0.4	6.3 ± 0.3
PN-N	Inner	1.7 ± 0.5	1.3 ± 0.1	1.8 ± 0.1	2 ± 0.1
(μM)	Outer	1.1 ±	1 ± < 0.05	1.2 ± 0.1	1.3 ± 0.1
PO_4-P	Inner	0.09 ± 0.02	0.08 ± 0.01	0.11 ± 0.01	0.15 ± 0.04
(μM)	Outer	0.06 ± 0	0.02 ± < 0.005	0.12 ± 0.01	0.14 ± 0.01
DOP-P	Inner	0.08 ± 0.02	0.11 ± 0.01	0.22 ± 0.03	0.12 ± 0.03
(μM)	Outer	0.1 ± 0.04	0.08 ± 0.01	0.32 ± 0.04	0.12 ± 0.02
PP-P	Inner	0.1 ± 0.01	0.12 ± 0.01	0.14 ± 0.02	0.11 ± 0.02
(μM)	Outer	0.1 ± 0.02	0.7 ± < 0.005	0.08 ± 0	0.06 ± 0.01
$Si(OH)_4$	Inner	11.5 ± 1.2	6.2 ± 0.3	10.5 ± 2	6.5 ± 1.4
(μM)	Outer	11.2 ± 0.6	3.1 ± 0.2	2.5 ± 0.4	2.2 ± 0.2
Chl *a*	Inner	0.38 ± 0.05	0.48 ± 0.02	0.48 ± 0.06	0.4 ± 0.09
(μg L^{-1})	Outer	0.3 ± 0.02	0.36 ± 0.01	0.34 ± 0.03	0.39 ± 0.02
Susp. Solids	Inner	1.6 ± 0.2	2.0 ± 0.1		3.4 ± 2.4
(mg L^{-1})	Outer	0.8 ± 0.3	0.6 ± 0.1	0.7 ± 0.1	0.5 ± < 0.05

Inshore GBR waters are influenced by freshwater inputs from two large, fifteen medium, and numerous small rivers, draining the adjacent North East Coast Drainage division. The 31 river basins abutting the coast have an aggregate area of 424 000 km^2 – some 21% larger than the Marine Park itself. The long-term average discharge from all basins is close to 40 km^3 of freshwater per year. Topography and rainfall vary considerably between catchments (table 3.2). Consequently the degree of rainfall running off catchments varies from 7% in the Fitzroy basin to 74% in the Tully basin. Despite low run-off rates the Fitzroy and the Burdekin catchments account for 37% of this discharge because of their greater catchment size.

Rainfall and topography are also primary factors dictating land use, crop selection and fertiliser applications rates in catchments (Pulsford 1993). Extensive areas of the wetter sections of the coastal plain are planted with sugar cane and horticultural crops. Grazing, is the primary land use on drier catchments and accounts for ~76% of the total drainage area adjacent to the GBR (Moss et al. 1992). While cultivation of wet climate crops such as sugar cane has the potential to cause high area-specific rates of sediment and nutrient run-off (Arakel et al. 1989), the greatest losses result from grazing activities, due to the large areas involved (Moss et al. 1992).

A number of cities line the coast adjacent to southern and central parts of the GBR. Six have populations in excess of 50 000, and most of the remainder have populations above 10 000. The predominant standard of sewage treatment is secondary and disposal is via discharge, either into the lower reaches of a river, or directly to the sea (Brodie 1995).

2.2.2 Temporal variation

Weather is the predominant factor influencing oceanographic processes of the GBR. Water temperature has a well-defined seasonal cycle, which although small in range (~18–30°C) is a primary factor influencing all processes related to nutrient cycling and biological productivity.

Outer-shelf waters are episodically influenced by upwelling of nutrient rich, Coral Sea thermocline waters which intrude over extended areas through the shelf matrix (Andrews and Gentien 1982; Furnas and Mitchell 1986, 1996; Liston et al. 1992). Upwelled waters are an important input to the nutrient budget of the central GBR (16–19°S) providing 24% of gross nitrogen and 71% of estimated gross phosphorus imports (Furnas and Mitchell 1996). The contribution of upwelled nutrients to the northern and southern sections of the GBR has not been quantified.

Riverine discharge is seasonal and highly episodic, with largest flows following summer monsoonal rain depressions (Lough 1993). In the larger dry catchments such as the Burdekin and Fitzroy rivers, several years may pass between major flows. In contrast the 'wet tropics' rivers display a more even year-to-year discharge pattern. As the largest proportion of the annual discharge of sediments and nutrients from rivers into the GBR occurs during large floods, it is important to understand if, and how, extreme water quality conditions associated with floods, influence reefs in the GBR. Large rivers swollen by monsoonal rain can sometimes push sediment and nutrient laden freshwater plumes out to the middle and outer-shelf (e.g. Wolanski and van Senden 1983; Wolanski et al. 1984; Preker 1992) impinging on underlying seagrass (e.g. Preen et al. 1995) and coral reef communities (e.g. van Woesik et al. 1995; DeVantier et al. 1996).

Tropical cyclones episodically pass through the central and southern GBR, inducing dramatic regional-scale changes in water quality by resuspending sediments and releasing trapped nutrients and organic matter (Furnas 1989; Gagan et al. 1990). Following cyclones, dissolved nutrient and phytoplankton concentrations in lagoon waters can be several times those of ambient conditions.

Rainfall, river run-off, shelf-break upwelling and cyclonic activity can all vary significantly between consecutive years and over decadal time-scales (Lough 1993). These are most commonly the result of global scale El Niño Southern Oscillation (ENSO) events. An El Niño induced drought persisted through the 1991–94 period and regional run-off was considerably below the long-term average (Furnas and Brodie 1996).

Significant short-term variability in nutrient concentrations and plankton biomass has been documented over hourly to weekly time-scales (Andrews and Muller 1983; Crossland and Barnes 1983; Walker and O'Donnell 1981; Andrews and Gentien 1982; Revelante and Gilmartin 1982; Furnas and Mitchell 1986; Steven et al. 1992; Liston 1990; Ayukai 1993).

2.3 MONITORING NUTRIENT STATUS IN THE GREAT BARRIER REEF LAGOON: CONCEPTUAL CRITERIA

2.3.1 Operational and statistical criteria

The following criteria were considered essential for a long-term monitoring program of nutrient status:

- *Focused*: to adequately sample and accurately measure key parameters which are representative indicators of regional water quality status;

- *Sensitive*: to changes in regional water quality while the processes causing change are still small and hopefully reversible;
- *Robust*: to discriminate between changes due to human effects and natural events without giving false alarms;
- *Economical*: to allow the program to be sustained over the time period of the expected change;
- *Attractive*: to the participants and stakeholders involved in the program to ensure the data are collected properly and used for the intended purpose;
- *User friendly*: techniques must be simple to use and reliable; and
- *Comparable*: to techniques and data used in other systems to allow results to be compared and generalisations made.

2.3.2 Indicator selection: chlorophyll as a nutrient status bioindicator

Phytoplankton must obtain a range of essential nutrients, minerals and vitamins from their environment to sustain continued growth and division. The nutrients, nitrogen and phosphorus, are present at low environmental concentrations and are widely considered to be limiting to the growth of phytoplankton. Nitrogen is essential for the synthesis of amino acids and their anabolic products. Phosphorus is essential for the synthesis of nucleic acids and structural compounds such as phospholipids, and in cyclic-phosphorylation.

Measurement of chlorophyll *a* (universally present in marine algae) is one the most frequently employed techniques for assessing phytoplankton standing stock. As phytoplankton stocks respond quickly to changes in nutrient availability, measurement of chlorophyll *a* concentration was chosen as a proxy indicator of nutrient status. The advantages of monitoring chlorophyll *a* concentrations as compared with nutrient concentrations include:

- *Integration over time*: phytoplankton assimilate available nutrients over their life-time, whereas water column inorganic nutrient concentrations are notoriously variable over much shorter time scales;
- *Bioavailable nutrients*: phytoplankton take up only those forms of nutrients which are bio-available. These include organic nitrogen and phosphorus compounds which comprise a major proportion of total nutrient stocks, and are analytically difficult to measure;
- *Sensitive*: phytoplankton respond rapidly to pulsed nutrient inputs that might otherwise go undetected by regular nutrient sampling;
- *Ease of collection*: chlorophyll *a* samples require minimal processing and storage in the field and are not easily contaminated; and
- *Cost*: chlorophyll *a* is cheap in comparison to the analysis of a full suite of dissolved nutrients.

However, chlorophyll *a* is a relatively crude measure of phytoplankton abundance, and a number of other factors other than nutrient availability must be considered: phytoplankton productivity responds seasonally to changes in photosynthetically active radiation and temperature (Parsons et al. 1984); and cross-shelf differences in phytoplankton composition result from environmental gradients of 'water quality'.

2.3.3 Phytoplankton in the Great Barrier Reef and their responses to nutrient availability

In the GBR lagoon chlorophyll *a* concentrations typically range from 0.3 to 1.0 $\mu g\ L^{-1}$ (Furnas and Brodie 1996). Small pico-planktonic (< 2 μm) cyanobacteria, prochlorophytes and coccoid eukaryotes are the dominant phytoplankton, contributing between 50% to 80% of measured chlorophyll stocks (Furnas and Mitchell 1986). Coccoid prochlorophytes and cyanobacteria dominate oceanic and outer-shelf waters, along with a diverse but numerically sparse assemblage of oceanic dinoflagellates (Hallegraeff 1995). Diatoms and cyanobacteria are abundant in the near-shore waters, the most conspicuous being the diazotrophic (nitrogen fixing) *Trichodesmium* which forms large dense blooms in the upper water column (Revelante and Gilmartin 1982).

Much of the pico-plankton community is consumed by protozoan grazers, which are in turn grazed by metazoan copepods capable of consuming algal and detrital particles > 10 μm in size (e.g. Liston 1990; McKinnon and Thorrold 1993). Benthic filter-feeding assemblages on reefs and inter-reefal areas capture a wide range of planktonic particles (e.g. Fabricius 1995).

Low dissolved inorganic nitrogen (DIN) stocks in the water column are sufficient to support only one doubling of phytoplankton biomass, and thus must be rapidly recycled (Furnas and Mitchell 1996). In contrast, phosphorus and silicate stocks are sufficient for many biomass doublings (Furnas and Mitchell 1996). Phytoplankton communities respond rapidly to increased nutrient availability resulting from events such as floods (Steven et al. 1996; Brodie and Furnas 1996), upwelling (Furnas and Mitchell 1986, 1996) or resuspension (Furnas 1989). Within one or two days short-lived blooms may develop with chlorophyll concentrations increased several-fold (Steven et al. 1996; Brodie and Furnas 1996).

Any increase in nutrient inputs from land-based sources will result from (1) an increase in nutrient loading of rivers; (2) an increase in the frequency or magnitude of peak flow; and (3) a change in the processes governing remineralisation of nutrient standing stocks. Any increase in nutrient loading is expected to be rapidly taken up by phytoplankton communities, but also by benthic autotrophic communities. Changes in the relative ratios of essential nutrients may favour the proliferation of some species over others resulting in changes in composition or the numerical dominance by one, or a few, species. The ability of a particular phytoplankton species to assimilate nutrients depends upon its adaptation to oligotrophic conditions and is measured both by its ability to utilise nutrients at low concentration, termed the half-saturation constant (K_s) and the maximum specific rate at which nutrients are acquired. Under nutrient-limiting conditions the atomic ratio of nitrogen to phosphorus (the Redfield ratio) contained within phytoplankton is ~16:1 (Redfield 1958). N:P values can deviate greatly in shallow coastal waters where 'new' (Dugdale and Goering 1967; Dugdale et al. 1990) inputs of nutrients from adjacent land-masses are significant relative to regeneration rates of existing nutrients. In the case of flood plumes, diatoms may be favoured because of the large inputs of silicate. However, where there have been sustained increases in nitrogen and phosphorus and no change in silicate availability the resulting increase in DIN:DSi may favour other species (Officer et al. 1984; Rahm et al. 1996). The frequency and size of nitrogen-fixing *Trichodesmium* blooms may be a good indicator of increased phosphorus availability (Bell 1992).

2.3.4 Monitoring and modelling for management

If monitoring of chlorophyll concentrations is to be used as a basis for informed environmental management decisions, then definitions of unacceptable concentrations and change are needed. Defining levels of acceptable ecological change is the basis of the concept of assimilative or carrying capacity (Cairns 1977; Stebbing 1992). Determining these levels is fraught with difficulties primarily because of the variety of spatial and temporal scales over which ecosystems vary, and because biota do not respond in similar or predictable ways. Many of the criteria developed to date are generic and not applicable to the oligotrophic conditions of the GBR lagoon. The Australian Water Quality guidelines (ANZECC 1992) and the draft Queensland water quality guidelines (Department of Environment and Heritage 1995) both propose a generic chlorophyll *a* concentration standard of 1 $\mu g\ L^{-1}$ for marine waters.

For coral reefs, there are few studies which document nutrient or chlorophyll concentrations at which a perceived ecosystem decline has occurred. The only other comparable levels are from a eutrophication gradient in Barbados (Tomascik and Sander 1985). Correlating coral growth with chlorophyll *a* concentration, they found that lowest coral growth rates were correlated with mean chlorophyll *a* concentrations of 0.4 $\mu g\ L^{-1}$. DIN levels were ~1 µM and phosphate levels were 0.06–0.07 µM. In Kaneohe Bay, mean chlorophyll *a* concentrations before the diversion of the sewage outfall were 0.68 $\mu g\ L^{-1}$ with 0.23 $\mu g\ L^{-1}$ phosphate and 1.1 $\mu g\ L^{-1}$ DIN (Smith et al. 1981). Szmant and Forrester (1996) in a comprehensive examination of nutrient and chlorophyll *a* concentrations in the Florida Keys found that mean chlorophyll *a* concentrations were ~0.25 $\mu g\ L^{-1}$, but significantly higher close to sewage outfalls and ports.

Two publications have proposed threshold or tolerance limits of coral reefs to nutrient enrichment, based on mean chlorophyll *a* concentration as an estimator of ecosystem change. Hawker and Connell (1989) proposed water quality criteria for coral reefs based on observed decreases in coral growth. For an acceptable 20% change in coral growth they derived a threshold of 48% increase in mean chlorophyll *a* concentration over ambient. This was equivalent to 0.59 $\mu g\ L^{-1}$ DIN. Bell (1992) proposed a eutrophication threshold of 0.5 $\mu g\ L^{-1}$, equivalent to DIN concentrations of ~1 µM and phosphate levels of 0.1–0.2 µM. However, these studies are not widely accepted and many feel that the development of generic criteria is unrealistic.

Modelling is an important monitoring component, firstly because it provides a conceptual framework for the integration of process knowledge derived largely from experimental studies, and the incorporation of other datasets (figure 2.2). Secondly, modelling provides an effective interface between management and monitoring by hindcasting or predicting the impacts of past and future management actions, and allowing the development and analysis of management strategies (Pernetta and Milliman 1995; Gordon et al. 1996).

The simplest eutrophication models are bottom-up controlled NP models which consider only the interaction between the limiting nutrient concentration (N) and plant biomass (P). More complex NPZ models incorporate zooplankton grazing (Z) as a top-down control on phytoplankton biomass and are capable of modelling complex dynamical behaviours. Most modellers stop at incorporating herbivorous zooplankton in their models, but there is debate about how the loss due to higher trophic orders – trophic closure – is represented in the model.

Figure 2.2, from Harris et al. (1996), is an example of an NPZ model which identifies some important implications for managers. At low nutrient loads, N, P and Z are constant and approach a steady-state solution. As nutrient loads increase, P may initially show little response, remaining low and constant. However, a further small increase in nutrient load may surpass a threshold, triggering a switch to a more dynamic and unstable system where P periodically blooms as a result of fluctuating levels of N and Z. This phenomenon, known as the 'paradox of destabilisation of enrichment' (Rosenweig 1971), arises from the fact the phytoplankton–zooplankton interaction becomes very unstable when nutrient loads increase and grazing can no longer cope with the increased phytoplankton biomass. This critical loading will be dependent upon (1) the steady-state phytoplankton biomass (set by zooplankton parameters), (2) the maximum (light-limited) growth rate of phytoplankton, and (3) the degree to which water-column recycling amplifies the nutrient loading (Harris et al. 1996). From a management viewpoint, the increase in peak concentrations above the instability threshold could represent a significant shift in the nutrient status, or deterioration, of the ecosystem. In this context the threshold loading is a measure of assimilative capacity.

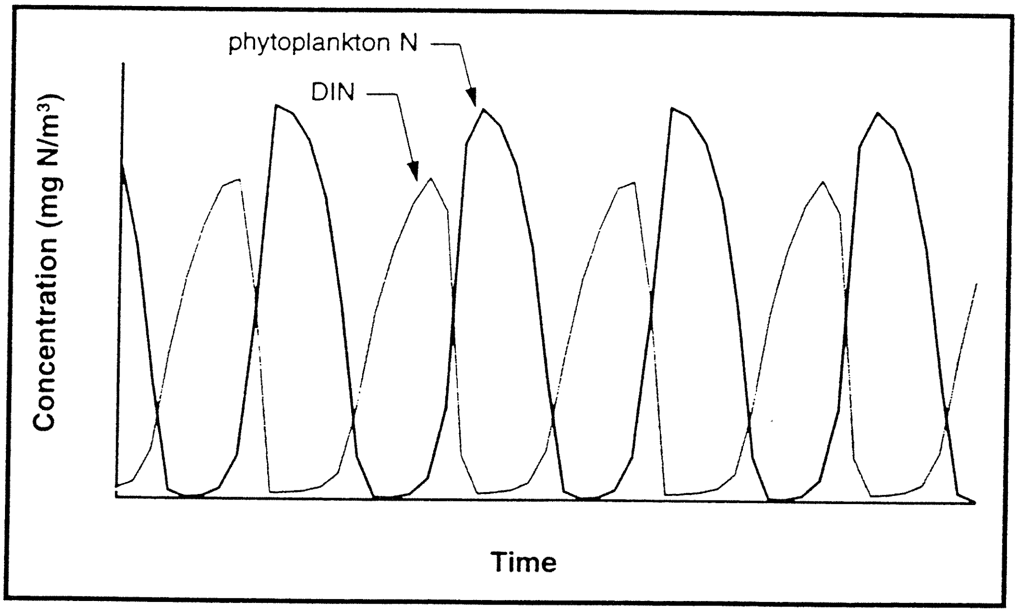

Figure 2.2 Example of NPZ models, from Harris et al. (1996): (a) plot of concentration of DIN and phytoplankton N vs time, in response to a constant load exceeding the threshold load by 20%; (b) change in mean and maximum phytoplankton biomass in response to different nutrient loads

3. NETWORK DESIGN

3.1 OBJECTIVES AND SCOPE

The goal of the Network is to monitor at a regional scale long-term changes in phytoplankton biomass (as chlorophyll *a*) as a proxy indicator of land-based nutrient input to the GBR lagoon. Continued routine sampling will define regional ambient chlorophyll *a* concentrations, which can be used to bench-mark future changes in the nutrient status of GBR waters. Specifically, the Network is designed to:

1. *Quantify regional and cross-shelf patterns of phytoplankton biomass within the GBR lagoon which may be related to regional differences in nutrient inputs.*
2. *Determine how much temporal variability (seasonal, event related) in phytoplankton biomass may reflect changing nutrient inputs to GBR shelf waters.*

3.2 ROLES AND RESPONSIBILITIES

As the principal funding agency GBRMPA is responsible for the overall direction and coordination of the Network. Additionally, GBRMPA is responsible for data management, interpretation and dissemination. The Biological Oceanography Group of the Australian Institute of Marine Science (AIMS) provides laboratory analysis, technical advice and data interpretation. The agencies contracted to undertake sampling ensure proper and timely collection of samples.

3.3 SAMPLING FREQUENCY

Sampling at approximately monthly intervals was chosen because it was important to quantify seasonal changes in phytoplankton biomass. More frequent sampling was constrained by operational costs. The date for sampling within a calendar month is decided by the individual contracted agencies, and depends on prevailing weather conditions and other commitments. Collecting agencies are on standby to undertake sampling of chlorophyll and other nutrient parameters following monsoonal flood events.

3.4 SAMPLING LOCATIONS

Five regional (quasi-latitudinal) clusters of sampling stations have operated since late 1992 (figure 3.1): Lizard Island (14°S), Port Douglas (15°S), Cairns (16°S), Keppel Bay and Capricorn (23°S). Monitoring of further clusters of stations commenced off Townsville in late 1995, and in the Whitsundays and in the Far Northern Section in 1996. These clusters are neither spatially representative of the GBR lagoon nor explicitly linked to putative nutrient inputs. Some clusters extend from close to the coast to the outer shelf, while others are confined to either inshore (< 20 km from the coast) or offshore waters. Rather, the location of clusters was dictated by the availability of personnel equipped to undertake routine sample collections. Staff from the regional offices of the Queensland Department of Environment and Heritage sample Cairns, Townsville and Keppel Bay clusters; Lizard and Capricorn are respectively sampled by staff from Lizard Island and Heron Island Research Stations; and interpretive staff from Reef Biosearch sample the Port Douglas cluster.

Five to eight stations are sampled within each cluster. Stations are fixed, rather than random, and are relocatable by GPS. Although some stations are often adjacent to reefs, they are all located in inter-reefal waters. Stations 5–8 within Lizard Island Reef are the exception but they are not strictly part of the Network – they are a component of routine sampling by the Lizard Island Research Station. Stations within the Port Douglas, Cairns and Townsville clusters extend from inshore coastal waters to the shelf-break. Although the Keppel Bay and Capricorn clusters are operationally distinct they can be functionally considered as a regional cross-shelf cluster.

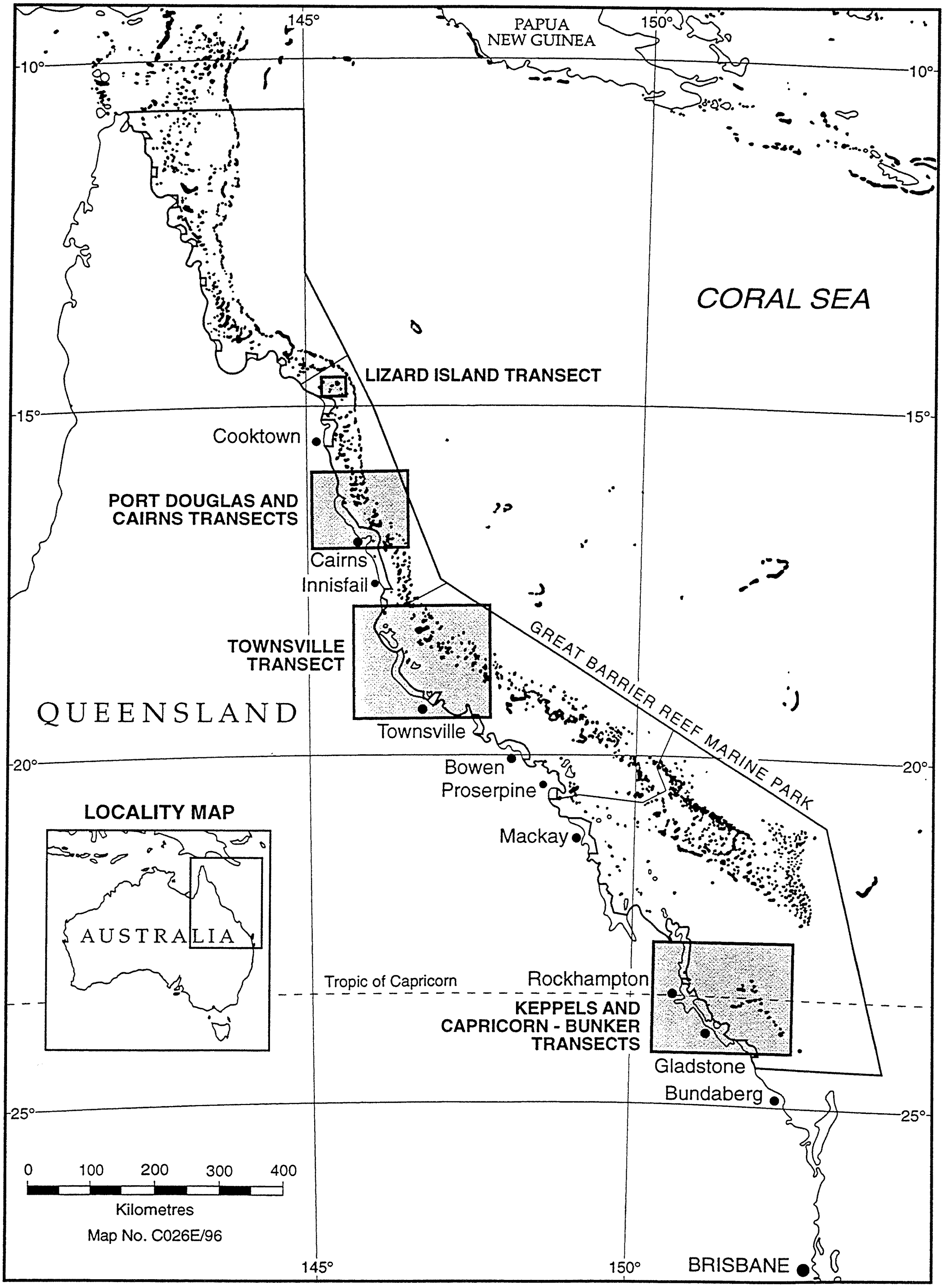

Figure 3.1 Map of the Great Barrier Reef indicating latitudinal distribution of sampling clusters

Table 3.1 summarises for each cluster, the number of stations, latitudinal and cross-shelf position, sampling institutions and commencement dates.

Table 3.1 Summary of Network sampling clusters

Cluster	Collecting Institution	Latitude (°S)	Cross-shelf position	No. Stations	Date Commenced
Lizard Island	Lizard Island Research Station	14.7	offshore	8	Jan 1993
Port Douglas	Reef Biosearch Pty Ltd	15–16	cross-shelf	7	Dec 1992
Cairns	Department of Environment and Heritage	16.5	cross-shelf	7	Dec 1992
Townsville	Department of Environment and Heritage	17.5–19	cross-shelf	8	Oct 1995
Keppel Bay	Department of Environment and Heritage	23	inshore	6	Jan 1993
Capricorn	Heron Island Research Station	23	offshore	5	Jan 1993

Relevant geographic and demographic characteristics of the adjacent catchments are described below.

Lizard Island

The continental shelf from 14°S to 15°S occupies an area of 11 300 km^2 (Hopley et al. 1989). The adjacent north-east Cape York Peninsula catchment is largely undeveloped; un-improved pasture for grazing and national parks are the predominant land use, while less than 0.1% of the catchment is used for cropping (table 3.2). Climatically the region experiences average annual rainfall of 1300 mm. Annual run-off for the total area is estimated to be 19 100 ML (Moss et al. 1992). The Endeavour, Starcke and Jeannie rivers are the only significant rivers to discharge into the coastal region. The only significant town is Cooktown (population 1350) which discharges ~400 m^3 day^{-1} of secondary treated sewage into the Endeavour River. There are no significant industrial developments in this region.

Cairns and Port Douglas

The continental shelf between 15°S and 16°S widens from only 42 km off Cape Tribulation to 57 km off Cairns. Most of the coral reefs are free-standing platform reefs in greater than 30 m water depth. Inshore, there are a number of wooded cays, notably Green Island and Low Isles. Rapid and intensive agricultural and urban growth, combined with the relatively narrow shelf make these coastal waters perhaps the most susceptible in the GBR to changes in nearshore nutrient status (Hopley 1988).

The adjacent Mossman–Daintree catchments have a total area of 2615 km^2. World Heritage-listed rainforest occurs on the steeper slopes of the catchment and there are both State and National parks in the south-west. Beef cattle grazing is the major agricultural land use, while cropping, mostly sugar cane, occurs on the lowlands. In 1990, 340 tonnes of nitrogen and 100 tonnes of phosphorus were applied as fertiliser, mostly to sugar cane (table 3.2). Annual rainfall in the area is 2518 mm. The Daintree River drains much of the upper catchment, discharging to the north of Port Douglas. The southern area of the catchment is drained by the Mossman River which discharges south of Newell. Port Douglas and Mossman with a combined permanent population of 3000, have a combined sewage discharge of 14 150 m^3 day^{-1}, of which 12 870 m^3 day^{-1} is reticulated onto land (Tarte et al. 1996).

The Barron catchment (2175 km^2) encompasses the northern reaches of the Atherton Tableland and the city of Cairns (population 90 000) on the coastal plain. Agricultural cropping lands (maize, peanuts, tobacco and sugar cane) and grazing account for 8.5% and 48% respectively of the catchment area (table 3.2). The Barron River flows some 160 km through the catchment ending in a 10 km tidal estuary which discharges north of Cairns into Trinity Bay. It has an average annual discharge of 0.83 x 10^6 ML (Mitchell and Furnas 1997).

A mass balance model for the region estimated that riverine discharge accounted for 31% of new nitrogen and 39% of phosphorus (Furnas et al. 1995). During monsoonal peak-flow conditions, the

Cairns offshore region is also influenced by discharges from the Johnstone and Russell–Mulgrave catchments which coalesce to form a single northward flowing plume (Steven et al. 1996).

Urban discharges are significant in this region. Three secondary sewage treatment plants discharge into the Barron River with a combined average input of 37 350 m^3 day^{-1}, contribute ~ 3.7% and 13% of new nitrogen and phosphorus inputs to the region (Furnas et al. 1995). Significant eutrophication of Trinity Inlet is recognised and attempts to manage and reduce nutrients inputs are one of the goals of the Trinity Inlet Management Program (Hollingsworth Dames and Moore 1993).

Townsville

The adjacent Herbert and Black River catchments are semi-arid, experiencing warm humid to sub-humid summers and mild dry winters. Rainfall varies greatly across the region – from 640 mm in the Burdekin to over 1500 mm in the Black River catchment (table 3.2).

The major land uses in the Herbert Catchment (12 000 km^2) are grazing (71%) and forestry (10%). The catchment is considered a major sugar producing area, though less than 4% of the total catchment is used. Sugar cane accounted for 90% of the 9800 tonnes of nitrogenous fertiliser used in 1990 and 77% of the 1330 tonnes of phosphorus (Pulsford 1993). Much of the Black River catchment is dry savannah woodland with little agricultural development.

The Herbert River annually discharges on average 4.99 x 10^6 ML through several channels north of Lucinda into the Hinchinbrook Channel (Lough 1993). The surrounding coastal lands are low-lying swamp with extensive mangroves and significant fish nurseries. A number of existing and planned land-based aquaculture facilities are located in the Hinchinbrook Channel area. Ingham (population 6000) sewage facilities discharge an estimated 5280 m^3 day^{-1}, mostly onto land. Coastal waters are infrequently influenced by river flows from the Haughton and Burdekin rivers following major monsoonal rainfall events (Wolanski and van Senden 1983) or cyclones (Furnas 1989).

Townsville (population 130 000) extends along the Ross River. Urban effluent discharge is 41 545 m^3 day^{-1}, much of it reticulated onto land. Major industries include a nickel refinery and ore loading facility and plans for a zinc refinery. The port has been expanded in recent years with extensive land reclamation to the south of Townsville city.

Keppel Bay and Capricorn

There are no comprehensive oceanographic measurements in this region (table 3.2). The adjacent Fitzroy River catchment (142 645 km^2) is the largest catchment in Queensland (table 3.2). Major land uses are beef cattle grazing (87%), cotton and grain growing (5%). Industry is centred about coal mining, power generation and the manufacture of bulk chemicals, notably alumina and aluminium, cement and sodium cyanide. The region is dry, receiving on average 702 mm annually (table 3.2). The Fitzroy River discharges 40 km south-east of Rockhampton into a narrow, low energy environment behind Curtis Island. It flows infrequently with a mean annual flow of 4.94 x 10^6 ML (Lough 1993). Four sewage treatment plants and two abattoirs discharge on average 37 340 m^3 day^{-1} (Tarte et al. 1996).

Keppel Bay supports several important commercial fisheries and receives extensive tourist and recreational use. It contains 15 continental islands, many with well-developed fringing reefs. Significant flooding occurred in 1991 following cyclone Joy. Low salinity water of 8‰ persisted in Keppel Bay for three weeks (O'Neill et al. 1992) causing significant phytoplankton blooms (Brodie and Mitchell 1992) and coral mortality on fringing reefs (van Woesik et al. 1995).

Advection of low salinity nutrient rich water masses may reach the Capricorn stations following significant monsoonal rainfall events. For example, during the 1991 Fitzroy River floods salinities, as low as 28‰ were recorded (Preker 1992).

Table 3.2 Land use and climatic demographics of major catchments adjacent to the Great Barrier Reef. Data compiled from various sources.

Catchment	Area	% Land use[1]					Fertiliser applied 1990 (tonnes)[2]		Annual rainfall[1]	Annual run-off[1]	RO/RF
	10^3 ha	Timber	Pristine	Grazing	Cropping	Urban	TN	TP (t)	mm	10^3 ML	%
North-east Cape York	43 300	3.1	–	62	0.1	–					
Daintree	213	37.7	31.7	26.7	1.9	2	340	100	2 518	3 560	65
Mossman	49	30.4	11.0	44.6	14.0	3.9	82	240	687	2 459	57
Barron	218	36.4	2.0	47.7	8.5	625	1 680	625	1 477	1 153	37
Mulgrave–Russell	202	16.9	25.1	38.9	13.3	605	4 720	605	3 233	4 193	64
Johnstone	233	25.3	12.8	41.6	15.9	1 700	7 300	1 700	3 405	4 698	59
Tully	169	62.5	2.1	20.7	11.1	530	2 660	530	2 970	3 683	74
Murray	114	32.9	27.3	29.6	7.0	220	3 950	220	24 850	1 628	57
Herbert	1 013	9.5	9.7	71.1	7.0	1 330	9 800	1 330	1 331	4 991	37
Black	108	18.0	9.3	67.4	1.1	0	5	0	1 510	509	31
Haughton	365	0.8	10.8	74.0	10.9	613	8 805	613	923	756	22
Burdekin	12 986	1.0	1.3	94.8	1.0	256	180	256	640	10 100	12
Don	389	0.2	2.6	91.3	2.8	380	1 445	380	1 022	689	17
Proserpine	249	9.6	4.0	74.6	7.5	459	3 040	459	1 562	1 431	37
O'Connell	244	7.6	4.4	70.5	11.1	539	4 390	539	1 705	1 668	40
Pioneer	149	22.7	6.1	48.5	18.0	648	5 490	648	1 418	994	47
Plane	267	4.3	2.9	67.4	21.0	995	7 685	995	1 499	1 370	34
Fitzroy	15 264	6.7	2.3	87.5	3.3	786	7 290	786	702	7 127	7

[1] Rayment and Neil (1997)
[2] Pulsford (1993)

3.5 LIMITATIONS, FLEXIBILITY AND REVIEW OF NETWORK

Given the size and scope of the Network it is inevitable that the design will need to be modified and implemented in stages as funds and resources for sampling become available. Several changes have already occurred: depth sampling was discontinued after 18 months at all clusters except Capricorn; in the Port Douglas cluster, weekly sampling was modified to monthly following changes in trip schedules; additional clusters commenced off Townsville, the Whitsundays and in the Far Northern Section.

