GREAT BARRIER REEF
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Flood Plumes in the Great Barrier Reef: Spatial and Temporal Patterns in Composition and Distribution

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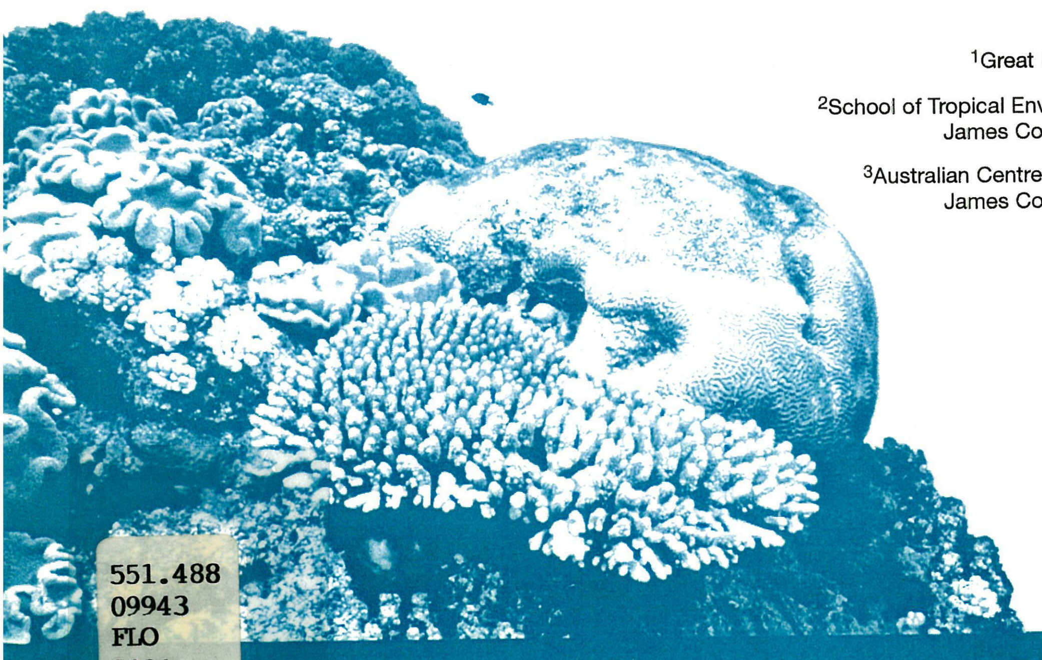

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Reef

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SUMMARY

Protecting water quality in the Great Barrier Reef World Heritage Area is recognised as one of the major challenges facing management of the area. One of the most important processes directly impacting the Great Barrier Reef (GBR) is the input of terrestrially derived nutrients and sediments to nearshore regions. This mainly occurs via river run-off, especially during periods of intense rainfall typically associated with tropical cyclones. Flood plumes occur at a time when the majority of inputs into the GBR lagoon are at peak concentrations and reefs and other inshore marine ecosystems then experience the highest concentrations of pollutants. The principal threat to the water quality of the reef arises from changes to the composition of the riverine discharge due to changed land use on coastal catchments. The characteristics of the plume water, including salinity, nutrients, sediment and toxicants pose a range of potential threats to the health of inshore ecosystems.

One of the key research areas of the Great Barrier Reef Marine Park Authority (GBRMPA) is the assessment of riverine input into the GBR lagoon, the importance of flood plumes as a source of nutrients and sediments and the impact of flood plumes on nearshore reef and seagrass communities. The Great Barrier Reef Marine Park Authority, in conjunction with other agencies, runs a multi-institutional research and monitoring program on the discharge properties, composition and spatial dynamics of river plumes entering the GBR. This work forms a component of a larger research and monitoring program to understand the sources, transport and effects of terrestrial pollution on the GBR. This study has monitored and measured flood plumes associated with cyclones from 1991 to 1999. The sampling events were cyclones Joy (1991), Sadie (1994), Violet (1995), Ethel (1996), Justin (1997), Sid (1998) and Rona (1999).

Plume distributions presented in this report establish that the main driving influence on plume dispersal is the direction and strength of wind and discharge volume of the river. Wind conditions are dominated by south-easterly winds which drive the plume north and towards the coast. The greatest number of plumes mapped over this study (Violet, Ethel, Justin, Sid and Rona) were restricted to a shallow nearshore northward band by stronger south-easterly winds following the cyclone. However, under relatively calm conditions such as those following Sadie, light offshore winds allowed the plume to disperse seaward and north over much of the shelf and there was a short period of direct impingement upon mid- and outer-shelf reefs. The flood plume associated with cyclone Joy in the Fitzroy River also moved offshore, following light northerly winds, eventually impinging on reefs of the Capricorn-Bunker group.

The amount of rainfall that falls over a particular catchment can have a marked effect on the distribution of the plume. Another factor in the distribution of flood plumes is the influence of headlands on the movement of the plumes ('steering'). This can be observed most clearly in the vicinity of Cape Grafton (slightly south-east of Cairns) in extent of the Sadie, Violet and Ethel plumes where northward moving plumes are steered across Green Island Reef. Green Island Reef appears to be the one mid-shelf reef of the GBR south of the Daintree, which is regularly covered by river plume water. Therefore the assessment of plumes impacting on mid-shelf reefs adjacent to the Barron River (Green Island) are expected to be underestimates due to effects from other river systems to the south 'steering' past Cape Grafton.

Modelling of the plumes associated with specific weather conditions has demonstrated that inshore reefal areas adjacent to the Wet Tropics Catchment (between Townsville and Cooktown) regularly experience extreme conditions associated with plumes. Inshore areas (north of the Burdekin and Fitzroy Rivers) receive riverine waters on a less frequent basis.

Spatial distribution of the frequency of plume coverage delineates the inshore area of the GBR, which is annually inundated by flood plume waters. This report presents a summary of the frequency and distribution of all flood plumes mapped in the GBR over the last 10 years. From this information, an assessment of the area of risk from river run-off has been developed. Inshore reefs and seagrass beds within this high frequency area and adjacent to agricultural catchments, are seen to be the highest risk from catchment activities.

As part of the assessment of the impact of flood plumes on GBR ecosystems, an estimate is required of the areal and volumetric extent of plumes emanating from the rivers draining to the GBR. The observed distribution of flood plumes between 1994 and 1999 serves as a baseline for evaluating plume distribution with respect to variables controlling plume extent. Based on these observations, a summary of plume distribution for waters discharging in the vicinity of the Russell-Mulgrave and Barron rivers, has been developed with six qualitative fields of plume distribution (inner1, inner2, inner-mid, mid, mid-outer, and outer).

A model has been developed to estimate the expected distribution of a plume using variables which include wind speed and direction coupled with river flow data. Formulation of expected plume distributions over a longer time period than individual observations allows for the identification of reefs that are subject to plumes and an estimate as to the frequency of impact. Based on the model an estimate of spatial extents of plumes has been made using the Barron River as a case study.

Flood plumes from the Barron River are visually apparent from aerial observations with discharges in the order of 30 000 to 40 000 MLd^{-1} (data for Myola gauging station). Based on this information a figure of 30 000 MLd^{-1} was assigned to historical flow data as a primary variable that needed to be exceeded for a plume to develop. Relationships between the discharge criteria and wind conditions experienced between the 1994 and 1999 period were documented to ascertain the extent of the plumes with respect to these two variables. Integrating the wind and discharge data with the mapped plume extents produced a matrix for prediction of plume distribution based on similar historical conditions. The hindcasted plumes provide a preliminary estimate of how frequently plumes extend to a particular area of the GBR. Based on the data for the Barron River it is estimated that in the past 58 years a plume may have reached the mid-shelf reefs (outer category) on 18 occasions.

Plume mapping and use of the model indicates that some reefs in the GBR experience river waters annually, some episodically, some rarely and some never at all. 'Hot spots' can be assigned to the reefs that are inundated by river plumes each year. Inshore reefs, north of the Palm Island group, see river plumes most years. These inshore reefs include Gould Island, King Reef, Brooks Family Group, Frankland Islands, Fitzroy Island, Double Island, Low Isles and Snapper Island. Reefs south of the Palm Islands, including Pandora, Acheron, Rattlesnake, Herald and Phillip Reefs, Magnetic Island reefs and the Whitsundays reefs experience river plumes from coastal and Burdekin River catchment run-off less frequently; perhaps every two to three years. Reefs in the Keppels and Cumberland groups experience river water even less frequently perhaps every four to six years. However, these latest predictions are based on a very limited observational record. Offshore reefs in the southern GBR experience river waters infrequently; only once in the 10 years of this monitoring study. However, a few mid-shelf reefs in the northern GBR do experience river water quite frequently, particularly Green Island.

Data from flood plumes clearly indicate that the composition of plumes is strongly dependent on particular events, between days and through a single event, depths and catchment. Timing of sampling is critical in obtaining reliable estimates of material exported in the flood plumes. There is a hysteresis in the development of a flood plume, which is related to catchment characteristics (size, vegetation cover and gradient) rainfall intensity, duration and distribution and flow volume and duration. The time lag difference is significant in the smaller Wet Tropic rivers (Herbert to Daintree) compared to the larger Dry Tropic rivers of the Burdekin and Fitzroy.

Dissolved inorganic nitrogen (DIN) concentrations measured in the plume are generally high compared to ambient (non-flood) conditions. The number of sites with elevated nutrients suggests that the high nutrient concentrations in the flood plumes extend over a significant area and over a number of days. DIN concentrations are in the range of 1–10 μM, compared to ambient concentrations, typically 0.1 μM.

Dissolved organic nitrogen (DON) and dissolved organic phosphorus (DOP) concentrations were relatively constant throughout individual plumes, with DOP ranging between 0.1–1.0 μM and DON concentrations typically found between 5 and 15 μM. There seems to be no relationship between increasing salinity and organic nutrient concentrations as organic nutrient concentrations in river waters and lagoon waters in the lagoon have approximately similar concentrations. Organic nutrients, particularly DON, are relatively stable and not known to be rapidly used in any biological process.

Particulate nutrients and suspended matter were higher than ambient conditions with peak concentrations measured adjacent and north of the flooding rivers. Concentrations of particulate nitrogen (PN) reached a maximum of 24 μM and generally were higher than 15 μM at low salinity levels. Concentrations of particulate phosphorus (PP) reached a maximum of 1.0 μM and concentrations of PP were generally higher than 0.5 μM at low salinity levels. Particulate matter settles out over relatively short distances, though concentrations are significantly higher than ambient concentrations for all samples taken within the surface waters associated with flood plumes. PN and PP can be a source of continually desorbing nutrients over long periods. The resulting dissolved nutrients can serve as a nutrient source for phytoplankton growth.

Chlorophyll *a* concentrations had an inverse pattern of increasing concentrations at some distance from the river mouth. This was likely to be influenced by the length of time which water column phytoplankton have been exposed to flood generated nutrients and the increasing light as the suspended matter settled out. Chlorophyll *a* concentrations were higher than phaeophytin concentrations in all samples, confirming that most of the chlorophyll detected was associated with new algal biomass stimulated by flood water discharge. Chlorophyll *a* levels were highest in the Fitzroy surface plume, generally 20 times ambient (non-flood) inshore values, indicating an extensive phytoplankton bloom within the plume.

Measurements of all parameters taken further away from the river are influenced by the physical and biological processes occurring over time as the elevated concentrations in the river water mixed with the lagoonal waters of the GBR. Concentrations of NO_x and DIP ranged from 10–15 μM and 0.2–0.5 μM at sites close to the river mouth and declining to levels between 0–2 μM (NO_x) and 0–0.2 μM (DIP) at higher salinity concentrations. Though these later concentrations are still high in comparison to baseline concentrations they do reflect influences by other processes. The distribution of nutrients within the plume is a function of riverine inputs, mixing and biological activity which adds or removes nutrients.

Mixing profiles demonstrate initial high concentrations of all water quality parameters in low salinity waters, with decreasing concentrations over the mixing zone. Mixing patterns for each water quality parameter are variable over catchment and cyclonic event, though there are similar mixing profiles for specific nutrient species. Processes occurring in addition to mixing can include the biological uptake by phytoplankton and bacteria, sedimentation of particulate matter and mineralisation or desorption from particulate matter. These processes can occur at the same time and make it difficult to determine which processes dominate. Nutrients carried into coastal waters by river plumes have a marked effect on productivity in coastal waters.

NO_x and DIP demonstrate a gradual decrease of concentration in the plume away from the river mouth, with a rapid decline in the nutrient concentrations at salinities between 26 and 30. This salinity range is in the area of highest productivity where there is greatest uptake of nutrients by phytoplankton. Ammonia (NH_4) concentrations are far more scattered reflecting both variations in supply, uptake and production from biological processes in the plume. Concentrations of NH_4 remain elevated in the higher salinities suggesting sources of ammonia in the plume, for example, excretion by zooplankton. Values for the river end member were lower than some concentrations at intermediate salinities. This may be related to variability in riverine concentrations over time, combined with multiple discharge points and differing mixing dynamics in various regions of the plume, or higher values occurred at the frontal convergence where biomass levels were concentrated and perhaps regeneration of nutrients was enhanced.

In the initial mixing zone, water velocity is reduced and changes in salinity, pH and eH promote flocculation of particulate matter. Most of the river-derived particulate matter settles from the plume in this zone. This is most clearly shown in the results from the Burdekin for cyclone Sid where suspended solid and particulate phosphorus concentrations drop to very low levels only a few kilometres from the river mouth at salinity of approximately 10. However benthic sediment distribution information shows that the area off the mouth of the Burdekin River has a low proportion of fine sediments. This apparent inconsistency is best explained by the resuspension and northward transport and deposition in northerly facing bays of fine sediments which occurs throughout the year under the influence of the south-east wind regime on the inner shelf. Reductions in suspended sediment with increasing salinity in the plume are less clear in some of the other plumes but this is complicated by resuspension during the plume event in stronger wind conditions on these occasions.

The high spatial variance of nutrient concentrations in the plumes is related to plumes constrained and broken up by islands and reefs, with the complexity directed by the multiple rivers and streams acting as source water for the plume. Outlying scatter points in the mixing graphs could also be due to resuspension processes resulting from rough weather conditions. Samples in plumes are taken on one day (more or less) whereas concentrations of dissolved components vary greatly during flooding in the river, e.g. first flush.

Nutrients such as nitrogen associated with the discharge travel much further offshore than sediment. Concentrations of nitrate and orthophosphate measured in flood plumes reached 50 times the concentrations measured in non-flood conditions. These elevated concentrations are maintained at inshore sites adjacent to the Wet Tropics catchment for periods of approximately one week. Plumes associated with the larger Dry Tropics catchments, the Fitzroy and Burdekin rivers experience elevated concentrations for periods of up to three weeks, but on a less frequent basis.

Concentrations of dissolved nutrients experienced at inshore reefs are considerably above those known to produce adverse affects on coral reef ecosystems, particularly in respect to enhancement of algal growth, reductions in coral reproductive success and increase in mortality.

Changing land practices associated with loss from grazing lands and fertilised cropping has resulted in increases in inorganic nutrients in north Queensland rivers. This has resulted in inshore coral reefs experiencing higher concentrations of nutrients than in past years. Reefs offshore of the Wet Tropics catchment are at a higher risk, specifically those closest to the shore, with annual inundation from high nutrient riverine waters.

1. INTRODUCTION

1.1 The Great Barrier Reef – An Ecological System

The Great Barrier Reef (GBR) is the largest reef system in the world (figure 1). It covers an area of approximately 250 000 km^2 and consists of an archipelagic complex of over 3000 reefs (Collins & Wallace 1994; Veron 1996). The GBR region also supports extensive nearshore and deeper water seagrass beds (Lee Long et al. 1993; Coles et al. 1989). It is also the largest Marine Protected Area in the world, listed as the Great Barrier Reef Marine Park (hereafter known as the GBRMP), and the Great Barrier Reef World Heritage Area (GBRWHA), which cover an area of approximately 350 000 km^2.

Nearshore reefs and other ecosystems of the GBR have developed in an environmental regime influenced by the adjacent mainland environment (Devantier et al. 1997). Well within the last generation, there have been rapid increases in human activities such as land clearing, agriculture, urban development and industry on catchments adjacent to the GBR. These human driven changes have the potential to change processes in the GBR.

The main input of terrestrial material and contaminants into the GBR is through flooding rivers. The ecological resilience of a marine ecosystem is defined as its ability to receive and transfer a certain level of pollutants and to endure a certain frequency and intensity of disturbances without changing irreversibly. Therefore, knowledge of how flood plumes influence water quality regimes within the GBR is essential for the understanding and management of this ecological system. The challenge for environmental management of the GBR is to differentiate between natural and unnatural forces that cause change, and employ this knowledge for an integrated and effective management program.

1.2. The GBR Catchment

The catchments adjacent to the GBR occupy about 42 million hectares (the total area hereafter referred to as the GBR Catchment), about 75% larger than the continental shelf on which the reef is supported. Cattle grazing for beef production, associated with extensive woodland clearance (figure 2), is the largest single landuse (77% of the area) on the Catchment with cropping, mainly sugarcane (3%) and urban/residential development (3%) considerably smaller in areal extent. Other significant landuse includes mining and areas of cotton cropping. Landuse practices on the catchment depend on the landform, climate, availability of irrigation, soil types and the economics of adapting natural conditions to produce various horticultural and agricultural crops (Pulsford 1996). Most of the soils of the region are naturally deficient in the elements, nitrogen, phosphorus and potassium. Addition of these nutrients has been necessary for large-scale crop production, particularly sugarcane, cotton and fruit and vegetable crops. Human population densities in north Queensland are low and concentrated along the coastline. Only five urban centres have populations exceeding 40 000 persons.

The GBR Catchment (figure 1) is made up of a diverse range of areas best categorised as 'Wet tropics', e.g. Johnstone and Tully river catchments, 'Dry tropics', e.g. Fitzroy and Burdekin river catchments, and 'intermediate', e.g. Burnett, Pioneer and Herbert River catchments. Wet Tropics catchments are areas where rainfall is significant through the winter as well as summer; called the 'early autumn' pattern in Finlayson & McMahon (1988) and the southern Dry Tropic catchments are described by rainfall in moderate late summer. Hereafter Wet Tropics will denote all rivers located between and including the Daintree and Herbert catchments and the Dry Tropics will include the Burdekin and Fitzroy River catchments. These catchments are all located in areas of distinct wet/dry seasonal rainfall and subject to intense cyclonic rainfall over periods of a few days to a few weeks (Brodie & Furnas 1996).

Finlayson and McMahon (1988) note that Australia has highly variable annual river flows and annual floods compared to the rest of the world's continents. Seasonal variability is related to the monsoonal climate of north Queensland, with a wet summer and a dry winter. Over decadal time scales, regional rainfall and river discharge are also modulated by the strength and duration of the summer monsoon, which, in turn is coupled to El Ninõ Southern Oscillation (ENSO) variability (Lough 1992). Thus rainfall and run-off vary considerably, both between and within years and across river basins draining to the GBR.

Discharge in both wet and dry river systems is dominated by large flood events associated with tropical cyclones and monsoonal rainfall (Furnas & Mitchell 1997; Mitchell et al. 1997b). Flow rates of these rivers are characterised by high inter-annual, seasonal and event-coupled variability of flow (Furnas et al. 1996) (figure 3). Most rivers of the Wet Tropics drain small catchments with low inter-annual variability of rainfall and are characterised by multiple short-duration flow events each year (figure 4, Barron River). In contrast, discharge from the two largest Dry Tropics rivers, the Burdekin and Fitzroy, typically occurs as one or two small annual flows, but occasionally as a very large flood event which may last for several weeks and greatly exceeds discharge from other regional rivers (Furnas & Mitchell 1997; Furnas et al. 1996). These events significantly raise nutrient and sediment loads in Queensland rivers (Furnas & Mitchell 1997).

1.3 The Great Barrier Reef Lagoon

The Great Barrier Reef largely isolates the continental shelf sea (the Great Barrier Reef lagoon) from the adjacent Coral Sea along the northern Queensland coast (figure 1). In general, oceanic water exchanges freely between the Coral Sea and outer barrier reefs, whereas coastal run-off and inshore processes are the major determinant of inshore lagoon water quality (Haynes et al. 2001).

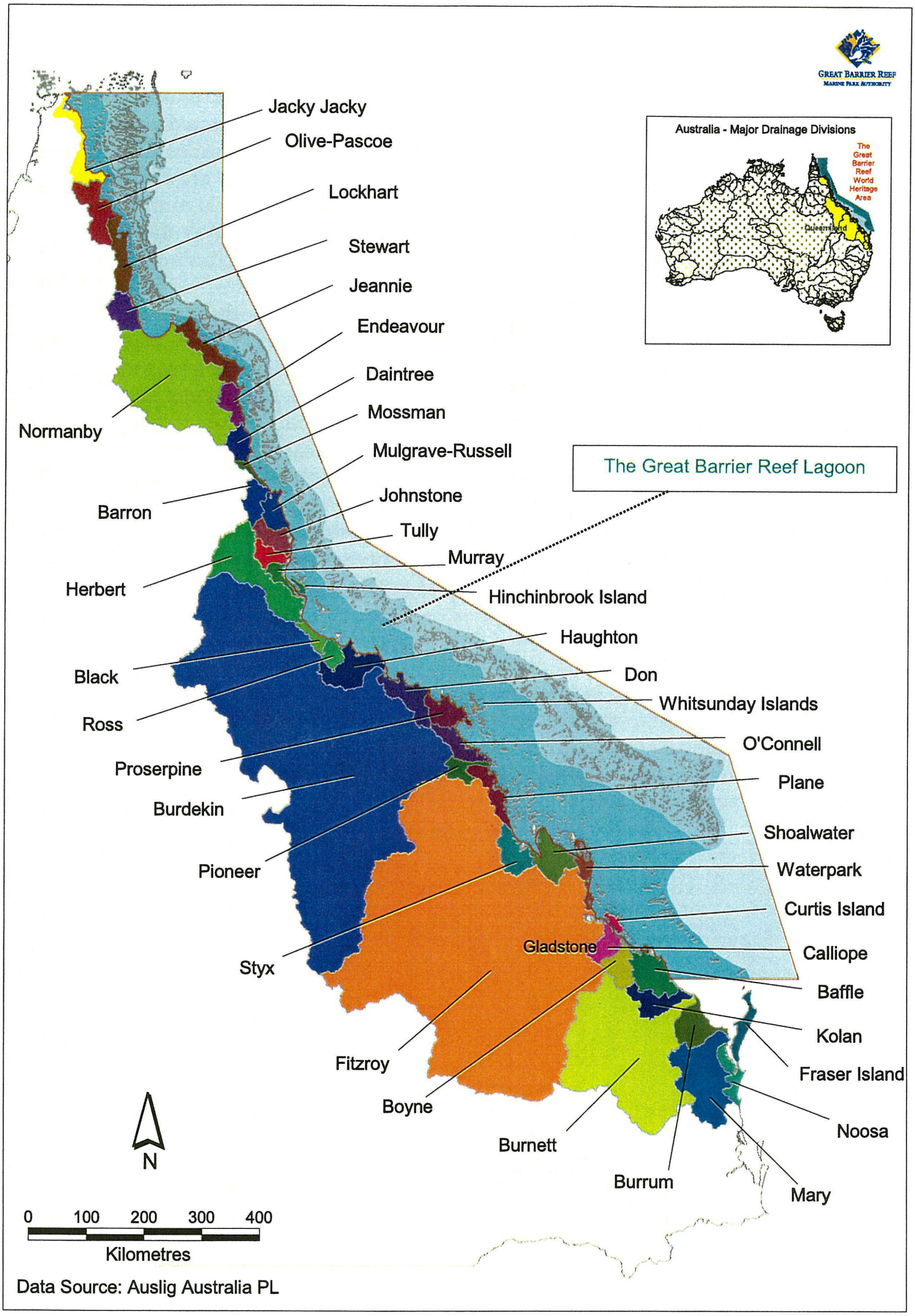


Figure 1. Map of the Great Barrier Reef Catchment and major rivers draining into the Great Barrier Reef Lagoon

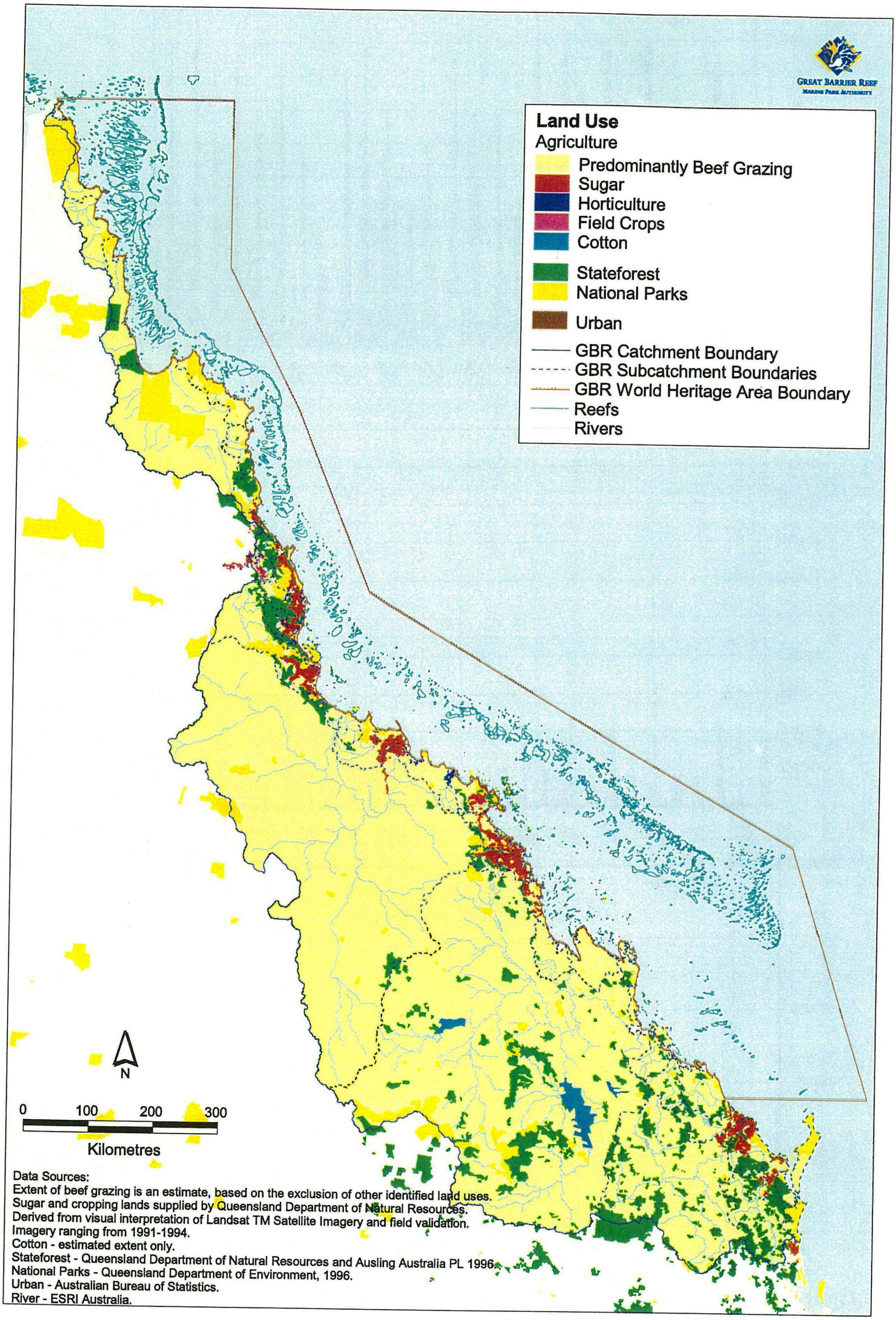


Figure 2. Landuse characteristics of the Great Barrier Reef Catchment

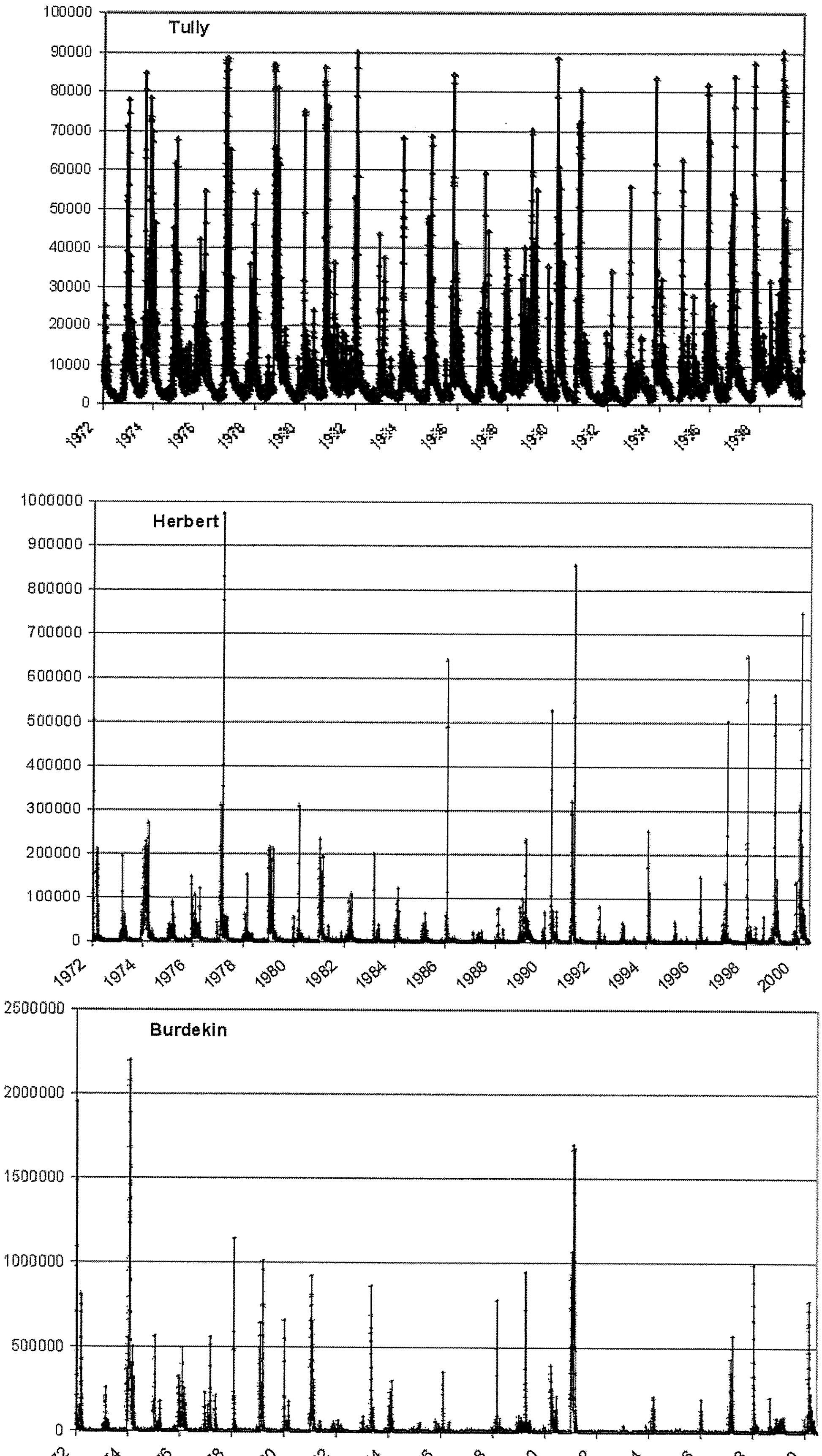


Figure 3. Differences in flow rate between the Tully (Wet Tropics), Herbert (intermediate) and the Burdekin River (Dry Tropics)

a) b)

Figure 4. Seasonal extremes in the Barron River, from the Atherton Tablelands the Barron River flows through the World Heritage rainforest (a) dry season – October 1994 (b) wet season – March 1995 floods. (*Photos: J. Taylor 1995)*

1.4 Why are Rivers and Flood Events Important?

On the Queensland coast, as in many coastal areas around the world, riverine source waters make up the largest single source of new nitrogen and phosphorus to coastal waters (Furnas et al. 1995). Movement of river waters into nearshore systems is part of an interconnected ecological system. Freshwater inflow is one of the most influential landscape processes affecting biological community structure and function in lagoons, estuaries and deltas of the world (Sklar & Browder 1998). Most of the transport of materials from land to sea is via river systems and the natural and anthropogenic changes to catchment habitats and processes can have major impacts on the quantities of sediment, nutrients and water entering the coastal seas. As a natural process, freshwater flow and the downstream movement of nutrients is one of the primary controls of the productivity of estuarine systems and coastal seas.

Coastal plumes associated with river outflow are biologically rich mesoscale features, characterised by strong horizontal and vertical salinity gradients (McManus & Fuhrman 1990). Movement of freshwater plumes into the marine environment is an important part of the ecological process that drives productivity in the coastal area. They can be recognised in surface waters with the naked eye through the sharp colour change and accumulation of foam and flotsam at the interface of plumes and oceanic waters (figure 5) (Brodie & Furnas 1996; McManus & Furhman 1990).

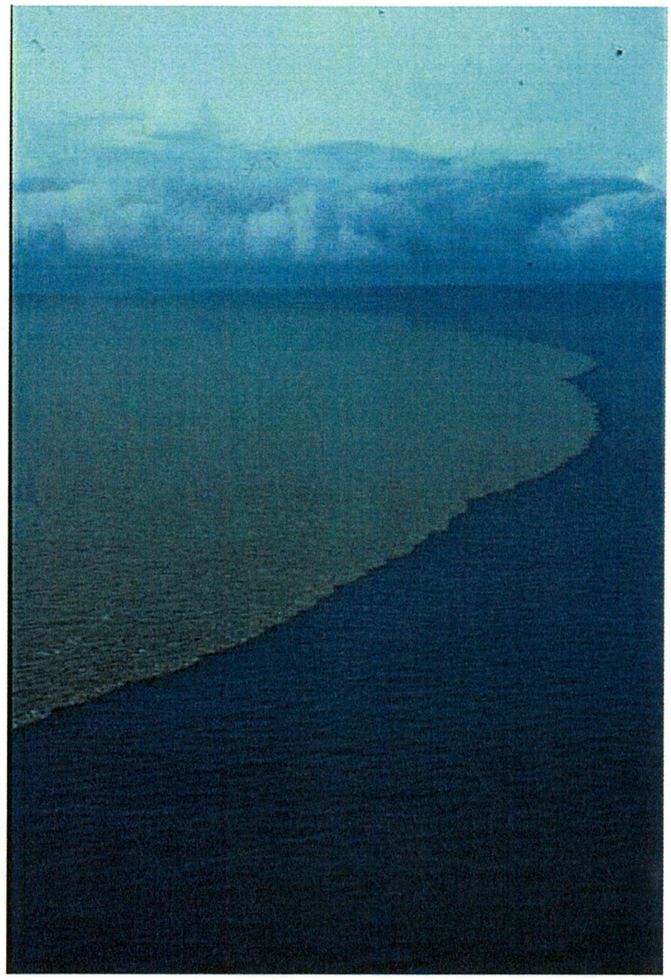


Figure 5. Aerial photograph of plume boundary intersecting with oceanic water, Fitzroy River area, 1991

Published studies of the variations in water quality in GBR rivers during flood events (Hart et al. 1988; Mitchell et al. 1997a; Furnas & Mitchell 1997; Taylor 1997, 1991; Eyre & Davies 1996; Furnas et al. 1996; Hunter et al. 1996) show that there can be major changes in nutrient and sediment concentrations during flood events. Additionally these are the times when most of the suspended sediment and nutrients are transported to the estuarine/inshore system. The importance of flood events in the transport of particulate and dissolved matter is even more pronounced in the monsoonal tropical region of north Queensland where short-term extreme flow events move the highest concentrations of nutrients and sediments into the GBR lagoon. Nutrient and suspended sediment concentrations vary significantly between river systems, between seasons and within seasons in relation to catchment type and streamflow dynamics (Furnas & Mitchell 1997). Figure 6 demonstrates the high variability in concentrations of dissolved and particulate nitrogen over annual flow events in the Tully and Burdekin rivers.

Input of terrestrially derived nutrients and sediments into the nearshore reefal system is an important process directly impacting on the GBR. During flood conditions inshore ecosystems experience the highest concentrations of dissolved nutrients throughout the year. Suspended sediment concentrations and particulate nutrients are high at these times though higher loads may be generated by resuspension of inshore sediments during periods of significant south-east winds (Woolfe et al. 1998).

