WORKSHOP SERIES No 22

Cyclone Sadie Flood Plumes in the Great Barrier Reef Lagoon: Composition and Consequences

Proceedings of a workshop held in Townsville Queensland, Australia,
10 November 1994,
at the Australian Institute of Marine Science.

Edited by Andrew Steven

GREAT BARRIER REEF
MARINE PARK AUTHORITY

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COVER PHOTOGRAPH
Maria Creek, Kurramine in flood, 2 February 1994
Photograph by Andrew Elliott Great Barrier Reef Marine Park Authority

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Preface

In late January of 1994, cyclone Sadie brought intense rainfall to north Queensland catchments, the first significant monsoonal event since 1991. Several organisations responded, by monitoring the composition and fate of these riverine waters as they flowed through catchments and into nearshore marine waters of the Great Barrier Reef lagoon.

The Great Barrier Reef Marine Park Authority (GBRMPA) convened a workshop on cylone Sadie on the 10 November 1994 in Townsville, Australia, with a view to:

- Presenting research findings on the composition and fate of the flood waters;
- Assessing the likely consequences of this event on coastal catchments and nearshore benthic and necktonic communities;
- Assessing factors governing magnitude and spatial extent of flood plumes;
- Quantifying the significance of flood plumes as new inputs of sediments and nutrients to the Great Barrier Reef lagoon; and
- Discussing methods of better integrating future efforts to monitor significant flood events.

The eight papers in this proceedings contribute to a growing database on the significance of monsoonal events to marine ecosystems. The increased nutrients, sediment and organic loads that can result from these moonsoonal events are often far in excess of base-flow conditions, and can profoundly alter the structure and tropho-dynamic flow of the benthic communities they impinge upon. Comprehending their significance is essential in assessing the potential impact of other natural and anthropogenicallly induced phenomena.

Current efforts to retrospectively model past monsoonal events, and to predict the likely consequences of future events, rely on continued ground truthing of these events. This workshop, and other more recent meetings, have greatly improved our ability to respond rapidly, and in a coordinated fashion to future monsoonal events.

Andrew Steven
Manager Water Quality Program

CYCLONE SADIE WORKSHOP PROGRAM

10th November 1994, Australian Institute of Marine Science

9.00	Introduction and opening	Jon Brodie
9.05	The extent of the river plumes associated with cyclone Sadie rainfall	Jon Brodie
9.30	Nutrients and suspended sediment discharged from the Johnstone river catchment during cyclone Sadie	Heather Hunter
10.00	Export of nutrients and suspended sediment from the Herbert river catchment during a flood event associated with cyclone Sadie	Alan Mitchell / Rob Bramley
10.30	Morning tea	
11.00	Nutrient Dynamics in the Barron River and offshore during cyclone Sadie	Jeremy Taylor
11.30	Preliminary results on Phosphorus status of suspended sediment from cyclone Sadie	Christine Pailles
12.00	Lunch	
1.00	Offshore measurements late in the river plumes associated with cyclone Sadie	Michelle Devlin
1.30	The effects of cyclone Sadie on coral communities of nearshore reefs in the central Great Barrier Reef	L. DeVantier, E. Turak, T. Done, J. Davidson
2.00	Hydrographic and nutrient measurements in the Daintree river plume and its vicinity	Tenshi Ayukai
2.30	Preliminary results from farm scale monitoring of sediments and nutrients in the Johnstone river catchment (Paper not submitted)	B. Prove
3.00	Afternoon Tea	
3.20	Planning for the next one	
4.30	Close	

Nutrients and suspended sediment discharged from the Johnstone river catchment during cyclone Sadie

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Abstract

Flood-waters of cyclone Sadie were sampled intensively at three sites in the Johnstone River system to assess nutrient and suspended sediment concentrations and loads discharged to the Great Barrier Reef Marine Park. Very high flow rates were recorded during the flood event. Concentrations of suspended sediment and nutrients rose markedly and were very much higher than measured under baseflow conditions. However, water quality rapidly improved as flood-waters subsided. Almost 200 000 tonnes of suspended sediment were discharged from the river system over the four day flood event, as well as 858 tonnes of nitrogen, 314 tonnes of phosphorus and 2214 tonnes of organic carbon. The suspended sediment load accounted for 97% of the phosphorus discharged and 84% of the nitrogen, but only 45% of the organic carbon. Sources of the suspended sediment were not determined but may have included soil erosion in the catchment (both rural and urban), stream-bank erosion and mobilisation of stream-bed sediments. Management strategies to minimise soil/sediment movement in the catchment should be very effective in reducing both sediment and nutrient loads discharged in flood-waters to the Great Barrier Reef.

Introduction

Considerable concern has been raised in the scientific community and elsewhere, that discharges of nutrients and sediments from many Queensland coastal rivers may be harming the Great Barrier Reef (GBR). Until recently however, there has been little quantitative information available on what nutrient and sediment loads are being discharged by rivers to waters of the GBR, and on specific land use practices linked to these discharges.

A detailed study of water quality and stream nutrient and suspended sediment (SS) fluxes in the Johnstone River system in north Queensland which commenced in early 1991 is now addressing these issues (Hunter 1993). The study was initiated as part of a Queensland Government pilot study for Integrated Catchment Management in the Johnstone catchment. Principal objectives of the study are to:

- quantify fluxes of nutrients and SS moving downstream in the Johnstone River system and into waters of the GBR;
- assess sources and relative contributions from different land use practices to the measured flows, and
- assess water quality (for nutrients and SS) at strategic locations in the Johnstone catchment.

A feature of the study is its emphasis on intensive monitoring at key sites to quantify fluxes during periods of high stream flow, when most movement of SS and associated nutrients is likely to occur (e.g. Cullen et al. 1978; Cosser 1989). Major stream rises occurred in the Johnstone catchment in association with Cyclone Sadie and caused serious flooding in coastal parts of the catchment. These conditions provided an ideal opportunity to quantify nutrient and SS fluxes during one of the biggest floods experienced in the lower catchment in recent years.

Methods

Study location

The Johnstone River system drains an area of 1634 km^2 in the wet tropics of north Queensland. Major streams are the Johnstone and South Johnstone Rivers, both rising in the south-eastern section of the Atherton Tableland and discharging through a common estuary at Innisfail to waters of the central GBR (Fig. 1). The principal towns are Innisfail, Malanda and Millaa Millaa.

Coastal parts of the catchment receive approximately twice the annual rainfall of tableland areas, with long-term averages of 3546 mm and 1672 mm at Innisfail (1881-1993) and Malanda (1916-1993), respectively (source: Bureau of Meteorology). The catchment area and annual discharge of the Johnstone River are respectively about twice those of the South Johnstone River; with a mean annual discharge from the combined river systems of approximately 3 million megalitres.

Approximately 50% of the catchment has been cleared, with most remaining native rain forest now listed on the World Heritage register. The major land uses on cleared land are grazing (dairy and beef, 26%) and cropping (predominantly sugarcane and bananas, 14%).

Sampling during cyclone Sadie

Innisfail received 648 mm of rainfall over the three day period from 30 January to 1 February 1994, as a result of cyclone Sadie. Much less rain fell in upper parts of the catchment, Malanda receiving 212 mm over the same period. Major flooding occurred only in coastal parts of the catchment. The cyclone followed a three year period of predominantly below-average rainfall and river flows in the catchment.

Six of the sites monitored in the long-term study were selected for priority sampling during the Sadie event (Fig. 1): the Johnstone River at Innisfail (NI) and at Tung Oil (NT); the South Johnstone River at Innisfail (SI) and upstream of South Johnstone Mill (SU); Fisher Creek at Nerada (FN) and Taylor Creek at Waraker (TW).

Intensive sampling was undertaken manually during the event at SU, SI and NI but very few samples were taken at NT since a bridge wash-out early in the event prevented further access to the site. Samples were taken at SI and NI from the Jubilee and Geraldton bridges, respectively, while SU was sampled from a tram bridge just downstream of the gauging station. The main flood event peaked during daylight hours at the 3 sites, allowing both rising and falling stages to be intensively sampled in relative safety. The flood peak was the highest recorded at SU and at that stage flood-waters were 300 mm below the tram bridge decking (H McDermott pers. comm.). Rainfall samples were collected periodically at SU, SI and NI in acid-washed rain gauges located away from overhanging vegetation.

Automatic sampling units located at FN and TW failed to adequately sample the event. The sampler at TW failed completely; while all sample bottles at FN were filled during early stages of the event, prior to the main flood peak.

Depth-integrated samples were taken using P61, D49 and/or locally-made "horizontal gulp" samplers (Wong et al. 1992). At each sampling time, across-stream variability in SS/nutrient concentrations was measured by sampling at three points along each bridge (at approximately the 1/4, 1/2 and 3/4 points across the stream). On one occasion at Tung Oil (30 January, from 1637 to 1807 h) variability with depth was assessed by sampling with a P61 sampler suspended from a cable across the river (Wong et al. 1992) to sample at depths of approximately 0.9 and 3.5 m at three points on the stream transect.

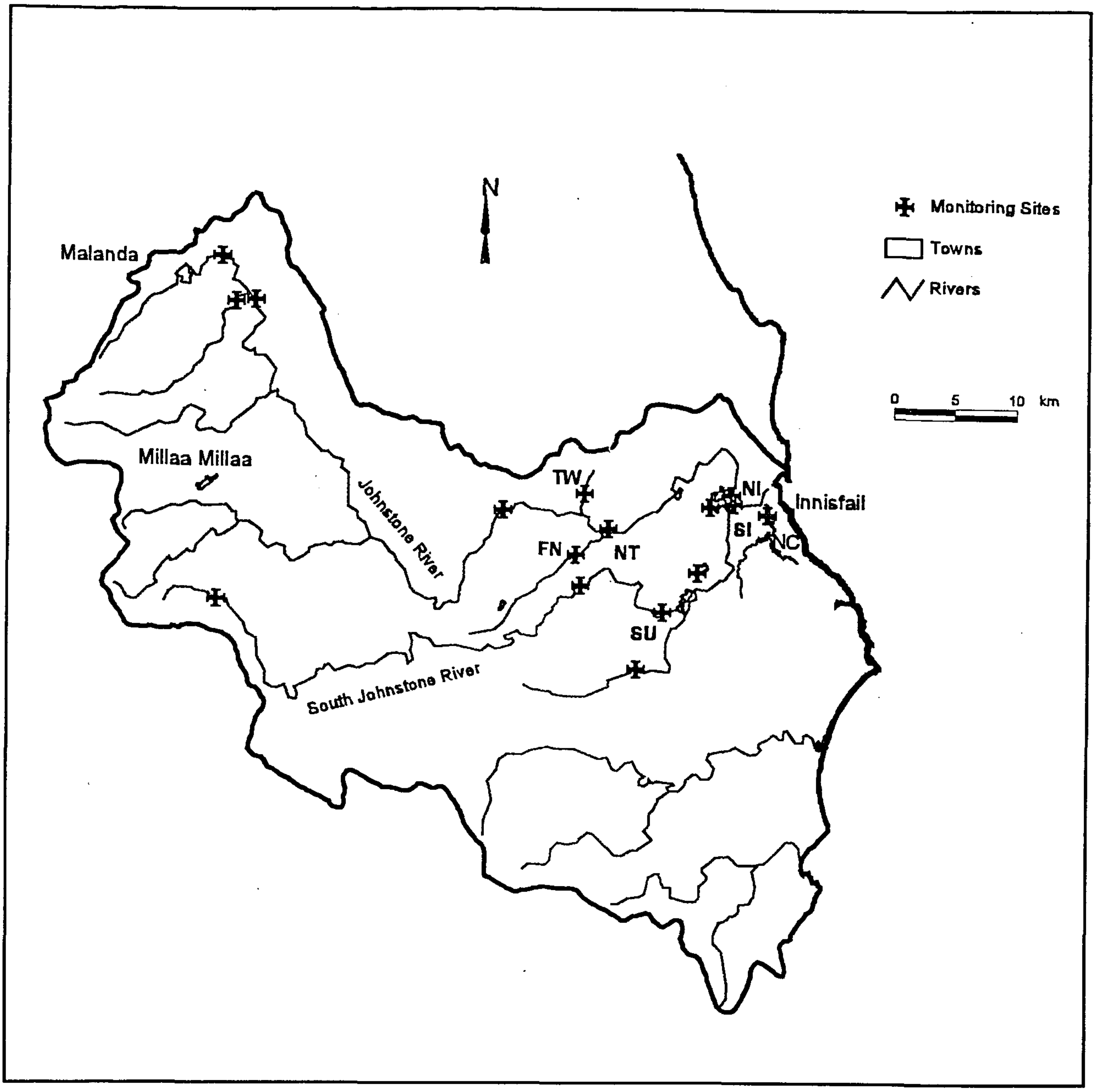

Fig. 1. Location of monitoring sites in the Johnstone River catchment. Sites sampled during cyclone Sadie are marked with the relevant site codes (see text).

Chemical analysis

Samples were filtered on site (using pre-combusted, acid-washed Whatman GFF filters) and both filtered and non-filtered subsamples were held in acid-washed polyethylene bottles. Samples were stored in portable refrigerators and frozen as soon as possible. An additional one litre sample was taken for SS analysis.

Parameters measured included SS, total phosphorus (P), total nitrogen (N), Kjeldahl N (TKN), ammonium, oxidised N (nitrate plus nitrite), filterable reactive P and organic carbon (OC). Details of analytical methods are given in Hunter (1993) and broadly followed those described in APHA (1989). Particulate concentrations of TKN and total P were derived by difference between results for paired filtered and non-filtered samples; and concentrations measured in filtered samples were considered to represent the dissolved fraction (although possibly including a fine colloidal fraction also). Total N was calculated as TKN (non-filtered sample) plus oxidised N; and dissolved organic N as TKN (filtered) minus ammonium-N.

Calculation of discharge and fluxes

Stream-flow data at SU, NT, FN and TW were obtained from nearby gauging stations. Accurate flow data were not available for NI and SI (non-gauged tidal sites) so estimates were made from discharge at upstream gauged sites, by applying a factor for each site based on relative catchment areas and mean annual rainfall (M Greer pers. comm.); and adding a lag time of 2.5 and 2 hours for NI and SI, respectively. Tidal influences were considered to have been insignificant during a major flood. Discharge data for NI and SI were calculated as follows:

Discharge at NI = 1.15 x discharge at NT;
Discharge at SI = 1.35 x discharge at SU.

Flood-waters had largely subsided by 3 February and nutrient and SS fluxes for the Sadie event were therefore calculated for the four day period from 30 January to 2 February, inclusive. Software packages *Datread* and *Datman* (Doherty and Brebber 1992) were used to calculate fluxes by interpolating concentrations to discharge measuring times and integrating the product with respect to time.

Results and Discussion

Nutrient and suspended sediment concentrations

Very high flow rates were recorded in the lower catchment during cyclone Sadie, with peak flow rates of 1756 m^3/s recorded at SU and 3932 m^3/s at NT (compared with typical wet season base flows at these sites of 45 and 68 m^3/s, respectively). Suspended sediment concentrations increased markedly with increasing flow rates (Fig. 2), the SS presumed to be predominantly soil particles mobilised upstream due to soil erosion in the catchment, stream bank collapse and/or entrainment of stream-bed sediments. At all sites, SS concentrations decreased quickly as flood waters subsided.

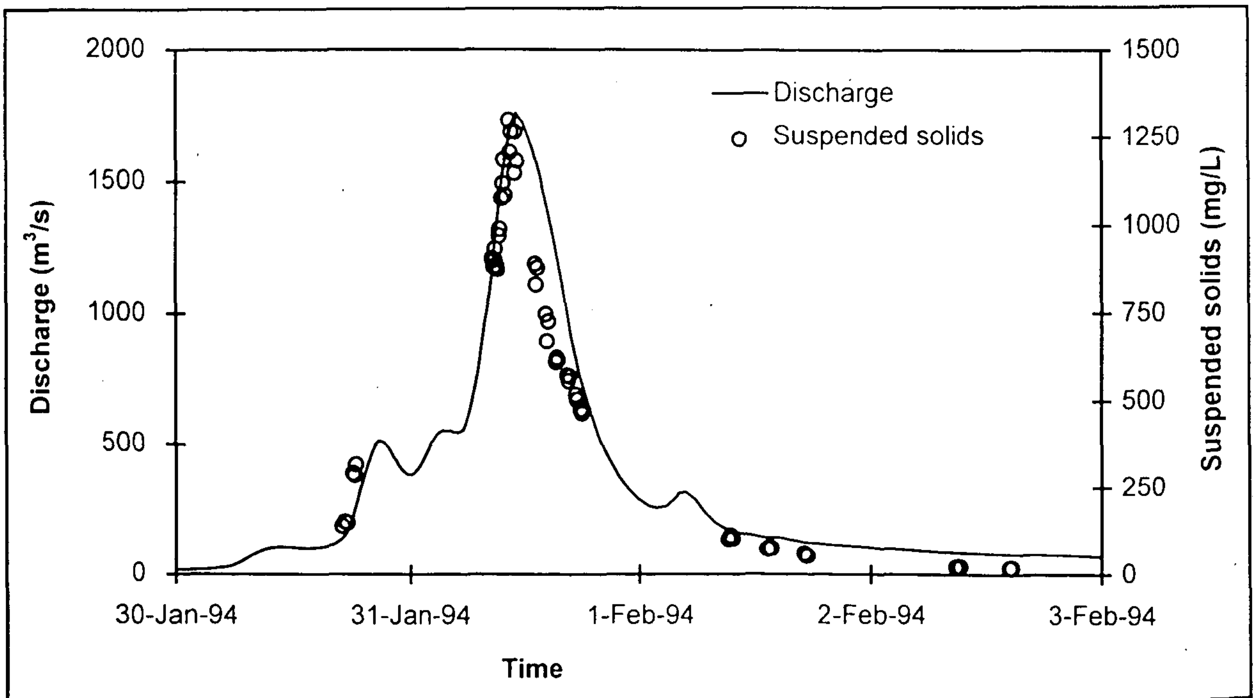

Fig. 2. River discharge and suspended sediment concentrations measured in the South Johnstone River upstream of S. Johnstone Mill during cyclone Sadie.

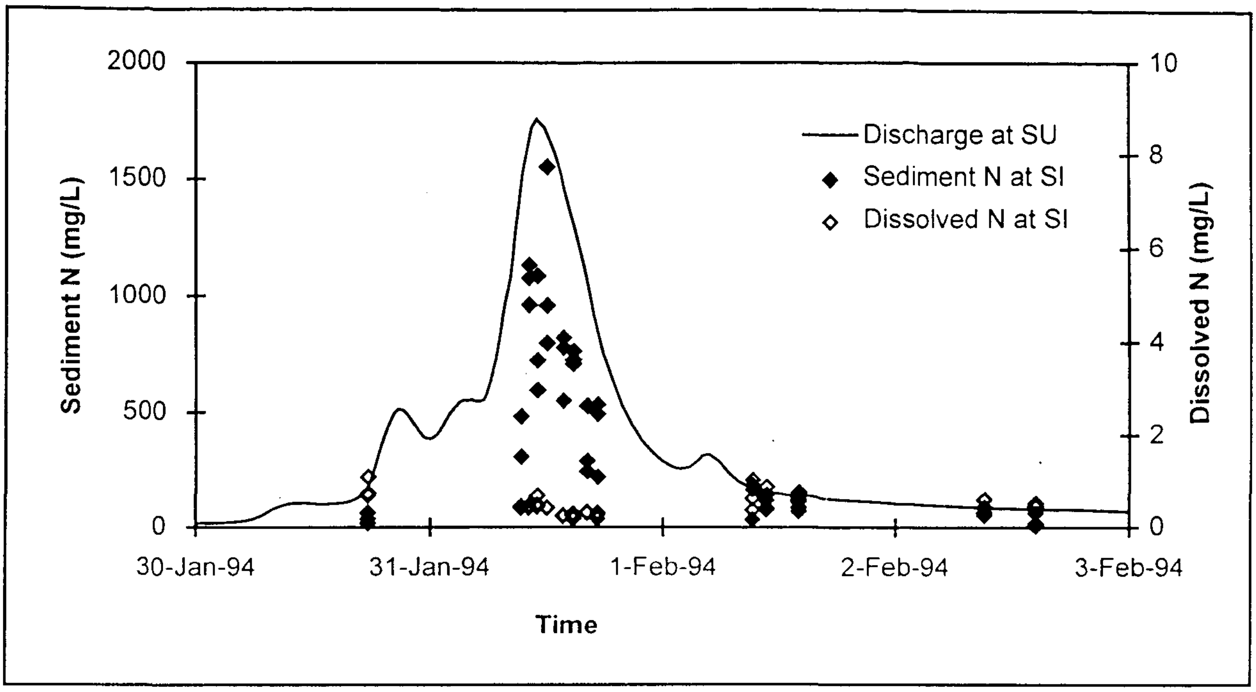

Fig. 3. Concentrations of sediment-bound N and dissolved N in the South Johnstone River at Innisfail during cyclone Sadie.

Nutrient concentrations similarly increased markedly with increasing flow rate, most of the nutrients being associated with the SS fraction. This is illustrated (Fig. 3) for N concentrations at SI; with similar trends occurring at the other sites and for P.

Median concentrations of total N, P and OC during the event were higher in the South Johnstone River at SU and SI than in the Johnstone River at NI (Table 1); possibly because relatively more of the discharge from the latter river system is derived from the Atherton Tableland, where only minor runoff and flooding occurred. Median concentrations of these parameters were very much higher during the Sadie flood event than corresponding median concentrations over a preceding two-year period of well-below-average rainfall and discharge.

Table 1. Median nutrient concentrations (mg/L) at three sites[1] in the Johnstone catchment during cyclone Sadie and comparison with concentrations during low flow conditions in 1991–1993[2].

	Cyclone Sadie			1991–1993
	NI (n=44)	SI (n=44)	SU (n=59)	NI (n~220)
Suspended sediment	218	551	557	6
Total Kjeldahl N	1.06	1.36	2.23	0.18
Total P	0.40	0.54	0.74	0.02
Total OC	4.8	6.5	6.3	–
Filterable Kjeldahl N	0.20	0.22	0.29	0.12
Filterable total P	0.03	0.02	0.03	0.01
Filterable total OC	3.4	3.6	3.6	–
Ammonium-N	0.035	0.044	0.040	0.021
Oxidised N	0.140	0.139	0.126	0.080
Filterable reactive P	0.007	0.006	0.007	0.004

[1] NI (Johnstone R., Innisfail); SI (Sth. Johnstone R., Innisfail); SU (Sth. Johnstone R. upstr. Sth. Johnstone Mill)

[2] Median concentrations at NI for 1991–1993 are given as an example. There were minor differences in median concentrations of some parameters at SI and/or SU.

By contrast, there were only small increases in median concentrations of dissolved (filterable) N and P fractions during the Sadie event, including the inorganic fractions of ammonium-N, oxidised N and filterable reactive P (Table 1). Median concentrations of dissolved N and P in both rivers during cyclone Sadie were low in terms of the potential to cause eutrophication in freshwaters, but oxidised N and ammonium-N concentrations exceeded proposed indicative guideline limits for estuarine and coastal waters (ANZECC 1992).

The median ammonium-N concentration in rain-water collected during cyclone Sadie was considerably lower than was measured in rain-water during much smaller events in 1991–1993 (Table 2). This may have reflected the much more widespread nature of the Sadie event, compared with the earlier rainfall, which may have absorbed ammonia from local sources, (e.g. volatilised from surface applications of urea fertiliser). Moreover, concentrations of N and P in rain-water during cyclone Sadie (Table 2) were very much lower than respective dissolved concentrations in river water during the flood event (Table 1).

Table 2. Comparison between median concentrations of N and P (mg/L) in rain-water during cyclone Sadie[1] and during much smaller events in 1991–1993[2].

	Sadie	**1991–1993**
Total Kjeldahl N	<0.06	<0.06
Total P	<0.02	<0.02
Ammonium-N	0.005	0.034
Oxidised N	0.008	0.018
Filterable reactive P	<0.001	0.002

[1] Includes samples taken at Johnstone R. at Innisfail (NI); South Johnstone R. at Innisfail (SI); and Sth. Johnstone R. upstream of South Johnstone Mill (SU); n=10

[2] Most samples taken at Johnstone R. at Tung Oil (NT)); n=20

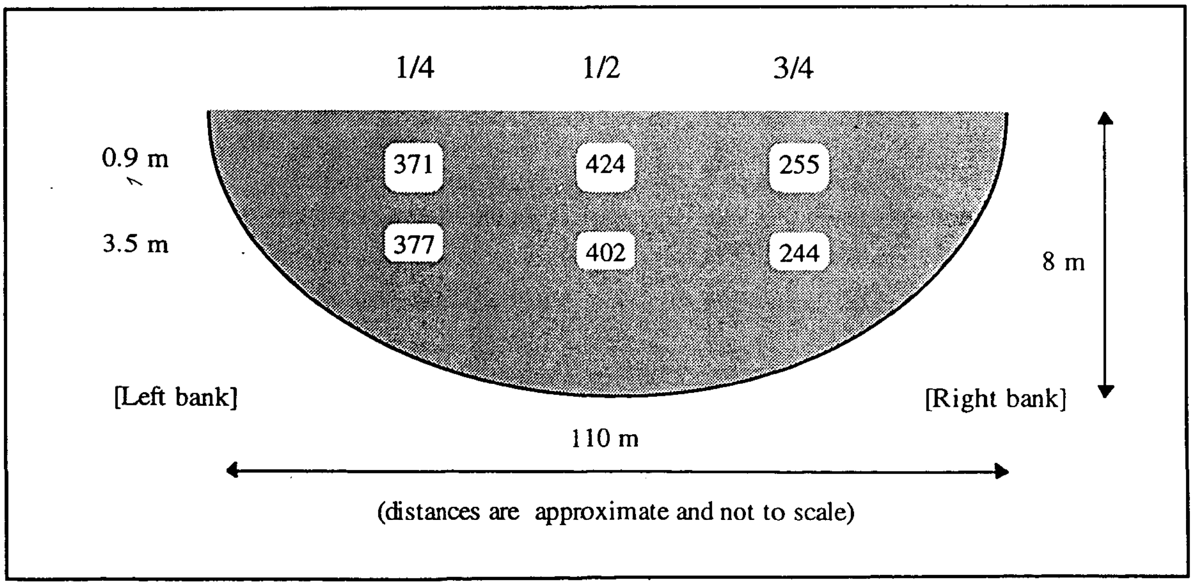

Fig. 4. Distribution of suspended sediment (mg/L) in discharge at Tung Oil on 30 January, 1994 (1637–1807 h) at three points on the stream transect.

Distribution of suspended sediment in flood waters

During the early stages of the flood event, SS concentrations at NT were higher mid-stream and towards the left bank than near the right bank, but there was little difference between respective concentrations at depths of 0.9 and 3.5 m (Fig. 4). Under near peak-flow conditions on 31 January, depth-integrated samples taken at NI, SI and SU showed river waters to be well mixed across the stream (particularly at SI and SU), with relatively small differences only in SS concentrations between samples taken at three points on the transect at each site (Table 3). This was in contrast to some previous smaller events (when for example, SS concentrations near the left bank at SI were approximately double those near the right bank) and probably reflected the relatively intense, uniform and widespread nature of the rainfall in the lower catchment during cyclone Sadie.

Table 3. Cross-sectional variation in concentrations of suspended sediment (mg/L) under near peak-flow conditions during cyclone Sadie.

Site	**Point on stream transect**		
	$^1/_4$	$^1/_2$	$^3/_4$
Johnstone R. at Innisfail	1298	1207	1265
South Johnstone R. at Innisfail	1109	1118	1065
South Johnstone R. upstr. S. Johnstone mill	1301	1181	1113

Fluxes of suspended sediment and nutrients

Almost 200 000 tonnes of SS were discharged in flood waters of the Johnstone River system over the four day period of the Sadie flood event (Table 4); most of the discharge occurring on 31 January (Fig. 2). More of the total SS, N and P flux came from the Johnstone River (58%, 57% and 60%, respectively), while more (57%) of the OC came from the South Johnstone River.

Table 4. Fluxes of suspended sediment and nutrients from the Johnstone River system during the cyclone Sadie flood event[1]

	Flux (tonnes)		**Total flux**
	NI	**SI**	**(NI + SI)**
Suspended sediment	111 206	81 346	192 552
Nitrogen	492	366	858
Phosphorus	189	125	314
Organic C	958	1256	2214

[1] Fluxes calculated for the four day period from 30 January to 2 February 1994, inclusive.

Of the total nutrient flux from the Johnstone River system, 97% of the total P and 85% of the total N were associated with the SS load (Table 5). In contrast, much less of the OC (45%) was associated with the SS load, particularly in the Johnstone River. Averaged across the two rivers, the soluble N fraction (15% of the total N flux) contained oxidised N (46%), organic N (42%) and ammonium-N (12%).

Table 5. Relative amounts of nutrients associated with the suspended sediments in river discharges during cyclone Sadie

	Sediment-bound nutrients (%)[1]		
	NI	**SI**	**NI + SI**
Nitrogen	87	81	85
Phosphorus	97	97	97
Organic carbon	34	54	45

[1] (sediment-bound nutrient flux / total nutrient flux) x 100

Conclusions

Cyclone Sadie provided an ideal opportunity to measure nutrient and SS fluxes in the lower Johnstone River system during a major flood event and provide quantitative information on loads discharged to the GBR. Nutrient and SS concentrations were very much higher than measured under baseflow conditions, but concentrations fell quickly as flow rates decreased. Since the cyclone followed a period of prolonged dry weather the levels of soil and nutrient loss in the catchment may have been higher than would occur during a flood event following more typical weather conditions. The nutrient loads in flood waters were predominantly associated with the SS load. Thus management options for reducing fluxes of both sediment and nutrients should focus on minimising soil movement in the catchment. Sources of the SS/nutrients during the flood event were not determined but probably included soil erosion (e.g. from farm paddocks, road-side verges and urban runoff); stream bank erosion and mobilised stream-bed sediments.

Acknowledgements

This work was part of a longer term study of nutrient and suspended sediment dynamics in the Johnstone River system and involved many staff of the Queensland Department of Primary Industries. Funding was provided under the Government's Integrated Catchment Management initiative. I would particularly like to thank Henry McDermott and other members of the hydrographic team at Mareeba, for their dedication and skill in collecting samples under extremely difficult conditions during cyclone Sadie. I also thank laboratory technical staff Derek Wiffen, Ivan Pereira and Murray McDowell for their valuable contributions and Richard Walton and George Rayment for helpful discussions and comments on the manuscript.

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Export of nutrients and suspended sediment from the Herbert river catchment during a flood event associated with cyclone Sadie

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Abstract

Intense rainfall associated with the passage of cyclone Sadie in January 1994, led to flooding of the Herbert River catchment. Dynamic changes in the nutrient and suspended sediment concentrations were monitored over the course of the flood via sampling in the Herbert River by two agencies, the Australian Institute of Marine Science and the Commonwealth Scientific and Industrial Research Organisation. Estimates of nitrogen, phosphorus and suspended sediment export during this event were made using the combined results.

Introduction

Tropical regions of north Queensland are subject to high intensity rainfall events during the wet season, often associated with cyclones (Sumner and Bonnel 1986), which may result in rapid flooding in river catchments. Leaching and runoff associated with these flood events leads to large fluxes of nutrient and sediment to the coastal zone.

Within the Herbert River catchment, rainfall from cyclone Sadie was concentrated in the coastal plain, with highest falls recorded at Dalrymple Creek and Stone River (Fig. 1). A large, though unresolved proportion of the Herbert catchment rainfall discharged through the Cattle Creek system to the south of the main Herbert River channel, due to overflow from the Stone River. In this paper, we summarise the work of two agencies, the Australian Institute of Marine Science (AIMS) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO), to estimate the output flux from the Herbert River catchment following the passage of cyclone Sadie in January 1994. This study is reported in more detail in Mitchell et al. (in press).

Background to sampling program

Water-borne nutrients and sediments within the lower catchment of the Herbert River are presently being sampled by three research agencies, AIMS, CSIRO (Townsville) and the Bureau of Sugar Experimental Stations (BSES, Ingham). The collaborative sampling program of AIMS/BSES, is primarily concerned with assessing riverine export of nutrients and suspended sediment (Furnas et al. 1995), while the broader CSIRO program seeks to resolve the major source areas for nutrients and sediments leaving the catchment (Bramley et al. 1994; Bramley and Johnson 1996). This paper refers to one of the sampling sites that is common to both programs, John Row Bridge at Ingham.

Flood sampling

Sampling opportunities throughout the catchment during the Sadie flood were restricted due to flooding of access roads. The John Row Bridge remained the only site accessible during peak flow. Time series sampling at this site commenced 13 hours after the initial rise in river discharge, 10 hours before the flood peak. Independent concurrent sampling was made by both AIMS and CSIRO personnel through the course of this flood event, resulting in two overlapping sample sets. Sampling at other catchment sites in the course of this flood and other temporal sampling, before this event and through a subsequent flood event, three weeks after the Sadie flood are described in Mitchell et al. (in press).

There were small differences in sampling and analytical methodologies between the two organisations (Furnas et al. 1995; USEPA 1984; Mitchell et al. in press). Water discharge in the Herbert River was monitored at a flow gauging station (116001E), located immediately upstream of the John Row Bridge (Department of Primary Industries, Water Resources, Mareeba).