The most conspicuous limitation of the present design is that neither the clusters, nor the stations, are spatially representative of the GBR lagoon. Stations are not explicitly related to land-based nutrient discharges. Rather their choice was primarily dictated by the availability of personnel, contracted to undertake routine, long-term sampling.

The initial few years of data collection were intended to identify the major sources of spatial and temporal variation in chlorophyll *a*, providing a basis for more cost effective allocation of sampling effort. The program is committed to reviewing the efficiency and expediency of the present design.

3.6 INTEGRATION WITH OTHER MONITORING STUDIES

It is intended that results from the Network will be integrated with the results of other ongoing research and monitoring programs to provide a more comprehensive evaluation of regional and local-scale water quality status. In particular, the results from the Network need to be explicitly related to ongoing catchment and river monitoring studies. This will allow the development of nutrient budget models. Monitoring is currently being undertaken by the Australian Institute of Marine Science (AIMS), the Queensland Department of Natural Resources, the Queensland Department of Environment and Heritage and the Queensland Department of Water Resources.

The Network builds upon a body of previous work, in particular, oceanographic studies initiated by AIMS oceanographers in the late 1970s (Wolanski et al. 1981; Andrews and Gentien 1982; Revelante and Gilmartin 1982) and continued since 1983 by the AIMS Biological Oceanography Group (Furnas and Mitchell 1984; Furnas et al. 1988, 1992, 1995). This group has monitored over 100 stations once to several times per year. Comprehensive hydrographic, nutrient (particulate, dissolved organic and dissolved inorganic forms) and pigment analyses are made at each station.

As part of GBRMPA's wider water quality research program, projects aimed at answering specific questions regarding the physical and nutrient dynamics of river plumes and correlations between benthic composition and water nutrient concentrations will be integrated wherever possible.

High resolution satellite imagery from SEAWHIFs and AIDOS will allow greater spatial inference of the scale at which changes in phytoplankton abundance might occur (e.g. Gabric et al. 1990). The Network will provide important ground-truthing data to refine algorithms for surface chlorophyll estimates.

4. SAMPLING AND DATA PROTOCOLS

4.1 SAMPLING STRATEGY AND PARAMETERS

At each station, two casts of a Niskin bottle (5 L) are used to collect water samples from near-surface waters. The same procedure is used to sample waters ~ 2 m above the bottom. From each bottle, duplicate water samples (~ 100 ml) are filtered onto GF/F filter papers for chlorophyll *a* analysis. This sampling strategy is represented schematically in figure 4.1. Details on representative sampling and filtering techniques are given in table 4.2.

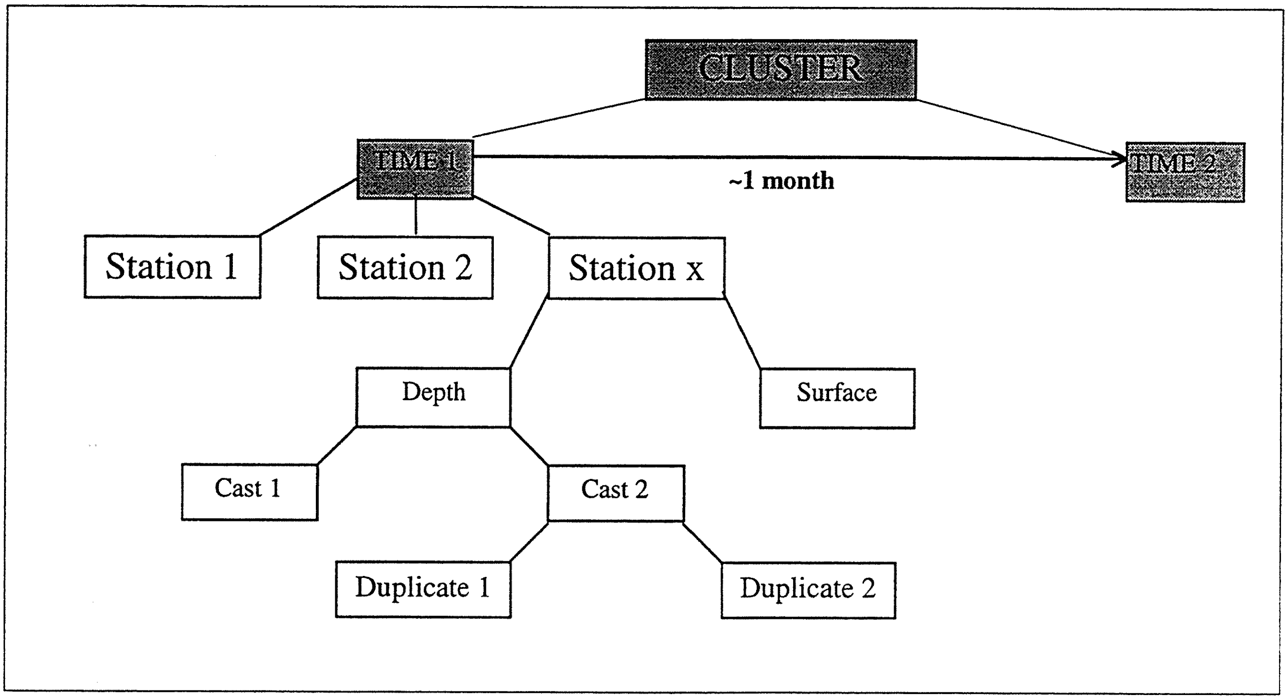

Figure 4.1 Schematic of chlorophyll *a* sampling strategy within each cluster

At each station, a range of weather and hydrographic measurements, listed in table 4.1, are collected to aid interpretation of the chlorophyll *a* results.

Table 4.1 Weather and hydrographic parameters measured at each station

Parameter	Unit	Method of Determination
Weather		
Wind Speed	kmph	Anemometer
Wind Direction	360 degrees	Ribbon and compass
Wave Height	m	Visual estimation: trough to peak
Wave Direction	360 degrees	Compass
Cloud cover	octets (^{x}/8)	Visual estimation
Rainfall		Scale: 1–none; 2–light; 3–moderate; 4–heavy
Hydrographic		
Depth	m	Vessel depth sounder
Salinity	‰	Salinometer or refractometer in field
Temperature	^{o}C	Field meter or thermometer
Secchi Depth Clarity	m	Secchi disc
Trichodesmium	1/0	Visual: present or absent

Chlorophyll samples are transported to GBRMPA where they are stored in a holding freezer (-10°C) until they are transferred (frozen) in batches to AIMS. Samples are stored in a laboratory freezer until flurometric analysis (table 4.2).

Table 4.2 Notes on chlorophyll sampling and laboratory procedures

Representative Water Sampling

Two water samples are collected from near the surface and near the bottom of the water column using Niskin bottles. Surface samples are taken one metre below the surface to avoid the immediate water surface in which chlorophyll concentrations are highly variable and affected by surface-floating *Trichodesmium* or other organic matter. If high concentrations of *Trichodesmium* are observed (a surface scum of tiny filaments), an additional sample right at the surface should be taken. These samples should be filtered last to avoid contaminating the other two samples. Bottom samples are taken ~two metres above the substrate to avoid contamination with material from the sediment. Each water sample is divided into two replicates for chlorophyll analysis.

Chlorophyll filtering

The phytoplankton in the seawater samples are filtered onto GF/F filters and analysed for chlorophyll (and phaeophytin) content by fluorescence (see 'Chlorophyll determination'). The technique is highly sensitive, so only a small volume (~100 ml) needs to be filtered. Filtration of the water samples should be carried out within six hours of sampling. Samples should be kept in cool, dark storage conditions prior to filtration. Avoid filtering the water samples in full sunlight as chlorophyll degrades with light. One or two drops of 1% $MgCO_3$ solution are added during filtration to minimise further degradation during storage. Two 100 ml subsamples are taken from each replicate water sample. When filtered, immediately remove the filter funnel and using the filter forceps, fold one half of the first filter back onto itself to contain the sample. Transfer this filter semicircle to a piece of alfoil, keeping fingers away from the filter as much as possible. Repeat with the second filter and fold the alfoil such that both filters are contained within one packet. Filters are immediately stored in alfoil packets and frozen. Alfoil packets are labelled as follows:

Cluster name; Station number; Trip number; Surface (S) or Bottom (B); Cast (A = first, B = second cast); Duplicate (1 or 2)

Chlorophyll determination

The analytical procedure for chlorophyll follows the basic flurometric method set out in Parsons et al. (1984). Individual filters are thoroughly ground under dim light conditions at room temperature in 90% (v/v) reagent grade acetone with a tissue grinding tube and teflon pestle. The homogenate is transferred to a 12 ml graduated plastic centrifuge tube and the volume made up to 10 ml with 90% acetone. The tubes are capped to prevent evaporation. Samples are swirled to distribute the extracted pigment then centrifuged for 10 minutes to clear the supernatant.

The chlorophyll fluorescence of the supernatant is read in a quartz cuvette with a Turner Designs Model - 005R Fluorometer. A small volume (1–2 drops) of 10% HCl is added to the cuvette and the new fluorescence recorded. Between analyses, the Fluorometer cuvette is washed with 90% acetone and a small amount of the next sample. The blank-corrected fluorescence readings volumes of water filtered and of extract and instrument scale factors are noted for each sample on a worksheet. The Fluorometer is periodically calibrated against diluted chlorophyll extracts prepared from log-phase diatom cultures (chlorophylls *a* and *c*). The chlorophyll contents of the concentrated primary calibration extracts (as $\mu g\ mL^{-1}$) are determined spectrophotometrically using the wavelengths and equations specified by Jeffrey and Humphrey (1975). Series of chlorophyll dilutions in 90% acetone are made up to give multiple concentration readings on each of the individual instrument gain scales. Functional relations are derived to calculate chlorophyll (as $\mu g\ L^{-1}$) based upon the fluorescence readings and instrument scale factors, assuming 10 ml extract volumes.

4.2 DATA HANDLING AND ASSURANCE

The data-sheets containing weather and hydrographic measurements are entered into a spread sheet by the data collectors. To facilitate standard data input, a custom-made application has been written in Access™ database format. These are uploaded into a relational database table (Access™).

Chlorophyll results are given to GBRMPA on spreadsheets which are uploaded into a separate Access™ database. The database facilitates a range of queries that can be made on both tables to summarise data or extract particular parts of the data. Many of the fields in the database have built in data validation ranges to screen erroneous data. Data is available in a range of generic ASCII formats. It is hoped in the near future that data will be made available on GBRMPA's web site (http:// www.gbrmpa.gov.au).

Confidence that data accurately reflects in situ values is attained through replication, standardisation and use of internationally accepted techniques of sample analysis.

- Ideally, the electronic SCT meters are regularly calibrated.
- The fluorometer for chlorophyll *a* analysis is regularly calibrated against diluted chlorophyll extracts prepared from log-phase diatom cultures.
- Validation checks are delimited for various fields in the database to minimise data entry errors.
- Data analysis and interpretation is peer reviewed.

4.3 STATISTICAL ANALYSIS AND REPORTING

As chlorophyll concentrations are often positively skewed, it is often necessary to transform the data – typically $\log_{10}(x)$ – to conform with parametric assumptions of normality and homogeneity. Outliers (extreme values) make the choice of summary statistic important. Means are greatly affected by outliers, whereas median values are more conservative, but use only 50% of the data. Other techniques such as trimmed mean and M statistics have the advantage of retaining most of the information, yet are obviously more robust to the presence of outliers.

Analysis of long-term temporal trends in chlorophyll concentrations predominantly use non-parametric techniques. These techniques are robust against non-normal distributions, extreme values, serial correlation and seasonality, and can handle missing and censored data. The Seasonal Kendall tau test is used for decoupling monotonic trends in water quality parameters from seasonality (Hirsch et al. 1982; Hirsch and Slack 1984). This test sums the number of positive differences between an observation and all latter observations, minus the sum of all negative differences. The value is then divided by the square root of the variance to form the standard normal variate. The trend slope is estimated from the seasonal Kendall slope estimator, which can be characterised as the median annual change adjusted for seasonality (Hirsch et al. 1982). This estimator is resistant to extreme values and seasonality. All tests are two-sided, since both the upwards and downward trends are possible.

PART 2

CHLOROPHYLL MONITORING IN THE GREAT BARRIER REEF LAGOON 1993–1996

The following five chapters present summary hydrographic data and chlorophyll *a* results from five regional clusters. These results are descriptive rather than analytical. The results for all clusters, except Townsville, cover the period January 1993 to July 1996. This represents approx. 40 sampling occasions – sufficient data to enable a preliminary status report on the major spatial and temporal factors influencing chlorophyll concentrations.

To identify cross-shelf patterns within clusters extending across the width of the shelf (i.e. Port Douglas, Cairns and Townsville), stations have been grouped into inshore or offshore categories. Keppel Bay and Capricorn are functionally considered as inshore and offshore respectively. Median chlorophyll *a* values have been used to summarise cross-shelf, monthly and interannual patterns. Monthly mean chlorophyll *a* concentrations were used to present the results of individual stations.

Temperature, salinity and Secchi depth are presented graphically. Most of the temperature and salinity measurements are dubious because of malfunctioning and calibration problems with the SCT meters used. Consequently, there has been little attempt to relate chlorophyll *a* concentrations to hydrographic measurements or prevailing weather conditions.

Chapter 10 (Summary and Assessment) summarises regional and temporal patterns in the data, and considers the implications for resolving changes in chlorophyll *a* concentration that can be meaningfully related to changes in nutrient availability.

---

5. LIZARD

5.1 CLUSTER DESCRIPTION

Collectors: *Lizard Island Research Station*

Dr Anne Hoggett, Dr Lyle Vail

Eight stations are sampled within and adjacent to Lizard Island Reef (figure 5.2). Stations 1 and 2 lie ~ 22 km from the coast in less than 20 m water depth. Stations 3 and 4 lie to the east of Lizard Island, and are ~30 km from the mainland, in greater than 20 m water depth (table 5.1). They have been sampled ~monthly since January 1993. Near-surface samples have been collected from stations 5–8 around Lizard Island Reef since April 1993, for the purposes of Lizard Island Research Station (LIRS). Apart from station 8 off Lizard Head, all are in less than 10 m water depth. Sampling dates and prevailing weather and sea conditions are summarised in table 5.4.

Table 5.1 *Lizard sampling stations*: location, mean depth and distance from mainland

Station		Location (dec. degrees)		Mean depth	km to mainland
ID	Name	Longitude	Latitude	(metres)	
1	Near Martin Reef	145.32	14.77	18.2	11.9
2	Eagle Islet	145.35	14.67	17.6	22.4
3	North Reef	145.47	14.63	23.6	33.9
4	Macgillivray Reef	145.52	14.65	28.9	36.8
	Within Lizard Island Reef				
5	Blue Lagoon	145.46	14.69	8.1	30.3
6	Sunbird Mooring	145.44	14.68	3.8	28.3
7	Watson's Bay	145.45	14.66	8.6	29.6
8	Off Lizard Head	145.47	14.69	27.6	30.0

5.2 HYDROGRAPHIC CONDITIONS

Sea surface temperatures were greatest from January to March (~29°C), while minima (~24°C) occurred during July–September of each year (figure 5.1). Interestingly, the temperature range in 1995 (23.9–29.4°C) is less than the previous two years (table 5.2). Temperatures at stations 1–4 and 5–8 were very similar throughout the sampling period (figure 5.1).

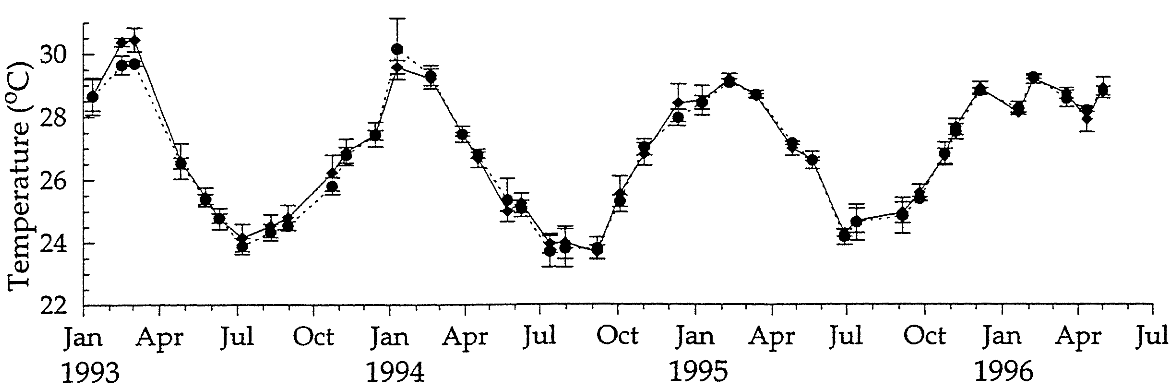

Figure 5.1 *Lizard*: mean (± 1 S.D.) monthly surface temperature (°C) at stations 5–8 around Lizard Island (◆) and stations 1–4 (●)

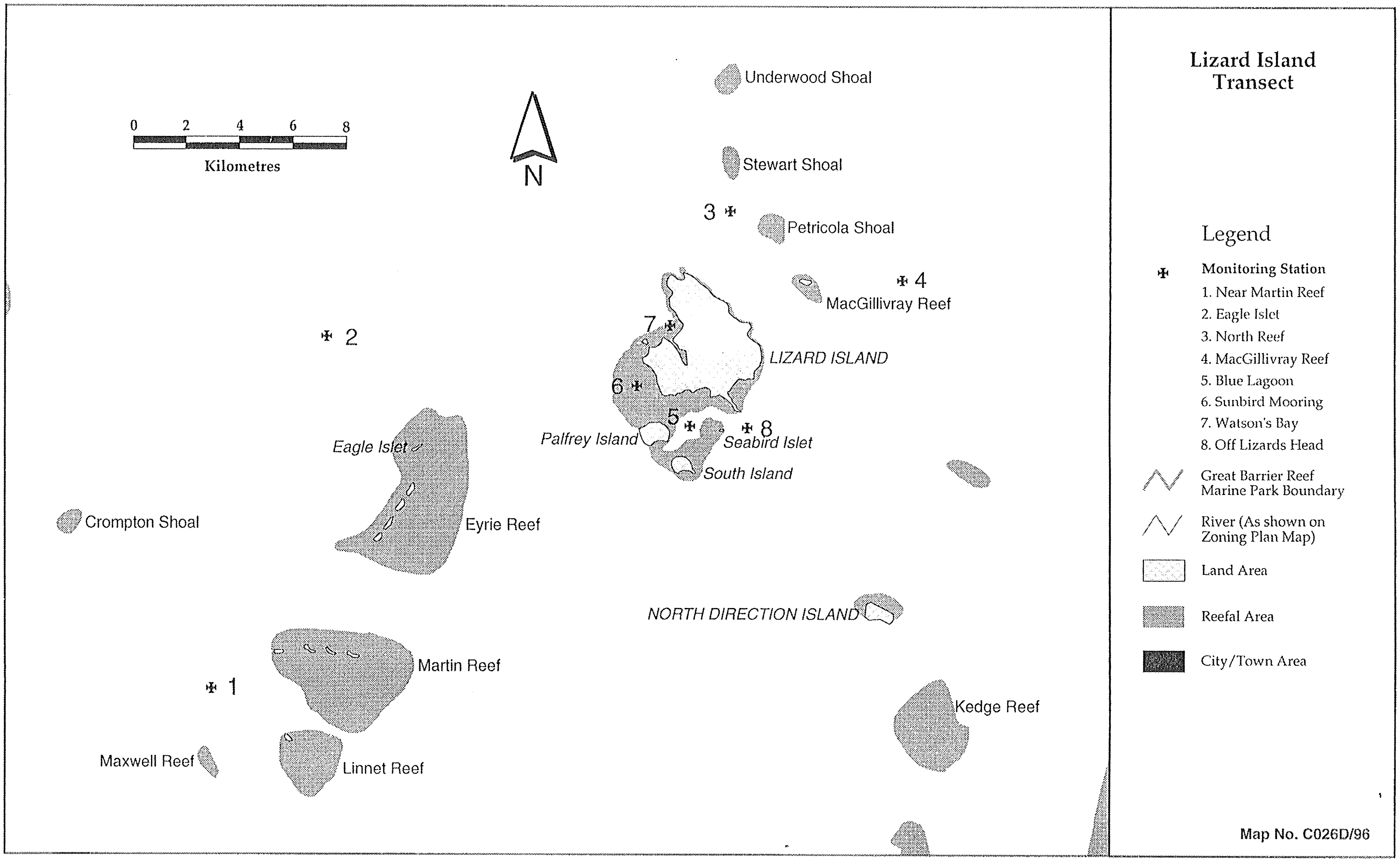

Figure 5.1 Map of sampling stations 1–8 in the Lizard cluster

Table 5.2 *Lizard*: Annual summary statistics of temperature, salinity and chlorophyll *a* concentrations

	Temperature (°C)			Salinity (‰)			Chlorophyll *a* (μg L^{-1})		
	Min	Median	Max	Min	Median	Max	Min	Median	Max
1993	23.5	25.85	30.5	33.0	35.4	35.7	0.08	0.23	1.44
1994	23.2	27.7	31.4	33.5	35.1	35.5	0.07	0.22	0.59
1995	23.9	28.6	29.4	33.7	35.1	35.5	0.07	0.20	0.57
Mean	23.5	26.8	31.4	33.0	35.1	35.7	0.07	0.23	1.44

Salinities were ~35.1‰ throughout most of the year (table 5.2). Significant short-term decreases (figure 5.3) were recorded in February 1993 (33.2‰), December 1994 (33.4‰) and March 1996 (33.6‰). Regional decreases in salinities (33–34‰) persisting for more than two months occurred in February–May 1994 and February–June 1995. Significant rainfall brought by cyclone Sadie (February 1994) and cyclone Violet (February 1995) was probably responsible. Lowest salinities were generally recorded at station 1, off Martin Reef (figure 5.2).

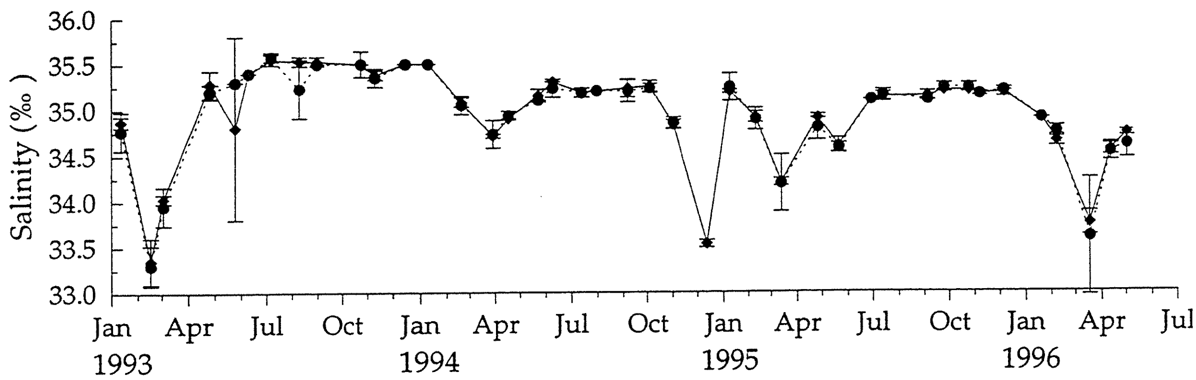

Figure 5.3 *Lizard*: mean (± 1 S.D.) monthly surface salinity (‰) at stations 5–8 around Lizard Island (◆) and stations 1–4 (●)

Secchi depth ranged from 5 m to 20 m with stations 5–8 having greater transparency than stations 1–4 (figure 5.4). Secchi depth was not linearly related to surface chlorophyll concentration ($R^2 = 0.14$). In 4.4% of observations the presence of *Trichodesmium* blooms was recorded, generally from March to June.

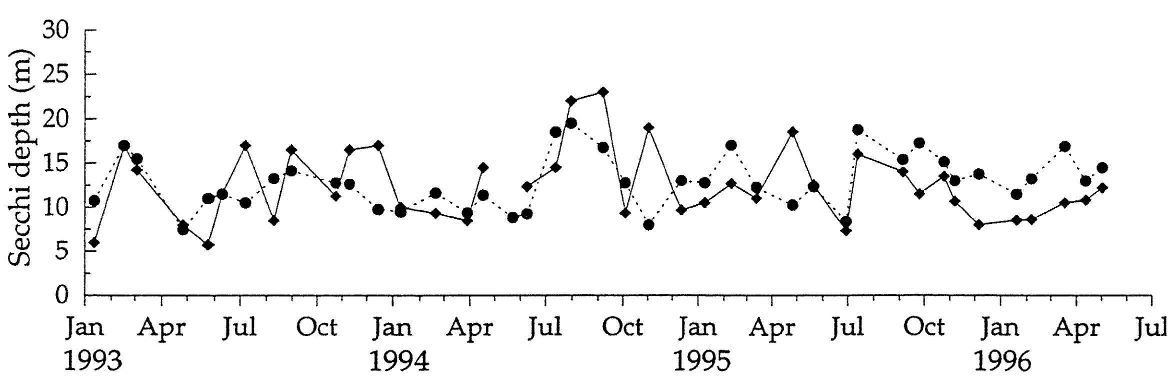

Figure 5.4 *Lizard*: mean monthly Secchi depth (metres) at stations 5–8 around Lizard Island (◆) and stations 1–4 (●). Error bars omitted for clarity.

5.3 CHLOROPHYLL CONCENTRATIONS

Near-surface chlorophyll *a* concentrations for the cluster varied from 0.07–1.44 µg L^{-1} with a median of 0.23 µg L^{-1} (table 5.2). Median annual chlorophyll *a* concentrations were similar over 1993–95 (table 5.2). The maximum chlorophyll *a* concentration was 1.44 µg L^{-1} in May 1993.

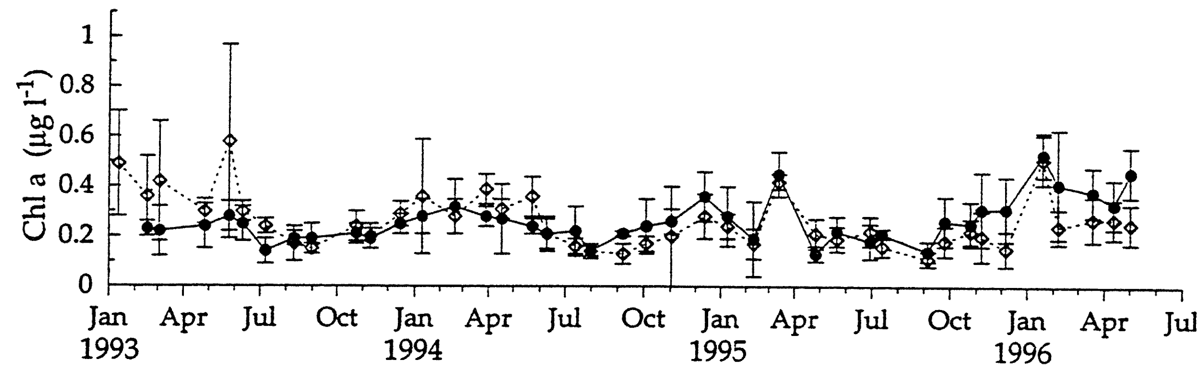

Figure 5.5 *Lizard*: mean (± 1 S.D.) monthly surface chlorophyll *a* concentration (µg L^{-1}) at stations 1–4 (◊) and 5–8 (●)

In 1994, there were no significant 'bloom' concentrations; concentrations ranged from 0.07–0.59 µg L^{-1}. Median chlorophyll *a* concentrations in 1995 were similar to 1994, varying from 0.16–0.42 µg L^{-1} with peak concentrations (0.57 µg L^{-1}) occurring in March. In 1996, high chlorophyll *a* concentrations were recorded in January (0.67 µg L^{-1}) and February (0.79 µg L^{-1}).

Monthly median chlorophyll *a* values were similar between years (figure 5.6). From July to September chlorophyll *a* concentrations were below 0.2 µg L^{-1}, but were sometimes greater than 0.4 µg L^{-1} from January through March.

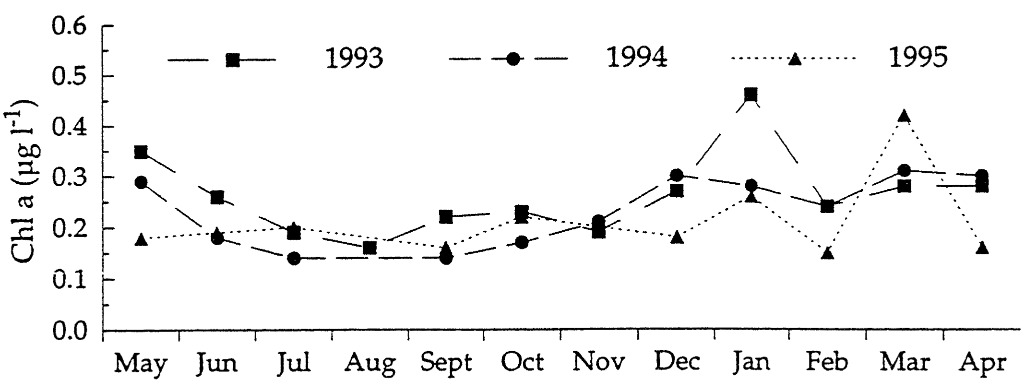

Figure 5.6 *Lizard*: median monthly chlorophyll *a* concentrations (µg L^{-1}) averaged over stations 1–8 in 1993–95

Between station-comparisons of median surface chlorophyll *a* concentrations varied from 0.2 µg L^{-1} at station 2 to 0.26 µg L^{-1} at station 1, off Martin Reef (table 5.3). At stations 1–4, mean chlorophyll *a* concentrations varied greatly in 1993 compared to 1994 and 1995 (figure 5.7). Stations 2, 3 and 4 exhibited similar temporal trends (figure 5.7 b–d) and summary statistics (table 5.3). Near-surface and near-bottom chlorophyll *a* concentrations differed from 0–0.55 µg L^{-1}; with the greatest differences between depths occurring during summer months (figure 5.7). The average variability between duplicate samples from any one cast was 0.02 ± 0.03 µg L^{-1}.

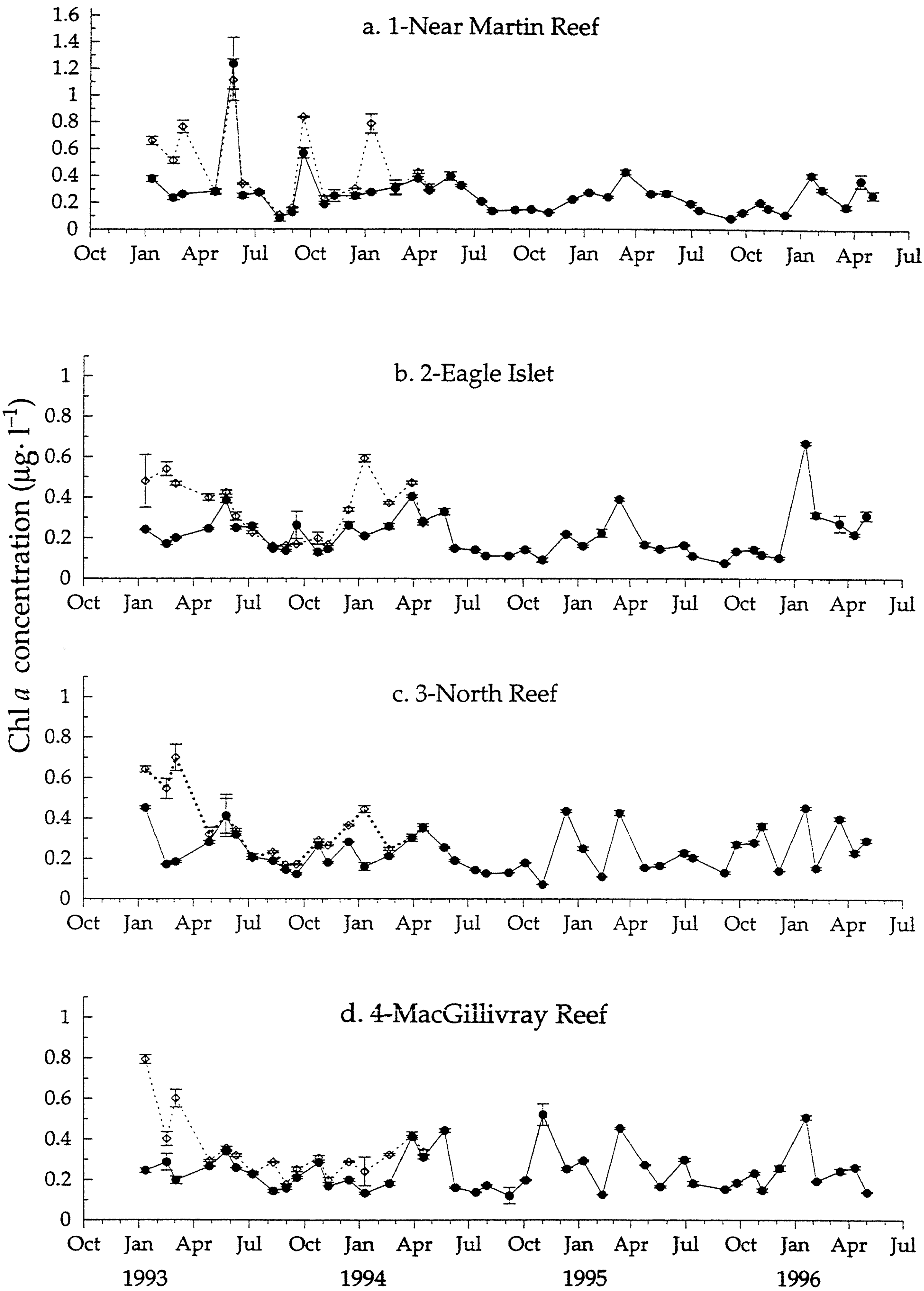

Figure 5.7 *Lizard stations 1–4*: mean (± 1 S.E.) monthly near-surface (●) and near-bottom (◊) chlorophyll *a* concentrations (µg L^{-1})

Chlorophyll *a* concentrations at stations 5–8 around Lizard Island varied between 0.07 µg L^{-1} and 0.8 µg L^{-1}, **and** were greater from October to May (figure 5.8). Chlorophyll *a* concentrations at station 5 located in shallow water within Blue Lagoon, were greater than the other three stations (table 5.3).