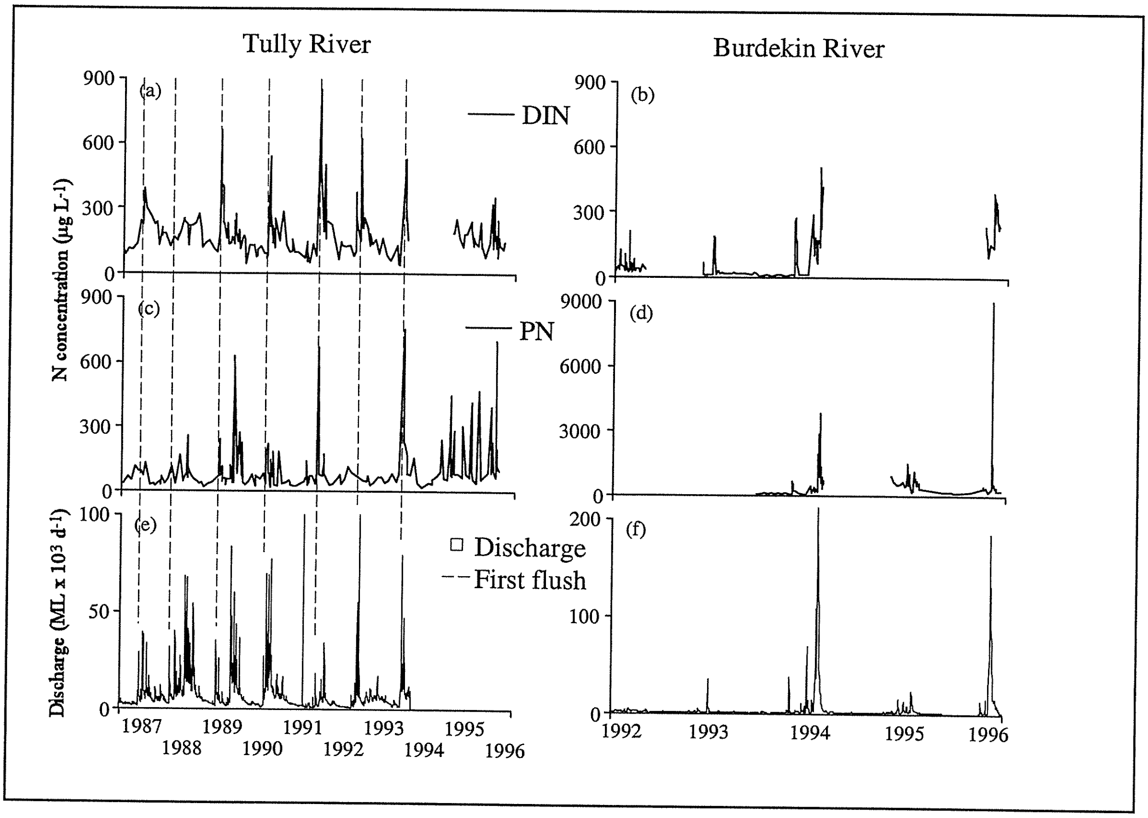


Figure 6. Nutrient concentration in response to flow rate from the Burdekin and Tully Rivers. (Source: Mitchell et al. 1997b)

Flood plumes can be beneficial for inshore communities. High inputs of particulate and dissolved matter influence water column productivity (Bunn & Arthington 1997; McKinnon & Thorrold 1993), species composition and fish abundance (Thorrold & McKinnon 1995). Studies of coastal systems in Australia (Drinkwater & Frank 1994; Thorrold & McKinnon 1995) have found correlation between freshwater inflow and fisheries production. Healthy fish communities require diverse habitat and river flows providing conditions suitable for each species during its life cycle. Waterways contribute to fisheries productivity by providing spawning, nursery and feeding grounds and fisheries dispersal routes. Platten (1996) has shown that marine fisheries in the GBR lagoon are positively influenced by periodic freshwater flows. Plumes and associated frontal structures present a rich food environment for larval and juvenile fish (Lohrenz et al. 1990).

1.5 Extent of River Plumes in the Great Barrier Reef

Water movement in the GBR Lagoon is driven by the prevailing south-east wind regime, tidal forces and the East Australian Current (EAC) and the Hiri Current (Burrage et al. 1997). On the outer edge of the shelf these produce an overall southerly movement south of 16°S and northerly movement north of 16°S. Tidal forces produce cross-shelf water movements. The wind regime produces a net northerly water movement in the inshore part of the lagoon (Burrage et al. 1997).

The areal extent of a flood plume is governed by many factors. Physical oceanographic studies of plumes in the GBR (Wolanski & van Senden 1983; Wolanski & Jones 1981) and modelling studies (King et al. 1997) suggest plumes are constrained close to the coast by the oceanographic conditions imposed by coriolis forces and the prevailing wind regime. The coriolis effect is a deflection of water caused by a rotation of the earth of objects travelling over the surface of the earth. This deflection is to the left in the southern hemisphere and to the right in the northern hemisphere. Plumes generally move northward as a geostrophic, density current. Other properties of flood plumes are their ephemeral nature, with rapid break-up of river plumes following cessation of freshwater inflow. Break-up is assisted by the presence of headlands, islands and capes, resulting in complex coastal flows and mixing processes (Wolanski et al. 1996). Studies by Gagan et al. (1987) imply a strong interdependence between flood plume extent and run-off rate.

Overall forcing components generally drive river plumes northward and towards the coast in the GBR. Riverine material is deposited and trapped close to the coast and has minimal influence on outer shelf reefs (Johns 1988; Gagan et al. 1987; Belperio 1983; Wolanski & Jones 1981). Wolanski & Jones (1981) showed the Burdekin River created buoyant freshwater plumes along the coast of GBR Lagoon, but there was no evidence of plumes directly reaching the mid and outer GBR. In all observations, the Burdekin River plume was deflected onto the shoreline and advected northwards, a mechanism, which prevented its contact with GBR. However in the 1981 Burdekin River flood, Wolanski & van Senden (1983) showed that river plumes from this event reached the mid-shelf of the GBR. The Burdekin River will automatically move northwards as a result of the interaction of buoyancy and coriolis forces, with motion being enhanced by barotropic flow (Wolanski & Jones 1981). Belperio (1983) showed by analysis of types of bottom sediments from Cape Upstart to Townsville that terrigenous sediment is primarily trapped in coastal embayments and does not extend more than a few kilometres offshore. Terrestrial marker chemicals (Currie & Johns 1989) generally show a similar pattern of terrestrial influence. Gagan et al. (1987) show restricted terrestrial carbon input out of the Johnstone River during high river discharge associated with cyclone Winifred and concluded terrestrial run-off has not reached the reef in historical times, except during rare Burdekin River floods. A recent assessment of mechanisms of sediment delivery to the GBR lagoon indicates that the delivery of sediment via river plumes results in extremely small masses deposited on mid-shelf reefs (Orpin et al. 1999). Some terrestrial influence is observable to the outer edge of the GBR as shown in $\beta^{13}C$ isotope ratios in corals, but there is a strong negative correlation between terrestrial carbon as a food source and distance across the shelf (Risk et al. 1994). In the Cairns area (and further north) where the main reef is close to the coast, river water may have a stronger influence on mid-shelf reefs (Furnas et al. 1995).

1.6 Changes in the Great Barrier Reef Catchment

Clearing of forest and woodland in the GBR Catchment has continued throughout the last 130 years with rapid losses of *Melaleuca* and brigalow woodlands (*Acacia harpophylla*) since the 1940s (Graetz et al. 1995). In the Herbert River catchment, *Melaleuca* wetlands have been reduced in area from 30 000 hectares in pre-European times to less than 5000 hectares in 1996 (figure 7) (Johnson et al. 1998) while in the lower Johnstone River catchment a 78% loss occurred between 1951 and 1992 (Russell & Hales 1994). In the Fitzroy River catchment during the Brigalow Woodland Clearance Schemes (1950–1975) approximately four million hectares of brigalow woodland was cleared for conversion to grasslands for beef grazing (Gasteen 1987; Fitzgerald 1984). Loss of vegetation in most catchments for agricultural use has led to greatly increased soil erosion and subsequent increased sediment yield to coastal areas (Pringle 1986).

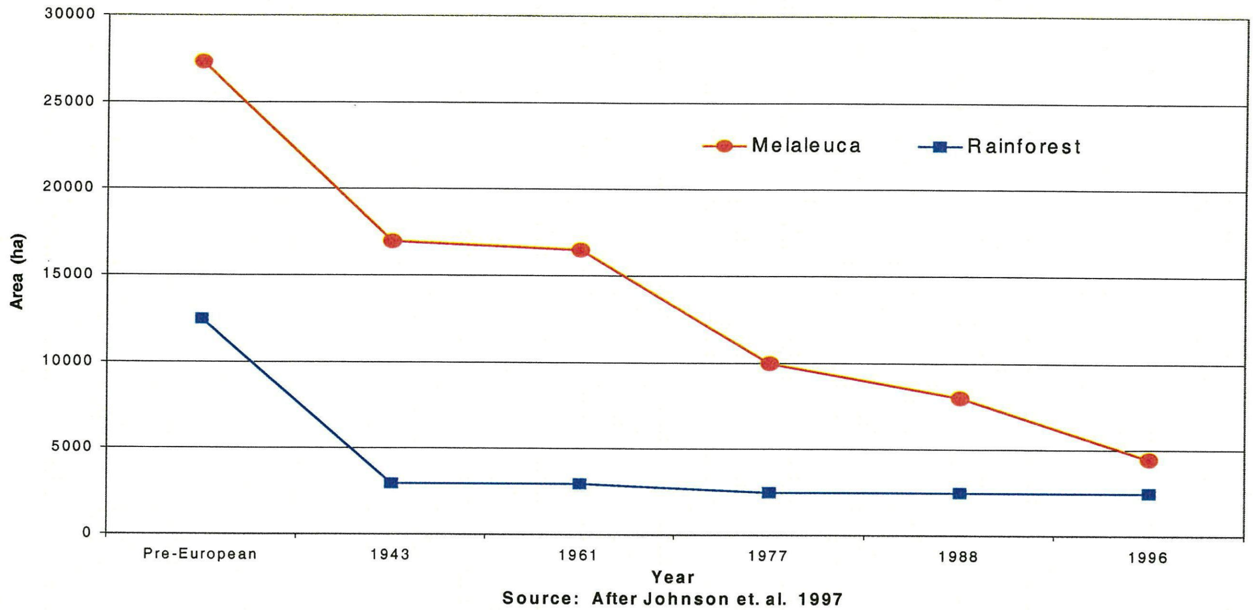


Figure 7. Changes in vegetation cover of the Herbert Catchment for Melaleuca and rainforest since pre-European times

Fertiliser usage on most of the GBR Catchment has increased greatly in recent decades (Pulsford 1996, 1991). Modern agricultural practices, particularly the use of fertilisers, have been strongly linked with elevated nutrient concentrations in the aquatic environment (Caraco & Cole 1999; Jickells 1998). Figure 8 shows the increase in the usage of nitrogen and phosphorus fertiliser applications on the GBR Catchment. For a single catchment, such as the Barron River, the use of fertiliser has increased 25 fold between 1960 and 1980 (Valentine 1988).

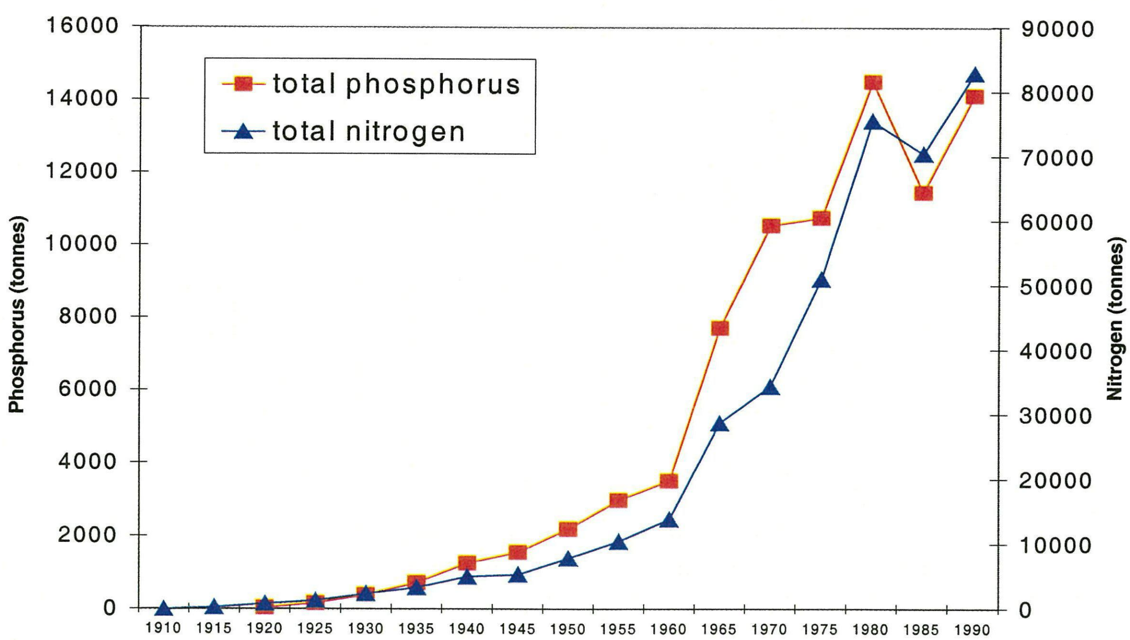


Figure 8. Increases in the application of nitrogen and phosphorus fertilisers to the Great Barrier Reef Catchment

First-order estimates of total river discharges of sediment and nutrients (nitrogen and phosphorus) from the GBR Catchment have been derived from models relating erosion and regional landuse patterns (Rayment & Neil 1997; Moss et al. 1992). In these models the importance of the large 'dry' catchments where cattle grazing is the dominant land use is evident. Overall, 66% of the estimated sediment flux is estimated to come from grazing lands, with 8% from cropping lands and 26% from 'pristine' areas (Neil & Yu 1996). The flux of sediment is estimated to be three to five times higher than that prior to European settlement (Rayment & Neil 1997; Moss et al. 1992).

In many overseas catchment areas the loss of forest cover, reduction in vegetation cover, hardened surfaces in urban areas and transport systems, and modified drainage schemes have been shown to produce higher rates of water run-off. Downstream effects include larger floods with greater discharge volumes as well as a faster, more concentrated discharge pattern. However the presence of dams on many GBR rivers may also act to moderate flows to some extent. About 10% (8 km^3) of the average annual discharge from the GBR Catchment (75 km^3) can potentially be captured in existing large reservoirs (Gilbert, forthcoming). Table 1 presents data from each catchment in relation to catchment area, agricultural use and mean annual flow and run-off rate (modified from Gilbert, forthcoming).

Table 1. Land use areas and other statistics for catchments of eastern Queensland. (Source: Gilbert, forthcoming)

	Land Use Areas (km^2)								
		Grazing							
Catchment	Pristine	DPI Estimate	Un-allocated	Total grazing	Cropping	Urban	Total	Mean Annual Flow (GL)	Mean Annual Run-off (ML/km^2)
Fitzroy	12782	119320	3428	112748	7065	50	142645	7100	0.05
Shoalwater Bay-Sarina	2459	4970	3367	8337	464	10	11270	3700	0.33
Pioneer-O'Connell	740	1940	706	2646	509	30	3925	2650	0.68
Proserpine	549	1670	102	1772	159	5	2485	1400	0.56
Don	83	3850	1	3851	41	10	3985	700	0.18
Burkedin-Haughton	2344	118060	11672	129732	1384	50	133510	10850	0.08
Ross-Black	530	850	1400	2250	10	100	2890	1100	0.38
Herbert	1584	7970	114	8084	447	15	10130	5000	0.41
Tully-Murray	1861	530	273	803	151	10	2825	2300	1.88
Johnstone	916	570	465	1035	359	20	2330	4700	2.02
Mulgrave-Russell	982	160	550	710	313	15	2020	4200	2.08
Barron	869	1200	110	1090	116	100	2175	1150	0.53
Mossman-Daintree	1977	930	405	525	98	15	2615	4250	1.63
North-East Cape York	9043	29720	4505	34225	22	10	43300	19100	0.44

1.7 Potential Impacts on the Great Barrier Reef from Changes in Water Quality Associated with Flood Plumes

There are a substantial number of marine environments that have either fully or in part become eutrophic (i.e. nutrient overloaded). The water bodies are all semi-enclosed with low rates of water flushing and are adjacent to extensive agricultural operations or large population centres. Well documented examples include the Baltic Sea (Jansson & Dahlberg 1999), Kanehoe Bay (Smith et al. 1981), the Irish Sea (Allen et al. 1998) the Black Sea (Mee 1992) and the North Sea (Riegman et al. 1992). These overseas systems have all suffered ecological damage as a result of pollution from land based sources. There has been significant contamination by higher nutrient and sediment loads, pathogenic microbes and toxic chemicals. The affected systems are characterised by rapid increases in intensive agriculture and urbanization with significant losses of riparian and wetland areas on the catchment.

Eutrophication within these systems has taken place over a period of decades, with highly elevated nutrient loads, changes in phytoplankton dynamics and higher primary production. These nutrient-rich waters support phytoplankton algal blooms and fast-growing filamentous macroalgae. Decreased light penetration and increased sedimentation of organic matter result in higher benthic oxygen consumption and alterations in benthic communities. These changes can lead to reductions in species diversity, with opportunistic settler species finding ecological niches in place of natural species.

Landuse changes resulting in increased sedimentation and turbidity in tropical coastal waters are among the most serious environmental problems facing coral reefs worldwide (van Woesik et al. 1999; Rogers 1990). The nearshore coral communities of the GBR, arguably the best protected reefs in the world (Bradbury et al. 1992), are potentially at risk from increased eutrophication and siltation from land-based activities (Bell 1991, 1992; Yellowlees 1991). High turbidity and sedimentation associated with increased sediment yield from terrestrial sources have the potential to cause significant mortality of scleractinian corals on fringing reefs (thus affecting the integrity of coral communities), and also to influence reef geomorphology (Rogers 1990). Enhanced nutrient inputs may cause phytoplankton blooms, macroalgal blooms (Smith et al. 1981), reduced coral reproductive success (Koop et al. 2001) and reduced reef growth (van Woesik et al. 1999).

The impact of changing catchment land use practices on the GBR is currently the subject of considerable concern, with the extent and definition of the impact on the inshore systems widely debated (Larcombe & Wolfe 1999; Hunter et al. 1996). Variability in natural processes and lack of information on impacts makes it difficult to assess the actual changes caused by declining river water quality. The dynamics of near-shore reef communities in the GBR have always been shaped by terrestrial run-off but inshore coral reefs may still be susceptible to increased siltation and terrestrial run-off of nutrients. However, clear long-term and regional-scale effects on GBR ecosystems from accelerated run-off of sediment and nutrients are difficult to quantify. Three problems in defining the impact are:

1. the frequent natural disturbance of GBRWHA coastal ecosystems by cyclones and floods;
2. the relatively short period of careful observation (ca. 15 years) relative to the natural disturbance frequency; and
3. the lack of unambiguous pristine controls for comparison.

Currently there is little direct evidence of an impact and in other cases the impact must be regarded as potential. Potential threats to the environment are derived from the current understanding of ecology or more broadly based on direct comparison with the known effects in similar situations overseas.

In the Fitzroy flood of 1991, associated with cyclone Joy, extensive mortality of corals in shallow water in the reefs associated with the Keppel Islands occurred (van Woesik & Done 1996). This was primarily attributed to the extended period of low salinity at these sites (Brodie & Mitchell 1992; O'Neill et al. 1992). The Daintree River flood event of March 1996, associated with cyclone Ethel was probably the cause of the almost total mortality of corals on shallow reef slopes of the entire south face coral population of Snapper Island (Ayling & Ayling 1998). Depth correlated mortality, with an abrupt lower limit at just over three metres, is typical of flood plume affects on reef corals (van Woesik & Done 1996). At Snapper Island all corals on the outer reef flat, all the acroporids down to over three metre depth and at least 70% of other coral groups (Ayling & Ayling 1998) suffered mortality on the south face. However coral mortality on the north side of Snapper Island was reduced significantly due to the upwelling of deeper shelf waters on the lee side (Ayling & Ayling 1998), suggesting that impacts of flood plumes can be variable around a reef. In cases of terrestrial run-off, it is sometimes difficult to determine whether impacts on the reef are due to sedimentation, light loss associated with turbidity, freshwater, nutrient enrichment or a combination of factors (Rogers 1990).

Present observations show that tolerance of corals to terrestrial run-off differs between species (Stafford-Smith & Ormond 1992; Dodge & Vaisnys 1977). Seagrass and inshore coral reefs along the coast, have recruited, grown and evolved in the presence of natural freshwater, terrestrial nutrient and sediment inputs. Van Woesik et al. (1999) has recently concluded that reductions in coral growth on Whitsunday reefs in the GBR are related to an eutrophication gradient associated with the Proserpine River. Sakai and Nishihira (1991) showed strongly correlated decreases in species diversity of a coral community due to terrestrial run-off. Physical disturbance has been suggested as a force to maintain higher species diversity in some coral communities (Connell 1978). However, periodic run-off, with deteriorating water quality, can impact on vulnerable corals and decrease species diversity. The rapid destruction of coral reef communities and associated reef organisms by sedimentation has been particularly prevalent in developing areas where rapid clearing of land for agricultural development has occurred.

Increased nutrient supply can enhance the growth of phytoplankton, turf algae and macroalgae. This effect has been demonstrated in numerous coral reef systems worldwide such as the Red Sea (Walker & Ormond 1982), Barbados (Tomascik & Sander 1987a, 1985) and Indonesia (Edinger et al. 1998), with the best documented example in Kanehoe Bay, Hawaii (Smith et al. 1981). Perhaps less dramatic, but nonetheless clear demonstration of links between sediment and nutrient inputs to changes to reef systems have been recorded in a number of laboratory based and field manipulative studies (e.g. Koop et al. 2001; Grigg 1994; Grigg & Dollar 1990). Enhancement of phytoplankton growth from increased nutrient supply leads to increased filter feeder (e.g. tubeworms, sponges, bivalves) growth (Smith et al. 1981). Macroalgal blooms may overgrow coral, both competing for space and shading the colonies (Lapointe 1997; Littler & Littler 1984). Filter feeders compete with coral for space and bioerode the reef structure (Keine & Hutchings 1994). Neither macroalgae nor most filter feeders add to reef consolidation through calcification. In the Caribbean, particularly in Jamaica, complex interactions between decreased grazing pressure from loss of grazing fish and echinoderms versus increased nutrient supply, are a source of controversy regarding the cause of macroalgal blooms preventing the recovery of coral reefs after cyclone related mechanical damage (Lapointe 1999; Hughes et al 1999). Excessive phosphorus concentrations result in coral colonies with less dense and hence weakened skeletons making the colony more susceptible to damage from storm action (Rasmussen et al. 1992: Kinsey & Davies 1979).

A more serious problem for reefs in inshore areas may be the synergistic effect of high suspended sediment loads and eutrophic conditions leading to the formation of marine 'snow' (Fabricius & Wolanski 2000). Corals and other small sessile invertebrates have to expend considerable energy to rid themselves of the large marine snow particles compared to the normal, smaller 'clean' sediment particles of oligiotrophic waters (Fabricius & Wolanski 2000).

Research is now directed at understanding the natural history of these communities in the presence of multiple and changing stresses as patterns of land run-off are changed (van Woesik & Done 1996; Done & Potts 1992). Research is required to determine whether apparent changes in inshore reefs from a hard coral dominated to a macroalgal or soft coral dominated state are part of a natural successional process or symptoms of long-term eutrophication (Fabricius & De'ath 1997; McCook & Price 1997; Schaffelke & Klumpp 1998a, b).

1.8 The Present Study

The Great Barrier Reef Marine Park Authority (GBRMPA) has been coordinating rapid response monitoring of flood events over the last 10 years with two aims. Firstly, to determine the spatial influence of plumes and examine their effect on the underlying benthic habitat (Steven et al. 1996) and secondly, to quantify the significance of river discharge as new inputs of sediments and nutrients to the GBR Lagoon. Since 1990 flood plumes associated with seven cyclonic events have been studied—cyclone Joy (Brodie & Mitchell 1992), cyclone Sadie (Brodie et al. 1997; Devlin 1997), cyclone Violet (Steven et al. 1996; Brodie & Furnas 1996), cyclone Ethel (Taylor & Devlin 1997), cyclone Justin (Devlin et al. 1998), cyclone Sid (Devlin et al. 1998) and cyclone Rona (Devlin forthcoming).

A significant proportion of the material lost from the land during flood events invariably finds its way via river discharges to the GBR lagoon (Furnas & Mitchell 1997; Cosser 1989). To gain a better understanding of the possible effects of flood plumes and the likely spatial extent of these effects, the physical and chemical characteristics of seasonal flood plumes must be documented. Flood events were sampled as rapidly as possible after the onset of high river discharge to categorise the plume composition and to quantify concentrations of dissolved (inorganic and organic) and particulate nutrients, suspended solids, and other physico-chemical parameters in the freshwater and marine environments.

Tracing particulate and dissolved nutrient concentrations over time, as the sediment and nutrient-rich flooding river water mixes with the inshore ocean waters, provides a greater understanding of the sorption and desorption processes of particulate nutrients. Knowing the temporal and spatial scales over which nitrogen and phosphorus is released from particulate matter to solution remains a critical factor in evaluating nutrient bioavailability and in documenting the biological processes occurring over time in flooding rivers and associated offshore plumes. Knowledge of flood plume processes requires an understanding of where the water comes from; the changes that are occurring as it flows downstream; where the water and sediment are transported; and how this flood water can impinge/affect nearshore biota. The design of this research project is set up to answer those questions.

1. What are the nutrient and sediment concentrations occurring in the onset and duration of a freshwater flood plume in the GBR lagoon?

2. What is the fate of dissolved and particulate nutrients from the river discharge when it interacts with the inshore lagoon waters?

3. How does the nutrient and sediment concentration and speciation in the plume change over days and weeks after the initial flooding event?

4. What are the water quality extremes (in nutrient concentrations) that an inshore reef system will experience in the onset and duration of a flood plume?

2. HISTORY OF RESEARCH AND MONITORING OF CYCLONES AND FLOOD PLUMES IN THE GREAT BARRIER REEF

Cyclones are the most important natural agents of disturbance on coral reefs in non-equatorial regions (Done 1992). Cyclones can affect the community composition of reef corals and thus on coral reef structure, both directly and through its influence on biological interactions. Both direct effects such as cyclone generated waves, and indirect effects such as turbid, sediment laden river plumes can substantially alter the physical structure and community composition of reefs (Puotinen et al. 1997; Done 1992; Done et al. 1991; Woodley et al. 1981). Direct effects may include the removal of the reef matrix via scouring and fragmentation (Van Woesik et al. 1991) and both direct and indirect structural damage from breaking waves and wave-borne debris (Done et al. 1991). Decline in salinities may cause coral bleaching and mortality of shallow reef corals (Brodie et al. 1997; Devantier et al. 1997; Van Woesik et al. 1995; Rainford 1925).

Research reviewed in this chapter has been mostly directed at sampling post-cyclone impacts and water quality conditions in the aftermath of large cyclone-related flood plumes. However other work has focused more on the damage to the benthic communities and mechanical movement of plumes and sediments rather than the water quality conditions of the flood plume and physio-chemical changes in the water column. Table 2 summarises cyclone characteristics and sampling undertaken for selected cyclonic events in the GBR from 1918 to 1988.

Early observations were made by Orr (1933) of the presence of flood plumes around Low Isles in February 1929 where he noted that the adjacent Daintree River was in flood. Widespread loss of coral cover in the Whitsunday area associated with the major floods of January 1918 (the 'Mackay' cyclone) in the Whitsunday's area, was reported by Rainford (1925) and Hedley (1925). Anecdotal accounts of freshwater at the surface eight miles offshore were also recorded. The probable effects of wind direction on plume dispersion were noted at this time. Pickard et al. (1977) noted that the bulk of river run-off occurs during a few short-lived floods.

High concentrations of dissolved nutrients were recorded off Townsville and in Bowling Green Bay, up to 50 km north of the Burdekin River mouth for periods of two or more weeks during the 1977–78 wet season (Revelante & Gilmartin 1982) and following cyclone Charlie in 1988 (Liston 1990). These concentrations decreased as a result of uptake by local phytoplankton and zooplankton populations, which developed a pronounced bloom in response to the increase in available nutrients. On Boulder Reef, off Cooktown, Davies and Hughes (1983) found elevated levels of suspended sediments during cyclone Dominic, which they surmised, were derived from the transport of terrigenous clays from the flood plumes of the Endeavour River.

Burdekin River plumes in the flood events of 1980 and 1981 (Wolanski & van Senden 1983; Wolanski & Jones 1981) resulted in lowered salinity from the mouth of the river north to Cairns and 40 km across the GBR lagoon.

Cyclone Winifred (1 February 1986) was a severe tropical cyclone with maximum wind gusts of 198 km/hr (Gagan et al. 1987) that crossed the coast south of the Johnstone River. It caused heavy rainfall and near record flooding (5715 m^3/s) of the Johnstone River. The resultant large freshwater plume from Winifred caused reductions in shelf waters with measured salinities ranging from 10 to about 35. Geographic influence of the bio-physical impacts of Winifred was largely restricted to areas between Cooktown and Cairns. Short-term, extreme changes were noted to be increased turbidity, nutrient resuspension and changes in current patterns (Done et al. 1986). Long-term changes were related to plant and animal succession (Furnas & Mitchell 1986). Water quality sampling following Winifred showed concentrations of inorganic nitrogen species were readily detectable and often quite high (> 1 μM) with chlorophyll concentrations up to 18 μg/L (Furnas 1989).

Table 2. History of cyclones and significant flood events in the Great Barrier Reef and their biological impacts

Year	Cyclone	Duration of Flooding	'Rivers'	Wind Speed/ Direction	Sampling Dates/Areas	Observed Effects
1918	'Mackay'	22/1/18–29/1/18	Pioneer Don Burdekin	Lowest pressure recorded was 933hPa	'Observations' at Port Denison 3.6 m storm surge into Mackay	Storm surge: 4 m Freshwater at sea (8 miles from land) Loss of coral cover on Stoney Reef (Hedley 1925; Rainford 1925)
1932			Daintree			Low Isles (Orr 1933)
1934		12/3/34		SE-NE	Low Isles	Changes to geomorphology and death of coral (*Montipora, Porites*) clams (*Hippopus*) Changes in community structure post event (Moorhouse 1936)
1943					5/6/44	Observations of physical damage to various reefs (Gleghorn 1947)
1977	'Otto' 'Keith'		Wet Tropics		GBR central lagoon	Phytoplankton blooms (Pickard et al. 1977)
1977–78	'Peter'	1/01/79 – 10/01/79	Wet Tropics		GBR central lagoon	Phytoplankton blooms (Revelante & Gilmartin 1982)
1979	Kerry	13/3/79–6/3/79	Burdekin	Wind gusts reached 76 knots	Adjacent and north of Burdekin catchment	Measurements of low salinity (Wolanski & Jones 1981)
1981			Burdekin			Measurements of low salinity (Wolanski & van Senden 1983)
1983	Dominic				6/4/83–11/4/83	Sedimentation at Endeavour Reef (Davies & Hughes 1983)

Table 2 cont.

1986	Winifred			175 km/hr Central pressure of 958 hPa SW–SE (1/2/86) NE-N (2/2/86)	Inshore and offshore Central	Sediment resuspended and moved across shelf (Gagan et al. 1987, 1990) Phytoplankton blooms (Furnas & Mitchell 1986)
1988	Charlie			Cape Bowling Green recorded 981hPa. Wave heights up to 3.1 m	Inshore Central	(Brodie & Furnas 1996) (Liston 1990)
1989	Aivu	Pioneer and Proserpine Rivers		959 hPa recorded 20 km from coast	Inshore and Offshore Central	3 m storm surge in Upstart Bay

Gagan et al. (1987) showed that most of the terrestrial plant detritus from the Johnstone and other Wet Tropic rivers, during floods associated with cyclone Winifred, was deposited close to the coast with none being detected further than 15 km offshore. From their study, based on carbon isotope ratios of organic matter in shelf sediment before and after the cyclone, they concluded that terrestrial run-off has not reached the mid- and outer-shelf reefs of the GBR in historical times except possibly during major Burdekin River floods. While noting the possible modifying effects of water circulation patterns on plume dispersal they did not specifically address the effects of the wind regime on the extent of influence of the flood plumes (Gagan et al. 1987). In a subsequent paper, based on shelf sediments collected immediately before and after the passage of cyclone Winifred, they demonstrated extensive sediment transport which occurred during the cyclone due to shelf sediment resuspension (Gagan et al. 1990). This study showed that tropical cyclones provide an alternative method of transporting fine-sediment and nutrients within the GBR.

Following cyclone Ivor in 1990, direct physical damage, included damage to the reef matrix, dislodgment of massive coral heads, stripping of soft corals and breaking of hard corals, occurred (van Woesik et al. 1991). There was also indirect damage from burial by sediments re-suspended during the cyclone.

Cyclone Joy (1990–91), produced significant floods in most rivers between the Barron and Fitzroy rivers (Keane 1992). Floods from the Burdekin and Fitzroy rivers lasted for a number of weeks. In the associated plume, salinity dropped to 22, 25 km east of Magnetic Island with concurrent rises in chlorophyll concentrations, a change in dominant phytoplankton species to diatoms and the presence of enhanced larval fish populations (Thorrold & McKinnon 1995; McKinnon & Thorrold 1993).

Following the major flooding in the Fitzroy River catchment from cyclone Joy (Brodie & Mitchell 1992; Prekker 1992), low-salinity plume water was observed offshore for a period of three weeks (O'Neill et al. 1992). Low-salinity water (down to 8) caused significant coral mortality (van Woesik et al. 1995; van Woesik 1991) to the fringing coral reefs around the Keppel Islands. In the Capricorn-Bunker group of reefs, more than 200 km from the mouth of the river, salinities as low as 28 were recorded and some damage to corals was observed

(Prekker 1992). Winds appeared to be a major factor influencing the movement of the plume on the shelf. During the first two weeks of the flood, fresh south-easterly winds prevailed and the plume was held close to the coast and moved to the north. In the third week of the flood the winds weakened and shifted to the north. During this period, large lobes of the plume broke away ('calving') and moved southeast toward and into the Capricorn-Bunker area (O'Neill et al. 1992).

3. METHODOLOGY

3.1 Flood Plume Monitoring Program

Studies of Queensland rivers and their plumes in flood conditions are made difficult by access roads becoming untrafficable, rough seas associated with cyclonic winds, dangerous wind conditions for sampling and the difficult logistics of sampling with minimal preparation time. These difficulties partly explain the small number of studies of water quality conditions in plumes. The Great Barrier Reef Marine Park Authority, in conjunction with other agencies, manages a multi-institutional research effort to collect quantitative information on the composition and spatial dynamics of flood plumes. The sampling methodology was initially designed to sample flood events and at this stage seven GBR cyclones and their associated floodwaters have been mapped and sampled for water quality data between 1991 and 1999. Data from this flood monitoring program describes the water quality conditions of plumes and the movement, distribution and composition of these flood plumes.

Sampling methodology is highly dependent on the particular event, where it is, where it floods and how fast the plume moves offshore. In setting up this flood program, sampling has been ad hoc and updated as different techniques and strategies in sampling of the flood plumes have evolved. Differences in sampling strategies for each plume is a consequence of the difficulties associated with sampling under extreme weather conditions and the unpredictable spatial and temporal nature of tropical cyclones. The nature of this study means that sampling must be undertaken in less than ideal conditions.

Water samples were taken in cyclonic flood plumes over a period of three to five days. The main objective of the sampling was to take water samples of the initial intrusion of the freshwater plume to inshore waters and to identify concentration gradients of water quality parameters (salinity, temperature, dissolved inorganic, organic and particulate nutrients, suspended solids and chlorophyll *a*). Salinity and temperature depth profiles were recorded.

This flood sampling program has an evolving, flexible design, and will continue to change as more information becomes available following each new flood event. The current design will contribute to a more complete database of flood plume characteristics. Eventually it may be possible to link land use and catchment characteristics with the composition of the plume and to estimate the short and long term effects of flood water impingement on reef biota.

3.2 Aerial Mapping and Distribution of Flood Plumes

Over the monsoonal season, weather reports were monitored closely and all low pressure rain depressions monitored. The onset of a rain depression /cyclone was the catalyst for a rapid sampling plan to be activated. As soon as logistically possible after the onset of flooding, mapping of the flood plume, and sampling of water quality parameters commenced. Aerial surveillance was used to define the geographical limits of the plume and in some instances, movement of the plume over a period of days.

Flood plumes associated with cyclone Joy (1991), cyclone Sadie (1994), cyclone Violet (1995), cyclone Ethel (1996), cyclone Justin (1997), cyclone Sid (1998) and cyclone Rona (1999) were mapped on flights along and outwards from the coast. Plumes are readily observable as brown turbid water masses contrasting with cleaner seawater (figure 9). The locations of the plume fronts were fixed with geographic positioning systems (GPS) and loaded into a geographic information system (GIS) where the approximate spatial extent of the flood waters is presented.

3.3 Long term Patterns of Cyclones and Rainfall

Climate conditions and seasonal variation is controlled by sea-surface temperature, sea-level pressure, surface winds, tropical cyclones and rainfall and river flow for adjacent areas (Lough 1994). Frequency of cyclones and plumes are related to the wet and dry seasonal pattern, which is in turn controlled by the El Ninõ/Southern Oscillation (ENSO). For Queensland, the associations between rainfall and ENSO vary with season, region and through time. Generally, times of 'weak' Southern Oscillations are known to be of less variable rainfall in Queensland and also times of weaker associations between Queensland rainfall and other climatic variables (Puotinen et al. 1993; Lough 1992). During times of strong development of the Southern Oscillation, rainfall variations show a greater amount of co-variation in space and within the monsoon season than at times of weak Southern Oscillation development. The shift of the summer monsoon circulation away from the north-eastern Australia during ENSO years also dramatically impacts tropical cyclone activity along the GBR. During an ENSO year, the number of tropical cyclones drops to two with about 2.5 tropical cyclone days. This relates to years, such as late 1991–1994, where there was very little rainfall and no real plume development. During anti-ENSO years the level of tropical cyclone activity increases, with, on average, about 7.5 tropical cyclones and 8.5 tropical cyclone days in the region of the GBR (Lough 1994).

Figure 9. Observable plume in aerial flyover. Edge of plume defined by series of latitudinal and longitudinal points (Russell-Mulgrave River plume)

3.4 Water Sampling

Water samples were collected from multiple sites within the flood plume. Location of samples were dependent on which rivers were flooding and the areal extent of the plume but generally samples were collected in a series of transects heading out from the river mouth, with additional samples taken in between river mouths if more than one river was in flood. Transects and station locations are shown in figures 11–19. Time of sampling was also dependent on the type of event and how quickly boats were mobilised. The majority of samples were collected inside the visible area of the plume, though some samples were taken outside the edge of the plume for comparison. Range of analyses and the parameters measured in the plumes are presented in table 3. Depth, number and location of samples were dependent on the extent and area of the flood plume.

Table 3. Sampling strategies of each plume event

CYCLONE	Joy	Sadie	Violet	Ethel	Justin	Sid	Rona
Salinity	profile	profile	profile	profile	profile	profile	profile
Temperature	profile	profile	profile	profile	profile	profile	profile
Water samples	profile	profile	profile	surface	surface	surface	surface
				Water analyses			
DIN	√	√	√	√	√	√	√
DIP	√	√	√	√	√	√	√
DON	√	√	√	√	√	√	√
PN	√		√	√	√	√	√
PP	√		√	√	√	√	√
SS	√	√	√	√		√	√
Chl *a* Phaeo	√	√	√	√	√	√	√

Note: 'profile' denotes where samples were taken through the water column and 'surface' denotes where samples where taken within the first 0.5 m of the water surface. √ denotes that the analysis was done for that parameter.