Nutrient dynamics through the flood

At the time flood sampling commenced, concentrations of dissolved inorganic nitrogen (DIN = nitrate + nitrite + ammonia) were declining, and fell to a minimum (ca. 100 μg L^{-1}) around the flood peak, but thereafter recovered (ca. 350 μg L^{-1}) with falling discharge (Fig. 2a). Concentrations of orthophosphate (PO_4) similarly declined to a minimum near peak flow (12 μg L^{-1}), recovered slightly in the falling stages of the flood, then declined to very low (1 μg L^{-1}) levels (Fig. 2b). DON (dissolved organic nitrogen) concentrations were relatively constant through the flood, around 200-300 μg L^{-1} (Fig. 2c). Measured DOP (dissolved organic phosphorus) concentrations differed considerably between the two agencies (Fig. 2d), with the AIMS results suggesting decline around the peak of discharge but CSIRO data suggesting an increase. Concentrations of both particulate nitrogen (PN) and phosphorus (PP) increased with rising discharge to maximum levels (1200 μg PN, 225 μg PP L^{-1}) at the flood peak, but declined rapidly thereafter to low levels (250 μg PN, 30 μg PP L^{-1}) with falling discharge.

Concentrations of suspended sediment exhibited a similar pattern to PN and PP, with a maximum at the flood peak (Mitchell et al. in press). Measures of silicate and potassium concentrations, pH and electrical conductivity, exhibited inverse relationships with discharge during the course of the Sadie flood. Good correlations were found between the sample determinations of AIMS and CSIRO for DIN, PO_4, PN and PP. Higher concentrations of DON and especially DOP were determined in the CSIRO analyses.

Discussion of dynamic behaviour

The cyclone Sadie flood event was the first major flush of the Herbert River catchment in the 1993/94 wet season. The first flush of the year is typically characterised by elevated concentrations of dissolved inorganic nutrients and to a lesser extent, particulate forms, a phenomenon well documented in both temperate rivers (e.g. Walling and Foster 1978; Webb and Walling 1985; Anon 1987) and tropical rivers (e.g. Lewis 1986; Mitchell and Furnas 1994; Mitchell et al. 1996). Soluble and readily erodable particulate material accumulated within the catchment over the dry season is transported to the river by leaching and surface runoff, raising river-water concentrations during early wet-season discharges. In the Herbert River, briefly elevated nutrient concentrations were observed two weeks prior to the Sadie flood, during a very small flow event (Mitchell et al. in press).

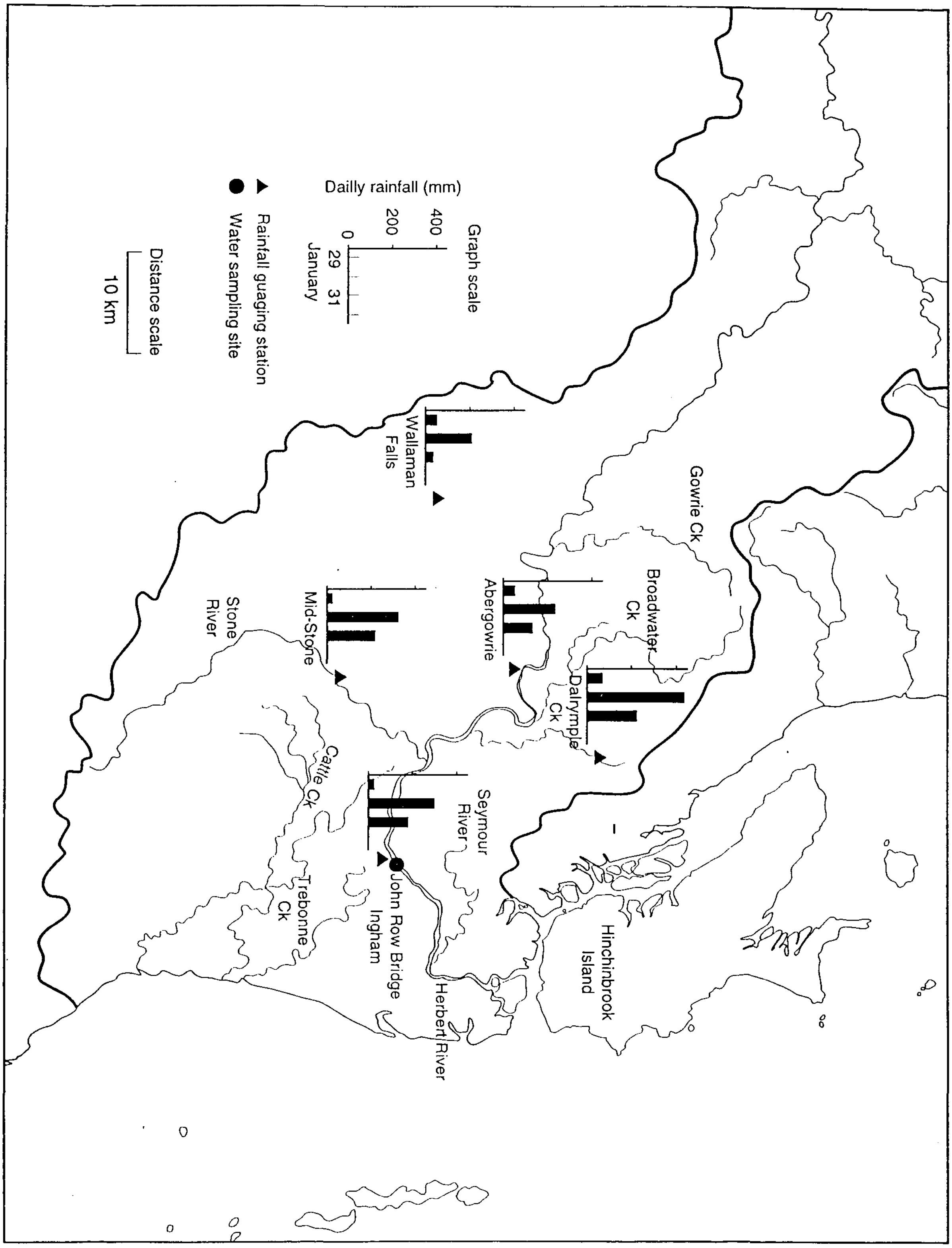

Fig. 1. Lower catchment of Herbert River. Sampling station at John Row Bridge, Ingham shown as filled circle. Rainfall measurement stations within catchment denoted by filled triangles. Daily rainfall over four days of flood shown by histograms.

Concentrations of DIN and orthophosphate were both falling at the commencement of sampling during the Sadie flood, 13 hours after the initial rise in river discharge (Fig. 2a, b). Based on high first flush concentrations previously observed in the Herbert River (Mitchell and Furnas 1996; Mitchell et al. in press), it is likely that concentrations of these dissolved nutrient forms peaked in the early stages of the flood, before sampling commenced. The decrease in concentrations of dissolved inorganic N and P to minima around the discharge peak and their subsequent recovery during falling discharge suggests dilution by the large volume of water entering the lower catchment. In contrast to DIN, orthophosphate concentrations only recovered briefly before falling off sharply, indicating that exhaustion of readily leachable stocks had occurred.

Concentrations of particulate forms (PN, PP or suspended sediments) rapidly increased with river flow (Fig. 2e, f), a result of higher levels of erosion and sediment mobilisation with increasing rainfall (Milliman and Meade 1983; Anon 1987). Particulate concentrations showed near-linear relationships with discharge, though at considerably higher concentrations in the rising stage than during the falling stage of the Sadie flood hydrograph (Mitchell et al. in press). This rapid fall-off in suspended material during the flow decline probably reflects some exhaustion of readily mobilised sediment and reduced hydraulic forces with decreasing rainfall. The dynamic behaviour of dissolved organic nutrients during flood events in tropical rivers is poorly reported, though the slight elevation observed through the Sadie flood peak suggests that in addition to leaching, a degree of mobilisation by runoff processes may be operating.

Research into sources of nutrients within the lower Herbert catchment (Bramley et al. 1994; Bramley and Johnson 1996) suggest that inputs of nutrients, in particular the dissolved inorganic forms, largely arise as a result of N and P fertiliser applications to land under sugar cane. However, the contribution of these inputs to nutrient export during rainfall events is unresolved.

Export estimates

Estimates of nutrient and suspended sediment exports from the Herbert River catchment during the Sadie flood were estimated by two methods using the combined data from both AIMS and CSIRO determinations. Estimations by these methods, one applying the arithmetic average of nutrient concentrations measured during the flood to the total discharge (flood averaged) and another, applying an interpolation technique (Anon 1987) using individual sample concentrations and the instantaneous discharge for each interval period (flow-weighted; see Mitchell et al. in press for details) are compared in Table 1.

Table 1. Exports of nutrients and suspended sediments from Herbert River through course of cyclone Sadie flood from samples taken at John Row Bridge. Period used = 10 am 30th January to midnight 5th February 1994; discharge = 538 100 ML; nutrient concentrations in µg L^{-1}; suspended sediment concentrations in mg L^{-1}; exports in tonnes.

Category	DIN	DON	PN	Tot N	PO4	DOP	PP	Tot P	SS
Flood averaged[1]									
Average conc.	*203*	*242*	*576*	*1020*	*14.9*	*6.3*	*99.7*	*120.9*	*156*
Export (t)	109	130	310	549	8.0	3.4	53.7	65.1	84 152
Flow-weighted[2]									
Export (t)	153	132	309	595	8.9	3.6	52.1	64.6	101 408

[1] Exports calculated by applying the average flood concentrations, of the combined AIMS and CSIRO determinations, to the total flood discharge.

[2] Exports calculated by interpolating sample concentrations over each inter-sample period with the instantaneous discharge for each period.

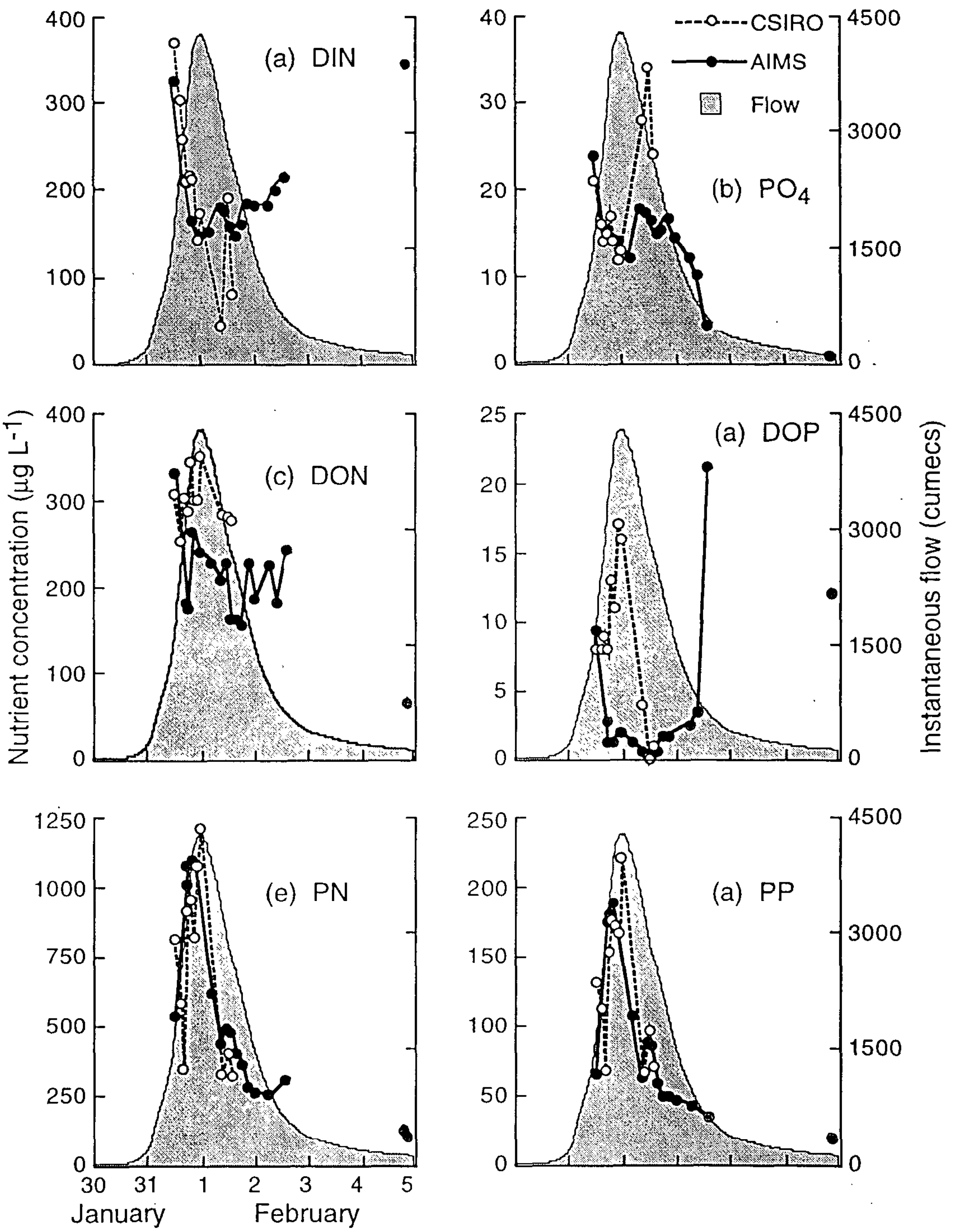

Fig. 2. Concentrations of N and P nutrient forms (µg l^{-1}) from samples taken by AIMS (closed circles) and CSIRO (open circles) at John Row Bridge on the Herbert River during the cyclone Sadie flood. Shaded area represents instantaneous flow (cumecs) measured at John Row Bridge. (a) DIN = dissolved inorganic nitrogen; (b) PO4 = orthophosphate; (c) DON = dissolved organic nitrogen; (d) DOP = dissolved organic phosphorus; (e) PON = particulate organic nitrogen; (f) POP = particulate organic phosphorus.

Similar estimates of export flux were obtained by the two procedures for most nutrient forms. The estimated export for DIN was 40% higher using the flow-weighted method, partially due to the assumption of high first-flush concentrations. Particulate forms dominated export flux, accounting for more than 50% of N and 80% of P. This finding is consistent with observations in other north Queensland rivers that suspended sediment is primarily transported during stormflow events, and that the proportion of particle-bound nutrients increases with the intensity of the flood event (Mitchell et al. 1996).

It was estimated that approximately 600 t of N and 65 t of P were discharged past the John Row Bridge site during the Sadie flood (Table 1). An estimated flux of 100 000 t of suspended sediment during this event (Mitchell et al. in press) was similar to an independent estimate using whole water-column sampling during the falling stages of this flood and a subsequent discharge event in the Herbert River (Wong 1996). A number of unresolved factors, detailed in Mitchell et al. (in press), chiefly those concerning ungauged discharge, suggest that these estimates understate the true magnitude of exports from the Herbert catchment during the Sadie flood.

Conclusions

It is estimated that flooding in the Herbert River associated with cyclone Sadie resulted in the export of at least 600 t N, 65 t P and 100 000 t suspended sediments from the catchment over a six and a half day period, with most of this (85%) occurring over just two days. Particulate fractions of N (50%) and P (80%) constituted the bulk of the nutrient flux from the Herbert River, consistent with findings in other North Queensland rivers. Combined with the simultaneous flux of neighbouring flood-affected rivers, from the Mulgrave River south to Crystal Creek, the Sadie flood event would have represented a large proportion of the annual wet season output from this region. It dramatically illustrates the episodic nature of riverine export to the GBR Marine Park.

While the contribution of agricultural fertiliser to nutrient loadings in the Herbert River is still unresolved, it is clear that the potential exists in tropical catchments for high levels of nutrient export from areas of intensive agriculture during wet season storm events such as cyclone Sadie. There is a need to better resolve the input sources of nutrients, and also to improve our understanding of the ecological impact of such large intermittent deliveries of nutrients and sediments to the coastal shelf.

Acknowledgments

The CSIRO component of this work was carried out as part of the CSIRO Coastal Zone Program. We are most grateful to Delia Muller, Warren Hicks, Shelly Farr, Belinda Wilson and Silvia Campbell for their technical assistance. The AIMS component of this work was carried out as part of the Coastal Processes and Resources Program. This is AIMS Contribution No. 1123. AIMS acknowledges financial support from CRC Reef Research and the Great Barrier Reef Marine Park Authority. We gratefully acknowledge advice from Miles Furnas and technical support by Michele Skuza and Neil Johnston. We also thank the efforts made by Helen Sturmey of AIMS and the staff of BSES, Ingham for their dedicated help in the flood sampling exercise. Grateful acknowledgement is made to Department of Primary Industries, Water Resources, Mareeba branch for the supply of gauging data.

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Nutrient distribution in the Barron River and offshore during cyclone Sadie

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Abstract

Following intensive rainfall associated with ex-tropical cyclone Sadie runoff from the Barron River catchment produced flooding in the lower reaches and an extensive plume offshore. Rainfall recorded at Cairns between 30 January and 1 February, 1994 was 627 mm. Significant fluvial discharge assisted by light northerly winds enabled the plume to extend to the mid-shelf reefs. Water quality was monitored throughout the flood event in the Barron River and offshore to the plume edge. Data display a rapid change for all parameters collected (Conductivity, suspended solids, temperature and total nutrients) along the lower reaches of the River. Elevated levels of particulate nutrients were evident within 5 km of the coast with an increased dissolved organic component further offshore. Timing of sampling is important as the plume had moved 15-20 km prior to sampling. Data show a significant decrease in concentration between sampling periods of 2 and 4 February.

Introduction

Coastal water quality in the Cairns region is inferred to have altered from 'natural' levels due to mainland runoff from the anthropogenically altered coastal catchments (Moss et al. 1992; Rasmussen 1994). In this region the continental shelf is relatively narrow (ca. 40 km), which influences the proximity of coral reefs to the mainland (ca. 25 km) and hence serves as an important location for study due to the influence of terrigenous runoff following flood events (Hopley 1982).

There are many references to show that the major proportion of the annual fluvial sediment and nutrient load can be transported during flood events (Schubel 1971; Cullen et al. 1978; Hart et al. 1988; Cosser 1989; Furnas 1995). Hart also noted that the situation may be 'more pronounced in tropical regions' due to the distinct wet season that is characterised by a predominance of rainfall over short periods of time. Recent research (Brodie and Mitchell 1992) has confirmed that increased nutrient levels may be apparent in coastal waters following the first flush after an extended dry period. Therefore, to facilitate reasonable estimates of fluvial sediment and nutrient input to the Great Barrier Reef Lagoon, sampling has focussed on these flood events.

Data collection during periods of high fluvial discharge in this region are made difficult by the adverse conditions associated with such events, and by the relatively unpredictable spatial and temporal nature of individual events. Inability to plan a research program around such events has meant that data collection and results have often been patchy. The establishment of a core group of researchers in the area, and the coordination of sampling programs at a number of locations on various rivers, has lead to a significant increase in the amount of data now available.

A rain depression following cyclone Sadie produced significant rainfall along the northern wet tropical coast and provided the opportunity for the research group to simultaneously sample various rivers. This paper presents data collected in the Barron River and offshore area before and after the rain event associated with cyclone Sadie (28 January to 5 February 1994) and provides an assessment of the nutrient dynamics that occur during a flood event.

Study Details

Cairns is located in the wet tropics. The region is characterised by marked seasonality in the rainfall with 75% falling in the monsoon period between December and April (Hausler, 1990). Cyclone Sadie, after crossing the Carpenteria Gulf coast, weakened into a rain depression and produced extensive rainfall on the east coast between Townsville and Cooktown. This was accompanied by light north-east winds which assisted in the development of expansive river plumes. Rainfall was most intense on the coastal fringe, with Cairns receiving 627mm between 30 January and 1 February (Fig. 1). This represents almost one third of the average annual Cairns rainfall in three days. The extent of the plume was mapped on 1 February by aerial surveillance in order to establish suitable offshore sampling sites. Sampling was conducted on 2 and 4 February. The extent of the plume and sample locations are shown in Fig. 2.

Water samples (suspended solids, total and dissolved nutrients) and physico-chemical measurements (salinity/conductivity and temperature) were collected in the Barron River and up to 5 km offshore from the mouth prior to the flood event. Physico-chemical parameters were measured in situ at approximately 30 cm below the water surface using a calibrated TPS 90 FL fieldmeter attached to a weighted tripod. Water samples were also collected at this depth by pumping samples using a diaphragm pump. Samples were filtered in the field or stored in 1 L polyethylene bottles on ice and in the dark if sample integrity was likely to be compromised by filtering on site. Water samples for dissolved nutrient analyses were vacuum filtered through 0.45 µm cellulose acetate filter papers and stored frozen in polypropylene tubes prior to analysis. A known volume of water was vacuum filtered through pre-weighed GF/F glass fibre filters for suspended solid concentration.

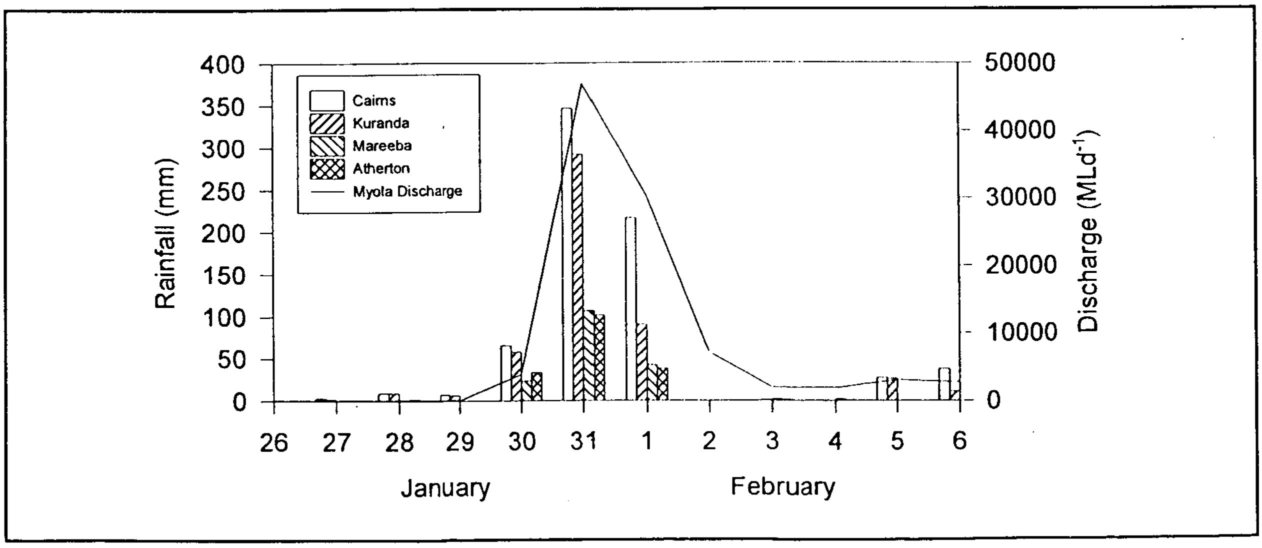

Fig. 1. Rainfall and river discharge in the Barron River catchment.

Water samples from the plume were collected at six sites on 2 and 4 February from 30 cm, 2 m and 10 m below the water surface (if site depth was < 10 m the sample was collected from 1 m above the substrate). An additional site was sampled on the first day on either side of the estimated plume front. A further six sites within 5 km of the mouths of the Barron River and Thomatis Creek were sampled at the surface and near bottom for the same parameters. Filtering of all samples for the plume monitoring study was completed after returning to port and accomplished within 10 hours of sampling.

Results

Prior to the onset of rain, water samples were collected in the river and offshore from the mouth of the Barron River at sites A, B, C and BR 4-1,2 & 3 (Fig. 2). Site A represents a freshwater section of the Barron River while B is a mid estuary site, and C lower estuary. Sampling continued at these locations throughout the rain event and summary time series plots of the data collected is presented in Fig. 3.

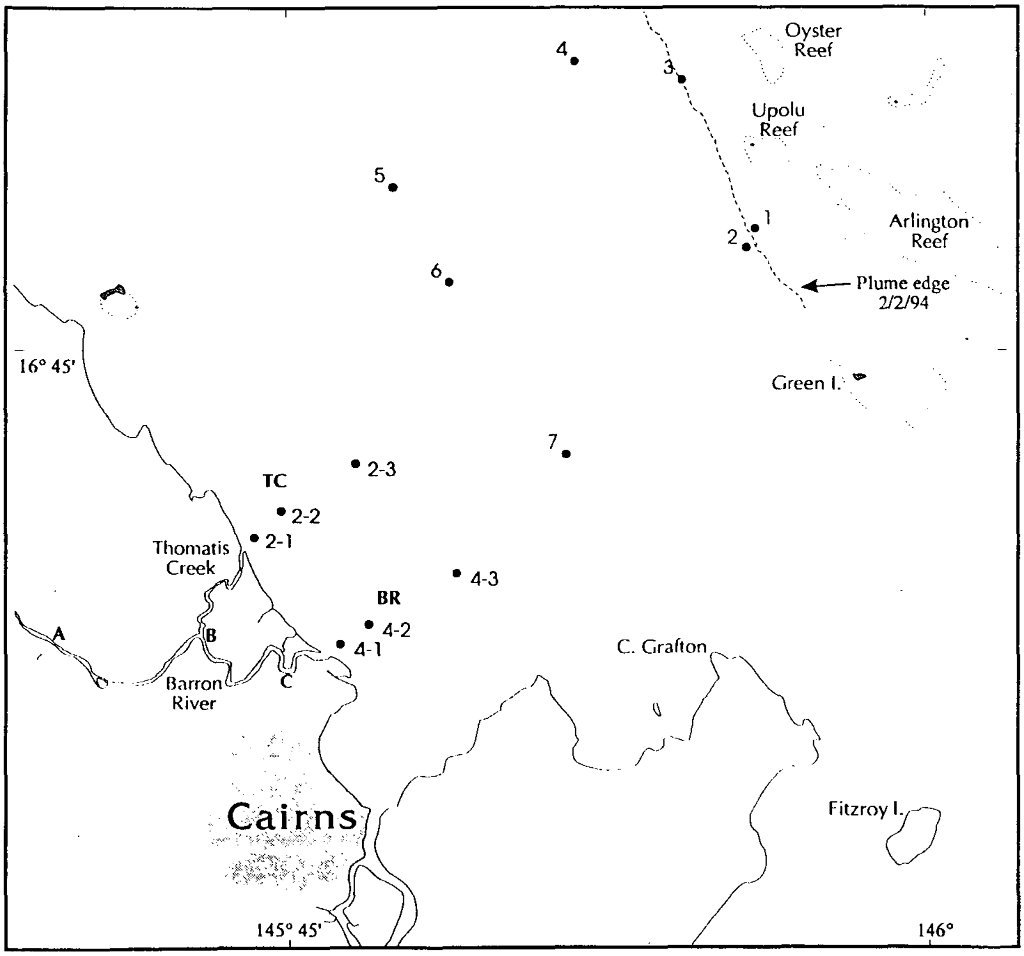

Fig. 2. Plume extent (2 February) and sampling locations

Mapping the extent of the plume was conducted by aerial surveillance to establish sampling locations. On 1 February the plume had reached 15-20 km from the mouth of the Barron River and was moving in a north easterly direction. While the rainfall was intense on the coastal fringe there was no official flooding recorded (Bureau of Meteorology pers. comm.) and the light winds and neap tides allowed the water discharged from the Barron to extend to the mid shelf reefs within a few days.

Summary graphs (Figs. 4-7) are provided to demonstrate the spatial and temporal variability of nutrient partitioning that was experienced during this seasonal runoff event.

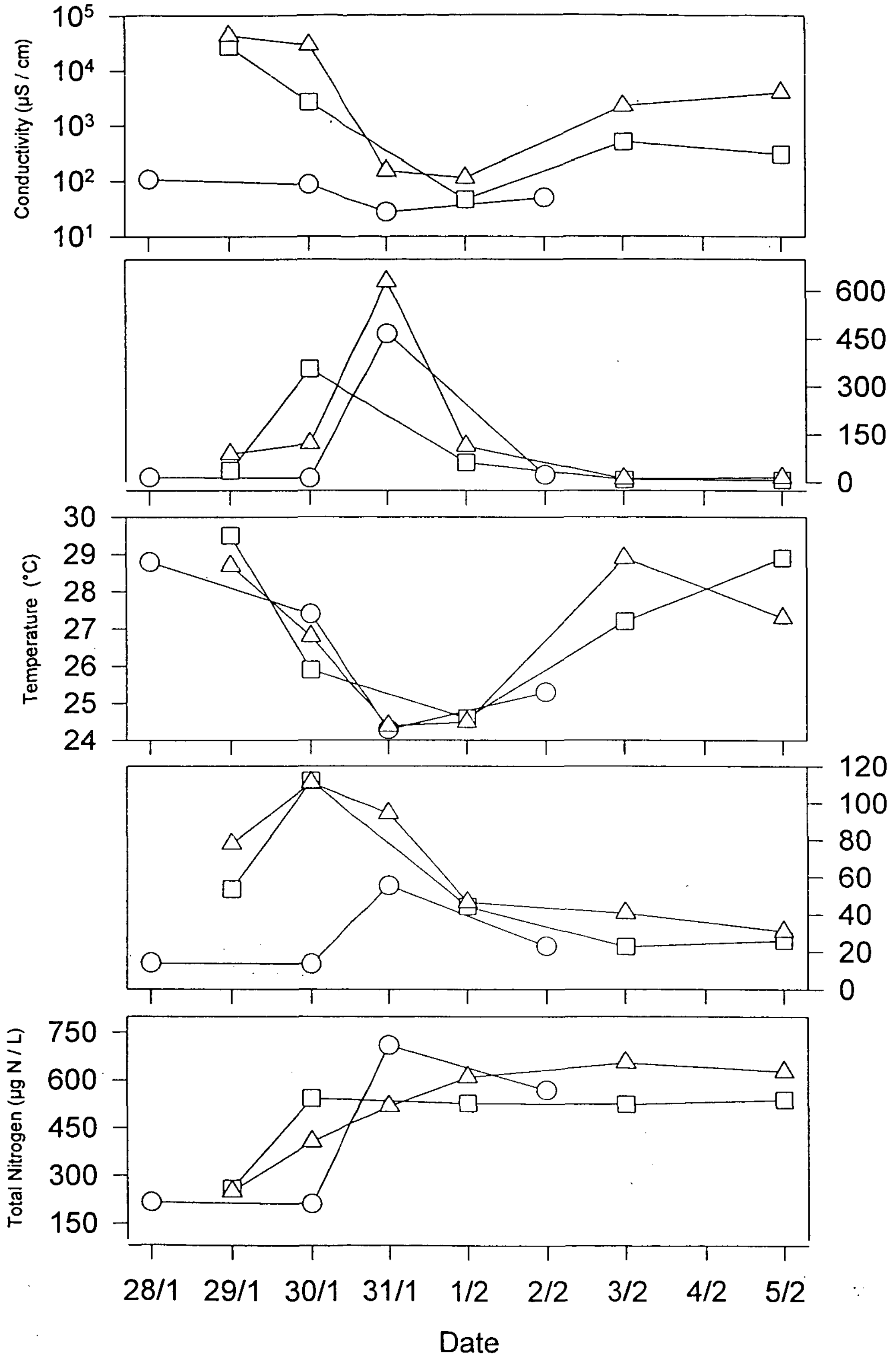

Fig. 3. Time series plots of conductivity, suspended solids, temperature, total phosphorus and total nitrogen at 3 river sample locations (Site A = O; B = □; C =Δ)