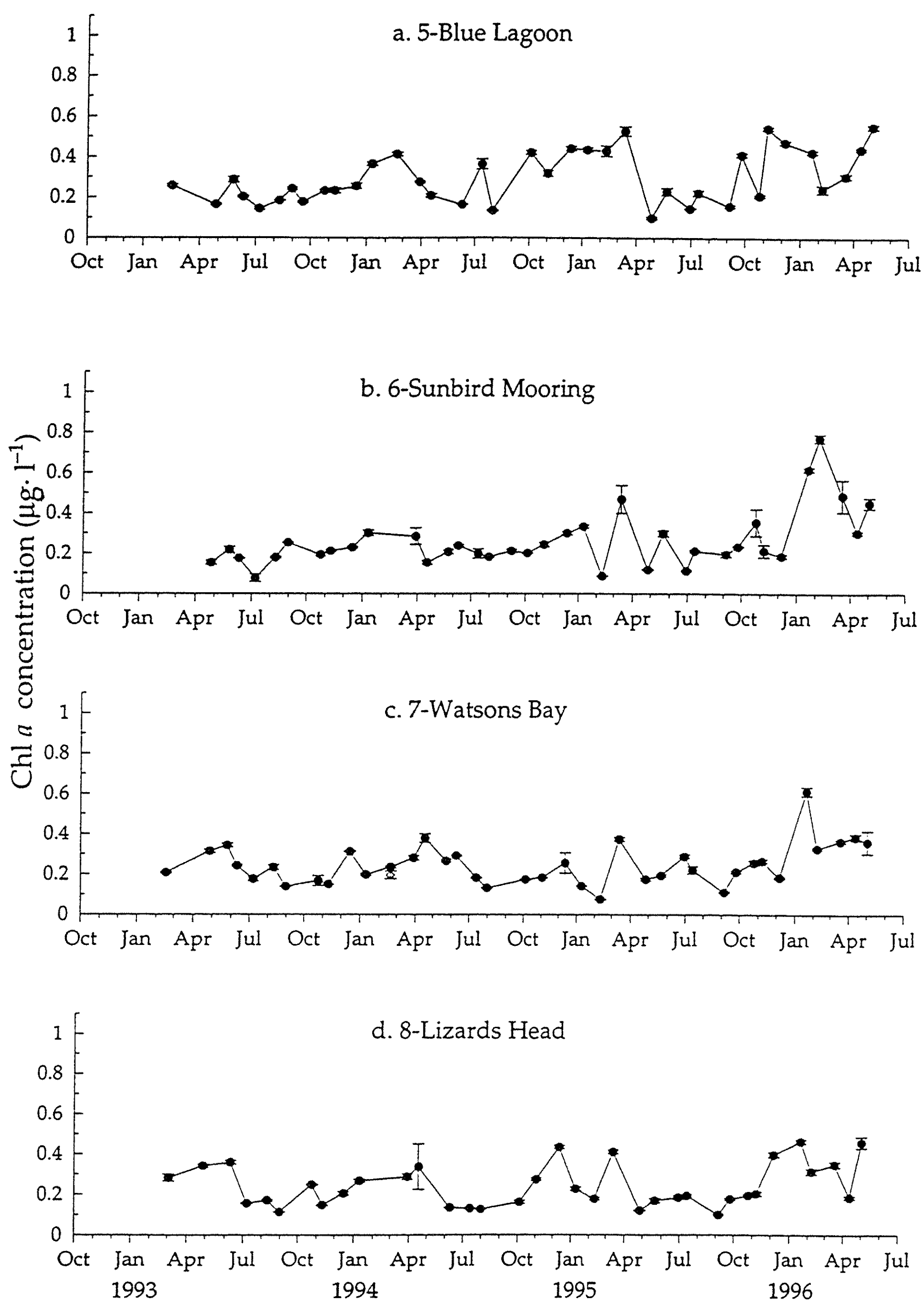

Figure 5.8 *Lizard stations 5–8*: mean (± 1 S.E.) monthly near-surface (●) and near-bottom (◊) chlorophyll *a* concentrations (µg L^{-1})

Table 5.3. *Lizard*: Summary statistics of chlorophyll *a* concentrations

	Chlorophyll *a* concentration (µg L^{-1})						
Station	N	Mean	S.D.	S.E.	Median	Min	Max
1 Martin Reef	84	0.28	0.18	0.02	0.26	0.08	1.44
2 Eagle Islet	84	0.23	0.12	0.01	0.20	0.07	0.67
3 North Reef	84	0.25	0.11	0.01	0.23	0.07	0.54
4 Macgillivray Reef	84	0.25	0.11	0.01	0.23	0.08	0.59
5 Blue Lagoon	76	0.30	0.13	0.01	0.27	0.09	0.58
6 Sunbird Mooring	74	0.26	0.14	0.02	0.22	0.09	0.80
7 Watson's Bay	76	0.25	0.10	0.01	0.23	0.07	0.65
8 Lizard Head	70	0.24	0.11	0.01	0.20	0.10	0.49
Overall Mean	632	0.26	0.13	0.01	0.23	0.07	1.44

Table 5.4 *Lizard*: sampling dates and prevailing weather and sea conditions

Sampling		Wind		Swell		Cloud	
Date	Stations missed	Speed *(knots)*	Direction *(degrees)*	Height *(metres)*	Direction *(degrees)*	Cover *(ˣ/8)*	Rainfall *(1–4)*
12-Jan-93	5–7	1–14	22–90	0.2–1.2	0–360	2–7	1–2
16-Feb-93	6–8	3–8	67–338	0–0.5	22–338	3–5	1–1
3-Mar-93	5,7	3–8	135–202	0–0.3	185–280	1–4	1–1
26-Apr-93		2–16	157–157	0.5–2	157–157	2–4	1–1
27-Apr-93		2–2	112–157	0.5–2	112–157	3–3	1–1
25-May-93	8	2–18	112–135	0.3–1.5	112–135	1–6	1–2
10-Jun-93		12–15	135–135	0.2–0.8	135–135	1–3	1–1
7-Jul-93		1–18	112–135	0.2–0.7	135–135	1–8	1–1
10-Aug-93		12–12	112–135	0.4–1	135–135	2–6	1–1
31-Aug-93		1–11	90–135	0.2–0.7	90–135	3–6	1–2
24-Oct-93		12–17	135–135	0.2–1	135–135	1–7	1–1
25-Oct-93		14–17	135–135	0.7–1	135–135	5–5	1–1
10-Nov-93		1–12	90–135	0.2–0.8	135–135	2–3	1–1
15-Dec-93		1–12	112–135	0.3–1	135–135	3–7	1–1
10-Jan-94		3–14	112–180	0–1	135–237	1–3	1–1
19-Feb-94	7,8	1–8	45–90	0.1–0.5	45–90	4–7	1–1
29-Mar-94		2–18	112–135	0.3–1	112–135	1–5	1–2
17-Apr-94		12–18	112–135	0.2–1.2	135–135	4–7	1–2
23-May-94		14–18	135–135	0.3–1.8	135–135	3–6	1–2
9-Jun-94		12–15	135–135	0.2–10	135–135	2–4	1–1
13-Jul-94		8–14	135–135	0.2–1	2–135	2–3	1–3
31-Jul-94		1–8	135–157	0.1–0.5	135–135	1–6	1–1
7-Sep-94	5,7,8	1–12	112–135	0.1–0.5	135–135	2–4	1–1
4-Oct-94		5–8	112–135	0.1–0.4	135–135	4–7	1–1
2-Nov-94		1–8	23–90	0–0.1	23–45	1–1	1–1
12-Dec-94		1–14	112–135	0.1–0.8	112–135	1–1	1–1
9-Jan-95		10–14	112–135	0.1–0.8	112–135	2–3	1–1
10-Feb-95		3–8	45–112	0.1–0.5	45–112	4–7	1–2
13-Mar-95		2–8	22–315	0–0.5	0–315	8–8	1–2
26-Apr-95		14–20	112–135	0.3–1	135–135	1–2	1–1
21-May-95		8–12	112–180	0.3–1	112–180	2–4	1–1
12-Jun-95		5–5	130–130	0.2–0.2	130–130	6–6	1–1
29-Jun-95		12–18	135–135	0.3–1.2	135–135	5–7	1–1
13-Jul-95		0–5	135–135	0–0.1	135–135	1–3	1–1
5-Sep-95		3–6	135–180	0–0.2	0–180	1–6	1–1
25-Sep-95		8–10	112–135	0.1–0.5	112–135	1–6	1–1
25-Oct-95		3–3	90–135	0–0.3	90–135	2–6	1–1
7-Nov-95		5–8	90–90	0.1–0.7	90–135	1–2	1–1
6-Dec-95		5–5	90–130	0.1–0.3	90–130	6–7	1–1
20-Jan-96		8–12	90–160	0.2–0.7	90–160	3–8	1–2
7-Feb-96		6–10	110–170	0.2–0.6	110–170	6–7	1–1
18-Mar-96		0–5	0–180	0–0.1	0–135	1–3	1–1
12-Apr-96		6–8	100–135	0.1–0.7	100–135	2–4	1–1
2-May-96		0–4	0–330	0–0.1	0–0	1–6	1–3

6. PORT DOUGLAS

6.1 CLUSTER DESCRIPTION

Collectors: *Reef Biosearch Pty Ltd*
Douglas Baird, Andrew Dunstan, Ibrahim Elmetri

The Port Douglas cluster of stations extends from Port Douglas to Agincourt Reef, approximately 40 km from the coast (figure 6.2). The five stations sampled were chosen primarily because they were visited weekly by vessels operated by Quicksilver Pty Ltd. Stations were sampled at ~weekly intervals from December 1992 until December 1994. Due to a change in boat availability, sampling has subsequently occurred either fortnightly or monthly. Near-bottom sampling was discontinued after July 1994 and recommenced during flood events in March 1995 and 1996.

Stations 10 and 11 lie within 13 km of the coast. Stations 20 and 21 sampled by Cairns office of the Queensland Department of Environment and Heritage (QDEH) from January 1993 to January 1994 lie in close proximity and have been grouped with stations 10 and 11. All four inshore stations are in less than 20 m water depth. Stations 12–14 are greater than 33 km from the coast adjacent to reef complexes in 30–50 m bottom depth, and are collectively grouped as offshore. Table 6.4 summarises sampling dates and the prevailing weather and sea conditions. Significantly no samples were collected in August, October and November 1995.

Table 6.1 *Port Douglas sampling stations*: location, mean depth and distance from mainland

Station		Location (dec. degrees)		Mean depth	km to mainland
ID	Name	Longitude	Latitude	(metres)	
	Inshore				
10	Near Port Douglas	145.46	16.49	5.6	2.0
11	Low Isles	145.54	16.37	19.1	13.8
20	Port Douglas 2 (QDEH)	145.50	16.43	14.2	10.7
21	Low Isles 2 (QDEH)	145.61	16.42	16.1	18.2
	Offshore				
12	Undine Reef	145.54	16.10	22.9	33.5
13	Inside Agincourt 4 Reef	145.81	15.97	21.2	39.1
14	Outside Agincourt 4 Reef	145.88	15.95	81.9	47.6

6.2 HYDROGRAPHIC CONDITIONS

Salinity and temperature data were collected throughout 1993, but only intermittently because the SCT meter malfunctioned (figures 6.1, 6.3). In 1993 inshore and offshore temperature profiles were similar, ranging from 21.5–31.5°C (figure 6.1).

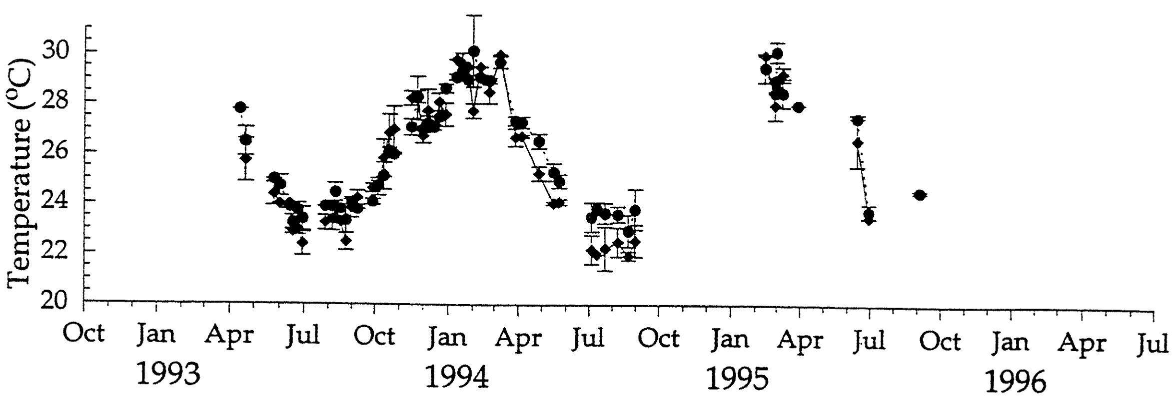

Figure 6.1 *Port Douglas*: mean (± 1 S.D.) monthly surface temperature (°C) at inshore (◆) and offshore (●) stations

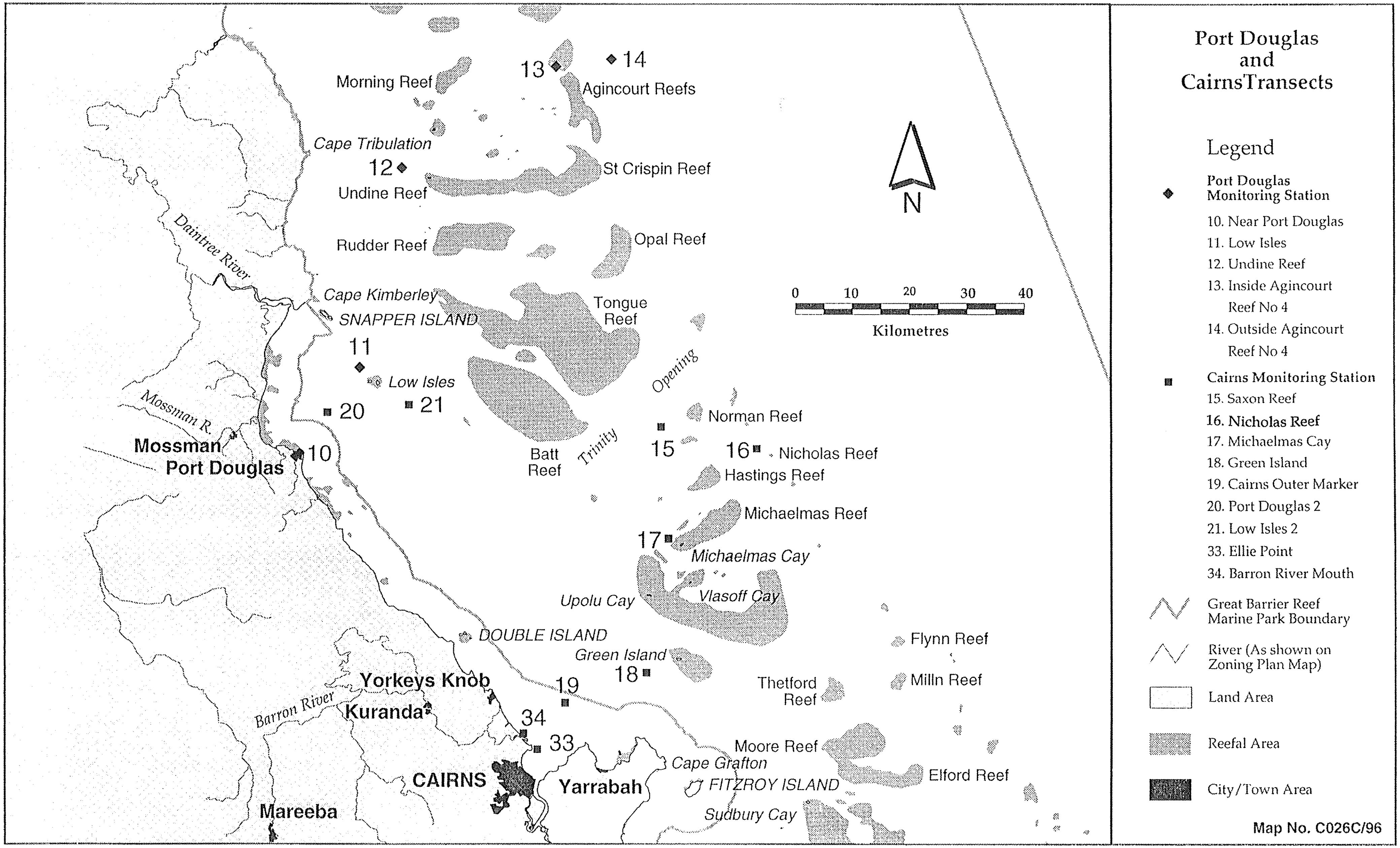

Figure 6.2 Map showing location of stations in the Port Douglas cluster

The 1993 salinity data is dubious given the implausible range of 22‰ to 40‰ (figure 6.3).

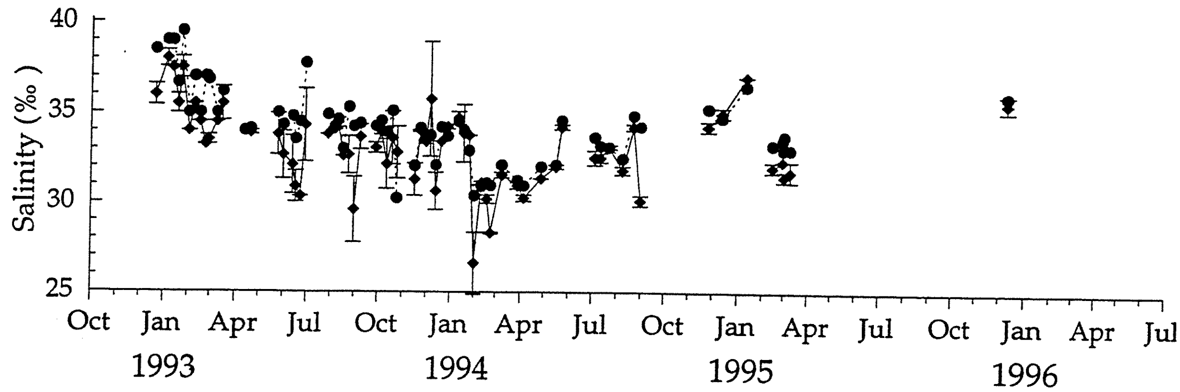

Figure 6.3 *Port Douglas*: mean (± 1 S.D.) monthly surface salinity (‰) at inshore (◆) and offshore (●) stations

Secchi depth ranged from 7.5–40.0 m at offshore stations and 0.1–20.0 m inshore (figure 6.4). There was no linear relationship between Secchi depth and chlorophyll concentration at either inshore ($R^2 = 0.38$) or offshore ($R^2 = 0.07$) stations.

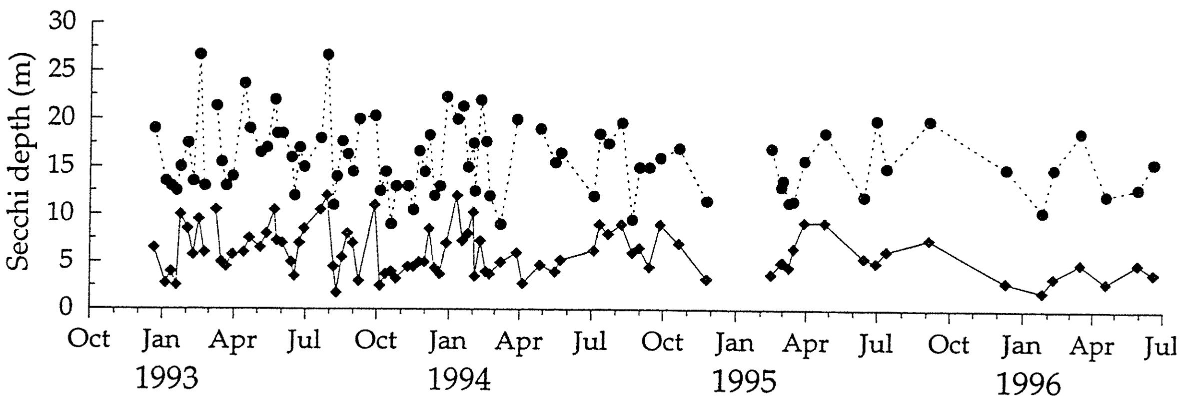

Figure 6.4 *Port Douglas*: mean monthly Secchi depth (metres) at inshore (◆) and offshore (●) stations. Error bars omitted for clarity.

Trichodesmium was recorded in 6.8% of sampling observations throughout this cluster. *Trichodesmium* were observed more frequently at inshore stations, and were most common from November to January. *Trichodesmium* were not recorded from March to October of each year, and interestingly, not at all in 1994.

6.3 CHLOROPHYLL CONCENTRATIONS

Mean chlorophyll *a* concentrations at inshore stations were 0.45 µg L^{-1} – nearly twofold greater than offshore stations (table 6.3).

Temporal changes in chlorophyll *a* concentrations at inshore and offshore stations were only superficially similar; the very large weekly variation at inshore stations obscured any clear pattern (figure 6.5).

Inshore stations

Chlorophyll *a* concentrations ranged from 0.03–2.49 µg L^{-1} with a median of 0.48 µg L^{-1} (table 6.3). Median annual concentrations were higher in 1993 (0.46 µg L^{-1}) than 1994 (0.39 µg L^{-1}) and 1995 (0.41 µg L^{-1}). From June to September chlorophyll *a* concentrations were less than 0.5 µg L^{-1} (figure 6.6).

Table 6.2 *Port Douglas*: Annual summary statistics of temperature, salinity and chlorophyll *a* concentrations at inshore and offshore stations

	Temperature (°C)			Salinity (‰)			Chlorophyll *a* (µg L⁻¹)		
	Min	Median	Max	Min	Median	Max	Min	Median	Max
Inshore	21.5	25.6	30.2	22.0	33.5	40.0	0.03	0.45	2.49
1993	22.0	24.8	29.9	24.8	33.8	40.0	0.11	0.46	1.73
1994	21.5	26.7	30.2	22.0	32.1	37.8	0.03	0.39	2.49
1995	23.5	28.3	30.0	31.0	32.8	37.0	0.08	0.41	1.16
Offshore	22.4	26.0	31.4	28.9	34.2	40.0	0.04	0.24	1.68
1993	22.9	24.9	28.8	29.0	34.8	40.0	0.07	0.25	0.90
1994	22.4	27.15	31.4	28.9	32.8	36.1	0.04	0.20	0.79
1995	23.5	28.0	30.5	32.5	33.5	36.5	0.10	0.21	1.68

Table 6.3 *Port Douglas*: summary statistics of chlorophyll *a* concentrations

	Chlorophyll *a* concentration (µg·L⁻¹)						
Station	N	Mean	S.D.	S.E.	Median	Min	Max
Inshore	318	0.58	0.41	0.02	0.48	0.03	2.49
10 Port Douglas	159	0.81	0.43	0.03	0.80	0.08	2.49
20 Port Douglas 2	24	0.38	0.19	0.04	0.34	0.09	0.89
11 Low Isles	159	0.36	0.22	0.02	0.31	0.03	1.37
21 Low Isles 2	22	0.27	0.15	0.03	0.22	0.10	0.63
Offshore	378	0.28	0.18	0.01	0.24	0.04	1.68
12 Undine Reef	155	0.32	0.18	0.01	0.28	0.09	1.03
13 Inner Agincourt	146	0.22	0.12	0.01	0.20	0.04	1.08
14 Outer Agincourt	54	0.30	0.25	0.03	0.24	0.05	1.68
Overall Mean	696	0.42	0.34	0.01	0.29	0.03	2.49

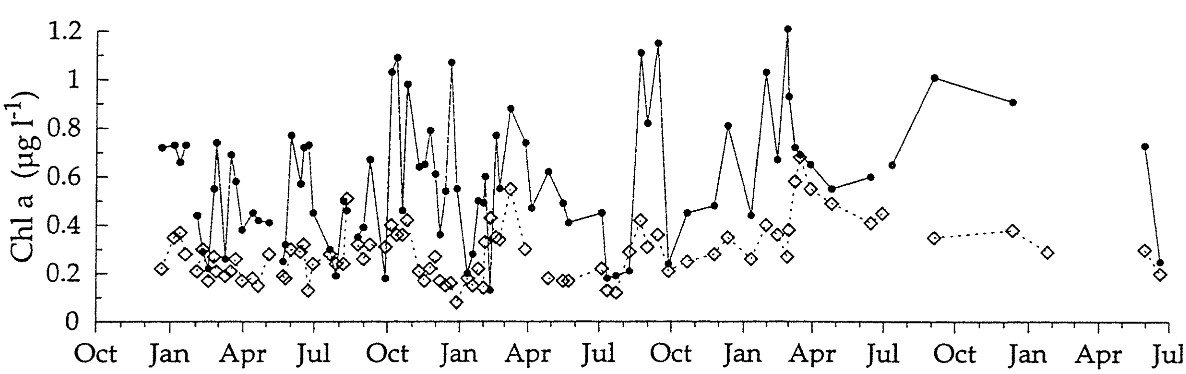

Figure 6.5 *Port Douglas*: mean monthly surface chlorophyll *a* concentration (µg L⁻¹) at inshore (●) and offshore (◊) stations. Error bars omitted for clarity.

Chlorophyll *a* concentrations were highest during February–April, but there was no consistent between year pattern. At station 10, 2 km from Port Douglas, chlorophyll *a* concentrations ranged from 0.4–2.1 µg L⁻¹ with a median of 0.80 µg L⁻¹ (table 6.3). At the other three inshore stations median concentrations were 0.22–0.34 µg L⁻¹. At station 10 (figure 6.7a) high concentrations were measured in August 1994 (2.1 µg L⁻¹) and March 1995 (1.5 µg L⁻¹). High concentrations were measured at station 11 in February 1994 and January 1996 (figure 6.7c). These 'bloom' concentrations were short-lived and not usually present on the following sampling occasion.

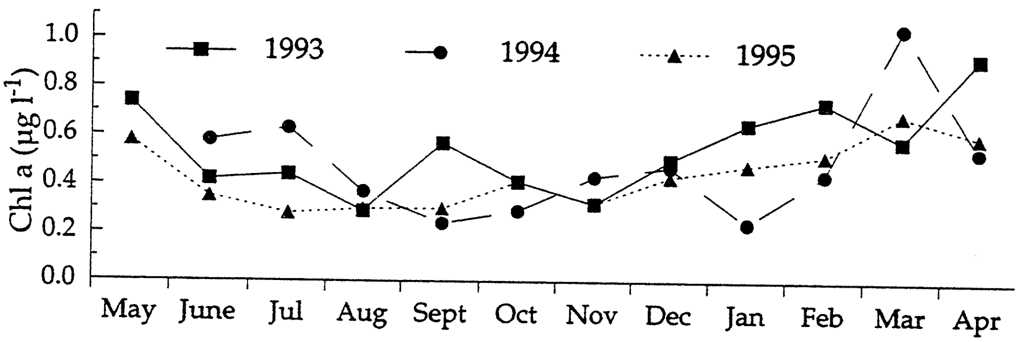

Figure 6.6 *Inshore Port Douglas stations*: median monthly chlorophyll *a* concentrations (μg L^{-1}) in 1993–95

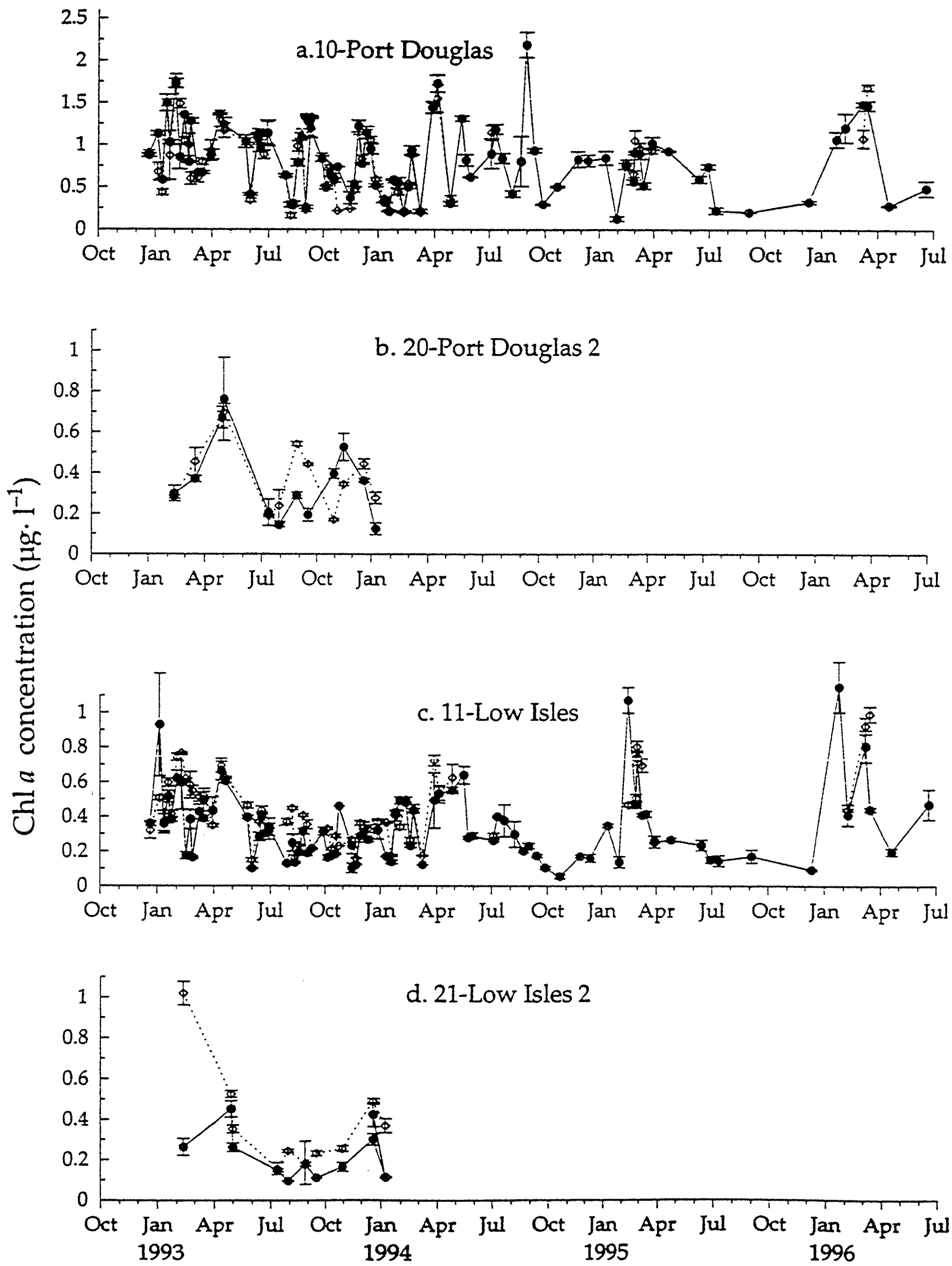

Figure 6.7 *Inshore Port Douglas stations*: mean (± 1 S.E.) monthly near-surface (●) and near-bottom (◊) chlorophyll *a* concentrations (μg L^{-1})

Comparison of the monthly sampling at stations 20 and 21 with stations 10 and 11 demonstrated that the monthly sampling did not reflect the short-term variability in chlorophyll *a* concentrations detected in the weekly sampling (figure 6.7). Comparison of near-bottom chlorophyll *a* concentrations to surface values ranged from 0.0–1.08 μg L^{-1}.

Offshore stations

Chlorophyll *a* concentrations varied from 0.04–1.68 μg L^{-1}, with a median of 0.24 μg L^{-1} (table 6.3). Similar to inshore stations, median chlorophyll *a* concentrations were considerably higher in 1993 (0.25 μg L^{-1}) than in 1994 (0.20 μg L^{-1}) and 1995 (0.21 μg L^{-1}). Monthly median chlorophyll *a* values 1993–1995 were similar (figure 6.8). Chlorophyll *a* concentrations were less than 0.3 μg L^{-1} from May–December, and increased during January–April; they were, however, seldom greater than 0.4 μg L^{-1}.

Station 12 had a higher median concentration (0.28 μg L^{-1}) than stations 13 (0.20 μg L^{-1}) and 14 (0.24 μg L^{-1}) close to Agincourt Reef. High chlorophyll *a* concentrations were recorded at all three stations in February and March 1993, and in March 1996 (figure 6.9). No significant 'bloom' concentrations occurred throughout 1994 and 1995.