Surface samples were collected at 0.5 m below the surface, with either a reversing thermometer Niskin bottle or a rinsed clean sampling container with temperature measured by thermometer. Samples taken at depth were collected with Niskin bottles. Salinity and temperature profiles were measured at all sites with a YSI salinity meter. Secchi disk clarity was determined at each station.

Water samples for nutrient and chlorophyll analysis were collected, filtered and stored for further analysis. Volumes filtered for all analyses were dependent on the turbidity of the water. Subsamples were filtered through GF/F (glass fibre) filters for chlorophyll and phaeophytin, the filter and retained algal cells were wrapped in aluminium foil and frozen. The second subsample was filtered through pre-weighed 0.45 µm membrane filters for suspended solids. The third subsample was filtered through pre-combusted GF/F for particulate nutrient analysis, wrapped in aluminium foil and frozen.

Dissolved nutrient samples were collected using sterile 50 ml syringes, pre-rinsed three times with the seawater to be sampled. A 0.45 µm disposable membrane filter was then fitted to the syringe and a 10 ml sample collected in tubes pre-rinsed in filtered water. Tubes were placed upright in tube holders, which were then stored either on ice in an insulated container or in a freezer dependent on the sampling vessel. Further samples were taken in tubes for silicate analysis and stored at room temperature. Samples were analysed for dissolved inorganic nutrients (NH_4, NO_2, NO_3, NO_2 + NO_3, PO_4 and Si) and Total Dissolved Nitrogen and Phosphorus (TDN, TDP).

3.5 Analytical Methods

Dissolved inorganic nutrient concentrations were determined by standard procedures (Ryle et al. 1982) implemented on a Skalar 20/40 autoanalyser, with baselines run against artificial seawater. Immediately prior to analysis, the frozen samples were thawed to room temperature. Dissolved organic nitrogen (DON) and phosphorus (DOP) concentrations were calculated by difference after seven hours oxidation of the samples with high intensity UV light (Walsh 1989) and measurement of the total dissolved nitrogen or phosphorus.

Particulate nitrogen concentrations of the particulate matter collected on the GF/F filters were determined by high temperature combustion using an ANTEK Model 707 Nitrogen Analyser. The filters were freeze dried before analysis. Following primary (650°C) and secondary combustion (1050°C), the nitrogen oxides produced were quantified by chemiluminescence.

Particulate phosphorus was determined colorimetrically (Parsons et al. 1984) following acid-persulfate digestion of the organic matter retained on the glass fibre filters. Acid-wash glass mini-scintillation vials were used as reaction vessels. Filters were placed in the vials with 5 ml of 5% w/v potassium persulfate and refluxed to dryness on an aluminium block heater using acid-washed marbles as stoppers for the vials. Following digestion, 5 ml of deionized water was added to each vial and the filter and salt residue resuspended and pulverized to dissolve all soluble material. The residue in the vials was compressed by centrifugation and the inorganic P determined colorimetrically in aliquots of supernatant. Inorganic and organic P standards were run with the batch of samples.

Chlorophyll *a* and phaeophytin concentrations were determined by fluorescence following maceration of algal cells and pigment extraction in acetone (Parsons et al. 1984). A *Turner 10-005R* fluorometer was used for analysis and was periodically calibrated against diluted chlorophyll extracts prepared from log-phase diatom cultures (Jeffery & Humphrey 1975). Blanks were also run routinely over the analysis period (Devlin & Lourey 1996).

Suspended solids concentrations were determined gravimetrically from the difference between loaded and unloaded membrane filter weights after drying the filters overnight at 60°C. Wet filter salt blanks were subtracted from the resulting weight.

4. RESULTS

4.1 Movement and Physical Characteristics of Flood Plumes

The cyclone-associated plumes that have been mapped are as follows:

• Joy (1991)	Fitzroy River coast
• Sadie (1994)	Wet Tropics coast
• Violet (1995)	Wet Tropics coast
• Ethel (1996)	Wet Tropics coast
• Justin (1997)	Wet Tropics coast and Burdekin River coast
• Katrina (1998)	Wet Tropics coast
• Sid (1998)	Wet Tropics coast and Burdekin River coast
• Rona (1999)	Wet Tropics coast

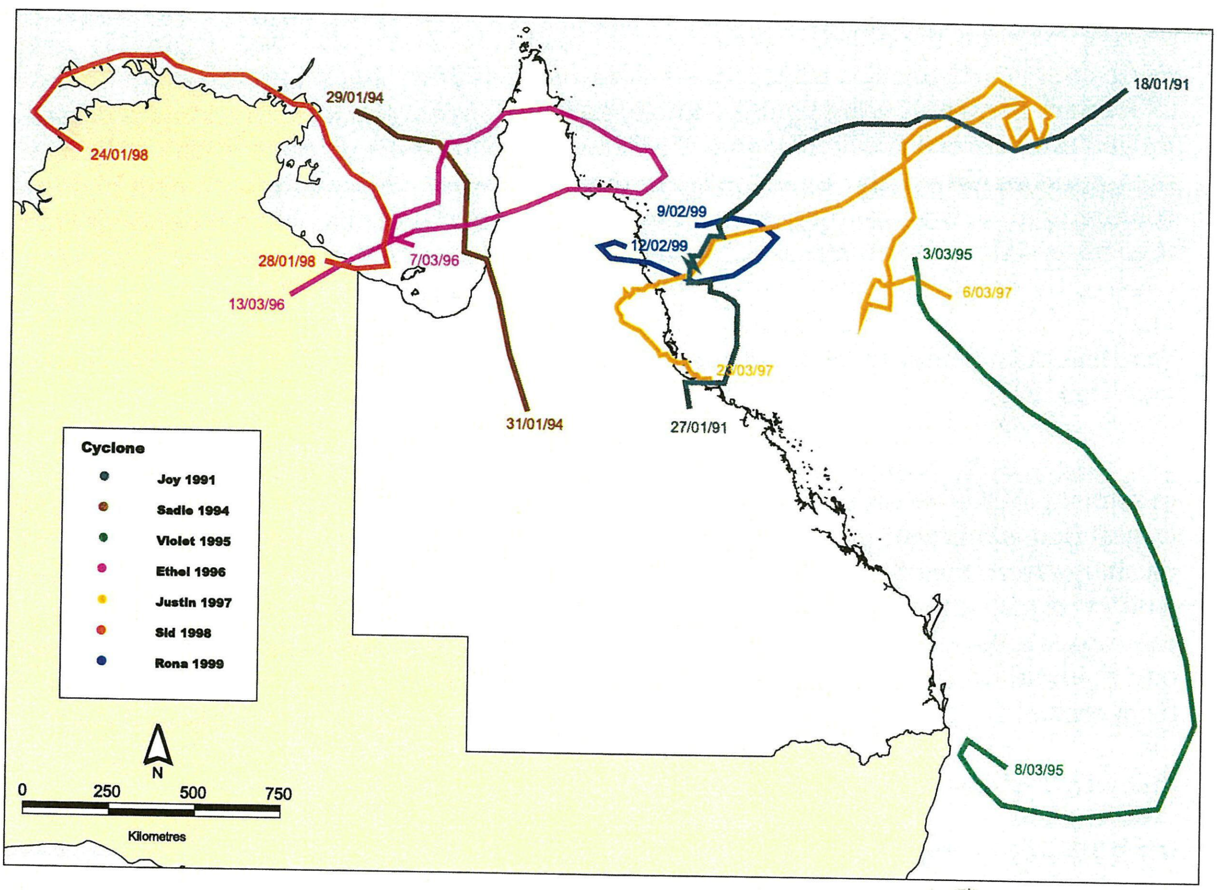


Figure 10. Tracks of cyclones over the Queensland coast

Each event has a range of conditions that affects the cross-shelf and latitudinal dispersion of the plume, including magnitude and duration of the rainfall event, wind strength and direction. Catchment characteristics can also have a defining role in extent and composition of the plume.

Table 4 shows a summary of characteristics for the parameters measured in each plume, including wind direction and strength, rainfall and flow rate, duration of event and time of sampling. Table 5 relates monitored biological changes from the impacts of these flood plumes on the GBR.

Sites sampled within each plume are presented in figures 11–19 over the areal extent of each plume. Wind direction and speed are presented for the day(s) that the aerial extent of the plume was mapped with an arrow and with numeric wind speed. Each cyclone has a set of wind characteristics, acting with other physical forces, that creates a specific type of plume distribution.

4.1.1 January 1991 – Cyclone Joy

On the 26 December 1990, severe tropical cyclone Joy crossed the eastern Australian coast near Ayr. The cyclone subsequently turned into a rain depression, causing widespread flooding throughout various sections of the Fitzroy, Pioneer and some parts of the Burdekin river catchment. The 1991 Fitzroy flood, which resulted in more than 18.5 million megalitres of flood waters, was the third largest on record (Byron & O'Neill 1992; Keane 1992).

During the initial period of high discharge (30 December–13 January), the predominant winds over the southern GBR were south-easterlies of moderate strength (~12 knots). During this time, the plume was constrained relatively close to the coast (figure 11) moving north and was distinctly visible at least as far north as Port Clinton. From 14 January until 27 January the winds were light (~6 knots) and predominantly northerly and the plume moved offshore eventually reaching the Capricorn Island Group. After reaching the area of the Capricorn Group, the leading edge of the plume was still quite distinct, with highly coloured plume water and carrying a number of terrestrial plants. The plume water was then observed to flow in an easterly direction through the Wistari Channel and quickly covered the south-east reef flat of Heron Island (O'Neill et al. 1992; Prekker 1992). The Fitzroy plume reached the Capricorn-Bunker reef system at a distance of 200 km from the coastline in late January 1991, with reductions in salinity levels to 27 at the Capricorn reefs (Prekker 1992).

The Fitzroy is the second largest river outflowing along the east coast of Australia and its catchment area is exceeded in area only by the Murray-Darling system. This was one of the largest floods this century with flow rates and volume discharged greatly exceeding discharge from the other studied cyclones in this monitoring program. The Fitzroy plume study was also unusual in that it was not associated with cyclonic wind conditions, which can cause resuspension of bottom sediments from relatively deep water. Where such events occur simultaneously with the flood plumes it is difficult to separate the fluxes of nutrients from each of the three possible sources – flood, rain and resuspension. Samples taken in the plume (12–23 January 1991) were representative of the particulate and dissolved material that was discharged from the flooding Fitzroy River.

4.1.2 February 1994 – Cyclone Sadie

Cyclone Sadie formed as a weak tropical cyclone in the north-western Gulf of Carpentaria and moved in a south-east trajectory (figure 10) towards central Queensland in late January 1994. The rain depression caused by the cyclonic low-pressure system resulted in rising river water levels and subsequent discharge into the GBR lagoon from rivers between Townsville and Cooktown. North-east winds aided in dispersing the resulting plume 60–100 km offshore where it impinged on many mid-shelf coral reefs (figure 12).

A transect was sampled within the cyclone Sadie plume from the Brook Islands to the Russell-Mulgrave River with further sampling being concentrated around the Barron River (figure 12). Water quality parameters measured included dissolved nitrogen and phosphorus species, chlorophyll *a*, suspended solids and salinity and a range of in situ readings (temperature, secchi depth, weather conditions) (Devlin & Lourey 1996).

Table 4. Flood plumes and summary of characteristics

Year	Cyclone	Duration of flooding	Rivers	Total flow (Megalitres)	Average flow/day	Wind Speed[2] (knots) and direction	Sampling areas	Sampling dates	Aerial flyover
1991	Joy	26/12–31/1/91	Fitzroy Burdekin	1 7148 000		< 5 NW/NE	Inshore and offshore Fitzroy River	17-18/1/1991	12/1/91 19/1/91 23/1/91
1994	Sadie	30/1/94–4/2/94	Wet Tropics[1]	808 929	134 821	< 10 NW/NE < 10 NW/NE	(1) Barron mouth–Fitzroy (2) Offshore Herbert–Tully	1/2/94 4/2/94-5/2/94	1/2/94–2/2/94
1995	Violet	25/2/95–2/3/95	Wet Tropics	794 766	132 461	10 SE/SW < 5 SE	Wet Tropics (2) Offshore Herbert–Tully	1/3/95-2/3/95 2/3/95	28/2/95
1996	Ethel	5/3/96–10/3/96	Wet Tropics	1 827 959	304 659	10–15 S/SE 5–10 SE	(1) Barron mouth–Green Island (2) Daintree mouth–Snapper (3) Tully-Herbert	5/3/96-6/3/96 7/3/96 18/3/96	6/3/96
1997	Justin – 1		Pioneer Burdekin	59 433 805 683	9906 134 280	10–15 SE	Burdekin mouth–south of Townsville	4/3/97-5/3/97	4/3/97
1997	Justin – 2		Wet Tropics Burdekin	1 040 203 2 102 423	173 367 350 403	10–20 N/NW	Wet Tropics	24/3/97-27/1/97	25/3/97
1998	Sid		Wet Tropics Burdekin			10 SE 15–25 E 5–10 NE 10 SE	Wet Tropics Burdekin Magnetic Is.–Pandora Russell-Mulgrave mouth-Franklins	13/1/98-14/1/98 15/1/98-16/1/98 22/1/98-23/1/98 27/1/98	13/1/98 21/1/98
1999	Rona		Wet Tropics			10 NE-SE 10 SE	(1) Wet Tropics (2) Offshore Herbert–Tully	16/2/99-19/2/99	14/2/99

[1]Wet Tropics rivers refer to the Barron, Russell-Mulgrave, Johnstone, Tully and Herbert rivers. [2]Wind data supplied from Bureau of Meteorology

Plumes associated with cyclone Sadie from Wet Tropics Rivers (figure 12) were also unusual among those documented in this report, with weak north-westerly and north-easterly winds allowing the plume to move offshore. A number of studies were carried out during and after cyclone Sadie (Steven et al. 1996) which gave an overall assessment of many of the processes occurring in the plume.

Table 5. Flood plumes and cited biological impacts

Year	Cyclone	Observed effects
1991	Joy	• Intertidal mortality (Barnacles, oysters and gastropods) (Coates 1992) • Coral mortality in Keppel Reefs (Van Woesik et al. 1995) • Impacts on fish spawning aggregations (Thorrold & McKinnon 1995; McKinnon & Thorrold 1993).
1994	Sadie	• Major short-term response: severe bleaching at Pandora Reef, less severe at Orpheus and Brook Islands • Bleaching across wide range of taxa through to 10m depth (Devantier et al. 1997)
1995	Violet	
1996	Ethel	• Bleaching and coral mortality at Snapper Island Reef (Ayling & Ayling 1998)
1997	Justin – 1 &2	
1998	Sid	• Unprecedented coral bleaching on GBR, particularly along inshore fringing reefs (Berkelmans & Oliver 1999)
1999	Rona	

4.1.3 February 1995 – Cyclone Violet

Cyclone Violet formed as an intense tropical cyclone approximately 200 km offshore from Cairns in late February 1995 and moved in a south-easterly direction down the coast. Moderate south-easterlies following the cyclone constrained the resulting plume to within 10 km of the Queensland coastline (figure 13). Plumes from flooding rivers (28 February 1995) moved in a northerly direction. Plumes were segmented and individual rivers observed south of the Herbert and north of Innisfail (figure 13).

Water sampling of the plume during cyclone Violet was pre-planned and undertaken as coordinated effort between a number of agencies. This included a rapid response plan where vessels, personnel and sampling equipment were all on standby in the event of a rain/cyclonic event. Water samples were collected within and adjacent to five rivers at 33 stations (figure 13) on 1 and 2 March 1995 (Steven et al. 1996). The same parameters as those measured in cyclone Sadie were analysed with the addition of particulate nutrients.

4.1.4 March 1996 – Cyclone Ethel

Cyclone Ethel formed as a weak tropical cyclone in the south-eastern Gulf of Carpentaria in early March 1996 and initially moved easterly across Queensland, north of Weipa and then in a westerly direction, back into the Gulf. The resultant depression caused heavy rains over most of the northern Queensland catchments. The area covered by resultant flood plumes was continuous from the Herbert River to the Daintree River. Moderate south-easterlies constrained the plume to within 15 km of the coast, and an aerial flyover was undertaken on 6 March 1996 (figure 14).

The Australian Institute of Marine Science (AIMS) Long-term Monitoring Program opportunistically sampled transects within the Ethel plume from south of Cairns to north of the Daintree River. Samples were analysed for all parameters including dissolved nitrogen and phosphorus species, particulate nutrients, chlorophyll *a*, suspended solids and salinity and a range of in situ readings (temperature, secchi depth, weather conditions).

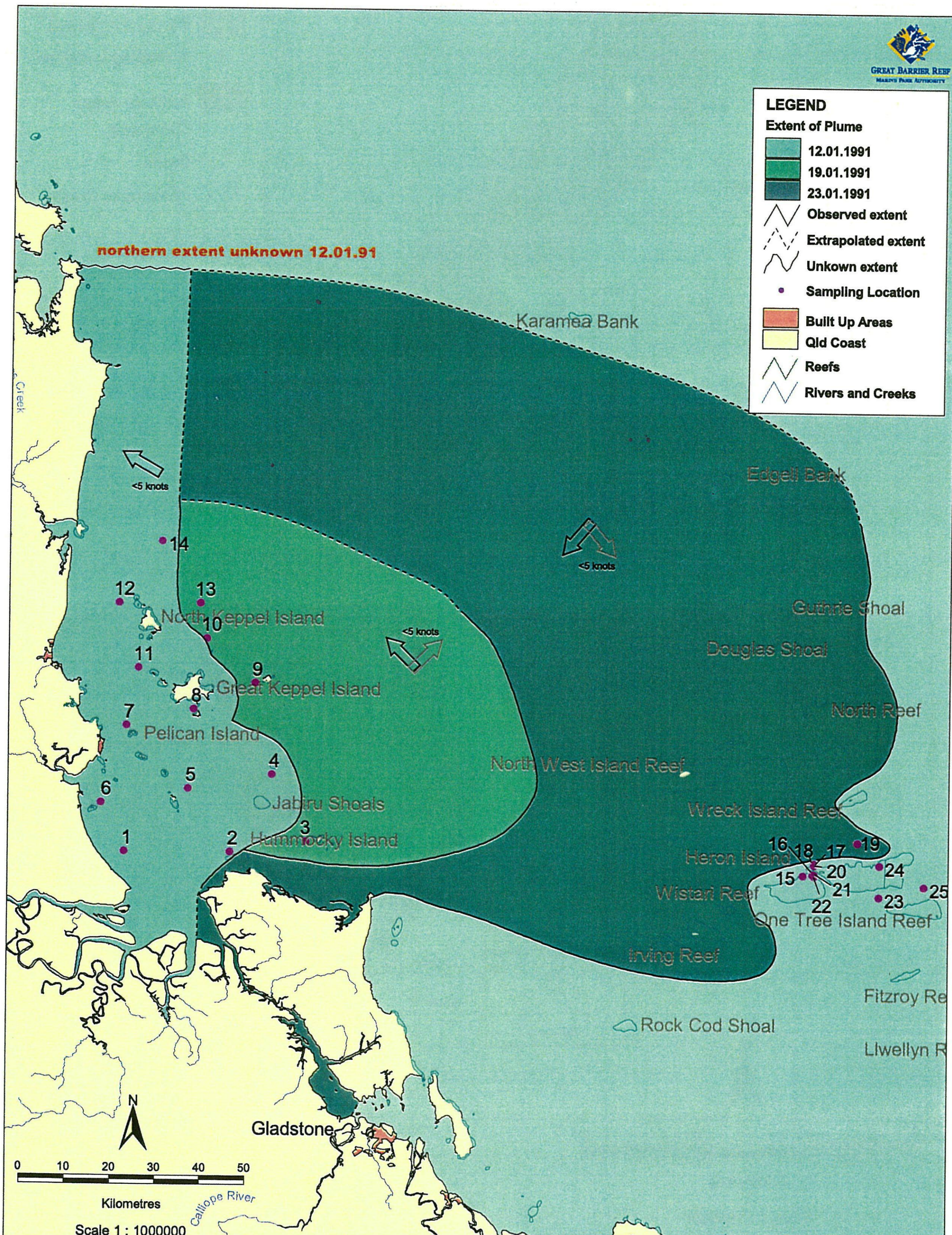


Figure 11. Flood plume associated with cyclone Joy (1991) from the Fitzroy River

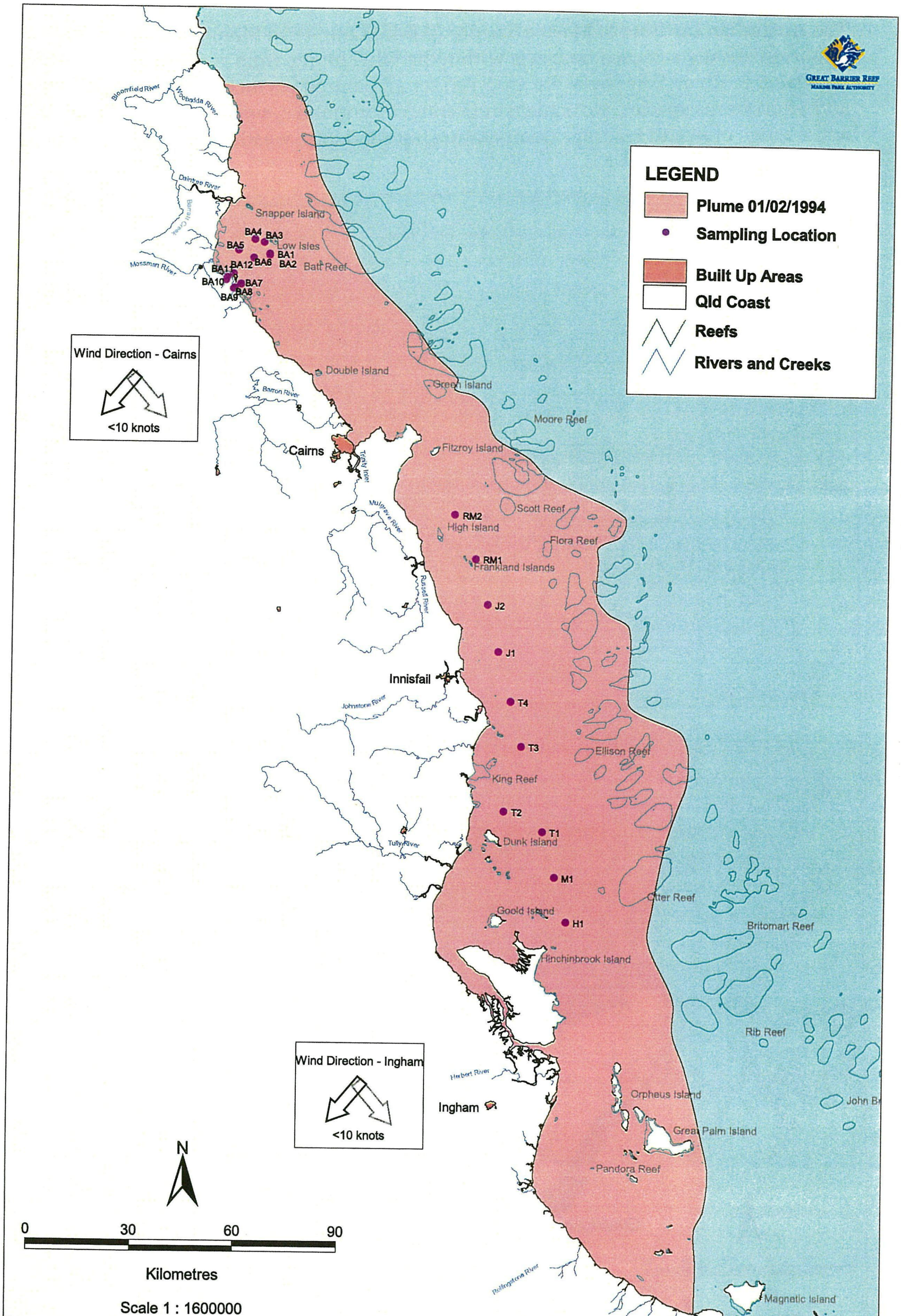


Figure 12. Flood plume associated with cyclone Sadie (1994) from Wet Tropics Rivers

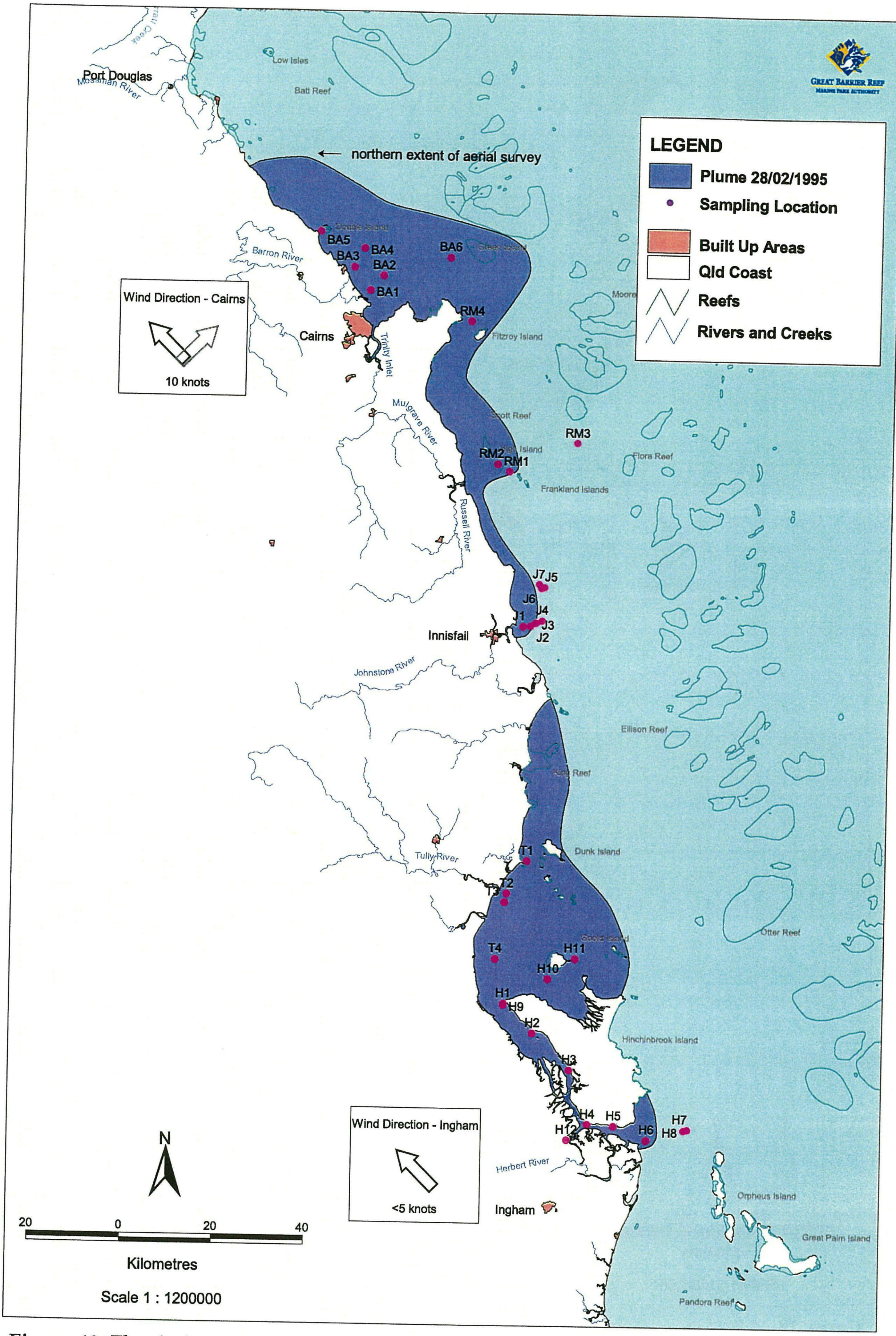


Figure 13. Flood plume associated with cyclone Violet (1995) from Wet Tropics Rivers

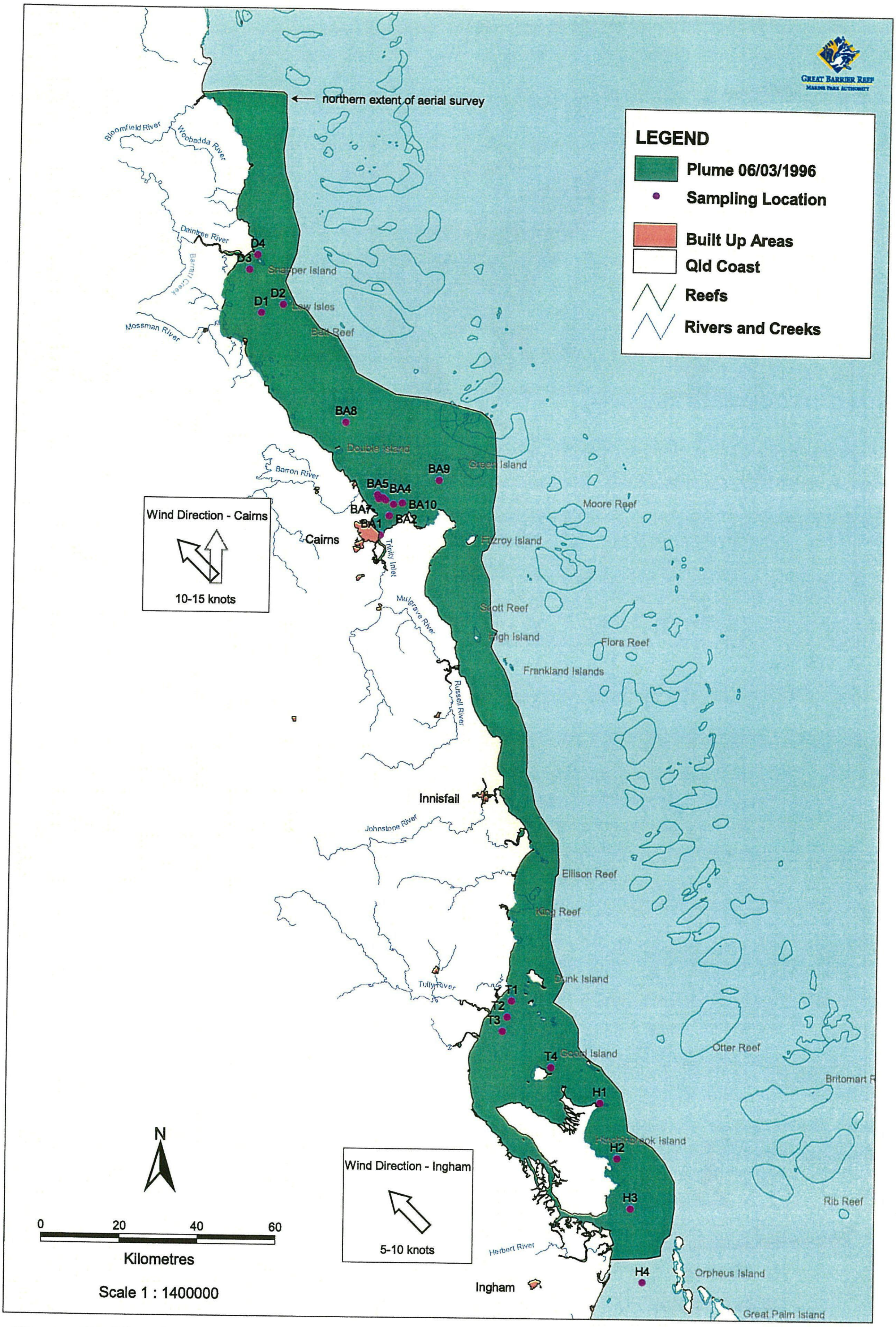


Figure 14. Flood plume associated with cyclone Ethel (1996) from Wet Tropics Rivers

4.1.5 March 1997 – Cyclone Justin

Cyclone Justin developed in the Coral Sea on 7 March 1997, approximately 800 km east of Cairns (figure 10). The cyclone intensified over the next three days, which produced heavy seas along the north Queensland coast. The cyclone subsequently weakened and then intensified as it travelled erratically around the Coral Sea over the next 12 days. It made landfall near Cairns on 22 March, causing widespread wind and rain damage before tracking south and finally moving out to sea south of Townsville as a tropical low. It produced flooding rains to the Queensland coast between Cardwell and Townsville as it moved south. Cyclone Justin was an unusually long active cyclone. It initially created flooding in the Burdekin catchment and then headed out to sea. It reversed direction and came over the coast near Cairns, which created a significant amount of localised flooding in the Wet Tropics area.

Flood plumes discharged from catchments between Townsville and Cairns following cyclone Justin were mapped along and outwards from the Queensland coast on 4 March and 25 March 1997 (figures 15 and 16). Water samples were collected from multiple sites from plumes originating from the Herbert, Tully, Johnstone, Russell-Mulgrave and Barron rivers.

The first part of cyclone Justin resulted in flooding in the Pioneer and Burdekin Rivers in early March 1997 (figure 15). The plume from the Burdekin River moved south, directed by north-easterly winds. This resulted in a plume that moved in a south-easterly direction and covered a number of inshore Whitsunday reefs. In the second part of cyclone Justin (late March 1997), when the Wet Tropics rivers flooded, the wind changed to a south/south-easterly direction and guided the plume northwards along the coast in a similar pattern to Ethel (figure 14) and Rona (figure 19).

4.1.6 December 1997/January 1998 – Cyclones Sid and Katrina

Cyclone Sid developed at the top of Arnhem Land on 26 December 1997 and moved through the Gulf of Carpentaria over the following three days. The cyclone subsequently weakened and formed a rain-bearing depression over land on 29 December 1997 and slowly moved south for the following week. As a rain depression, it caused widespread wind and rain damage in the areas between and including Barron and Burdekin River catchments. There was widespread flooding in these rivers with heavy rains falling on the upper Burdekin catchment, resulting in significant floods south of Ingham and north of Ayr.

Cyclone Katrina developed in the Coral Sea on 3 January 1998 approximately 700 km due east of Cairns. The cyclone intensified over the following week, which produced heavy rains along the north Queensland coast. The cyclone subsequently weakened and re-intensified as it travelled erratically around the Coral Sea.

Water samples were collected from multiple sites from plumes originating from the Burdekin, Herbert, Tully, Johnstone, Russell-Mulgrave and Barron rivers (figure 17). Water samples were collected for an initial three days at the onset of flooding, with further collections off Townsville and the Burdekin over the following two weeks.

Wind direction during cyclone Sid was variable, resulting in a fragmented plume along the coast that generally moved in a northerly direction and strongly constrained to the coastline (figures 17 and 18). The volume of water moving out of the Burdekin River during the event also helped move the plume in a northerly direction. Plumes associated with Sid were relatively long lasting and still visible after two weeks.