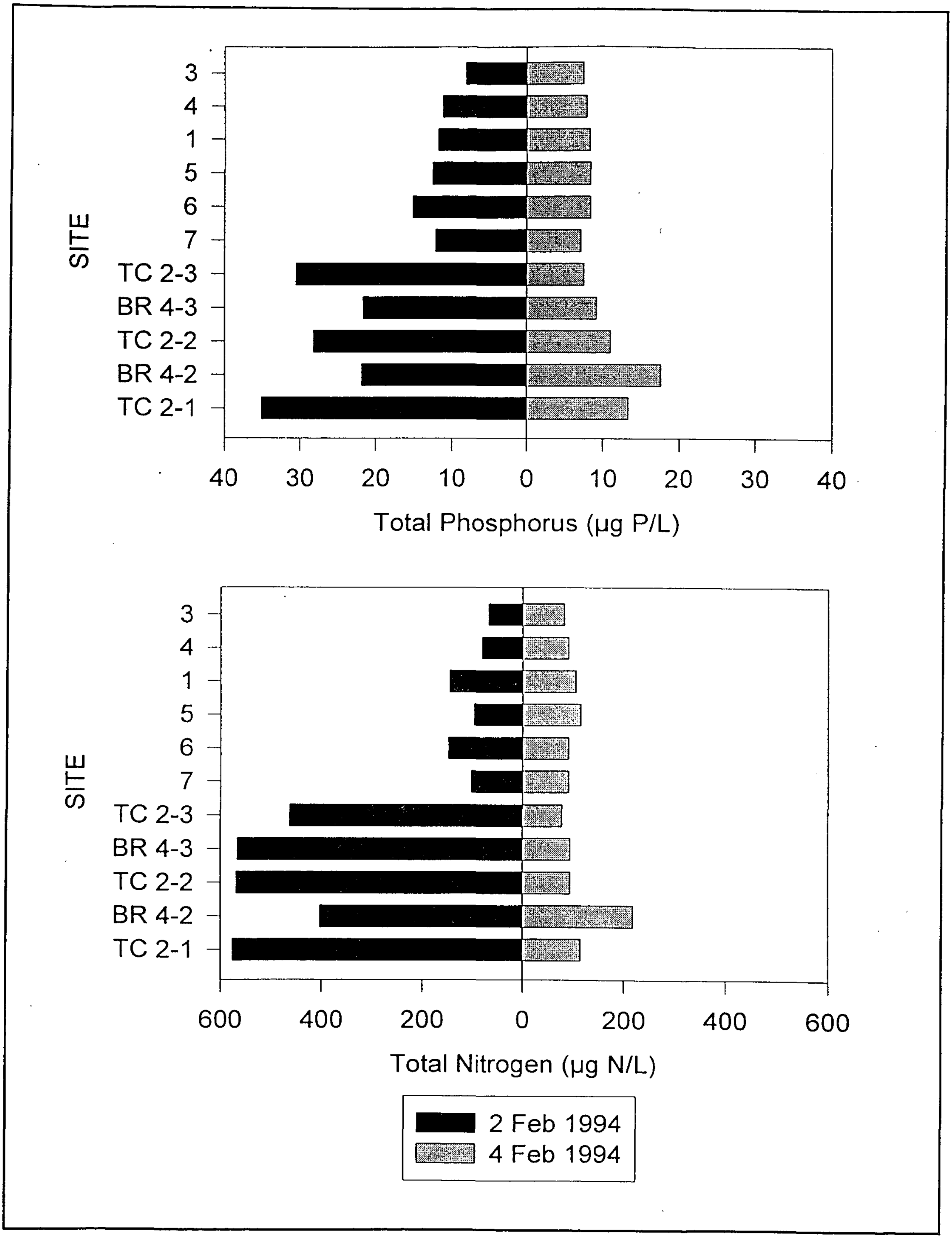

Fig. 4. Surface total phosphorus and total nitrogen concentrations

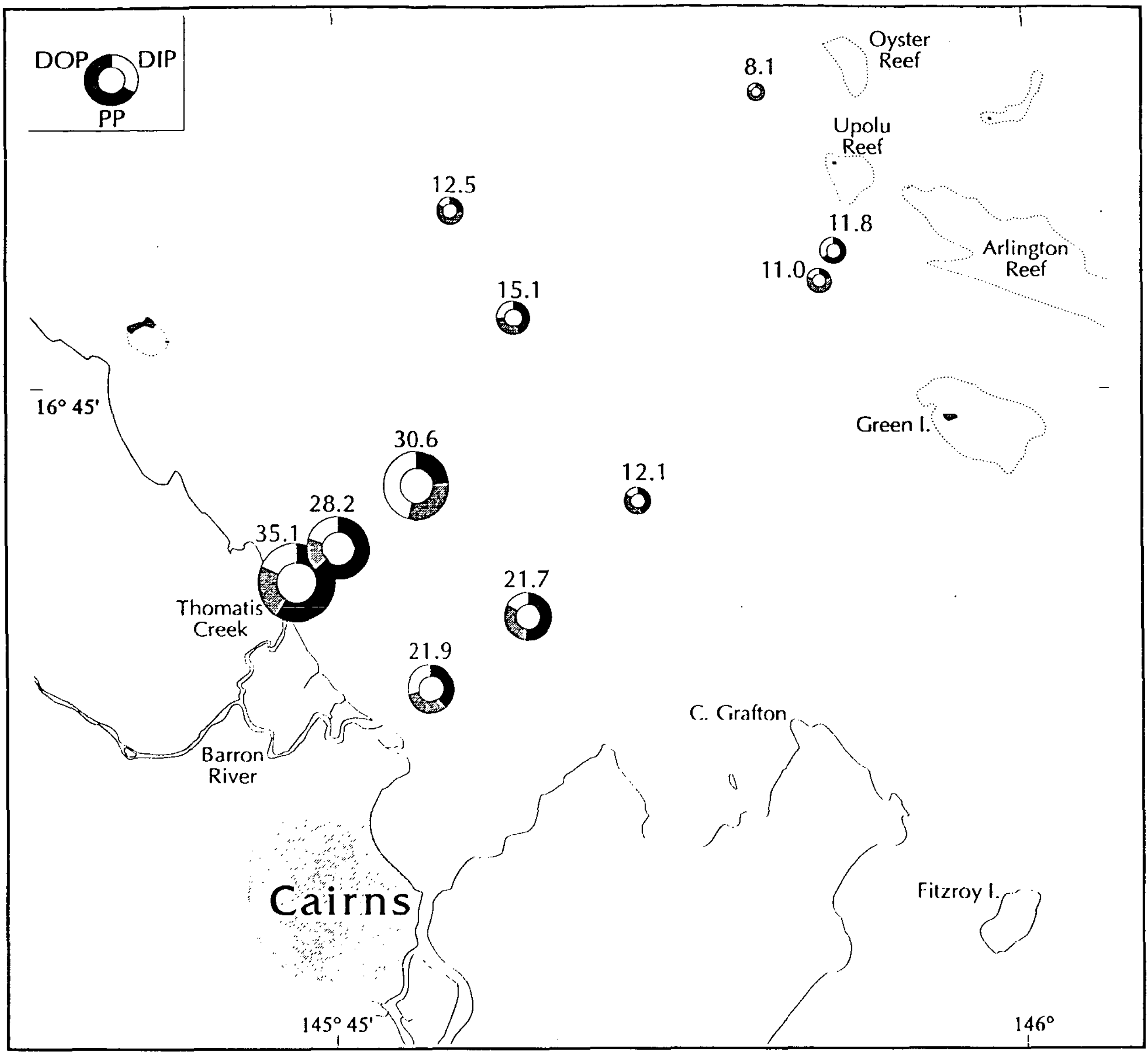

Fig. 5. Phosphorus partitioning of surface samples on 2 February. Values indicate total phosphorus concentration (µg P/L)

Discussion

There are clear spatial and temporal differences along the Barron River due to the freshwater runoff. It can be clearly seen that for site A there is a slight drop in conductivity, but 3 orders of magnitude difference at the mid estuary site, B. Suspended solids peak with the highest rainfall and subsequent runoff, with B peaking on the 30 January while A and C have maximum concentrations on 31 January. This is an artefact of the sampling times and lack of a sample for B on 31 January. Data collected by a current meter suggests that the flood may have peaked during the night and the highest concentrations were not sampled due to the timing of sampling. Temperature further demonstrates that the river along the entire estuary became relatively homogeneous with a fall of 4 - 5 °C during the flood peak. Total phosphorus peaks prior to maximum river discharge at sites B and C with the peak for the upstream site C occurring the next day. This can be attributed to the upstream sample being collected early in the day while the other sites were sampled later with the hydrograph still rising. Total nitrogen shows a different pattern to total phosphorus with its concentration remaining reasonably constant even after the peak discharge has passed. While dilution can be attributed to suspended solid and total phosphorus concentrations decreasing this is not the case for nitrogen and therefore the fluvial nitrogen load will be proportionally higher than phosphorus for this event. Due to the dynamic nature of flood events and especially the rapidity of change, caution needs to be given to interpreting results. Many factors need to be considered, for example, timing of sampling is critical but often has to be compromised because of financial and logistical constraints.

The highest concentrations of suspended sediment and nutrients are located near the mouth of the Barron River and Thomatis Creek. Depth-weighted mean water values for the Cairns area have been estimated as TP ca. 10 μg P/L; TN ca. 115 μg N/L (Furnas 1990; Furnas et al. 1995). Data collected shows that the total phosphorus and nitrogen concentrations are elevated in the area up to 5 km offshore on 2 February with values returning to mean background levels two days later. Total phosphorus displays some evidence of slightly elevated concentrations at the other sampling locations, closer to the reef also on the first sampling day.

The distribution of the plume over a much wider area may act to dilute the nutrients and suspended sediment rather than concentrate them if the plume was more constrained in area. This data demonstrates the need to understand the timing of sampling with respect to the plume's life as elevated concentrations may be short lived in the water column.

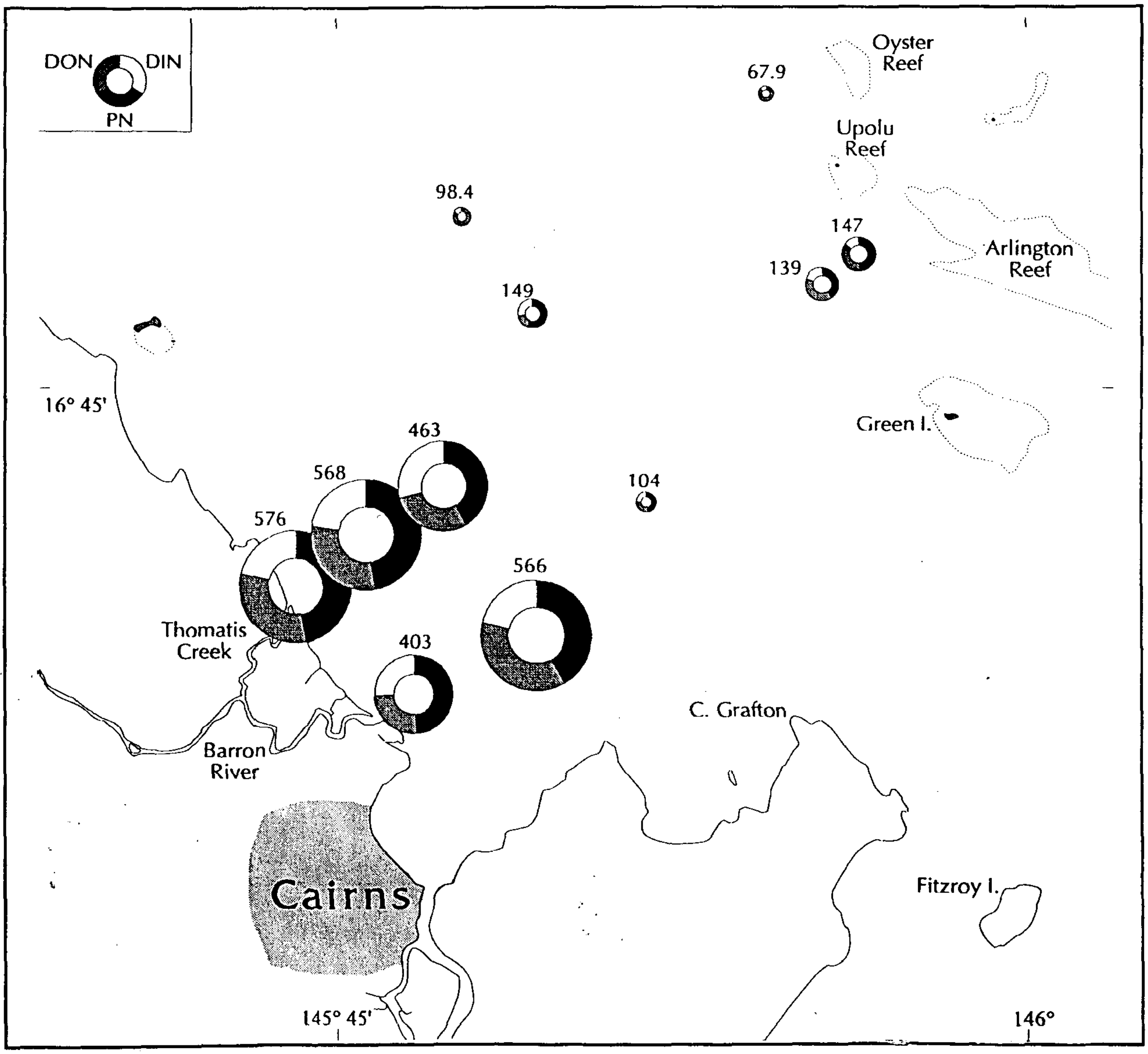

Fig. 6. Nitrogen partitioning of surface samples on 2 February. Values indicate total nitrogen concentration (μg N/L)

The partitioning of nutrients is generally dominated by particulate and dissolved organic forms for both nitrogen and phosphorus. The particulate material is slightly higher in proportion within 5 km of the coast, with the material further offshore generally having an increased dissolved organic component. The timing of sampling should be noted as the plume front had moved 15 - 20 km offshore on 1 February when the plume was mapped.

However, this data agrees with other observations which display dissolved organic and particulate nutrients as the dominant fractions after a cyclonic event (Furnas 1990). The Barron River has not had a major flood since 1979 so extrapolation needs to be conducted with some caution as each event can be unique.

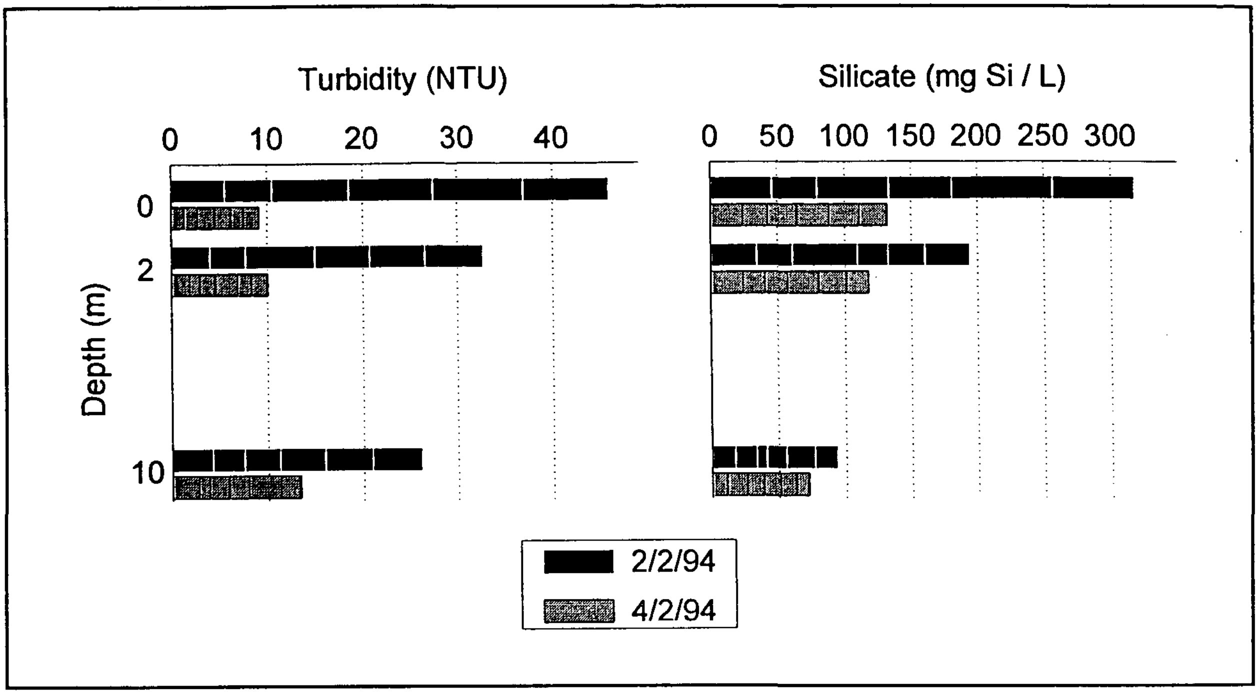

Fig. 7. Turbidity and silica temporal variability with depth. Bars are cumulative for Sites 1, 3-7.

Due to the unpredictable timing and location of these seasonal flushing events it is difficult to plan sampling strategies, and sampling is often opportunistic in nature. Timing of sampling is critical to understanding the dynamics of nutrient and suspended material movement during flood events. Also as important is the depth to which these concentrations persist as this will provide a volume estimate as to the amount of material transported. Grouping all the plume study sites that were collected on 2 and 4 February shows a marked change both temporally, as has been seen for nitrogen and phosphorus, but also spatially. The general water mass has elevated turbidities and silicate concentrations on 2 February compared to 4 Febraury for all depths sampled. However, there is a different relationship with depth that is observed between turbidity and silicate on the second day of sampling. While silicate is reduced at all depths there is an increase in turbidity with depth. While there could be a number of explanations for this, the most likely would be material settling from the water column.

A more concerted effort to understand the dynamics of nutrients associated with these events has meant that a greater wealth of information is now becoming available. Future work on these events should concentrate on understanding the partitioning of nutrients and their transformation on a more intensive time scale. Data is needed before, during and after the peak of the plume discharge period for these runoff events to fully understand the processes operating.

Despite time limitations, this small study has led to some interesting conclusions about the fate of dissolved nutrients in a freshwater plume. Generally the concentrations of dissolved nutrients (Table 2) and phytoplankton (Table 3) in the cyclone Sadie plume were higher than non-flood periods with high variability between sites and position in the water column. The variability between sites may be related to catchment characteristics and the specific upstream activities connected with each catchment. The low concentrations of some dissolved species in the plume indicates that the uptake of the dissolved nutrients by the phytoplankton may have occurred within a relatively short time.

Clearer resolution of flood waters effects in the GBR lagoon would involve increased sampling of all dissolved and particulate nutrient species and the initiation of sampling as close as possible to the start of the flood event. The successful monitoring of any large flood event could only be improved by rapid and intensive sampling techniques and greater awareness of the individual characteristics of each catchment.

Acknowledgments

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The extent of the river plumes associated with cyclone Sadie rainfall

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Abstract

Intense rainfall associated with cyclone Sadie, falling on catchments between Cooktown and Townsville, produced major flood flows in the coastal rivers of this area. Plumes from the rivers were able to be mapped, as they dispersed into the Great Barrier Reef lagoon, using aerial observation in the calm sea and high visibility atmospheric conditions. The plumes were observed to travel as far as the matrix of the outer reefs of the GBR but were of short duration with little evidence of plume water remaining in the lagoon one week after the flood peaks.

Introduction

Key objectives of water quality studies in the Great Barrier Reef (GBR) region are to quantify the amounts of sediment and nutrients entering the GBR from the major rivers and how these have changed as a result of human use of the catchments. A third objective is to understand the spatial distribution of river plumes and the fate and importance of the entrained material with respect to nutrient budgets and cycling on the GBR shelf. In association with river estuary and GBR-lagoon bed sediment studies, work on river discharges and plumes over the last 15 years has clarified the spatial and temporal extent of influence of river discharge. The content of the plumes, in comparison to water quality in non-plume conditions, is also considerably better understood.

Opinions as to the spatial extent of terrestrial runoff across the GBR continental shelf differ (Belperio 1983; Wolanski et al. 1986; Currie and Johns 1989; Johnson and Carter 1988; Gagan et al. 1987, 1990). King and Wolanski (1992) have shown by modelling how river plumes are normally constrained close to the coast by hydrodynamic conditions generated by the prevailing south-east wind regime and Coriolis effects. Under other wind conditions however, river plumes can reach the mid- and outer-shelf reefs. It is also now clear that rivers comprise a major source of new nutrients to the GBR system (Furnas et al. 1995) equal or greater than that provided from Coral Sea upwelling, rainfall and, in the case of nitrogen, atmospheric fixation.

Results from the Burdekin River in the early 1980s (Wolanski and Jones 1981; Wolanski and van Senden 1983) and the Fitzroy & Burdekin Rivers in 1991 (Brodie and Mitchell 1992) confirm that, during flood events, plumes from the larger rivers can travel hundreds of kilometres from the river mouth and persist as recognisably distinct water masses for several weeks.

Australian rivers are known to have unusually erratic flow patterns (Harris 1995). The larger dry-catchment coastal Queensland rivers such as the Burdekin and Fitzroy are extreme in this sense with average intervals between major flows of several years. The 'wet tropics' rivers, on the other hand, although also displaying highly event driven discharge, display a more even discharge pattern with one or more major flows almost every year. This is a consequence of their location in the relatively reliable monsoon rainfall 'wet tropics' coastal region. Over the last decade, with regular wet season plumes, studies of these rivers (Endeavour, Daintree, Barron, Russel-Mulgrave, Johnstone, Tully and Herbert) have allowed preliminary conclusions as to the behaviour of the plumes to be made.

The Discharge Event

Cyclone Sadie originated in the Gulf of Carpentaria and after crossing the coast moved inland in a southerly direction parallel to the east coast (Fig. 1). Short, but intense, rainfall resulted on coastal catchments with the major flows between 30 January and 2 February 1994 (Table 1). Fig. 2 show discharge hydrographs for the most downstream gauging stations on the Daintree, Barron, Mulgrave, Russell, North Johnstone, South Johnstone, Tully and Herbert Rivers during the main event period.

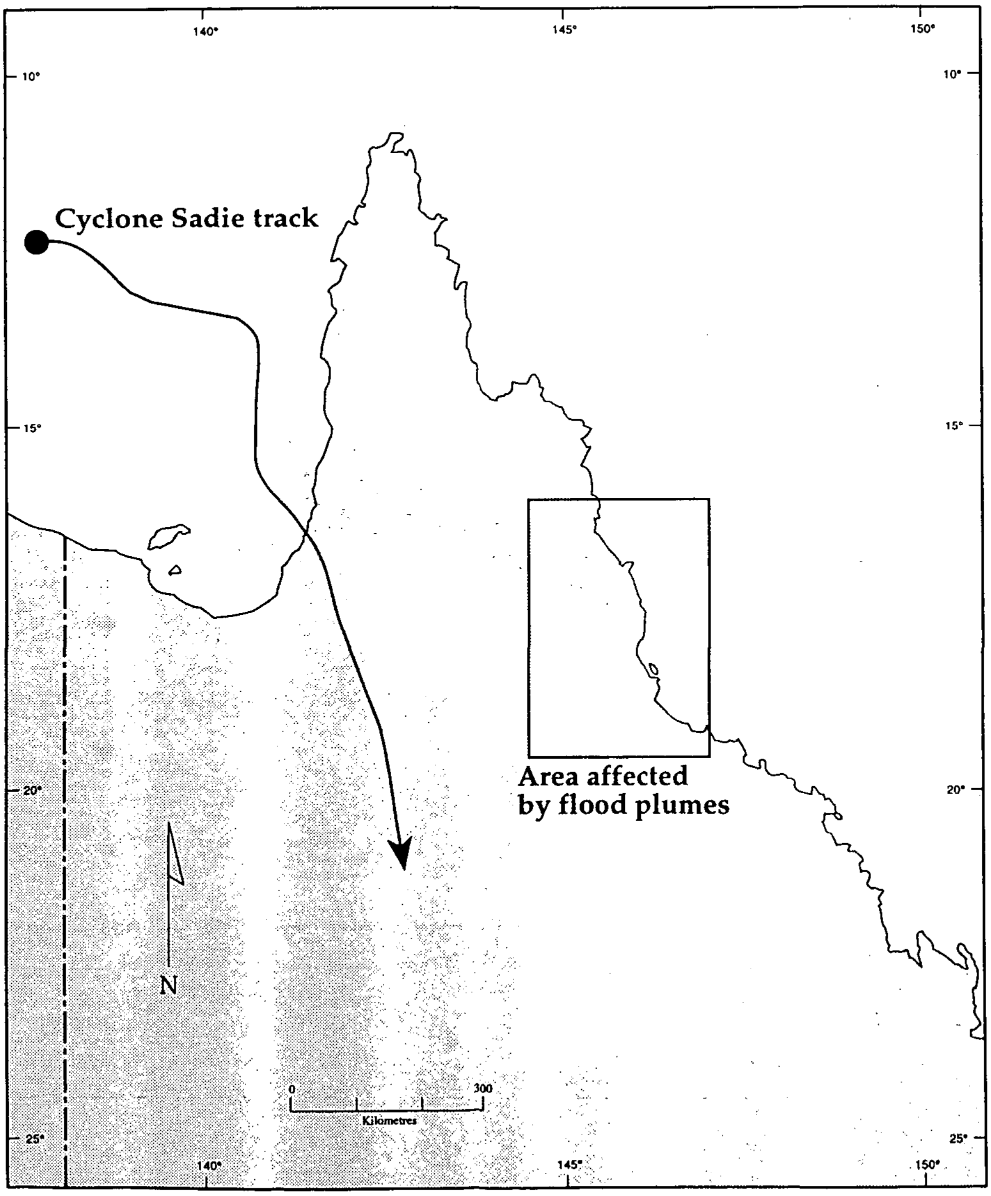

Fig. 1. Track of cyclone Sadie

The Plume

Winds offshore were slight and with no lagoonal resuspension turbidity river plumes in the period 31 January to 4 February were easily able to be mapped (Fig. 3). The plume was observed from the air on 2 and 3 February and the edge plotted using GPS positioning. Plumes originating from rivers from the Black River in the south to the Daintree in the north formed a continuous plume on 3 February (Fig. 3). The combined plume reached the outer-shelf near Noreaster Reef.

Table 1. Daily rainfall (mm) recorded at stations on coastal catchments during the passage of cyclone Sadie (26 Jan.-5 Feb. 1994). Superscripts denote the total rainfall over that number of days

Catchment & gauging stations	26/1	27/1	28/1	29/1	30/1	31/1	1/2	2/2	3/2	4/2	5/2
Mossman/Daintree											
Mossman	0.8	1.2	11	14.6	92.8	207	27	1.8	16.8	16.6	11.8
Daintree	0	23	34	67	226	73	0	0	0	0	21
Cape Tribulation	7	23	32	34	67	226	73	0	0	0	21
Barron											
Atherton	0	0.2	2	0	33	101	38	0	1	1	1
Mareeba	0	0	2	0		137	38	0	23	0	
Kuranda	0	2	9	6	57	291	90	0	1	0	26
Russell/Mulgrave											
Gordonvale		2^2	4			447^3	163	0	0	0	
Mount Sophia	0	8	49	15	99	381	209	0	0	0	0
Babinda		16^2	49	11	128	336	295	0	0	0	0
Johnstone											
Malanda	0	2	7	2		164^2	48	0	19	0	
Millaa Millaa	0	16	27	3	60	128	32	9		0	4
Crawford's lookout	1	40	7	12	123	472	41	0	2	0	23
Corsis	7	58	13	12	157	464	68	31	1	2	18
Mena Vale	1	26	26	36	161	323	74	37	5	2	5
Innisfail	4	8	19	28	158	264	226	0	2	1	2
Tully											
Kareeya		15^2	13			230^3	27	1	6	0	
Cardstone	4	7	21	4	85	193	37	1	3	0	6
Koombooloomba Dam	2	12	28	3	58	180	34	0	0	0	8
Tully	0	30	33	50	159	394	88	0	0	0	9
Herbert											
Mount Garnet	0	0	0	0	12	19	5	7	2	0	0
Gleaneagle	0	0	0	0	13	60	4	0	0	2	0
Ravenshoe	0	0	8			103^3	17				29^4
Abergowrie	0	5	7	14	52	271	227	0	0	2	2
Ingham	3	8	9	33	21	309	216	1	15	2	1
Lucinda	0	0	2	0		149^2	176	17	2	2	

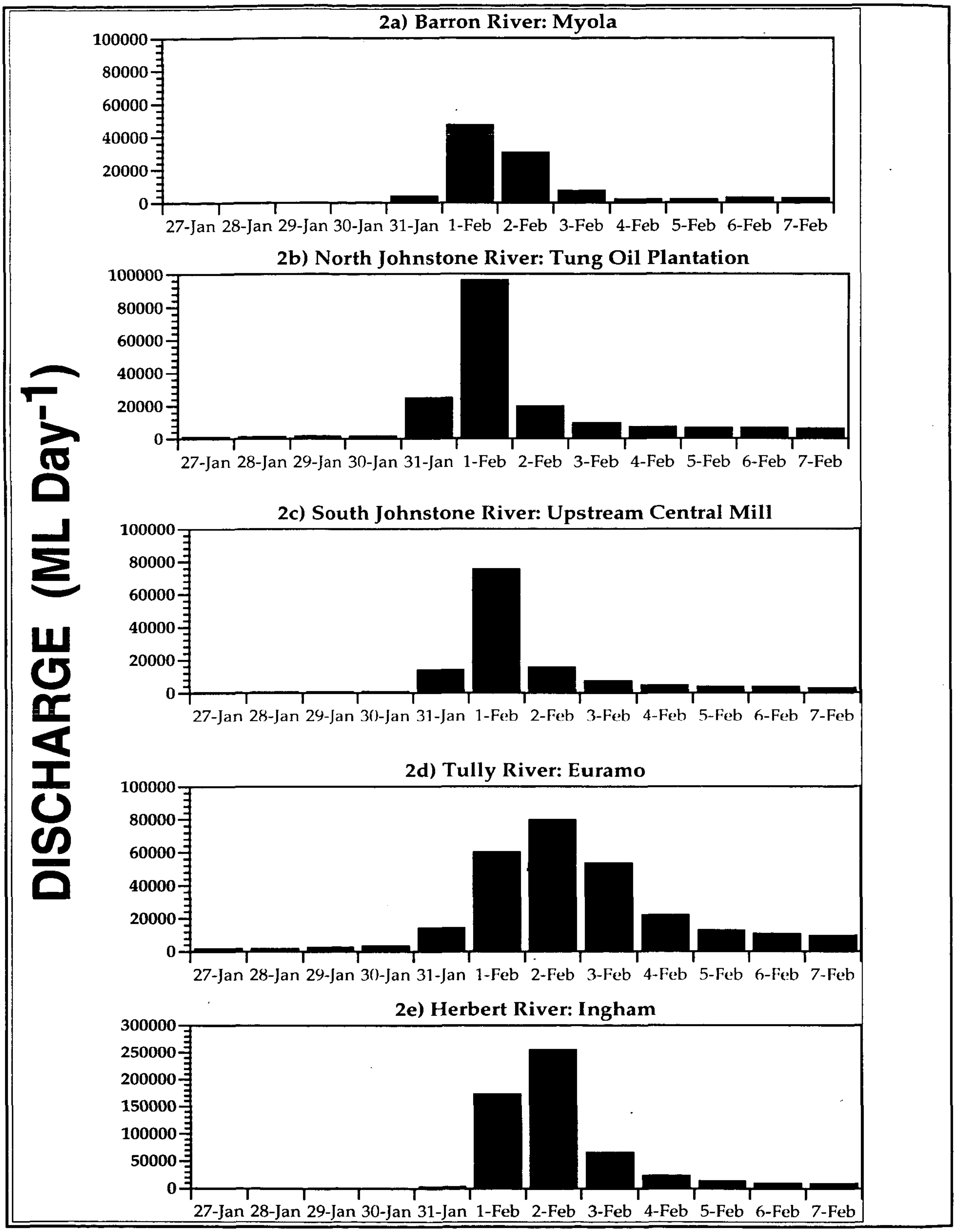

Fig. 2. Total river discharge (ML) per day from Jan 27 to Feb 7 1994 measured at the lowest gauging stations on the Barron River (a), North Johnstone R.(b), South Johnstone R. (c), Tully R. (d), and Herbert R. (e)

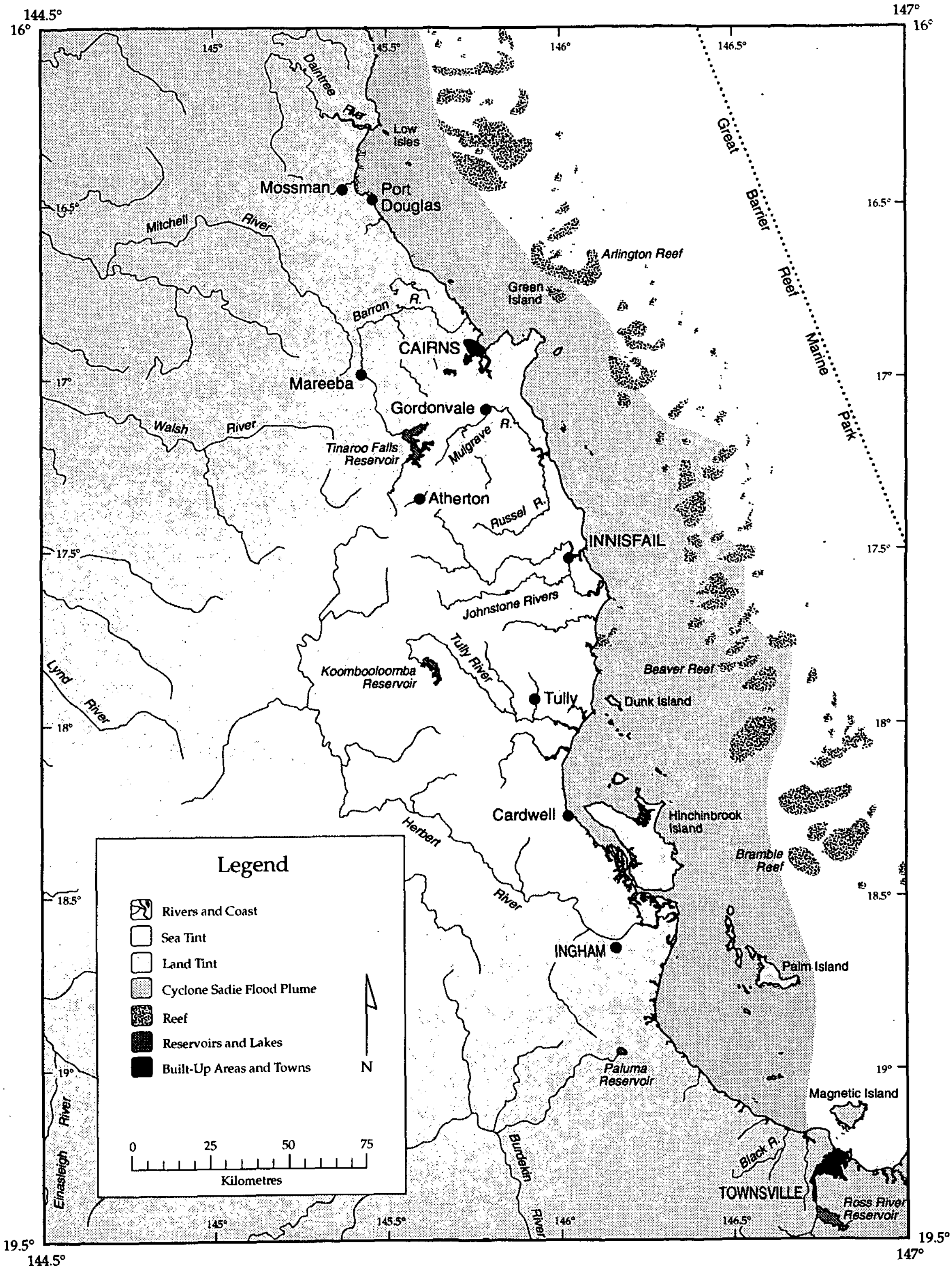

Fig. 3. Spatial extent of flood plumes recorded on 1 and 2 February 1994

Discussion

A comparison of the behaviour of coastal waters in the Townsville - Cooktown region during cyclones Winifred and Sadie reveals some of the complexities of the effects of cyclones on the water column. Cyclone Winifred originated in the Coral Sea and crossed the coast near Innisfail on 1 February 1986 (Dutton 1986). The category 3 cyclone caused substantial waves in the GBR lagoon and the resuspension of lagoon-floor sediments to a depth of 60 mm in waters up to 25 m deep (Gagan et al. 1990). It was concluded from this event that wave resuspension could be a major agent of terrestrial sediment movement across the GBR shelf, but that river plumes from the wet tropics rivers were unlikely to ever reach the mid- and outer-shelf reefs of the GBR in this region (Gagan et al. 1987). Large river flows resulted from the associated rain on the catchments, but the extent of the visible muddy river plumes was unable to be determined in the presence of wave-resuspended sediment in the lagoon. Lagoonal resuspension and river plume input of nutrients caused a phytoplankton bloom in the lagoon off the Johnstone River one to three days after the passage of the cyclone (Furnas 1989).