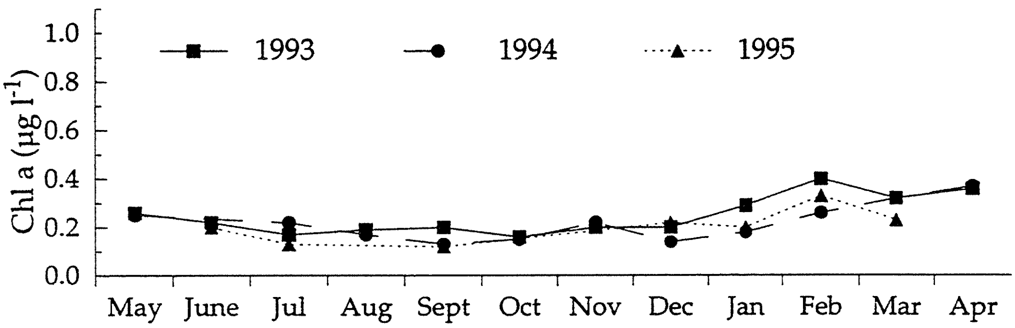

Figure 6.8 *Offshore Port Douglas*: median monthly chlorophyll *a* concentrations (μg L^{-1}) in 1993–95

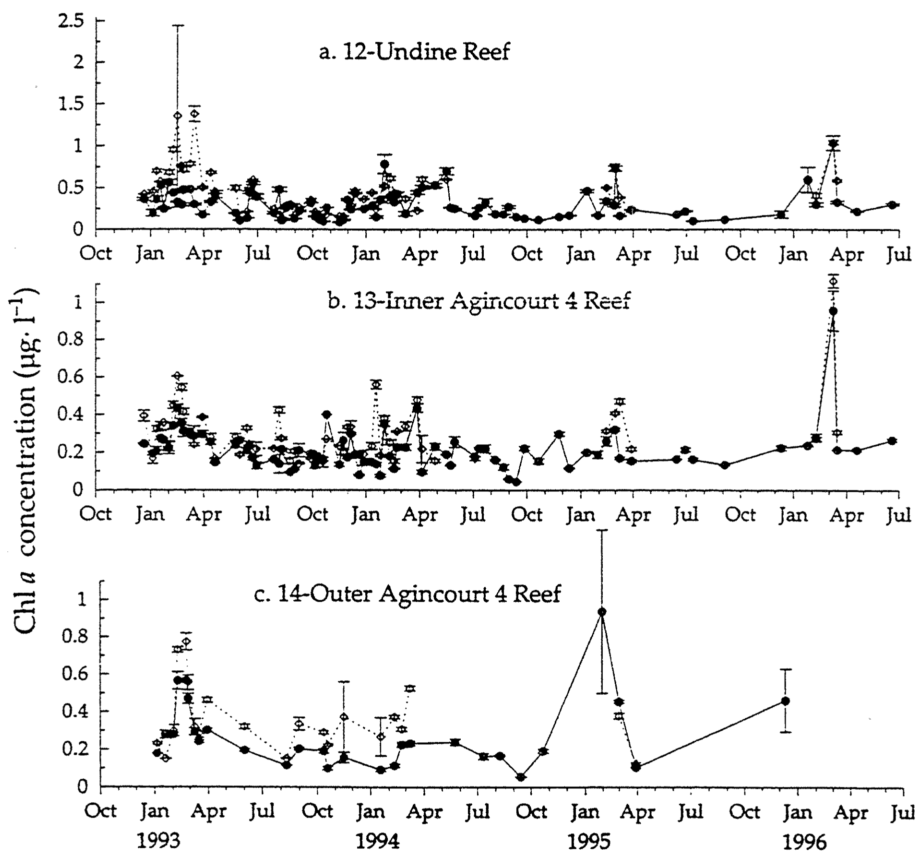

Figure 6.9 *Offshore Port Douglas stations*: mean (± 1 S.E.) monthly near-surface (●) and near-bottom (◊) chlorophyll *a* concentrations (μg L^{-1})

Table 6.4 *Port Douglas*: Sampling dates and prevailing weather and sea conditions

Sampling		Wind		Swell		Cloud	
Date	Stations missed	Speed *(knots)*	Direction *(degrees)*	Height *(metres)*	Direction *(degrees)*	Cover *(ˣ/8)*	Rainfall *(1–4)*
21-Dec-92		25–25	–	1.5–1.5	–	8–8	3–4
5-Jan-93		0.5–0.5	–	0–0.25	–	1–1	1–1
12-Jan-93		3–6.5	0–315	0.2–0.5	0–45	3–8	1–1
19-Jan-93		3–12	90–110	0.2–2	90–110	7–8	1–2
24-Jan-93		2–9	90–140	0.2–1	90–95	7–8	1–3
2-Feb-93		15–22	130–150	0.6–3	90–150	7–8	1–4
9-Feb-93		2.5–5	50–120	0.2–3	50–120	5–7	1–1
16-Feb-93		2–15	30–150	0.2–0.4	70–150	7–8	1–1
23-Feb-93		1–5.5	20–320	0.1–0.8	20–320	4–8	1–2
26-Feb-93		4–6	90–150	0.1–0.5	50–50	1–3	1–1
9-Mar-93		8–18	110–140	0.3–2	110–140	1–3	1–1
16-Mar-93		2–4	40–280	0.1–2	40–280	1–1	1–1
22-Mar-93	12,13	5–15	110–140	0.3–1	110–140	1–2	1–1
24-Mar-93	10,11,14	15–15	140–140	2–2	140–140	1–1	–
30-Mar-93		4–9	120–130	0.1–1	80–130	1–4	1–1
13-Apr-93		15–18	120–130	0–1.1	110–130	1–2	1–1
20-Apr-93		24–26	120–130	0.5–1.2	90–130	5–7	1–2
4-May-93	10–12	3–10	130–135	0.2–0.4	135–135	6–6	1–1
5-May-93	13	15–15	135–135	0.5–0.5	135–135	3–3	1–1
12-May-93	10–14	5–8	120–150	0.3–3	80–140	3–3	1–1
22-May-93	10–13	15–21	225–225	1–1.5	225–225	3–8	1–3
25-May-93		6–6	–	0.2–0.2	–	4–8	1–2
1-Jun-93		8–12	120–165	0.1–2	75–165	1–3	1–1
13-Jun-93		3–15	135–135	0.1–0.3	135–135	1–3	1–1
17-Jun-93		15–24	110–130	0.1–0.8	100–120	7–7	1–3
23-Jun-93		20–20	120–150	0.3–0.8	110–150	1–6	1–1
29-Jun-93		20–22	120–135	0.5–0.8	90–120	1–3	1–1
20-Jul-93	10–13	10–18	120–130	0.1–0.6	90–130	3–4	1–2
28-Jul-93		5.5–12	170–240	0.1–0.3	160–170	1–5	1–1
6-Aug-93		14–20	130–140	0.3–0.9	90–140	1–2	1–1
10-Aug-93		3–10	130–180	0.1–1.4	120–180	1–2	1–1
17-Aug-93		2–12	90–140	0.2–0.5	90–140	1–1	1–1
24-Aug-93		12–16	140–160	0.2–0.8	70–160	7–8	1–2
31-Aug-93		4–7.5	120–130	0.1–0.2	90–130	1–4	1–1
8-Sep-93		10–12	120–130	0.1–0.9	90–130	5–8	1–1
18-Sep-93	10,11,13,14	1.5–6	60–180	0.1–0.1	60–80	1–4	1–1
28-Sep-93		10–22	120–130	0.2–1	80–120	3–8	1–2
5-Oct-93		2–20	135–145	0.4–0.6	135–145	2–8	1–2
12-Oct-93		5–6.5	90–120	0.1–1	90–120	1–2	1–1
19-Oct-93		4–7	70–130	0.2–1.2	70–110	1–4	1–1
25-Oct-93		6–10	120–140	0.1–0.4	90–140	3–4	1–1
9-Nov-93	10,11,13	8–12	80–110	0.2–0.5	80–110	1–7	1–1
16-Nov-93		7–10	90–90	1–1	90–90	1–2	1–1
23-Nov-93		5–12	30–90	0.01–0.1	30–90	1–4	1–1
30-Nov-93		20–25	90–130	0.8–1.2	90–130	6–8	1–3
6-Dec-93		15–22	135–135	0.3–1.7	135–135	1–1	1–1
13-Dec-93		18–25	110–130	0.3–1.3	100–130	3–8	1–1
20-Dec-93		9–20	90–120	0.3–1	110–120	1–5	1–1
28-Dec-93		6–8	160–180	0.1–0.1	160–160	2–7	1–1
11-Jan-94		4–12	90–180	0.1–0.2	90–140	6–8	1–1
18-Jan-94		3–6	160–320	3–3	120–120	1–1	1–1
25-Jan-94		15–18	130–150	0.3–1	80–150	2–7	1–1
1-Feb-94		3–4	260–320	0.5–0.5	320–320	8–8	1–1
3-Feb-94	10–14	3–18	10–350	0.5–0.5	10–350	1–2	1–1
10-Feb-94		6–14	110–130	0.1–1.5	70–130	5–8	1–2

Table 6.4 (continued)

Sampling		Wind		Swell		Cloud	
Date	Stations missed	Speed *(knots)*	Direction *(degrees)*	Height *(metres)*	Direction *(degrees)*	Cover *(x/8)*	Rainfall *(1–4)*
17-Feb-94		12–16	80–130	0.2–0.8	75–110	5–7	1–2
22-Feb-94		5–15	80–240	0.2–1.1	70–120	8–8	2–3
8-Mar-94		4–8	110–140	0.5–0.7	80–80	2–7	1–1
28-Mar-94		18–20	130–140	0.2–1.1	90–140	1–6	1–2
5-Apr-94		18–20	110–140	0.1–0.9	90–120	3–6	1–1
27-Apr-94		15–24	120–130	0.3–0.7	110–140	8–8	1–2
16-May-94		8–20	160–160	0.2–0.7	100–160	7–8	1–1
23-May-94		12–16	130–140	0.1–3	80–140	2–2	1–1
4-Jul-94		18–25	80–140	0.2–1.5	80–110	3–8	1–2
11-Jul-94		2–14	130–150	0.1–0.2	90–150	1–4	1–1
22-Jul-94		15–18	140–140	0.2–0.3	100–140	1–4	1–1
8-Aug-94		3–15	120–150	0.01–2	90–150	1–1	1–1
22-Aug-94		5–14	140–270	0.2–0.8	100–150	4–8	1–1
31-Aug-94		16–20	130–140	0.1–0.7	100–140	4–8	1–3
13-Sep-94		5–10	110–120	0.1–2	70–120	1–3	1–1
27-Sep-94		15–18	330–340	0.3–0.3	330–340	1–1	1–1
21-Oct-94		3–5	135–160	1–1	100–100	1–1	1–1
25-Nov-94		15–15	68–160	0.5–1	68–160	4–5	1–1
12-Dec-94		5–8	120–120	0.1–0.2	120–120	1–2	1–1
11-Jan-95		18–20	110–120	0.3–0.8	80–140	3–8	1–2
30-Jan-95		5–10	320–340	0.5–0.8	340–340	1–1	1–1
14-Feb-95		3–5	5–54	0.01–0.01	5–5	5–7	1–1
27-Feb-95	13	5–15	135–135	0.5–1	135–135	8–8	2–2
28-Feb-95		–	–	–	–	8–8	1–1
1-Mar-95		10–18	135–135	0.5–0.5	135–135	7–8	1–2
9-Mar-95		5–15	320–350	0.5–1.2	10–10	5–6	1–1
15-Mar-95		15–15	135–135	1–1	135–135	6–6	1–1
29-Mar-95		2–10	130–140	0.25–1.2	90–190	1–3	1–1
25-Apr-95	12,13	5–15	110–150	0.01–0.2	150–150	1–2	1–1
14-Jun-95		6–12	135–135	0.25–0.5	135–135	1–1	1–1
29-Jun-95		10–25	135–135	0.75–2	134–135	1–4	1–1
12-Jul-95		8–10	225–225	0.25–0.3	225–225	1–1	1–1
4-Sep-95		3–5	135–135	0.1–0.2	135–135	1–2	1–1
11-Dec-95		0–5	45–45	0–0.4	45–45	1–1	1–1
25-Jan-96		5–5	90–90	0–0	–	5–7	1–1
8-Feb-96		0–3	45–45	0.1–0.2	45–135	7–7	1–1
15-Mar-96		8–12	113–113	0.4–0.5	113–113	5–7	1–1
19-Apr-96		2–5	135–158	0.2–0.4	135–160	7–7	1–1
30-May-96		5–10	135–135	0.2–0.5	135–135	1–1	1–1
19-Jun-96		10–15	135–135	0.3–1.5	113–135	2–7	1–1

7. CAIRNS

7.1 CLUSTER DESCRIPTION

Collectors: *Queensland Department of Environment and Heritage, Far Northern Region*

Michael Short, Sarah Strawbridge

Seven stations are currently sampled between the mouth of Trinity Inlet and the shelf-break some 58 km offshore (figure 7.2). Stations 20 and 21 were discontinued in July 1993 in favour of sampling adjacent to the mouth of Trinity Inlet (33) and the Barron River (34). This was to support and complement river catchment monitoring by the Queensland Department of Environment and Heritage 'Ambient Water Quality Monitoring' project. The present configuration thus comprises an inshore group of stations (19, 33 and 34) within 20 km of the coast and an offshore group (15, 16, 17, 18) located 35–58 km from the coast, along the southern side of Trinity Opening (figure 7.2). Near-bottom sampling was discontinued after April 1994. Sampling often occurs over two-day cruises as other day-to-day management activities are undertaken. Sampling dates and prevailing weather and sea conditions are given in table 7.4.

Table 7.1 *Cairns sampling stations*: location, mean depth and distance from mainland

Station		Location (dec. degrees)		Mean depth	km to mainland
ID	Name	Longitude	Latitude	(metres)	
	Inshore				
19	Cairns Outer Marker	145.51	16.51	9.9	8.0
33	Ellie Point–Lyons Point	145.50	16.55	4.8	0.6
34	Barron River Mouth	145.48	16.52	5.5	1.6
	Offshore				
15	Saxon Reef	145.59	16.28	48.1	47.2
16	Nicholas Reef	145.05	16.30	57.6	58.0
17	Michaelmas Cay	145.60	16.37	22.2	36.3
18	Green Island	145.58	16.49	34.0	20.5

7.2 HYDROGRAPHIC CONDITIONS

Temperature and salinity profiles are inaccurate due to calibration problems with the SCT meter particularly in 1995 (figures 7.2, 7.3). Temperatures ranged between 21°C and 30°C (table 7.2). Temperatures were generally similar between inshore and offshore groups, though winter minima were less at inshore stations.

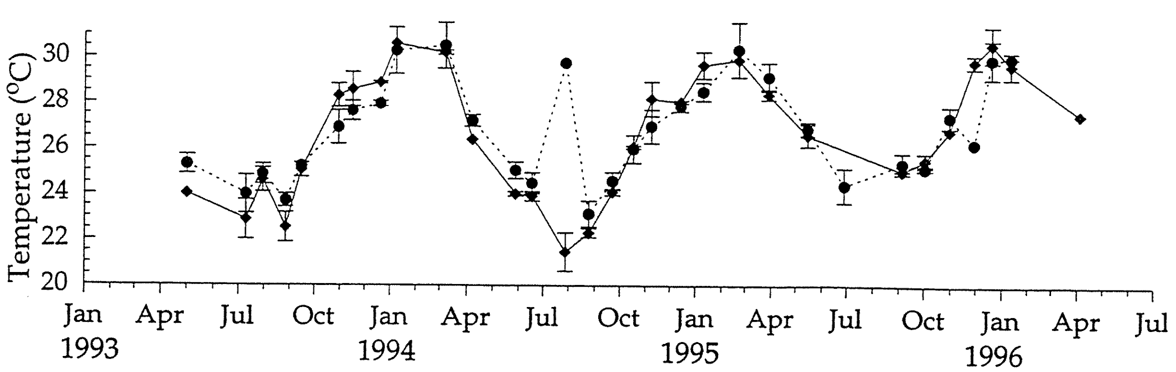

Figure 7.1 *Cairns*: mean (± 1 S.D.) monthly surface temperature (°C) at inshore (◆) and offshore (●) stations

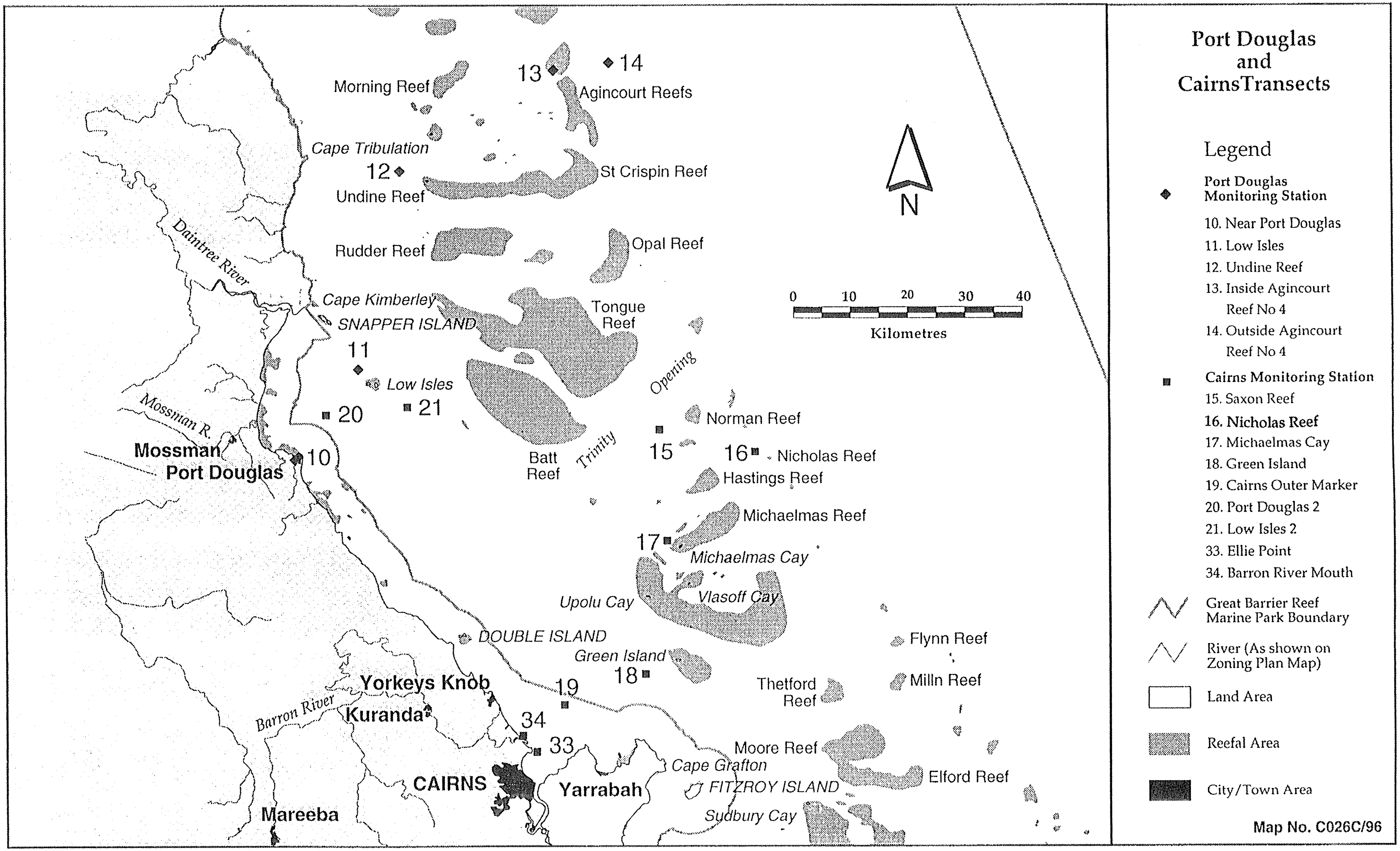

Figure 7.2 Map showing location of stations in the Cairns cluster

The salinities plotted in figure 7.3 show a steady downwards drift indicating calibration problems. The meter was recalibrated in August 1995 but salinities are still lower than expected. The summary salinity values given in table 7.2 are of dubious value.

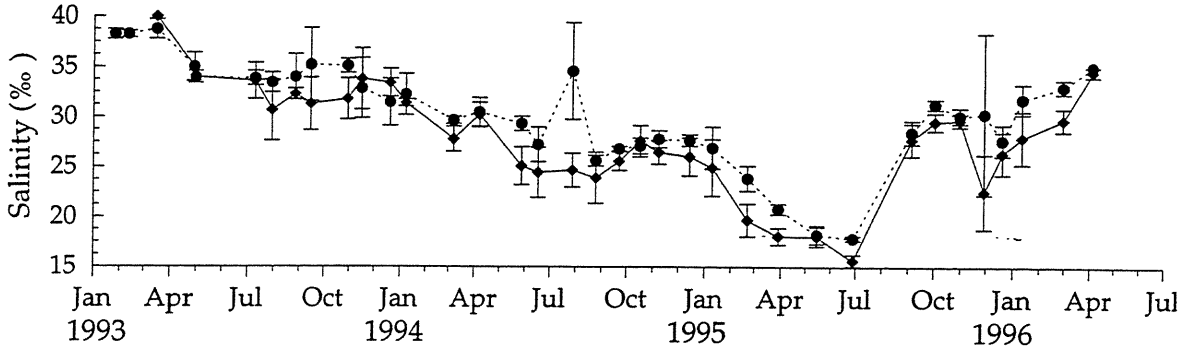

Figure 7.3 *Cairns*: mean (± 1 S.D.) monthly surface salinity (‰) at inshore (◆) and offshore (●) stations

Secchi depth ranged between 5 and 30 m at offshore stations but was less than 5 m inshore (figure 7.4). There was no significant linear relationship between Secchi depth and chlorophyll *a* concentration at inshore ($R^2 = 0.24$) or offshore ($R^2 = 0.09$) stations.

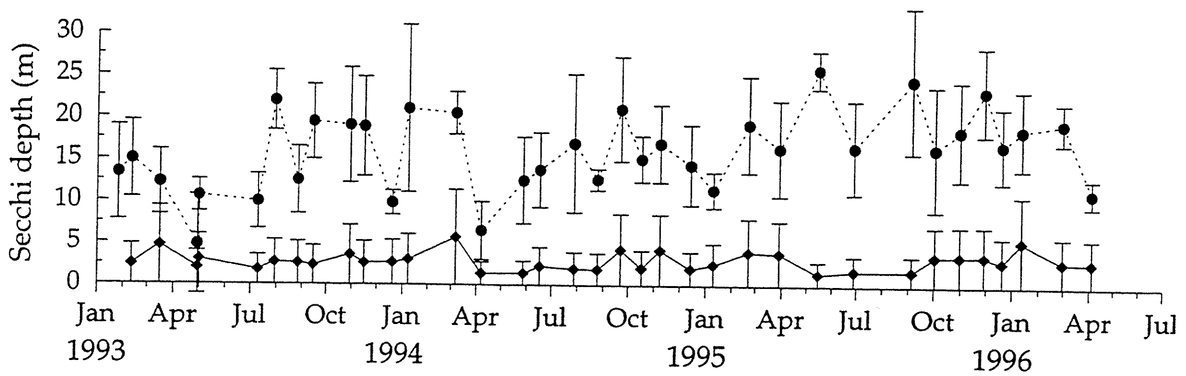

Figure 7.4 *Cairns*: mean (± 1 S.D.) monthly Secchi depth (metres) at inshore (◆) and offshore (●) stations

Trichodesmium was recorded as present on 8.3% of sampling observations, generally during October to March.

Table 7.2 *Cairns*: Annual summary statistics of temperature, salinity and chlorophyll *a* concentrations at inshore and offshore stations

	Temperature (°C)			Salinity (‰)			Chlorophyll *a* (µg L^{-1})		
	Min	Median	Max	Min	Median	Max	Min	Median	Max
Inshore	20.5	26.65	31.8	15.0	28.7	40.0	0.07	0.46	3.50
1993	21.8	25.0	29.9	27.2	33.5	40.0	0.13	0.51	3.50
1994	20.5	26.0	31.8	21.0	27.0	37.8	0.07	0.46	1.62
1995	22.5	27.9	32.0	15.0	24.6	30.9	0.15	0.47	1.84
Offshore	15.5	27.0	37.0	17.5	30.5	40.0	0.03	0.17	1.27
1993	23.5	25.2	28.0	28.9	34.9	40.0	0.08	0.24	1.27
1994	23.3	26.9	–	25.1	28.5	37.0	0.05	0.16	0.66
1995	15.5	27.0	30.3	17.5	26.6	39.1	0.03	0.12	0.45

7.3 CHLOROPHYLL CONCENTRATIONS

At inshore stations, median surface chlorophyll *a* concentrations were 0.50 ± 0.49 μg L^{-1} and ranged from 0.04–3.50 μg L^{-1} (table 7.2). Maximum concentrations for the entire sampling period were recorded during 1993 in three significant but short-lived events: March (0.73 μg L^{-1}); September (1.4 μg L^{-1}); November (0.96 μg L^{-1}). In April 1994, chlorophyll *a* concentrations of 0.66 μg L^{-1} were recorded. This 'bloom' appears to have been regional as high concentrations were recorded over all stations (figures 7.5, 7.6, 7.8). Median chlorophyll *a* concentrations were lowest in 1995 (0.11 μg L^{-1}) and varied little (0.05–0.24 μg L^{-1}) compared to 1994 and 1995 (table 7.2).

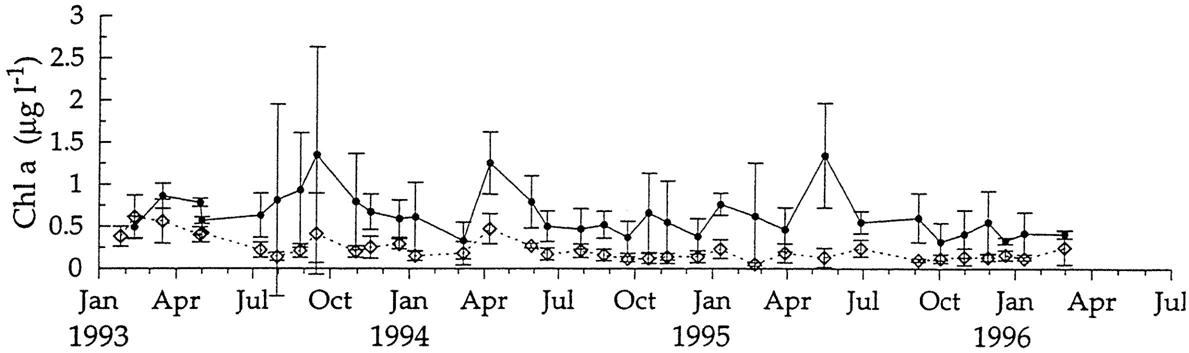

Figure 7.5 *Cairns*: mean (± 1 S.D.) monthly surface chlorophyll concentration (μg·L^{-1}) at inshore (◊) and offshore (●) stations

Inshore stations

Median concentrations varied ~fivefold between stations (table 7.3); they were greatest at station 33 (0.82 μg L^{-1}) and least at station 19 (0.30 μg L^{-1}). In 1994 there was little seasonal variation in chlorophyll *a* concentrations compared to 1993 and 1995 (figure 7.6). Chlorophyll *a* concentrations were greatest in April 1993 and in May 1995.

Table 7.3 *Cairns*: summary statistics of chlorophyll *a* concentrations

	Chlorophyll *a* concentration (μg L^{-1})						
Station	N	Mean	S.D.	S.E.	Median	Min	Max
Inshore	282	0.51	0.49	0.03	0.36	0.04	3.5
19 Outer Marker	70	0.36	0.21	0.02	0.30	0.07	0.94
33 Ellie Point	59	1.04	0.74	0.10	0.82	0.20	3.50
34 Barron River	60	0.56	0.32	0.04	0.46	0.18	1.76
Offshore	198	0.22	0.17	0.01	0.17	0.03	1.27
15 Saxon Reef	70	0.19	0.14	0.02	0.15	0.05	0.96
16 Nicholas Reef	56	0.21	0.23	0.03	0.14	0.03	1.27
17 Michaelmas Cay	72	0.25	0.14	0.02	0.21	0.04	0.73
18 Green Island	70	0.21	0.13	0.02	0.17	0.04	0.62
Overall Mean	480	0.39	0.42	0.02	0.26	0.03	3.50

Mean chlorophyll *a* concentrations were greatest at station 33 in July (3.50 μg L^{-1}) and September (3.41 μg L^{-1}) 1995 (figure 7.7). These bloom concentrations were short-lived and not detected at the other two inshore stations. Variability between duplicate samples ranged from 0.00–0.43 μg L^{-1}, with a median of 0.03 μg L^{-1}, or 8% of variance.

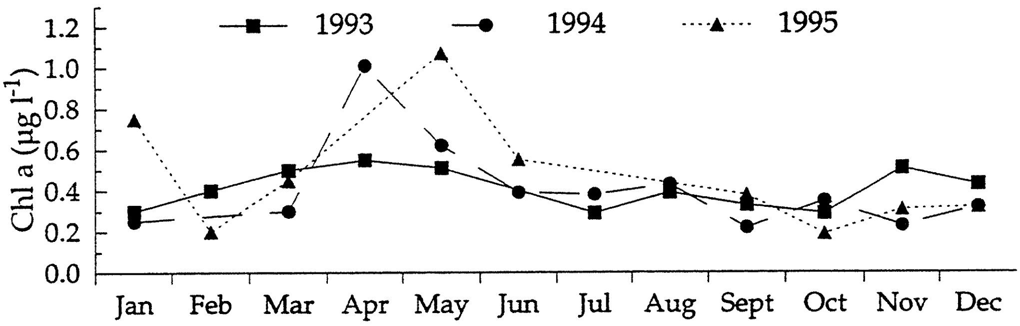

Figure 7.6 *Inshore Cairns stations*: median monthly chlorophyll *a* concentrations (µg·L^{-1}) in 1993–95

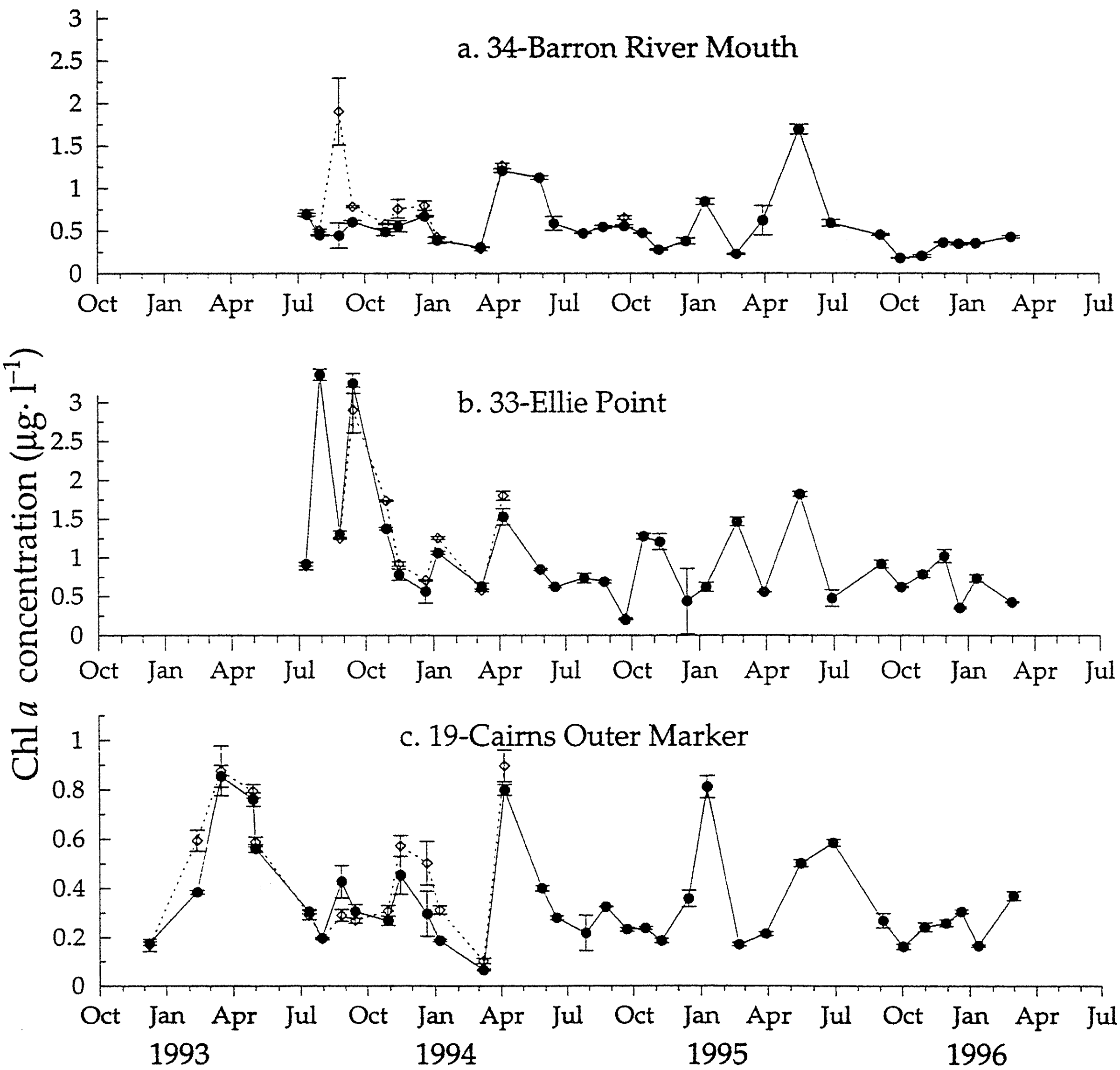

Figure 7.7 *Inshore Cairns stations*: Mean monthly (± 1 S.E.) near-surface (●) and near-bottom (◊) chlorophyll *a* concentrations (µg L^{-1})

Offshore stations

Across four stations median chlorophyll *a* concentrations ranged from 0.03–1.27 µg L^{-1} with a median of 0.17 µg L^{-1} (table 7.3). There was significant interannual variability; chlorophyll *a* concentrations declined from 0.24 µg L^{-1} in 1993 to 0.11 µg L^{-1} in 1995 (table 7.3).

Highest chlorophyll *a* concentrations usually occurred from January–April (figure 7.9), but this was not consistent among years (table 7.2). Variability between duplicate samples was 0.00–0.43 μg L^{-1}, with a median of 0.01 μg L^{-1} or 6% of variance.