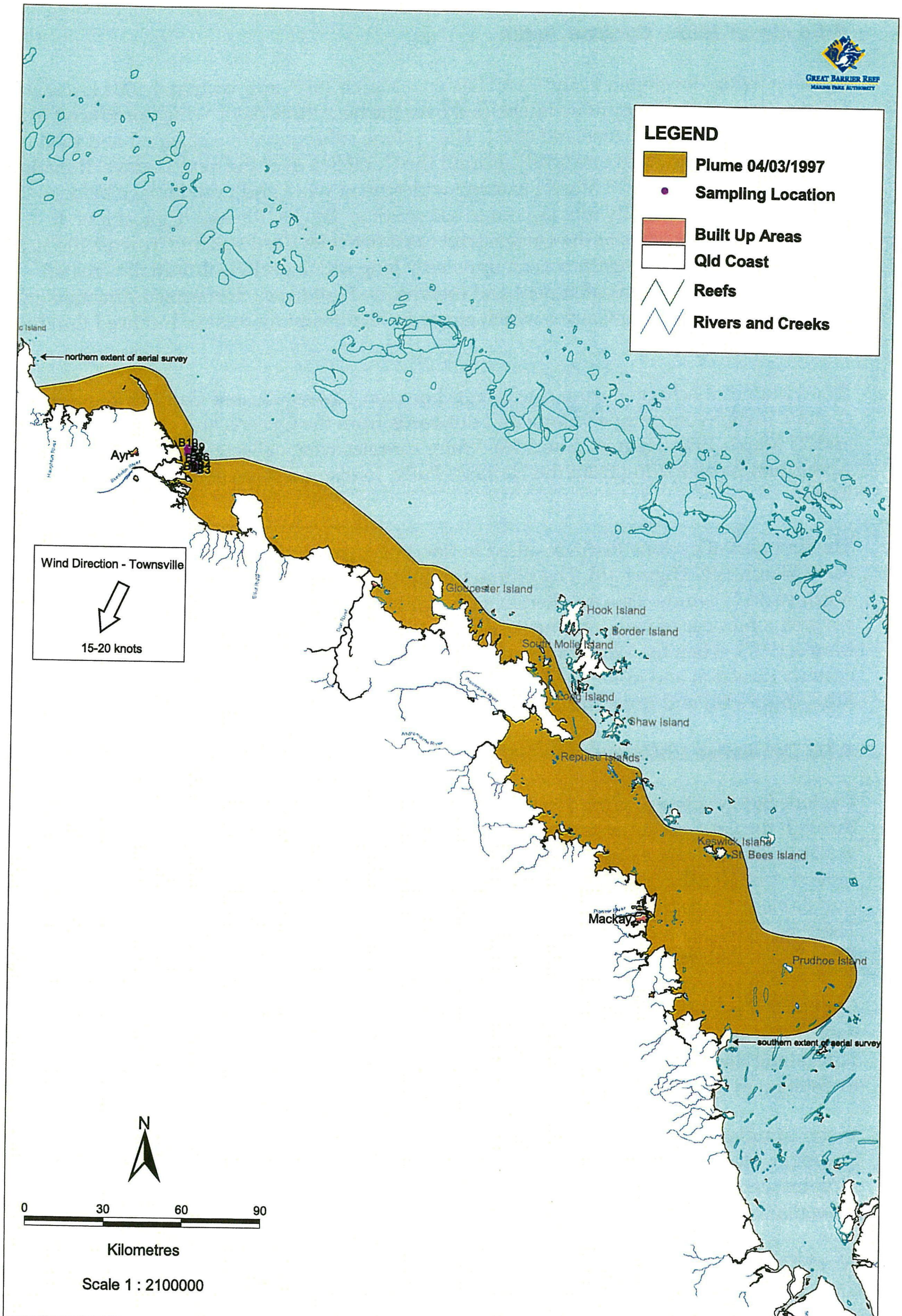


Figure 15. Flood plume associated with cyclone Justin (1997) from Burdekin River

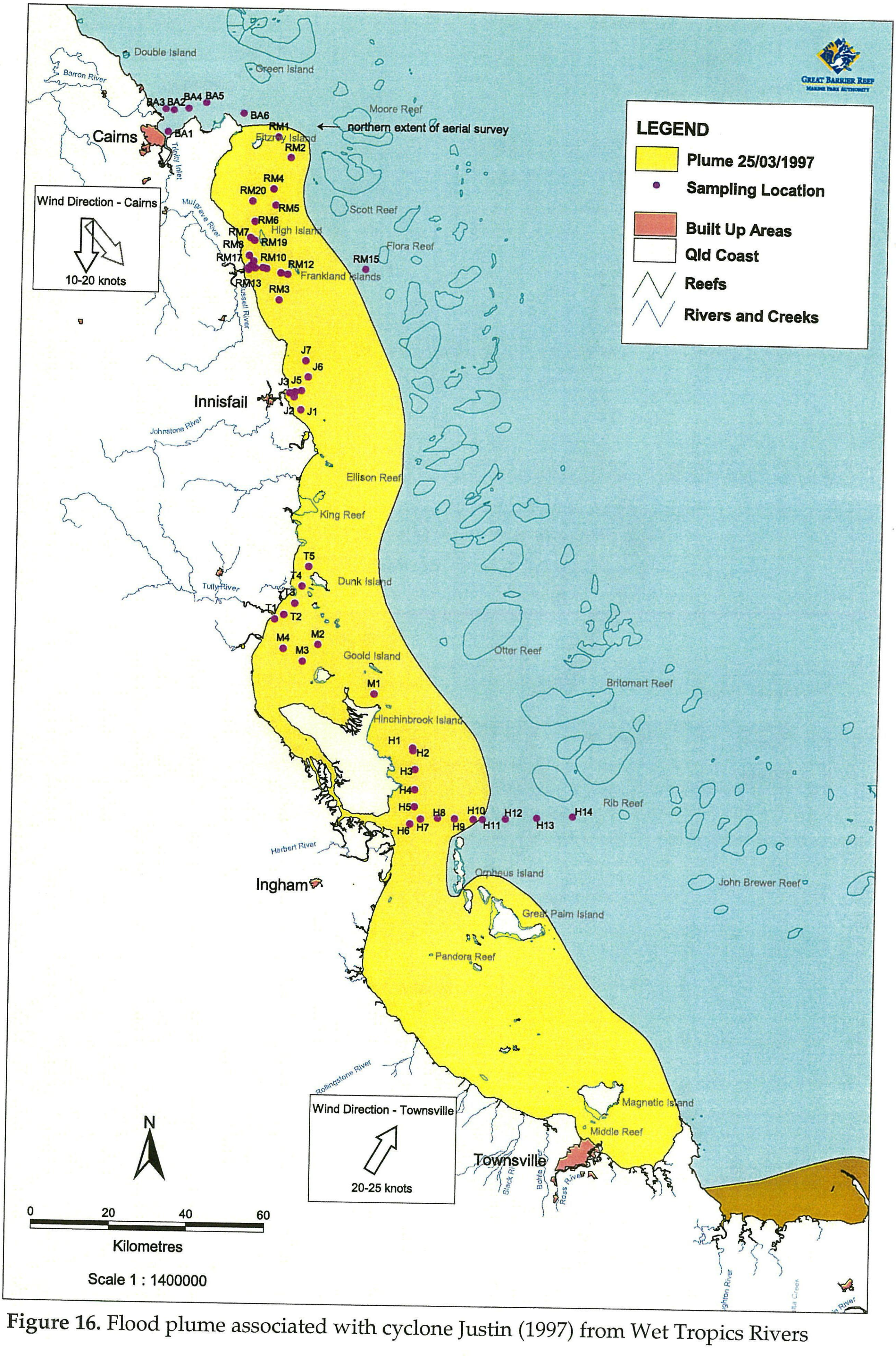


Figure 16. Flood plume associated with cyclone Justin (1997) from Wet Tropics Rivers

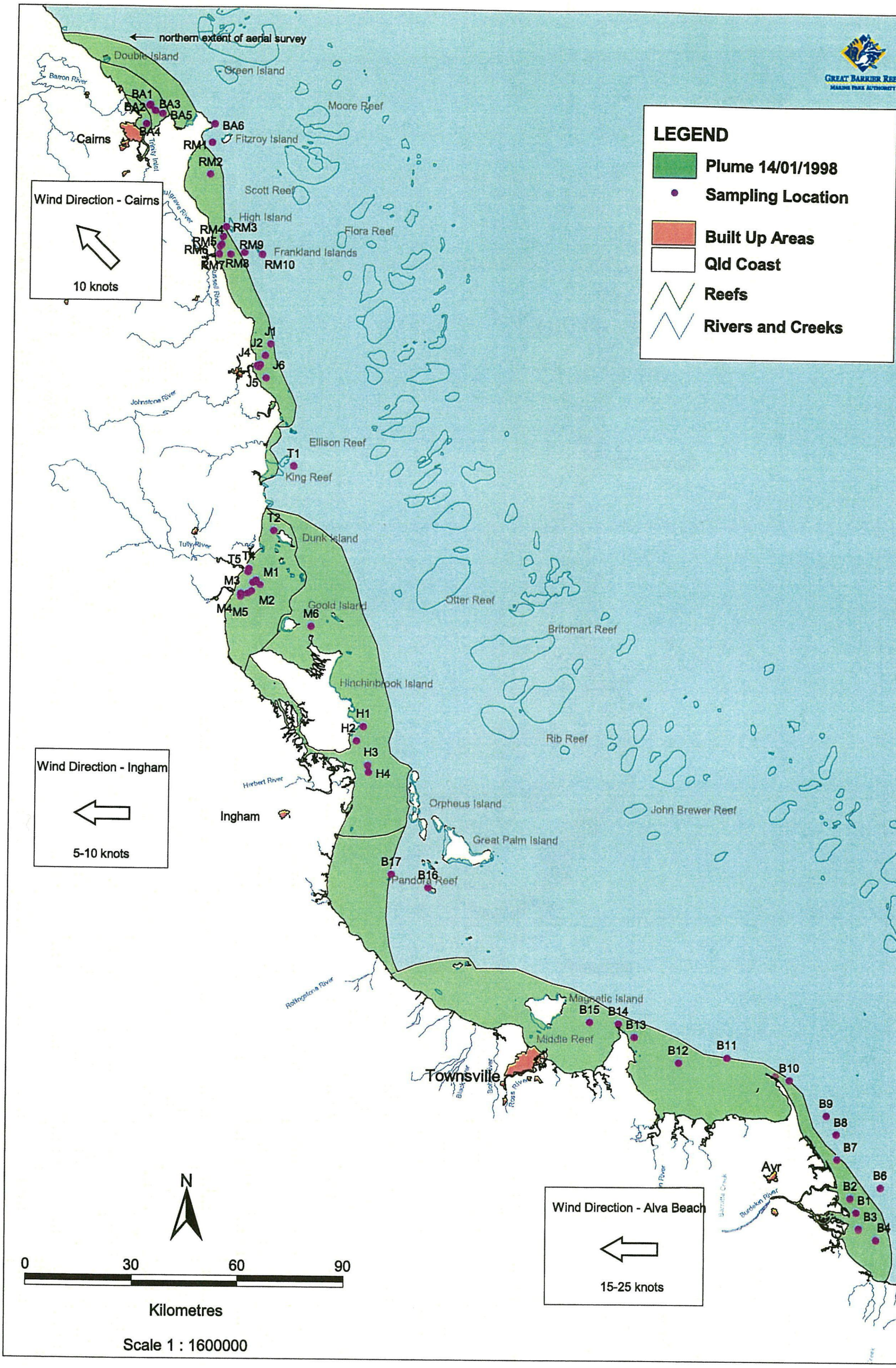


Figure 17. Flood plume associated with cyclone Sid (1998) from Wet Tropics and Burdekin Rivers

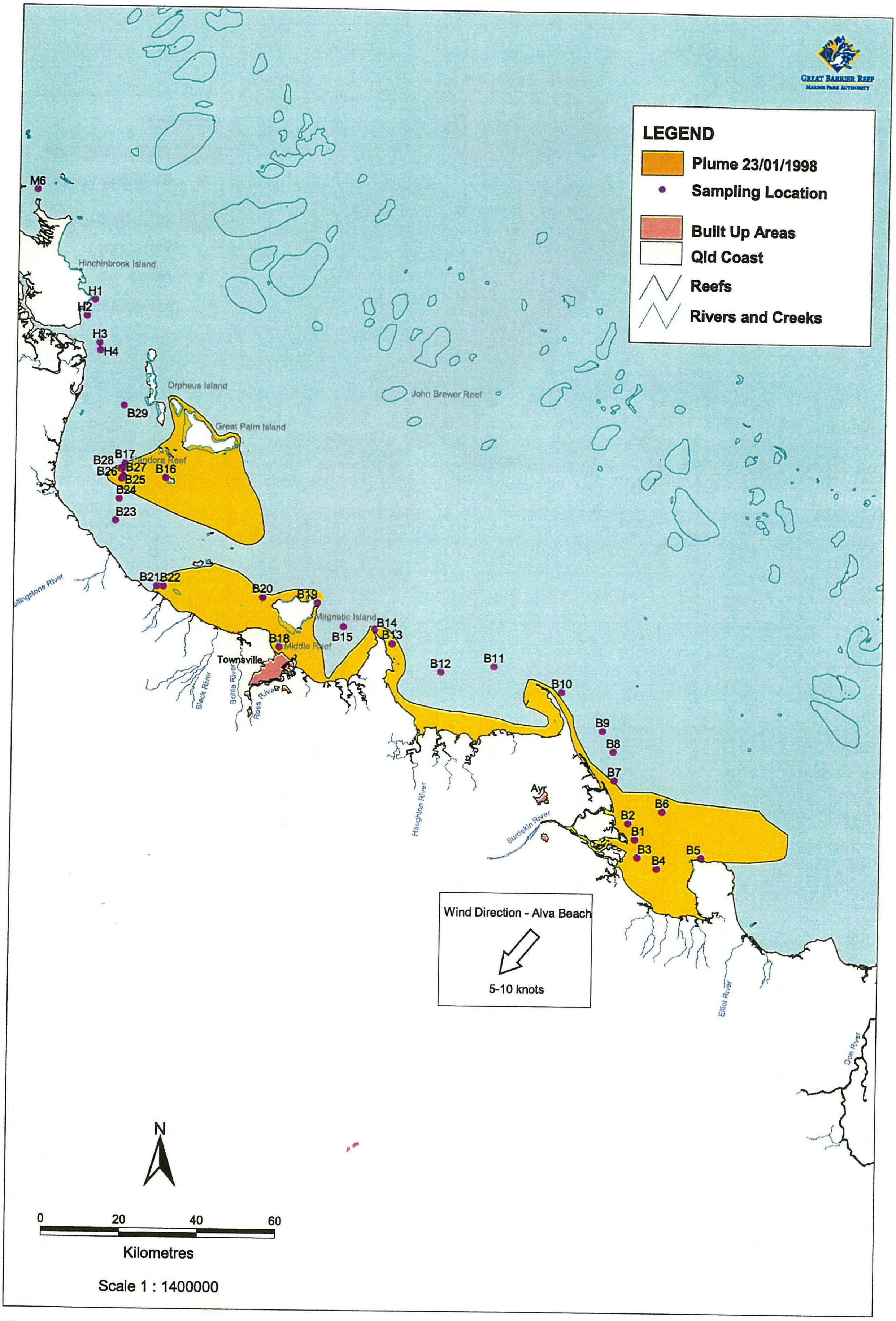


Figure 18. Flood plume associated with cyclone Sid (1998) from Burdekin River

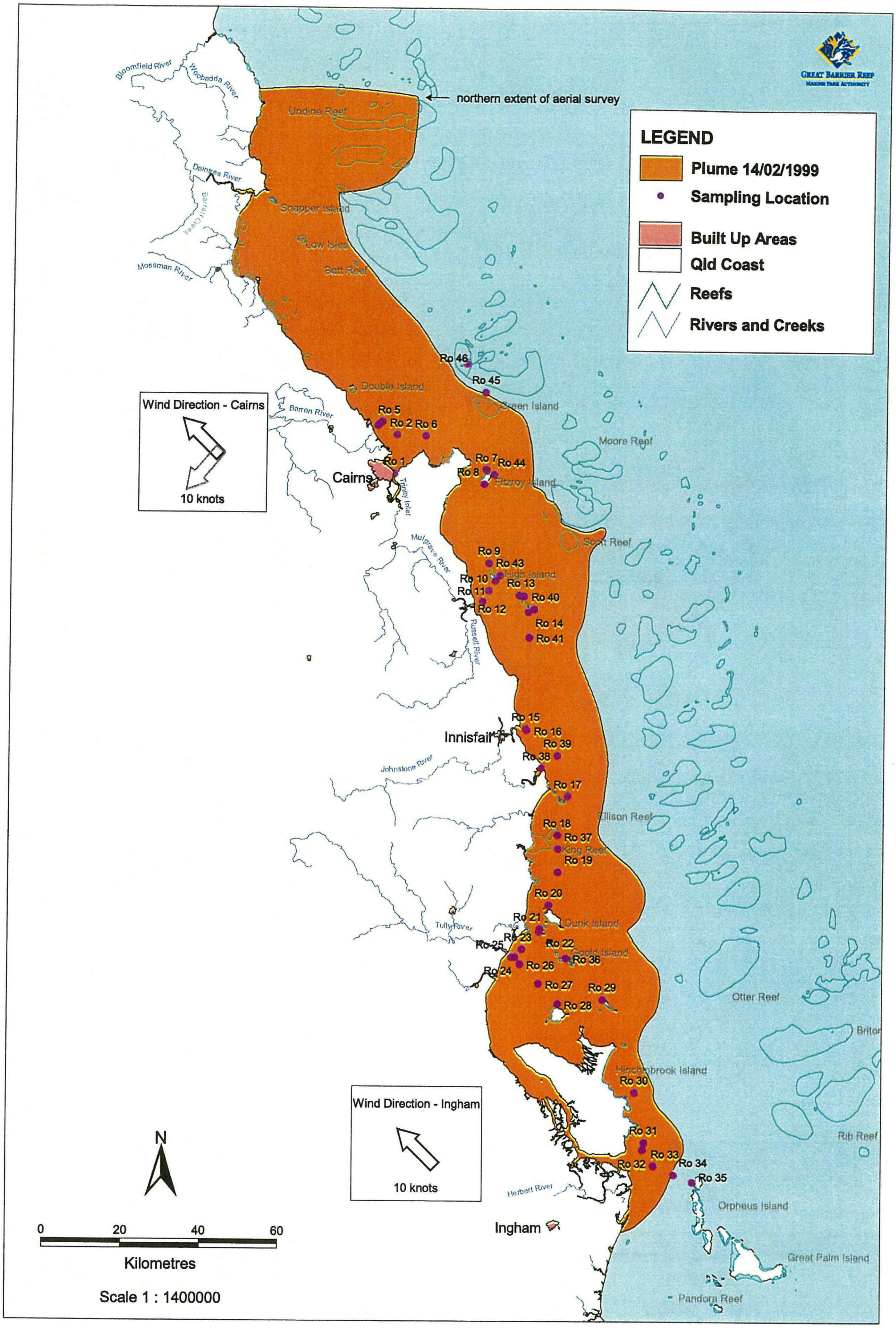


Figure 19. Flood plume associated with cyclone Rona (1999) from Wet Tropics Rivers

Cyclones Justin and Sid were associated with high flow from the Wet Tropics rivers as well as substantial flow from the Pioneer River (Justin) and Burdekin River (Justin and Sid). Large dark plumes moving out from the Burdekin River were mapped on both occasions (figures 15 and 18). This flooding from a large dry catchment resulted in plumes with area coverage that was equivalent to combined plumes discharging from the Wet Tropics rivers.

4.1.7 February 1999 – Cyclone Rona

On 11 February 1999 cyclone Rona made landfall just to the north of the Daintree River. The main wind damage extended from Newell Beach to Cape Tribulation with the major damage between Cape Kimberly and Cape Tribulation. Maximum wind gusts of 71 knots were recorded at Low Isles. Major flooding occurred between Cairns and Townsville. Sampling was undertaken in the plume from the Barron River to south of the Herbert River 16–19 February 1999 (figure 19). The flood plume associated with cyclone Rona was similar to cyclone Violet (Steven et al. 1996) and Ethel (Taylor & Devlin 1997) where discharges from a number of north Queensland Wet Tropics rivers (in particular, the Herbert, Tully, Johnstone, Russell-Mulgrave, Barron and Daintree), merged into a broad plume that extended north from the river mouths (figures 13, 14 and 19).

Previous work has shown (Taylor & Devlin 1997; Devlin 1997; Brodie & Furnas 1996) that the timing of sampling is critical to obtaining reliable estimates of nutrient concentrations in the flood plumes. It is worth noting that aerial mapping and water sampling were usually carried out after the main peak flow, and therefore may not be representative of the total extent of the plume and maximum concentrations. However, the data obtained provides a conservative estimate of flood conditions in the inshore GBR lagoon.

4.2 Plumes, Hydrological Conditions and Distribution of Plume Waters

Movement of the cyclone can also affect the weather conditions that are associated with a flood event. Figure 10 shows tracks of the cyclones studied over the last nine years and the length of time they were active.

Figures 21–28 present plumes from individual catchments, with the position of sites sampled in each plume. The importance of wind as a factor in the distribution of a flood plume has been established in addition to a number of other crucial factors such as river flow rates and catchment rainfall, which can impact on plume extent and coverage. The flow rates and catchment rainfall are presented over the time of the event in figures 21–28. This data was provided by the Department of Natural Resources and the Bureau of Meteorology respectively. Values are taken from the lower most gauging station in each catchment.

4.3 Plumes and Water Quality Processes

Tables 6 and 7 present data collected in flood plumes adjacent and north of Wet Tropics catchments and those adjacent and north of the southern Dry Tropics catchments. This provides a good contrast between smaller river catchments, which flood annually, and a dry river, with a greater catchment area and more infrequent flood events. Concentrations of water quality parameters measured in the plume surface waters are almost always elevated in comparison to ambient water quality concentrations measured throughout the dry season.

Table 6. Minimum salinities and maximum nutrients, chlorophyll and suspended particulate matter concentrations in the Wet Tropics sampled in GBR waters following cyclonic events. Concentrations presented here are from the surface samples (< 1 m).

Cyclone	Sadie	Violet	Ethel	Justin	Sid	Rona	Ambient* (non-flood)
Date	**Feb 94**	**Mar 95**	**Mar 96**	**Mar 97**	**Jan 98**	**Feb 99**	
Shelf region sampled	Central Lagoon	Central Lagoon	Northern Inshore	Central Inshore	Central Inshore	Central Inshore	Cairns
Salinity	6.4	2.2	12.5	0	0	6.3	34.18 ± 0.11
NH_4	3.6	12.8		3.6	9.3	3.13	0.03 ± 0.04
NO_2	0.3	1.2	1.1	.3	.5	0.31	0.03 ± 0.09
NO_3	6.9	14.3	1.3	9.1	4.5	5.27	0.08 ± 0.36
DON	18.4	40.4	9.65	27.1	16.7	12.9	4.9
PN		10.0	10.3	20.3	19.1	17.8	1.6 ± 0.9
DIP	0.5	.31	0.6	2.5	0.6	0.33	0.07 ± 0.27
DOP	0.3	2.8	2.7	0.8	1.6	0.36	0.30
PP		1.3	0.96	0.9		0.96	0.13 ± 0.08
$Si(OH)_4$	27	112		221	112	167	12.7 ± 11.9
Chlorophyll *a*	2.2	4.6	2.0	4.6	2.5	2.2	0.56 ± 0.44
Phaeophytin	4.2	2.6	1.0	3.0	1.4		0.26 ± 0.21
Suspended solids	150	49	62		39		3.0 ± 0.1

*from Furnas et al. (1995). Annual mean (±SD) salinity and concentrations of nutrients, chlorophyll and suspended solids sampled between 1979 and 1994 for the inshore central and southern GBR in non-flood conditions. Inner refers to coastal waters less than 10 m depth.

4.4 Spatial Dynamics of Materials in Plumes

Flood plumes evolve over time in response to a number of factors. The concentrations of dissolved and particulate matter within the plume are extremely variable in space and time. The protean nature of water quality in plumes is connected to the spatial and temporal dynamics and can be difficult to assess what changes are in response to which factors. This section defines the water quality processes that take place in the plume over spatial and temporal scales.

4.4.1 Vertical Distribution

Depth of sampling is a critical factor in obtaining reliable concentration of materials in the plume. Figure 20 presents data taken from the Barron River plume on 15 March 1995, demonstrating the changes in the concentrations of parameters with depth (Taylor 1995). Sampling of the upper part of the water column characterises the lower salinity, higher turbidity waters associated with the plume and may reveal the sorption/desorption processes occurring during mixing between the highly turbid low salinity surface waters and the clearer, oceanic water beneath the plume. Figure 20 shows that for this event the plume had a thickness of up to 3–4 m. Depth profiling can also provide an insight into resuspension, inferred from the elevated turbidities in the lower parts of the water column. All the data shown here have been collected in the first metre of the water column.

Table 7. Minimum salinities and maximum nutrients, chlorophyll and suspended particulate matter concentrations from the plumes associated with the Dry Tropics rivers sampled in GBR surface waters

Cyclone	Joy	Justin	Sid	Ambient*
Date	Jan 91	Jan 98	Jan 99	
River	Fitzroy	Burdekin	Burdekin	
Shelf region	Southern Inshore	Southern Inshore	Central Inshore	Townsville
Salinity	7	1.0	0.5	35.61± 0.5
NH_4	4.0	3.0	4.3	0.50 ± 0.66
NO_2	1.0	0.52	0.5	0.11 ± 0.24
NO_3	2.4	17.2	12.0	0.17 ± 0.11
DON	20.6	17.2	28.9	4.7
PN	8.1			1.6 ± 0.5
PO_4	1.6	1.16	0.7	0.09 ± 0.10
DOP	2.0	0.9	0.8	0.32
PP	0.9	2.3	4.4	0.13 ± 0.09
$Si(OH)_4$	174		126	5.6 ± 0.9
Chlorophyll *a*	15.9	2.0	1.8	0.93 ± 0.83
Phaeophytin	1.2	0.8	0.9	0.55 ± 0.36
Suspended	36	125	672	5.3 ± 7.3

*from Furnas et al. (1995). Annual mean (±SD) salinity and concentrations of nutrients, chlorophyll and suspended solids sampled between 1979 and 1994 for the inshore central and southern GBR in non-flood conditions. Inner refers to coastal waters less than 10 m depth.

4.4.2 Spatial Distribution of Water Quality Parameters in Flood Plumes

Figures 21–29 demonstrate water quality concentrations measured for three particular events discharging from Fitzroy, Wet Tropics and Burdekin Rivers respectively. The graphs show concentrations measured at each of the individual sites, with sites arranged in order of increasing distance away from the river mouth. These figures show individual concentrations measured through plume waters over different events. The magnitude of increase for nutrient concentrations measured in flood plumes range from 5–100 fold greater than ambient water quality conditions (Furnas et al. 1995). The main distinguishing factor of flood plumes is the extreme and variable concentrations of dissolved and particulate nutrients that can be measured in the surface plume.

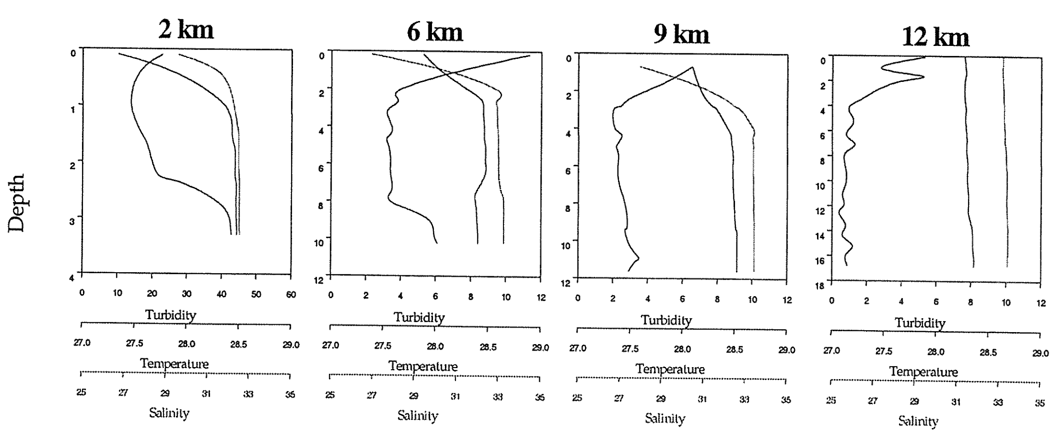


Figure 20. Depth profiles of salinity, temperature and turbidity on a transect out from the Barron River mouth. Note: Sampling over 12 km distance from mouth and 17 m depth.

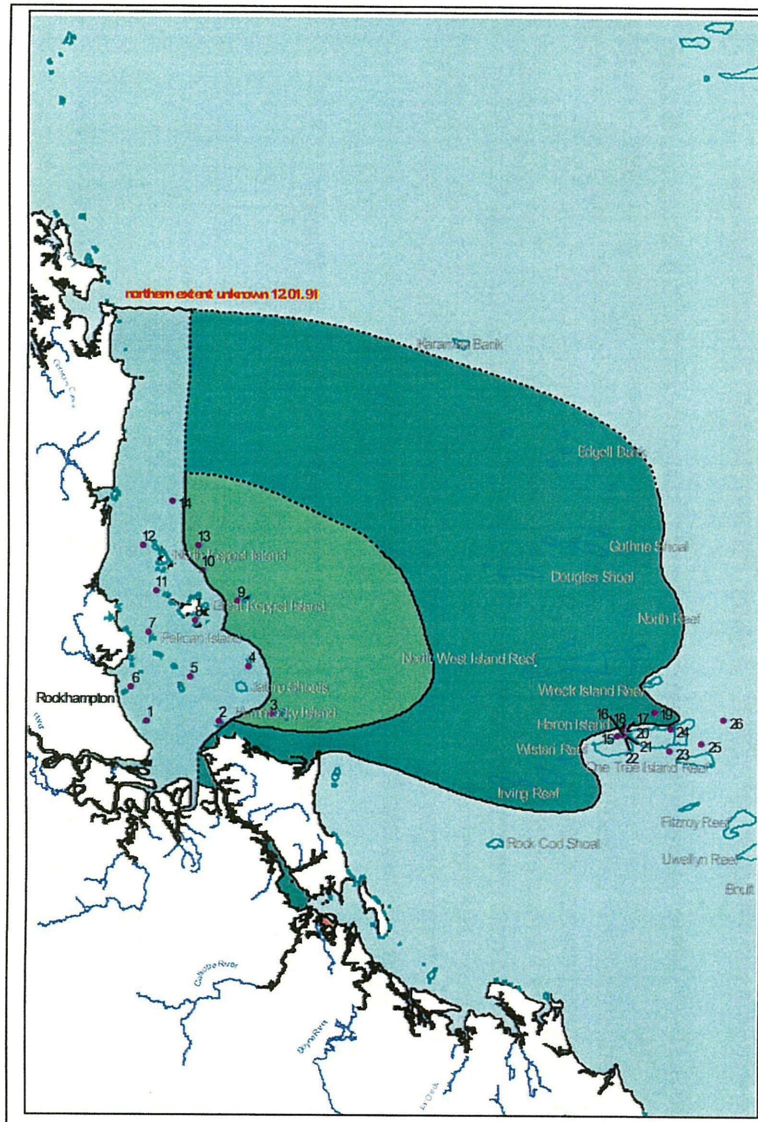
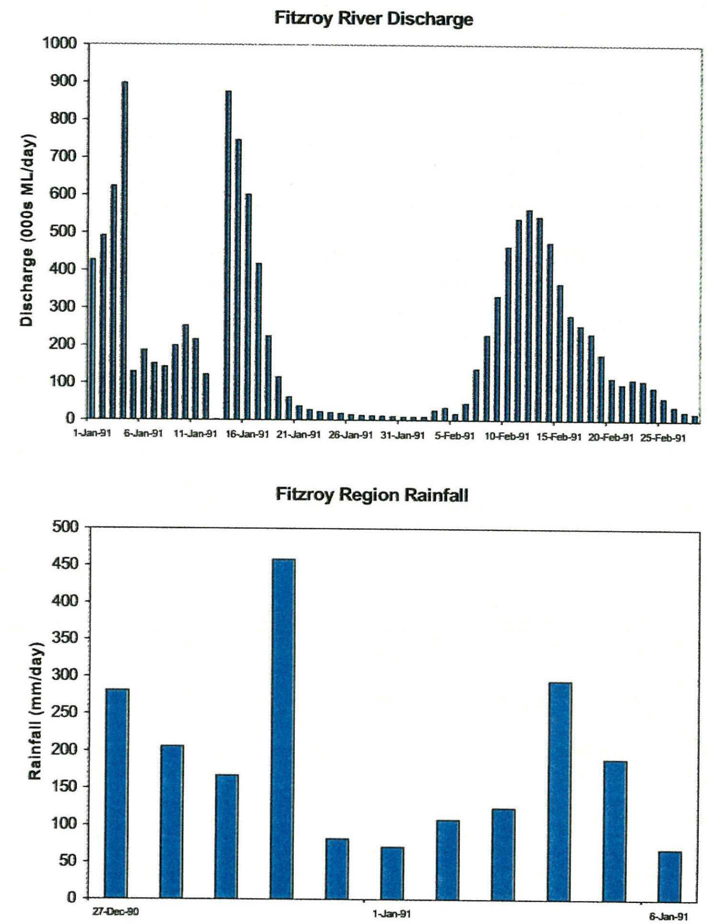


Figure 21a: Cyclone Joy 19/01/91 - Fitzroy River Hydrological Conditions and Sampling Locations

Wind: <5 knots SE-NE/NW



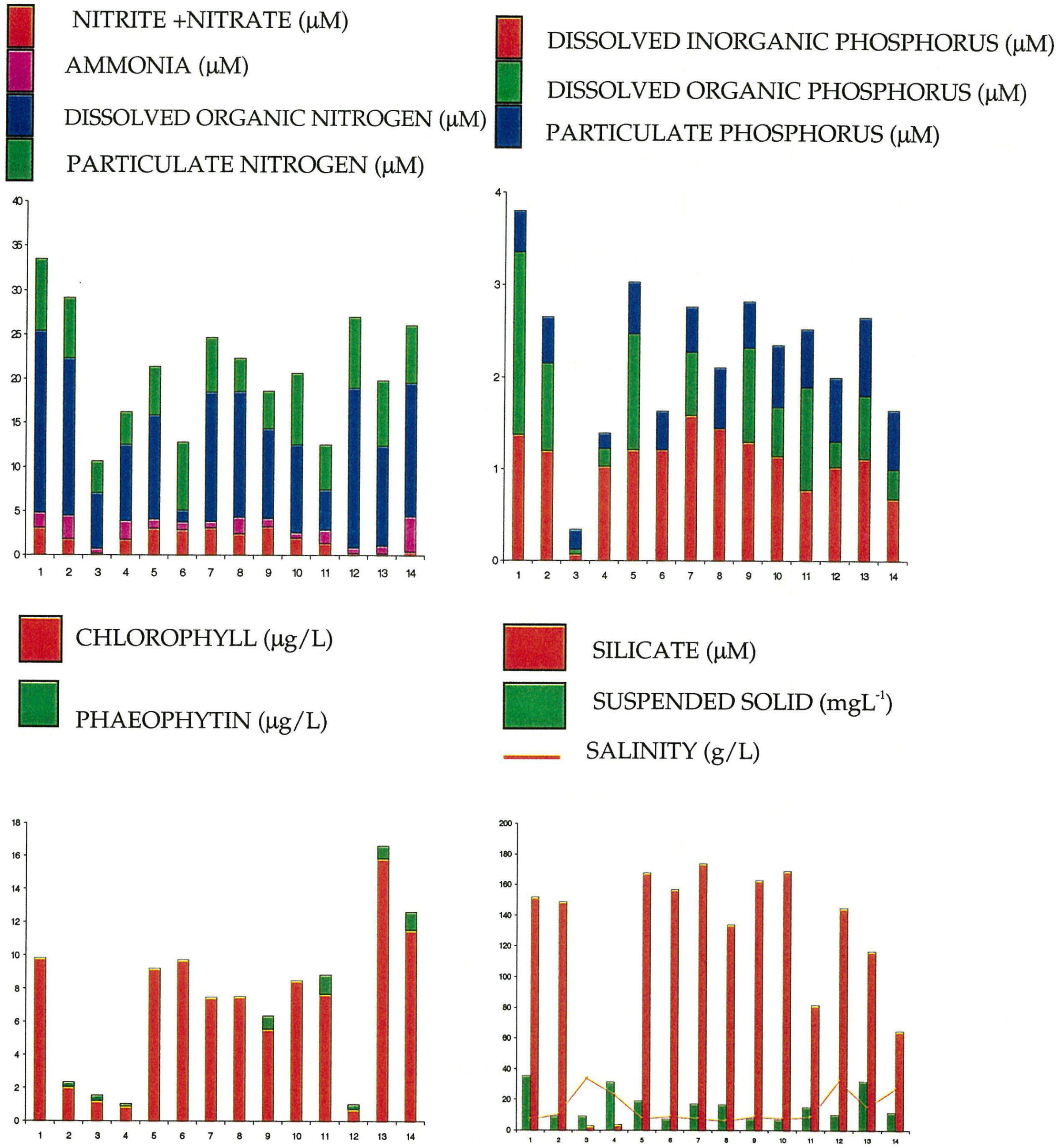


Figure 21b. Concentrations of water quality parameters adjacent to the Fitzroy River in the flood plume associated with cyclone Joy (1991). Note: Sites 1–7 were sampled on 17 January 1991 and 7–14 on 18 January 1991.

Samples taken from cyclone Joy, the Fitzroy flood plume (1991) are from a large dry catchment, with high dissolved and particulate nutrient concentrations (figures 21 and 22). Samples taken over small temporal and spatial scales in the Fitzroy plume show changes in nutrient speciation in the dispersal of the flood plume and the formation of a phytoplankton bloom in the nutrient enriched coastal waters.

Concentrations measured in the plume waters associated with cyclone Sid are presented to show concentrations associated with the Burdekin River, another large dry catchment. The data from this event was collected between a period of eight days, which demonstrates the changes in nutrient and sediment concentrations over a considerable time scale (figures 25, 26 and 27). Suspended sediment and particulate nutrients are high in the Burdekin plume, particularly close to the river mouth, but fall out rapidly over distance. However there are elevated concentrations of dissolved and particulate nutrients in the Burdekin plume, eight days after the original sampling time.

Samples from cyclone Justin (1997) were taken adjacent to the Wet Tropics catchments and the Burdekin Catchments. Concentrations measured in waters adjacent to the Wet Tropics are presented (figures 22, 23 and 24) and comparisons between concentrations taken in two separate Burdekin plumes (figures 28, 29 and 30) for cyclone Justin (1997) and cyclone Sid (1998).