In contrast during cyclone Sadie, with a very light wind regime, no lagoon-floor resuspension occurred and the visible turbid water areas could be ascribed completely to river plumes. The combined plume was able to reach the outer shelf of the GBR under these conditions contradicting the conclusions drawn by Gagan et al. (1987) from the cyclone Winifred results. The plume was short-lived with little evidence of it in the water column by 6 February (Devlin 1996).

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Hydrographic and nutrient measurements in the Daintree River plume and its vicinity

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Abstract

Hydrographic and nutrient measurements were conducted at four stations off Cape Tribulation - Port Douglas before and after cyclone Sadie. A significant decrease in salinity and an increase in nutrient concentration at the sea surface were observed at inshore to mid shelf stations a day after the peak rainfall. This low salinity and high nutrient sea surface water was quickly dissipated in the following two days. A series of hydrographic measurements after another heavy rainfall in late February revealed that the plume from Daintree River stretched along Cape Kimberley nearby and then away from the coast towards mid shelf reefs, suggesting the presence of a strong buoyant jet at the mouth of the river. The plume was only 2 - 3 m thick at most of the stations and was carrying ca. four to five times more dissolved inorganic nitrogen and twice the amount of dissolved organic nitrogen than the surrounding water. Chlorophyll concentration in the plume was relatively low, probably because of the short lapse after its formation and the limited light available to phytoplankton (high turbidity).

Introduction

Flood plumes introduce a large quantity of nutrients and sediments into Great Barrier Reef (hereafter GBR) shelf waters. There is, however, a degree of controversy over how far flood plumes extend offshore and the extent, to which they influence coral reef communities in the GBR. Davies and Hughes (1983) suggested the transport of terrestrial clays to mid-shelf coral reefs during cyclone Dominic, whereas Gagan et al. (1987) claimed that the transport of terrestrial carbon introduced during cyclone Winifred was confined to near-shore areas. King and Wolanski (1996) have shown, using numerical model simulations of flows in the GBR, that the mixing properties of the GBR are highly spatially variable; this may explain the discrepancy between the results of Davies and Hughes (1983) and Gagan et al. (1987).

The magnitude of flood plumes is one of the factors affecting their cross-shelf dispersion. Flood plumes usually stretch northward along the coast through the interaction of the Coriolis force with the pressure gradient across the shelf and do not reach the GBR (Wolanski 1981; Wolanski and Jones 1981). Wolanski and van Senden (1983), however, have suggested the possibility that very large flood plumes may extend over the width of the shelf.

Other factors that may have a significant consequence on the cross-shelf dispersion of flood plumes include the presence or absence of geographic features, such as headlands, islands and coral reefs (King and Wolanski 1992, 1996). Furthermore, the intensity of buoyant jets at the river mouth can vary depending on the size and morphology of rivers and catchment areas and the amount and continuity of rainfall. This paper presents the results of hydrographic and nutrient measurements in the Daintree River plume and its vicinity and urges the need for understanding the dispersion of flood plumes in the local/regional context.

Methods

Pre- and post-cyclone observation

Sampling was conduced at three stations located between Port Douglas and Undine Reef (Fig. 1, stations A - C) and at a station on the leeward side of Agincourt Reef (Stn D) twice before (January 11 and 18) and twice after cyclone Sadie (February 1 and 3). Water samples were collected with a water bottle from the sea surface and the near bottom at each of four stations. The salinity of water collected was immediately determined using a YSI conductivity meter. Duplicate 10 ml subsamples were collected from each bottle, filtered with disposable syringe filters and stored frozen for later analyses of nitrate and phosphate using a multichannel segmented flow autoanalyzer (Ryle et al. 1981).

Observation of the Daintree River plume

A series of hydrographic measurements were conducted at eleven stations off Cape Tribulation - Port Douglas on February 21 (stations 11) and 22 (stations 1-10). At stations 5-8, water samples were collected from two to four different depths using Niskin bottles. Duplicate 10 ml subsamples were obtained, processed as described above, and analysed for dissolved inorganic and organic nitrogens after the procedures of Strickland and Parsons (1972) and Ryle et al. (1981). A 100 ml sub-sample was also obtained from each bottle, filtered onto a Whatman GF/F glass fibre filter, stored frozen and analysed for chlorophyll by fluorometry (Strickland and Parsons 1972).

Results and discussion

Pre- and post-cyclone observation

Cyclone Sadie brought about 250 - 400 mm of rainfall during a three day period between January 29 and 31 in the north of Cairns (Fig. 2; Daily Rainfall Bulletin, Bureau of Meteorology).

Although the YSI conductivity meter used was not as reliable as initially expected, the data clearly show a significant decrease in sea surface salinity at stations B and C in response to the rainfall associated with the cyclone (Fig. 3). This low salinity sea surface water was quickly dissipated and was not observed on 3 February, only three days after the peak rainfall.

Fig. 4 shows the sea surface and near bottom concentrations of phosphate and nitrate at stations A - D. The concentrations of these nutrients were mostly below the detection limit before the cyclone. The sea surface concentration of phosphate at Stns. A and B reached > 0.19 μM a day after the cyclone-associated peak rainfall and droped to < 0.05 μM in the following two days. Nitrate showed a similar variation pattern to phosphate.

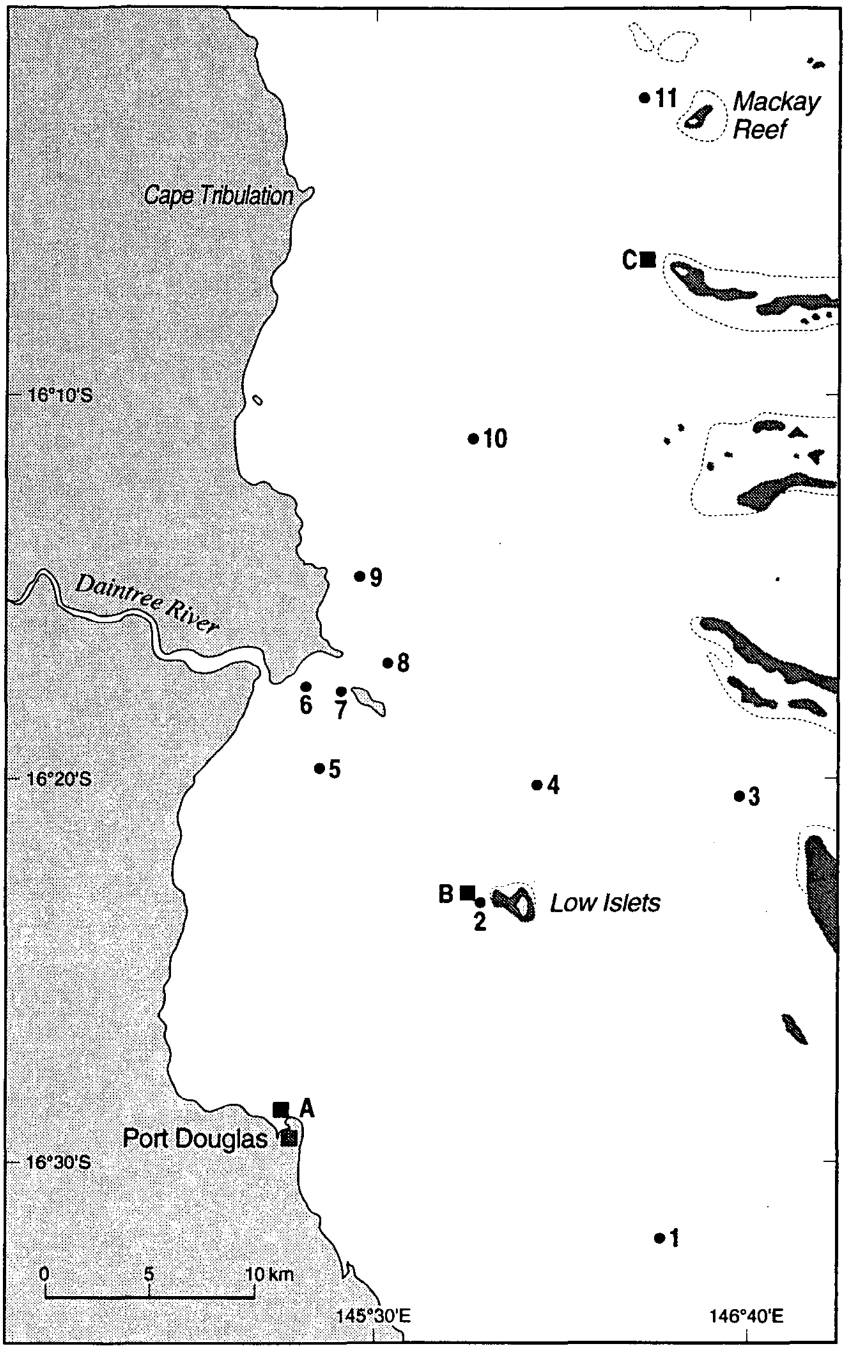

Fig. 1. Location of hydrographic stations sampled before and after cyclone Sadie (stations A-C) and after the heavy rainfall in late February, 1994 (stations 1-11)

The influence of the rainfall associated with cyclone Sadie on the sea surface salinity and nutrient concentration was significant, but rather short-lived. Unfortunately, however, the data are insufficient for answering the question of whether or not the observed changes in salinity and nutrient concentration were due to the flood plume caused by the cyclone. About a half of freshwater inputs into the GBR occurs through direct rainfall over the shelf (Wolanski 1981). Rain water itself may contain relatively high levels of nutrients (e.g. Furnas et al. 1995; Paerl and Fogel 1994). Furthermore, sampling stations were located relatively close to reefs and might be under some influence of water washed off reefs.

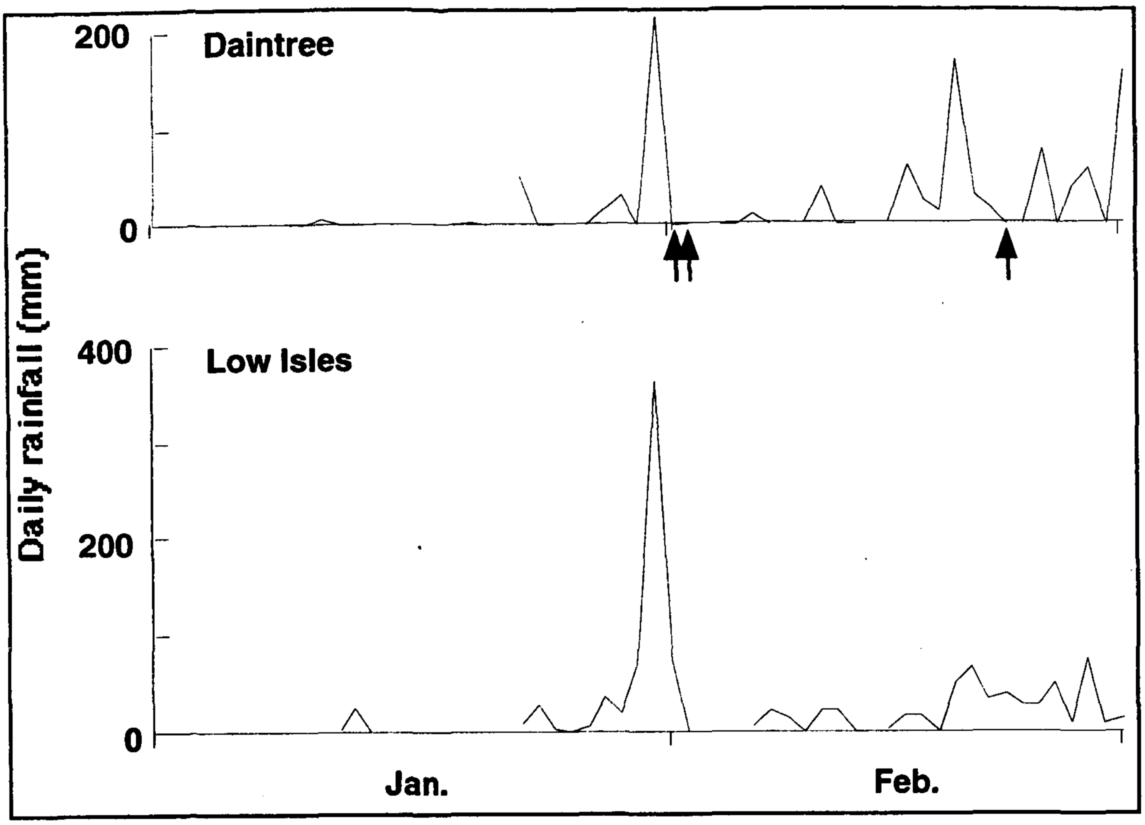

Fig. 2. Daily rainfalls in the Daintree and Low Isles areas between January and February, 1994 (from the Daily Rainfall Bulletin, Bureau of Meteorology)

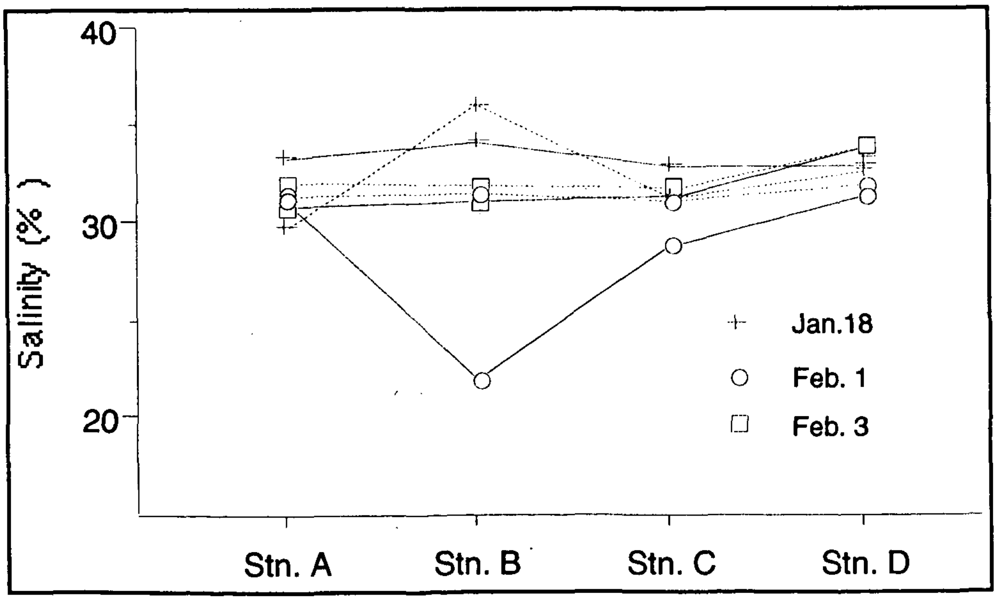

Fig. 3. Variation in salinity at the sea surface (solid line) and the bottom (broken line) at four stations off Cape Tribulation - Port Douglas before and after cyclone Sadie

Observation of the Daintree River plume

Observation of the Daintree River plume was conducted following the rainfall on 18-20 February (Fig. 3). Overall, this rainfall was not as wide-spread and not as intense as the one associated with cyclone Sadie. The Daintree area, however, received on February 18 about 170 mm of rainfall, similar to the peak rainfall during cyclone Sadie.

The sea surface salinity at the mouth of Daintree River was below 27‰ (Fig. 5). The plume stretched along Cape Kimberley and then away from the coast towards mid shelf reefs. A water mass of relatively high salinity (> 31‰) existed between the coast and the plume. The plume was only 2 - 3 m thick at most of stations and there was no significant sign of the plume at 5 m depth (Fig. 6).

There is a discrepancy between the general understanding of the behaviour of flood plumes and the observed features of the Daintree River plume. As mentioned earlier, flood plumes usually stretch northward along the coast through the interaction of the Coriolis force with the pressure gradient of plumes. A passive trajectory model also predicted that the plume would be adhered onto the coast under the tide and prevailing wind conditions during the time of the observation. The observed behaviour of the plume can be explained only by assuming a strong buoyant jet at the mouth of Daintree River: i.e. a buoyant jet is strong enough that its momentum in interaction with Cape Kimberley drives the plume offshore. It is interesting to note that the estimated speed of the vessel (from GPS) was about 7 knots from station 11 to station 9, whereas it increased to 10.5 to 11 knots during the run in the opposite direction. This gives an estimated current speed of approximately 2 knots (1 m s^{-1}), which is in good agreement with the current speed reported by Wolanski and Jones (1981) for the Burdekin River plume.

Fig. 7 shows the vertical profiles of dissolved organic and inorganic nitrogen (DON and DIN) and chlorophyll in the plume (station 6) and its vicinity (stations 3 - 5) for comparison. The plume was carrying about 4 - 5 times more DIN and twice the amount of DON than the surrounding water. Chlorophyll

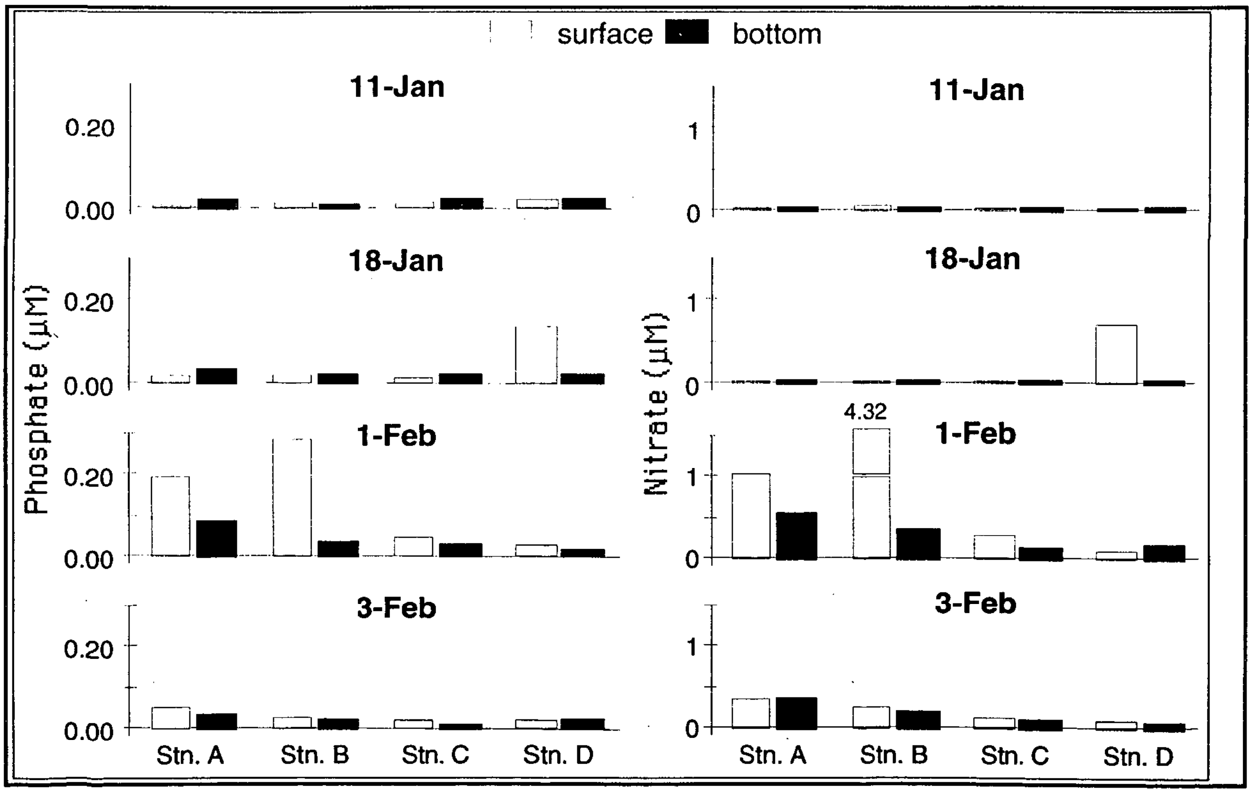

Fig. 4. Variations in phosphate and nitrate concentrations at the sea surface (open) and the bottom (filled) at four stations off Cape Tribulation - Port Douglas before and after cyclone Sadie

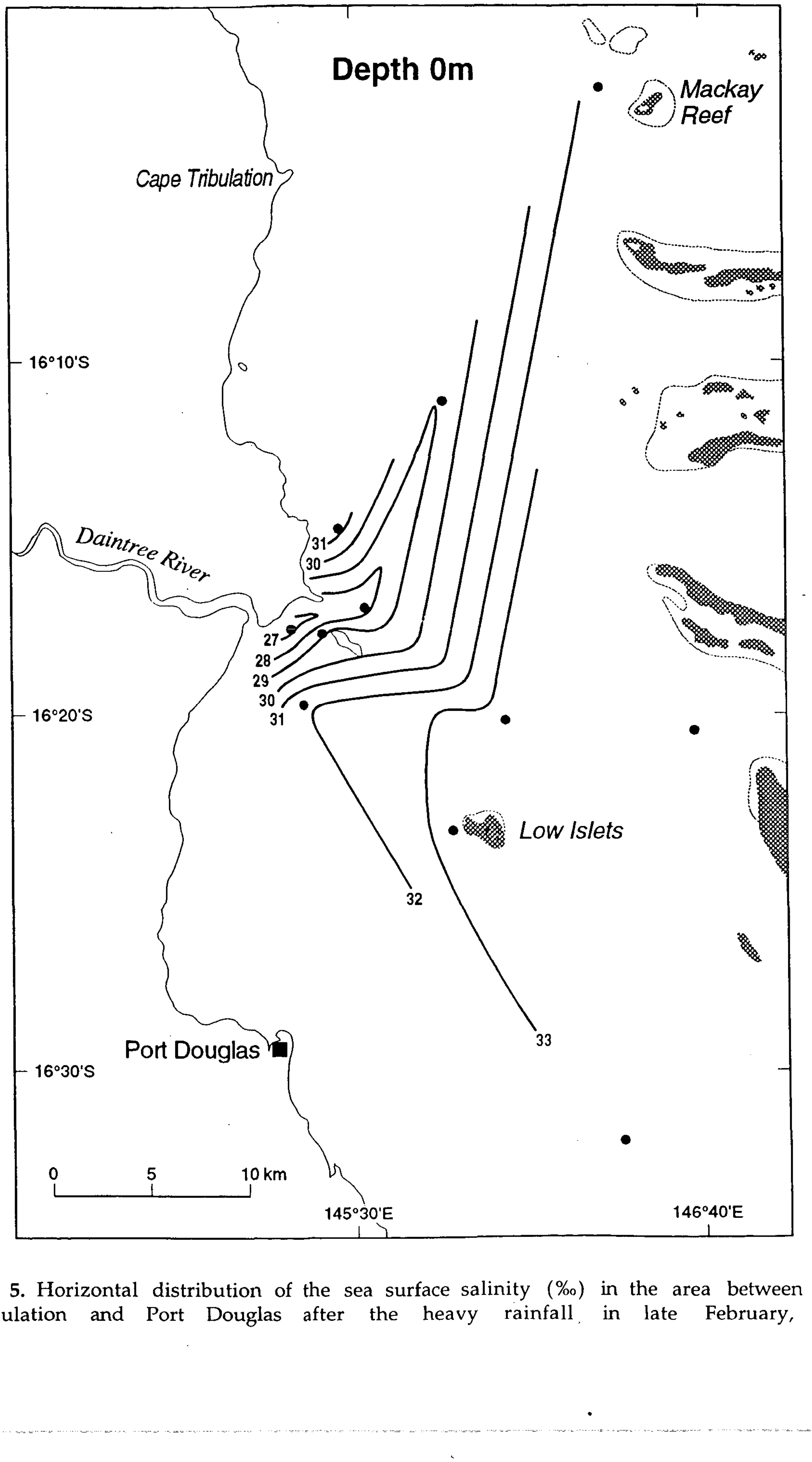

Fig. 5. Horizontal distribution of the sea surface salinity (‰) in the area between Cape Tribulation and Port Douglas after the heavy rainfall in late February, 1994.

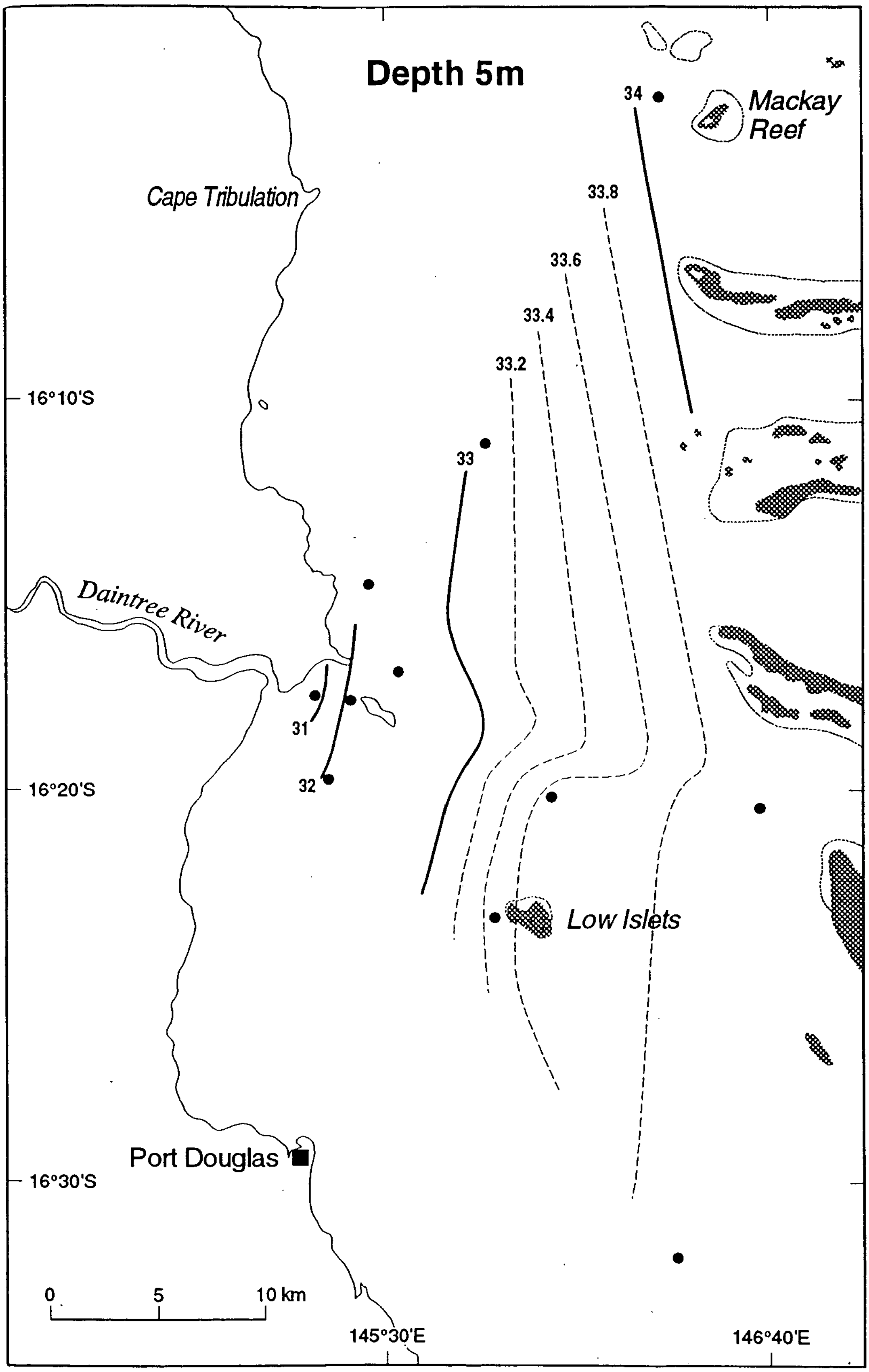

Fig. 6. Horizontal distribution of salinity (‰) at 5 m depth in the area between Cape Tribulation and Port Douglas after the heavy rainfall in late February, 1994.

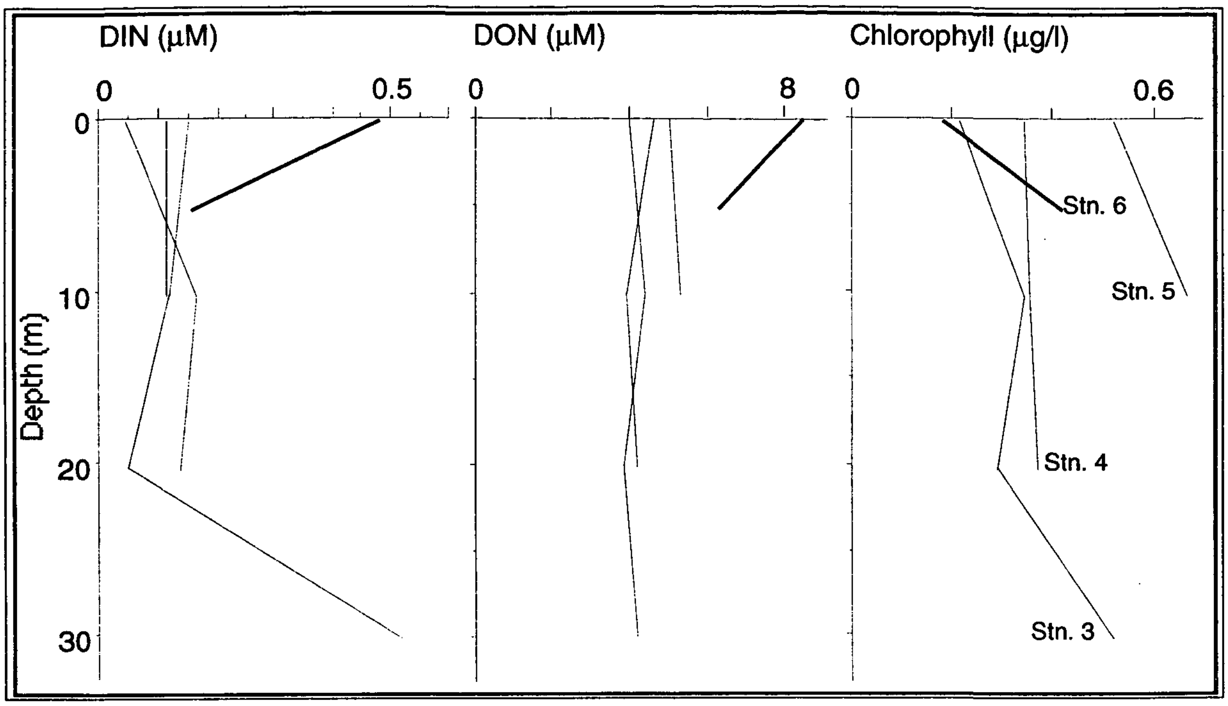

Fig. 7. Vertical distributions of dissolved inorganic (DIN) and organic nitrogens (DON) and chlorophyll in the Daintree River plume (station 6; bold) and its vicinity

concentration in the plume was relatively low, probably because of the short lapse after its formation and the limited light available to phytoplankton (high turbidity).

The observed river plume had a very thin vertical structure and might be dissipated fairly quickly through vertical mixing. The amount of nutrients and sediments carried offshore by the plume, because of its ephemeral nature, can not be estimated unless the plume is properly modelled and the model is verified against more field data. Yet, this study suggests a possibility that flood plumes can constitute an important mechanism for the cross shelf transport of nutrients and sediments in the study area.

Caveat

Riverine nutrient inputs into GBR shelf waters have significantly increased through decades of coastal development and a range of agricultural practices (Moss et al. 1992). This has raised concern over the effect of eutrophication on the health of GBR. Furthermore, it has been argued that eutrophication of GBR shelf waters may have a significant consequence on the growth and survival of the larvae of crown-of-thorns starfish and hence the dynamics of their adult populations (Bell 1992; Ayukai 1993). The results of field and modelling studies (Wolanski and van Senden 1983; King and Wolanski 1992; this study) suggest that there may be places, where the cross shelf transport of nutrients is locally enhanced through characteristic geographic features and urge the need for such concern being carefully dealt with in the local/regional context.

Acknowledgments

We are grateful to the crew of the M/V Karina and the R/V Harry Messel for their generous help in collecting samples. Steve Clarke helped in drawing figures. This study was partly funded by the Great Barrier Reef Marine Park Authority. This is AIMS contribution no. 840.