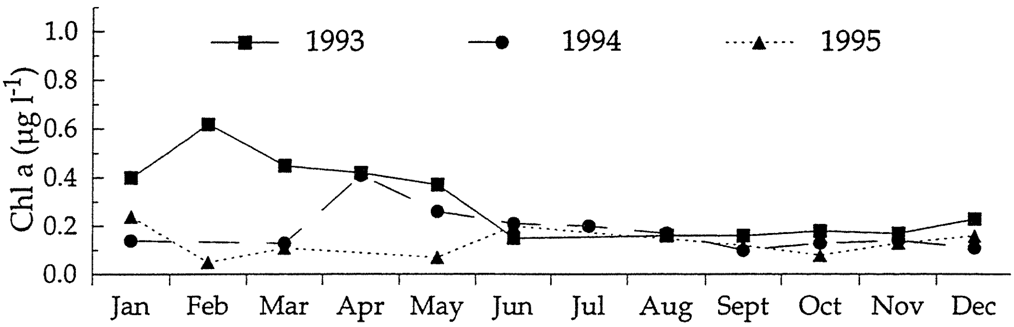

Figure 7.8 *Offshore Cairns stations*: median monthly chlorophyll *a* concentrations (μg L^{-1}) in 1993–95

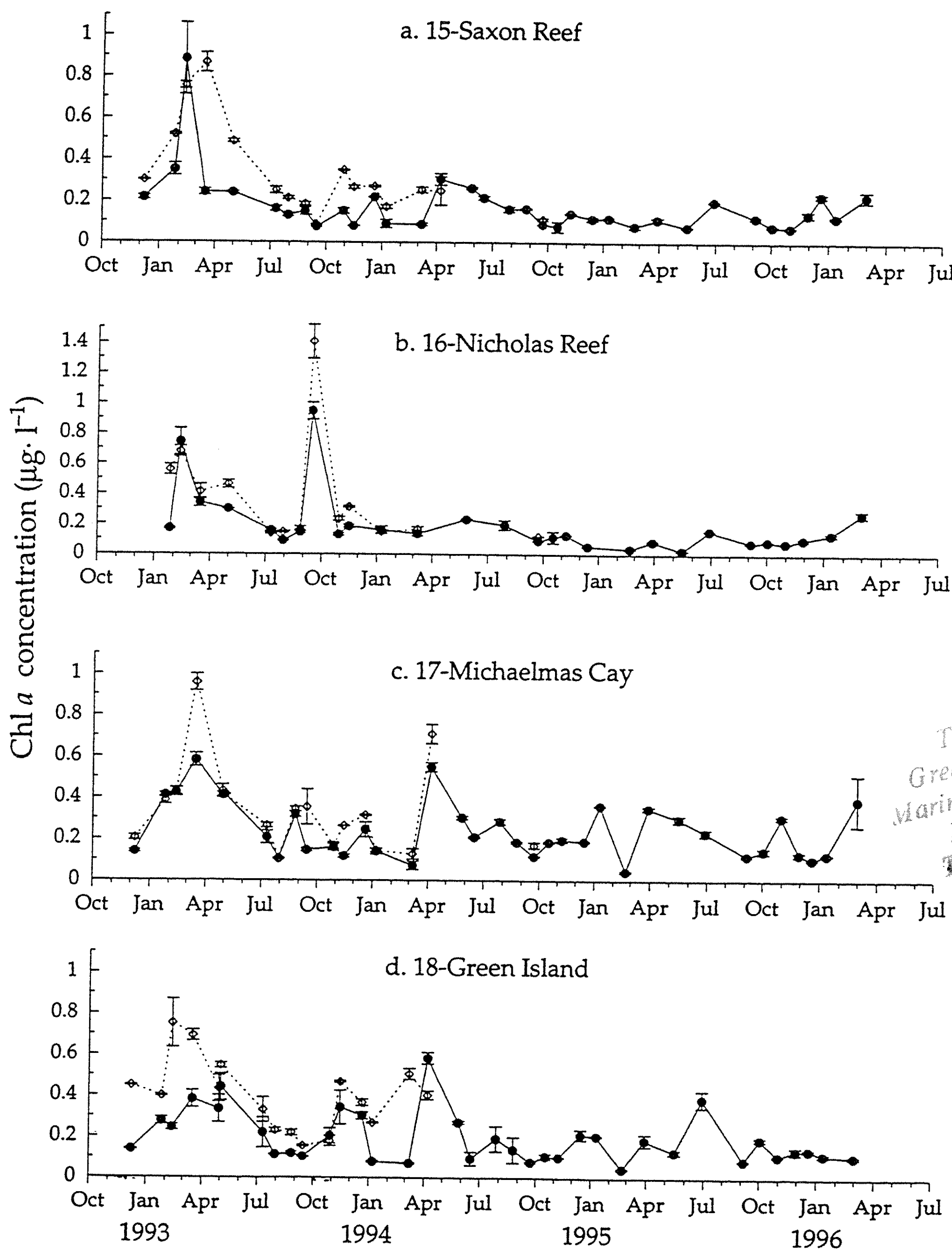

Figure 7.9 *Offshore Cairns stations*: mean (± 1 S.E.) monthly near-surface (●) and near-bottom (◊) chlorophyll *a* concentrations (μg L^{-1})

Table 7.4 *Cairns*: sampling dates and prevailing weather and sea conditions

Sampling		Wind		Swell		Cloud	
Date	Stations missed	Speed *(knots)*	Direction *(degrees)*	Height *(metres)*	Direction *(degrees)*	Cover *(x/8)*	Rainfall *(1–4)*
26-Jan-93		10–10	–	0.5–1.2	–	2–5	1–1
11-Feb-93		0–10	0–200	0.2–0.5	45–200	5–7	1–1
12-Feb-93		0–5	140–140	0–0	4–4	3–4	1–1
16-Mar-93		5–10	0–225	0–0.5	0–45	1–7	1–1
28-Apr-93		15–25	135–135	1–2	135–135	7–8	1–1
29-Apr-93		20–20	135–135	0.5–1.2	135–135	6–6	1–1
1-May-93		10–15	135–180	0.2–1.5	135–180	1–8	1–1
2-May-93		10–10	135–135	0.2–0.2	135–135	1–3	1–1
10-Jul-93		10–18	135–135	0–2	0–135	3–8	1–1
12-Jul-93		10–15	135–135	0.5–1	135–135	1–1	1–1
29-Jul-93		5–5	135–135	0.2–0.3	135–135	1–1	1–1
30-Jul-93		5–15	135–135	0.3–1	135–135	1–3	1–1
26-Aug-93		10–15	135–135	0.2–1	135–135	3–6	1–1
27-Aug-93		8–15	90–135	0.2–1.5	90–135	3–8	1–1
14-Sep-93		5–10	135–135	0.05–0.3	135–135	1–2	1–1
15-Sep-93		8–10	135–135	0.3–1.5	135–135	1–4	1–1
29-Oct-93		1–2.7	20–20	0.3–0.4	20–20	1–1	1–1
30-Oct-93		2.3–5.5	0–0	0.2–0.5	0–0	1–1	1–1
15-Nov-93		1–5.3	50–90	0.15–0.3	50–90	1–3	1–1
16-Nov-93		0.3–2.5	50–135	0–0.3	50–135	1–5	1–1
20-Dec-93		12–15	135–135	0.5–1.4	135–135	2–7	1–1
21-Dec-93		5–10	90–135	0.2–0.4	90–135	2–2	1–1
7-Jan-94		0.5–5	0–70	0.05–0.7	0–70	1–2	1–1
8-Jan-94		2–5.5	360–360	0.3–0.6	360–360	1–1	1–1
7-Mar-94		2–5	90–90	0–0.2	0–160	1–2	1–1
8-Mar-94		5–5	90–90	0.2–0.2	90–90	3–3	1–1
6-Apr-94		15–18	135–135	0.5–0.8	135–135	1–6	1–1
7-Apr-94		20–20	135–135	1.4–1.4	135–135	7–7	2–2
27-May-94		10–15	135–135	0.3–2	135–135	3–7	1–1
28-May-94		15–15	135–135	1.5–1.5	135–135	4–4	1–1
16-Jun-94		8–18	135–135	0.2–1.5	135–135	3–6	1–3
17-Jun-94		18–18	135–135	1–1	135–135	2–2	1–1
27-Jul-94		10–18	135–135	0.1–0.5	135–135	1–1	1–1
28-Jul-94		15–15	135–135	1.5–1.5	135–135	1–2	1–1
24-Aug-94		15–20	135–135	0.2–1	135–135	1–6	1–1
25-Aug-94		20–20	135–135	1.5–1.5	135–135	7–7	2–2
22-Sep-94		5–8	135–135	0–0.3	0–135	1–2	1–1
17-Oct-94		5–15	45–135	0.1–1.3	45–135	1–2	1–1
8-Nov-94		3–10	0–338	0.1–1	0–338	0–2	1–1
14-Dec-94		18–18	135–135	1.2–1.8	135–135	2–6	1–1
15-Dec-94		15–18	135–135	0.3–1.2	135–135	3–4	1–1
10-Jan-95		15–20	90–135	0.3–1.5	90–135	1–4	1–1
21-Feb-95		5–10	135–135	0.1–0.3	135–135	1–1	1–1
29-Mar-95		6–10	180–270	0.1–1	180–270	1–1	1–1
15-May-95		10–13	135–135	0.4–1.5	135–135	3–4	1–1
16-May-95		10–12	135–135	0.2–0.2	135–135	2–3	1–1
28-Jun-95		10–13	135–180	0.2–0.8	135–180	1–1	1–1
5-Sep-95		7–10	315–360	0.5–0.7	315–360	1–1	1–1
2-Oct-95		10–15	135–180	0.3–1	135–180	3–8	1–1
31-Oct-95		5–15	135–180	0.3–1.2	135–180	1–1	1–1
29-Nov-95		5–10	90–180	0.2–1	90–180	2–4	1–1
20-Dec-95		7–15	45–325	0.3–0.5	45–325	1–1	1–1
12-Jan-96		5–6	180–360	0.2–0.5	180–360	1–2	1–1
29-Feb-96		5–5	135–135	0.2–0.3	135–135	1–3	1–1
4-Apr-96		15–20	135–135	0.4–0.5	135–135	6–7	1–1

8. TOWNSVILLE

8.1 CLUSTER DESCRIPTION

Collectors: *Department of Environment and Heritage, Northern Region*

David Savage, Patrick Centurino, Craig Purdon

Four of the eight stations in the Townsville cluster lie between Cleveland Bay and Halifax Bay (figure 8.2). Stations 35 and 36 were monitored for several years by Walker (1981). Stations 37–40 lie greater than 50 km from the mainland, adjacent to reefs (table 8.1). Stations have only been sampled since October 1995. Given the paucity of data collected to date there has been no attempt to interpret the data – only to present it graphically. Table 8.3 summarises sampling dates and the prevailing weather and sea conditions.

Table 8.1 *Townsville sampling stations*: locations, mean depth and distance from mainland

Station		Location (dec. degrees)		Mean depth	km to mainland
ID	Name	Longitude	Latitude	(metres)	
	Inshore				
35	Inside Cleveland Bay	146.90	19.20	9.8	9.4
36	Outside Cleveland Bay	146.92	19.01	19.5	29.3
41	Near Lucinda	146.35	18.48	7.8	7.1
42	Pandora Reef	146.45	18.84	16.6	16.8
	Offshore				
40	East of Palms (outside)	146.63	18.58	32.8	50.7
37	West of Lodestone Reef	147.00	18.70	43.0	167.4
38	Near Myrmidon Reef	147.33	18.32	99.0	121.7
39	North of Kelso Reef	146.98	18.40	63.3	91.0

8.2 HYDROGRAPHIC CONDITIONS

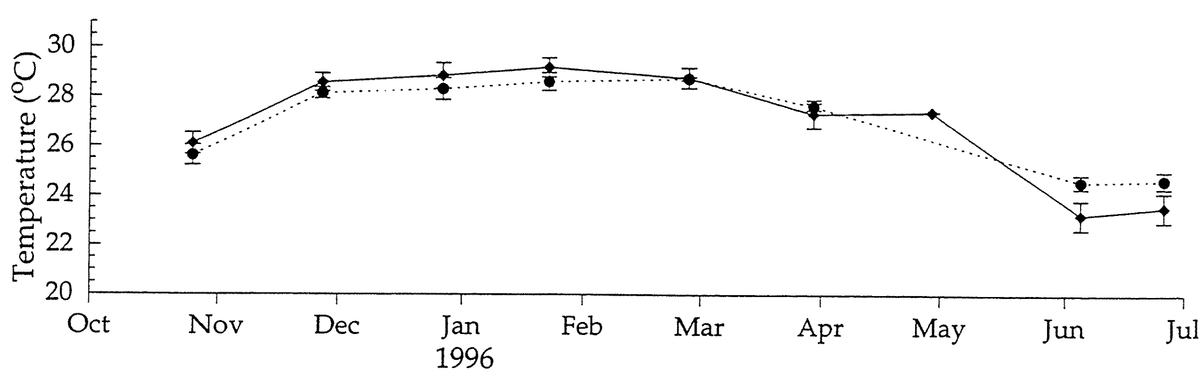

Figure 8.1 *Townsville*: mean (± 1 S.D.) monthly surface temperature (°C) at inshore (◆) and offshore (●) stations

Salinities were very erratic indicating a potential problem with the SCT meter (figure 8.3).

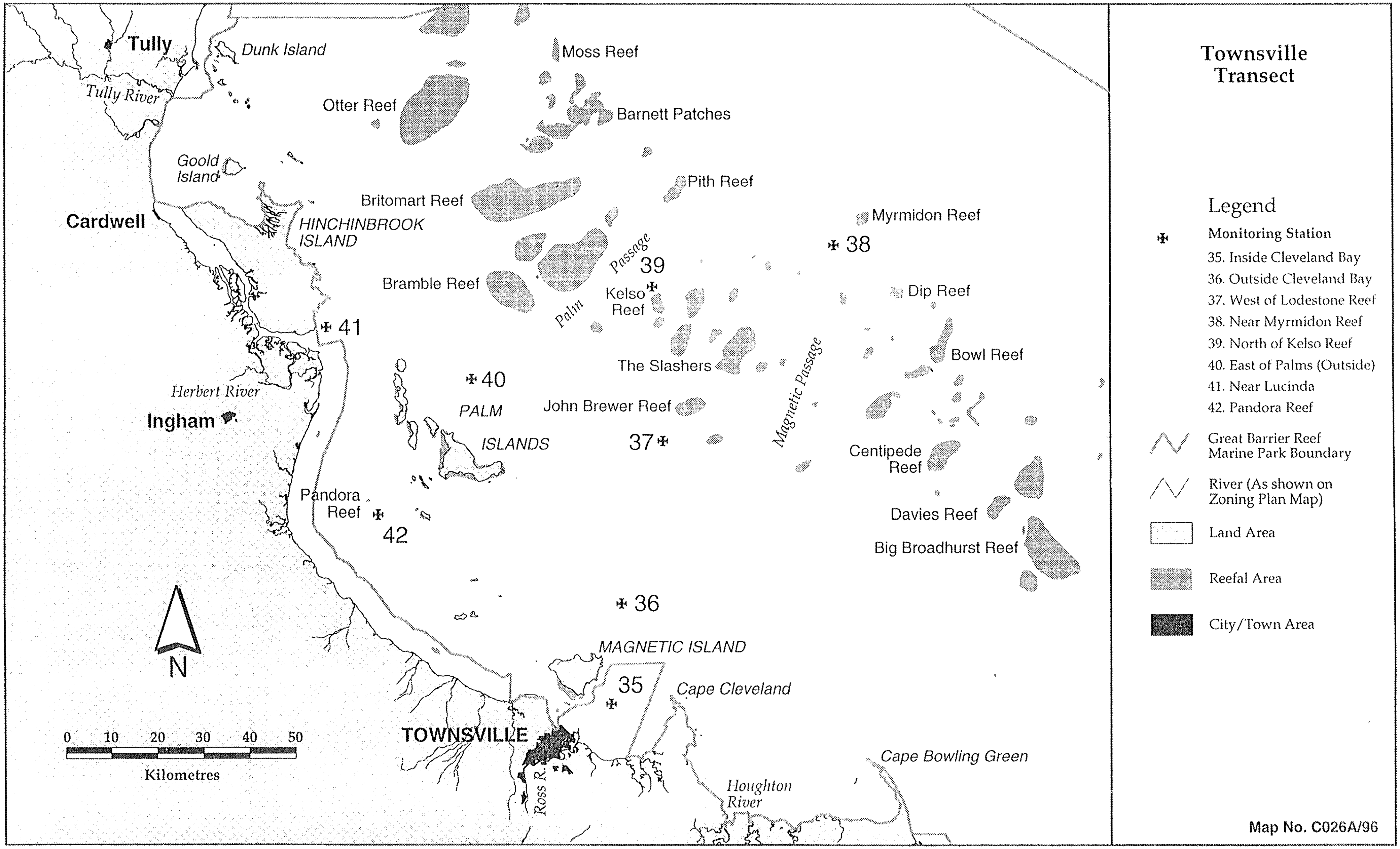

Figure 8.2 Map of sampling stations 35–42 in the Townsville cluster

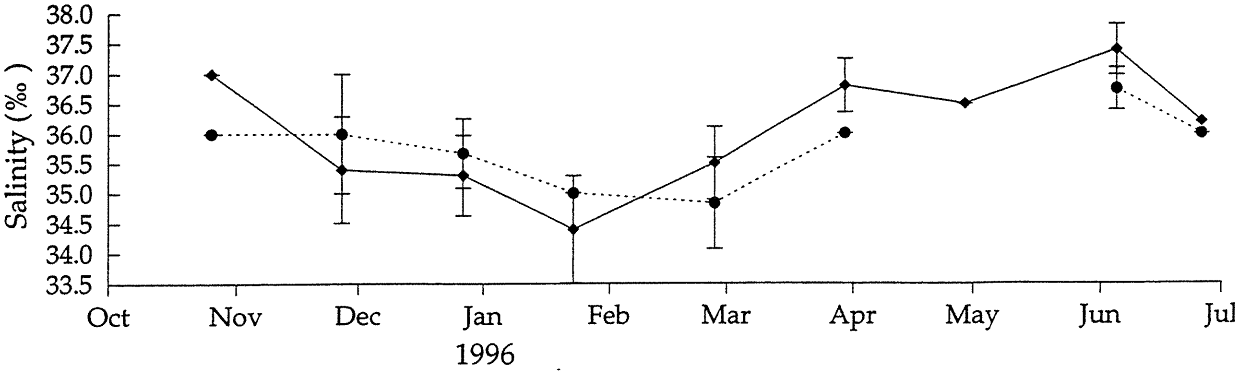

Figure 8.3 *Townsville*: mean (± 1 S.D.) monthly surface salinity (‰) at inshore (◆) and offshore (●) stations

Secchi depths were 10–20 m at offshore stations but less than 10 m offshore (figure 8.4).

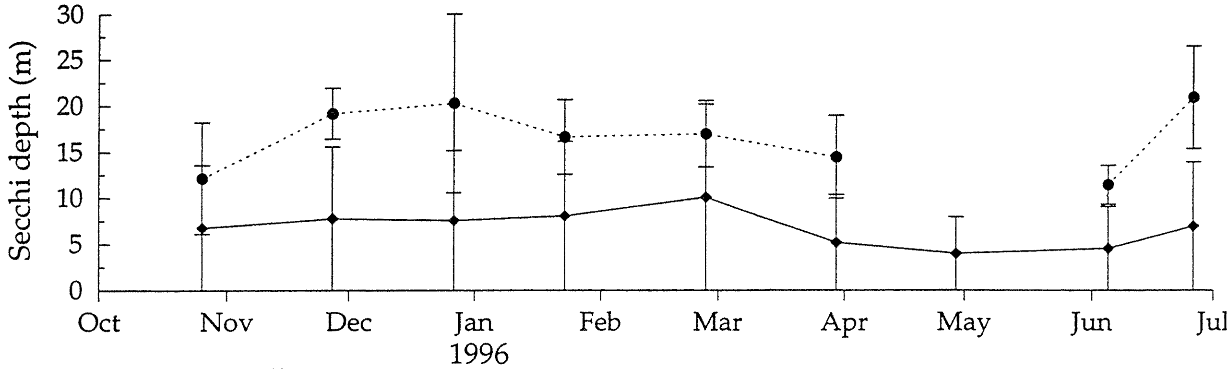

Figure 8.4 *Townsville*: mean (± 1 S.D.) monthly Secchi depth (metres) at inshore (◆) and offshore (●) stations

8.3 CHLOROPHYLL CONCENTRATIONS

Mean chlorophyll *a* concentrations at stations 0.4–1.0 µg L^{-1} whereas they were less than 0.3 µg L^{-1} offshore (figure 8.5).

Table 8.2 *Townsville*: summary statistics of chlorophyll *a* concentrations

	Chlorophyll *a* concentration (µg L^{-1})						
Station	N	Mean	S.D.	S.E.	Median	Min	Max
Inshore							
35 Inside Cleveland Bay	18	0.69	0.45	0.10	0.73	0.18	1.84
36 Outside Cleveland Bay	18	0.49	0.27	0.06	0.41	0.17	1.00
41 Near Lucinda	16	1.09	0.76	0.19	0.82	0.34	2.91
42 Pandora Reef	16	0.38	0.23	0.06	0.28	0.17	0.98
Offshore							
40 East of Palm Is	16	0.26	0.14	0.03	0.21	0.11	0.55
37 Lodestone Reef	16	0.33	0.39	0.10	0.23	0.08	1.56
38 Myrmidon Reef	14	0.12	0.07	0.02	0.09	0.07	0.27
39 Kelso Reef	16	0.28	0.12	0.03	0.32	0.11	0.45
Overall Mean	130	0.47	0.46	0.04	0.31	0.07	2.91

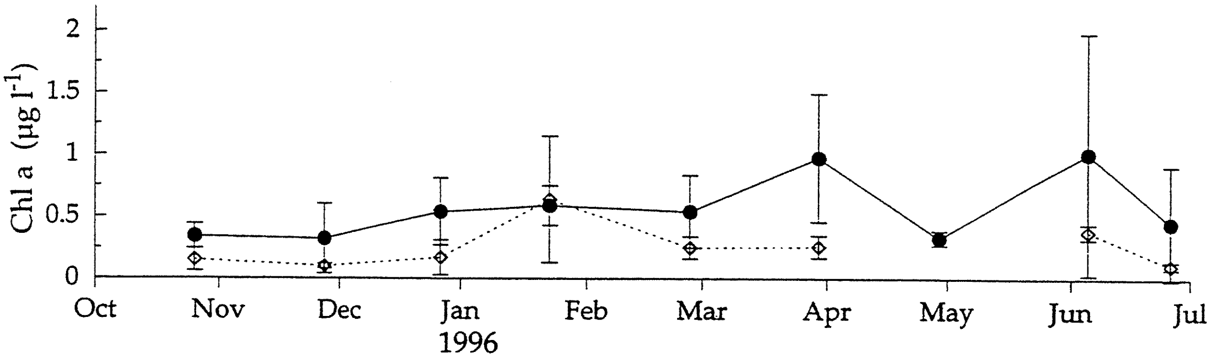

Figure 8.5. *Townsville*: mean (± 1 S.D.) monthly surface chlorophyll *a* concentration (µg L^{-1}) at inshore (●) and offshore (◊) stations

Table 8.3 *Townsville*: sampling dates and prevailing weather and sea conditions

Sampling		Wind		Swell		Cloud	
Date	Stations missed	Speed *(knots)*	Direction *(degrees)*	Height *(metres)*	Direction *(degrees)*	Cover *(x/8)*	Rainfall *(1–4)*
26-Oct-95		5–12	135–135	0.1–1.7	135–135	1–5	1–1
27-Oct-95		6–8	135–135	0.1–0.5	112.5–135	1–1	1–1
27-Nov-95		9.5–16	80–110	1–3.5	90–110	3–5	1–1
28-Nov-95		10–13	90–110	0.3–1	90–110	3–5	1–1
27-Dec-95		7–12	70–100	0.6–1.6	70–90	3–5	1–1
28-Dec-95		3–3	70–90	0.1–0.1	70–90	1–4	1–1
23-Jan-96		10–15	90–120	0.4–1.5	90–120	2–5	1–1
24-Jan-96		8–12	100–130	0.5–0.7	100–120	3–7	1–2
27-Feb-96		0.5–10	90–120	0.2–0.7	90–120	3–6	1–1
28-Feb-96		0–3	120–120	0–0.2	120–120	1–2	1–1
30-Mar-96		12–20	110–120	0.7–2	90–120	1–5	1–1
31-Mar-96		12–13	110–115	0.5–0.7	110–115	7–8	1–2
29-Apr-96		20–25	110–125	1.2–2.3	110–125	8–8	1–1
5-Jun-96		18–22	90–110	0.8–2	100–135	1–7	1–1
6-Jun-96		15–18	115–120	0.5–1	115–120	5–6	1–1
26-Jun-96		0–12	0–360	0–0.6	0–320	1–4	1–1
27-Jun-96		0–5	100–100	0–0.1	0–320	1–1	1–1
30-Jul-96		2–12	120–240	0–0.8	180–240	0–1	1–1
31-Jul-96		6–8	150–190	0.1–0.2	150–190	1–1	1–1
29-Aug-96		10–15	80–120	0.5–2	60–120	3–8	1–1
30-Aug-96		5–7	210–220	0.1–0.2	210–220	2–2	1–1

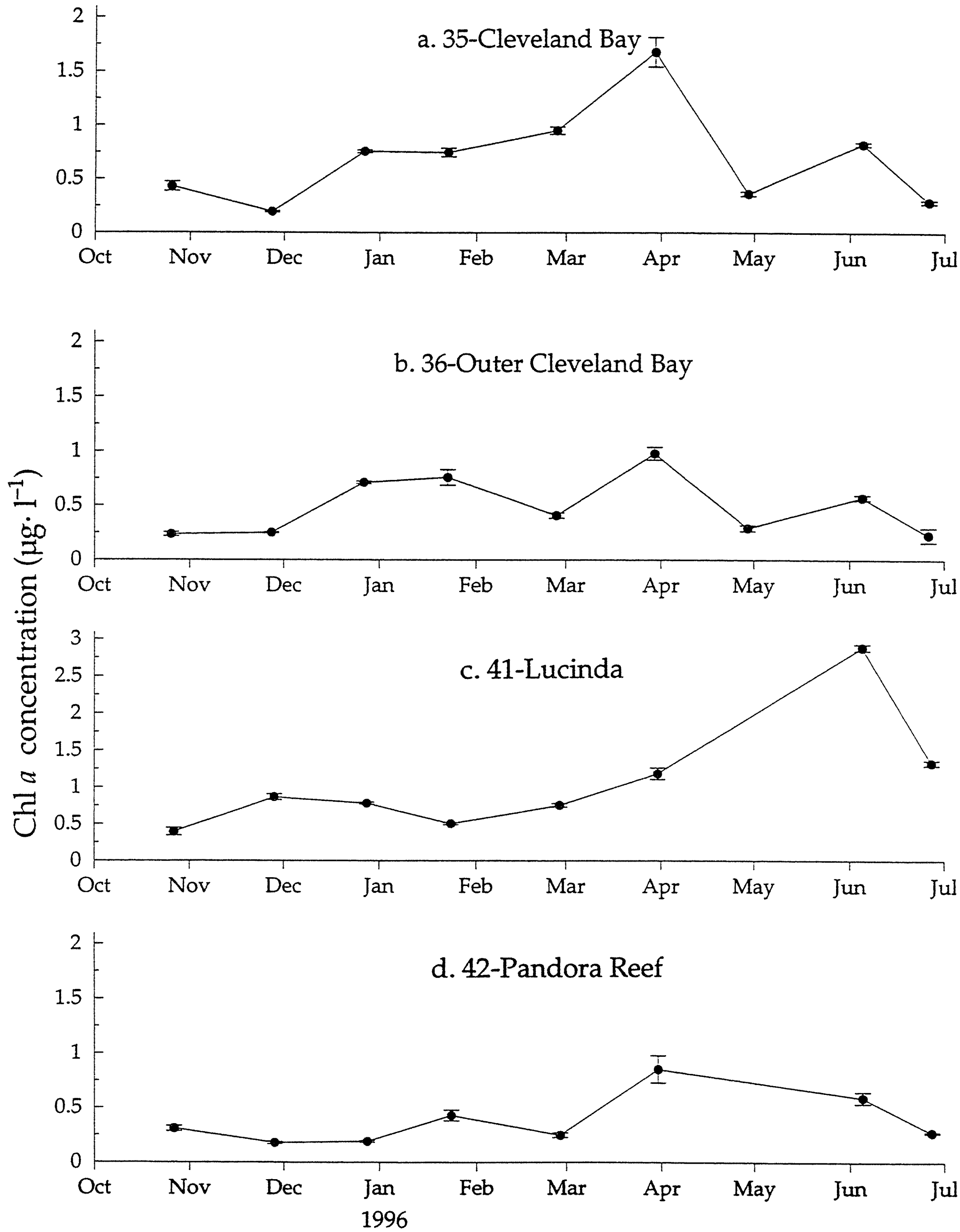

Figure 8.6 *Inshore Townsville stations*: mean (± 1 S.E.) monthly near-surface chlorophyll *a* concentrations (µg L^{-1})

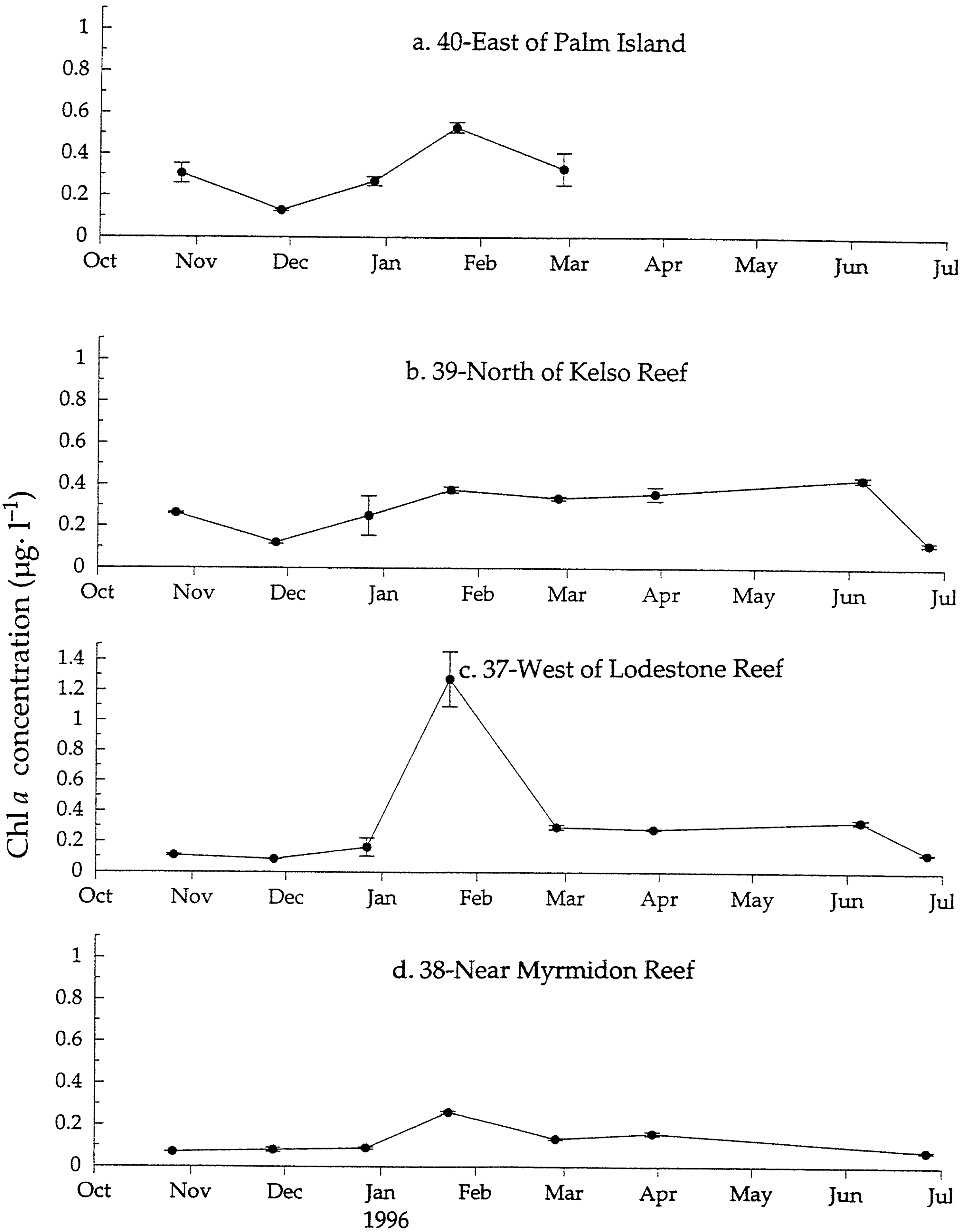

Figure 8.7 ***Offshore Townsville stations***: mean (± 1 S.E.) monthly near-surface chlorophyll *a* concentrations (µg L^{-1})

9. KEPPEL BAY AND CAPRICORN

9.1 KEPPEL BAY

9.1.1 Cluster description

Collectors: *Department of Environment and Heritage, Central Coast Region*

Paul O'Neill, Chris Maple, John Messersmith, Brian Morris, John Olds

Six stations (22–27) extend from the mouth of the Fitzroy River (27) northwards into Keppel Bay (figure 9.3). All stations are within 30 km of the coast and in less than 23 m water depth (table 9.1). Stations have been sampled monthly since March 1993. Depth sampling was discontinued after April 1994. Sampling dates and prevailing weather and sea conditions are summarised in table 9.4.

Table 9.1 *Keppel Bay sampling stations*: location, mean depth and distance from mainland

Station		Location (dec. degrees)		Mean depth	km to mainland
ID	Name	Longitude	Latitude	(metres)	
22	Outer Rock	150.91	23.06	21.2	5.2
23	Wreck Point	150.77	23.14	5.1	2.0
24	Pelican Island	150.89	23.22	11.2	7.1
25	Barren Island	151.04	23.19	22.5	23.0
26	Hummocky Island	151.10	23.39	17.8	28.8
27	River Mouth	150.96	23.40	10.2	14.6

9.1.2 Hydrographic conditions

There were significant calibration problems with the SCT meter particularly in 1995. Consequently, the salinity and temperatures data is of dubious accuracy. Calibration problems aside, maximum surface temperatures of up to 30.1°C in February fall steeply to minima of ~18°C in July–August (figure 9.1).