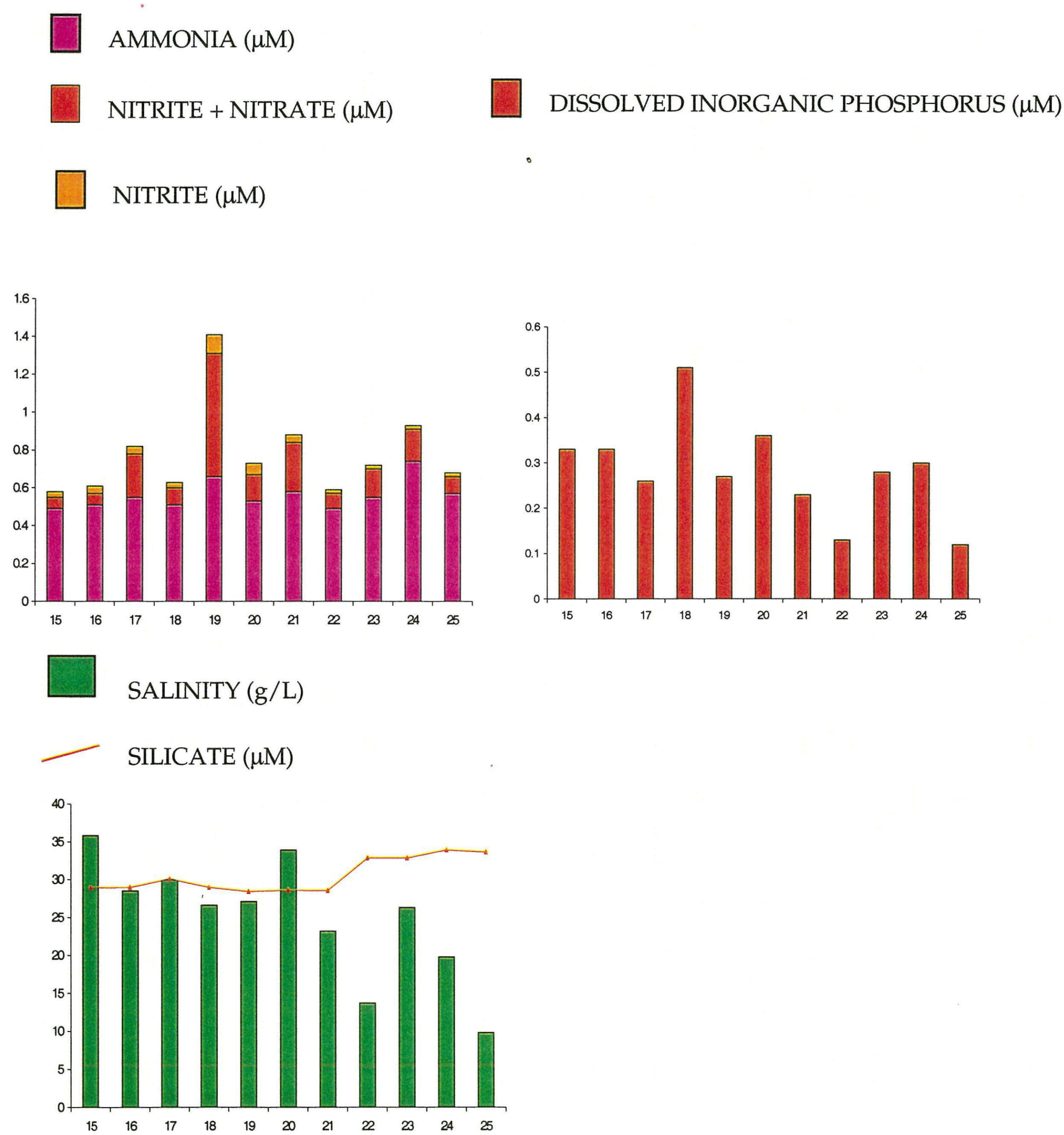
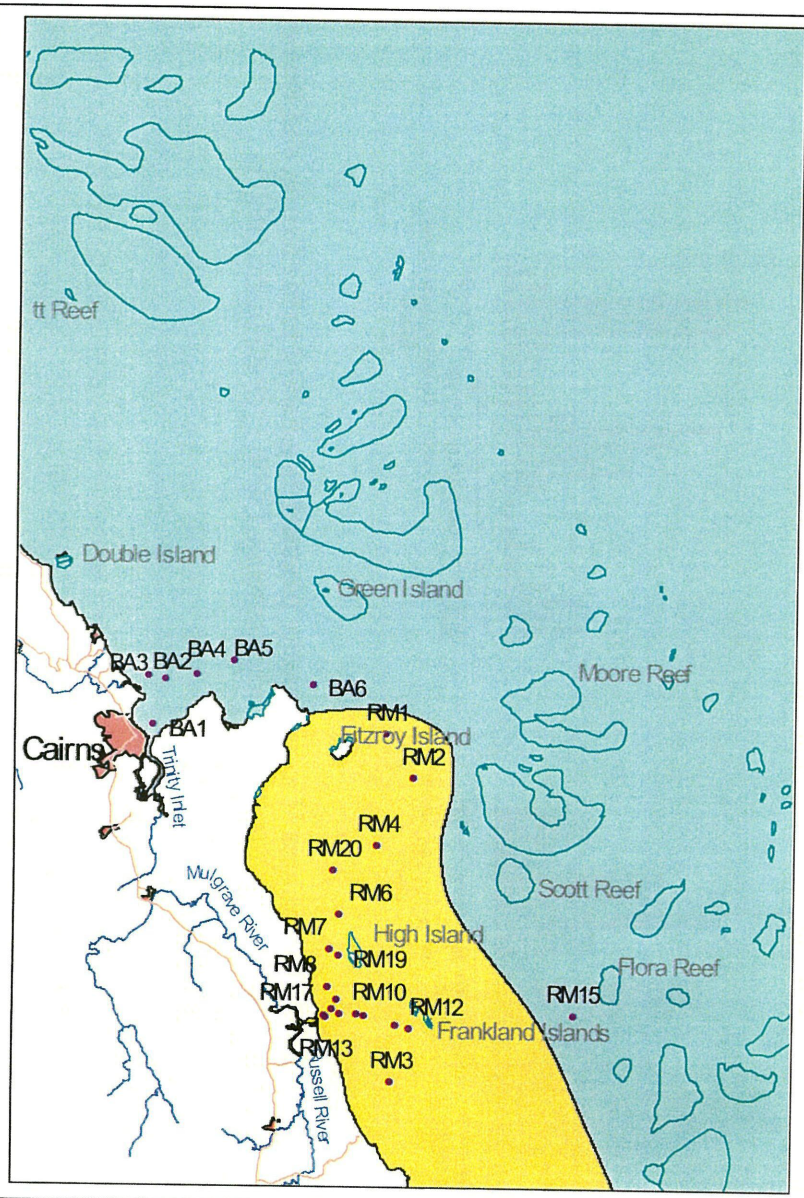
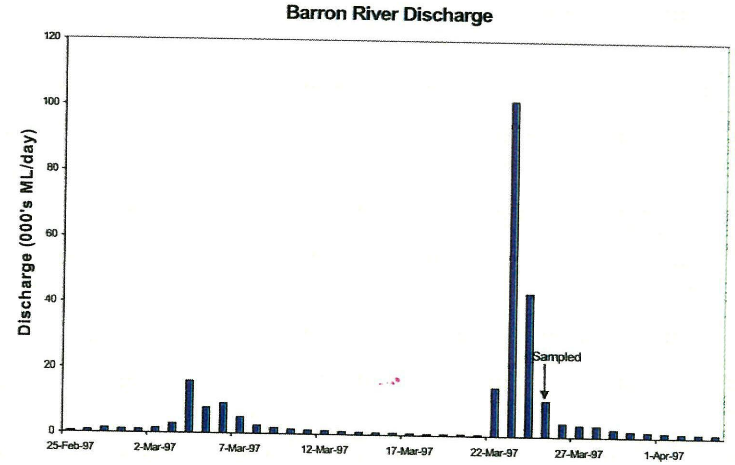


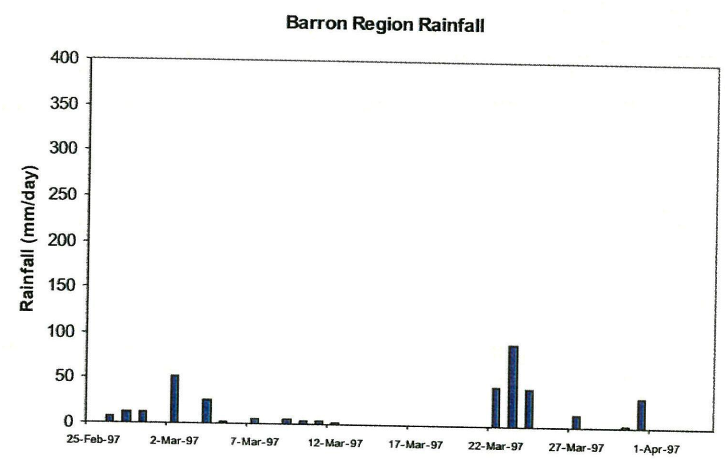
Figure 21c. Concentrations of water quality parameters adjacent to the Fitzroy River in the flood plume associated with cyclone Joy (1991). Sites 15–25 were sampled on 23 & 24 January 1991. Samples were taken in the Capricorn Group (Myriam Prekker, pers comm.).

Figure 22a: Cyclone Justin 25/03/97 - Barron River Hydrological Conditions and Sampling Locations

Wind: 10-20 knots N-NW







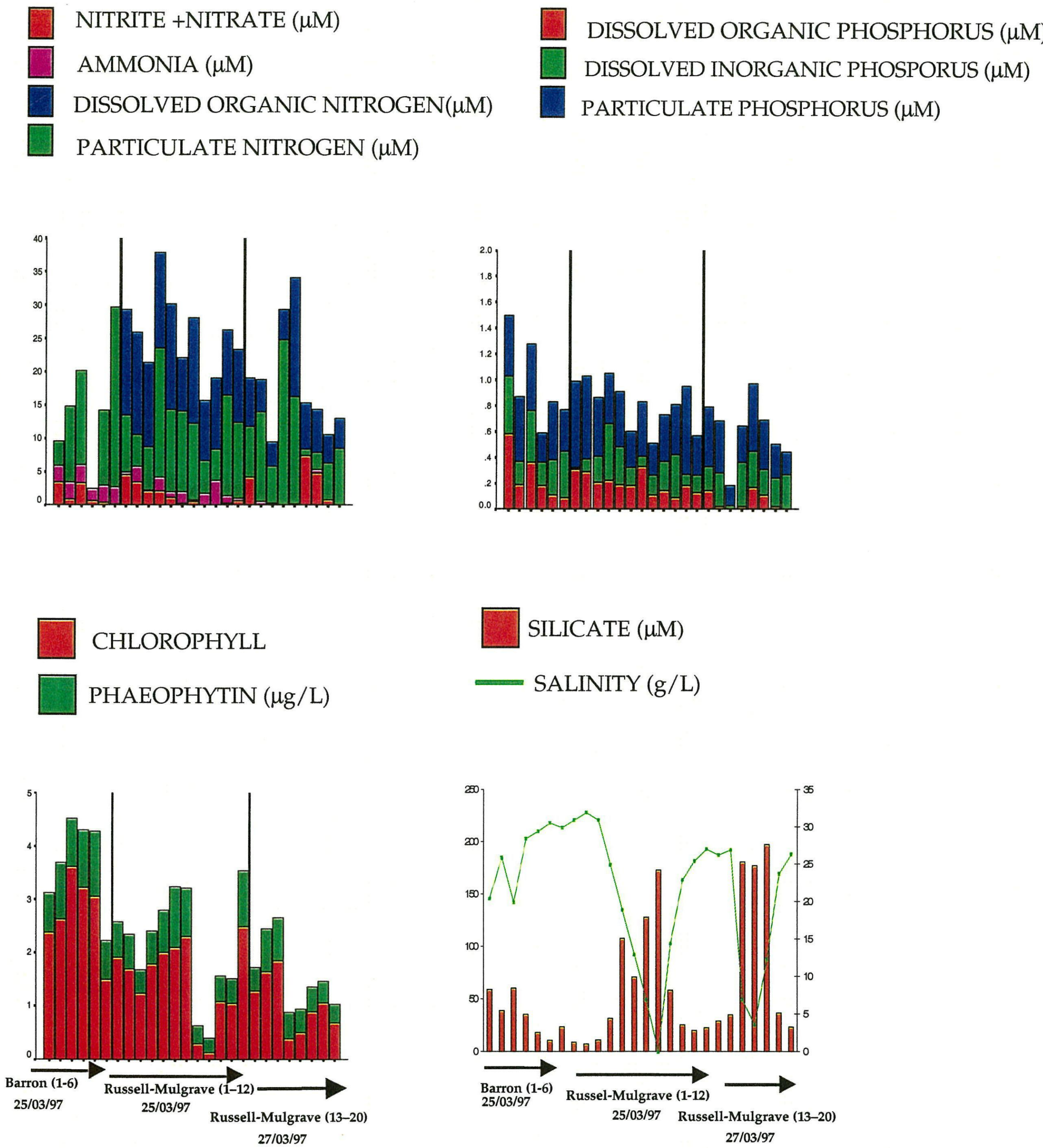


Figure 22b. Concentrations of water quality parameters adjacent to the Barron and Russell-Mulgrave rivers in the flood plume associated with cyclone Justin (1997)

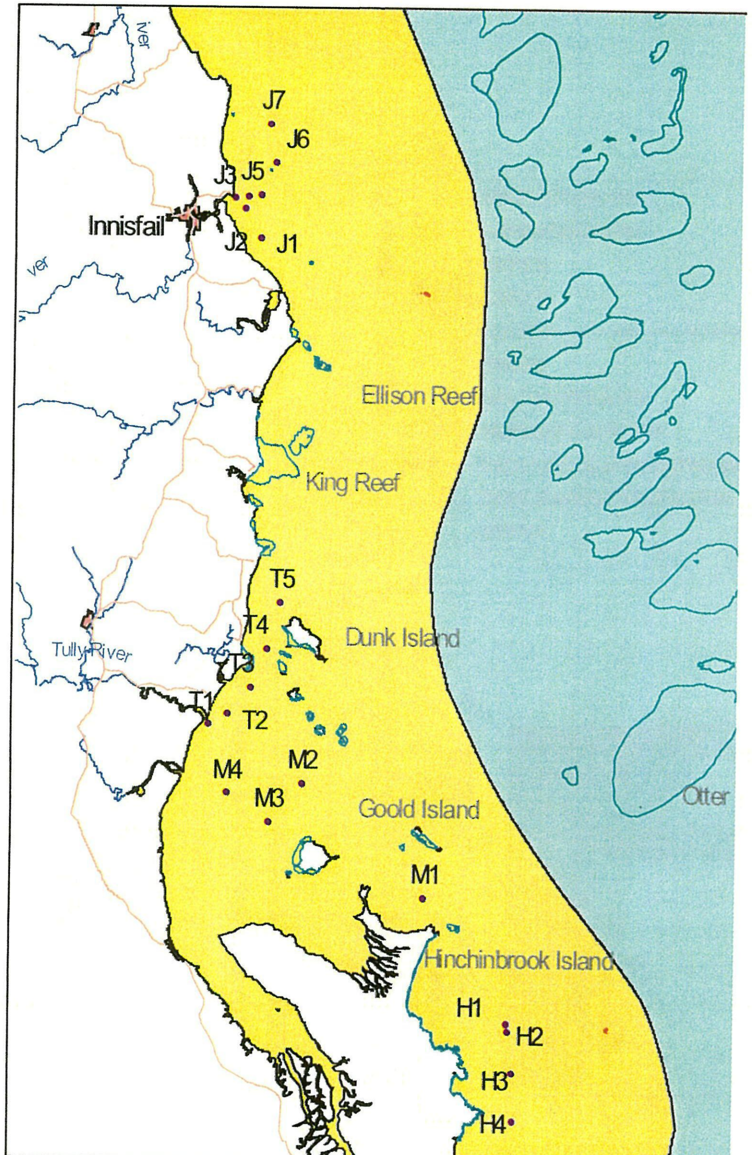
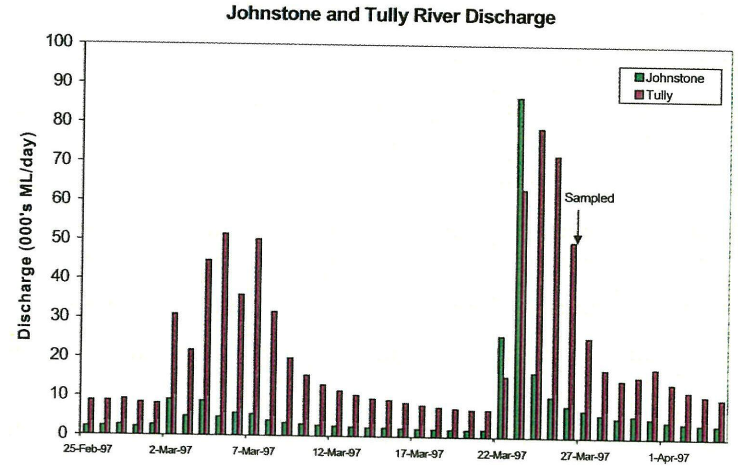
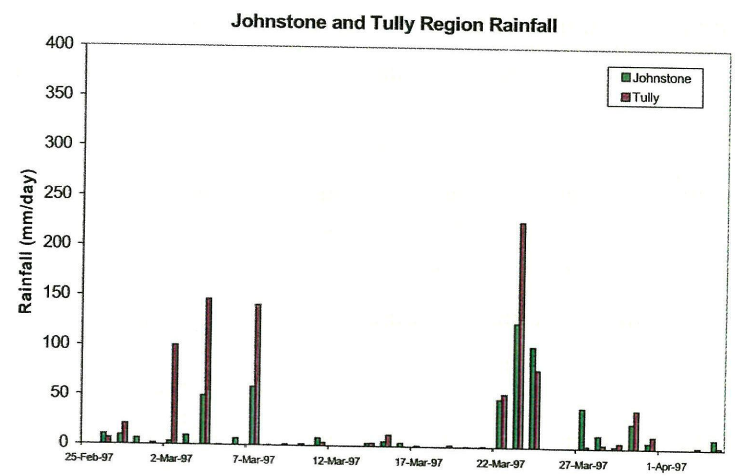


Figure 23a: Cyclone Justin 25/03/97 - Johnstone & Tully Rivers Hydrological Conditions and Sampling Locations

Wind: 10-15 knots E-W





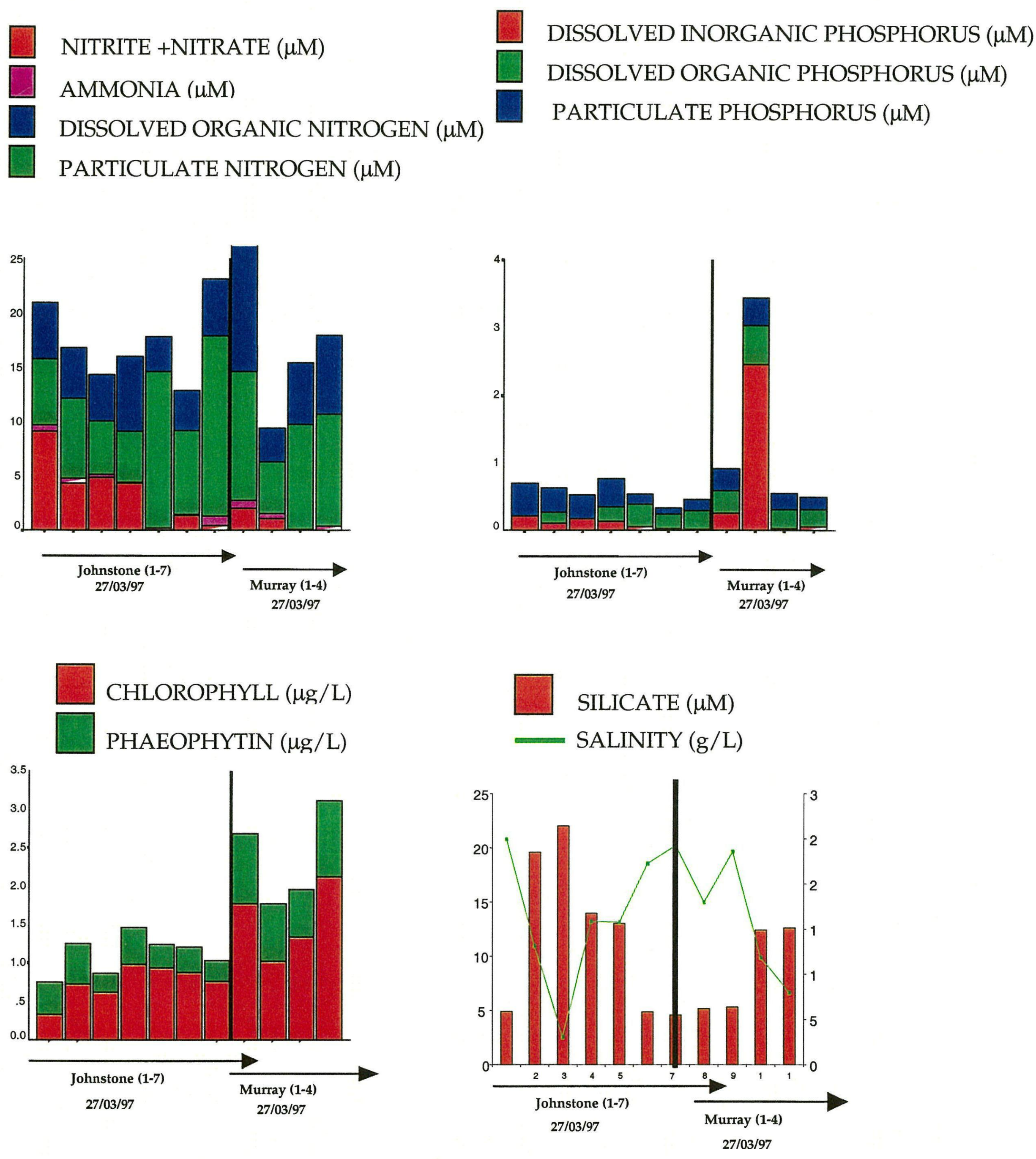
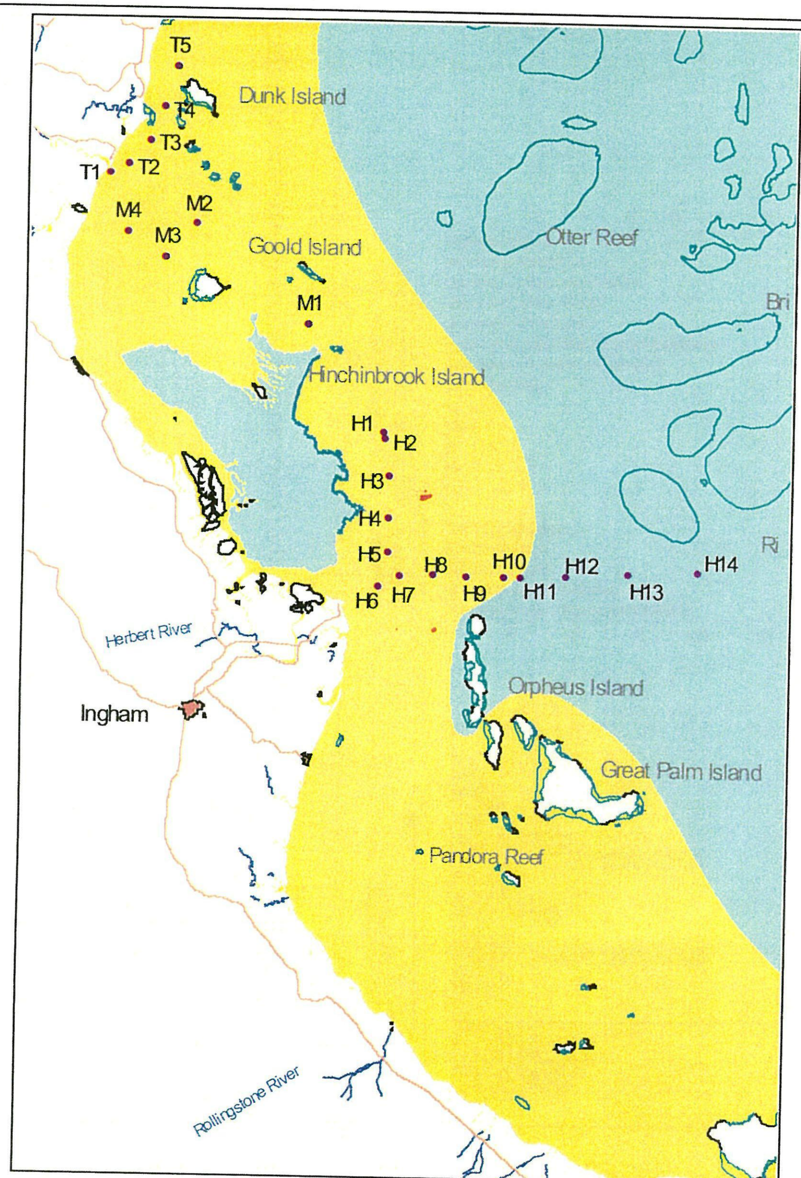
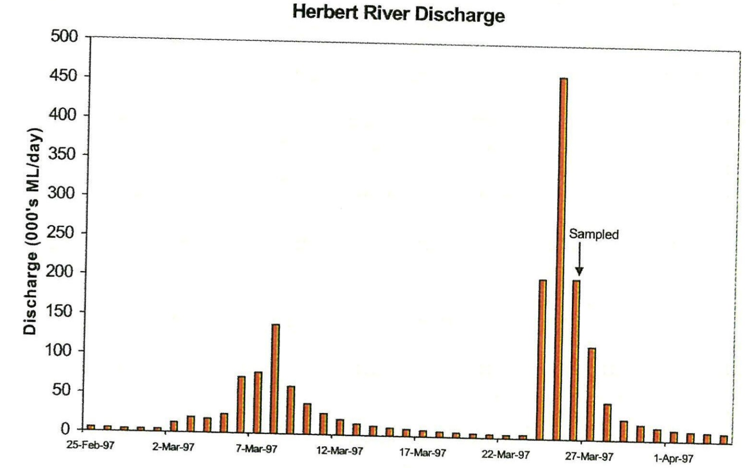


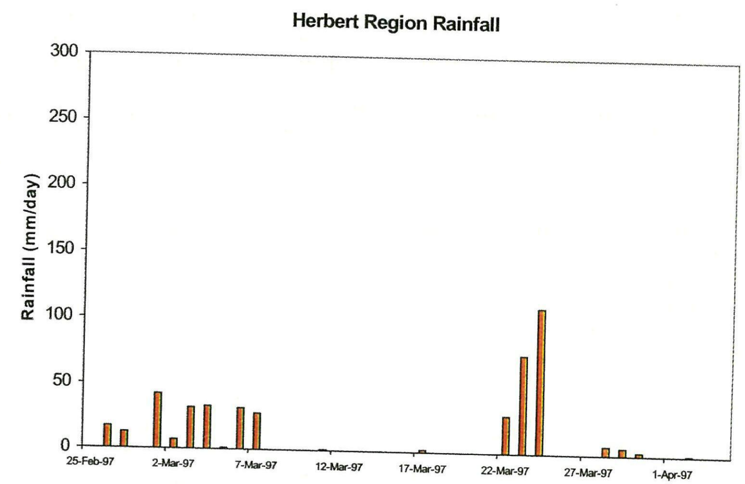
Figure 23b. Concentrations of water quality parameters adjacent to the Johnstone and Murray rivers in the flood plume associated with cyclone Justin (1997)

Figure 24a: Cyclone Justin 25/03/97 - Herbert River Hydrological Conditions and Sampling Locations

Wind: 10-15 knots E-W







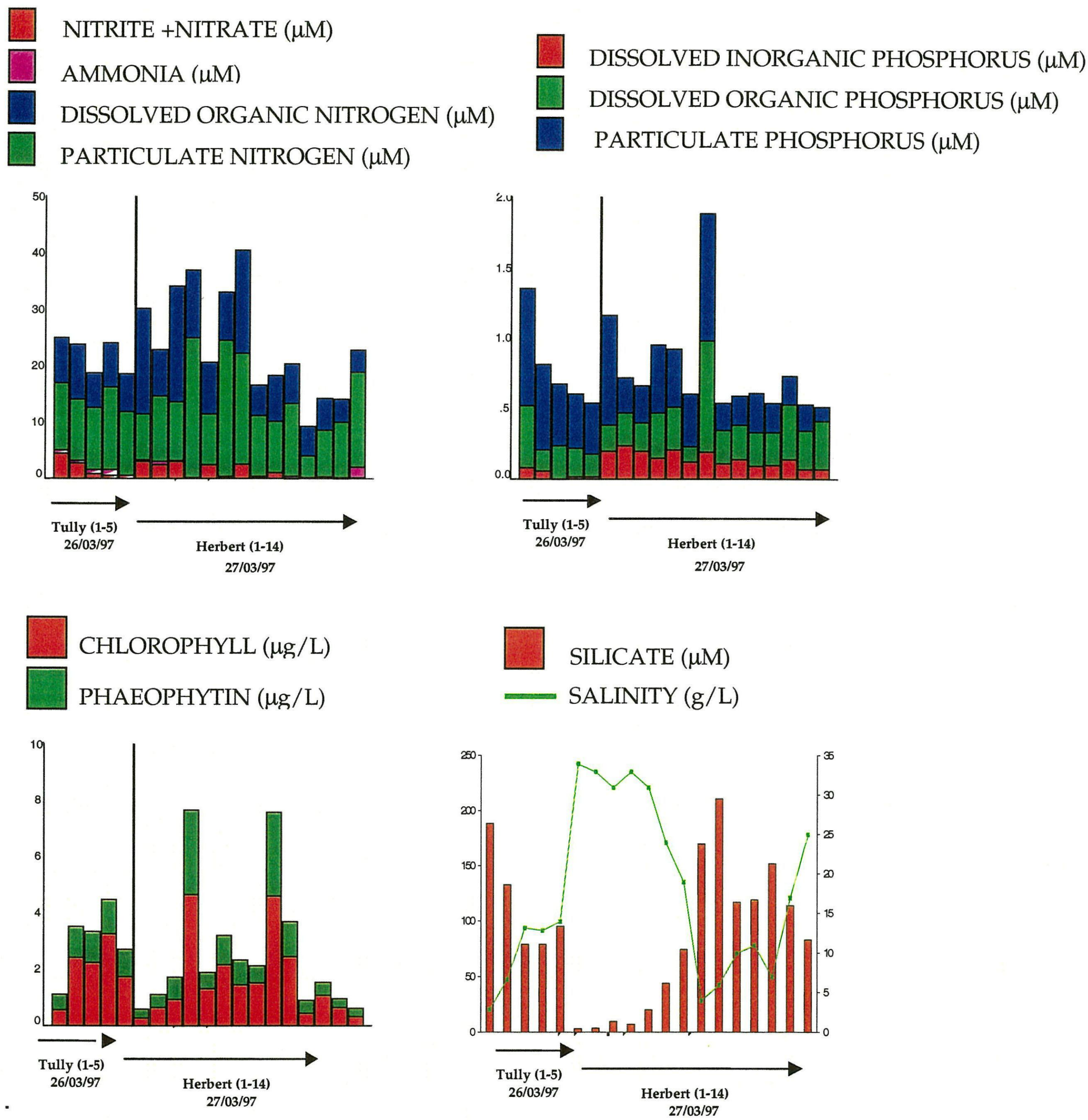
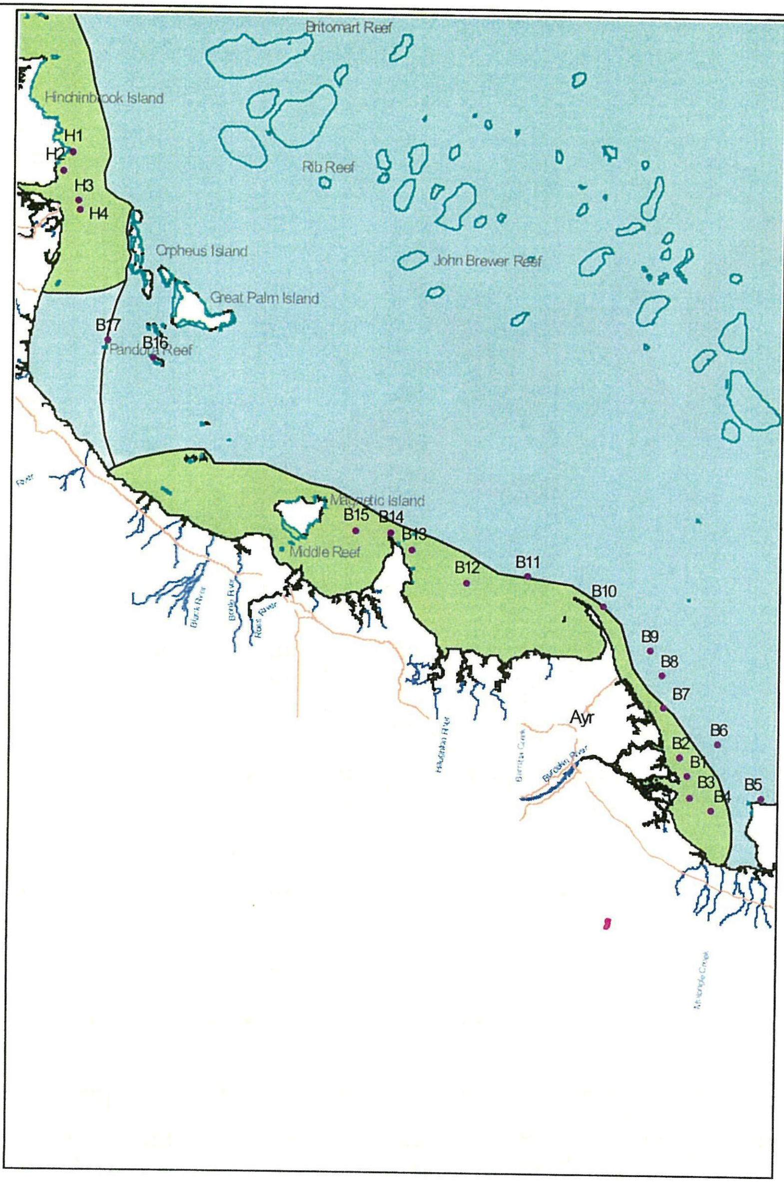
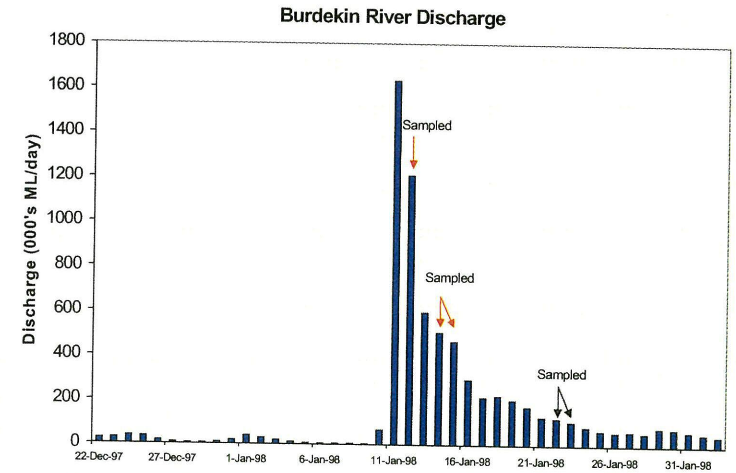


Figure 24b. Water quality concentrations from the Tully and Herbert rivers taken in the cyclone Justin plume (March 1997)

Figure 25: Cyclone Sid 14/01/1998 - Burdekin Rivers Hydrological Conditions and Sampling Locations

Wind: 15-25 knots E





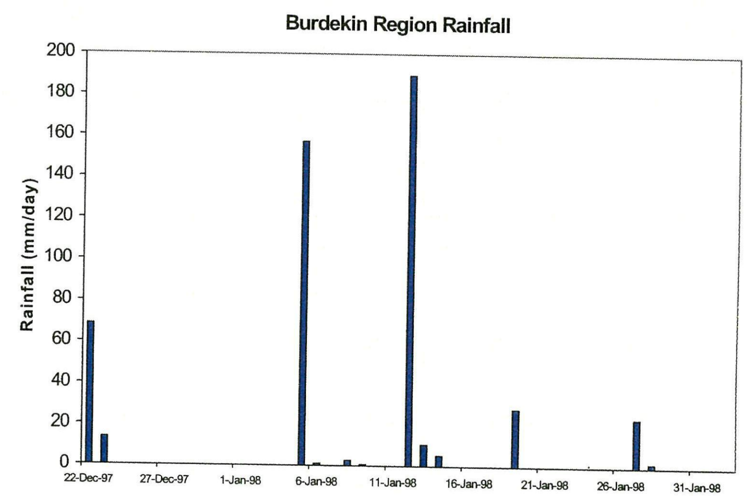
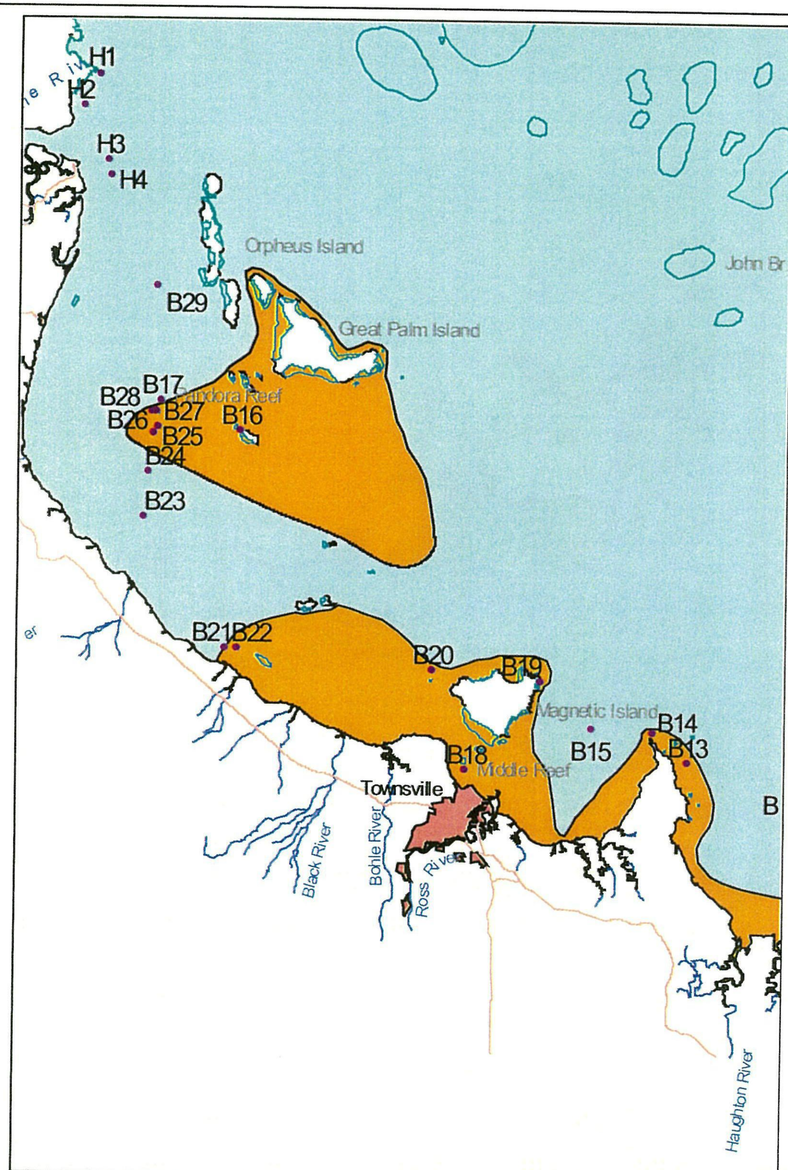
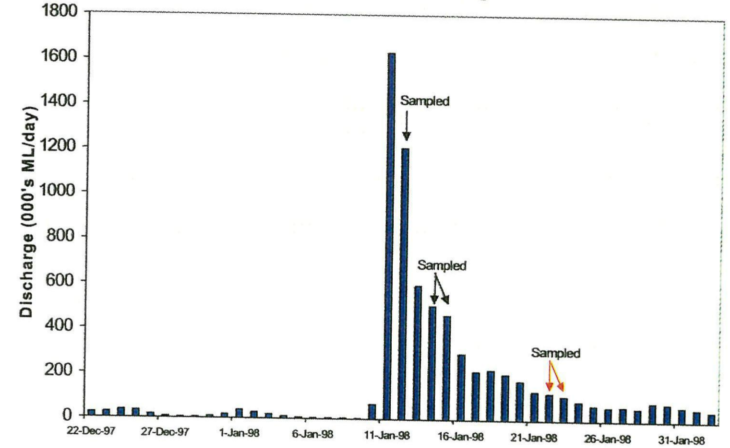
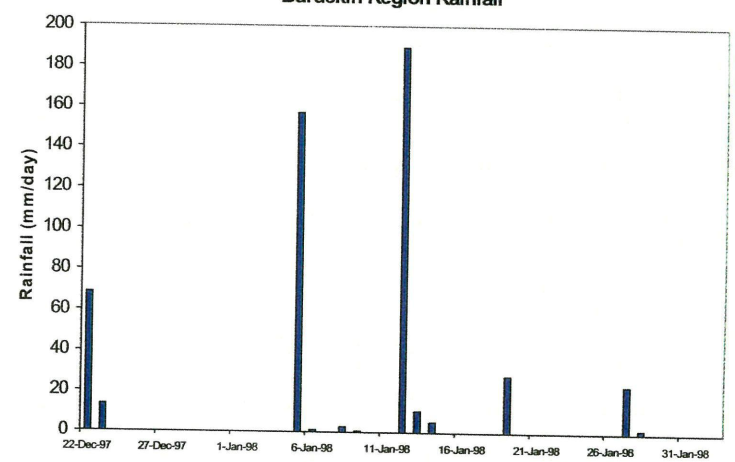


Figure 26: Cyclone Sid 23/01/1998 - Burdekin River Hydrological Conditions and Sampling Locations

Wind: 5-10 knots NE







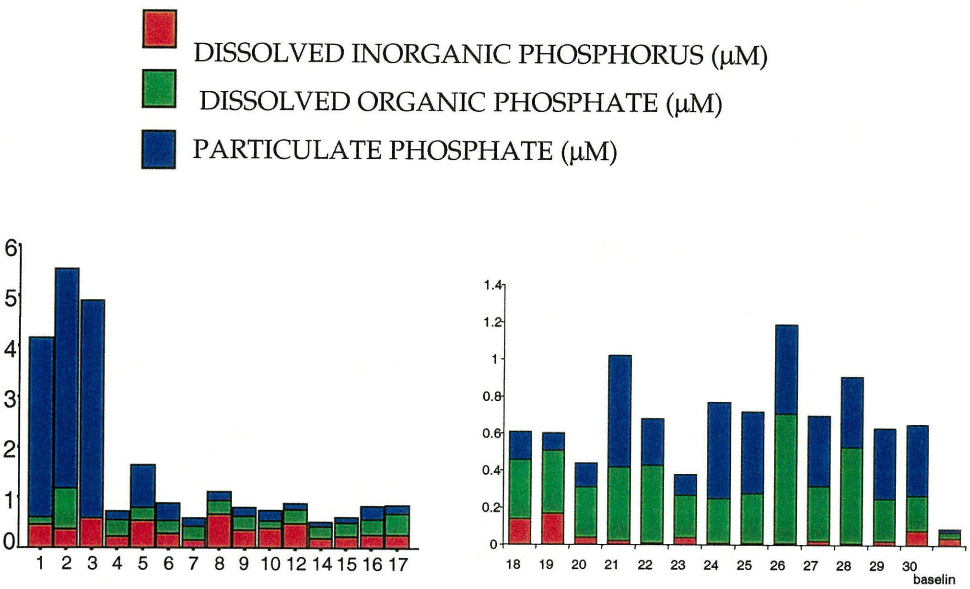


Figure 27a. Distribution of dissolved and particulate phosphorus on two different sampling occasions (8 days apart) following cyclone Sid in January 1998. Water samples were collected on a transect from the Burdekin mouth to Pandora Reef on 15 January 1998 and on transect from Cape Bowling Green to Pandora Reef on 23 January 1998.