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Offshore measurements late in the river plumes associated with cyclone Sadie

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Abstract

Cyclone Sadie caused a large rain depression over most of the north Queensland catchment area, with river runoff creating a complex plume that stretched to the outer reefs. On the 4th of February 1995, the Long Term Monitoring Program (LTMP) collected water quality samples along a transect between the Brook Islands and the Mulgrave river in the aftermath of cyclone Sadie. Water quality parameters measured included dissolved nitrogen and phosphorus species, chlorophyll a, suspended solids and salinity, which were sampled at four depths through the water column.

While the concentrations of nutrients, suspended solids and chlorophyll were found to be higher than 'normal' they were lower than other recorded flood events. As the minimum salinity was 29 ‰ for all of the sites, it is probable that mixing processes had returned salinity to near 'normal' levels. Elevated ammonia concentrations were recorded at all sites, though some surface levels were low indicating that phytoplankton activity had taken up much of the available ammonia. High NO_3*-*NO_2 *levels were only recorded at one site. Dissolved organic nitrogen (DON) concentrations were generally similar to non-flood levels. High values were recorded at sites which corresponded to high levels of silicate, indicating that the high DON water had a terrestrial origin. Levels of dissolved inorganic and organic phosphorus remained relatively low at all sites, suggesting that most phosphorus coming from the rivers was transported and remained as particulate matter. Chlorophyll levels were generally high across the sites with the most elevated levels recorded where ammonia levels were low.*

The low concentrations of dissolved nutrients associated with the cyclone Sadie plume may be either related to the two day time lag between the rain event and actual sampling or the plume characteristics itself (weather or catchment affected). This discrepancy will only be completely resolved as more cyclone datum, comparing different events and different catchments, becomes available.

Introduction

The Long Term Monitoring program (LTMP) based at the Australian Institute of Marine Science (AIMS) has a water quality component which monitors a range of water quality parameters over a whole-Great Barrier Reef (GBR) spatial scale, once to several times per year. Comprehensive hydrographic, nutrient (dissolved organic and inorganic forms) and chlorophyll measurements are made at each site.

The LTMP emphasis on broad-scale spatial monitoring does not generally allow sampling of flood events which episodically occur in the central and southern Great Barrier Reef. These events induce dramatic regional-scale changes in water quality (Furnas 1993). Typically, increased river runoff results in nutrient and phytoplankton levels far in excess of those measured under non-flood conditions. In order to enhance our knowledge of the complex spatial and temporal properties of the GBR shelf water, it is essential that any monitoring program must include sampling to measure variability associated with freshwater plumes or other large-scale disturbances.

During February 1994, the opportunity arose for the LTMP to take water samples along the central Great Barrier Reef coastline between the Brook Islands and the Mulgrave River (Fig. 1). The geographic extent of the bio-physical impacts arising from cyclone Sadie was largely restricted to rivers between Cairns and Cooktown. Because of time constraints, sampling was initiated on the February, two days after the main flood peak had occurred. The rain depression caused by the cyclonic low pressure system caused a rapid increase in river water levels and discharge into the Great Barrier Reef lagoon. The plume was visible for approximately four to five days, and eventually reached the outer reefs. The volume of river discharge was not large in comparison to other cyclonic events and there was essentially no sediment re-suspension caused by heavy winds within the lagoon. This lack of re-suspension, coupled with the time lag involved before commencement of sampling, may cause the concentrations of dissolved nutrients measured within this plume to be lower in comparison to other plumes (Furnas and Mitchell 1986; Brodie and Mitchell 1992).

Methods

Water samples hourly while the research vessel was steaming. Sampling consisted of either depth sampling stations (1, 4, 7 and 10) or a single surface sample. Sub-surface sampling consisted of three Niskin bottles spaced out over the depth profile with a surface sample taken by bucket (Figs. 2, 3). In situ temperatures were recorded by digital reversing thermometers attached to the Niskin bottles. At all other sites, surface water was collected with a bucket. At each station, cloud cover, wind speed, wind direction, tide and acoustic depth were recorded Water transparency was measured by secchi disk, and the presence of *Trichodesmium spp.* noted visually.

Sample processing was carried out using a work station which included a vacuum pump, vacuum reservoir, and filtration manifold. Sub-samples were dispensed from the Niskin bottles into appropriate containers. Filtration of water samples for chlorophyll analyses and suspended solids was carried out on the filtration manifold and nutrient and silicate samples were filtered with a 50 ml plastic syringe and individual 0.45 µm membrane disposable filters. Discrete sub-samples were retained for salinity measurements.

Water samples for nutrient analysis were analysed according to the Standard Operational Procedure (AIMS 1994) for inorganic ammonia (NH_4), nitrite (NO_2), nitrate (NO_3), total dissolved nitrogen (TDN), dissolved organic nitrogen (DON), dissolved inorganic phosphorus (PO_4), total dissolved phosphorus (TDP), dissolved organic phosphorus (DOP) and silicate (Si). Analysis of chlorophyll, suspended solids and salinity were carried out at AIMS according to Standard Operational Procedures (AIMS 1994).

Results and Discussion

Values for oceanographic and nutrient parameters within the plume were generally higher than values recorded in non-flood conditions (Furnas 1990), though concentrations of the parameters were lower than those taken in studies of other plumes (Brodie and Mitchell 1992; Furnas 1990). Water quality data available for the area, between Cape Grafton and Dunk Island, include nutrients, chlorophyll and transparency parameters (Furnas 1990; Furnas et al. 1993). Depth weighted average concentrations for midshelf water in this area (10 - 30 metres) in normal (non-flood) conditions are given in Table 1 and are compared with samples taken during flood conditions in the present study.

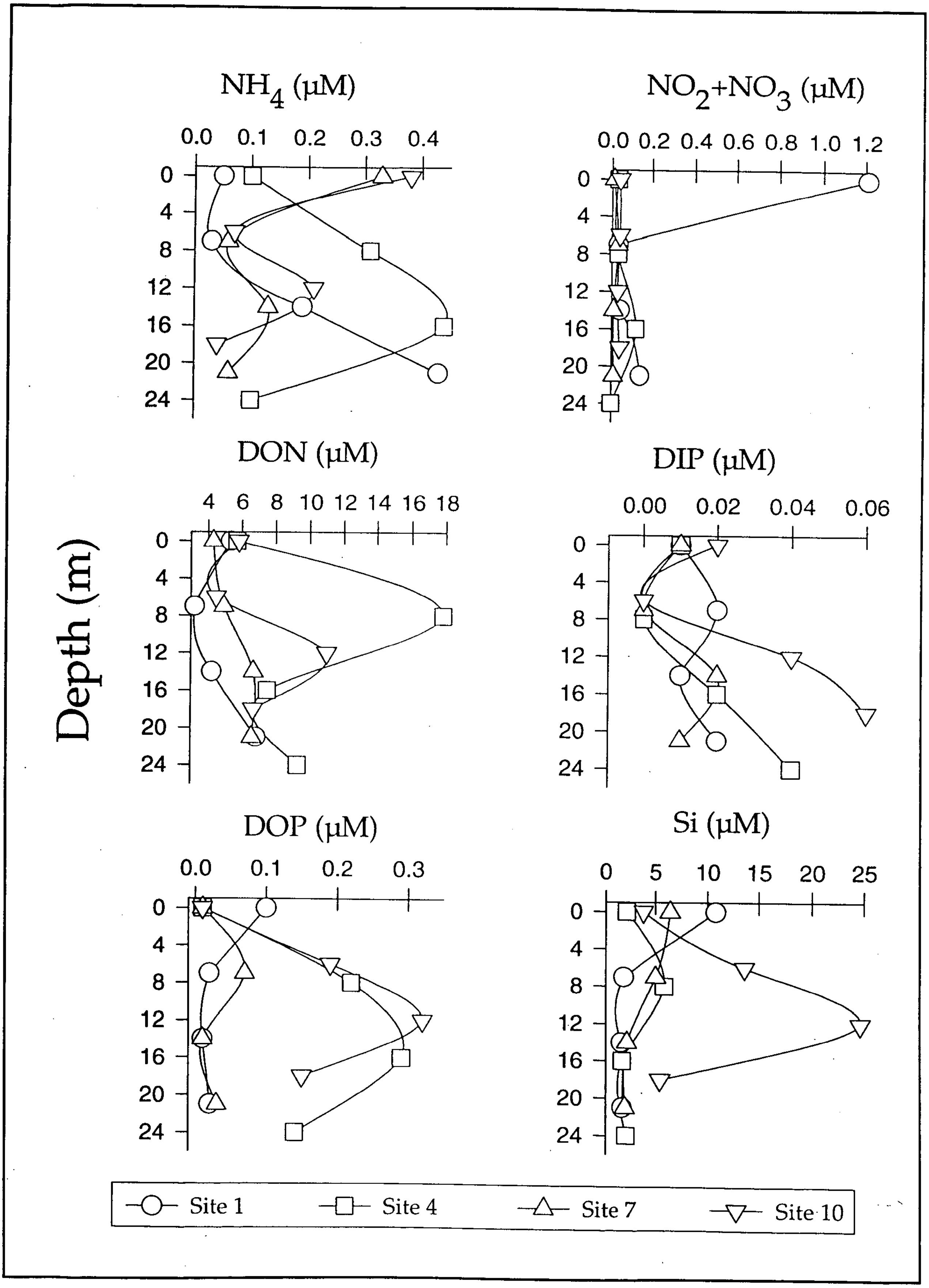

Fig. 2. Depth profiles of dissoved nutrients in the cyclone Sadie plumes at sites 1, 4, 7 and 10

Table 1. Summary statistics for mean water column concentrations of dissolved nutrients for theTully area (depth 10 to 30m) (Furnas 1991).

	NH_4 µmol/L	NO_2 µmol/L	NO_3 µmol/L	DON µmol/L	PO_4 µmol/L	DOP µmol/L	SiO_4 µmol/L	Chl µg/L
Mean	0.220	<0.010	0.040	5.260	0.140	0.180	0.3480	0.330
Std Dev	0.290	0.007	0.021	1.888	0.052	0.079	1.873	0.160
No. Sta.	27	27	27	12	27	12	27	26

Near surface salinity was diluted with freshwater at sites 1, 2 and 8 north of the Herbert, South and North Johnstone rivers (Fig. 4). Surface salinities ranged from 29 to 36 ‰, whereas in other studies freshwater influences have caused surface salinities to drop below 10 ‰ (Brodie and Mitchell 1992; Furnas 1990). This indicates that mixing processes between the surface and bottom layers had, within two days, returned salinity to near normal levels.

The chlorophyll levels measured in this study were higher than values recorded under non-flood conditions, indicating an increased level of phytoplankton growth. Chlorophyll concentrations were highest at site 1, approximately three times that of normal midshelf levels. The lower phaeophytin values confirm that most of chlorophyll detected was associated with new algal biomass rather than terrestrial or marine detrital material (Brodie and Mitchell 1992).

Table 2. Oceanographic data from cyclone Sadie sampling along coastline

Stn	Depth (m)	Temp °C	Salinity (ppt)	Chloro (µg/L)	Phaeo (µg/L)	SS (mg/L)
1A	0	-	29.2007	1.326	0.596	2.54
1B	7	28.94	35.3339	0.868	0.491	0.89
1C	14	-	35.5238	1.403	0.565	1.28
1D	21	28.70	35.3704	0.984	0.448	1.48
2	0	-	30.1633	-	-	-
3	0	-	35.5116	-	-	-
4A	0	-	35.3504	0.598	0.355	1.17
4B	8	29.43	35.3304	0.587	0.233	0.82
4C	16	-	35.397	0.796	0.311	1.12
4D	24	28.86	35.3911	0.934	0.378	1.41
5	0	-	35.4327	-	-	-
6	0	-	35.2484	-	-	-
7A	0	-	35.2594	0.574	0.182	1.43
7B	7	29.43	35.2261	0.564	0.211	1.5
7C	14	-	35.3131	0.962	0.225	1.16
7D	21	29.06	35.3123	0.752	0.355	1.29
8	0	-	34.2927	-	-	-
9	0	-	35.1034	-	-	-
10A	0	-	35.1881	0.565	0.278	1.73
10B	6	28.88	35.1371	0.644	0.315	1.19
10C	12	-	35.1763	0.730	0.357	0.93
10D	18	28.48	35.23	0.215	0.133	2.13
11	0	-	35.2723	-	-	-

NH_4 concentrations are low at the surface with an increase in concentration in the sub-surface samples. The surface NO_3 levels at site 1 are high with a sharp decrease down the water column. NO_2 levels stay constant throughout sites and depths at levels similar to non-flood values. Ammonia concentrations at the other sites are only slightly higher than the non-flood values recorded by Furnas

(1990) suggesting that though the plume was still visible the available dissolved nitrogen has to a large extent been assimilated into the phytoplankton. The highest chlorophyll reading was recorded in the surface layer at site 1.

As inorganic nitrogen species (NH_4, NO_2, NO_3) are quickly taken up by benthic or pelagic plants even eutrophic systems may not show high levels of dissolved inorganic nutrient species despite high inputs (Brodie and Mitchell 1992). During the two days between the flood event and the sampling, nutrient concentrations may have decreased from initial high flood levels. In a fairly brief time, some portion of terrestrial sediment would have fallen out of the water column, allowing greater light penetration. This, combined with the clearing of cloud cover, would allow the phytoplankton to take up the elevated concentrations of dissolved nutrients.

The dissolved nitrogen pool is dominated by dissolved organic nitrogen (figure 2). DON values are generally similar to non-flood events with the high concentrations recorded at sites 4 and 10. Cosser (1989) suggests that most phosphorus transported to the sea by Queensland river systems is bound to particulate matter. This is supported by the low dissolved inorganic phosphorus (DIP) levels recorded in the present study. DIP concentrations recorded in the Sadie plume are similar to non-flood values recorded for the Tully area (Furnas 1990). High concentrations of dissolved organic phosphorus (DOP) were recorded only in sub-surface samples at sites 4 and 10 which are slightly north of the Tully and Mulgrave-Russell rivers respectively. At all other sites, including the surface samples at sites 4 and 10, there were very low concentrations of DOP. These low values could have resulted from dilution processes of the seawater with the low organic levels contained in the freshwater plume. Future river plume sampling should include the measurements of particulate nutrient species to fully assess the transport of nutrients into the reef lagoon from rivers.

Table 3. Nutrient concentrations (μM) from cyclone Sadie plume sampling

STN	Depth	NH_4	NO_3	NO_2	DON	PO_4	DOP	Si
1A	0	0.05	1.20	0.01	5.34	0.01	0.10	10.8
1B	7	0.03	0.02	0.01	3.21	0.02	0.01	1.8
1C	14	0.19	0.03	0.01	4.23	0.01	0.18	1.5
1D	21	0.43	0.13	<0.01	6.85	0.02	0.06	1.6
4A	0	0.10	0.02	0.01	5.69	0.01	0.01	2.1
4B	8	0.31	0.02	<0.01	17.83	<0.01	0.22	5.8
4C	16	0.44	0.10	0.02	7.50	0.02	0.29	1.6
4D	24	0.10	<0.01	<0.01	9.30	0.04	0.14	2.0
7A	0	0.33	0.01	<0.01	4.31	0.01	0.01	6.4
7B	7	0.06	0.02	0.01	4.94	<0.01	0.07	5.0
7C	14	0.13	<0.01	0.01	6.70	0.02	0.01	2.1
7D	21	0.06	<0.01	0.01	6.60	0.01	0.03	1.9
10A	0	0.38	0.02	0.02	5.82	0.02	0.01	3.8
10B	6	0.07	0.03	0.01	4.49	<0.01	0.19	13.6
10C	12	0.21	0.01	0.02	10.98	0.04	0.32	24.6
10D	18	0.04	0.03	0.01	6.68	0.06	0.15	5.4

Despite time limitations, this small study has led to some interesting conclusions about the fate of dissolved nutrients in a freshwater plume. Generally the concentrations of dissolved nutrients (Table 2) and phytoplankton (Table 3) in the cyclone Sadie plume were higher than non-flood periods with high variability between sites and position in the water column. The variability between sites may be related to catchment characteristics and the specific upstream activities connected with each catchment. The low concentrations of some dissolved species in the plume indicates that the uptake of the dissolved nutrients by the phytoplankton may have occurred within a relatively short time.

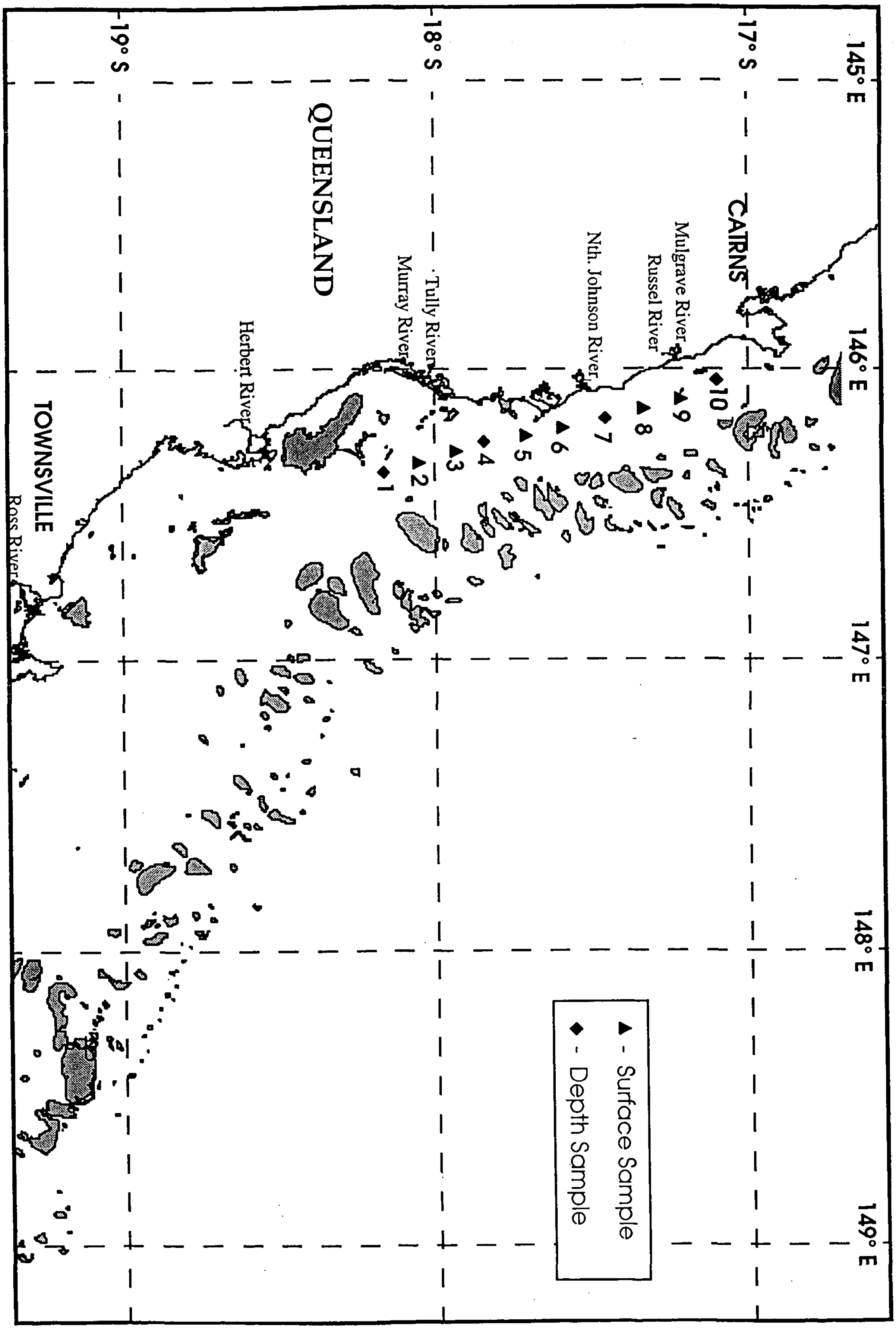

Fig. 1. Location of sampling sites taken by the R.V. Sirius on 4th February 1994

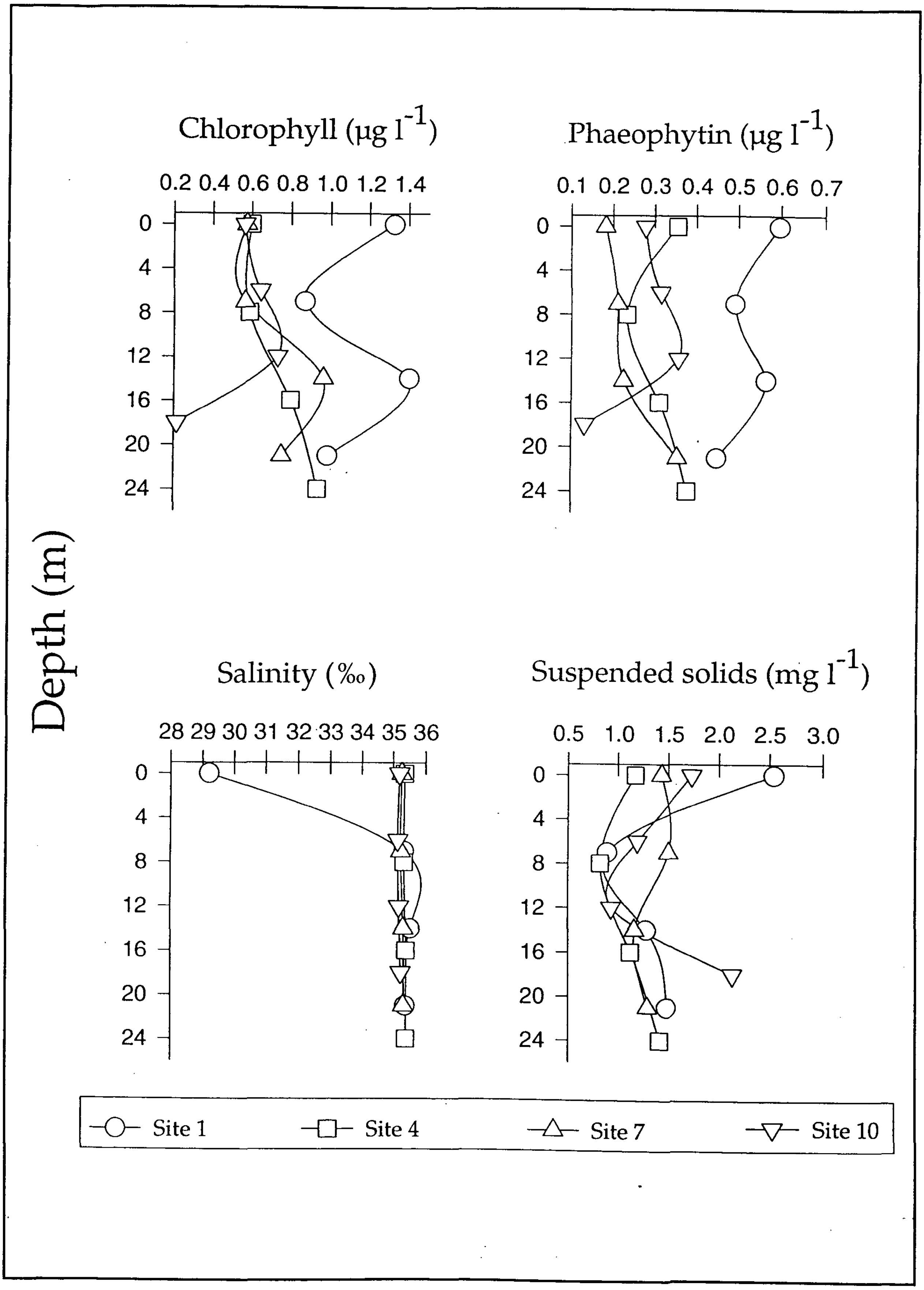

Fig. 3. Depth profiles of oceanographic data sampled in the cyclone Sadie plume at sites 1,4, 7 and 10

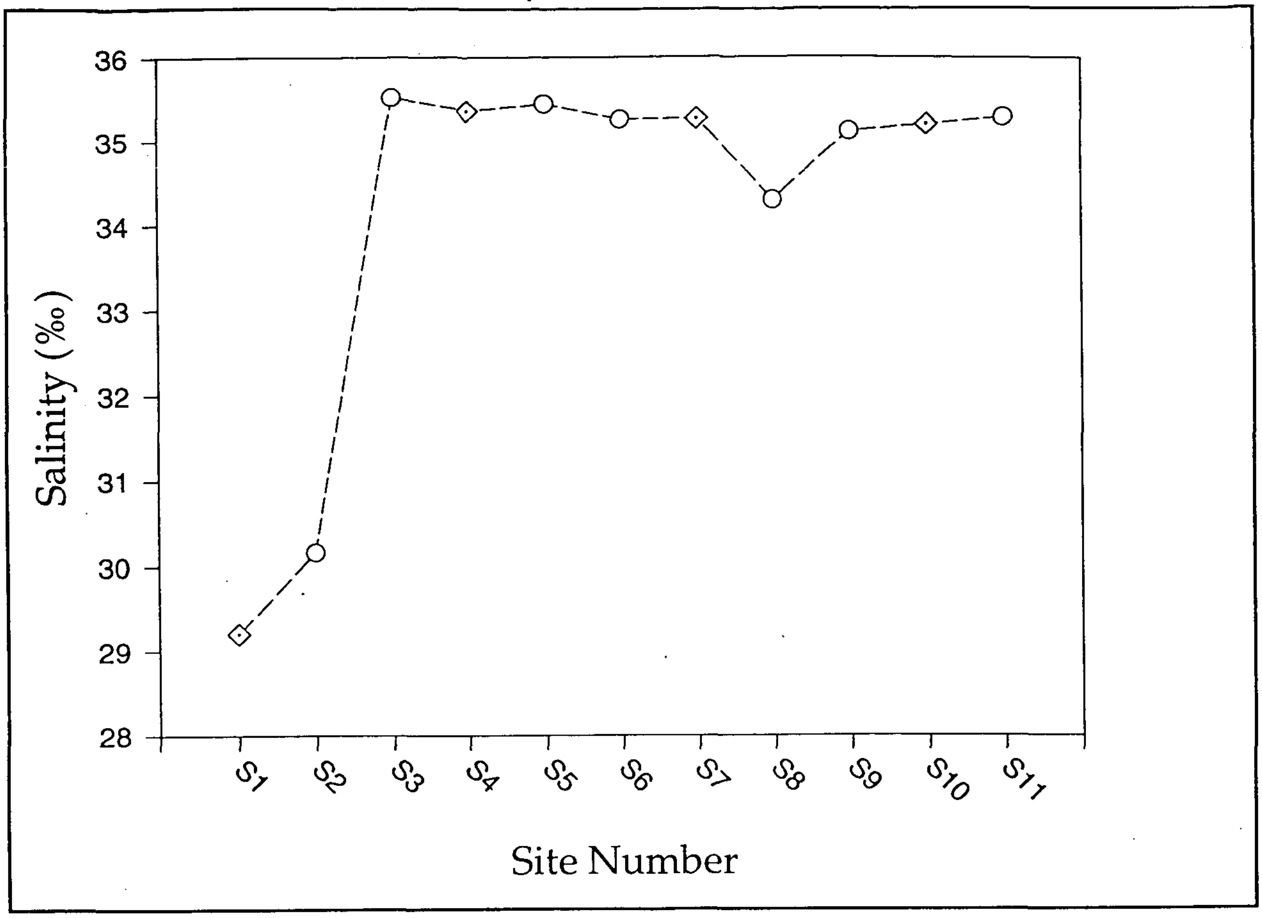

Fig. 4. Salinity surface levels across the sampling site

Clearer resolution of flood waters effects in the GBR lagoon would involve increased sampling of all dissolved and particulate nutrient species and the initiation of sampling as close as possible to the start of the flood event. The successful monitoring of any large flood event could only be improved by rapid and intensive sampling techniques and greater awareness of the individual characteristics of each catchment.

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Preliminary results on phosphorus status of suspended sediment from cyclone Sadie

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Abstract

The sediment plume generated by cyclone Sadie was sampled five days after the peak of the flood, along two transects from the mainland to the nearest reef. Although rapid mixing of flood water with marine waters had already occurred, sufficient amounts of suspended sediment for chemical analysis were collected in the Johnstone Rivers estuary and the adjacent nearshore area. Total phosphorus (P) concentrations of the plume sediments were high and of the same magnitude and range as those of bottom fluvial sediments of the catchment. Phosphorus sorption parameters of the suspended sediments indicated that they were not in equilibrium with the P status of their surrounding water and, although they could desorb large quantities of P into P-free water, there was no supportive evidence for such a desorption process occurring in-stream. Increasing salinity did not promote further P desorption.

Surficial sediments from the marine nearshore zone are undoubtedly of terrestrial origin but their total P content is much lower than that of plume sediment. Assuming that the suspended sediments discharged by the rivers are eventually deposited in the nearshore area, it can be inferred that during the deposition/diagenesis process, suspended sediments lose approximately 80% of their total P.

Introduction

Following the increasing concern on the fate and behaviour of suspended sediments and nutrients discharged by the major rivers along the Queensland coast, the long-awaited cyclone Sadie provided the ideal conditions to study sediment plumes. Since a comprehensive data set on the phosphorus (P) status of sediments from the Johnstone Rivers catchment and the adjacent offshore area has been generated over the past five years (Pailles and Moody 1992; Pailles et al. 1993), the main objectives of this study were (a) to determine the P status of suspended sediments discharged into the Great Barrier Reef lagoon during cyclonic events, and (b) to link the P status of suspended sediments to the P status of sediments in the catchment and in the marine offshore area. This linkage will contribute to a better understanding of P dispersion and dynamics in the transition from fluvial through estuarine to marine conditions.

Materials and methods

Water samples were collected on 5 February 1994, five days after the peak of the flood due to cyclone Sadie in the Johnstone Rivers. Samples were taken in two transects from the river mouth to the nearest offshore reefs (Fig. 1). Due to the low total suspended solids (TSS) load in the inner and mid-shelf waters (3 to 5 mg L^{-1}), sufficient suspended sediment samples for analysis could only be obtained by sampling the estuarine and nearshore waters where TSS concentrations ranged between 7 and 24 mg L^{-1}. Accordingly, suspended sediment samples were taken at five locations in the estuary and nearshore area (Fig. 1). Since the rivers had been flooding for five days, it is likely that, although the sediments were collected in an upstream direction, they were of similar origin. Water plus suspended sediment samples were collected 0.5 m below the surface in acid-rinsed and sample-rinsed polyethylene 20 L drums. Electrical conductivity (EC), temperature, pH, and redox potential (Eh) of the samples were measured in situ. A few drops of $HgCl_2$ were added to inhibit plankton growth and the samples were stored at 4° C in the dark. Analysis of the suspended sediments occurred in the following weeks.

In the laboratory, the samples were filtered through acid-washed and sample-washed 0.45 µm membrane filters. The filtrates were analysed for dissolved orthophosphate-P content using the methods described later. Equilibrium phosphorus concentration (EPC), total P and resin-P were determined on the suspended sediments separated by filtration. EPC of the suspended sediment was determined on separate samples at the in situ EC, and at an EC similar to that of sea water by using 3.5 % NaCl as the suspending solution. EPC was determined by the method described in Pailles and Moody (1992), except that 25 mg of sediment were shaken with 25 mL of the appropriate NaCl solution. Resin-P was determined by shaking (end-over-end at 30 rpm) for 18 h, 25 mg of sediment in 25 mL of deionised water with 15.6 cm^2 of each of a cation exchange and anion exchange resin strip. After shaking, the strips were removed from the suspension, rinsed with deionised water and P displaced from the anion exchange membrane by eluting with 40 mL of 0.15 M HCl. Orthophosphate-P (DIP) was determined on the eluate using an auto-analyser procedure (Warrell and Moody 1984) based on the Murphy and Riley (1962) colorimetric method. Desorbable P was calculated by measuring the solution orthophosphate-P concentration after shaking 25 mg of sediment in 25 mL of a P-free solution of the same EC and pH as the respective surrounding water (by adjusting the EC and pH with additions of NaCl and NaOH). Total-P was extracted by the sodium carbonate fusion method of Olsen and Sommers (1982) adjusted to a smaller quantity of sediment and analysed colorimetrically by the Murphy and Riley (1962) method. Orthophosphate-P in the water was also determined using an auto-analyser procedure (Warrell and Moody 1984) based on the Murphy and Riley (1962) colorimetric method. Total suspended solids (TSS) concentrations in the water were determined by filtering two aliquots of 100 mL through pre-weighed 0.45 µm membrane filters, then re-weighing the filters after drying at 40° C for 24 h.

Results and Discussion

Plume sediment characteristics

Five days after the peak of the flood, turbid waters were only encountered in the estuary and within 1 km offshore (station KK). A line separating brown freshwater from blue-green sea water was visible close to the coastline. Further offshore and up to the nearest reefs, the waters were clear. Field observations were confirmed by TSS concentrations obtained in the laboratory (Table 1). TSS decreased with increasing salinity (Fig. 2), indicating rapid mixing and dilution with sea water. Similarly, the EC of the water indicates that the influence of the freshwater discharged from the Johnstone Rivers was only detected within 1 km offshore (station KK). The EC of offshore waters were similar to those measured under fair-weather conditions (Pailles unpublished data). Furthermore, pH, EC, temperature and TSS data recorded at different depths suggest that, five days after the flood peak, there was no clear stratification of the sediment plume, and rapid mixing with sea water had occurred.

Experiments with plume sediments in situ

Orthophosphate-P concentrations in the suspension waters were much lower than the EPCs of the suspended sediments (cf. figures 2 and 3) suggesting that the sediments were not in equilibrium with their surrounding waters. This may be due to the suspended sediments being in equilibrium with the solution in the diffusion zone surrounding them (Froelich 1988), but this zone is 'insulated' from the bulk solution because of the low diffusion coefficient of P in solution.