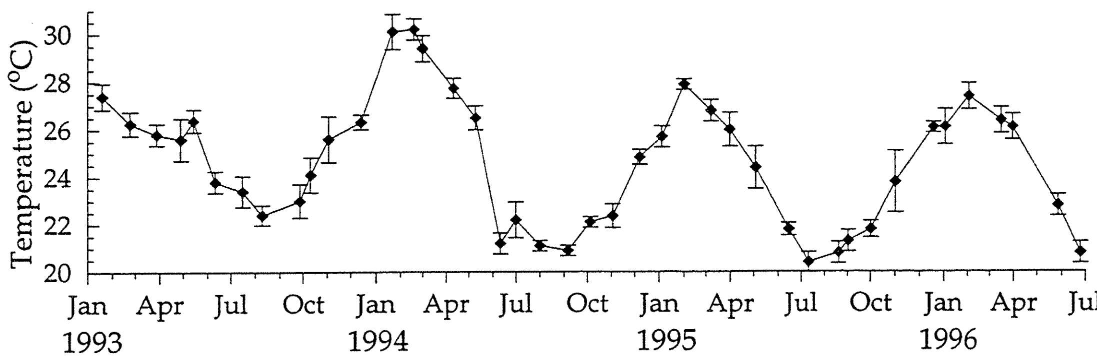

Figure 9.1 *Keppel Bay*: mean (± 1 S.D.) monthly surface temperature (°C)

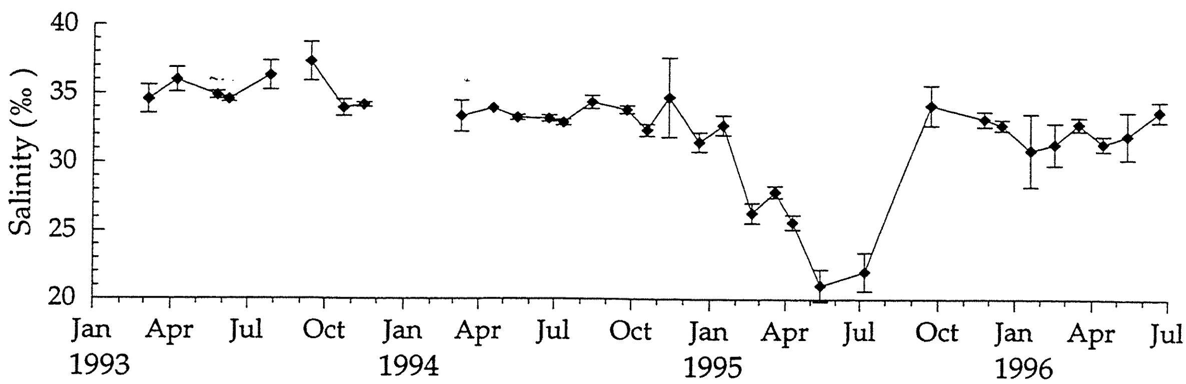

Figure 9.2 *Keppel Bay*: mean (± 1 S.D.) monthly surface salinity (‰)

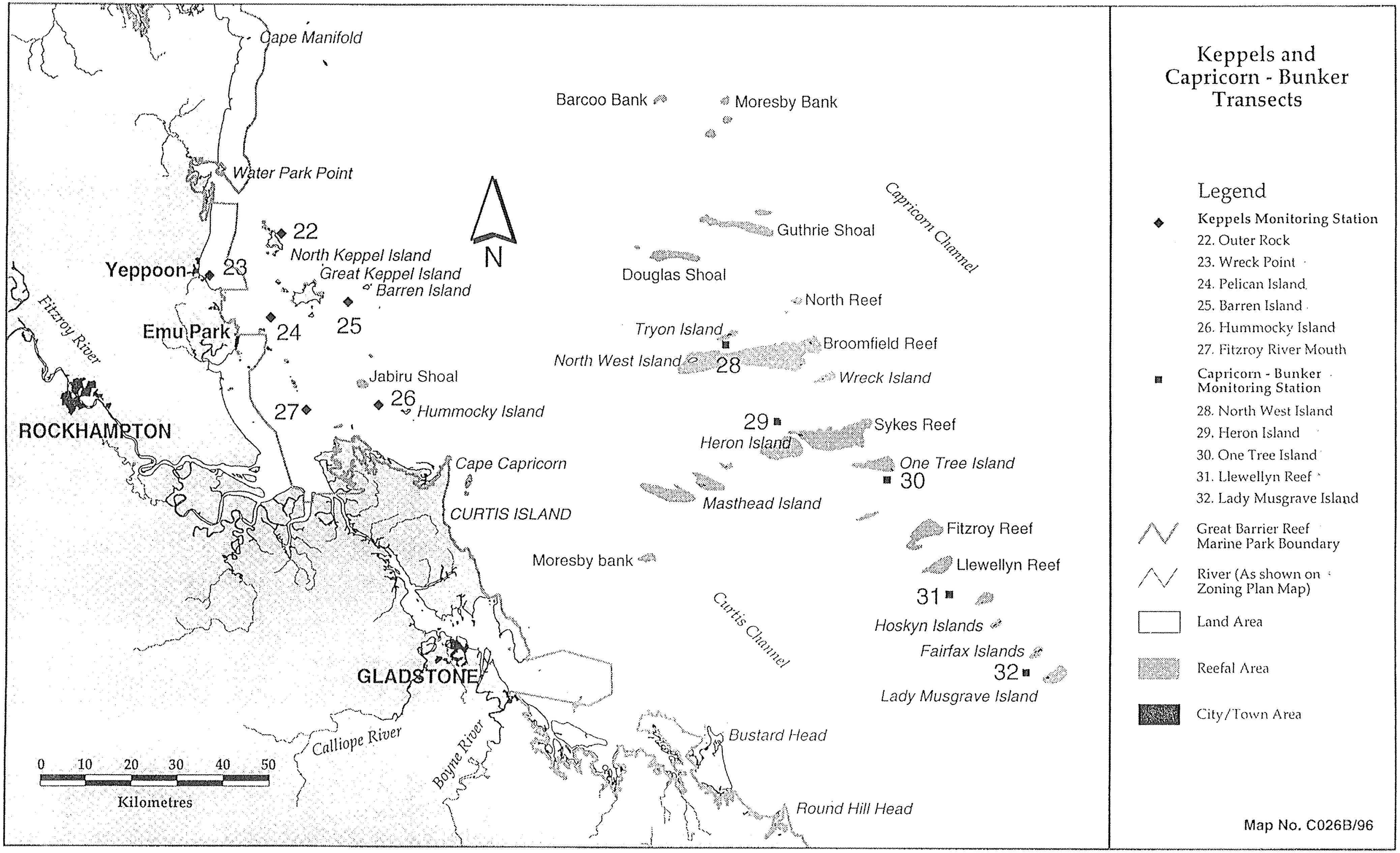

Figure 9.3 Map of sampling stations 22–27 in the Keppel Bay cluster and 28–32 in the Capricorn cluster

Median salinities were 34.8‰ in 1993 and 33.35‰ in 1994 (table 9.2). A salinity range of 31–38.9‰ (table 9.2) and the downward decrease from December 1994 until July 1995 (figure 9.2) indicate significant probe drift.

Secchi depth varied from 0.2–22.5 m, with water clarity greatest from June until December (figure 9.4). Secchi depth was not linearly related to chlorophyll *a* concentration ($R^2 = 0.05$).

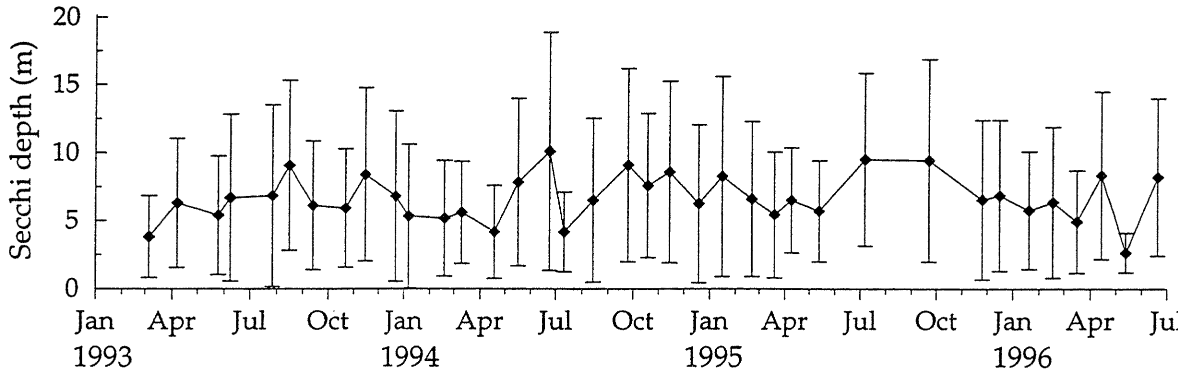

Figure 9.4 *Keppel Bay*: mean (± 1 S.D.) monthly Secchi depth (metres)

Trichodesmium slicks were observed in 37.2% of sampling events. They were present in greater than 40% of observations in March and September, but less than 20% of observations in January–May. In 1993, *Trichodesmium* slicks were only present in 18% of observations, whereas in 1994 and 1995 they were present in 44.4% and 42.6% of observations.

Table 9.2 *Keppel Bay*: annual summary statistics of temperature, salinity and chlorophyll *a* concentrations

	Temperature (°C)			Salinity (‰)			Chlorophyll *a* (μg L^{-1})		
	Min	Median	Max	Min	Median	Max	Min	Median	Max
1993	17.9	22.5	26.8	33.0	34.8	38.6	0.18	0.52	2.07
1994	18.4	23.9	30.1	31.0	33.3	38.9	0.11	0.53	6.09
1995	18.9	26.6	30.1	20.0	28.0	36.5	0.17	0.57	4.96
Mean	17.9	24.9	30.1	20.0	33.1	38.9	0.11	0.56	6.09

9.1.3 Chlorophyll *a* concentrations

Surface chlorophyll *a* concentrations for Keppel Bay varied from 0.11–16.09 μg L^{-1} with a median of 0.56 μg L^{-1} (table 9.2). Median chlorophyll concentrations in 1993 (0.52 μg L^{-1}) and 1994 (0.53 μg L^{-1}) were similar, but were higher (0.57 μg L^{-1}) in 1995.

Chlorophyll *a* concentrations varied more than twofold between stations (table 9.3). Median concentrations were greatest at station 27 (0.83 μg L^{-1}) and 23 (0.93 μg L^{-1}), both within 14 km of the coast (table 9.3). At stations 22, 25 and 26, greater than 18 km from the coast, median concentrations were 0.35–0.54 μg L^{-1} (table 9.3).

Chlorophyll *a* concentrations were greatest throughout Keppel Bay (figure 8.5) in November 1994 (6.10 μg L^{-1}) and in September 1995 (4.96 μg L^{-1}). During both these events stations 23 and 24 had the highest chlorophyll *a* concentrations (figure 9.7). Monthly chlorophyll *a* concentrations at station 22 (figure 9.8c) varied greatly between consecutive months; it lies within 5 km of the coast, and is adjacent to a creek.

Table 9.3 *Keppel Bay*: summary statistics of chlorophyll *a* concentrations

Station	Chlorophyll *a* concentration (µg L^{-1})						
	N	Mean	S.D.	S.E.	Median	Min	Max
27 Fitzroy River	61	1.00	0.65	0.08	0.83	0.40	3.89
23 Wreck Point	61	1.06	0.66	0.08	0.93	0.20	2.77
24 Pelican Island	60	0.81	1.08	0.14	0.50	0.17	6.09
25 Barren Island	61	0.46	0.38	0.05	0.35	0.11	2.46
26 Hummocky Island	62	0.64	0.53	0.07	0.54	0.13	4.00
22 Outer Rock	59	0.55	0.56	0.07	0.43	0.14	3.88
Overall Mean	364	0.76	0.71	0.04	0.56	0.11	6.09

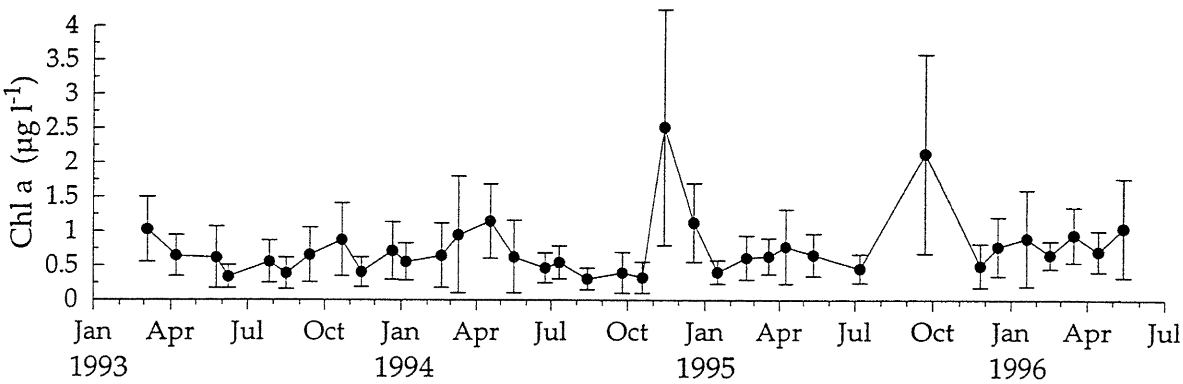

Figure 9.5 *Keppel Bay*: mean (± 1 S.D.) monthly surface chlorophyll *a* concentration (µg L^{-1})

From May to August median chlorophyll *a* values were below 0.6 µg L^{-1} and exhibited little interannual variation (figure 9.6). Chlorophyll *a* concentrations were greater from September to December; these were generally short-lived events with no consistent pattern between years (figure 9.6).

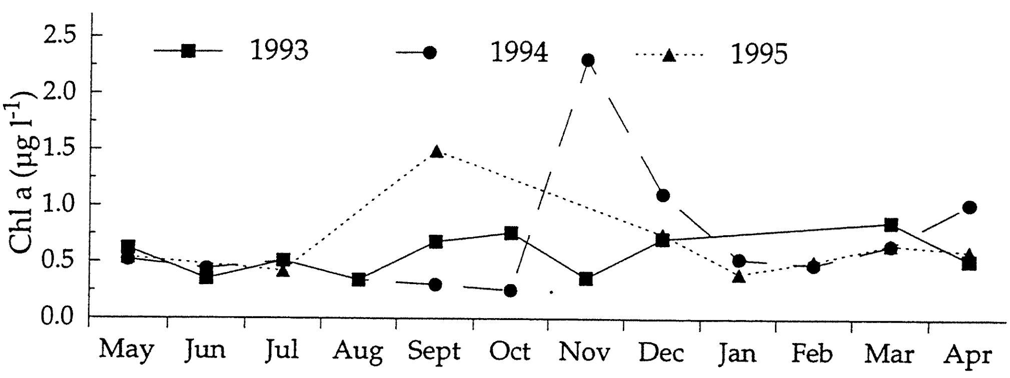

Figure 9.6 *Keppel Bay*: median monthly chlorophyll *a* concentrations (µg L^{-1}) in 1993–95

Differences between surface and near-bottom chlorophyll *a* concentrations ranged from 0.0–1.06 µg L^{-1} with a median of 0.08 µg L^{-1}. Chlorophyll *a* concentrations from samples taken in the presence of *Trichodesmium* had a higher mean concentration (0.98 ± 0.98 µg L^{-1}) than when slicks were absent (0.63 ± 0.46 µg L^{-1}). Duplicate sample variability was not correlated to mean chlorophyll *a* concentration (R^2 = 0.32). The median difference between duplicates was 9% of the overall median for the cluster.

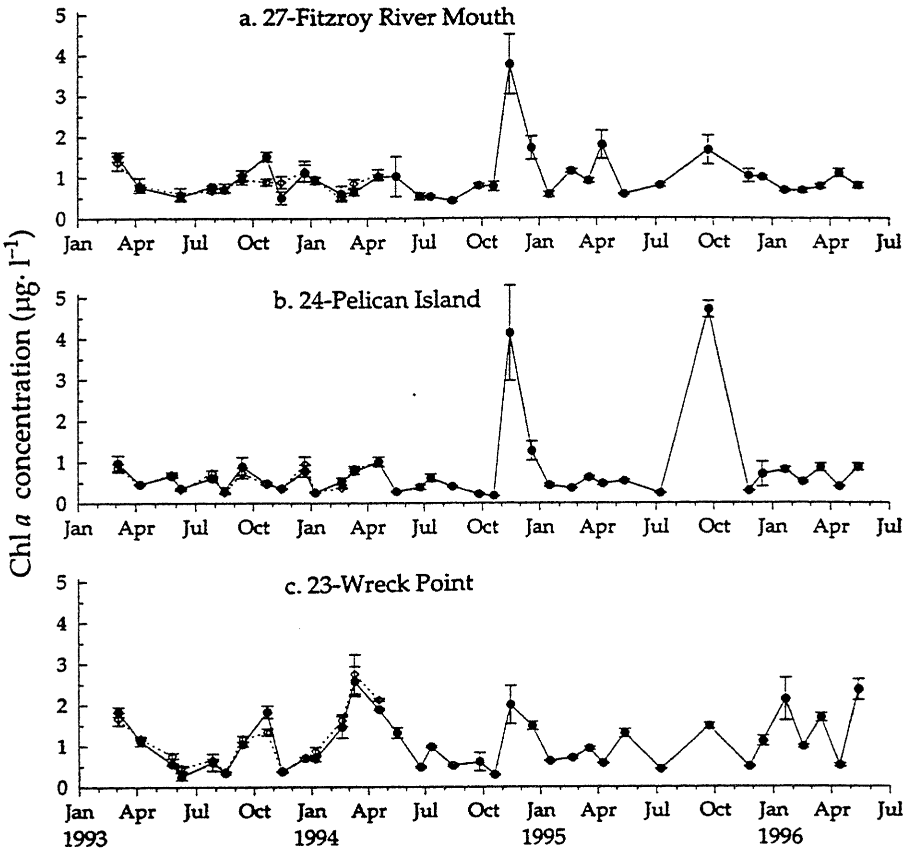

Figure 9.7 *Keppel Bay*: mean (± 1 S.E.) monthly near-surface (●) and near-bottom (◊) chlorophyll *a* concentrations (µg L^{-1}) at stations 23, 24 and 27

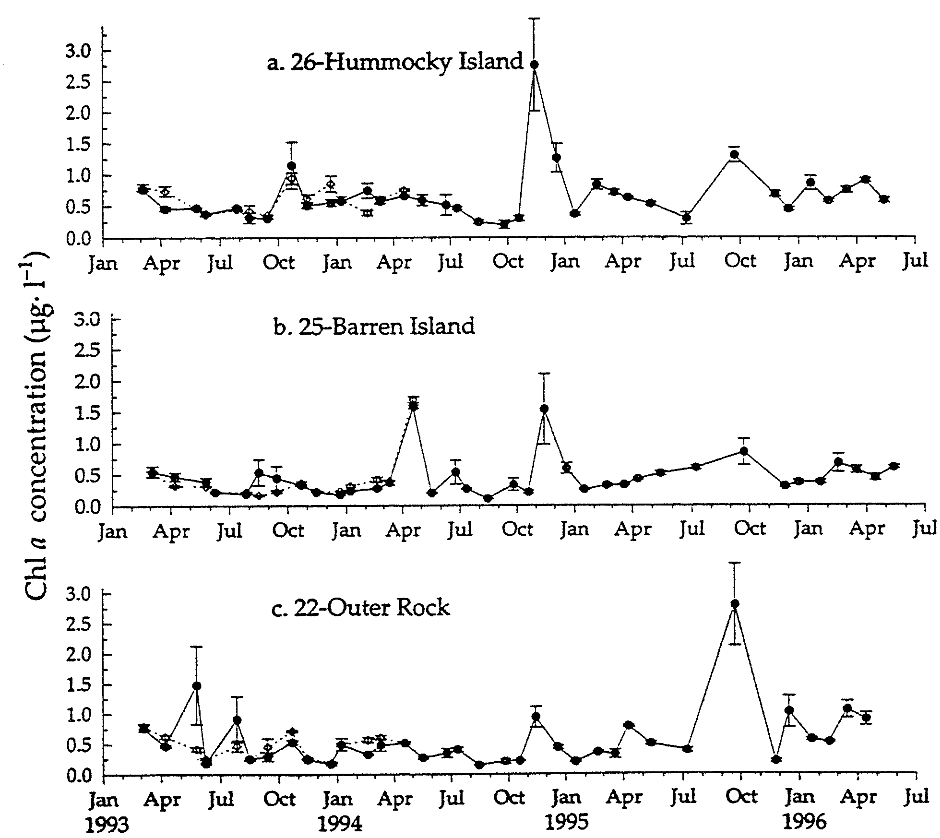

Figure 9.8 *Keppel Bay*: mean (± 1 S.E.) monthly near-surface (●) and near-bottom (◊) chlorophyll *a* concentrations (µg L^{-1}) at stations 22, 25 and 26

Table 9.4 *Keppel Bay*: sampling dates and prevailing weather and sea conditions

Sampling		Wind		Swell		Cloud	
Date	Stations missed	Speed *(knots)*	Direction *(degrees)*	Height *(metres)*	Direction *(degrees)*	Cover *(x/8)*	Rainfall *(1–4)*
4–Mar–93		1–25	9–135	0.5–0.8	0–135	6–7	1–1
5–Mar–93		2–2	135–135	1.5–1.5	135–135	3–3	1–1
7–Apr–93		0.5–5	45–135	0.1–0.5	90–135	1–1	1–1
25–May–93		1–1	180–180	0.5–0.5	180–180	1–1	1–1
8–Jun–93		1–15	135–180	0–1	0–180	1–1	1–1
27–Jul–93		1–8	90–270	0–0.5	0–225	6–8	1–1
16–Aug–93		3–5	0–45	0.5–1	30–330	1–1	1–1
13–Sep–93		12–17	90–90	0.5–1.5	90–90	1–8	1–1
22–Oct–93		11–15	–	0.5–1	–	1–5	1–2
15–Nov–93		1–5	20–20	0.2–0.5	20–20	1–1	1–1
22–Dec–93		1–17	0–30	0.5–1.5	0–30	1–4	1–1
7–Jan–94		2–5	0–315	0.2–0.5	0–335	1–3	1–1
18–Feb–94		1–12	65–65	0.5–0.8	90–90	6–7	1–1
10–Mar–94		1–8	90–90	0.3–0.5	110–110	1–3	1–1
18–Apr–94		1–13	135–135	0.25–1.5	90–135	1–2	1–1
17–May–94		5–12	90–180	0–1	132–135	0–1	1–1
24–Jun–94		0–12	0–315	0–0.5	0–0	0–2	1–1
11–Jul–94		10–18	135–135	0.5–1.8	135–135	1–8	1–1
14–Aug–94		5–10	90–180	0.25–0.5	90–180	0–0	1–1
25–Sep–94		5–12	0–315	0.25–0.75	0–315	0–0	1–1
19–Oct–94		3–15	0–0	0–0.4	0–90	0–1	1–1
14–Nov–94		3–11	67.5–68	0.3–0.5	0–45	2–5	1–1
19–Dec–94		12–20	100–135	0.5–1	135–135	1–8	1–2
16–Jan–95		0–10	0–60	0.1–0.1	60–90	1–1	1–1
20–Feb–95		10–122	90–135	0.25–0.5	90–135	1–6	1–1
19–Mar–95		2–10	30–180	0.25–0.5	30–135	1–1	1–1
9–Apr–95		5–15	120–180	0.2–1	120–180	1–1	1–1
13–May–95		10–15	135–135	0.5–1.5	135–135	1–1	1–1
7–Jul–95		8–15	120–180	0.25–1	100–135	1–7	1–2
22–Sep–95		0–8	0–90	0–0.5	0–90	1–2	1–1
25–Nov–95		0.5–10	40–110	0.3–0.7	40–135	1–3	1–1
16–Dec–95		2–12	9–135	0.25–1	90–135	1–1	1–1
20–Jan–96		10–14	90–135	0.5–1.5	0–135	1–8	1–1
17–Feb–96		2–15	0–225	0.25–1	0–315	1–2	1–1
16–Mar–96		5–12	90–90	0.25–1	60–90	1–1	1–1
14–Apr–96	22	5–10	0–0	0.5–1	0–0	1–3	1–1
13–May–96		5–10	112–180	0.1–0.4	90–180	1–1	1–1
20–Jun–96		3–8	5–230	0–0.2	0–230	0–0	1–1
16–Jul–96		12–18	180–185	0.1–0.9	180–185	0–0	1–1
13–Aug–96		2–6	170–200	0.15–0.4	60–120	0–0	1–1

9.2 CAPRICORN

9.2.1 Cluster description

Collectors: *Heron Island Research Station*

Myriam Preker, Mark Waugh (One Tree Island Research Station)

Stations 28–32 lie between 57 and 99 km from the coast and are collectively classified as offshore (figure 9.3). They have an average bottom depth of between 36 and 47 m (table 9.5). Near-surface and near-bottom samples have been collected ~monthly since December 1992. Sampling dates and the prevailing weather and sea conditions are summarised in table 9.8.

Table 9.5 *Capricorn sampling stations*: location, mean depth and distance from mainland

Station		Location (dec. degrees)		Mean depth	km to mainland
ID	Name	Longitude	Latitude	(metres)	
28	North West Island	23.27	151.77	36.5	98.6
29	Heron Island	23.42	151.87	38.5	69.1
30	One Tree Island	23.53	152.08	44.4	69.8
31	Llewellyn Reef	23.75	152.20	46.8	61.9
32	Lady Musgrave Island	23.90	152.35	41.6	57.0

9.2.2 Hydrographic conditions

Temperatures of ~30°C were recorded from January to March 1994, but were ~28°C in 1993 and 1995 (figure 9.9). Temperature minima below 22°C were recorded during June–September of each year. In 1993 temperatures did not fall below 22°C.

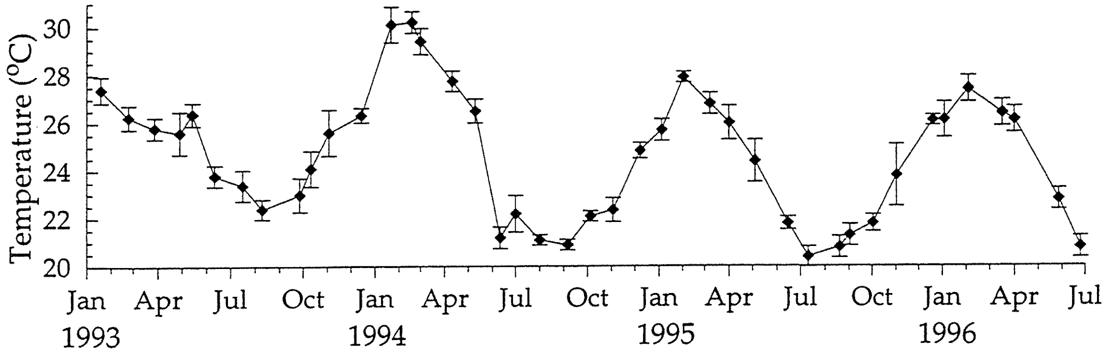

Figure 9.9 *Capricorn*: mean (± 1 S.D.) monthly surface temperature (°C)

Median salinities over all years were ~35.6 ‰ and were generally constant (figure 9.10). Low salinities were recorded in 1996 during February (34.85 ‰), March (35.22 ‰) and April (35.19 ‰). During 1993 and 1994 there were no notable salinity variations.

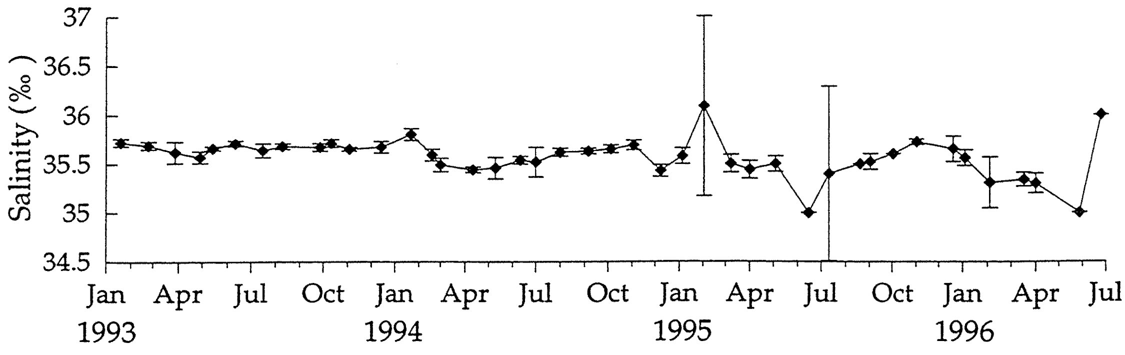

Figure 9.10 *Capricorn*: mean (± 1 S.D.) monthly surface salinity (‰)

Secchi depth measurements ranged from 3.5 and 21.5 m. Water clarity was greater than 14 m during April–May but less than 11.5 m during June–September (figure 9.11). There was no linear relationship between Secchi depth and chlorophyll *a* concentration ($R^2 < 0.00$).

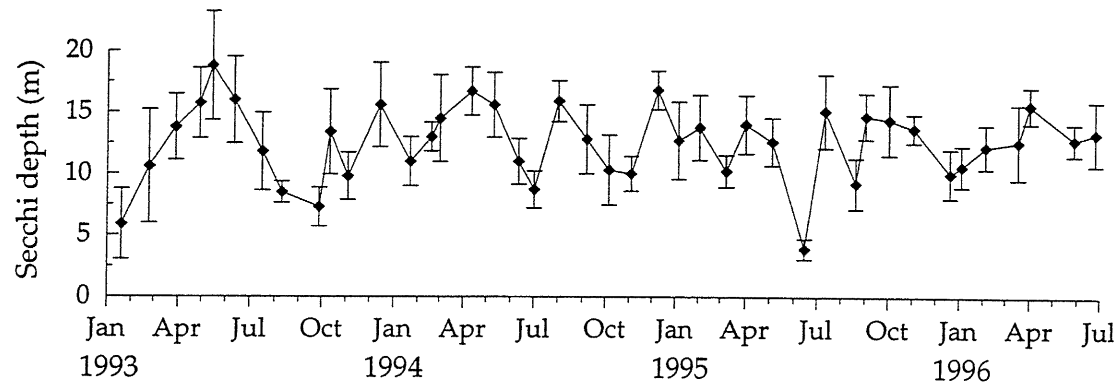

Figure 9.11 *Capricorn*: mean (± 1 S.D.) monthly Secchi depth (metres)

Trichodesmium slicks were recorded in 34.1% of all sampling observations. *Trichodesmium* slicks were most frequently observed from October to April (> 30%), whereas from May to September they were recorded infrequently.

Table 9.6 *Capricorn*: annual summary statistics of temperature, salinity and chlorophyll *a* concentrations

	Temperature (°C)			Salinity (‰)			Chlorophyll *a* (µg L^{-1})		
	Min	Median	Max	Min	Median	Max	Min	Median	Max
1993	22.0	25.0	28.0	35.46	35.67	35.78	0.16	0.38	9.59
1994	20.5	23.8	31.0	35.29	35.59	35.88	0.11	0.37	12.73
1995	20.0	25.3	28.0	35.32	35.55	35.78	0.07	0.32	4.03
Mean	20.0	25.0	31.0	34.00	35.60	37.40	0.07	0.36	12.73

9.2.3 Chlorophyll *a* concentrations

Near-surface chlorophyll *a* concentrations varied between 0.07–12.73 µg L^{-1} with a median of 0.36 µg L^{-1} (table 9.6). Median chlorophyll *a* concentrations were 0.38 µg L^{-1} in 1993 and 0.37 µg L^{-1} in 1994 (table 9.6). Lower monthly chlorophyll *a* concentrations from May–September 1995 (figure 9.13) resulted in a lower annual median concentration in 1995 of 0.32 µg L^{-1}.

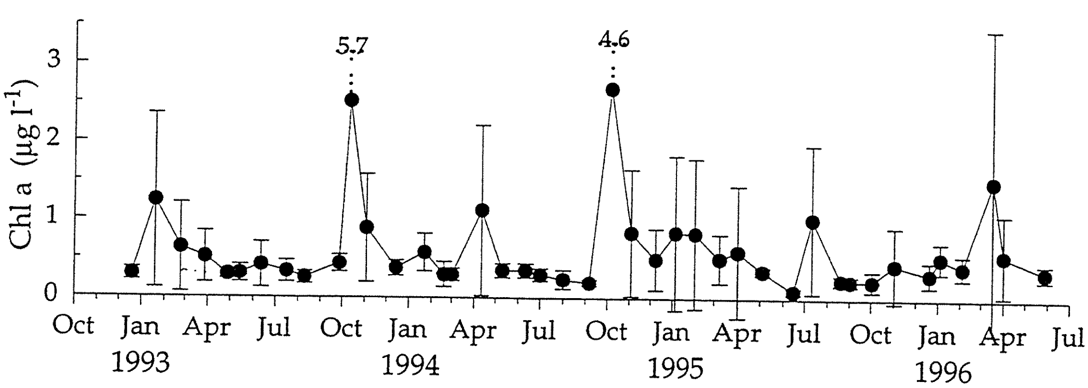

Figure 9.12 *Capricorn*: mean (± 1 S.E.) monthly surface chlorophyll *a* concentration (µg L^{-1})

High chlorophyll *a* concentrations were recorded in October and November 1993 (9.59 µg L^{-1}), and October 1994 (12.73 µg L^{-1}). Median chlorophyll *a* concentration at stations 28–30 were 0.38 µg L^{-1}, but were lower at stations 31 (0.36 µg L^{-1}) and 32 (0.31 µg L^{-1}) to the south. High concentrations were recorded on a number of occasions, but not usually across all five stations (figure 9.14): March 1996 (6.08 μg L^{-1}); April 1995 (4.03 μg L^{-1}); and June 1995 (3.17 μg L^{-1}).