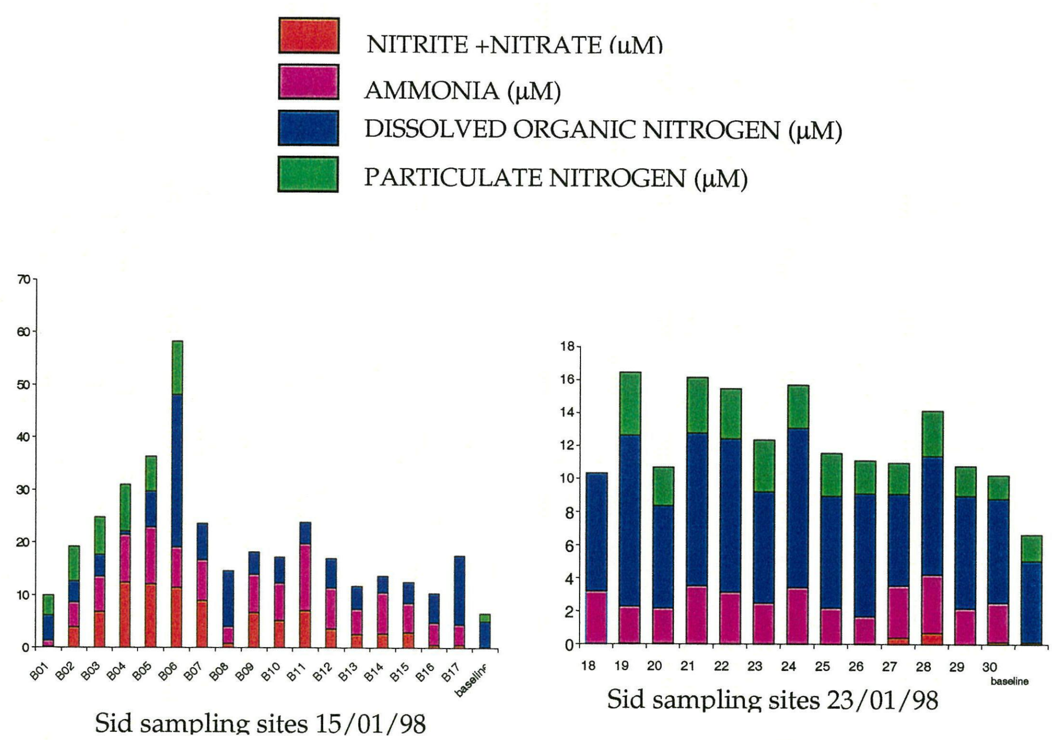


Figure 27b. Distribution of dissolved and particulate nitrogen on two different sampling occasions (8 days apart) following cyclone Sid in January 1998. Samples were taken in transects from the mouth of the Burdekin to Pandora Reef (15 January 1998) (1–17), from Cape Bowling Green and around Magnetic Island (22 January 1998) and from Magnetic Island to Pandora Reef (23 January 1998) (18–29).

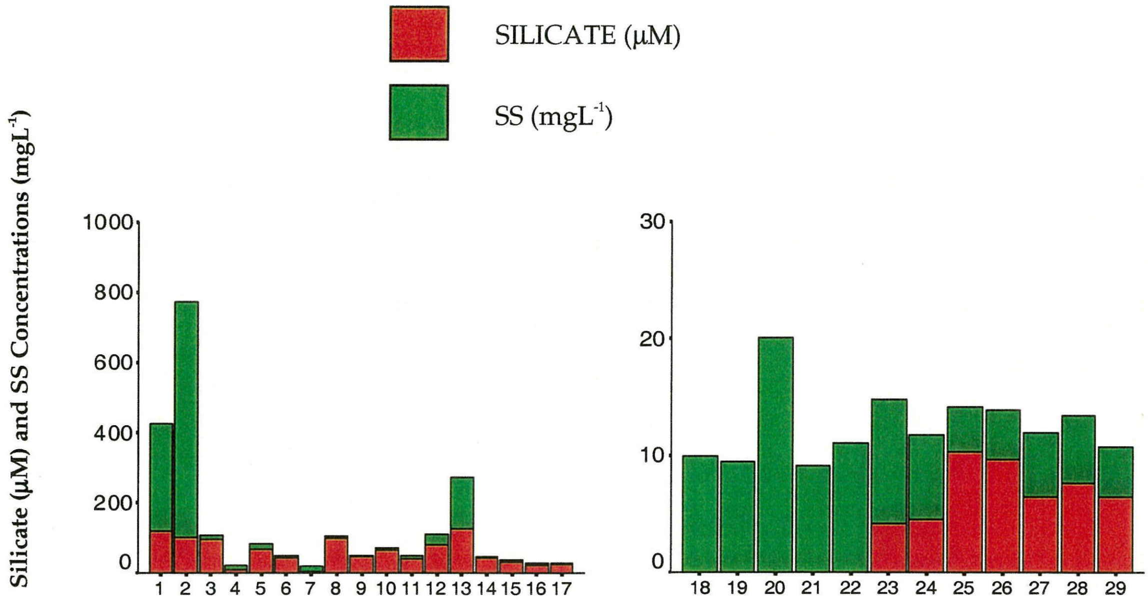


Figure 27c. Distribution of silicate and suspended solids from two sampling occasions from the Burdekin river plume taken during cyclone Sid (1997). Samples were taken in transects from the mouth of the Burdekin to Pandora Reef (15/01/98), from Cape Bowling Green and around Magnetic Island (23/01/98) and from Magnetic Island to Pandora Reef.

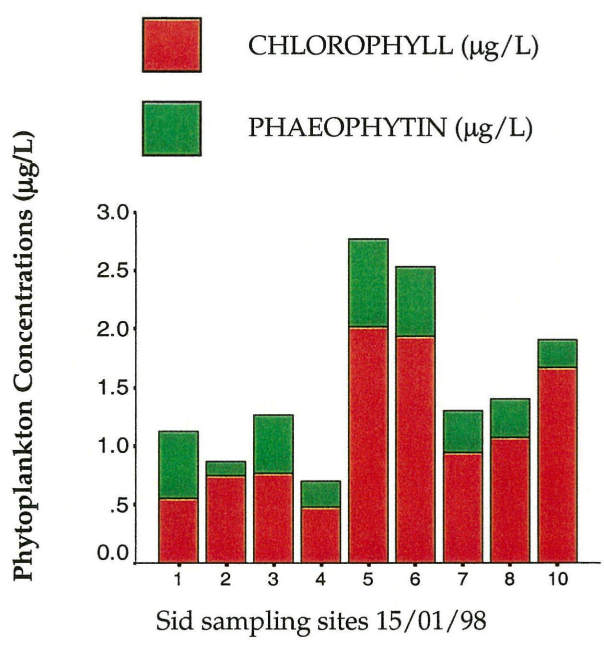


Figure 27d. Distribution of chlorophyll and phaeophytin from two sampling occasions from the Burdekin river plume taken during cyclone Sid (1998)

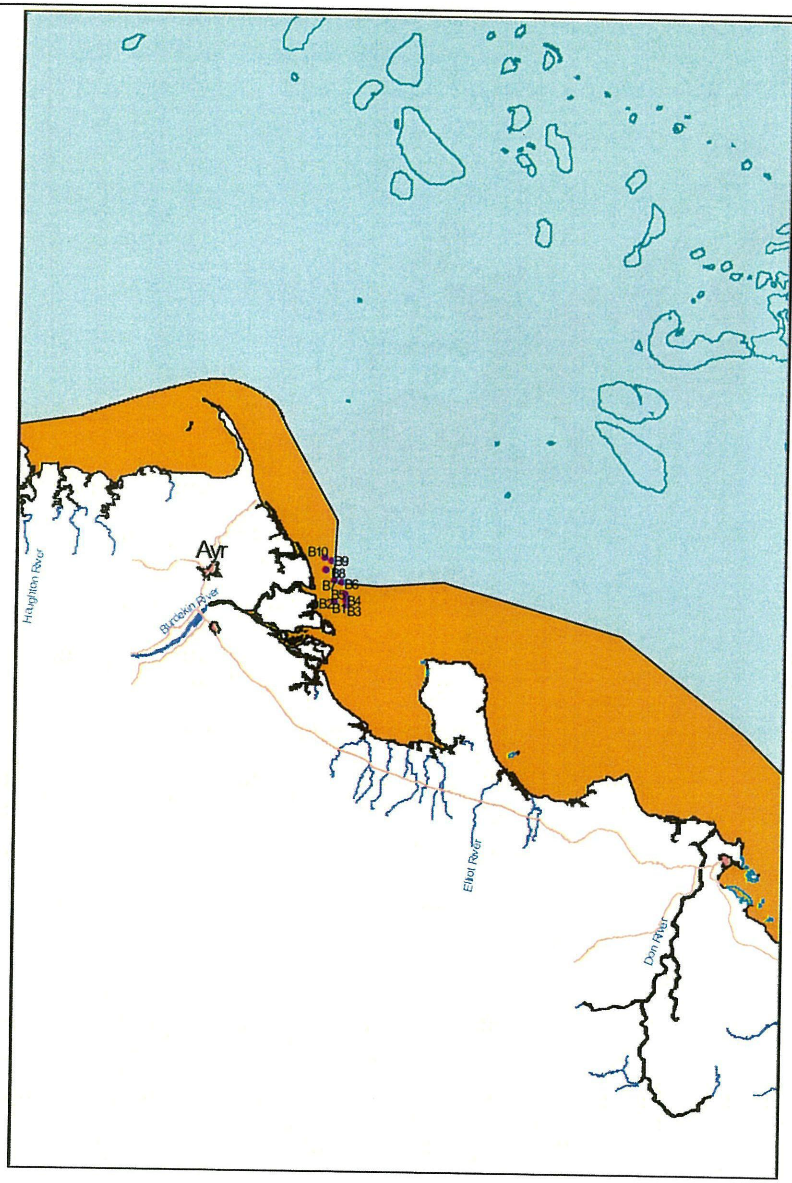
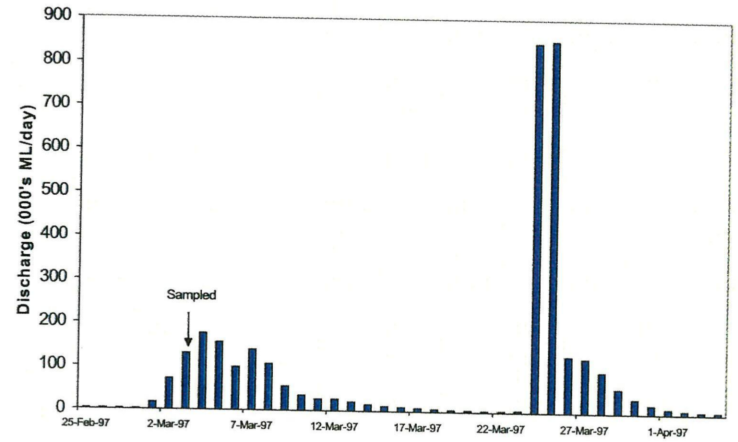


Figure 28: Cyclone Justin 04/03/97 - Burdekin River Hydrological Conditions and Sampling Locations

Wind: 10-15 knots SE

Burdekin River Discharge



Burdekin Region Rainfall

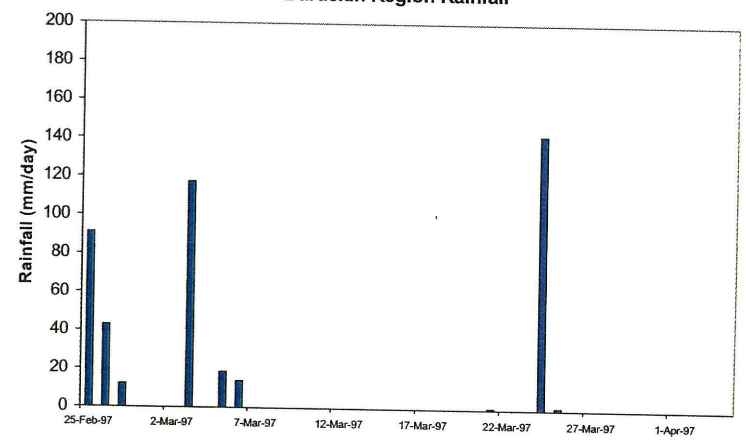
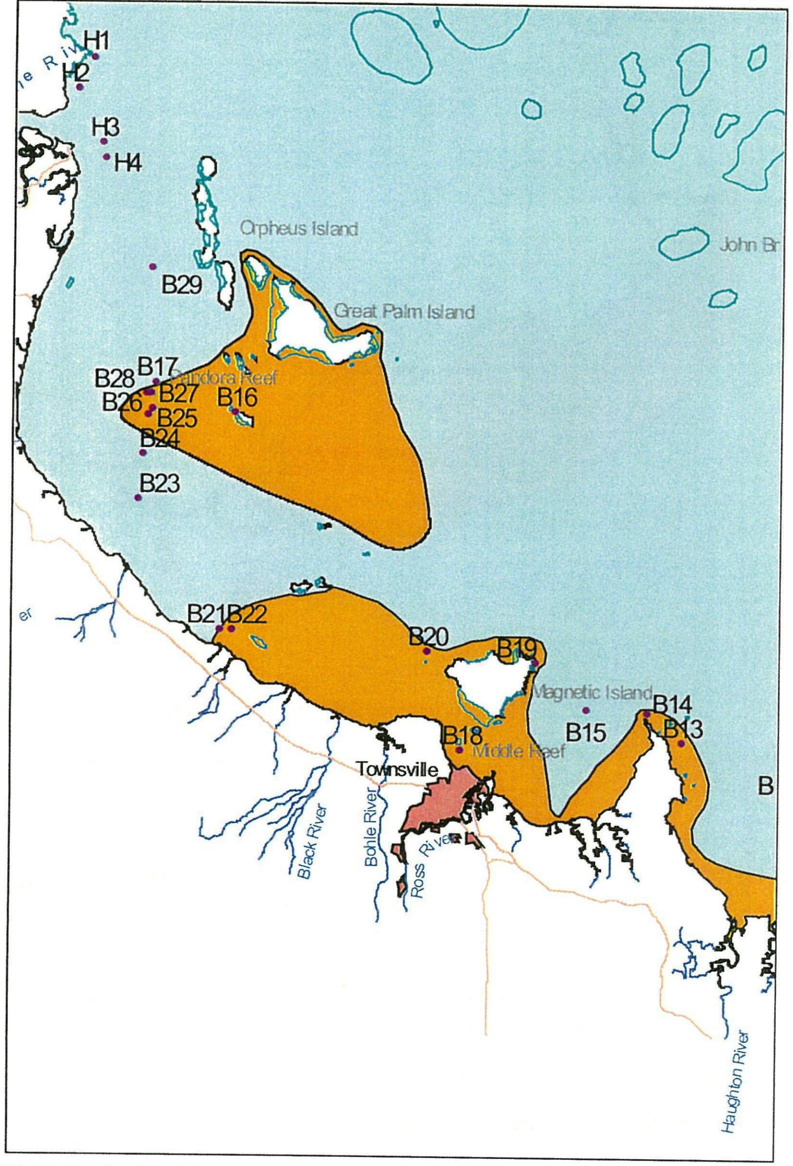
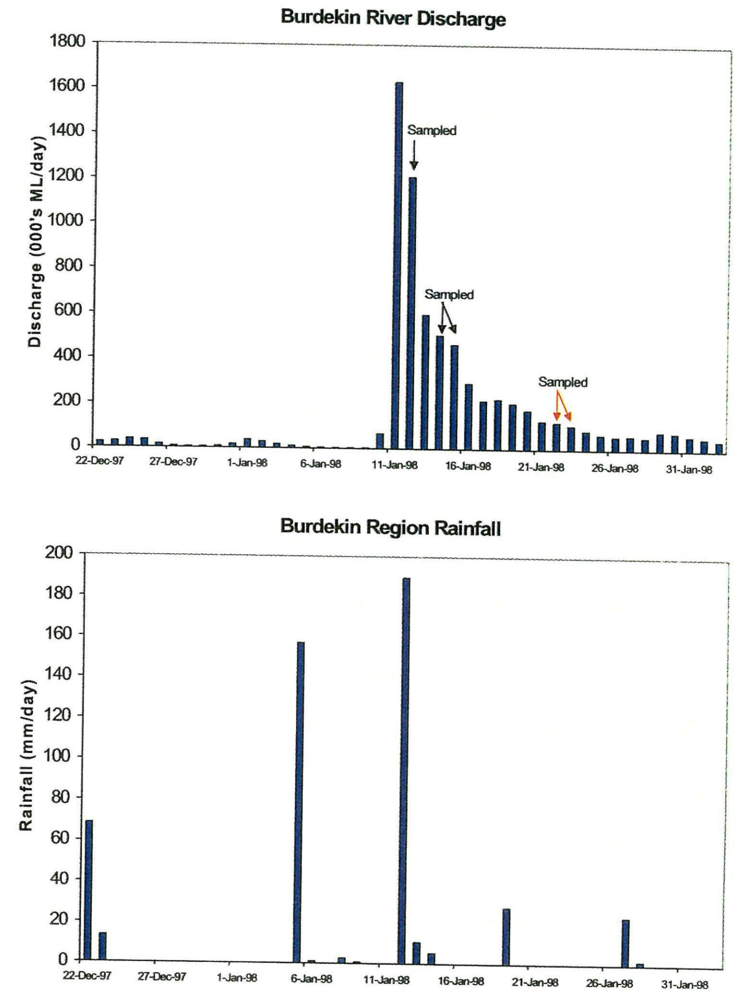


Figure 29: Cyclone Sid 14/01/1998 - Burdekin River Hydrological Conditions and Sampling Locations

Wind: 5-10 knots NE





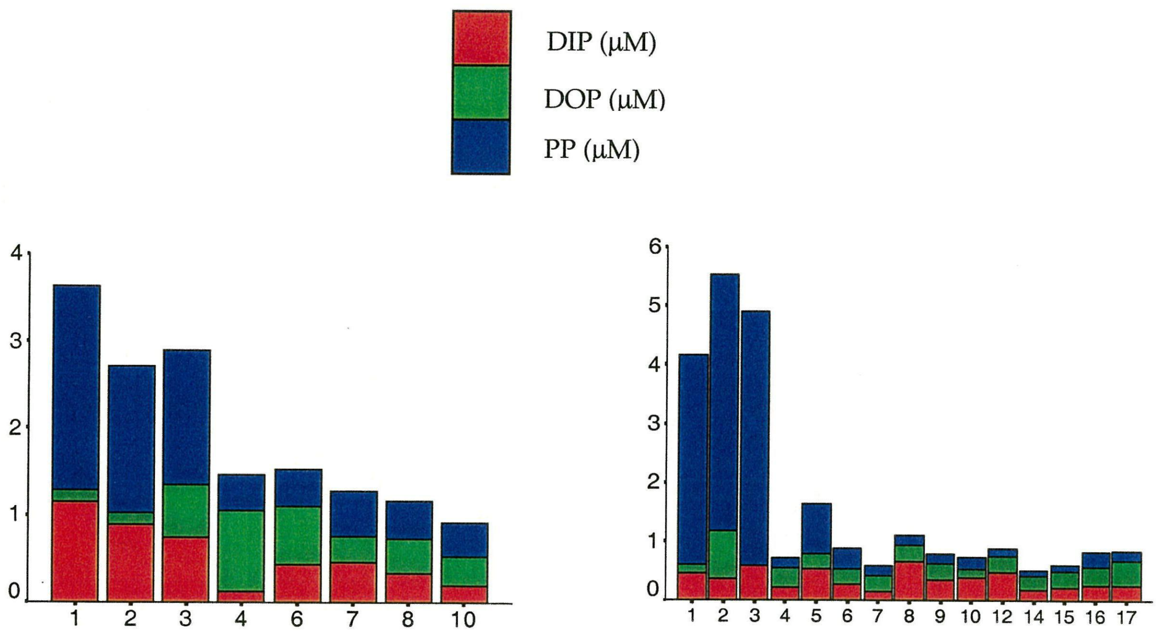


Figure 30a. Distribution of dissolved and particulate phosphorus on two sampling occasions over two flood events over consecutive years (1997 and 1998). Cyclone Justin (1997) and cyclone Sid (1998) resulted in significant flooding of the Burdekin catchment.

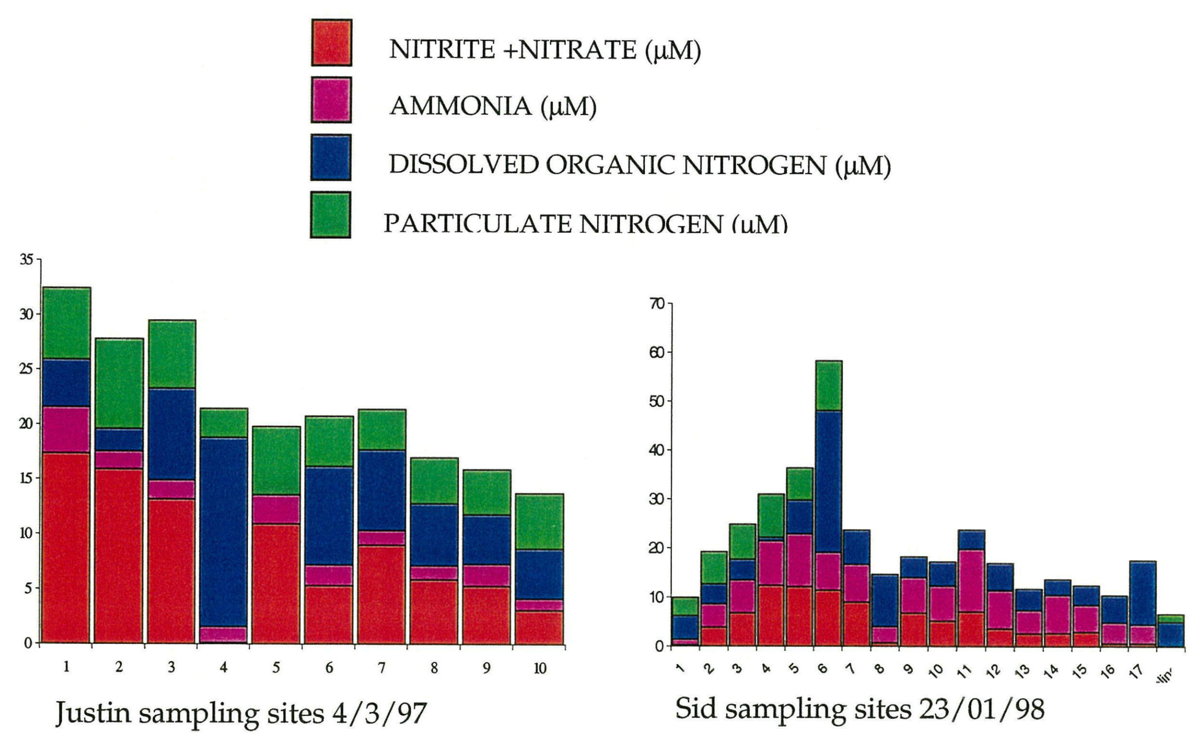


Figure 30b. Distribution of dissolved and particulate nitrogen on two sampling occasions over two flood events over consecutive years. Cyclone Justin (1997) and cyclone Sid (1998) resulted in significant flooding of the Burdekin catchment.

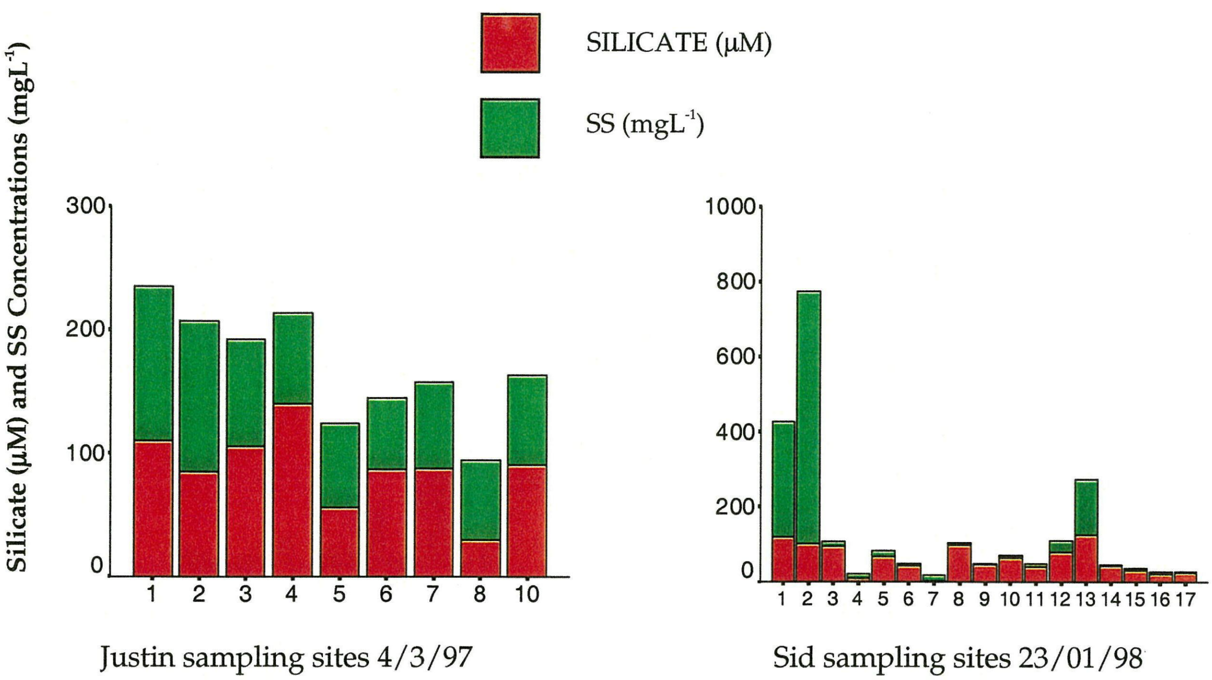


Figure 30c. Distribution of silicate and suspended solids on two sampling occasions over two flood events over consecutive years

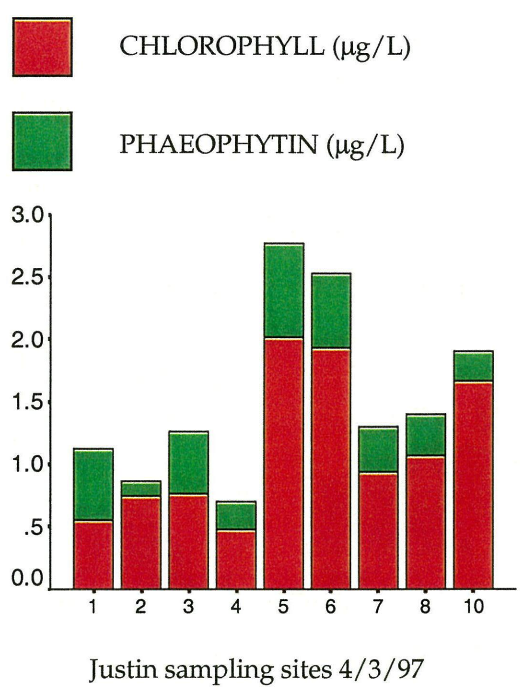


Figure 30d. Distribution of chlorophyll and phaeophytin on two sampling occasions over two flood events over consecutive years

5. DISCUSSION

5.1 Spatial Characteristics of Flood Plumes

5.1.1 Influences on the Spatial Distribution of Plumes

Plume distributions presented in this report support conclusions from other studies (Wolanski 1994; Gagan et al. 1987; Wolanski & van Senden 1983;) that the main driving influence of the movement of plume waters is the direction and strength of wind and discharge volume of the river. The greater number of plumes mapped over this study (Violet, Ethel, Justin, Sid and Rona) were restricted to a shallow nearshore northward band by strong south-easterly winds following the cyclone. However, under relatively calm conditions such as those following Sadie, light offshore winds pushed the plume seaward and north over much of the shelf (Brodie et al. 1997) and there was a short period of direct impingement upon mid- and outer-shelf reefs. The flood plume associated with cyclone Fitzroy with light northerly winds also moved offshore, eventually impinging on the Capricorn Island Group.

The amount of rainfall that falls over a particular catchment can have a marked effect on the distribution of the plume. Cyclone Ethel, though having a northerly moving plume had record rainfall over the Daintree catchment which resulted in record flows from the Daintree River. This particular event had significant impacts on the nearshore communities adjacent and north of the Daintree River (Ayling & Ayling 1998). Cyclone Sadie reached the mid-shelf reefs from the Barron River yet much of the rainfall had been restricted to the coastal fringe (Taylor 1997). The plume may have been more extensive had the rainfall been sustained in the upper catchments of the Wet Tropics rivers.

5.1.2 Steering of Plumes

Another factor in the distribution of flood plumes is the influence of headlands on the movement of the plumes (steering). This can be observed most clearly in the vicinity of Cape Grafton (slightly south east of Cairns) in extent of the Sadie, Violet and Ethel plumes (figures 12, 13 and 14) where northward moving plumes are steered across Green Island Reef. Green Island Reef appears to be the one mid-shelf reef of the GBR south of the Daintree, which is regularly covered by river plume water. Therefore the assessment of plumes impacting on mid-shelf reefs adjacent to the Barron River (Green Island) are expected to be underestimates due to effects from other river systems to the south 'steering' past Cape Grafton. Headland steering of low salinity water has been previously reported off Cape Kimberly by Ayukai et al. (1997).

5.1.3 Empirical Model of Plume Movement and Characteristics

As part of the assessment of the impact of flood plumes on the GBR ecosystems, an estimate is required of the areal and volumetric extent of plumes emanating from the rivers draining to the GBR. The observed distribution of flood plumes between 1994 and 1999 serves as a baseline for evaluating plume distribution with respect to variables controlling plume extent. Figures 11–19 demonstrate the protean nature of flood plumes studied and the conditions that were experienced that gave rise to their development. Table 8 presents a summary of the main characteristics that will determine the extent and distribution of plume waters.

Figure 30 presents a summary of the frequency and distribution of all flood plumes mapped in the GBR over the last 10 years. The dark red colours of the frequency map denote the areas which see plumes on a high frequency basis (every 1–2 years). From this information, we begin to estimate the area of risk from river run-off. Based on these observations, figure 31 presents a summary of plume distribution for waters discharging in the vicinity of the Russell-Mulgrave and Barron rivers, with six qualitative fields of plume distribution (inner1, inner2, inner-mid, mid, mid-outer, and outer).

Table 8. Fixed and random factors that determine distribution of plume extent and duration

<u>**Fixed factors**</u>
a. Bathymetry
b. Shape of coast
c. Coriolis forcing
d. Catchment size and hydrology
<u>**Variable factors**</u>
Variable 1: Wind speed (on the shelf)
a. Cyclonic (> 50 knots)
b. Trades (10–30 knots)
c. Light (< 10 knots)
Variable 2: Wind direction
d. South-East
e. North/North-east
Variable 3: Sea State
f. Swell – height, period and direction
g. Waves – height, period and direction
Variable 4: River flow and rainfall
Rainfall and flow are linked variables. Flow is best but in the absence of flow data, catchment rainfall can be used as a proxy for flow after incorporating hysteresis effects.
h. Extreme flow (e.g. Barron > 100 000 ML/day)
i. Small flow that produces an observable plume (e.g. Barron > 30 000 ML/day)
Variable 5: Period of discharge
j. Days (e.g. Wet Tropics rivers)
k. Weeks (e.g. Dry Tropics rivers)

The expected distribution of a plume can be estimated by evaluating recorded variables (hindcast) which, in the simplest sense, include wind speed and direction coupled with river flow data. Formulation of expected plume distributions, over a longer time period than individual observations, allows for the identification of reefs that are subject to plumes and an estimate as to the frequency of impact.

Based on aerial observations and field sampling of flood plumes between the 1994 and 1999 period, a first order estimate has been attempted in hindcasting the inferred spatial extents of plumes. As an example of the potential to hindcast plume occurrence, the Barron River was selected as a case study.

Observations demonstrated that flood plumes from the Barron River could be visually apparent with discharges in the order of 30 000 to 40 000 MLd^{-1} (data for Myola gauging station). Based on this information a figure of 30 000 MLd^{-1} was assigned to historical flow data as a primary variable that needed to be exceeded for a plume to develop. Table 9 summarises events with a daily discharge of greater than 30 000 MLd^{-1} during the 1994–1999 study period.

Table 9. Study period with a daily discharge of > 30 000ML at Myola (Barron River). 30 000 MLd^{-1} was assigned to historical flow data as a primary variable that needed to be exceeded for a plume to develop. Dashes refer to periods that meet criteria but are not associated with a known cyclone.

Year	Day/Month	Event	Barron Discharge (ML/d)
1994	31 January	Sadie	46 905
1994	1 February	Sadie	30 296
1994	19 February	-	36 343
1995	26 February	Violet	35 085
1995	12 March	-	36 690
1995	13 March	-	67 183
1995	14 March	-	63 672
1996	5 March	Ethel	37 655
1996	6 March	Ethel	59 223
1997	23 March	Justin	101 844
1997	24 March	Justin	43 474
1998	10 January	Sid/Katrina	41 737
1998	25 February	-	59 149
1999	12 February	Rona	233 656
1999	13 February	Rona	129 338
1999	14 February	Rona	55 362
1999	15 February	Rona	44 946
1999	28 February	-	34 750
1999	13 March	-	35 371
1999	14 March	-	58 394
1999	15 March	-	71 549
1999	16 March	-	51 717
1999	17 March	-	30 532

Relationships between the discharge criteria and wind conditions experienced between the 1994–1999 period were documented to ascertain the extent of the plumes with respect to these two variables. Data provided in figure 32 summarises the dates of discharge exceeding the set criterion, the date that the flood plume was primarily determined and the wind speed and direction experienced before, during and after the flood plume event. Integrating the wind and discharge data with the mapped plume extents, a matrix was developed to produce set criteria for a predicted plume distribution based on similar historical conditions. Table 10 outlines the types of plume distributions identified from observed events in 1994–1999. The determination of flood plume extent into three observed categories (inner, mid and outer) is gradational and partially subjective due to this assessment being a preliminary estimate and the application of limited factors (wind and river discharge) used to determine plume extent. An extreme category is hypothesised as a possible additional category that may exist in years other than those between 1994 and 1999.

Based on the predicted plume distributions from table 10, an assessment of historical river discharge from Myola and wind data available from Cairns was undertaken. Records of wind data for Cairns commenced in May 1941, therefore, the hindcasting analysis commenced with first event with > 30 000 MLd^{-1} in the Barron River, which is in February 1943. Table 11 provides a summary of the events that have exceeded the river discharge criteria with estimates of plume extent ascribed based on the predicted distributions defined in table 10. The hindcasted plumes provide a preliminary estimate of how frequently plumes extend to a particular area of the GBR. Based on the data for the Barron River it is estimated that in the past 58 years a plume may have reached the mid-shelf reefs (outer category) on 18 occasions.