Table 1. Physical and chemical characteristics of offshore waters following cyclone Sadie, n.d.: not determined

Station	Latitude	Longitude	Bottom depth	Sample depth	Temp	Cond.	pH	Eh	TSS	D.I.P
	dec degrees		*m*	*m*	°C	*mS/cm*		*mV*	*mg/L*	*µg/L*
GG	17 21 12	146 17 04	40	14	29.0	50.3	8.12	130	3	11.0
				1	28.5	52.3	8.10	120	4	6.0
FF	17 22 42	146 15 37	34	1	28.0	53.9	8.12	130	4	4.5
DD	17 25 16	146 11 84	23	15	29.0	54.6	8.14	120	4	5.5
				1	29.0	53.1	8.16	140	1	2.5
BB	17 28 62	146 07 74	20	18	29.0	53.3	8.17	158	4	4.5
				1	29.0	50.9	8.19	181	5	3.5
KK	17 30 03	146 05 18	4.5	2	30.0	52.5	8.03	158	4	13.0
	17 30 31	146 04 96	2	0.5	28.5	43.4	8.13	184	4	6.5
F	17 26 10	146 18 46	39	15	28.0	n.d.	8.04	195	5	4.0
				1	29.0	52.1	8.16	208	5	<1.0
D	17 25 15	146 14 44	30	15	29.0	53.0	8.08	212	11	<1.0
				1	30.0	51.6	8.02	195	5	1.0
A	17 28 60	146 09 90	21	19	29.0	52.2	8.08	203	4	2.0
				1	30.0	52.1	8.13	190	5	2.5
K	17 29 54	146 07 17	15	12	29.5	52.9	8.13	200	5	2.0
				1	30.0	52.0	8.14	193	3	2.0
2	17 30 81	146 04 86	2.5	0.5	28.0	31.5	8.03	188	1	5.0
1	17 30 43	146 04 69	2	0.5	28.0	23.1	7.76	180	7	9.0
3	17 30 51	146 04 22	2	0.5	26.0	16.4	7.49	188	24	2.0
4			4	0.5	27.0	8.9	7.19	177	21	7.5
5			5	0.5	27.0	3.2	7.10	160	15	7.0

The quantity of P that could be desorbed from the suspended sediments into P-free water of similar EC averaged 19 mg kg^{-1} (17-21 mg kg^{-1}) (Table 1), suggesting that P is easily desorbed. This amount of desorbable P is two orders of magnitude higher than that desorbing from fluvial and estuarine bottom sediments in similar experiments (Pailles and Moody 1992) (Table 2). However, there was no trend indicating the orthophosphate-P concentration in the water changed with salinity (Fig. 2). The concentration remained at a level which is indicative of offshore reef waters. Therefore, there is no clear evidence that suspended sediment is contributing P to the water column through desorption processes. This conclusion is further supported by the lack of any trends in either EPC (Fig. 3) or resin-P (Table 1) of the suspended sediments with increasing salinity.

Total P figures for the suspended sediments averaged 1886 ± 570 mg kg^{-1} (1069-2679 mg kg^{-1}) (Fig. 3). Similar total P figures were obtained by Pailles et al. (1993) for fluvial bottom sediments in the tributaries of the North and South Johnstone Rivers during the dry season. This suggests that the suspended sediments in the flood plume were derived from the same parent materials as the tributary sediments found during base flow conditions. The wide range in total P observed in suspended sediments is a reflection of the wide range in total P content of the parent material in the catchment. These range from P- rich basalt (ca. 400 mg kg^{-1}) to low-P granite (ca. 600 mg kg^{-1}).

Experiments with plume sediments in sea water (3.5 % NaCl)

Desorbable P and EPC decreased when suspended sediments were shaken in 3.5 % NaCl (Table 2) suggesting that P is more tightly bound to the particles in the marine environment. This result confirms our previous observations on the behavoiur of bottom fluvial and estuarine sediments in sea water (Pailles and Moody 1992).

Table 2. EPC and desorbable-P of plume sediments, fluvial and estuarine bottom sediments in situ and in artificial seawater, I.S. = Insufficient Sample

3.5% Nacl		*In Situ*					*Event*
EPC µg/L	P des. mg/kg	EPC µg/L	P des. mg/kg	Resin-P mg/kg	EC mS/cm	Sediment #	
							CYCLONE SADIE PLUME SEDIMENT
11	9	34	21	107	3.2	5	
19	15	I.S.	I.S.	152	8.9	4	
15	12	32	20	144	16.4	3	
53	30	I.S	I.S	160	23.1		
33	17	33	17	128	31.5	2	
							CYCLONE SADIE BOTTOM SEDIMENTS
3.1	I.S.	4.00	0.04				*Fluvial*
3.7	I.S.	3.70	0.04				
3.1	I.S.	5.60	0.11				
2.5	I.S.	8.10	0.10				
I.S.	I.S.	11	0.09				*Estuarine*
I.S.	I.S.	33	0.20				
55	I.S.	30	0.09				
							MARINE TERRIGENOUS ZONE
		65-105	I.S.	76-120			*Sludge Sediments*
		127-166	I.S.	82-84			*Surficial Sediments*

P sorption parameters of suspended sediments, offshore sludges, and surficial sediments of the terrigenous zone

EPCs of the suspended sediments were lower than those of the sludges and surficial sediments of the offshore terrigenous zone (Fig. 3). This result suggests that bottom sediments and sludges are more likely to desorb P than suspended sediments. Yet, their total P contents were much lower than those of suspended sediments (Fig. 3). The physical, mineralogical and geochemical characteristics of offshore sludges and sediments clearly indicate that they are of terrestrial origin (Pailles and Moody submitted).

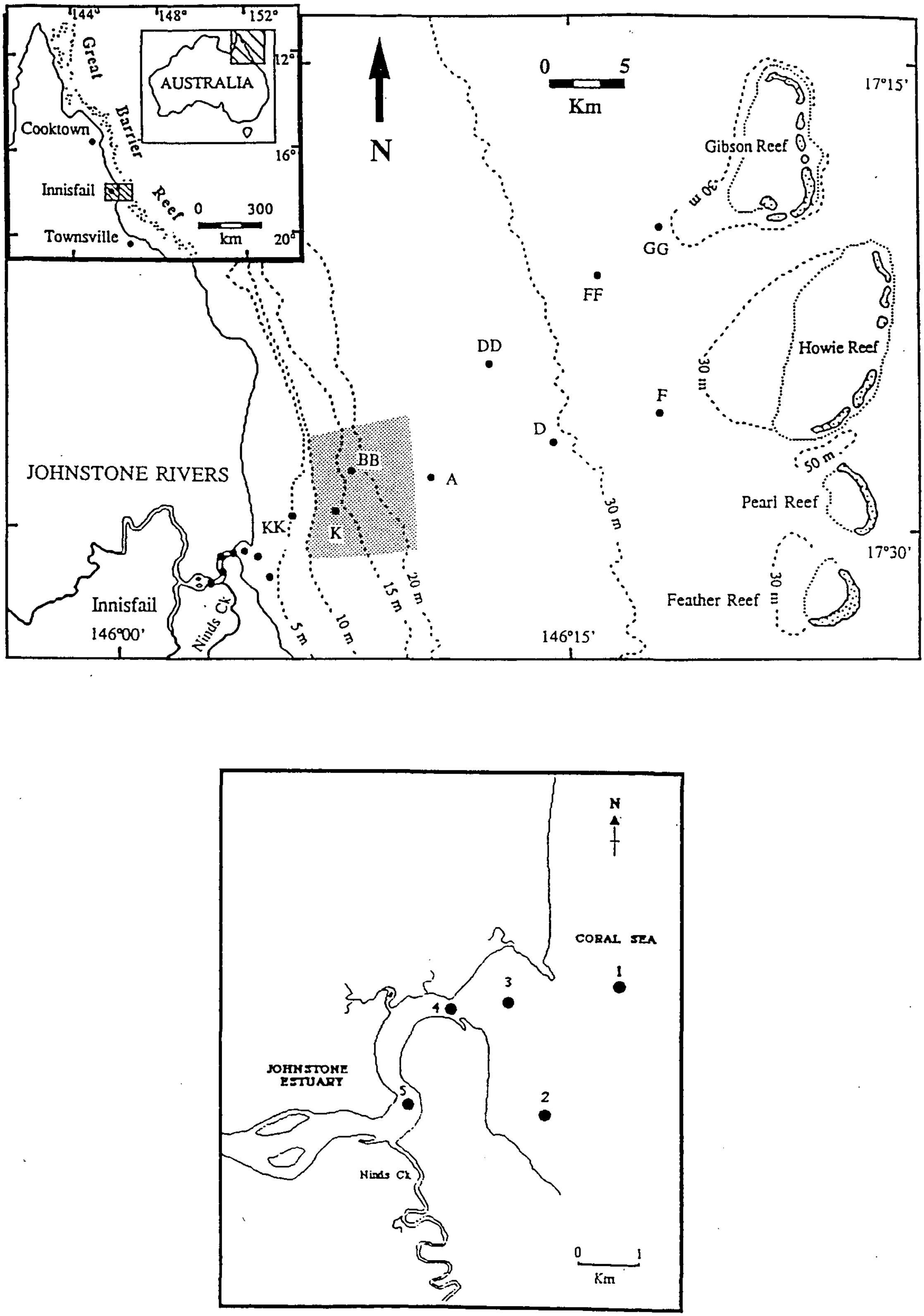

Fig. 1. Sample locations along the transects and in the estuary. The area shaded in grey represents anoxic terrigenous sediments

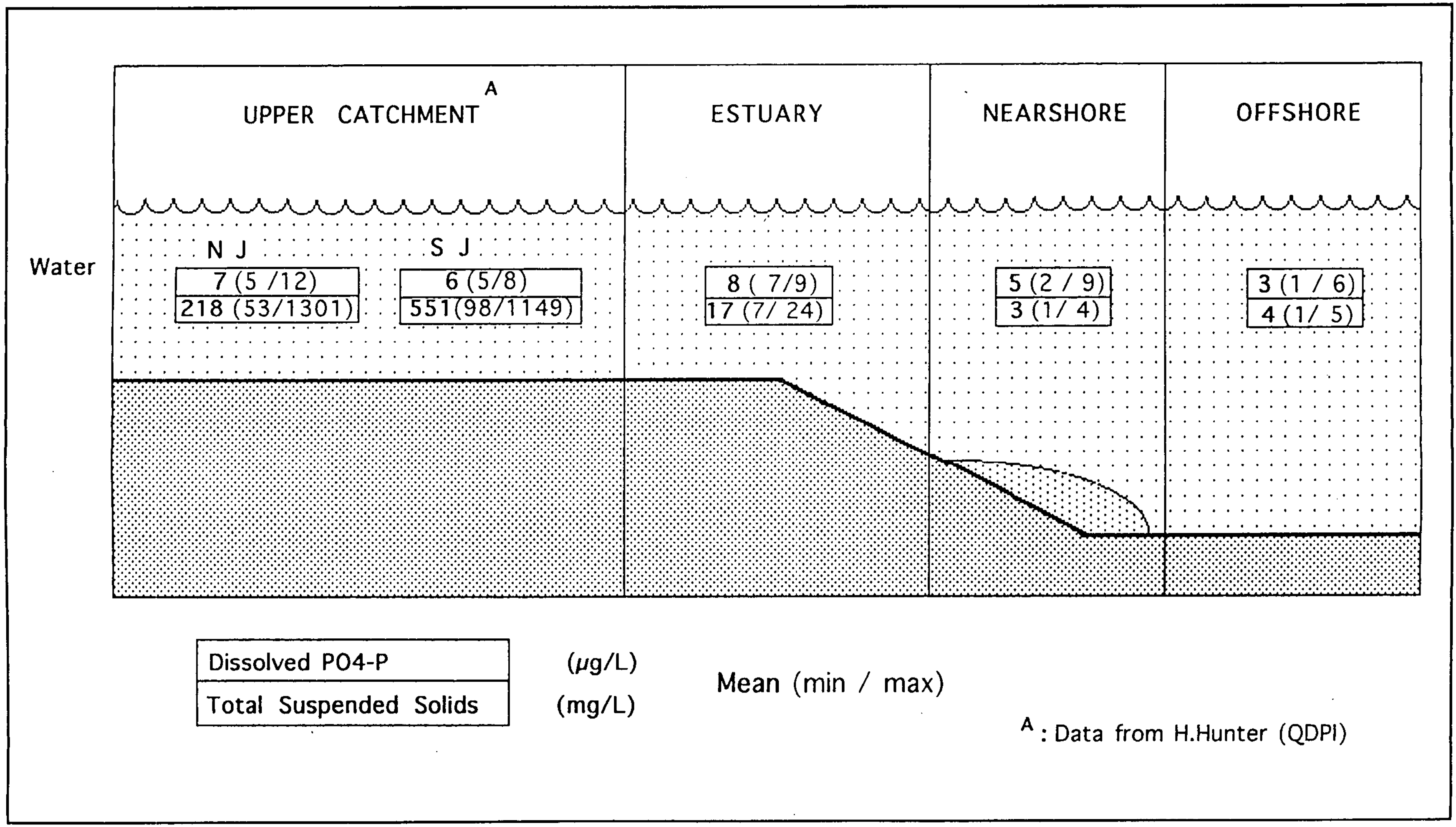

Fig. 2. Dissolved PO_4-P and total suspended solids in the waters of the Johnstone Rivers and the adjacent offshore area following cyclone Sadie

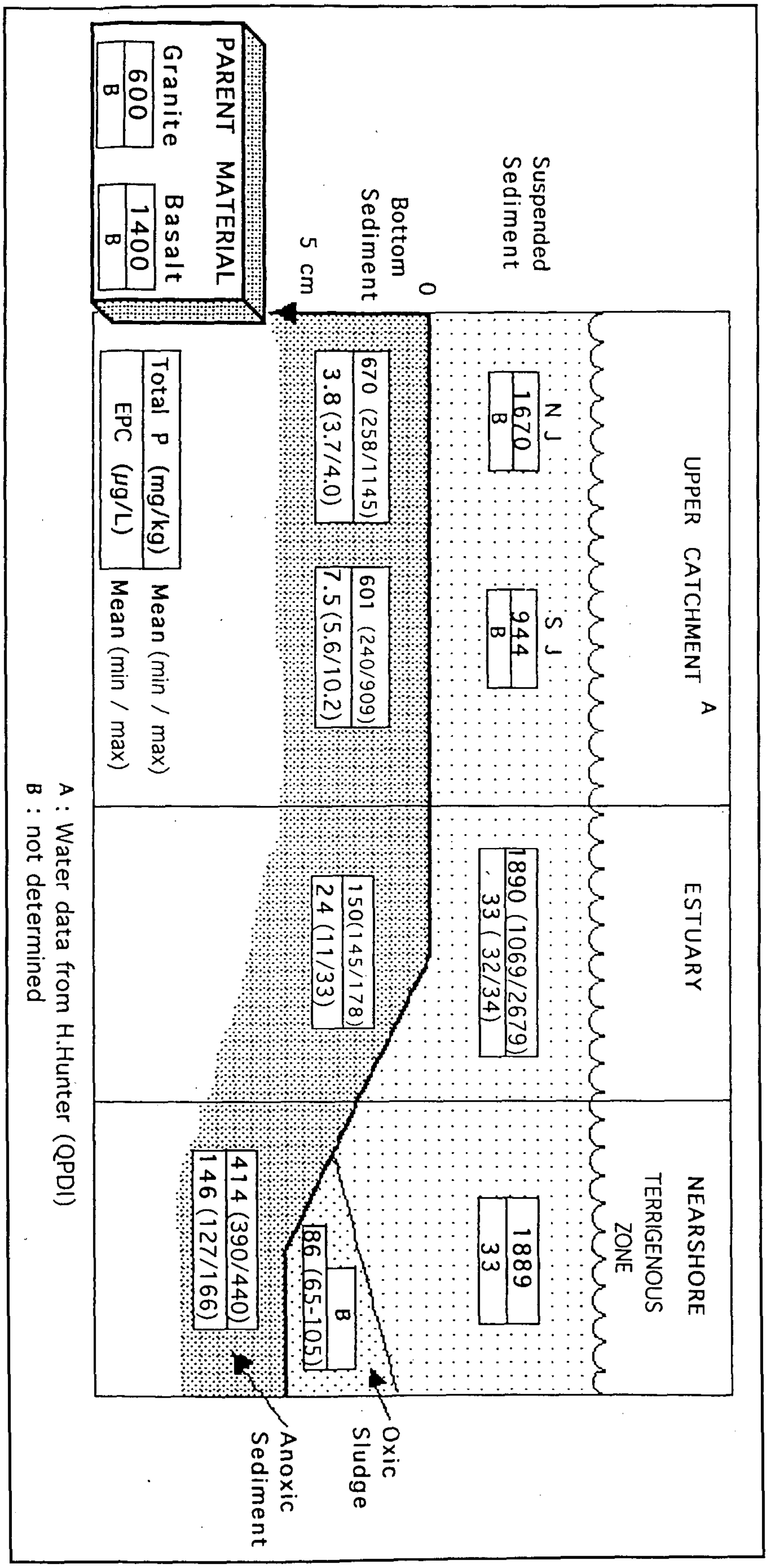

Fig. 3. Total P and EPC of suspended and bottom sediments in the Johnstone Rivers and adjacent nearshore area. Suspended sediment values correspond to cyclone Sadie whereas bottom sediment values correspond to base flow conditions

Thus assuming that the suspended sediments discharged by the rivers are eventually deposited in the nearshore area, it can be inferred that during the deposition/diagenesis process, suspended sediments lose 65 to 90% of their total P (Fig. 3). In contrast, resin-P concentrations in suspended sediments and in offshore sludges/surficial sediments are similar (Table 2), suggesting that the same amount of desorbable P is always available regardless of total P.

Data from Hunter (1996) indicate that, as a consequence of cyclone Sadie, 192 552 tonnes of sediment were discharged to the sea. Using an average total P concentration of 1890 mg kg^{-1} for suspended sediments, this sediment yield equates to 364 t of P discharged to the sea. This value is very close to the value given by Hunter (314 tonnes of P discharged during cyclone Sadie) which was arrived at using total P figures measured by Kjeldahl digestion. Nevertheless, on the assumption that suspended sediments will lose approximately 80% of their total P content, 251 to 291 tonnes of P (based on Hunter's and our data respectively) could therefore be released to the water column.

Conclusions

The results obtained from this study demonstrate that suspended sediments have a high total P content and that they are of the same origin as fluvial bottom sediments. Desorption experiment results confirm that increasing salinity does not promote the desorption of P from the suspended sediments. It is rather likely that the development of anoxic conditions (caused by the presence of significant amounts of organic C and a high clay content) in offshore surficial bottom sediments, and/or the presence of sulphates, would favour the release of P into solution (Caraco et al. 1989). This scenario would tend to support the findings of Bell (1991) that the release of P occurs after sediment re-suspension during major storms.

The results of this work highlight the need to investigate (a) if P is released from settled suspended sediments undergoing early diagenesis/reduction, (b) the factors governing desorption (eg. pH, Eh, salinity and sulphate content) and (c) the amounts of P released and the rate of release from sediments undergoing reduction.

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The effects of cyclone Sadie on coral communities of nearshore reefs in the central Great Barrier Reef

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Abstract

Freshwater, sediments and nutrients in flood plumes from Queensland rivers are thought to exert a major influence on the structure and dynamics of benthic populations and communities on nearshore reefs on the Great Barrier Reef. Bleaching of corals is a striking indicator of stress, and a logical measure of the geographic extent and depth of influence of flood plumes on coral reef communities. Surveys of three reefs within the influence of a coalesced flood plume from several creeks and rivers and associated with cyclone Sadie (January 1994) indicated a major short-term (< 1 month) response. At Pandora Reef, closest to one of the plume's sources (ca. 5 km), there was severe bleaching across a wide range of coral taxa throughout the full 10 m depth of the reef slope. At Orpheus Island and Brook Islands, both around 20 km from the river mouths, the bleaching was more limited, both in taxonomic diversity of species affected, and in depth range. Pandora Reef was resurveyed eight weeks after exposure to the plume. There was a high rate of recovery across most coral taxa, especially the scleractinian genera Acropora, Montipora and Porites and families Faviidae and Mussidae, which dominate hard coral cover. However there were significant losses (injury and death) in some less abundant and more ephemeral populations of scleractinian hard corals (especially families Pocilloporidae; Agariciidae), and the genus - Millepora (order Hydrozoa). To establish the extent, if any, of cause and effect relationships between river flows and bleaching, there is a need to link a variety of physiological thresholds with physical models and data which hindcast or predict the exceedance of such thresholds at specific reefs.

Introduction

Nearshore reefs of the Great Barrier Reef (GBR) have developed in a physico-chemical regime influenced by the adjacent mainland environment. These reefs are located in relatively shallow waters (< 15 m depth), which are likely to be more affected by heating of the land mass and related diurnal temperature fluctuations than waters further offshore. These waters also exhibit marked seasonal changes in salinity and in levels of suspended sediments and nutrients in relation to terrigenous inputs from coastal streams and rivers (Furnas and Mitchell 1986). With increasing agricultural, industrial and urban development of the north Queensland coast over the past 50 years, there has been increasing concern for the potential degradation of nearshore reefs from human-induced changes to the adjacent coastline (Bell and Tomascik 1993; CRC 1994). Apparent degradation of reef flat coral communities on some nearshore reefs has recently been reported (Wachenfeld in press).

In this paper we describe an intense, localised coral bleaching event that occurred on several nearshore reefs of the central GBR in late summer 1994. Bleaching, the expulsion of endo-symbiotic micro-algae (zooxanthellae) and/or photosynthetic pigments by corals and other reef organisms, results in a whitened appearance of the animal. Bleaching occurs in response to physiological stress, initiated by changes in a variety of environmental parameters, including fluctuations in temperature, ultraviolet light and salinity (see Glynn 1993 for review).

The bleaching event documented herein followed the flooding of coastal rivers after the degeneration of tropical cyclone Sadie into an intense rain depression over the north Queensland coast on 31 January 1994 (Fig. 1). The depression delivered over 500 mm of rain to the catchment of the Herbert River and adjacent streams (Fig. 2), causing a flood plume that extended approximately 20 km offshore into the GBR tract on 2 February 1994 (Fig. 1). Several nearshore reefs were covered by the plume, including Pandora Reef, and reefs fringing the Brook and Palm Island groups. Further heavy rain occurred some two weeks following the cyclone, particularly in the Ingham area (Fig. 2), causing a second flood of smaller magnitude than that associated with cyclone Sadie.

In common with many bleaching events from other coral reef regions (Glynn 1991, 1993; Williams and Bunkley-Williams 1990; Goreau 1992), this bleaching event followed a period of high temperatures of approximately 2 months duration (Fig. 3). Maximum air temperatures for Townsville in January 1994 reached 46°C and there were three periods when temperatures attained 35°C. Sea surface temperatures, although considerably lower than the air temperatures, were > 30°C for most of January 1994 (Orpheus Isand, Fig. 3). Bleaching occurred at the time of the high temperatures on several other near-shore reefs, particularly those fringing Magnetic Island in Cleveland Bay, where sea surface temperatures were > 1°C above normal (R. Berkelmans; B. Stobbard pers. comm.). However, benthic surveys made prior to the flood on Pandora Reef (15/12/1993 AIMS Monitoring team; 29/1/1994 Laurence McCook) and Brook Island Reef (10/1/1994, Lyndon Devantier) found no evidence of bleaching of shallow water corals.

Methods

Coral communities of three near-shore reefs were surveyed in February 1994 for evidence of impacts associated with cyclone Sadie. The reefs were Pandora Reef, Iris Point Reef (Orpheus Island) and Brook Islands Reef. Locations of the study sites were recorded with a portable GPS unit, using the WGS 84 map datum. Locations and dates of survey on the three reefs are listed in Table 1.

Inventories

Species lists of corals were recorded during meandering SCUBA and/or snorkel swims of approximately 100m length at depths of 0 to 3 m, 4 to 7 m and 8 to 12 m below approximate mean low water (m.l.w) level. For each species, the relative abundances of unaffected, partially bleached and totally bleached colonies were estimated subjectively to the nearest 20 %. On Iris Point and Pandora Reefs, the coral communities were filmed using a Sony Hi-8 Video camera from about 50 cm above the substrate during the swims, producing video profiles covering about 30-50 cm width of reef substrate (Carleton and Done 1995). The videos were inspected for additional species not previously recorded during the swims. On four partially-bleached massive corals, the perimeter of bleached tissue was filmed and marked with stainless steel nails.

Video transects

On Pandora Reef, video belt-transects of 50 m length were filmed at three depths (1 - 3 m, 4 - 6 m and 9 - 11 m below approximate m.l.w. level) at four sites around the reef perimeter (Fig. 1). The sites were selected haphazardly within areas known to support the range of major coral community types present (Done 1982; Johnson et al. 1985; Done 1986). Transects were marked with a glass fibre metric tape measure laid along the depth contours. The starting point of each transect was marked with a buoy. The transects were filmed from approximately 50 cm above the substratum, providing a video band-width of 30 to 50 cm (Carleton and Done 1995; Christie and Neale in press). Each transect took about 4 minutes to film.

The Pandora Reef sites were resurveyed in April 1994, some six weeks after the initial surveys (Table 1). The transects in the second survey were located near the buoyed positions, in the same depth ranges and community types, but did not follow the precise path of the original transects.

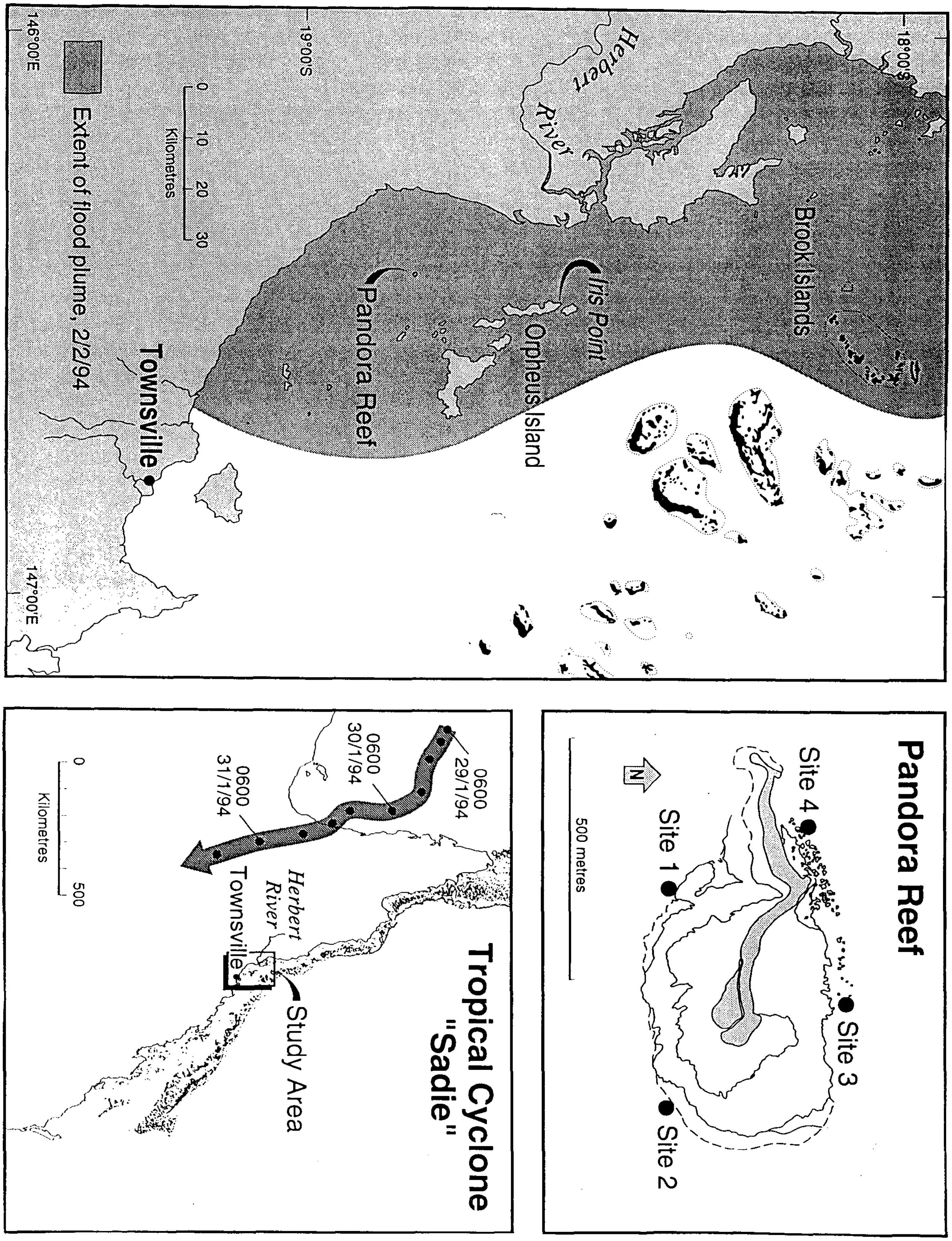

Fig 1. Location map. The track of cyclone Sadie, extent of the flood plume (J. Brodie pers. comm.), the study reefs - Pandora, Iris Point and Brook Is. Reefs, and sites on Pandora Reef are indicated

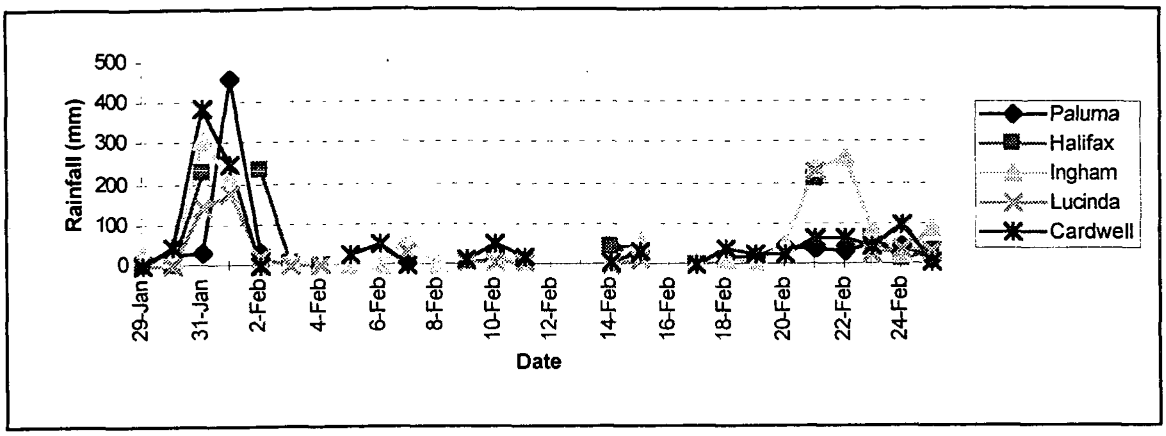

Fig. 2. Rainfall records for stations at Paluma, Halifax, Ingham, Lucinda and Cardwell in each 24 hr period from 9am 27th January to 9am 26th February 1994 (details courtesy of the Bureau of Meteorology - Queensland Regional Office, Townsville). Rainfall from the 29th January to the 4th February was from cyclone Sadie. Rainfall from the 19th to 25th February was associated with the monsoonal trough

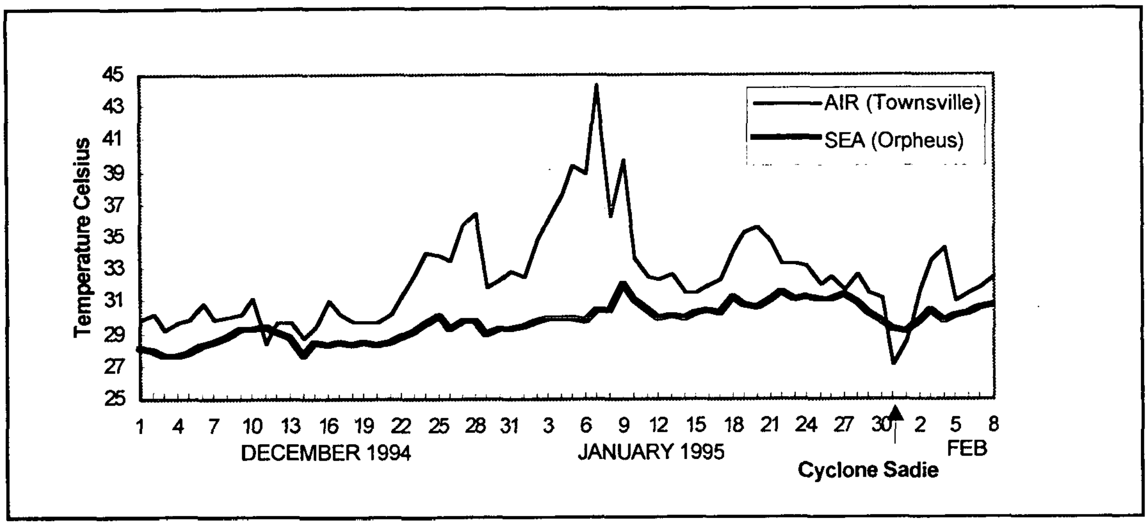

Fig 3. Air and sea surface temperatures at Townsville and Orpheus Island during December and January 1994. Air temperatures courtesy of the Bureau of Meteorology, sea temperatures courtesy of R. Berkelmans, GBRMPA

Table 1. Locations and dates of survey of study sites on near-shore reefs of the central GBR

Reef	Date	Site	GPS location		Survey type	
			Latitude (S)	Longitude (E)	Inventory	Video
Brook Is.	10/2/94	1	18°08.880'	146°16.860'	x	
		2	18°08.975'	146°17.000'		x
Iris Point	25/2/94	1	18°34.115'	146°29.411'	x	x
Pandora	26/2/94	1	18°48.919'	146°25.758'	x	x
	12/4/94	2	18°48.772'	146°26.163'	x	x
		3	18°48.673'	146°25.869'	x	x
		4	18°48.840'	146°26.160'	x	x

Video analysis

The video tapes were analysed to determine the extent and severity of bleaching in the major benthic groups. A timer code was displayed on each transect from which the elapsed time was determined. From the elapsed time, the transects were subsampled at regularly spaced intervals to provide 70 stops of the video tape along the 50 m transect (Christie and Mapstone 1994). At each stop of the tape, the identity of the benthic organisms under five fixed, 'face-centred' points was recorded into a spreadsheet. Identifications were made to the following levels: hard corals - species or genus and growth-form; soft corals - genus; most macro-algae - genus; sponges, zoanthids and other benthos - order.