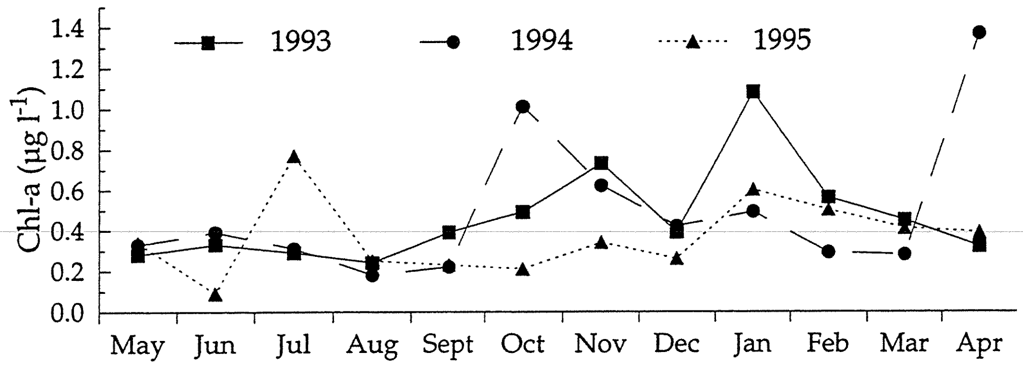

Figure 9.13 *Capricorn*: median monthly chlorophyll *a* concentrations (μg L^{-1}) in 1993–95

Differences between near-surface and near-bottom chlorophyll *a* concentrations ranged from 0.0–1.06 μg L^{-1} with a median of 0.08 μg L^{-1}. Chlorophyll *a* concentrations from samples taken in the presence of *Trichodesmium* had a higher median concentration (0.51 μg L^{-1}) than when they were absent; concentrations ranged from 6–12.73 μg L^{-1}. However on no sampling occasion did the replicate cast indicate similarly high values, this indicates the patchy aggregation of these slicks. Duplicate sample variability correlated well (r = 0.80) with mean chlorophyll concentration. Median variability between duplicates chlorophyll *a* samples was ~11% of the overall median concentration.

Table 9.7. *Capricorn*: summary statistics of chlorophyll *a* concentrations

	Chlorophyll *a* concentration (μg L^{-1})						
Station	N	Mean	S.D.	S.E.	Median	Min	Max
28 North West Island	84	0.68	1.22	0.13	0.38	0.07	9.59
29 Heron Island	82	0.76	1.54	0.17	0.38	0.08	12.73
30 One Tree Island	83	0.49	0.40	0.04	0.38	0.08	2.54
31 Llewellyn Reef	82	0.62	0.61	0.07	0.36	0.13	3.17
32 Lady Musgrave Is	82	0.54	0.81	0.09	0.31	0.08	6.08
Overall Mean	413	0.62	1.01	0.05	0.36	0.07	12.73

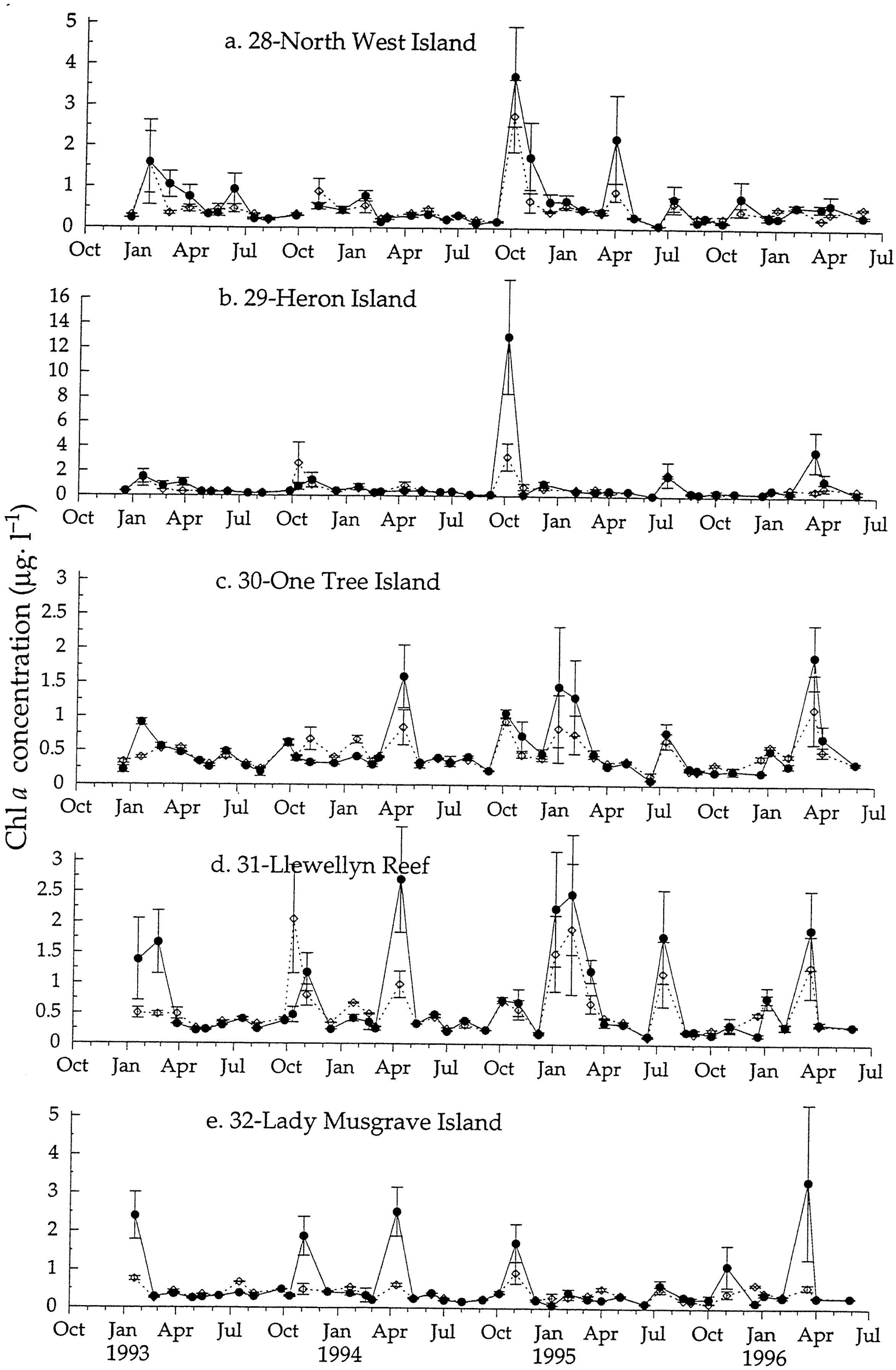

Figure 9.14 *Capricorn*: mean (± 1 S.E.) monthly near-surface (●) and near-bottom (◊) chlorophyll *a* concentrations (µg L^{-1})

Table 9.8 *Capricorn*: sampling dates and prevailing weather and sea conditions

Sampling		Wind		Swell		Cloud	
Date	Stations missed	Speed *(knots)*	Direction *(degrees)*	Height *(metres)*	Direction *(degrees)*	Cover *(x/8)*	Rainfall *(1–4)*
19-Dec-92		16-20	85–90	1.5–2	100–100	8–8	1–1
19-Jan-93		2.8-8	85–100	0.5–0.5	60–120	2–4	1–1
23-Feb-93		2-2	5–35.5	0.2–1.5	0–120	2–4	1–1
28-Mar-93		2-4	290–340	0.6–1	245–335	1–4	1–1
28-Apr-93		10-12	130–185	1–15.2	20–190	0–3	1–1
14-May-93		2-4	10–15	0.3–0.75	20–95	3–5	1–1
11-Jun-93		2-8	35–45	0.3–0.8	30–100	1–2	1–1
16-Jul-93		1-5	220–315	0.2–0.5	45–90	1–4	1–1
10-Aug-93		3.5-5	330–330	0.3–1	330–330	1–2	1–1
27-Sep-93		10-14	138–140	1–12	1.5–130	2–7	1–1
11-Oct-93		4-12	120–220	0.4–0.8	175–315	2–5	1–1
3-Nov-93		4-7	270–350	0.3–0.8	10–350	1–2	1–1
14-Dec-93		5-10	80–100	0.5–1.5	70–280	1–4	1–1
22-Jan-94		2-8	70–170	0.4–0.6	15–130	1–4	1–1
18-Feb-94		3-6	40–75	0.2–1	35–100	2–4	1–1
1-Mar-94		5-10	0–20	0.5–1.2	10–358	3–8	1–1
11-Apr-94		3-3	120–180	0.1–0.3	110–180	1–2	1–1
10-May-94		7-11	140–150	0.5–0.8	90–185	5–7	1–2
10-Jun-94		9-11	175–180	1.4–1.5	2–350	1–1	1–1
11-Jun-94		7-17	170–200	0.6–0.8	2–2	1–1	1–1
1-Jul-94		14-18	160–190	1.4–2.5	0–0	1–5	1–1
1-Aug-94		6-11	150–150	0.4–1.2	10–30	1–1	1–1
6-Sep-94		8-12	270–330	0.7–1.2	0–290	4–7	1–1
5-Oct-94		9-12	320–330	0.4–1.2	330–330	1–1	1–1
3-Nov-94		8-12	300–330	0.7–1.1	10–330	1–7	1–1
8-Dec-94		2-5	70–92	0.2–1.2	85–90	1–1	1–1
5-Jan-95	29	7-12	30–70	0.5–1.5	60–90	1–6	1–1
2-Feb-95		10-16	60–100	0.7–1.4	90–120	1–3	1–1
8-Mar-95		10-13	0–355	0.5–1	5–340	1–1	1–1
1-Apr-95		2-7	60–290	0.1–0.5	10–330	4–8	1–1
4-May-95		4-15	180–340	0.6–1	30–330	6–8	1–2
15-Jun-95		6-11	90–335	0.5–1.2	90–330	7–8	1–1
11-Jul-95		5-12	240–290	0.3–0.5	50–120	0–4	1–1
20-Aug-95		1-10	50–90	0.5–1	50–80	3–6	1–1
2-Sep-95		4-5	0–20	0.4–0.5	15–90	2–3	1–1
2-Oct-95		2-6	0–0	0.3–0.8	30–60	1–2	1–1
2-Nov-95		4-5	5–30	0.3–0.75	40–340	1–7	1–1
20-Dec-95		6-7	160–320	0.4–1	160–320	4–7	1–1
4-Jan-96		6-15	30–60	0.3–1.5	20–90	8–8	1–1
4-Feb-96		4-12	50–60	0.5–2	30–110	1–3	1–1
17-Mar-96		2-6	110–115	0.2–2	40–170	1–3	1–1
1-Apr-96		0.4-7	260–285	0.1–0.5	25–350	0–2	1–1
28-May-96		8-15	80–125	0.5–1.8	60–110	1–6	1–1
25-Jun-96		2-6	180–180	0.2–0.6	90–170	1–3	1–1

10. SUMMARY AND ASSESSMENT

The results presented for all clusters except Townsville cover the period January 1993 to July 1996. This is sufficient data to identify the major spatial and temporal patterns of chlorophyll *a* concentrations. To better elucidate these major trends, data has been grouped to reflect the cross-shelf and seasonal differences. Within a year, data were grouped into two seasons: a summer period from October to April inclusive (212 days) and a winter period from May to September (153 days).

Figure 10.1 summarises the spread of chlorophyll *a* concentrations as a function of regional cluster, cross-shelf position and season. Table 10.1 presents a range of summary statistics grouped by these same three variables.

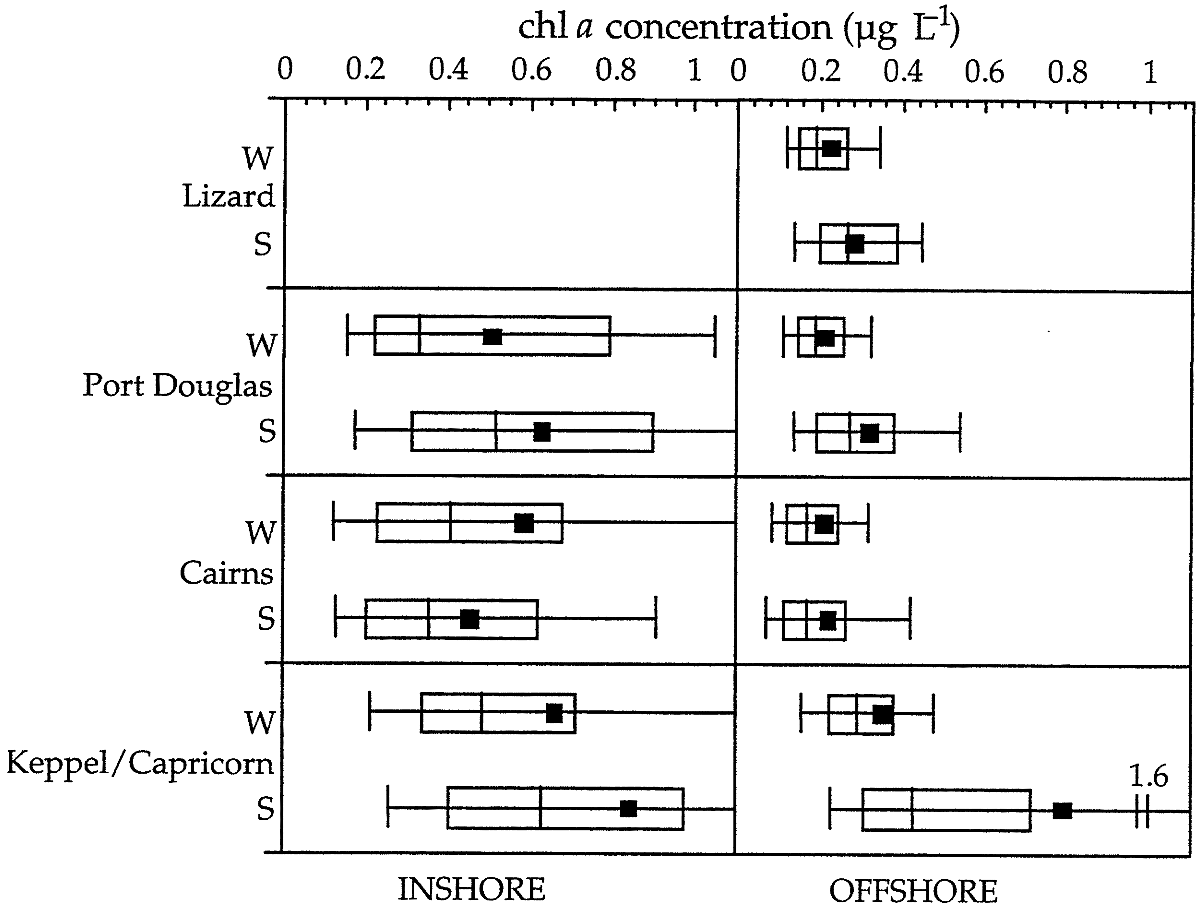

Figure 10.1 Box plots of surface chlorophyll *a* concentrations (µg L^{-1}) grouped by region, cross-shelf position (inshore, offshore) and season (summer [S], winter [W]). Box plots represent the spread of data. The box contains the middle half (50%) of the data, the outer and inner lines representing the 75th and 25th percentiles respectively. The line inside the box is the median (50th percentile). The whiskers extending from either end of the box encompass the data within the 10th and 90th percentile. The ■ represents the arithmetic mean of the data.

10.1 SPATIAL PATTERNS

Irrespective of season or latitude, chlorophyll *a* concentrations at inshore stations were ~2 fold higher than offshore, but also more variable (figure 10.1). Inshore, median chlorophyll *a* concentrations were greater than 0.5 µg L^{-1} in the Keppels and Townsville clusters, but were less in Cairns and Port Douglas clusters (table 10.1).

Table 10.1 Summary statistics of regional chlorophyll *a* concentrations grouped by season (summer and winter) and cross-shelf position (inshore and offshore)

Region	Season	Inshore Chlorophyll *a* (µg L^{-1})				Offshore Chlorophyll *a* (µg L^{-1})			
		Median	Mean	S.E.	n	Median	Mean	S.E.	n
Lizard		–	–	–	–	0.23	0.26	0.01	632
	S	–	–			0.26	0.28	0.01	378
	W	–	–	–	–	0.19	0.22	0.01	254
Port Douglas		0.48	0.58	0.02	318	0.24	0.28	0.01	378
	S	0.52	0.63	0.03	204	0.27	0.32	0.01	245
	W	0.33	0.50	0.04	114	0.17	0.21	0.01	133
Cairns		0.36	0.51	0.03	172	0.17	0.22	0.01	198
	S	0.36	0.46	0.03	110	0.17	0.22	0.02	124
	W	0.41	0.59	0.06	282	0.17	0.21	0.02	74
Townsville		0.53	0.66	0.00	68	0.20	0.25	0.07	62
	S	0.5	0.59	0.05	52	0.23	0.27	0.07	48
	W	0.59	0.87		16	0.14	0.20	0.07	14
Keppel Bay /		0.56	0.76	0.04	364	0.36	0.62	0.00	413
Capricorn	S	0.63	0.83	0.05	201	0.43	0.79	0.08	253
	W	0.49	0.66	0.05	163	0.29	0.35	0.02	160

At stations within 1–2 km of the coast, median chlorophyll *a* concentrations were greater than 0.7 µg L^{-1} (e.g. stations 10, 23, 27, 33, 35, 41).

Offshore, median chlorophyll *a* concentrations varied from 0.17 µg L^{-1} in the Cairns cluster, to 0.36 µg L^{-1} in the Capricorn cluster. Regionally, chlorophyll *a* concentrations were greatest in the Keppel Bay/ Capricorn cluster (table 10.1). These high chlorophyll *a* concentrations were related to the presence of *Trichodesmium* aggregations which were present in over 30% of all samples (table 10.2). In contrast, at all other clusters *Trichodesmium* slicks were recorded in less than 8% of all sample observations.

Table 10.2 Frequency of observations of *Trichodesmium* slicks during sampling events in each cluster

Cluster	Absent		Present		Total
	count	%	count	%	count
Lizard	604	95.57	28	4.43	632
Port Douglas	684	93.19	50	6.81	734
Cairns	444	91.74	40	8.26	484
Townsville	126	96.92	4	3.08	130
Keppels	270	62.79	160	37.21	430
Capricorn	272	65.86	141	34.14	413
Column total	2400	85.02	423	14.98	2823

With relatively few exceptions phytoplankton biomass was well distributed throughout the water column. Differences between concurrent near-surface and near-bottom chlorophyll *a* concentrations within a region were significant only at offshore stations, particularly during summer months (table 10.3). Significant differences also occurred during winter months at stations in the Port Douglas and Cairns clusters, where the depth difference between near-surface and near-bottom samples is greater (21–82 m). These differences are unlikely to be ecologically significant, given the tendency for phytoplankton in high-light environments to photo-adapt by reducing their chlorophyll content (Brodie et al. 1996). Given the high correlation between near-surface and near-bottom samples, near-bottom sampling is redundant in the context of this monitoring program.

Table 10.3 Summary of paired t-tests between near-surface and near-bottom chlorophyll *a* concentrations within each regional cluster and grouped by season (summer and winter) and cross-shelf position (inshore and offshore)

		Inshore			Offshore		
Source	Season	df	t-ratio	P < t	df	t-ratio	P < t
Lizard	S	–	–	–	93	-7.60	<0.0001
	W	–	–	–	49	-0.57	0.2856
Port Douglas	S	162	0.2	0.5791	187	-6.90	<0.0001
	W	59	-0.45	0.3267	63	-2.16	0.0174
Cairns	S	69	-1.46	0.0746	76	-5.91	<0.0001
	W	49	-0.64	0.2641	45	-3.04	0.0020
Keppel Bay–Capricorn	S	104	-0.54	0.2967	251	2.01	0.9770
	W	57	1.18	0.8778	159	-0.77	0.2202

The average variability of surface chlorophyll *a* concentrations from replicate casts were greater than 0.6 μg L^{-1} in the Keppel Bay and Capricorn clusters (table 10.4). Small scale *Trichodesmium* patches (< 100 m) are the most likely reason for these large differences. Replicate casts in the Cairns and Port Douglas clusters differed on average by 0.25 μg L^{-1}, and by 0.17 μg L^{-1} in the Lizard cluster.

Table 10.4 Mean (± S.E.) variability of chlorophyll *a* concentration between replicate casts from surface waters, and between duplicates derived from the same cast. Regional mean chlorophyll concentrations are given for comparative purposes.

	Mean (± 1 S.E.) Chlorophyll *a* (μg L^{-1})		
Cluster	Regional	Cast Variability	Duplicate variability
Lizard	0.26 ± 0.01	0.17 ±0.01	0.02 ± 0.00
Port Douglas	0.42 ± 0.01	0.26 ±0.02	0.05 ± 0.00
Cairns	0.39 ± 0.02	0.24 ± 0.03	0.04 ± 0.00
Capricorn	0.62 ± 0.05	0.61 ± 0.09	0.22 ± 0.04
Keppel Bay	0.76 ± 0.04	0.65 ± 0.07	0.11 ± 0.01
Townsville	0.47 ± 0.04	0.06 ± 0.01	0.03 ± 0.00

Likewise, variation between duplicate samples was greatest in the Keppel Bay and Capricorn clusters (table 10.4). In the other clusters, duplicate samples varied on average, by less than 0.05 μg L^{-1}. This variance is a composite of sample and laboratory error, plus small scale patchiness (< 5 litres).

10.2 TEMPORAL TRENDS

Figure 10.2 summarises interannual variation in chlorophyll *a* concentration by region. In all offshore clusters median chlorophyll *a* concentrations of near-surface waters were greater in 1993 than 1994 and 1995. Median chlorophyll *a* concentrations in inshore near-surface waters of Port Douglas and Cairns clusters were greater in 1993 than the subsequent two years; in Keppel Bay median chlorophyll *a* concentrations were considerably less in 1993 than the following two years. An El Niño related drought persisted through 1991–94, and regional run-off was considerably below the long-term average. Following monsoonal depressions in late February 1994 and 1995, significant flow occurred from rivers between the Herbert and the Daintree Rivers.

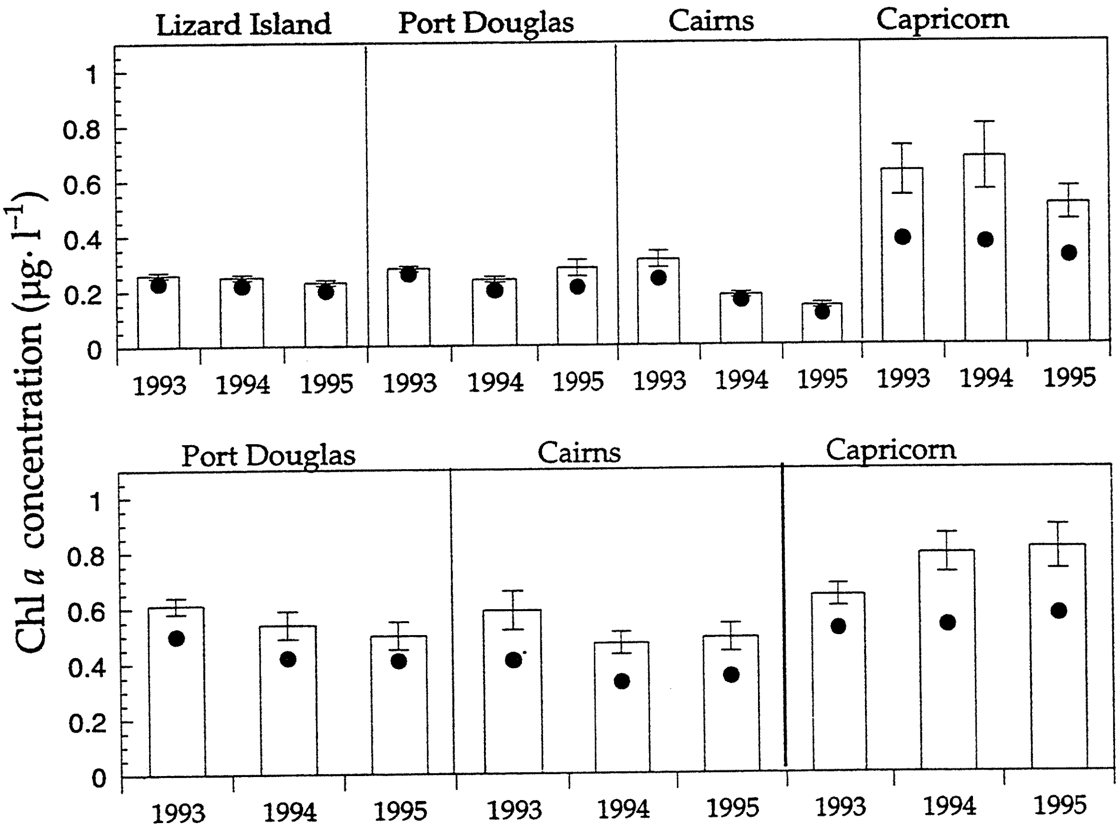

Figure 10.2 Annual mean (± 1 S.E.) chlorophyll a concentrations of offshore (a) and inshore (b) clusters. ● is the median value.

Seasonally, chlorophyll *a* concentrations were generally greater in summer than winter, except in the Cairns cluster (table 10.1). These seasonal differences were more discernible at offshore stations – the greater temporal variation at inshore stations obscuring seasonal patterns.

Figure 10.3 shows mean regional monthly chlorophyll *a* concentrations aggregated over 1993–1995, and grouped by cross-shelf position. Chlorophyll *a* concentrations were generally higher in all clusters from January to May. High chlorophyll *a* concentrations in the Capricorn cluster recorded in September and October, probably result from shelf-break intrusions or strong winds resuspending bottom sediments.

Preliminary non-parametric trend analysis was performed using the median monthly value of each cluster. The Seasonal Mann-Kendall test for trend estimates the size of the trend using the Seasonal Kendall slope estimator (Hirsch et al. 1982; Hirsch and Slack 1984). No significant changes in mean chlorophyll *a* concentration were detected for any cluster (table 10.5). At offshore stations, the negative slope estimate indicates a decline in chlorophyll *a* concentration of 0.01–0.04 µg L^{-1}, from 1993 to 1995. This is consistent with the observed interannual patterns shown in figure 10.3. Cairns inshore stations was the only cluster to show an increase (0.03 µg L^{-1}) over the same period. There was no indication of change in chlorophyll *a* concentration in the Keppels cluster over the sampling period – given the high temporal and spatial variability of this cluster this is to be expected.

In figure 10.4 chlorophyll *a* concentrations taken ~monthly at stations 10 and 11, are compared with the results from ~weekly sampling at stations 20 and 21. Stations 20 and 21 are within 10 km of stations 10 and 11, and sampling period is January 1993 to January 1994. It is clear that monthly sampling often does not detect short-lived (1–2 weeks) 'bloom' events detected by near-weekly sampling. The magnitude of between-week fluctuations in chlorophyll *a* concentrations was ~50% of overall mean monthly chlorophyll *a* concentrations.

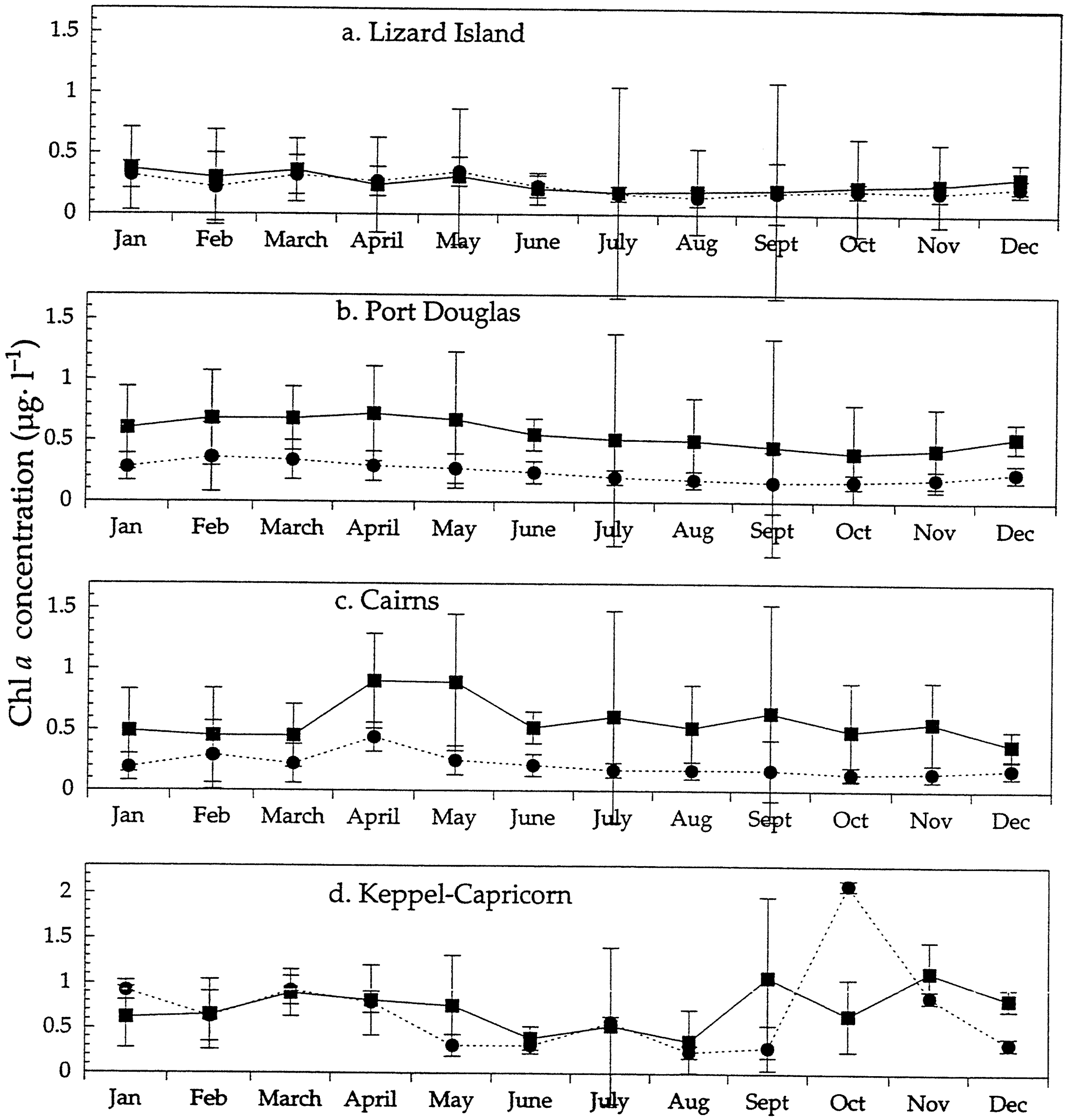

Figure 10.3 Regional monthly mean (± 1 S.D.) chlorophyll *a* concentration (μg L^{-1}) aggregated over years. Data are grouped into inshore(■) and offshore (●) clusters

Table 10.5 Results of seasonal Mann-Kendall test for trend in regional and cross-shelf clusters

Cluster	n	p value	Slope	95% confidence	
				Lower	Upper
Inshore					
Port Douglas inshore	35	0.30	-0.04	-0.11	0.01
Cairns inshore	31	0.67	0.03	-0.05	0.09
Keppel Bay	30	1.00	0.00	0.00	0.00
Offshore					
Lizard	34	0.26	-0.03	-0.06	0.01
Port Douglas offshore	30	0.28	-0.01	-0.07	0.01
Cairns offshore	31	0.20	-0.04	-0.26	0.02
Capricorn	36	0.79	-0.02	-0.08	0.01

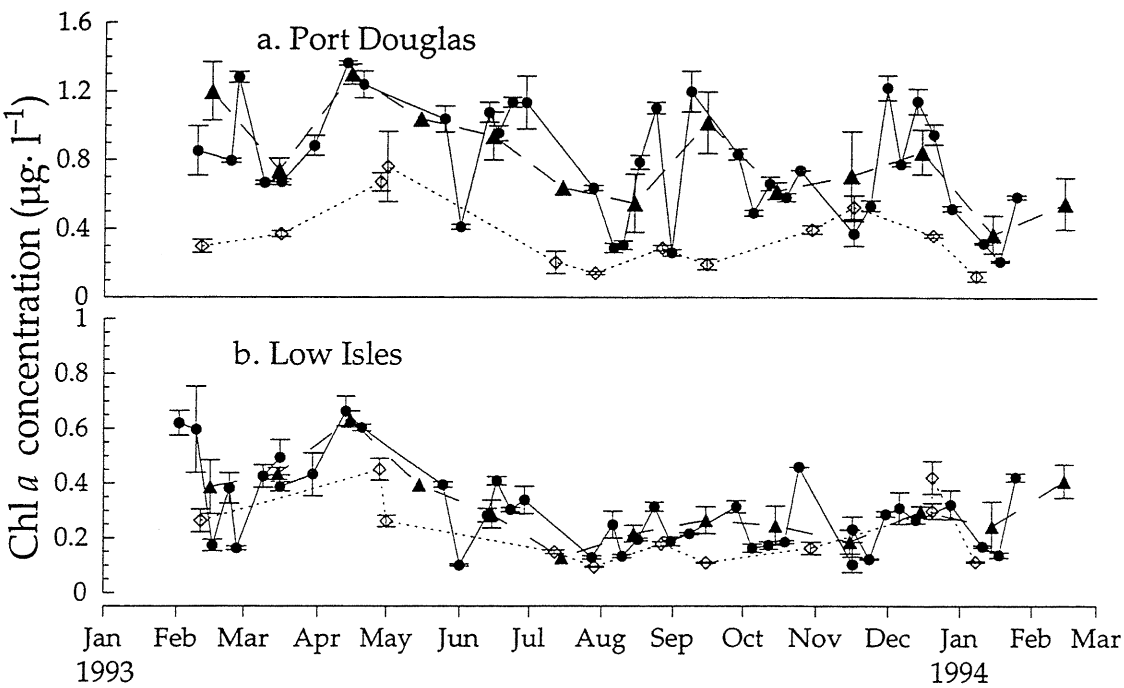

Figure 10.4 Comparison of mean (± 1 S.E.) chlorophyll *a* concentrations (µg L^{-1}) recorded at stations 10 and 20 (a) and stations 11 and 21 (b) over different sampling frequencies: (●) samples collected weekly at 10 and 11; (▲) monthly (calendar) average of samples collected weekly at stations 10 and 11; ◊). Monthly samples collected at stations 20 and 21.