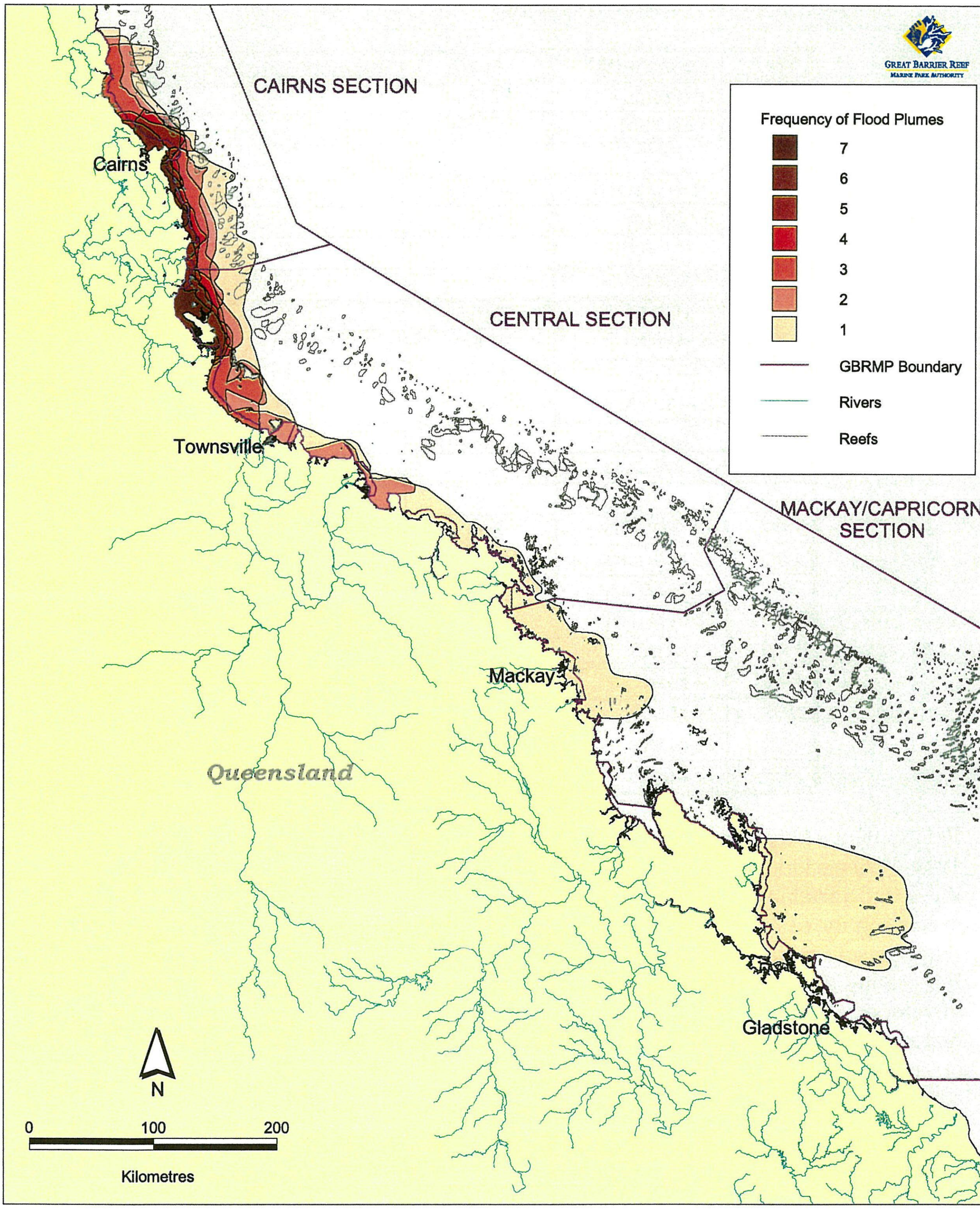
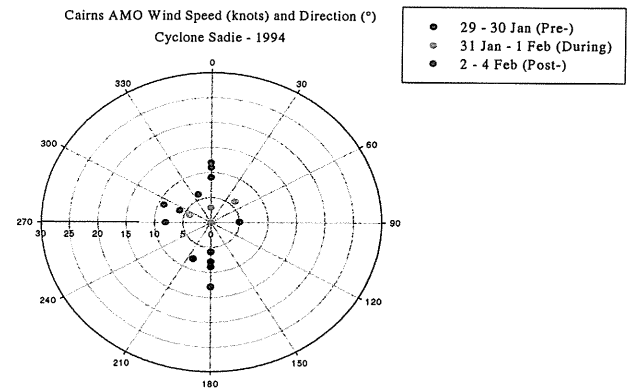
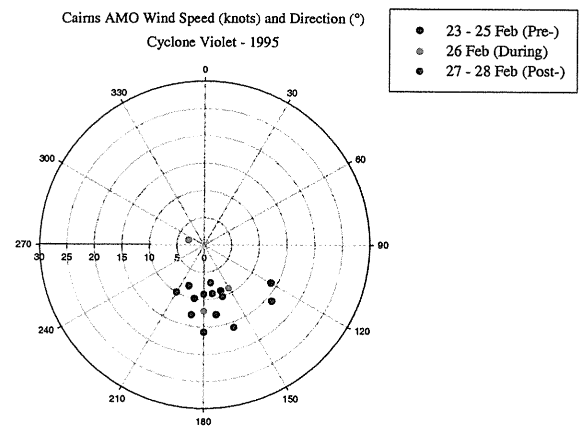


Figure 31. Frequency and distribution of plume coverage in the GBR from 1991–1999

Year	Day/Month	Cyclone
1994	29 January	
1994	30 January	
1994	31 January	Sadie
1994	1 February	Sadie
1994	2 February	
1994	3 February	
1994	4 February	



Year	Day/Month	Cyclone
1995	23 February	
1995	24 February	
1995	25 February	Violet
1995	26 February	Violet
1995	27 February	
1995	28 February	



Year	Day/Month	Cyclone
1996	3 March	
1996	4 March	
1996	5 March	Ethel
1996	6 March	Ethel

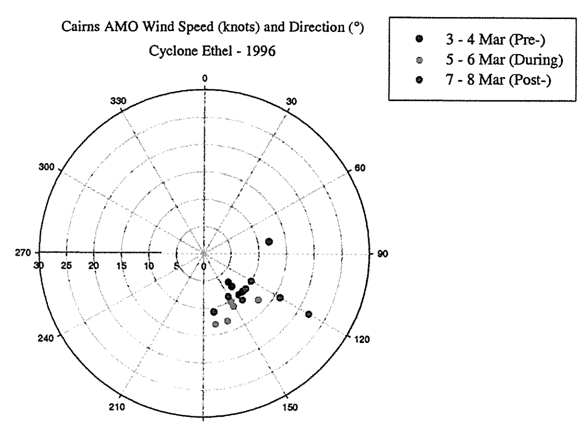
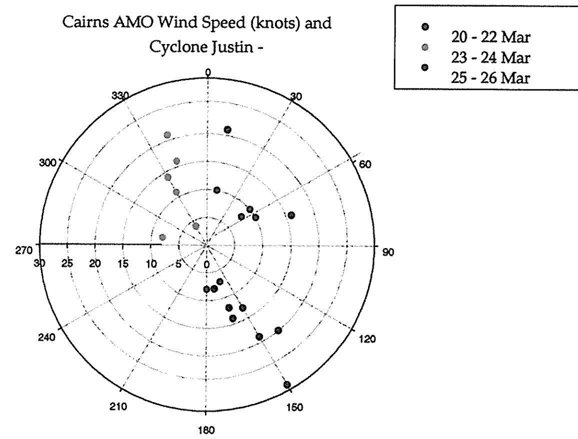


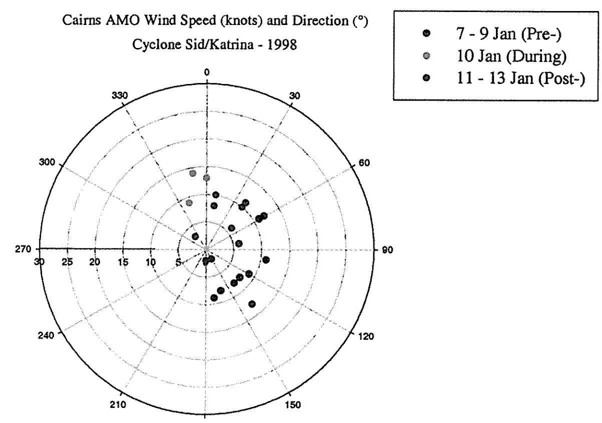
Figure 32. Summary of wind data measured at Cairns airport for cyclones studied from 1994–1999. Names of cyclones indicate days at which discharge in rivers was above the set criteria. Shaded box is the day in which the plume extent was primarily determined. Wind direction and speed (knots) for days preceding and following cyclone are presented in polar diagrams.

Figure 32 cont.

Year	Day/Month	Cyclone
1997	20 March	
1997	21 March	
1997	22 March	Justin
1997	23 March	Justin
1997	24 March	Justin
1997	25 March	



Year	Day/Month	Cyclone
1998	7 January	
1998	8 January	
1998	9 January	Sid/Katrina
1998	10 January	Sid/Katrina
1998	11 January	
1998	12 January	
1998	13 January	



Year	Day/Month	Cyclone
1999	9 February	
1999	10 February	
1999	11 February	Rona
1999	12 February	Rona
1999	13 February	Rona
1999	14 February	Rona
1999	15 February	Rona

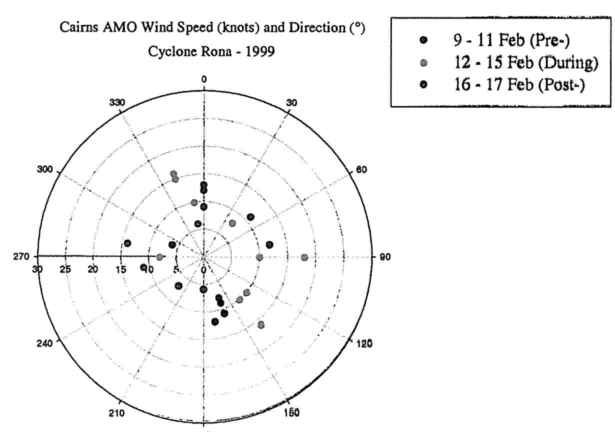


Table 10. Idealised plume distribution based on the observed events 1994–1999 for the Barron and Russell-Mulgrave River section. Criteria used for constructing the following table are wind direction, wind speed and flow rate.

Types of Plume Distribution	Observed Plume	Wind Direction (8pt)	Wind Speed	Flow rate (ML/d)
Inner	Violet Sid/Katrina	Independent	10 or less	< 45 000 for 1 day
Inner	Un-named March 1997	S /SE	> 12	> 30 000 for three consecutive days
Inner-Mid	Ethel	S/SE	< 12	> 30 000 for two consecutive days
Mid	Justin	NW/N	>10	> 30 000 for two consecutive days
Mid-Outer	Rona	SE/NE	¬ 10	> 30 000 for four consecutive days
Outer	Sadie	NW/NE	< 10	> 30 000 for two consecutive days

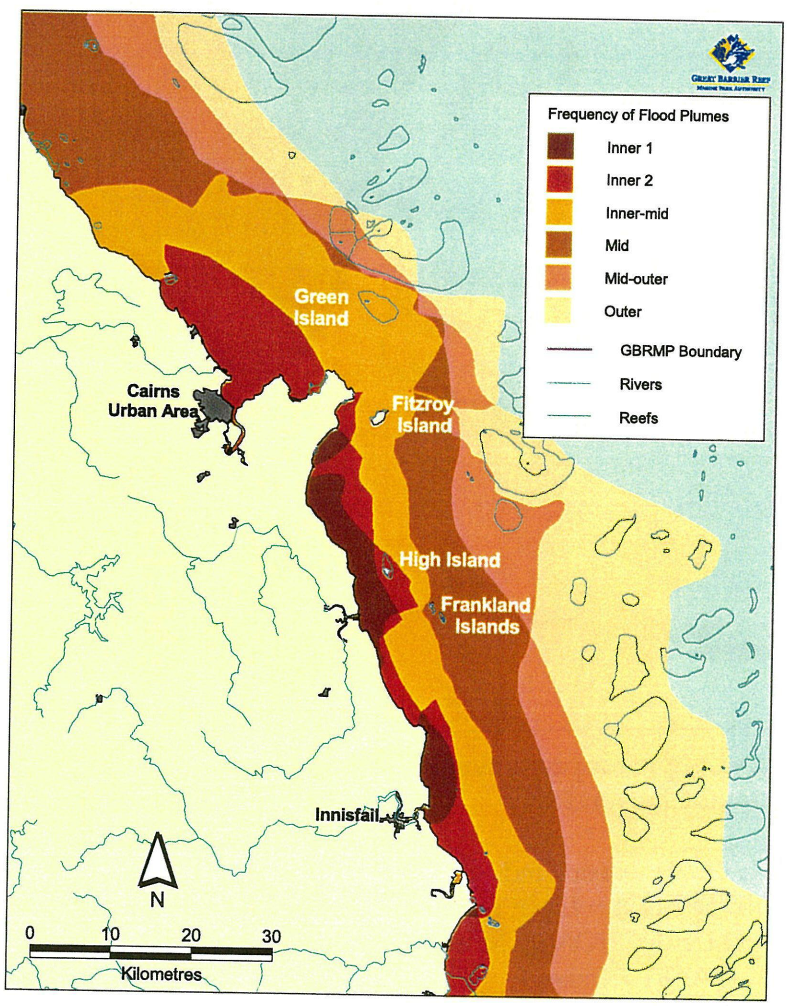


Figure 33. Plume distribution for the Wet Tropics area, between and including Johnstone and Barron Rivers

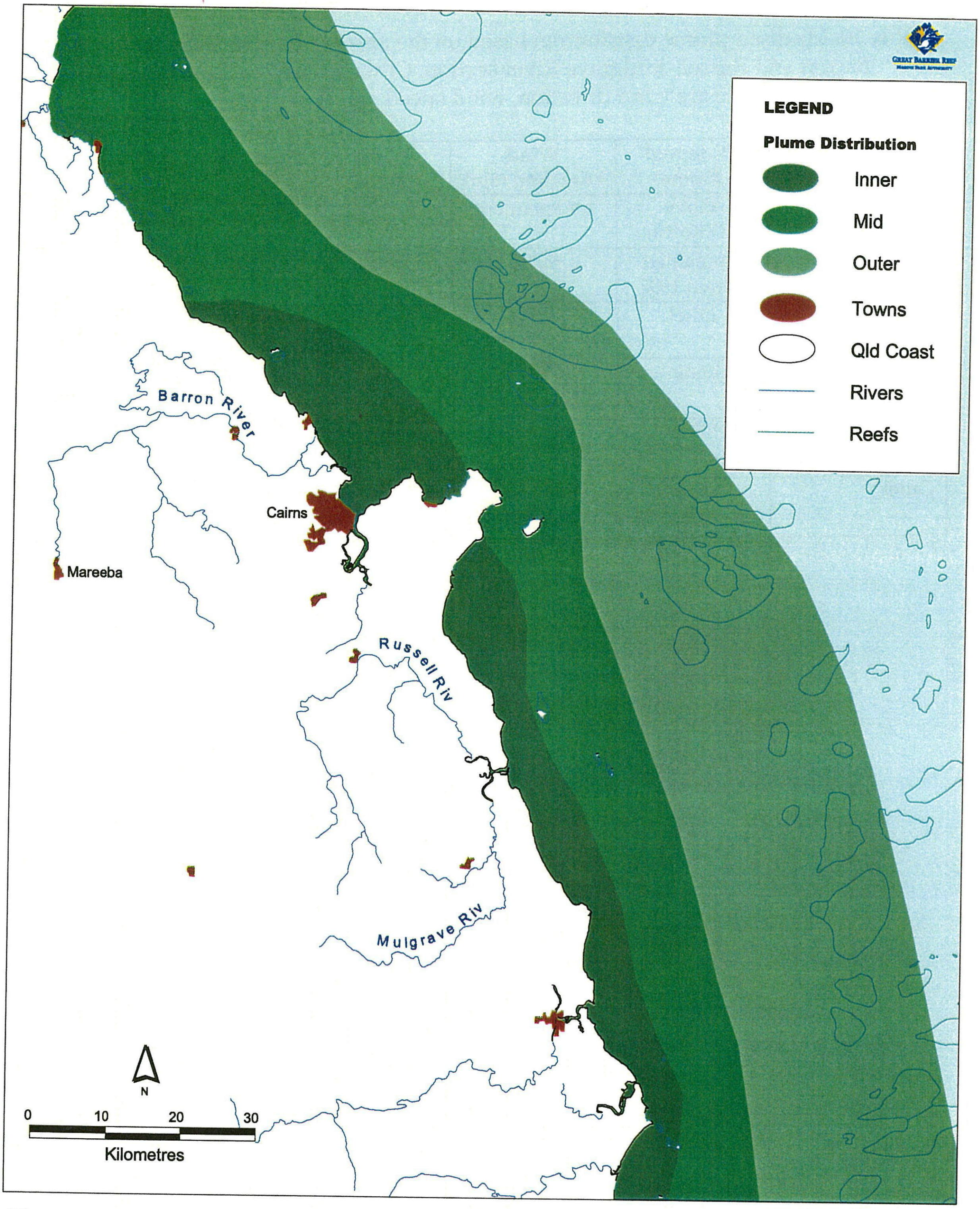
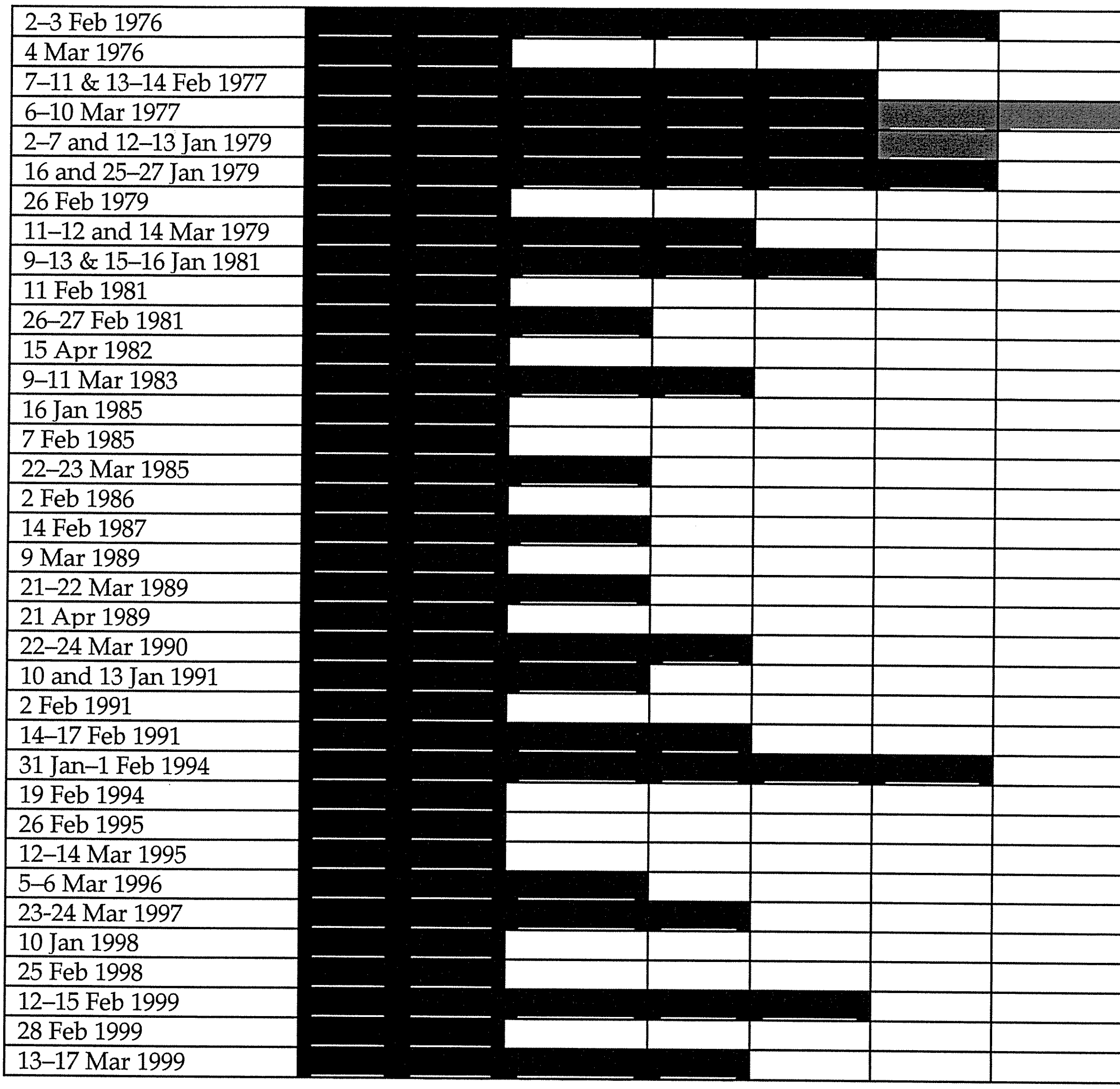


Figure 34. Working example for prediction of plume distribution using historical flow and wind data from the Barron River

Event: 31/01/94–01/02/94 (associated with cyclone Sadie)
VARIABLE 1: (WIND SPEED) = **Light (< 10 knots)**
VARIABLE 2: (WIND DIRECTION) = **North/North-east**
VARIABLE 3: (SEA STATE) = **Calm**
VARIABLE 4: (RIVER FLOW) **> 30 000 ML/day (flow that produces an observable plume)**
31/01/94 = 46 905 ML /day
01/02/94= 30 296 ML/ day
= OUTER PLUME DISTRIBUTION

Table 11. Predicted plume distribution based on the flow rates and wind data for the Barron River section for the period 1943–1999. Extreme events cannot be predicted by the model, as those series of variables have not been measured over the study period.

Date of Event	Inner	Inner2	Innermid	Mid	MidOut	Outer	Extreme
25–28 Feb 1943	■	■	■	■			
14–15 Feb 1944	■	■	■				
1–5 Feb 1945	■	■	■	■	■	■	░
4–6 Mar 1945	■	■	■	■			
18–20 Mar 1945	■	■					
29–30 Mar 1945	■	■					
2–4 Mar 1946	■	■	■	■			
12–13 & 15–16 Feb 1949	■	■	■	■	■	■	
30–31 Mar 1949	■	■	■				
14 Apr 1949	■	■					
15 Jan 1950	■	■					
6–7 Mar 1950	■	■	■				
9 Apr 1950	■	■					
21–22 Dec 1950	■	■					
17 Jan 1953	■	■					
30 Jan and 3–4 Feb 1953	■	■	■				
4–5 Mar 1955	■	■	■	■			
15-17 & 20-21 Mar 1955	■	■	■	■	■		
15–17 Feb 1956	■	■	■	■	■	■	
24–25 Mar 1956	■	■	■				
8–10 Jan 1957	■	■	■	■	■	■	
28 Mar 1957	■	■					
26 Feb 1958	■	■					
28–30 Mar 1958	■	■	■	■	■		
20 Jan 1959	■	■					
5–6 Mar 1959	■	■	■				
12–13 Mar 1959	■	■	■	■			
28 and 31 Jan 1960	■	■	■				
28 Feb 1960	■	■					
22 Feb 1962	■	■					
4 Feb 1963	■	■					
9 Feb 1963	■	■					
8–9 Apr 1963	■	■	■	■	■		
6–7 Mar 1964	■	■	■				
4 Feb 1967	■	■					
11–15 Mar 1967	■	■	■	■	■		
29 Jan 1968	■	■					
18–19 Feb 1968	■	■	■				
28 Jan 1969	■	■					
25 Mar 1969	■	■					
10–12 Mar 1971	■	■	■	■			
11 Apr 1971	■	■					
10 Jan 1972	■	■					
24–25 and 28 Feb 1972	■	■	■	■			
5 and 8–10 Mar 1972	■	■	■	■			
18–19 Mar 1972	■	■	■				
27–28 Mar 1972	■	■	■				
5–6 Mar 1973	■	■	■				
24–25 Jan 1974	■	■	■	■			
1 Feb 1974	■	■					
10–13 & 15–16 Feb 1974	■	■	■	■	■	■	
6–10 Mar 1974	■	■	■	■	■		
17–25 & 28-29 Mar 1974	■	■	■	■	■	■	



5.1.4 Plume Coverage and Reefs

Section 5.1 presents a desktop study of weather conditions and flow rates over the last 58 years for the Barron River catchment. By applying the same strategy to other catchments, an estimate of the number of times a particular reef has experienced a plume event can be estimated. By using these data in a decision tree, 'hot spots' can be assigned to the reefs that are inundated by river plumes each year. For the other catchments, there has been arbitrary selection into these groups by knowledge of the distribution of plume waters over the last 10 years. A complete desktop study of all catchments and plume distribution incorporating other factors will be completed in a subsequent report.

Plume mapping shows that some reefs in the GBR experience river waters annually, some episodically, some rarely and some never at all. Figure 33 summarises the frequencies that reefs are likely to encounter river water and delineates reefs with high frequency of run-off. Figure 35 denotes plume frequency experienced by reefs throughout the GBR. Reefs not identified by colour coding were not considered in this analysis due to limited data. Mapping of the plumes demonstrates inshore reefs, north of the Palm Island group, see river plumes most years. These inshore reefs include Goold Island, King Reef, Brooks Family Group, Frankland Islands, Fitzroy Island, Double Island, Low Isles and Snapper

Island. Reefs south of the Palm Islands, including Pandora, Acheron, Rattlesnake, Herald and Phillip Reefs, Magnetic Island reefs and the Whitsundays reefs experience river plumes from coastal and Burdekin River catchment run-off less frequently; perhaps every two to three years. Data in this report suggests that reefs in the Keppels and Cumberland groups experience river water even less frequently perhaps every four to six years. However, these predictions are based on a very limited observational sample. Offshore reefs in the southern GBR experience river waters infrequently; only once in the 10 years of this monitoring study. However, a few mid-shelf reefs do experience river water quite frequently, particularly at Green Island.

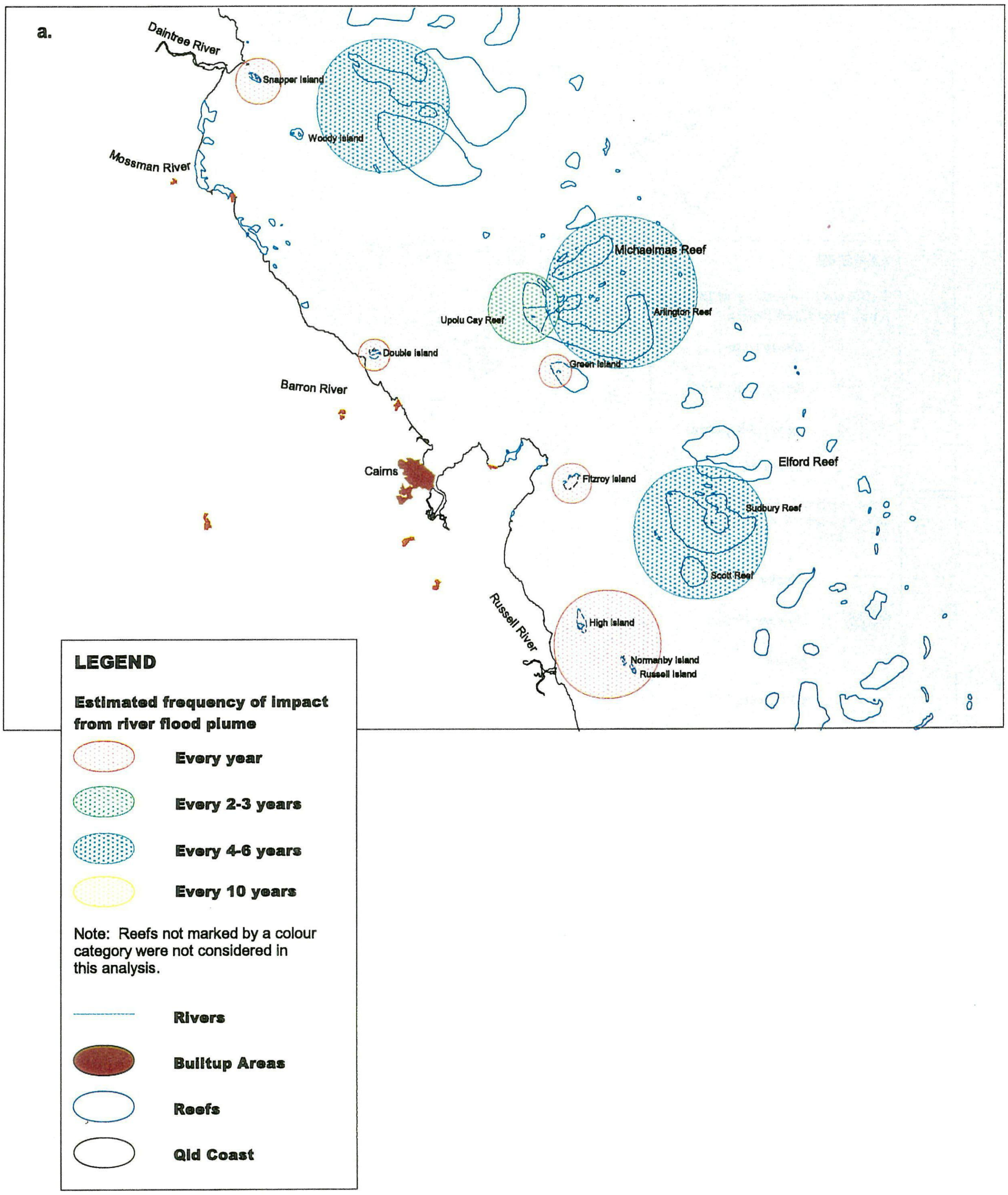
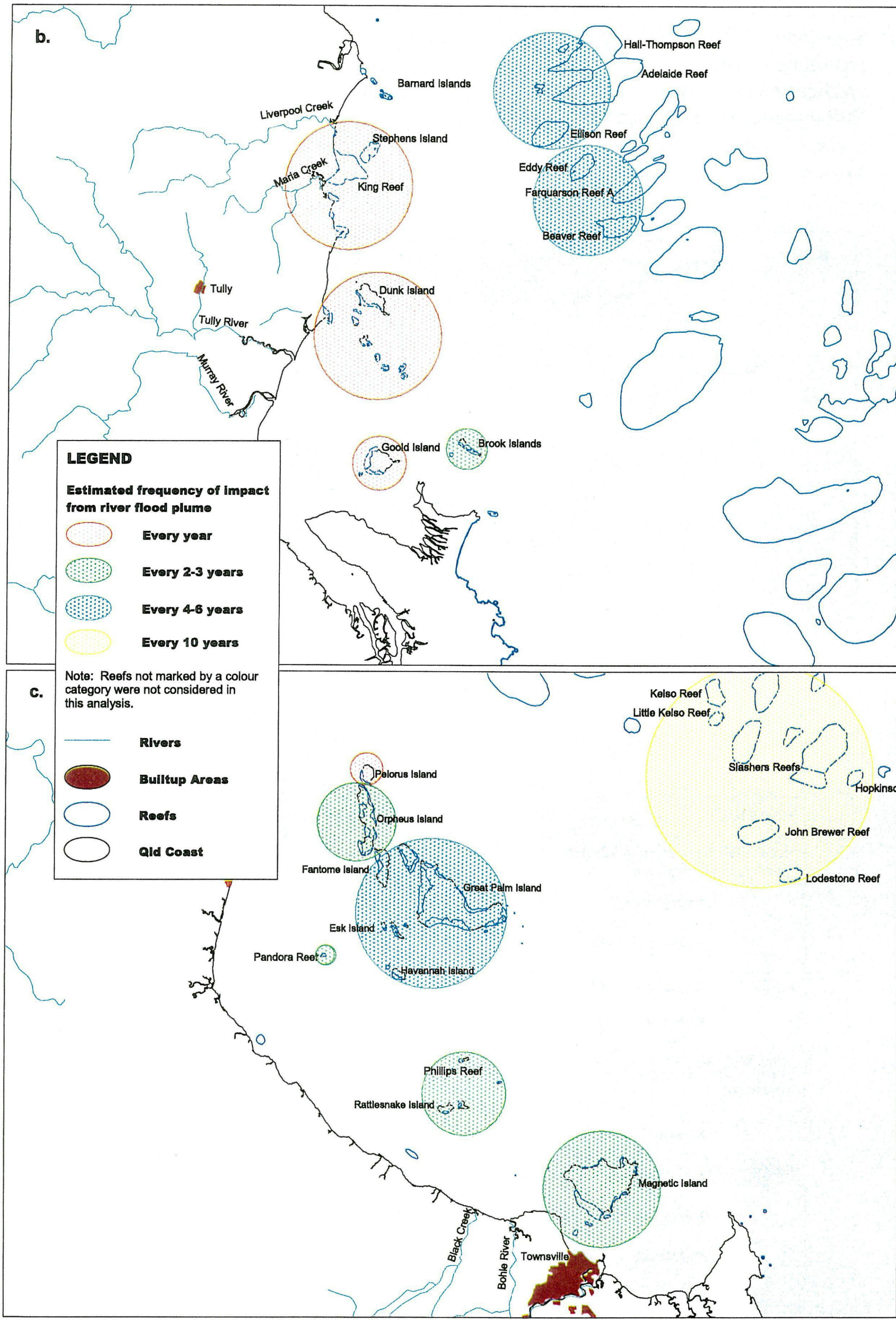
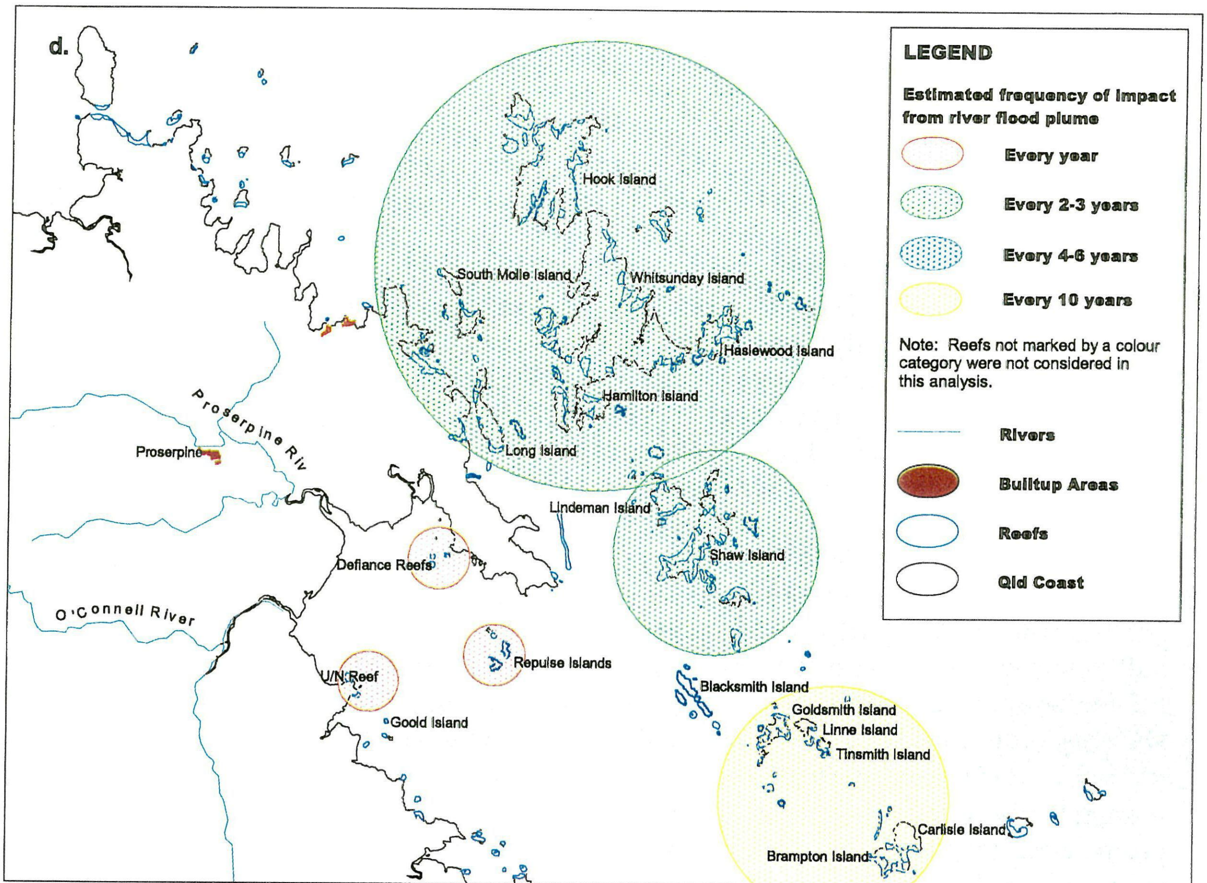
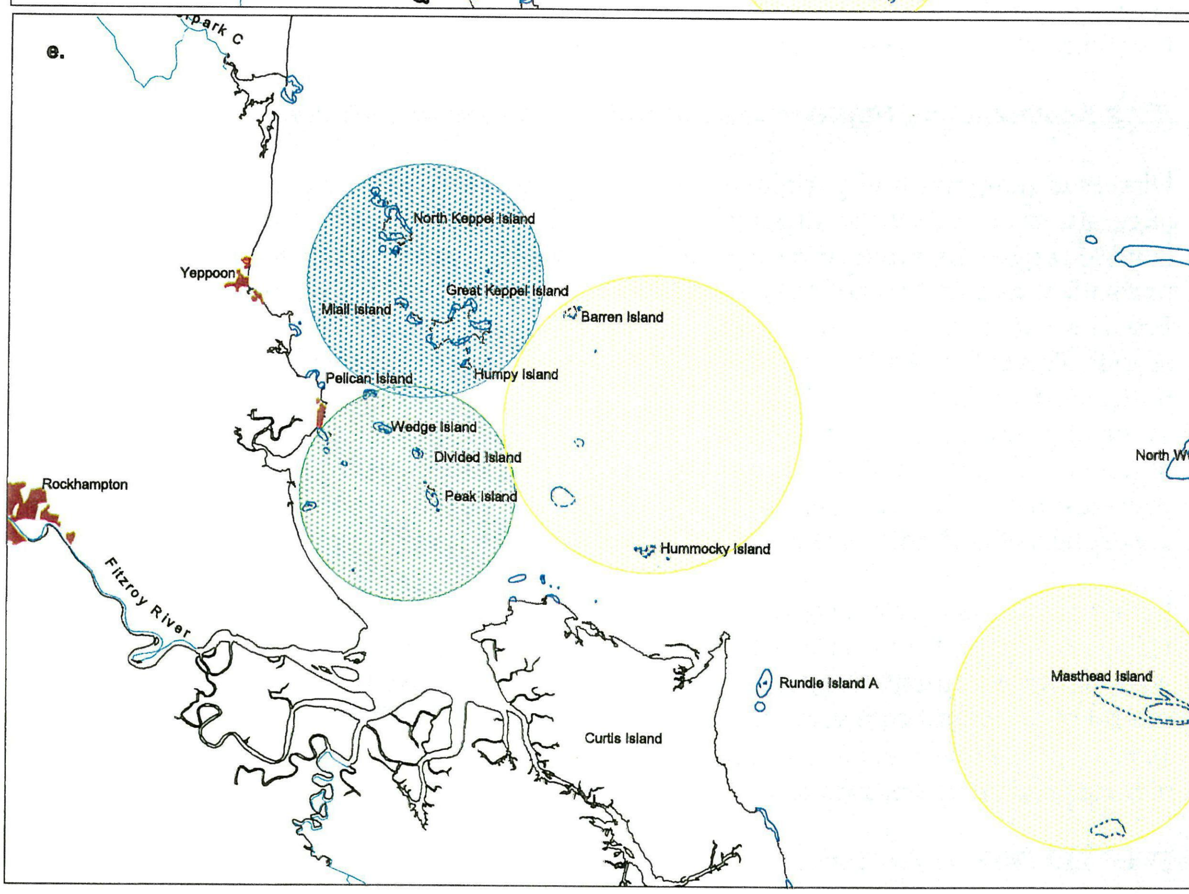


Figure 35. Frequencies of plume coverage for reefs within the GBR. Colour denotes the frequency on which reefs are 'impacted' by flood plumes.


b.
Barnard Islands
Hall-Thompson Reef
Adelaide Reef
Liverpool Creek
Stephens Island
Ellison Reef
Eddy Reef
Maria Creek
King Reef
Farquarson Reef A
Beaver Reef
Tully
Dunk Island
Tully River
Murray River
Goold Island
Brook Islands
LEGEND
Estimated frequency of impact from river flood plume
Every year
Every 2-3 years
Every 4-6 years
Every 10 years
Note: Reefs not marked by a colour category were not considered in this analysis.
Rivers
Builtup Areas
Reefs
Qld Coast
c.
Kelso Reef
Little Kelso Reef
Pelorus Island
Slashers Reefs
Hopkinso
Orpheus Island
John Brewer Reef
Fantome Island
Lodestone Reef
Great Palm Island
Esk Island
Pandora Reef
Havannah Island
Phillips Reef
Rattlesnake Island
Magnetic Island
Black Creek
Bohle River
Townsville


d.
LEGEND
Estimated frequency of impact from river flood plume
Every year
Every 2-3 years
Every 4-6 years
Every 10 years
Note: Reefs not marked by a colour category were not considered in this analysis.
Rivers
Builtup Areas
Reefs
Qld Coast
Hook Island
South Molle Island
Whitsunday Island
Haslewood Island
Hamilton Island
Long Island
Lindeman Island
Shaw Island
Proserpine
Proserpine Riv
O'Connell River
Defiance Reefs
Repulse Islands
U/N Reef
Goold Island
Blacksmith Island
Goldsmith Island
Linne Island
Tinsmith Island
Carlisle Island
Brampton Island


e.
North Keppel Island
Yeppoon
Great Keppel Island
Miall Island
Barren Island
Pelican Island
Humpy Island
Wedge Island
Divided Island
Peak Island
Rockhampton
Fitzroy River
Hummocky Island
Rundle Island A
Curtis Island
Masthead Island

5.2 Water Quality and Plumes

5.2.1 River Dynamics, First Flush and Changes in River Concentrations

Studies on north Queensland rivers have described the movement and activity of particulate and dissolved nutrients in river water discharge into the GBR lagoon. Seasonal peak concentrations of dissolved inorganic species are typically associated with the first significant rainfall event of the season, which reflects the mobility of the oxidised nutrients built up in the catchment during the dry season. Inorganic concentrations progressively decline over the course of the wet season. Concentrations of dissolved organic N and P remain low and relatively constant through the year. DON can decline with increasing discharge, suggesting relatively constant input from the watershed and dilutions during major flood events. Concentrations of PN and PP vary directly with river flow and typically peak during major seasonal flood events reflecting the transport of organic matter and soil particles through the watershed (Furnas & Mitchell 1997).