The 'extent' of bleaching was categorised as 'none', 'partial' or 'total' (Table 2). The 'severity' of bleaching of the tissue located under each of the 5 points on the video monitor was recorded as 'bleached' (white - no pigment visible in tissues), 'blanched' (some colour visible but not normal pigmentation), or 'normal' (normal pigmentation). Injured or recently-dead colony areas, indicated by the recent growth of algae on bleached surfaces, were also recorded. The percent cover of each taxon was determined as a proportion of the total number of points sampled ($n/ 350 \times 100$). The relative percentage of each category of bleaching among the sample points was calculated.

Table 2. Categories of bleaching used in analysis of video filmed at Iris Point and Pandora Reefs, 1994

Extent	Severity
none	normal
partial	blanched
total	bleached

Results

In February 1994, we recorded approximately 110 species (44 genera, 16 families) of hard corals, soft corals, hydrocorals and zoanthids with bleached colonies on the 3 reefs (Appendix 1). Within the Scleractinia, approximately 100 species (34 genera, 12 families) had bleached colonies. This represented over 95% of the species surveyed (Table 3).

Table 3. Numbers of taxa that had bleached colonies on three nearshore reefs of the central GBR in February 1994. The proportion of recorded species with bleached colonies is also listed

Taxon	Families	Genera	Species (bleached and blanched) Number	Proportion
Scleractinia	12	34	101	0.96
Alcyonarea		6	8	0.75
Hydrocorallia		2	3	1.0
Zoanthiidae		2	2	1.0

Only five scleractinian species and two alcyonarian species had no bleached colonies (Table 4). Of the Scleractinia, four species are common shallow water taxa, *Montipora digitata, Turbinaria mesenterina, Symphyllia recta* and *S. radians*. The fifth species, *Diploastrea heliopora* was very uncommon. In most affected taxa, different colonies had different levels of bleaching (Appendix 1). In some instances, this occurred between adjacent conspecifics (Fig. 4d - photos of adjacent colonies). Over 60% of the bleached species had some colonies that remained unbleached.

Table 4. Species not recorded as bleached in February 1994

Family	Species	Location
Scleractinia		
Acroporidae	*Montipora digitata*	Reef flat, shallow slope
Dendrophylliidae	*Turbinaria mesenterina*	Mid-slope
Mussidae	*Symphyllia recta*	Shallow slope
	S. radians	
Faviidae	*Diploastrea heliopora*	Mid-slope
Alcyonarea	*Clavularia* sp.	Shallow - mid-slope
	Briarium sp.	

The severity and extent of bleaching varied with both location and depth. At Pandora Reef, colonies of approximately 90 species of hard corals, soft corals, hydrocorals and zoanthids were severely affected. Although most severe at depths of < 5 m, bleaching had occurred to the base of the reef slope (> 10 m depth). On Brook Island Reef, further from the sources of the flood plume (Fig. 1), bleached colonies were recorded in 27 species, limited mostly to < 5 m depth. At Iris Point Reef (Orpheus Island), the level of bleaching was intermediate between Pandora and Brook Is. Reefs (53 species), to about 10m depth (Table 5).

Table 5. Numbers of species with bleached colonies at 3 depths on the three reefs in February 1994

Depth (m)	Brook Island	Iris Point	Pandora
1-3	27	41	54
4-7	5	16	55
8-12	0	13	53
Total	27	54	90

Brook Island Reef

The survey area on the leeward reef slope (Fig. 1) had a high coral cover (> 50%), high species richness (> 100 spp. of hard corals) and many large colonies (diam. > 200 cm, DeVantier and Endean 1989). Total bleaching was restricted mainly to branched colonies of the common pocilloporids (*Pocillopora damicornis, Stylophora pistillata* and *Seriatopora hystrix)*. Partial bleaching was common in *Montipora* and *Acropora* spp., and present in massive colonies in the Poritidae and Faviidae (Appendix 1). However, most massive corals and colonies of other growth-forms were unaffected. There was little evidence of any effects to other sessile taxa, apart from the partial bleaching of colonies of the zoanthid *Palythoa* sp. on the reef crest.

Iris Point Reef

The survey area had a moderate cover (10-30 %) and species richness (> 50 spp.) of hard corals. Most bleaching occurred in shallow waters (< 5 m depth), particularly on the reef flat, where most pocilloporids, acroporids, faviids, poritids and agariciids appeared either partially or totally bleached (Appendix 1).

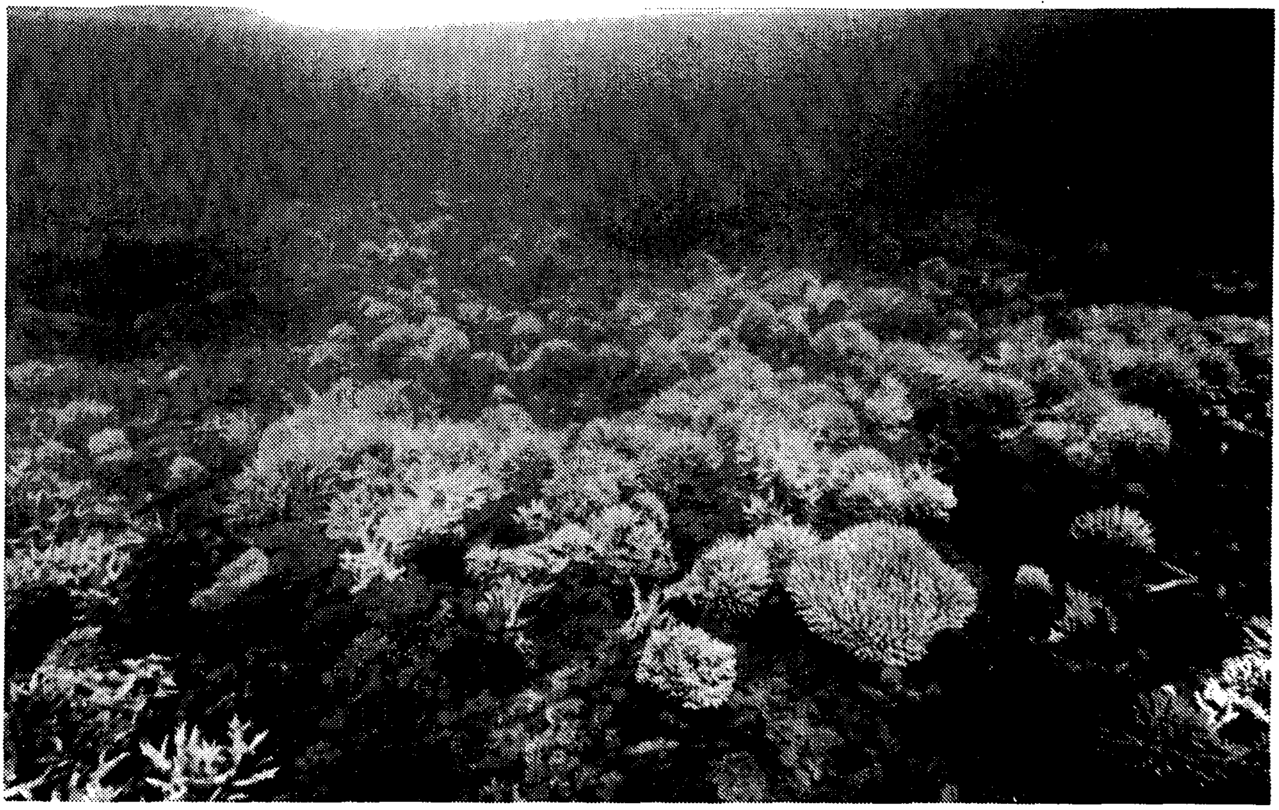

Fig. 4a. Shallow slope coral community dominated by branching corals of the genus *Acropora*. Pandora Reef, February 1994

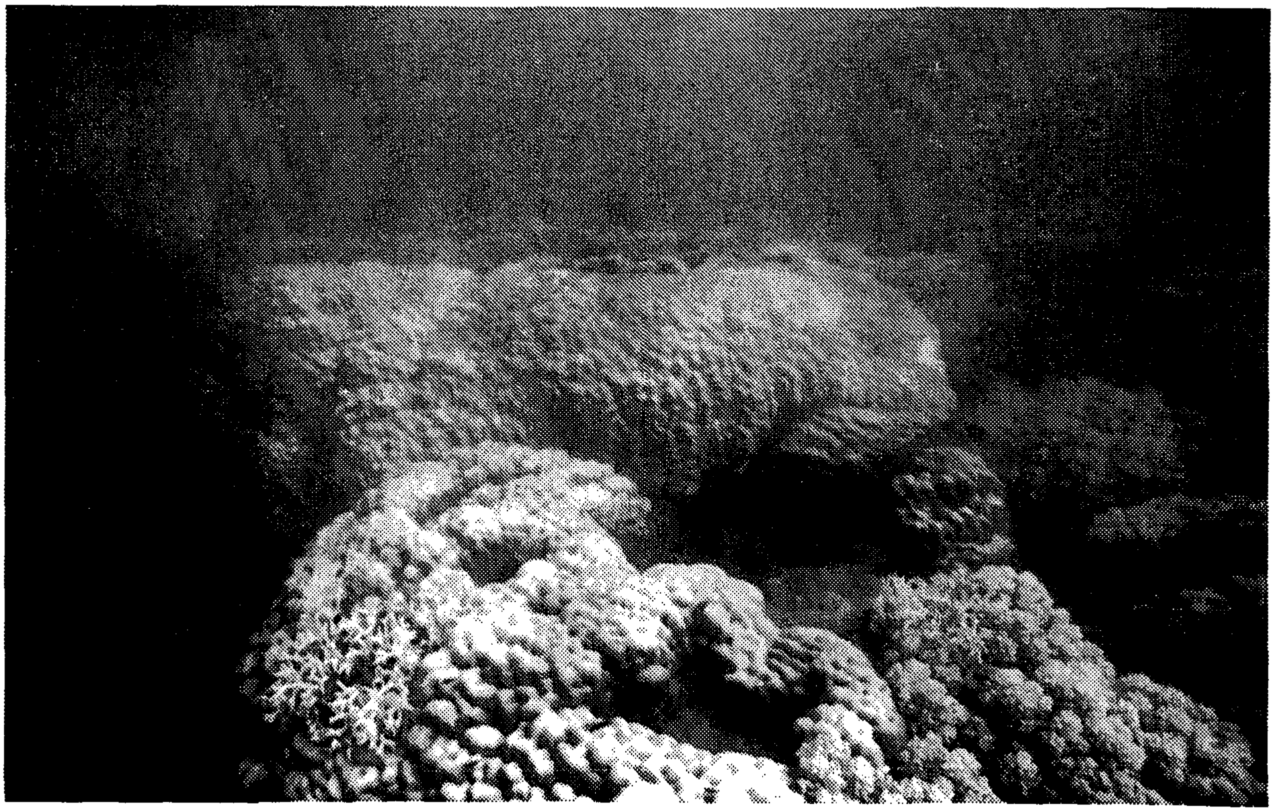

Fig. 4.b. Shallow slope coral community dominated by massive corals of the genus *Porites*. Pandora Reef, February 1994

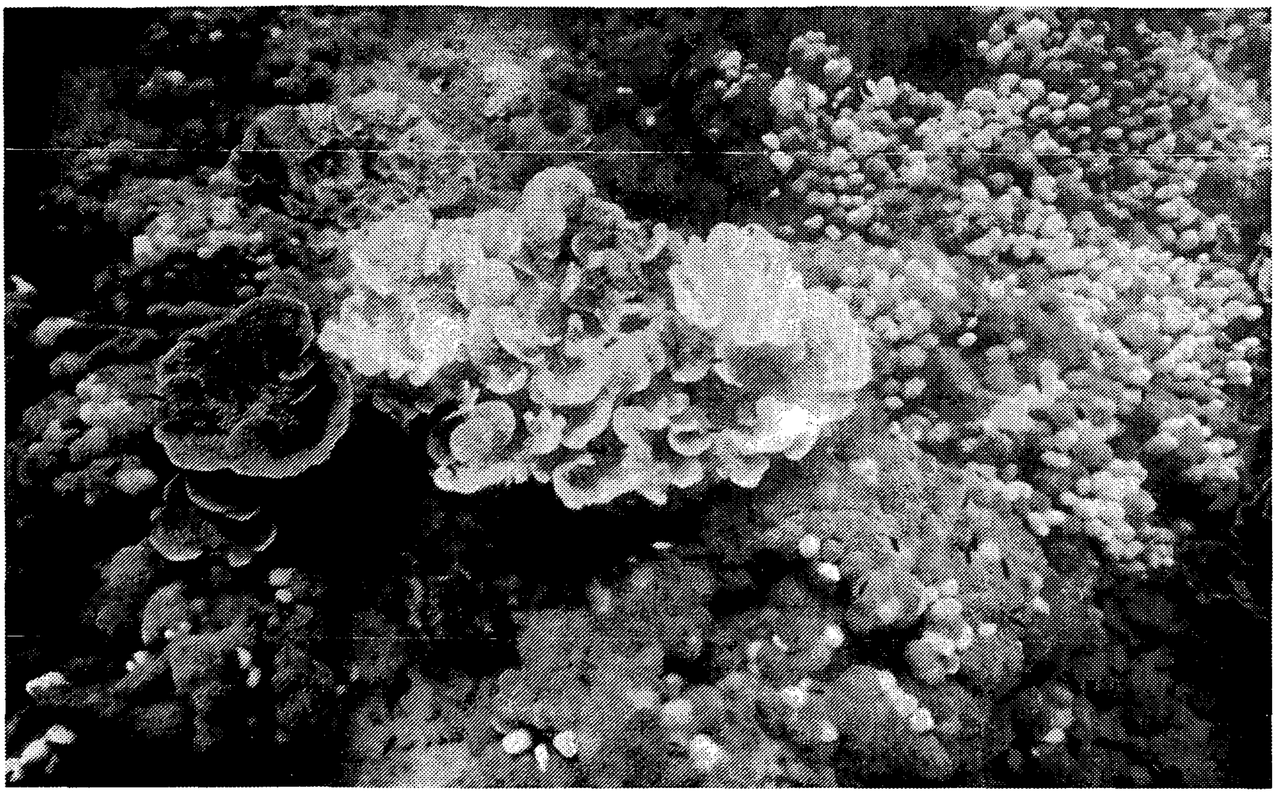

Fig. 4c. Deep slope coral community dominated by columnar and foliose corals of the genera *Goniopora* and *Echinopora*. Pandora Reef, February 1994

Fig. 4d. Mid-slope coral community showing intra- and interspecific differences in bleaching among tabular and staghorn colonies of *Acropora* and foliose colonies of *Montipora*. Pandora Reef, February 1994

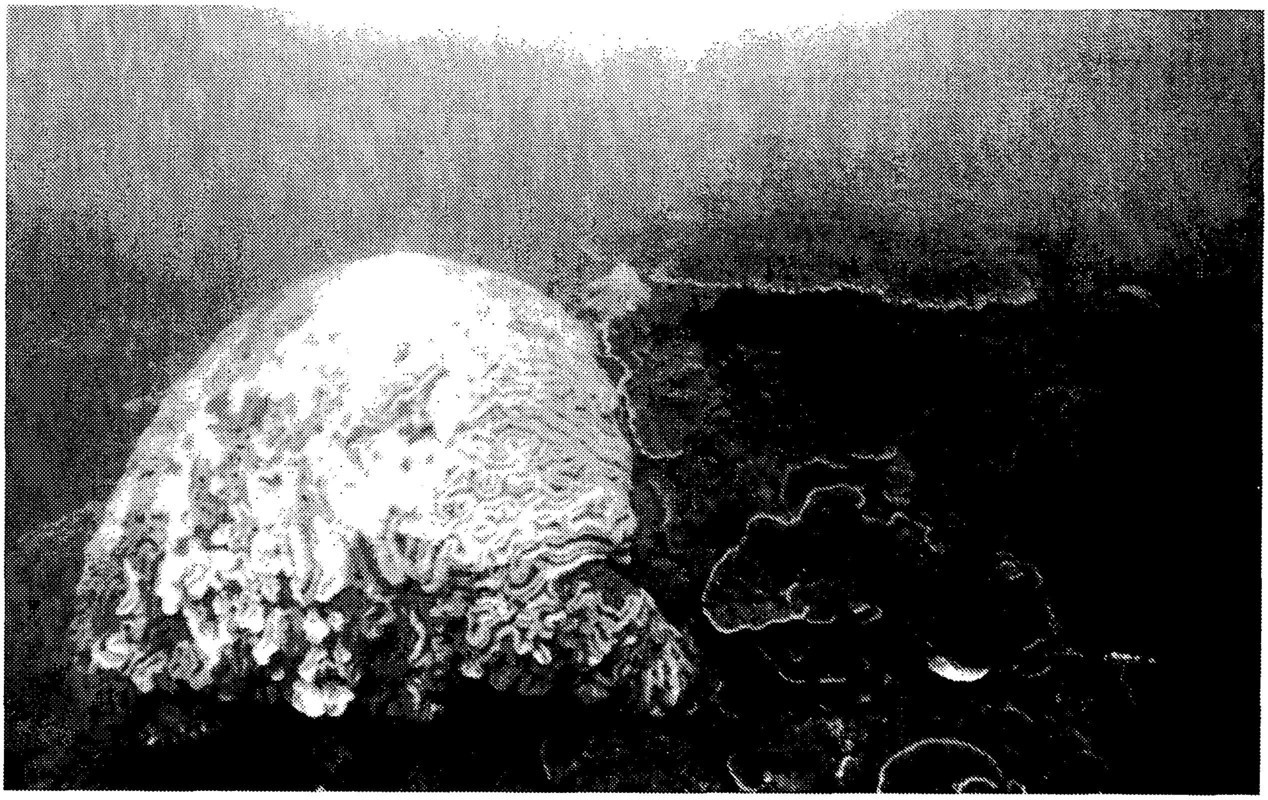

Fig. 4e. Mid-slope coral community showing bleaching of large, massive colony of *Lobophyllia hemprichii*. Pandora Reef, February 1994

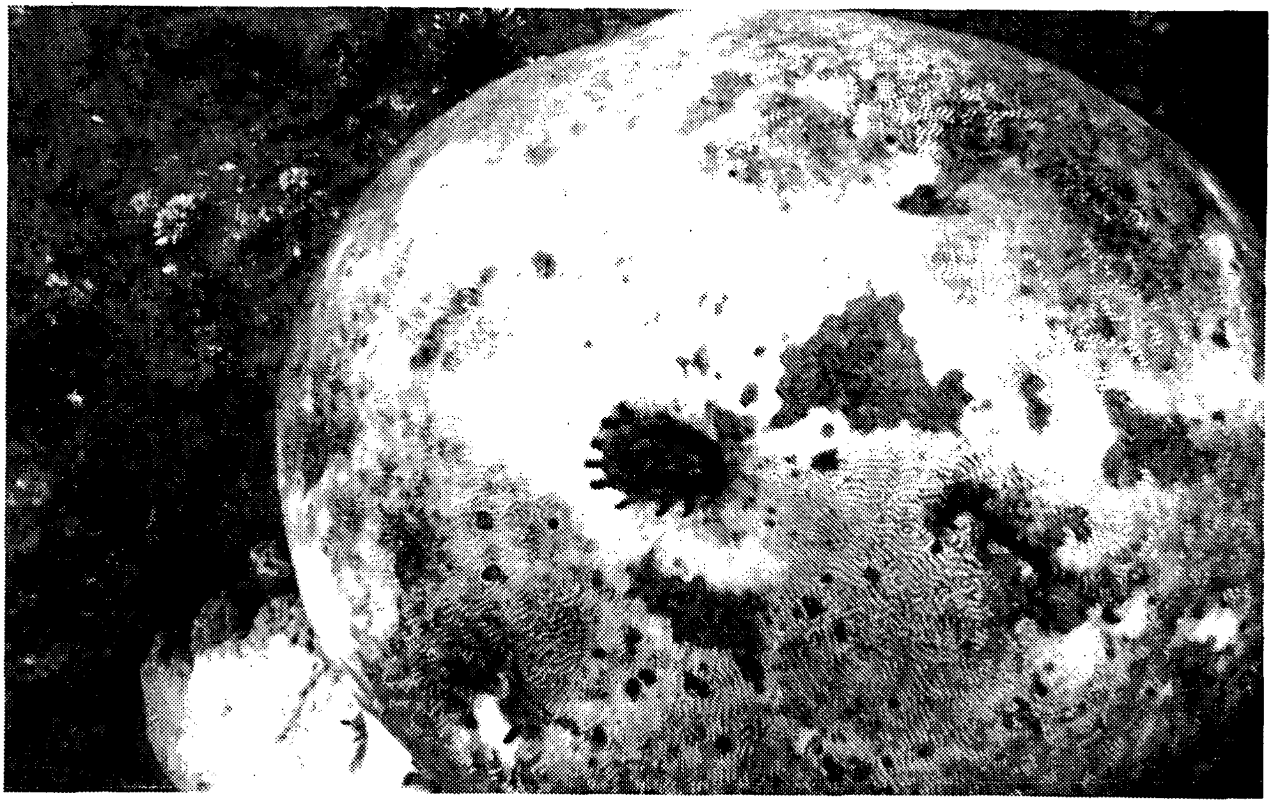

Fig. 4f. Bleached massive colony of *Platygyra daedalea* showing areas of sediment deposition and turf algae growth. Pandora Reef, February 1994

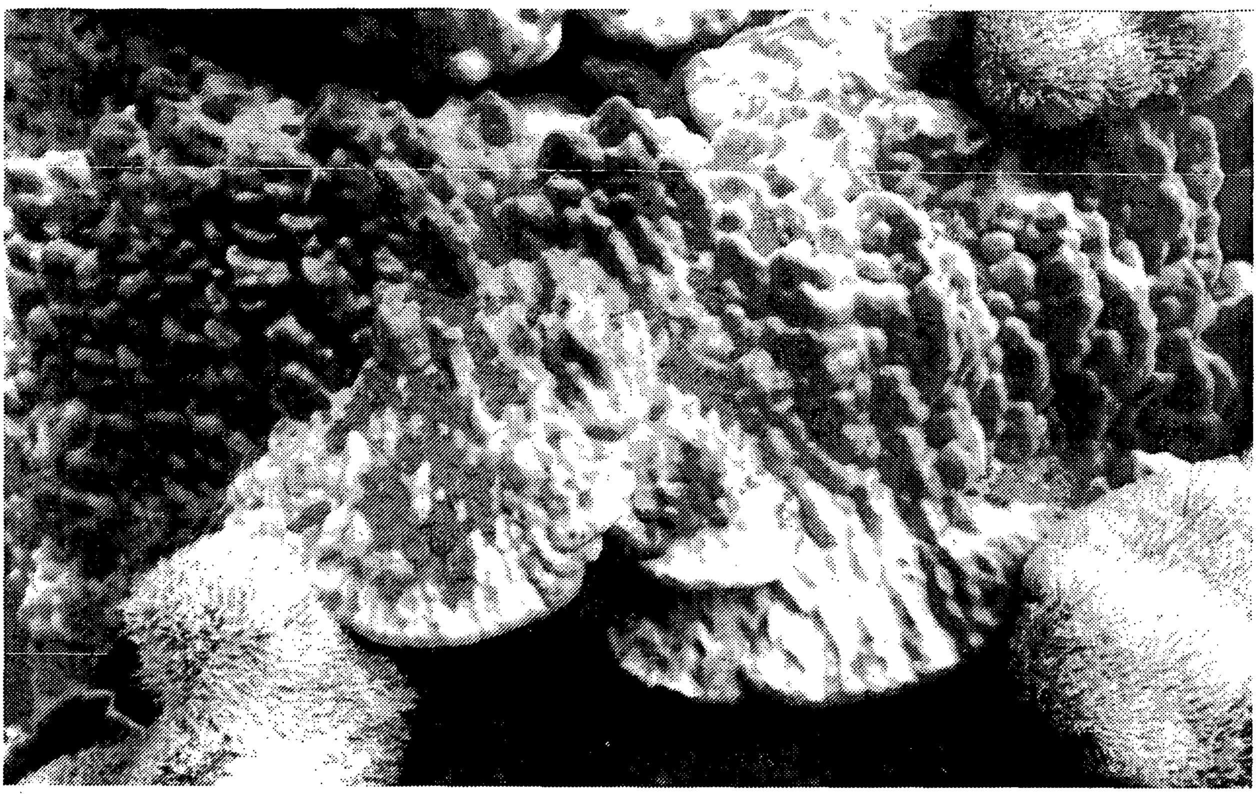

Fig. 4g. Sediment deposition on bleached massive colony of Porites. Pandora Reef, February 1994

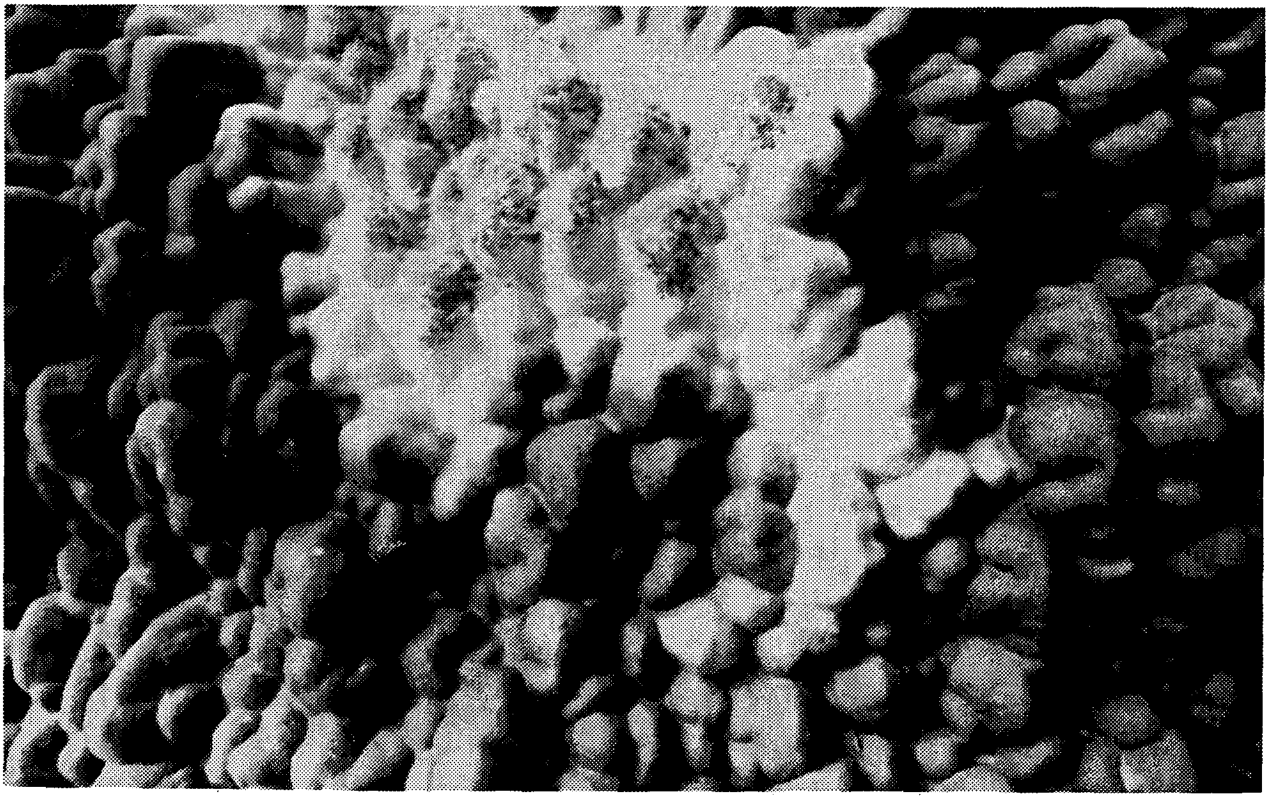

Fig. 4h. Turf algal growth on bleached surface of massive colony of *Porites*. Pandora Reef, February 1994

Pandora Reef

The survey areas (Fig. 1) had a high cover (> 50%, Table 6) and species richness (> 80 spp., Appendix 1) of hard corals, with colonies of several species attaining considerable size and age. Patterns of bleaching varied in the depth-related community types (Done 1982, 1986; Potts et al. 1985).

Table 6. Video-transect estimates of percent cover of hard and soft corals at three depths on Pandora Reef, February and April 1994. Cover is expressed as the mean (± s.d.) of four sites around the reef perimeter (Fig. 1)

Depth (m)	Hard coral		Soft coral	
	February	April	February	April
1-3	60.8 ± 15.6	61.9 ± 12.4	14.4 ± 10.9	11.5 ± 6.1
4-6	65.0 ± 9.9	62.4 ± 2.9	9.6 ± 6.7	13.4 ± 4.2
9-11	54.9 ± 22.2	65.5 ± 11.1	9.0 ± 6.6	6.0 ± 4.4

Bleaching and recovery

The shallow water communities (< 4 m depth) were composed predominantly of branching and tabular *Acropora* spp., digitate, encrusting and foliose *Montipora* spp., massive *Porites* spp. and faviids (particularly *Goniastrea* spp.), soft corals (mostly *Sinularia* and *Lobophytum* spp.) and macrophytes (mostly *Sargassum* spp.). Approximately 75% of the overall cover of hard corals, soft corals, hydrocorals and zoanthids in this community was bleached or blanched (Fig. 5). Over 80 % of the hard coral cover was bleached or blanched (Figs. 6, 7) in February 1994. By April 1994, there was substantial recovery of pigmentation to most colonies, such that about 75% of cover had regained 'normal' colour and < 10% of cover appeared bleached (Figs. 5, 6). There was less recovery of pigmentation (66%) in the family Acroporidae on the shallow slope than for hard corals overall (Figs. 6, 7).

Mid-slope communities (4-7 m depth) were composed of assemblages of massive and branching poritids (*Porites* and *Goniopora* spp.), mussids (*Lobophyllia* spp.), merulinids (*Hydnophora* spp.) and faviids (particularly *Platygyra*, *Leptoria*, *Favia* and *Favites* spp.), interspersed amongst branching acroporids and pocilloporids and foliose *Montipora*, *Pachyseris* and *Turbinaria* spp. The soft corals *Sinularia*, *Clavularia*, *Briarium* and *Sarcophyton* spp., hydrocorals *Millepora* spp. and stony octocoral *Heliopora coerulea* were also common. Over 60% of the overall cover of hard corals, soft corals, hydrocorals and zoanthids was bleached or blanched in February 1994, with approximately 50% blanched and 15% bleached (Figs. 5, 6). The bleached corals included several large massive colonies (*Porites*, *Platygyra*, *Leptoria*, and *Lobophyllia* spp.) estimated to be over a century old. Some of these colonies appeared totally bleached and had areas of sediment deposition on their upper surfaces (Figs. 4 e,f,g). By April, recovery had followed similar trends to the shallow communities (Figs. 5, 6). Acroporid colonies had restored colour more extensively (80%) than had those in shallower waters (Fig. 7).

At depths of 9 to 11 m, coral communities were comprised of large, monospecific beds of columnar-digitate *Goniopora* spp., foliose *Echinopora* spp., *Leptoseris yabei*, *Pavona cactus* and *Pachyseris* spp., with patches of fungiids and branching pocilloporids, *Acropora* and *Anacropora* spp. and the soft corals *Sinularia* spp. About 40% of coral cover in these communities was bleached or blanched in February 1994, (30% blanched, 10% bleached, [Figs. 5-7]). By April 1994, > 80% of cover had regained 'normal' colour, and < 10% was bleached.

Injury and death

By April 1994, recovery of colour in most corals was well advanced at all depths. Overall, injury and death accounted for < 1% of the total cover of hard corals at all depths. Injuries seen in April 1994 included dead patches on massive colonies of *Porites* and *Platygyra* spp. which were covered in sediment; necrosis on massive *Porites* spp.; fouling by turf algae of bleached colony surfaces of a variety of taxa, particularly the pocilloporids and branching hydrocorals *Millepora tenella*. Colonies of the branching pocilloporid taxa *Pocillopora* spp. (mostly *P. damicornis*) and *Stylophora pistillata*, branching *Acropora* spp. and the branching hydrocorals *Millepora* spp. exhibited most mortality (L. DeVantier; E. Turak pers. obs., Table 7).