10.3 PROGRAM ASSESSMENT

10.3.1 Network design

The first three years of data collection support the general cross-shelf trends identified by previous researchers (e.g. Furnas et al. 1988, 1992, 1995). Chlorophyll *a* concentrations in near-surface waters between Townsville and Lizard Island were generally low. Much of this region is characterised by an open matrix of reefs which facilitates exchange of surface waters of the Coral Sea. Chlorophyll *a* concentrations in the Keppel and Capricorn clusters (23°S) were considerably greater than the other clusters to the north. These high chlorophyll *a* concentrations and spatial variability, result from *Trichodesmium* aggregations, which were present in over 30% of all sampling dates. Why these blooms are more frequent in southern Great Barrier Reef waters is unknown. Given the paucity of oceanographic data in this region, this finding is significant. Inshore stations generally had greater mean concentrations and varied temporally much more than offshore stations. Chlorophyll *a* concentrations were usually higher in summer than winter, but these differences were not as great as regional and cross-shelf differences. 'Bloom' concentrations were episodic and short-lived, rarely lasting more than one sampling event. Chlorophyll a concentrations greater than 1 $\mu g\ L^{-1}$ often occurred in January–April following significant rainfall.

The malfunctioning of many of the salinity probes restrict any conclusions as to how these patterns of chlorophyll *a* concentration are related to changes in water masses resulting from riverine discharge, or from shelf-break upwelling. No significant correlations could be established between Secchi depth and chlorophyll *a* concentration.

The nutrient status of Great Barrier Reef waters cannot be inferred from these data as clusters are not explicitly linked to regional nutrient input data. Future analysis should focus on relating the observed patterns in chlorophyll *a* concentration to river flow data, the occurrence of shelf break upwelling events, and regional hydrographic and weather data.

The spatial and temporal patterns identified provide a basis for redesign of the Network, and reallocation of sampling effort. However, these design choices need to be predicated on explicit objectives and definitions of what is being measured (i.e. chlorophyll *a* or nutrients). Conceptually the following issues and recommendations should be considered before any redesign:

- Clear, explicit objectives are needed before any redesign takes place. These should include both broad strategic objectives for the maintenance of 'water quality' within the Great Barrier Reef lagoon, as well as specific technical objectives for the measurement of chlorophyll and inference of nutrient status.
- Explicit links to putative nutrient sources should be made. Monitoring stations should be linked to other ongoing catchment and river monitoring (e.g. Queensland Department of Environment and Heritage, Queensland Department of Natural Resources, Australian Institute of Marine Science).
- The techniques linking chlorophyll *a* concentrations to nutrient status have not been defined. This has been a major hindrance to the interpretation of the data. Technical expertise should be sought in developing these relationships and models.
- Other bioindicator techniques such as primary productivity estimates should be considered as part of the Network. These measurements could most routinely be carried out by research station staff.
- Remote sensing has the capacity to greatly extend the inferences made about spatial dynamics of regional chlorophyll *a* patterns. Both SEAWIFS and AIDOS will provide high-frequency coverage of the GBR region. The integration of this technology into the Network is recommended.

Following on from the above, the issues below should also be considered in any sampling reallocation:

- Inshore stations are expected to respond to changes in the frequency or magnitude of land-based inputs of nutrients before offshore stations. However, the high temporal and spatial variability of chlorophyll *a* concentrations in inshore waters will be a significant impediment to discriminating whether there has been any change in nutrient status. In contrast, it is highly unlikely that significant changes in nutrient status of offshore waters from land-based sources will occur. However, the greater spatial and temporal homogeneity of chlorophyll *a* concentrations in these waters would improve the detection of long-term changes in nutrient status.
- Monthly sampling often missed short-term blooms, but did reflect seasonal changes in basal concentrations of chlorophyll *a*. Sampling could be better allocated to sample more frequently during summer months, to detect these blooms and relate them to river run-off data.
- Differences between concurrent near-surface and near-bottom chlorophyll *a* concentrations were ecologically insignificant. Given the greater horizontal patchiness between casts, any additional sampling effort would be better invested in minimising this variance.
- Size fractionating samples into picoplankton ($< 2\ \mu m$) and phytoplankton ($> 2\ \mu m$) would provide greater inference as to which species are responding to changes in nutrient availability.
- Within the Lizard cluster, stations closer to the coast and also to the shelf-break are needed.

- Keppel Bay and Capricorn clusters should be linked with fewer stations concentrated around Keppel Bay and more between Keppel Bay and the Capricorn stations.
- Initiation of a sampling cluster adjacent to the Johnstone and Russell–Mulgrave rivers should be considered. Intensive agriculture occurs on these catchments which are also the focus for a number of pilot landuse and run-off studies.

10.3.2 Sampling and data protocols

A number of operational protocols need to be improved to ensure the integrity of the data collected, and the continued participation of stakeholders. Specifically:

- *SCT meters*: Problems occurred in the calibration and operation of nearly all the SCT meters over the last three years. This has resulted in considerable loss and inaccuracy of temperature and salinity data. All clusters need to be provided with reliable equipment for the routine measurement of temperature and salinity. Other technology should be considered; possibly simple refractometers for salinity, and reversing thermometers for temperature. Routine calibration is essential to ensure data integrity.
- *Transfer of chlorophyll samples*: Samples should be transferred by collectors to AIMS for analysis more frequently. Samples should not be left any longer the one to two months before transfer.
- *Data assurance*: Although publication of data and reports on the World Wide Web may be desirable, more rigorous quality assurance procedures need to be developed beforehand to ensure the integrity of the data; in particular the temperature and salinity data collected to date.
- *Reporting*: Future results need to be more readily available. Annual summaries of spatial and temporal patterns, and quinnenium status reporting is recommended.

ACKNOWLEDGMENTS

A sampling program of this magnitude and geographical scope could not possibly be achieved without the efforts and commitment of a large and disparate group of people. We would like to recognise the efforts of the major organisations listed below, who are involved in maintaining the sampling program:

- *Australian Institute of Marine Science*: Margaret Wright, Michelle Skuza, Miles Furnas and Alan Mitchell
- *Great Barrier Reef Marine Park Authority*: Jon Brodie, David Haynes, Rob McGill, Michael Baer
- *Lizard Island Research Station:* Anne Hoggett, Lyle Vail, Marek Cuhra, Marianne Pearce, Russell Markel, Marnie Horton, Stephanie Warrington, Lois Wilson, Anja Hansen, Dorte Kaadner, Cara Biega, Eunice and Linden Vail, Simone Aeberhard, David Randall, Margaret Hoggett, Perry Hankinson, Roberta Murchison
- *Quicksilver Connections Ltd and Reef Biosearch:* Douglas Baird, Ibrahim Elmetri, Andy Dunstan, Shane Down and Rick Kilpatrick
- *Heron Island Research Station:* Myriam Preker, Mark Waugh, Robyn Sweetapple
- *Queensland Department of Environment and Heritage, Far Northern Region*: Mike Short and Sarah Strawbridge
- *Queensland Department of Environment and Heritage, Northern Region*: Jon Day, John Hicks, David Savage, Norm Land
- *Queensland Department of Environment and Heritage, Central Coast Region*: Paul O'Neill, Chris Maple, John Messersmith and Brian Morris

The preparation of this report benefited greatly from comments by Tenshi Ayukai, John Beardall, Miles Furnas, Laurence McCook and Andrew Moss. The Commonwealth Scientific and Industrial Research Organisation are gratefully acknowledged for the use of figure 2.2, and Kim Davis, Leon Jackson and Brian Dare for production of the final report.

REFERENCES

Alongi, D.M. 1989. Benthic processes across mixed terrigenous-carbonate sedimentary facies on the central Great Barrier Reef continental shelf. Continental Shelf Research 9: 629–663.

Andrews, J.C. and P. Gentien 1982. Upwelling as a source of nutrients for the Great Barrier Reef ecosystem: a solution to Darwin's question. Marine Ecology Progress Series 8: 257–269.

Andrews, J.C. and H. Müller 1983. Space-time variability of nutrients in a lagoonal patch reef. Limnology and Oceanography 28: 215–227.

Arakel, A.V., C.M. Hill, J. Piorewicz and T.B. Connor 1989. Hydro-sedimentology of the Johnstone River estuary. Hydrobiologia 176–177: 51–60.

Australian and New Zealand Environment and Conservation Council 1992. Australian water quality guidelines for fresh and marine waters. Canberra, ACT. ANZECC Secretariat.

Ayukai, T. 1993. Temporal variability of the nutrient environment on Davies Reef in the central Great Barrier Reef, Australia. Pacific Science 47: 171–179.

Bell, P.R.F. 1992. Eutrophication and coral reefs – some examples in the Great Barrier Reef lagoon. Water Research 26: 553–568.

Bell, P.R.F. and I. Elmetri 1995. Ecological indicators of large-scale eutrophication in the Great Barrier Reef lagoon. Ambio 24: 208–215.

Belperio, A.L. 1983. Late quaternary terrigenous sedimentation in the Great Barrier Reef lagoon, pp. 71–76. *In* J.T. Baker, R.M. Carter, P.W. Sammarco and K.P. Stark (eds). Proc. Inaugural Great Barrier Reef Conf., Townsville, James Cook University Press.

Brodie, J.E. 1995. Management of sewage discharges in the Great Barrier Reef Marine Park. The sixth Pacific Congress on Marine Science and Technology. PACON 94, pp. 457–466.

Brodie, J.E. 1996. The problem of nutrients and eutrophication in the Australian marine environment, pp. 11–24. *In* L.P. Zann and D.C. Sutton (eds). The Marine Environment: State of the Marine Environment Report for Australia: Technical Annex 2. Great Barrier Reef Marine Park Authority, Townsville.

Brodie, J. and M.J. Furnas 1996. Cyclones, river flood plumes and natural water quality extremes in the central Great Barrier Reef, pp. 367–374. *In* H.M Hunter, A.G. Eyles and G.E. Rayment (eds). Downstream Effects of Land Use. Department of Natural Resources, Queensland.

Brodie, J.E. and A. Mitchell 1992. Nutrient composition of the January 1991 Fitzroy River flood plume, pp. 56–74. *In* G.T. Byron (ed.). Workshop on the Impacts of Flooding. Workshop Series No. 17. Great Barrier Reef Marine Park Authority, Townsville.

Brodie, J.E., M.J. Furnas, A.D.L. Steven, L.A. Trott, F. Pantus and M. Wright 1997. Monitoring chlorophyll in the Great Barrier Reef lagoon: trends and variability. Proc. 8th Int. Coral Reef Symp, Panama Vol. 1: 797–802.

Buhl-Mortensen, L. 1996. Type-II statistical errors in environmental science and the precautionary principle. Marine Pollution Bulletin 32: 528–531.

Cadee, G.C. 1986. Increased phytoplankton primary production in the Marsdiep area Western Dutch Wadden Sea. Netherlands Journal of Sea Research 20: 285–290.

Cairns, J. Jr. 1977. Aquatic ecosystem assimilative capacity. Fisheries 21–14.

Crossland, C.J. and D.J. Barnes 1983. Dissolved nutrients and organic particulates in water flowing over coral reefs at Lizard Island. Australian Journal of Marine and Freshwater Research 34: 835–844.

Currie, B.R. and R.B. Johns 1989. An organic geochemical analysis of terrestrial biomarkers in a transect of the Great Barrier Reef lagoon. Australian Journal of Marine and Freshwater Research 40: 275–284.

D'Elia, C.F., J.L.W. Harding, M. Leffler and G.B. Mackiernan 1992. The role and control of nutrients in Chesapeake Bay. Water Science & Technology 26: 2635–2644.

Degobbis, D. 1989. Increased eutrophication of the northern Adriatic Sea: second act. Marine Pollution Bulletin 20: 452–457.

DeVantier, L.M., E. Turak, T.J. Done and J. Davidson 1996. The effects of cyclone Sadie on coral communities of nearshore reefs in the central Great Barrier Reef, pp. 65–88. *In* A.D.L. Steven (ed.). Cyclone Sadie Flood Plumes in the Great Barrier Reef Lagoon: Composition and Consequences. Workshop Series No. 22. Great Barrier Reef Marine Park Authority, Townsville.

Dinesen, Z.D. 1983. Patterns in the distribution of soft corals across the central Great Barrier Reef. Coral Reefs 1: 229–236.

Done, T.J. 1982. Patterns in the distribution of coral communities across the central Great Barrier Reef. Coral Reefs 1: 95–107.

Driml, S. 1994. Protection for Profit: Economic and Financial Values of the Great Barrier Reef World Heritage Area and Other Protected Areas. Research Publication No. 35. Great Barrier Reef Marine Park Authority, Townsville. 90 pp.

Dugdale, R.C. and J.J. Goering 1967. Uptake of new and regenerated forms of nitrogen in primary productivity. Limnology and Oceanography 12: 196–206.

Dugdale, R.C., F.P. Wilkerson and A. Morel 1990. Realisation of new production in coastal upwelling areas: a means to compare relative performance. Limnology and Oceanography 35: 822–829.

Fabricius, K.E. 1995. Slow population turnover in the soft coral genera *Sinularia* and *Sarcophyton* on mid- and outer-shelf reefs of the Great Barrier Reef. Marine Ecology Progress Series 126: 145–152.

Furnas, M.J. 1989. Cyclonic disturbance and a phytoplankton bloom in a tropical shelf environment. pp. 271–277. *In* Red Tides: Biology, Environmental Science and Toxicology. Elsevier, New York..

Furnas, M.J. and J. Brodie 1996. Current status of nutrient levels and other water quality parameters in the Great Barrier Reef, pp. 9–22. *In* H.M. Hunter, A.G. Eyles and G.E. Rayment (eds). Downstream Effects of Land Use. Department of Natural Resources, Queensland.

Furnas, M.J. and A.W. Mitchell 1984. A hydrographic, nutrient and phytoplankton biomass survey in Palm Passage (central Great Barrier Reef) during 1983. Data Report Oceanography Series. Australian Institute of Marine Science.

Furnas, M.J. and A.W. Mitchell 1986. Phytoplankton dynamics in the central Great Barrier Reef 1. Seasonal changes in biomass and their relation to intrusive activity. Continental Shelf Research 6: 363–384.

Furnas, M.J. and A.W. Mitchell 1996. Nutrient inputs to the central Great Barrier Reef Australia from subsurface intrusions of Coral Sea Waters: a two-dimensional displacement model. Continental Shelf Research 16: 1127–148.

Furnas, M. J., A.W. Mitchell and M. Skuza 1995. Nitrogen and Phosphorus Budgets for the Central Great Barrier Reef Shelf. Research Publication No. 36. Great Barrier Reef Marine Park Authority, Townsville.

Furnas, M.J., A.W. Mitchell, P. Liston, M. Skuza, E. Drew and J.T. Wellington 1992. Biological and Chemical Oceanographic Measurements in the Far Northern Great Barrier Reef – February, 1990. Research Publication No. 34. Great Barrier Marine Park Authority, Townsville.

Furnas, M.J., A.W. Mitchell, J. Wellington and B. Brady 1988. Dissolved and Particulate Nutrients in Waters of the Whitsunday Island Group. Research Publication No. 16. Great Barrier Marine Park Authority, Townsville.

Gabric, A.J. and P.R.F. Bell 1993. Review of the effects of non-point nutrient loading on coastal ecosystems [review]. Australian Journal of Marine and Freshwater Research 44: 261–283.

Gabric, A.J., P. Hoffenberg and W. Boughton 1990. Spatio-temporal variability in surface chlorophyll distribution in the central Great Barrier Reef as derived from CZCS imagery. Australian Journal of Marine and Freshwater Research 41: 313–24.

Gagan, M.K., A.R. Chivas and A.L. Herczeg 1990. Shelf-wide erosion, deposition, and suspended transport during cyclone Winifred, central Great Barrier Reef, Australia. Journal of Sedimentary Petrology 60: 456–470.

Gagan, M.K., M.W. Sandstrom and A.R. Chivas 1987. Restricted terrestrial carbon input to the continental shelf during cyclone Winifred: implications for terrestrial run-off to the Great Barrier Reef Province. Coral Reefs 6: 113–119.

Goda, T. 1992. Eutrophication and its remedies in the Seto Inland Sea with respect to the characteristics of bed deposition, pp. 1217–1238. *In* R.A. Vollenweider, R. Marchetti and R. Viviani (eds). Marine Coastal Eutrophication. Elsevier, Amsterdam.

Gordon, D.C., P.R. Boudreau, K.H. Mann, J.E. Ong, W.L. Silvert, S.V. Smith, G. Wattayakorn, F. Wulff and T. Yanagi 1996. LOICZ Biogeochemical Modelling Guidelines. Netherlands Institute for Sea Research: LOICZ Core Project. LOICZ Reports and Studies.

Gourlay, M.R. and L.F. Hacker 1986. Pioneer River Estuary: Sedimentation studies. Dept of Civil Engineering, University of Queensland, Brisbane.

Gray, J.S. 1990. Statistics and the precautionary principle. Marine Pollution Bulletin 21: 174–176.

Gray, J.S. 1996. Environmental science and a precautionary approach revisited. Marine Pollution Bulletin 32: 532–534.

Gray, J.S., D. Calamari, R. Duce, J.E. Portmann, P.G. Wells and H.L. Windom 1991. Scientifically based strategies for marine environmental protection and management. Marine Pollution Bulletin 22: 432–440.

Great Barrier Reef Marine Park Authority 1994a. Corporate Plan, 1994–99. Great Barrier Reef Marine Park Authority, Townsville.

Great Barrier Reef Marine Park Authority 1994b. The Great Barrier Reef – Keeping it Great: A 25 Year Strategic Plan for the Great Barrier Reef World Heritage Area 1994–2019. Great Barrier Reef Marine Park Authority, Townsville.

Hallegraeff, G.M. 1995. Marine phytoplankton communities in the Australian regions: current status and future threats, pp. 85–96. *In* L.P. Zann and P. Kailola (eds). The Marine Environment: State of the Marine Environment Report for Australia: Technical Annex 1. Great Barrier Reef Marine Park Authority, Townsville.

Harding, L.W.J. 1994. Long-term trends in the distribution of phytoplankton in Chesapeake Bay: roles of light, nutrients and streamflow. Marine Ecology Progress Series 104: 267–291.

Harris, G., G. Batley, D. Fox, D. Hall, P. Jernakoff, R. Molloy, A. Murray, B. Newell, J. Parslow, G. Skyring and S. Walker 1996. Port Phillip Bay Environmental Study final report. Canberra, Australia, CSIRO.

Hawker, D.W. and D.W. Connell 1989. An evaluation of the tolerance of corals to nutrients and related water quality characteristics. International Journal of Environmental Studies, pp. 1–10.

Hirsch, R.M. and J.R. Slack 1984. A nonparametric trend test for seasonal data with serial dependence. Water Resource Research 20: 727–732.

Hirsch, R.M., J.R. Slack and R.A. Smith 1982. Techniques of trend analysis for monthly water quality data. Water Resource Research 18: 107–121.

Hollingsworth Dames & Moore 1993. Water Quality guidelines for Trinity Inlet. Report to the Queensland Department of Environment and Heritage.

Hopley, D. 1988. Anthropogenic influences on Australia's Great Barrier Reef. Australian Geographer 19: 26–45.

Hopley, D., K.E. Parnell and P.J. Isdale 1989. The Great Barrier Reef Marine Park: dimensions and regional patterns. Australian Geographical Studies 27: 47–66.

Jeffrey, S.W. and G.F. Humphrey 1975. New spectrophotometric equations for determining chlorophylls a, b, c_1 and c_2 in higher plants, algae and natural phytoplankton. Biochem. Physiol. Pflaanzen. 167: 191–194.

Johnson, C.R. and D. Neil 1996. Managing Australia's marine environment: the way ahead.

Josefson, A.B. 1990. Increase of benthic biomass in Skagerrak-Kattegat during the 1970s and 1980s. No effects of organic enrichment? Marine Pollution Bulletin 66: 117–130.

Justic, D. 1987. Long-term eutrophication of the northern Adriatic Sea. Marine Pollution Bulletin 18: 281–284.

King, B. and E. Wolanski 1991. Coastal dynamics along a rugged coastline, pp. 577–598. *In* D. Prangle (ed.). Dynamics and Exchanges in Estuaries and the Coastal Zone. Springer-Verlag, New York.

Kinsey, D.W. 1988. Coral reef system response to some natural and anthropogenic stresses. Galaxea 7: 113–128.

Kinsey, D.W. and P.J. Davies 1979. Effects of elevated nitrogen and phosphorus on coral reef growth. Limnology and Oceanography 24: 935–940.

Koop, K., W.R. Boynton, F. Wulff and R. Carman 1990. Sediment-water oxygen and nutrient exchanges along a depth gradient in the Baltic Sea. Marine Ecology Progress Series 63: 65–77.

Lapointe, B.E. 1997. Nutrient thresholds for eutrophication and macroalgal cover on coral reefs in Jamaica and south-east Florida. *In* H.A. Lessios (ed.). Proceedings of the 8th International Coral Reef Symposium, Panama.

Lapointe, B.E. and M.W. Clark 1992. Nutrient inputs from the watershed and coastal eutrophication in the Florida Keys. Estuaries 15: 465–476.

Lapointe, B.E. and W.R. Matzie 1996. Effects of stormwater nutrient discharges on eutrophication processes in nearshore waters of the Florida Keys. Estuaries 19: 422–435.

Lapointe, B.E. and J. O'Connell 1989. Nutrient enhanced growth of *Cladophora prolifera* in Harrington Sound, Bermuda: eutrophication of a confined, phosphorus limited ecosystem. Estuarine Coastal Shelf Sci. 28: 347–360.

Lapointe, B.E., M.M. Littler and D.S. Littler 1992. Modification of benthic community structure by natural eutrophication: the Belize Barrier Reef. Proceedings of the Seventh International Coral Reef Symposium Vol. 1: 323–334.

Lapointe, B.E., W.R. Matzie and M.W. Clark 1994. Phosphorus inputs and eutrophication on the Florida Reef tract. Proc. Colloquium on Global Aspects of Coral Reefs: Health, Hazards and History. V15–V21.

Lee, G. and R.A. Jones 1991. Effects of eutrophication on fisheries. Reviews in Aquatic Sciences 5: 287–305.

Liston, P.W. 1990. Spatial variability and covariability of chlorophyll and zooplankton on the Great Barrier Reef. PhD dissertation, James Cook University of North Queensland, Townsville, Australia.

Liston, P.W., M.J. Furnas, A.W. Mitchell and E.A. Drew 1992. Local and mesoscale variability of surface water temperature and chlorophyll in the northern Great Barrier Reef. Australian Continental Shelf Reserve 12: 907–921.

Littler, M.M., D.S. Littler and E.A. Titlyanov 1991. Comparisons of N- and P-limited productivity between high granitic islands versus low carbonate atolls in the Seychelles Archipelago: a test of the relative-dominance paradigm. Coral Reefs 10: 199–209.

Lough, J.M. 1993. Variations of some seasonal rainfall characteristics in Queensland, Australia: 1921–1987. International Journal of Climatology 13: 391–409.

Marshall, S.M. 1933. The production of microplankton in the Great Barrier Reef region. Sci. Rep. Great Barrier Reef Exped. 1928–29 2: 111–157.

Mckinnon, A.D. and S.R. Thorrold 1993. Zooplankton community structure and copepod egg production in coastal waters of the central Great Barrier Reef lagoon. Journal of Plankton Research 15(12): 1387–1411.

Mee, L.D. 1992. The Black Sea in crisis: a need for concerted international action. Ambio 21: 278–276.

Mitchell, A.W. and M.J. Furnas 1997. Terrestrial inputs of nutrients and suspended to the Great Barrier Reef lagoon, pp. 59–71. *In* The Great Barrier Reef: Science, Use and Management. A National Conference. Proceedings Volume 1. 25–29 November 1996, James Cook University, Townsville, Queensland, Australia. Great Barrier Reef Marine Park Authority, Townsville.

Montagioni, L.F., P. Cuet and O. Naim 1994. Effect of nutrient excess on a modern fringing reef (Reunion Island, Western Indian Ocean). Geological implications. Proc. Colloquium on Global Aspects of Coral Reefs: Health, Hazards and History. N27–N33.

Morton, B. 1985. Marine pollution induced environmental changes in Hong Kong – the Tolo Harbour case study. Pollution in the urban environment.

Moss, A.J., G.E. Rayment, N. Reilly and E.K. Best 1992. A preliminary assessment of sediment and nutrient exports from Queensland coastal catchments. Report to the Queensland Department of Environment and Heritage and the Department of Primary Industries, Brisbane.

Naim, O. 1993. Seasonal responses of a fringing reef community to eutrophication Reunion Island, western Indian Ocean. Marine Ecology Progress Series 99: 137–151.

Nakanishi, H., M. Ukita, M. Sekine, M. Fukagawa and S. Murakami 1992. Eutrophication control in the Seto Inland Sea, pp. 1239–1258. *In* R.A. Vollenweider, R. Marchetti and R. Viviani (eds). Marine Coastal Eutrophication. Elsevier, Amsterdam.

Neil, D.T. and B. Yu 1995. Simple climate-driven models for estimating sediment input to the Great Barrier Reef lagoon. Great Barrier Reef: Terrigenous sediment flux and human impacts. pp. 67–73.

Officer, C.B., R.B. Biggs, J.L. Taft, L.E. Cronin, M.H. Tyler and W.R. Boynton 1984. Chesapeake Bay anoxia: origin, development and significance. Science 223: 22–27.

O'Neill, J.P., G.T. Byron and S.C. Wright 1992. Some physical characteristics and movement of 1991 Fitzroy River flood plume, pp. 36–52. *In* G.T. Byron (ed.). Workshop on the Impacts of Flooding. Workshop Series No. 17. Great Barrier Reef Marine Park Authority, Townsville.

Pailles, C., D.M. McConchie, A.V. Arakel and P. Saenger 1993. The distribution of phosphate in sediments of the Johnstone Rivers catchment-estuary system, north Queensland, Australia. Sedimentary Geology 85: 253–269.

Parsons, T.R., Y. Maita and C.M. Lalli 1984. A Manual of Chemical and Biological Methods for Seawater Analysis. Oxford, Pergamon Press.

Pernetta, J.C. and J.D. Milliman 1995. Land–Ocean interactions in the coastal zone: implementation plan. Sweden, Graphics Systems. IGBP Global Change.

Peterman, R.M. and M. M'Gonigle 1992. Statistical power analysis and the precautionary principle. Marine Pollution Bulletin 24: 231–234.

Poiner, I.R. and C. Peterken 1995. Seagrasses, pp. 107–116. *In* L.P. Zann and P. Kailola (eds). The Marine Environment: State of the Marine Environment Report for Australia: Technical Annex 1. Great Barrier Reef Marine Park Authority, Townsville.

Preen, A.R., W.J. Lee Long and R.G. Coles 1995. Flood and cyclone related loss, and partial recovery, of more than 1000 km^2 of seagrass in Hervey Bay, Queensland, Australia. Aquatic Botany 52: 3–17.

Preker, M. 1992. The effects of the 1991 central Queensland floodwaters around Heron Island, Great Barrier Reef, p. 75. *In* G.T. Byron (ed.). Workshop on the Impacts of Flooding. Workshop Series No. 17. Great Barrier Reef Marine Park Authority, Townsville.

Pulsford, J.S. 1993. Historical Nutrient Usage in Coastal Queensland River Catchments Adjacent to the Great Barrier Reef Marine Park. Research Publication No. 40, Great Barrier Marine Park Authority, Townsville.

Rahm, L., D. Conley, P. Sanden, F. Wulff and P. Stalnacke 1996. Time series analysis of nutrient inputs to the Baltic Sea and changing DSi:DIN ratios. Marine Ecology Progress Series 130: 221–228.

Rayment, G. and D. Neil 1997. Sources of material in river discharge, pp. 42–58. *In* The Great Barrier Reef: Science, Use and Management. A National Conference. Proceedings Volume 1. 25–29 November 1996, James Cook University, Townsville, Queensland Australia. Great Barrier Reef Marine Park Authority, Townsville.

Redfield, A.C. 1958. The biological control of chemical factors in the environment. Am. Sci. 46: 205–22.

Resource Assessment Commission 1994. The Coastal Zone Inquiry. Australian Government Publishing Service, Canberra.

Revelante, N. and M. Gilmartin 1982. Dynamics of phytoplankton in the Great Barrier Reef lagoon. J. Plankton Res. 4: 47–76.

Risk, M.J., P.W. Sammarco and H.P. Schwarcz 1994. Cross-continental shelf trends in $^{\Delta}$13C in coral on the Great Barrier Reef. Marine Ecology Progress Series 106: 121–130.

Robertson, A.I. and D.M. Alongi 1995. Mangrove ecosystems in Australia: structure, function and status, pp. 119–134. *In* L.P. Zann and P. Kailola (eds). The Marine Environment: State of the Marine Environment Report for Australia: Technical Annex 1. Great Barrier Reef Marine Park Authority, Townsville.

Rosenweig, M.L. 1971. Paradox of enrichment: destabilization of exploitation ecosystems in ecological time. Science 171: 385–387.

Smith, S.V., W.J. Kimmerer, E.A. Laws, R.E. Brock and T.W. Walsh 1981. Kaneohe Bay sewage diversion experiment: perspectives on ecosystem responses to nutritional perturbation. Pacific Science 35: 279–402.

Stebbing, A.R.D. 1992. Environmental capacity and the precautionary principle. Marine Pollution Bulletin 24: 287–295.

Steven, A.D.L., J. Brodie, R. van Woesik and D. Hopley 1992. A Pilot Study of Baseline Levels of Water Quality around Green Island. Research Publication No. 14. Great Barrier Reef Marine Park Authority, Townsville.

Steven, A.D.L., M.J. Devlin, J. Brodie, M. Baer and M.J. Lourey 1996. Spatial influence and composition of river plumes in the central Great Barrier Reef, pp. 85–92. *In* H.M. Hunter, A.G. Eyles, G.E. Rayment (eds). Downstream Effects of Land Use. Department of Natural Resources, Queensland.

Stoddard, A., J.E.W. O'Reilly, T.C. Malone and J.F. Hebard 1986. The application and development of a compatible historical data base for the analysis of water quality management issues in the New York Bight. Oceans 86(3): 1030–1035.

Szmant, A.M. and A. Forrester 1996. Water column and sediment nitrogen and phosphorus distribution patterns in the Florida Keys, USA. Coral Reefs 15: 21–41.

Tarte, D., M. Hall and K. Stocks 1996. Issues in the Queensland marine environment, pp. 39–60. *In* L.P. Zann and D.C. Sutton (eds). State and Territory Issues: State of the Marine Environment Report for Australia: Technical Annex 3. Great Barrier Reef Marine Park Authority, Townsville.

Tomascik, T. 1991. Settlement patterns of Caribbean scleractinian corals on artificial substrata along a eutrophication gradient, Barbados, West Indies. Marine Ecology Progress Series 77: 261–269.

Tomascik, T. and F. Sander 1985. Effects of eutrophication on reef building corals. I. Growth rate of the reef building coral *Montastrea annularis*. Marine Biology 87: 143–155.

Tomascik, T. and F. Sander 1987a. Effects of eutrophication on reef building corals. II. Structure of scleractinian coral communities on fringing reefs, Barbados, West Indies. Marine Biology 94: 53–75.

Tomascik, T. and F. Sander 1987b. Effects of eutrophication on reef building corals. III. Reproduction of the reef building coral *Porites porites*. Marine Biology 94: 77–94.

Tomascik, T., Suharsono and A.J. Mah 1994. Case histories: a historical perspective and anthropogenic impacts in the Indonesian archipelago with a focus on Seribu, Java Sea. Proc. Colloquium on Global Aspects of Coral Reefs: Health, Hazards and History, pp. 304–310.

Underdal, B., O.M. Skulberg, E. Dahl and T. Aune 1989. Disastrous bloom of *Chrysochromulina polylepis* (Prymnesiophyceae) in Norwegian coastal waters 1988 – mortality in marine biota. Ambio 18: 265–270.

Valentine, P.S. 1988. A land use study to investigate potential agricultural chemical inputs to marine environments in the northern Great Barrier Reef Region. Report to the Great Barrier Reef Marine Park Authority.

van Woesik, R., L.M. DeVantier and J.S. Glazebrook 1995. Effects of cyclone 'Joy' on nearshore coral communities of the Great Barrier Reef. Marine Ecology Progress Series 128: 261–270.

Vollenweider, R.A. 1992. Coastal marine eutrophication: principles and control, pp. 1–20. *In* R.A. Vollenweider, R. Marchetti and R. Viviani (eds). Marine Coastal Eutrophication. Elsevier, Amsterdam.

Walker, T.A. 1981. Dependence of phytoplankton chlorophyll on bottom resuspension in Cleveland Bay, northern Queensland. Australian Journal of Marine and Freshwater Research 32: 981–986.

Walker, T.A. and G. O'Donnell 1981. Observations on nitrate phosphate and silicate in Cleveland Bay, north Queensland. Australian Journal of Marine and Freshwater Research 32: 877–887.

Ward, S. and P. Harrison 1997. The effects of elevated nutrient levels on settlement of coral larvae during the ENCORE experiment, Great Barrier Reef, Australia. *In* H.A. Lessios (ed.). Proceedings of the 8th International Coral Reef Symposium, Panama.

Wilkinson, C.R. and A.C. Cheshire 1988. Cross-shelf variations in coral reef structure and function – influences of land and ocean. Proceedings of the 6th International Coral Reef Symposium 1: 227–233.

Wilkinson, C.R. and A.C. Cheshire 1989. Patterns in the distribution of sponge populations across the central Great Barrier Reef. Coral Reefs 8: 127–134.

Williams, D.McB. 1982. Patterns in the distribution of fish communities across the central Great Barrier Reef. Coral Reefs 1: 35–43.

Wolanski, E. and D. van Senden 1983. Mixing of Burdekin River flood waters in the Great Barrier Reef. Australian Journal of Marine and Freshwater Research 34: 49–63.

Wolanski, E., M. Jones and W.T. Williams 1981. Physical properties of Great Barrier Reef lagoon water near Townsville II. Seasonal variations. Australian Journal of Marine and Freshwater Research 32: 321–324.

Wolanski, E., G.L. Pickard and D.L.B. Jupp 1984. River plumes, coral reefs and mixing in the Gulf of Papua and the northern Great Barrier Reef. Estuarine, Coastal and Shelf Science 18: 291–314.

Zevenboom, W., M. Rademaker and F. Coigin 1991. Exceptional algal blooms in Dutch North Sea waters. Water Science & Technology 24: 251–260.