Table 7. Video-transect estimates of recently-dead cover of benthic taxa during the April 1994 surveys. Cover is expressed as a relative proportion (± s.d.) of the total cover of the taxon at each depth

Taxon	Depth			
	1-3m	**4-6m**	**9-11m**	**Total**
Acropora branching	< 0.01	0.01 ± 0.01	0	< 0.01
Stylophora pistillata	0.5 ± 0.5	0.02 ± 0.02	0	0.26 ± 0.43
Pocillopora spp.	0.42 ± 0.42	0	0.08 ± 0.12	0.22 ± 0.32
Lobophyllia spp.	0	0.03 ± 0.05	0	0.03 ± 0.05
Hard coral	0.01 ± 0.01	< 0.01	< 0.01	< 0.01
Millepora tenella	0.36 ± 0.01	0.9 ± 0.1	0	0.63 ± 0.28

Discussion

There was a major localised bleaching event on nearshore reefs of the central Great Barrier Reef in the summer of 1994. Overall recovery was rapid and there was little effect on total coral cover by April 1994, some two months following the bleaching. However, for individual colonies and populations of several taxa, there was substantial injury and death.

Recovery of coral communities

Many of the bleached corals appeared in good condition during the February 1994 surveys, with polyps expanded and responsive to touch. By April, many corals, including three of the marked massive colonies, had restored pigment to much of their colony surfaces, presumably through the reproduction of remnant zooxanthellae populations surviving in unbleached or partially bleached portions of the affected colonies. Even for colonies that appear totally bleached, some zooxanthellae may remain, often within basal tissues. For colonies that have expelled all their symbiont algae, recovery is thought to be both more difficult and prolonged, as the colony would be required to capture zooxanthellae from surrounding waters (Williams and Bunkley-Williams 1990; Buddemeier and Fautin 1994).

Although recovery of colour was well advanced in many colonies of most taxa some two months following the flood, complete recovery of tissue biomass may take considerably longer. For example, biomass recovered at a much slower rate than the algal symbionts in the massive coral *Montastrea annularis* following the Caribbean bleaching event of 1987 (Fitt et al. 1993). The recovery process may be slowed considerably by injury (Meesters and Bak 1994). For injured corals, complete recovery will depend on the extent of the injury and the fate of interactions with epibiota that foul the injured surfaces (Bak and Steward van-Es 1980; DeVantier 1995; Meesters and Bak 1994). For species with colonies that were completely killed, particularly the pocilloporids, recovery of population structures will rely on new recruitment of planulae. These species are considered relatively opportunistic in comparison with most other corals (Loya 1976), being rapid colonisers following disturbances that provide space (DeVantier 1995; Done et al. 1988) and exhibiting rapid growth and early reproduction (Loya 1976). These characteristics are facilitated by the reproductive mode, internal

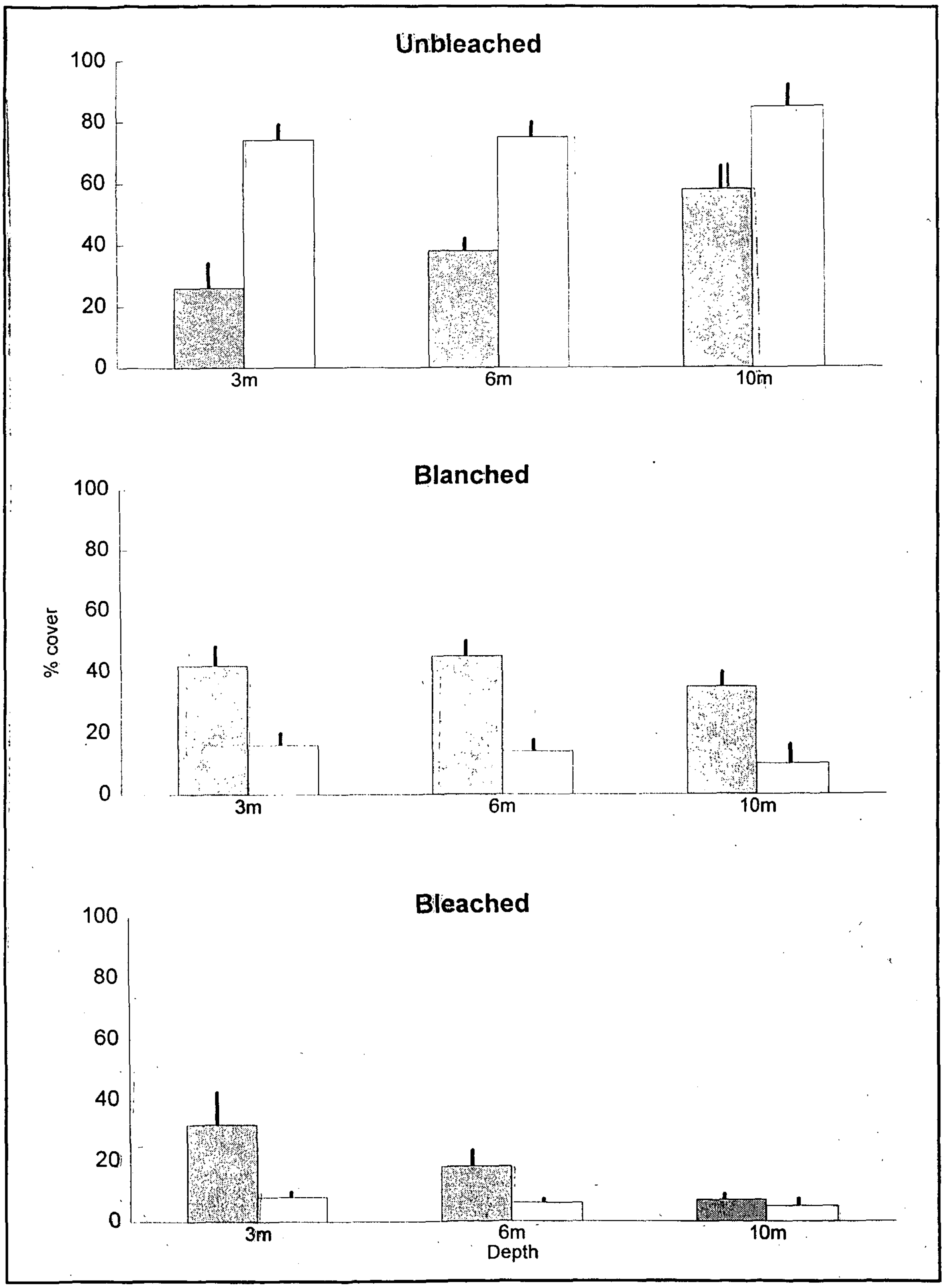

Fig. 5. Mean percent cover of hard corals, octocorals, hydrocorals that was unbleached, blanched or bleached at three depths at four sites around Pandora reef in February (stippled) and April (clear) 1994. Error bars indicate standard errors

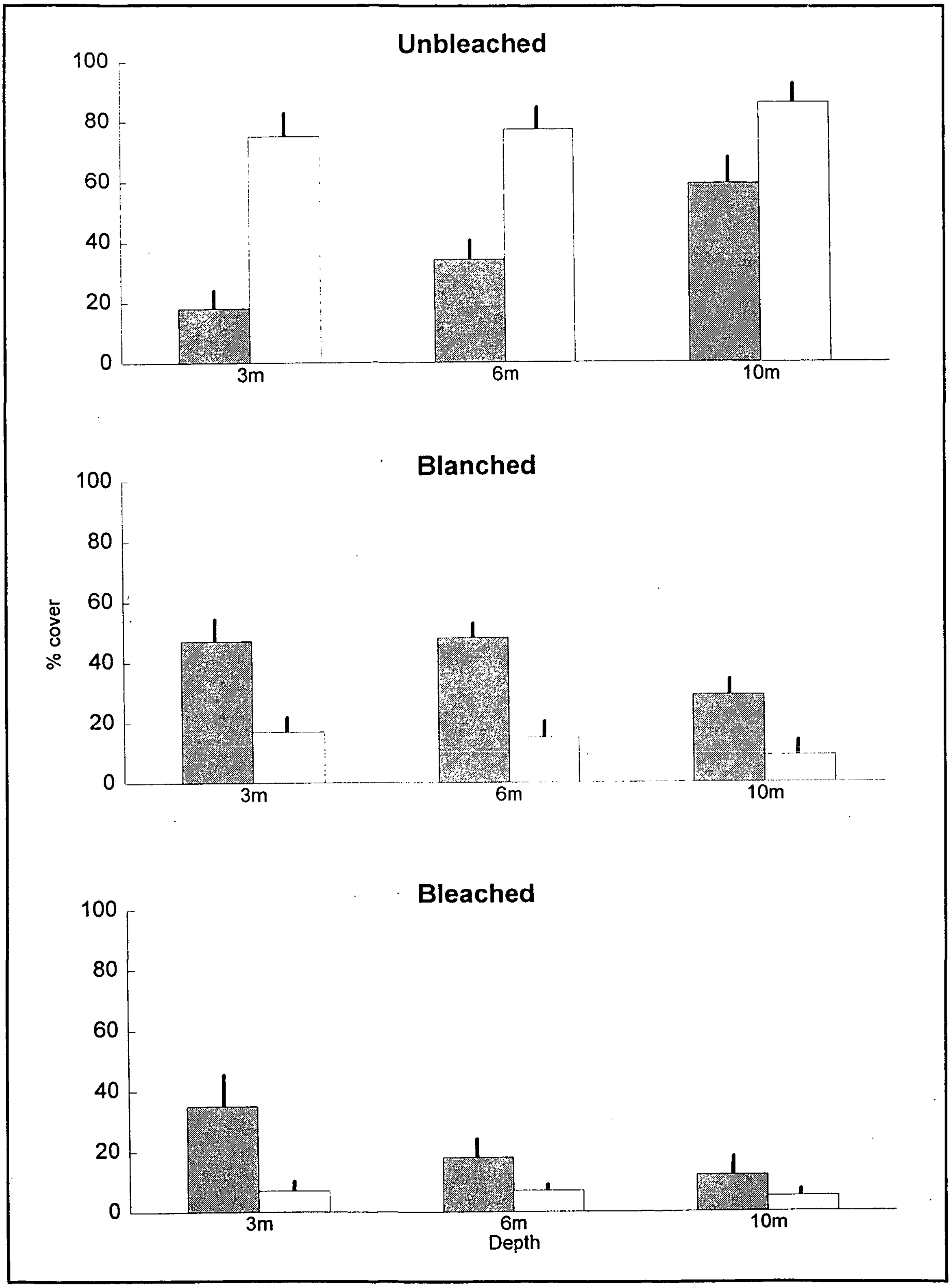

Fig. 6. Mean percent cover of hard corals that was unbleached, blanched or bleached at three depths at four sites around Pandora reef in February (stippled) and April (clear) 1994. Error bars indicate standard errors

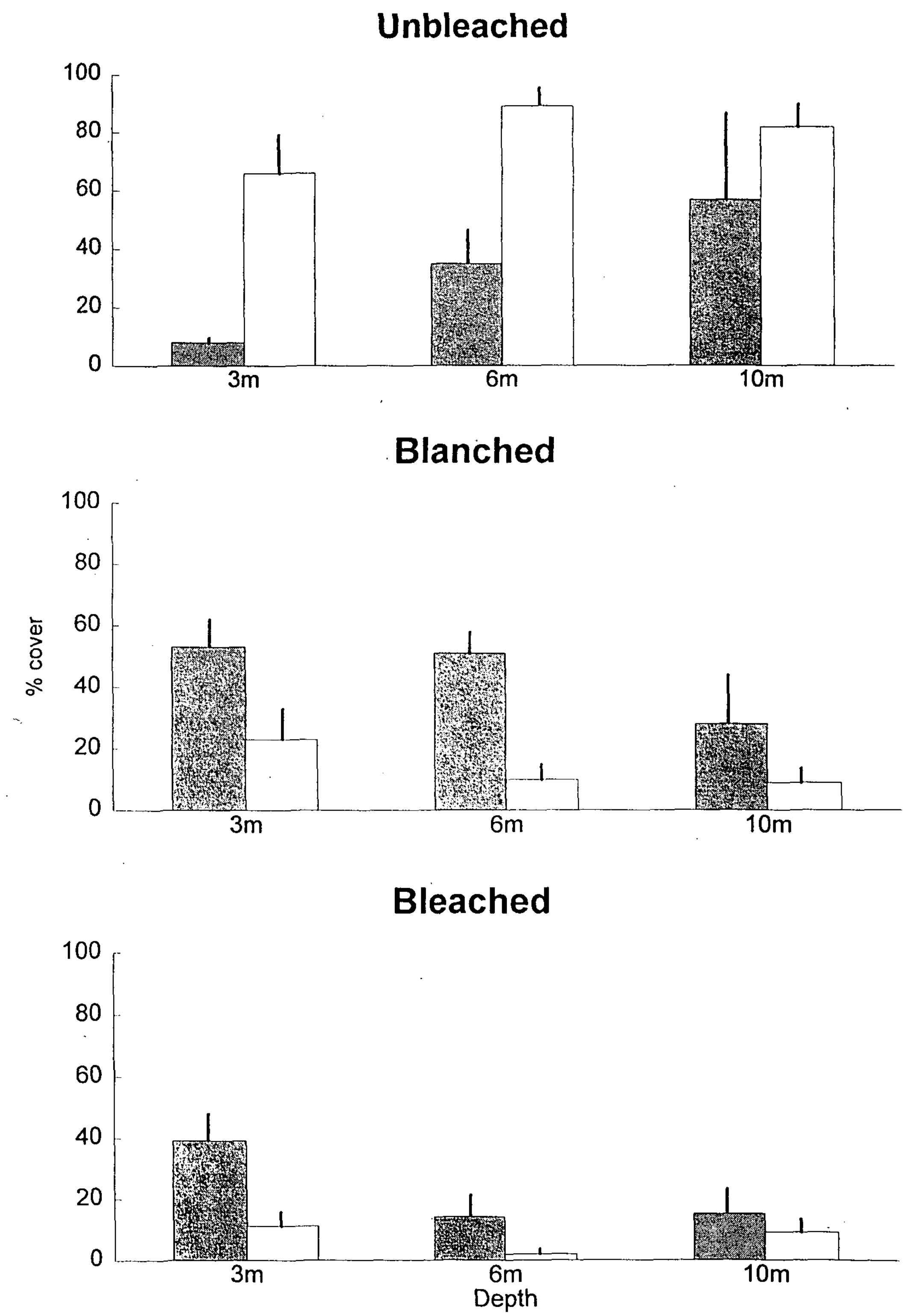

Fig. 7. Mean percent cover of Acroporidae that was unbleached, blanched or bleached at three depths at four sites around Pandora reef in February (stippled) and April (clear) 1994. Error bars indicate standard errors

brooding of planula larvae which are capable of rapid settlement following release (Richmond 1988; Stoddart 1986), rather than broadcast spawning (Harrison and Wallace 1990).

That different colonies of the same species in the same biotopes exhibited different degrees of bleaching, partial or total mortality indicate intra-specific differences in susceptibility to the environmental fluctuations. Such differences may be related to different 'types' of zooxanthellae (Rowan and Powers 1991; Buddemeier and Fautin 1994), and/or phenotypic or genotypic differences in the coral population structures. *Pocillopora damicornis*, one of the species most affected, can produce asexual planulae of identical genotype (clone-mates) to the parent (Stoddart 1986). The inter-colonial differences in mortality in this species may be linked to inter-clonal genotypic differences in susceptibility.

The intra- and inter-specific differences in bleaching and mortality suggest that such events can play a major role in the structuring of nearshore reef communities. If such mortality is genotypically-linked, these disturbances act as agents of natural selection on these nearshore reefs.

Possible causes of the bleaching

Bleaching is a response to stress. In the present case, we consider the stress to have been induced primarily by changes in salinity and temperature. Associated changes in water quality (turbidity, dissolved nutrients and other parameters) may also have had some effect, either separately or in synergism (Coles and Jokiel 1978).

Hyposalinity: The intense bleaching at Pandora Reef followed closely after the flooding of inshore waters during the rain depression from cyclone Sadie. By contrast, flooding of similar magnitude following passage of cyclone Winifred (1/2/1986) caused no bleaching on Pandora Reef (Done et al. 1986). Floods of a similar level to that associated with cyclone Sadie have occurred on a decadal time scale in the region over the past century (Fig. 8). Moreover, there were much greater floods from the Herbert River in 1927, 1967 and 1978 (see also Lourensz 1981 and Done 1992 for cyclone frequency).

There is no simple correlation between recorded river-flows and bleaching. Temperature and exposure to UV radiation have also been implicated. The main known differences between the 1986 and 1994 cyclone events were lower temperatures preceding cyclone Winifred (Fig. 9) and strong south to south-easterly winds associated with cyclone Winifred (Table 7). The cyclonic winds are likely to have caused the flood plume initially to move northward along the coastline away from Pandora Reef, rather than spreading across the Great Barrier Reef lagoon. Wolanski (1982) has demonstrated that plume movement in this region is generally northward. While a northerly boundary current carried the Sadie plume mainly to the north of the flooding rivers, north-easterly winds caused some floodwaters to extend seawards of Pandora Reef and the northern Palm Islands (Fig. 1).

The importance of wind velocity in influencing the spread of flood plumes has been known for many years. Following the Mackay cyclone of 1918, for example, flood waters from the Don River (Bowen) passed over the reef at Stone Island, the result of northerly winds following passage of the storm (Hedley 1925). During the cyclone, "... so heavy a fall of rain happened that a thick layer of fresh water floated far out on the surface of the sea. When the low tide fell, this surface water sank till the whole reef was immersed in it ... as deep as 10 feet below mean tide level" (Hedley 1925). A second cyclone several days later caused additional flooding, with a total of > 900 mm of rain having fallen in 8 days. "On the surface of the sea rain water a yard in depth had fallen; in addition to this the swollen rivers poured out a huge volume" (Hedley loc. cit.). The deluge coincided with spring tides produced by the full moon, exposing the reef to the full effects of the fresh-water lens. The effects apparently extended some 30 km from the mainland (see also Goodbody 1961; Goreau 1964).

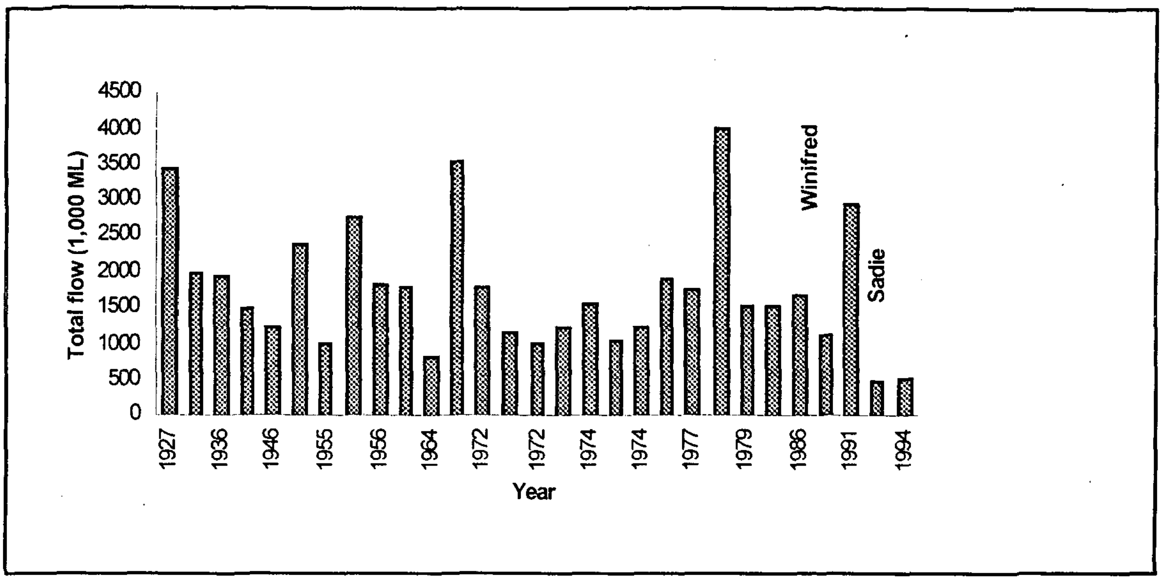

Fig. 8. Discrete periods (5-10 days) of major river flow from the Herbert River, Ingham, 1915-1994. Data courtesy Queensland Bureau of Water Resources

A similar effect of floodwaters was reported for the Keppel Island fringing reefs following cyclone Joy in 1990-91 (van Woesik 1991). Large areas of shallow corals, especially pocilloporids and acroporids, bleached and died. Effects were limited to the upper 2 m of reef slope, where salinity had been reduced to < 10 ppt. Salinities were not recorded in the cyclone Sadie flood plume. However, it is likely that salinity was reduced substantially. For example, the plume associated with cyclone Winifred had salinities inshore of <10 ppt (< 1/3 normal levels). Coles and Jokiel (1992) reported that a reduction in salinity to < 20 ppt for > 1 day produced bleaching in experimental studies.

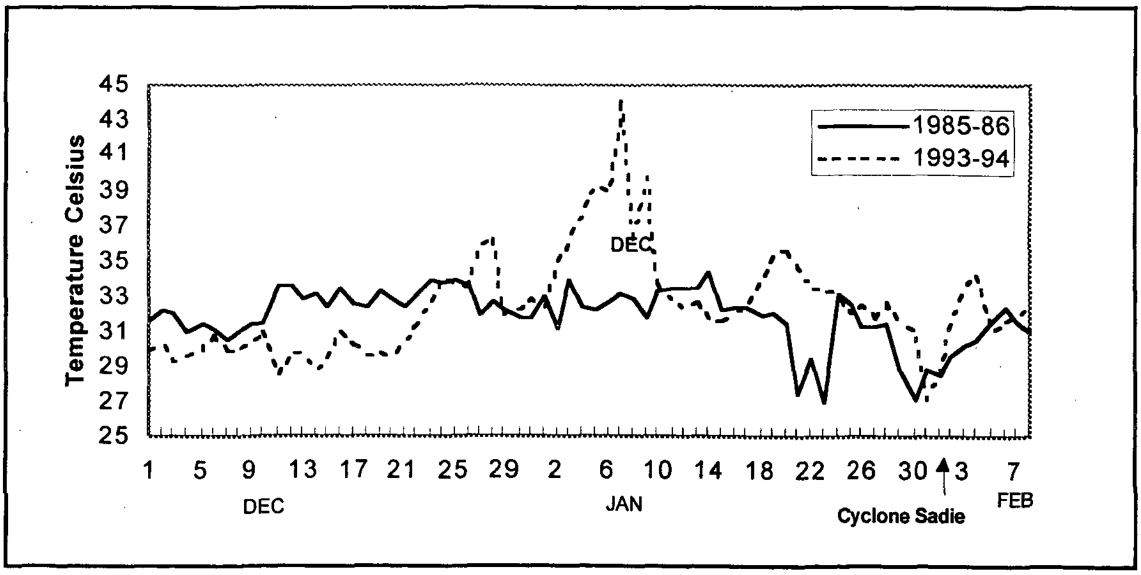

Fig 9. Maximum air temperatures at Townsville for the periods December - February 1985-6 and 1993-4 (courtesy of the Bureau of Meteorology)

Hyperthermia: In the present case, bleaching occurred to the base of the reef slope, implicating other causative factors in addition to a hyposaline surface lens of floodwaters. Bleaching on reefs fringing Magnetic Island in Cleveland Bay occurred during the period of high temperatures in January 1994, preceding the flood (L. DeVantier pers. obs.; R. Berkelmans pers. comm.). These high temperatures are likely to have stressed corals on the other nearshore reefs, potentially increasing their susceptibility to the following events. The synergistic effects of hyposaline floodwaters from cyclone Sadie, and associated rapid cooling of the sea surface, were probable triggers of the bleaching. A temperature decrease of approximately 2°C in sea surface temperature was recorded at Orpheus Island on 2 February 1994 (Fig. 3).

Water quality: Additional to the temperature fluctuations and reduction in salinity are increases in sediments, turbidity and dissolved nutrient concentrations (Table 8, and see Furnas and Mitchell 1986). The use of fertilisers on river catchments adjacent to the Great Barrier Reef has increased ten fold in the past four decades, and discharge of sediments and nutrients by rivers, the major source of these inputs to the Great Barrier Reef, has increased four fold in the past century (Moss et al.. 1992; Brodie 1995). Nutrient inputs can enhance phytoplankton growth. For example, the release of large amounts of nutrients into shelf waters following cyclone Winifred, from mixing and runoff, produced a phytoplankton bloom with chlorophyll concentrations 5-10 times the normal levels (Furnas and Mitchell 1986). Primary production in these waters was also 5-10 times normal. Enhanced production can affect dissolved oxygen concentrations in the surrounding water column, to the detriment of benthic communities. Thus there may have been a combination of environmental factors, some of which acted in synergy, contributing to the effects of cyclone Sadie on the nearshore reefs.

Table 8. Comparison of the effects of cyclones Winifred and Sadie on the central GBR (most data are from GBRMPA cyclone Winifred Workshop Proceedings, Dutton 1986)

Parameter	**Cyclone Winifred** February 1986	**Cyclone Sadie** February 1994
Bleaching on nearshore reefs	No	Yes
Wind direction	SE-NNW	ENE-NNE
Wind speed	Up to 200 km hr^{-1}	17-28 km hr^{-1}
Long-shore currents	North? - southward	Southward ?
Tides	Neaps (0.7-2.8 m)	Neaps (0.9-3.2 m)
Rainfall (Abergowrie)	347 mm	566 mm
Herbert River flow (Ingham)	> 1500 000 ML	> 500 000 ML
Extent of flood plume	To inner edge of reef tract	To outer reef tract
Plume structure	< 1 m - several m thick	?
Salinity	< 10 ppt inshore	?
Suspended material	Throughout water column	?
Turbidity	Increased from mixing and runoff	Increased from runoff
Sedimentation	Increased	Increased
Dissolved nutrients	Inorganic Nitrogen increased to >1μM	Inorganic Nitrogen increased to >1μM
Air temperatures	Normal (max. 34°C)	Elevated (3 periods > 35°C, 1 period > 45°C)

Conclusions

The bleaching episode described here did not result in any major shifts in community structure. Although many of the nearshore corals were stressed during the summer of 1994, in most colonies and taxa the stress was not sufficient to cause major injury or mortality. As such, the event may be regarded as an early warning signal. For Pandora Reef in particular, because of the long-term record of coral community structure (Done 1982; Done and Potts 1992), continuing detailed monitoring will remain a priority. Reconstruction of the environmental conditions associated with bleaching and lack of bleaching, as related to physical studies and acclaimation are essential. For example, to establish the extent, if any, of cause and effect relationships between river flow and bleaching, there is a need to link a variety of physiological thresholds with physical models and data. Salinity/temperature tolerance curves for key indicator species are needed to establish critical durations of exposure to hyposaline waters. Depth-stratified plume models forced by historical river flow data, by wind data from the meteorological record, and by longshore currents are needed to determine when in the past, and the likelihood in the future, of these thresholds being exceeded to specific depths and at specific reefs.

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Appendix 1

List of species of scleractinian corals and other taxa that showed evidence of bleaching on 3 near-shore reefs of the central GBR, Brook Is., Iris Point (Orpheus Is.) and Pandora Reefs, February 1994. The common growth form(s) of each species are listed as: M - massive; S - submassive; E - encrusting to laminar; F - foliose; B - branching; D - digitate; C - columnar; or Ta - tabular. For each species, the degree of bleaching, none (N), partial (P) or total (T), is listed. For species wherein different colonies exhibited different levels of bleaching, the range is indicated.

Family	**Growth form**	**Brook Is.**			**Iris Pt.**			**Pandora**		
Depth (m)		1-3	4-7	8-11	1-3	4-7	8-11	1-3	4-7	8-11
Acroporidae										
Montipora spp.	E-F	N-P			N-P			P-T	N-T	N-T
M. tuberculosa	E-F	P						P-T		
M. spongodes	E-C							P-T		
M. spumosa	E-C								P-T	
M. hispida	E-C	P								
M. stellata	E-B	P							P	
M. informis	E-S				N-P					
M. aequituberculata	E-F	P						N-T	P-T	T
M. hoffmeisteri	E	P			P			P-T	P	
M. foveolata	E	P			P			P-T		
M. danai	E				P		P			P-T
M. undata	E				P					
M. foliosa	E-F									P
Acropora palifera	E-C				P	P		P-T	N-P	
A. humilis	D-S				N-P					
A. gemmifera	D-S	N-P			N-T			T		
A. digitifera	D	N-P			N-P					
A. danai	B				N-P					
A. grandis	B									N-P
A. microphthalma	B	N-P						P-T	P-T	N-T
A. vaughani	B				N-P	N-P				
A. austera	B				N-P	N-P				
A. nobilis	B	N-P			N-P			P-T	P	
A. formosa	B							T	N-P	P
A. aspera	B	N-P			N-T			P-T		
A. millepora	B	N-T						P-T		
A. valida	B				N-P	N-P		P-T	N-T	
A. secale	B				N-P	N-P				
A. tenuis	B				N-P			P-T		
A. selago	B	N-P								
A. donei	B	N-P								
A. yongei	B							P-T		
A. dendrum	B							P		
Acropora tables	Ta							P-T	P-T	P
A. hyacinthus	Ta							N-T	P-T	P
A. latistella	B-Ta	N-P						P-T		
A. cerealis	B								P	
A. nasuta	B						P	P-T		
A. elseyi	B	N-P				N--P		P-T	P	P-T
A. longicyathus	B					N-P				
A. valenciennesi	B					P				
Astreopormyriophthalma	M									N-P

Family	**Growth form**	**Brook Is.**			**Iris Pt.**			**Pandora**		
Depth (m)		1-3	4-7	8-11	1-3	4-7	8-11	1-3	4-7	8-11
Poritidae										
Porites micro-atolls	M							P-T		
Porites massives	M	N-P						P-T	N-T	P
P. rus	E-S						P-T	T	N-T	
P. cylindrica	B								P	
Goniopora spp.	B-M							N-T		N-P
G. columna	M-C									N-P
G. minor	M-E							T		
G. pandoraensis	C-B								N-P	N-P
G. eclipsensis	C-B									N-P
Alveopora spp.	E							T	T	
Siderastreidae										
Psammocora digitata	E-C							P		
Coscinaraea columna	E-M									N-P
Agariciidae										
Pavona cactus	B-F							T		P
P. clavus	E-C				P					
P. varians	E-M							N-P		
Leptoseris explanata	E-F									P
L. yabel	E-F									P
Coeloseris mayeri	M				N-T					
Pachyseris rugosa	F-S							P-T	N-T	N-T
P. speciosa	E									P
Oculinidae										
Galaxea astreata	M							P	N-P	N-P
G. fascicularis	M								P	N-P
Mussidae										
Scolymia vitiensis	S						N-P			T
Lobophyllia hemprichii	M						N-P	N-P	P-T	N-T
Merulinidae										
Hydnophora exesa	E-M								N-P	
Merulina ampliata	E-F								N-P	
Caryophylliidae										
Euphyllia cristata	M									N-P
E. divisa	M									N-P
Faviidae										
Favia pallida	M	N-P			N-P			N-T	N-P	
F. favus	M							N-P		N-P
F. mathaii	M				N-P					
F. maritima	M				N-P					N-T
Favites abdita	E-M				N-P			T	P-T	P-T
F. halicora	E-M				N-P					
F. flexuosa	E-M				N-T				N-T	P
Goniastrea retiformis	M	N-P			N-P			P-T	P-T	
G. favulus	M				N-P					
G. aspera	M				N-T	N-P				
G. pectinata	E-M							T		T
G. australensis	E-M								N-T	
Faviidae										
G. palauensis	M									P
Platygyra daedalea	M				N-P			P	P-T	P-T
P. sinensis	E-M	N-P			N-P			P-T	N-P	P
Leptoria phrygia	M				N-P		N-P	T	P-T	P-T
Oulophyllia crispa	M								P-T	P
O. bennettae	M								P-T	

Family	Growth form	Brook Is.			Iris Pt.			Pandora		
Depth (m)		1-3	4-7	8-11	1-3	4-7	8-11	1-3	4-7	8-11
Montastrea curta	M								P-T	
M. magnestellata	M								P-T	
Echinopora lamellosa	E-F								N-P	P
E. gemmacea	E-F								N-P	P
Pocilloporidae										
Pocillopora damicornis	B	P-T	P-T		P-T	N-P	P-T	P-T	P-T	P-T
Seriatopora hystrix	B	N-T	N-T		N-T	N-P	P-T	P-T	P-T	P-T
Stylophora pistillata	B	P-T	P-T		N-T	N-P	N-P	T	N-T	T
Palauastrea ramosa	B								P	N-P
Fungiidae										
Ctenactis spp.	S								P-T	P-T
Heliofungia actiniformis	S								N-T	N-P
Fungia spp.	S						N-P	T	P-T	N-T
Fungia fungites	S						N-P			
F. concina	S						N-P			
Herpolitha limax	S						N-P			P
Dendrophylliidae										
T. reniformis	E-F	N-P						N-P	P	N-P
Scleractinia total species	**102**	**25**	**3**	**0**	**34**	**12**	**13**	**47**	**47**	**49**
Zoanthiidae										
Palythoa sp.	E	P	P		N-P	N-P		P-T		P-T
Protopalythoa sp.	E								P	
Alcyonaria										
Sinularea spp.	B	N-P	N-P		N-P	N-P		T	P-T	N-T
S. flexibilis	B				N-P	N-P		N-T	P-T	N-T
Sarcophyton spp.	F				N-P			P--T	P-T	P-T
Lobophyton spp.	E-S				N-P			T	P-T	
Nepthea spp.	B								N-P	
Other spp.	B				N-P					
Hydrocorals										
Millepora spp.	B-E				N-P	N-P		T	T	P-T
Heliopora coerulea	S							P-T	P-T	
Total no. taxa	**112**	**27**	**5**	**0**	**41**	**16**	**13**	**54**	**55**	**53**