First flush river concentration can exceed 100 μM for NO_3 and 4 μM for PO_4, reflecting the mobility of oxidised N (and P to a lesser extent) (Furnas & Mitchell 1997). The DIN concentration falls rapidly over time as the river water moves downstream though there are still relatively high source concentrations of inorganic nutrients in river waters in the initial mixing with the inshore lagoon waters. Generally flooding river waters reach the lagoon with high concentrations of DIN and DIP, which tend to fall out rapidly. DIN can reach 17 μM with a decline to 0.5 μM across the plume boundary (figure 35). Conversely dissolved inorganic phosphorus (DIP) can fall from 0.4 μM to low ambient levels of 0.05 μM across the plume interface (figure 36). Patterns of mixing vary for each flow event. River waters also contain high levels of PN and PP (figure 37 and 38), which reduce longitudinally through the plume due to mixing dilutions.

5.2.2 Sediment and Nutrient Concentrations Measured in Plume Waters

Dissolved inorganic and particulate phosphorus are elevated in the majority of samples (e.g. figures 26 and 29). Studies by Cosser (1989), Pailles & Moody (1992) and Mitchell et al. (1997b) suggest that most P transported to the sea by Queensland river systems is bound to particulate matter. Most of the particulate P settles out close to the river mouth. However Brodie & Mitchell (1992) show that a significant part of the P in the Fitzroy plume is present as DIP. This is the result of desorption of P from the particulate phase as river water mixes with seawater (Brodie & Mitchell 1992; Fox et al. 1985). This mechanism allows the P to move further offshore in the dissolved phase. DIP was elevated in samples taken adjacent to the Wet Tropics and Burdekin River plumes (figures 22–29). The relatively high concentrations of particulate phosphorus measured further offshore may be the result of re-adsorption of DIP onto particulate matter and an increase in phytoplankton biomass.

Levels of DIN are variable and concentrations measured in the plume are generally high in respect to ambient conditions (figure 35—NOx and figure 40—NH_4). The number of sites with elevated nutrients suggests that the high nutrient composition of the flood plumes extend over a significant area and over a number of days. DIN levels are in the range of 1–10 μM, compared to ambient concentrations, typically 0.1 μM (Furnas et al. 1995) with highest concentrations measured near the river mouth.

DON and DOP concentrations were relatively constant throughout individual plumes, with DOP ranging between 0.1–1.0 μM and DON concentrations typically found between 5 and 15 μM (figure 39). There seems to be no relationship between increasing salinity and organic nutrient concentrations as organic nutrient concentrations in river waters and lagoon waters in the lagoon have approximately similar concentrations. Organic nutrients, particularly DON, are relatively stable and not known to be rapidly used in any biological process (Furnas et al. 1996).

Particulate nutrients (figures 37 and 38) and suspended matter (figure 39) were higher than ambient conditions with peak concentrations measured adjacent and north of the flooding rivers. Concentrations of PN reached a maximum of 24 μM (figure 22b—Barron River in cyclone Justin) and generally were higher than 15 μM at low salinity levels (figure 37). Concentrations of PP reached a maximum of 1.0 μM (figure 40—Johnstone River in cyclone Rona) and concentrations of PP were generally higher than 0.5 μM (figure 38) at low salinity levels. Particulate matter settles out over relatively short distances, though concentrations are significantly higher than ambient concentrations for all samples taken within the surface waters associated with flood plumes. PN and PP can be a source of continually de-sorbing nutrients over a large time period, contributing to the dissolved component. Particulate nutrient concentrations measured in the surface plume waters are high in N and P but other studies demonstrate (Pailles & Moody 1992) bottom sediment can have lower nutrient concentrations than measured in the surface of the plume. This decline in nutrients in particulate matter may be related to desorption of nutrients from surface particulate nutrients and could serve as a food source for phytoplankton growth. Re-adsorption onto other particulate matter and uptake by phytoplankton can be seen in the higher concentrations of organic and particulate matter over time and space in the development of the plume.

Chlorophyll *a* concentrations had an inverse pattern of increasing concentrations at some distance from the river mouth (figure 39). This was likely to be influenced by the length of time which water column phytoplankton have been exposed to flood generated nutrients and the increasing light as the heavy suspended matter dropped out of the plume (Brodie & Mitchell 1992; Furnas 1989; Revelante & Gilmartin 1982). Chlorophyll *a* concentrations were higher than phaeophytin concentrations in all samples, confirming that most of the chlorophyll detected was associated with new algal biomass stimulated by flood water discharge (Brodie & Mitchell 1992). Chlorophyll *a* levels were highest in the Fitzroy surface plume (figure 44), generally 20 times normal inshore values, indicating an extensive phytoplankton bloom within the plume. This bloom was not visually obvious as associated seawater colour changes were obscured by the turbidity of the plume water. The highest chlorophyll concentrations were measured north and away from the river mouth, in correlation with the low nitrate values. This reflects water travel time from the river mouth, combined with greater light penetration in that area (Brodie & Mitchell 1992).

Measurements of all parameters taken further away from the river are influenced by the physical and biological processes occurring over time as the elevated concentrations in the river water mixed with the lagoonal waters of the GBR. Concentrations of NOx and DIP ranged from 10–15 μM (figure 35) and 0.2–0.5 μM (figure 36) at sites close to the river mouth and declining to levels between 0 to 2 μM (NOx) and 0 to 0.2 μM (DIP) at higher salinity concentrations.

5.2.3 Mixing Processes Occurring in the Plumes

Timing of sampling is critical in obtaining reliable estimates of material exported in the flood plumes (Taylor & Devlin 1997). There is a hysteresis in the development of a flood plume, which is related to catchment characteristics (size, vegetation cover and gradient) rainfall intensity, duration and distribution and flow volume and duration. The time lag difference is significant in the smaller Wet Tropic rivers (Herbert to Daintree) compared to the larger Dry Tropic rivers of the Burdekin and Fitzroy.

Study of the physico-chemical parameters in flood plumes has largely been opportunistic until recent years. There is data available from various studies (Brodie et al. 1997; Taylor & Cuff 1996; Devlin et al. 1996) which indicate that there can often be a rapid transformation in the physico-chemical parameters of a plume. There is typically a paucity of data for early in the plume event due to logistical and safety considerations. The timing of sampling is important to understand the full dynamics of the event rather than basing conclusions on the results available from a couple of days after the event. However, with logging equipment deployed on nearshore reefs (Devlin, in prep) and ongoing river studies (Mitchell et al. 1997a,b) there is the potential to further understand the physico-chemical dynamics of a flood plume in the early stages of the flood.

In a coupled estuarine-inner shelf environment like the GBR lagoon, winds, tides and river discharge are the three primary forces that drive the circulation, which in turn supports complex ecosystems. Each river system has unique features, so it is quite difficult to generalise from one system to the next. Coastal plumes associated with riverine flow are biologically rich waters bounded by strong horizontal and vertical salinity gradients (McManus & Fuhrman 1990). Plume waterfronts are an important part of the ecological processes that drive productivity in the coastal area. It can be recognised in surface waters by the naked eye and by a sharp colour change and accumulation of foam and flotsam. Nutrient distribution is principally determined by mixing processes between freshwater of high nutrient and seawater of low nutrient content.

The overall impact of these processes is strongly dependent on the physical characteristics of the system in question primarily because of the variability in dilution processes and coastal characteristics in the open waters adjacent to the coastal systems. Hence it is the extent of the exchange between the two systems that is such a strong influence. Measurements taken near the mouth of the river system are more representative of the processes that are occurring in the river and dependent on the characteristics of that river system. Samples taken early in the plume at close proximity to the mouth may generally be high in particulate matter related to the river source.

Data from flood plumes clearly indicate that the composition of plumes is strongly dependent on particular events, between days and through a single event, depths and catchment. The following section illustrates the changes in dissolved and particulate matter as the freshwater moves away from the river mouth into the inshore lagoon and mixes with seawater.

The concentrations of chemical constituents in plume water are directly related to the degree of mixing between the fresh and salt water. Where the changes in concentration result only from the dilution associated with mixing, the constituents are said to behave conservatively and one of the most useful techniques available for interpreting mixing processes is to examine whether data is consistent with conservative behaviour. This is undertaken by testing the linearity of the relationship between the concentration of the water quality parameter and an index of conservative mixing. In applying this technique, salinity is usually used as an index of conservative mixing (figure 36).

Deviations from linearity indicate enrichment or depletion of a particular water mass in excess of that to be expected from the simple mixing of a two-component system (Chester 1990). A non-linear relationship between the water quality parameter and salinity indicates some form of addition or depletion of that parameter through another process (figure 36). Processes occurring in addition to mixing can include, the biological uptake from dissolved to a particulate stage, sedimentation of particulate and the mineralisation or desorption of particulate to dissolved species. A number of these processes occur at the same time and thus make it difficult to determine the type of mixing relationship. Nutrients carried into coastal waters by river plumes have a marked effect on productivity in the region offshore from the river mouth (McKinnon & Thorrold 1993).

The distribution of nutrients within the plume is a function of riverine inputs, mixing and biological activity which adds or removes nutrients. Figures 35 to 37 present the relationship between NO_x, NH_4, DIP, PP and PN and salinity for three separate Wet Tropic flood events. Figures 39 and 40 summarise the relationship between DOP, DON, chlorophyll *a* and suspended solids, NH_4 and silicate and salinity for all Wet Tropic flood events (cyclones Violet, Justin, Sid and Rona). Figures 41 and 42 present the relationship between water quality parameters and salinities measured in plume water associated with the Burdekin and Fitzroy Rivers. These mixing profiles demonstrate initial high concentrations of all water quality parameters in low salinity waters, with decreasing concentrations over the mixing zone. Mixing patterns for each water quality parameter are variable over catchment and cyclonic event, though there are similar mixing profiles for specific nutrient species.

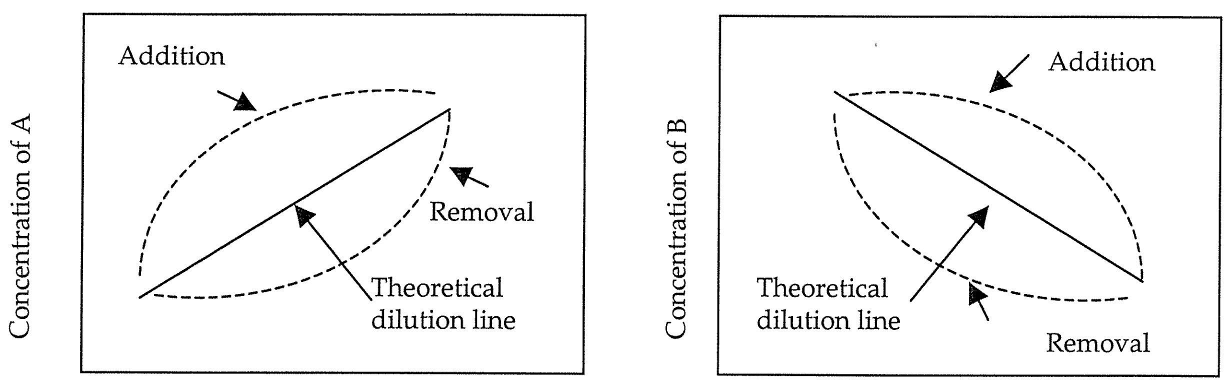


Figure 36. Idealized representation of the relationship between concentrations of a dissolved component and a conservative index of mixing for an estuary where there are single sources of river and seawater. For a component (A) is greater in seawater than in river water and (B) for a component whose concentration is greater in river water than in seawater (Chester 1990).

In the initial mixing zone, water velocity is reduced and most of the river derived particulate matter settles from the plume. This is most clearly shown in the results from the Burdekin for cyclone Sid (figure 41) where suspended solid and particulate phosphorus concentrations drop to very low levels only a few kilometres from the river mouth at salinity of approximately 10. However, sediment distribution information (Maxwell 1968) shows that the area off the mouth of the Burdekin River has a low proportion of fine sediments. This apparent inconsistency is best explained by the resuspension and northward transport and deposition in northerly facing bays of fine sediments which occurs throughout the year under the influence of the south-east wind regime on the inner-shelf (Woolfe et al. 1998). Reductions in suspended sediment with increasing salinity in the plume are less clear in some of the other plumes reported (figure 39), but this is complicated by the resuspension during the plume event in stronger wind conditions on these occasions.

NO_x and DIP concentrations generally follow a conservative mixing process, diluting in a linear pattern in relation to the salinity concentrations (figures 35 and 36). Source and end concentrations are variable between catchment and as a result, there are different slopes to the lines in relation to catchment. Figures 35 and 36 demonstrate these linear relationships, indicating the NO_x and DIP may not be utilised or released by chemical or biological processes occurring in the plume in the lower salinity ranges. However, there is some scattering of data at the higher salinity ranges, indicating some non-conservative mixing. Non-conservative mixing processes of the inorganic nutrients in the higher salinity ranges indicate processes, other than dilution, occurring in the plume. Plumes support a higher primary production with nutrients being removed by consumption by phytoplankton (Tian et al. 1993). The data supports a general pattern of nutrient distribution characterized by a gradual decrease of concentration across the plume surface with a rapid decline in the nutrient concentrations at about 26–30. This is most likely the area of high productivity where there is noticeable uptake of nutrients by phytoplankton. Concentrations of DIP approach detection limits at salinities greater than 30 suggesting biological mediated depletion.

Ammonia concentrations are far more scattered reflecting both variations in supply, uptake and production from biological processes in the plume (figure 40). Concentrations of NH_4 remain elevated in the higher salinities suggesting sources of ammonia in the plume, for example, excretion by zooplankton. Values for the river end member were lower than some concentrations at intermediate salinities. This may be related to variability in riverine concentrations over time, combined with multiple discharge points and differing mixing dynamics in various regions of the plume, or higher values occurred at the frontal convergence where biomass levels were concentrated and perhaps regeneration of nutrients was enhanced.

Concentrations of PN and PP vary directly with river flow (Furnas & Mitchell 1997) and can peak during major seasonal flood events (Mitchell et al. 1997b), reflecting the transport of organic matter and soil particles through the watershed. Particulate matter declines rapidly across the mixing zone, with concentrations falling from 8 to 20 μM to ambient levels for PN and 1.0 μM to ambient levels for PP (figures 37 and 38). Conversely there can be an increase in the particulate nutrients at a greater distance and time in the plume reflecting the succession of particulate nitrogen and particulate phosphorus from algal fixation of the dissolved nutrient component.

The fate of particle bound nutrients, particularly phosphorus, in the estuarine mixing zone has been studied for many rivers around the world, but not on the Queensland coast. Generally a large proportion of the phosphorus is desorbed from the bound particulate form into solution during estuarine mixing as major changes in pH, salinity and Eh (electrochemical potential) occur (Froelich 1988). Particulate phosphorus as a proportion of total phosphorus is high in the freshwater part of the river, declines as phosphorus desorbs into solution in the estuarine mixing zone and then increases again as dissolved phosphorus is taken up into phytoplankton and other biotic aggregates (Lebo 1991). The ability of particulate matter, particularly iron and aluminium oxides and organic matter, to absorb and desorb phosphorus and hence act as a phosphorus buffer has been suggested (Froelich 1988).

The high spatial variance of nutrient concentrations in the plumes is related to plumes constrained and broken up by islands and reefs, with the complexity directed by the multiple rivers and streams acting as source water for the plume. Outlying scatter points in the mixing graphs could also be due to resuspension processes resulting from rough weather conditions. Samples in plumes are taken on one day (more or less) whereas concentrations of dissolved components vary greatly during flooding in the river, e.g. first flush. This would affect the mixing curves.

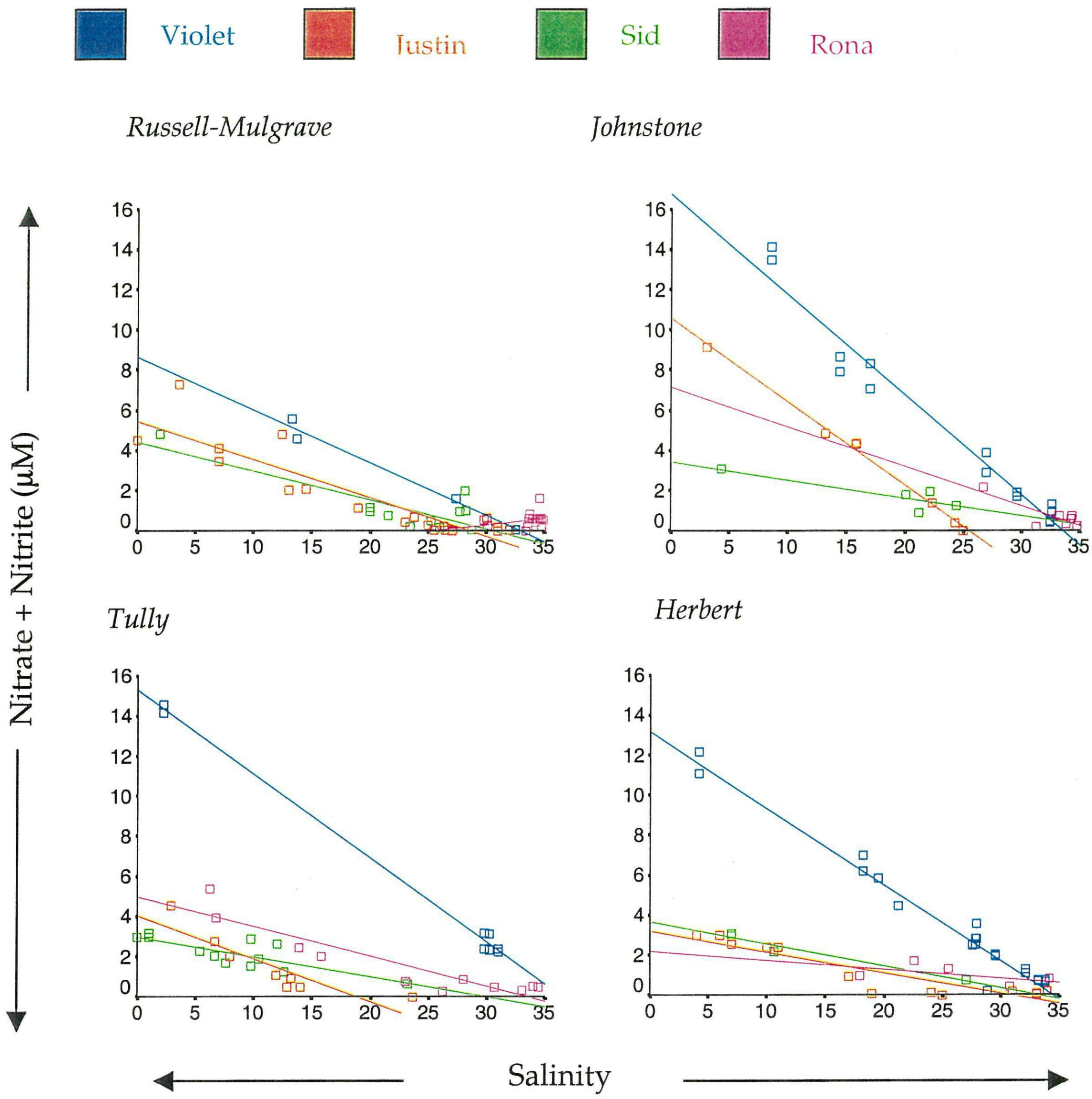


Figure 37. NOx (nitrate and nitrite) versus salinity from Wet Tropics river plumes associated with cyclones Violet, Justin, Sid and Rona. Lines of best fit have not been plotted for data sets where R^2 is less than 0.7.

5.3 Implications of Changed Land-use for River and Plume Waters

In understanding the processes and impacts of freshwater plumes in the marine environment, it is necessary to consider the nature and magnitude of these inputs. Water quality in north Queensland river system has been modified by changes in land use, vegetation clearing and agricultural practices. Worldwide the correlation of catchment development (population numbers or areas of intensive agriculture) and concentrations of contaminants such as nitrate is well established (Peierls et al. 1991). A similar correlation has been demonstrated for rivers on the GBR Catchment (Wachenfeld et al. 1998). Figure 43 shows the correlation between percentage catchment or sub-catchment development and dissolved inorganic nitrogen (nitrate + ammonia) concentrations in river flood flow for a number of rivers on the GBR Catchment. In general, concentrations of dissolved inorganic nitrogen (DIN) increase by a factor of 3–50 times on rivers draining to the GBR from highly developed compared to undeveloped or lightly developed catchments.

The comparison has been well documented for the Jardine River, with an undeveloped catchment and the Johnstone River catchment that has significant development. In peak flow conditions the Jardine and Johnstone Rivers measure DIN concentrations of 4 µM and 4–60 µM respectively (Mitchell et al. 1997; Eyre & Davies 1996). Nutrient concentrations in the Jardine River (Eyre & Davies 1996) are representative of water quality in a pristine river catchment. There has been limited land use changes or development in this catchment over the last 100 years. The upper part of the Johnstone catchment area is mainly used for grazing, with the lower river flood plain and coastal strip being used extensively for cultivation, dominated by sugarcane (Hunter et al. 1996). Concentrations of DIN measured in the Jardine River reach 4 µm in heavy flow conditions. DIN concentrations some distance offshore are likely to be in the range of 2 µM when plume waters intersect reefs or seagrass beds, i.e. below the effects levels for DIN on coral, seagrass and algae (ANZECC 1999; Koop et al. 2001; Ferrier-Pages et al. 2000; Schaffelke 1999). In comparison, using the Johnstone River as an example of a catchment with substantial agricultural and urban land-use, the river concentrations of DIN regularly reach 40–60 µM in heavy flow conditions (Mitchell et al. 1997b). DIN at inshore reef and seagrass ecosystems in flood events are likely to be in the range of 5–20 µM, i.e. well above the effect level of DIN.

Similarly the upper Tully River catchment, with largely undisturbed rainforest catchment has maximum DIN concentrations of 1 µM (Faithful & Brodie 1990) while in the lower Tully River catchment, dominated by sugarcane, horticulture, grazing and urban land uses, river water reaches DIN concentrations of 40 µM in heavy flow (Furnas & Mitchell 1997) and levels of 4–10 µM in the nearshore environment.

5.4 Implications of Changed Land-use in the Catchment for GBR Ecosystems

There has been concern for some time about increasing nutrient loading to the GBR (Bell 1991; Kinsey 1991; Bennell 1979). Some published material claims that the system is already eutrophic (Bell 1991, 1992) and other work demonstrates increases in the nutrient discharge to the GBR from rivers over the last 150 years (Moss et al. 1992). While increasing nutrient loads have been recognised as a major threat to reefs, the actual ways in which reefs respond to these increases is still being elucidated (Koop et al. 2001; Hatcher et al. 1989). Monitoring of point source discharges and changes in the ecosystem (Smith et al. 1981), defining eutrophication and pollution gradients (van Woesik et al. 1999; Hunte & Wittenburg 1992; Tomascik & Sander 1987a, b) and infield and laboratory experimental studies (Ferrier-Pages et al. 2000; Koop et al. 2001; Schaeffelke 1999; Marubini & Davies 1996; Kinsey & Davies, 1979;) have shown that increased nutrient levels profoundly affect corals and coral reef ecosystems.

Important marine communities along the GBR coast, such as coral reefs and seagrass beds have recruited, grown and evolved in the presence of natural land run-off. However, numerous studies (Preen et al. 1995; Jokiel et al. 1993; van Woesik 1991; Rogers 1990; Smith et al. 1981) have demonstrated that freshwater inundation or high sediment and nutrient loads can damage coral reefs and seagrass beds. This can be part of a natural cycle for inshore reefs, but to the extent that a recovery will occur over time is debatable if the biological processes are altered/ affected by high nutrient and sediment concentrations.

During the flood program sites have frequently been sampled which are at close proximity to reefs. Figures 46–49 show the locations of sampling sites situated near a series of inshore reefs. Nutrient concentrations associated with these sites give some indication of the extreme concentrations inshore reefs experience during a river plume. The selected inshore reefs were the Frankland Island reefs (Round, Russell and Normandy Islands), High Island, Goold Island, Pandora Reef and Keppel Islands (figures 46–49). Sites were chosen in relation to the flood plume that was sampled at a particular time and inclusion in this analysis was dependent on proximity to the selected reefs. Nutrient concentrations measured near these inshore reefs may not necessarily be representative of a particular river as the Wet Tropics river plume merged into one continuous plume. However, river waters from a particular river or catchment are likely to move in a northerly direction over reefs that lie in a northern direction away from the mouth.

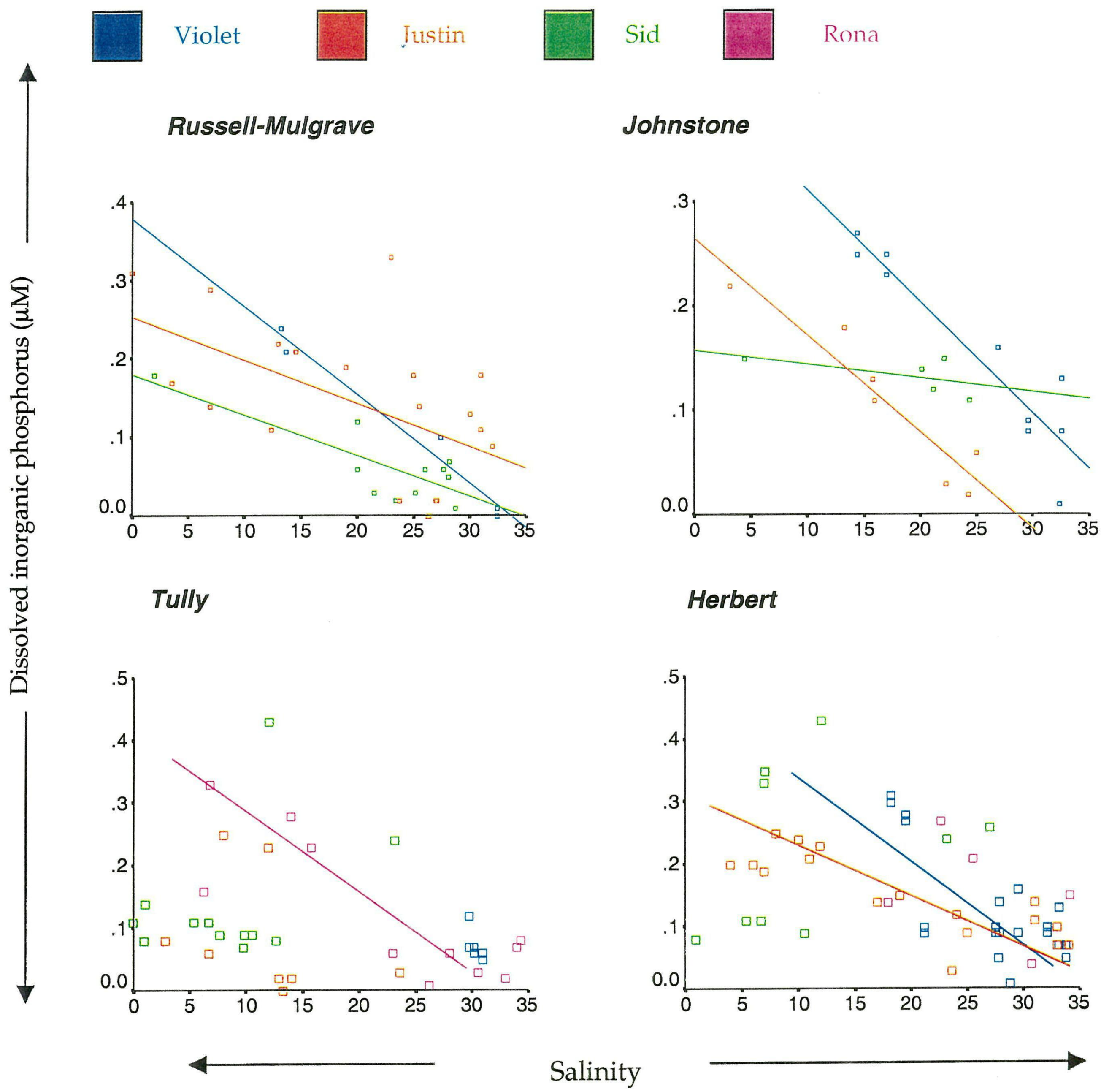


Figure 38. DIP versus salinity from Wet Tropics river plumes associated with cyclones Violet, Justin, Sid and Rona. Lines of best fit have not been plotted for data sets where R^2 is less than 0.7.

Coral reef systems are complex and it is difficult to assess how a particular variable, such as high concentrations of dissolved nutrients, can impact on the 'health' of the system. Assessment is hindered by the (nearly always) simultaneous impact of coincident high seawater temperatures and of low salinity and high turbidity caused by flood plumes. Direct experimental work on the susceptibility of corals to damage from elevated nutrient concentrations has been in progress in the GBR for the last decade and follows up the pioneering work of Kinsey and Davies (1979) at One Tree Island. Principal work has occurred at Orpheus Island Research Station using flow-through aquarium systems (Rasmussen et al. 1992), the Enrichment of Nutrients on a Coral Reef Experiment (ENCORE) project at One Tree Island Research Station, using micro-atolls as research units (Koop et al. 2001; Larkum & Steven 1994) and observations from Reef HQ in Townsville. From the results of this work, there have been tentative guidelines developed for trigger nutrient values for inshore marine waters. Trigger values are concentrations (loads) of key performance indicators, below which there is a low risk of adverse biological effects occurring (ANZECC 1999).

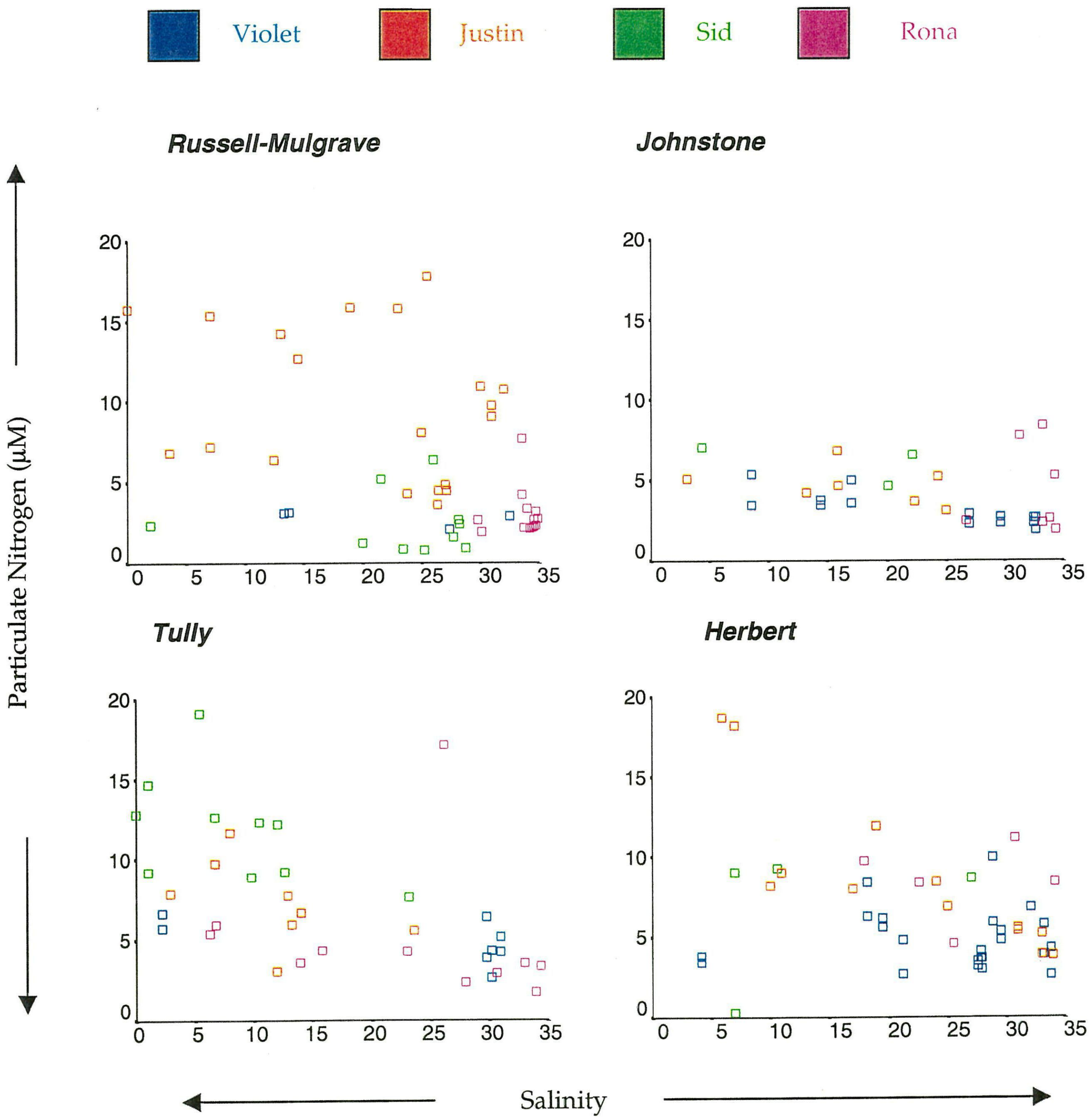


Figure 39. Salinity versus PN from Wet Tropics river plumes associated with cyclones Violet, Justin, Sid and Rona. Lines of best fit have not been plotted for data sets where R^2 is less than 0.7.

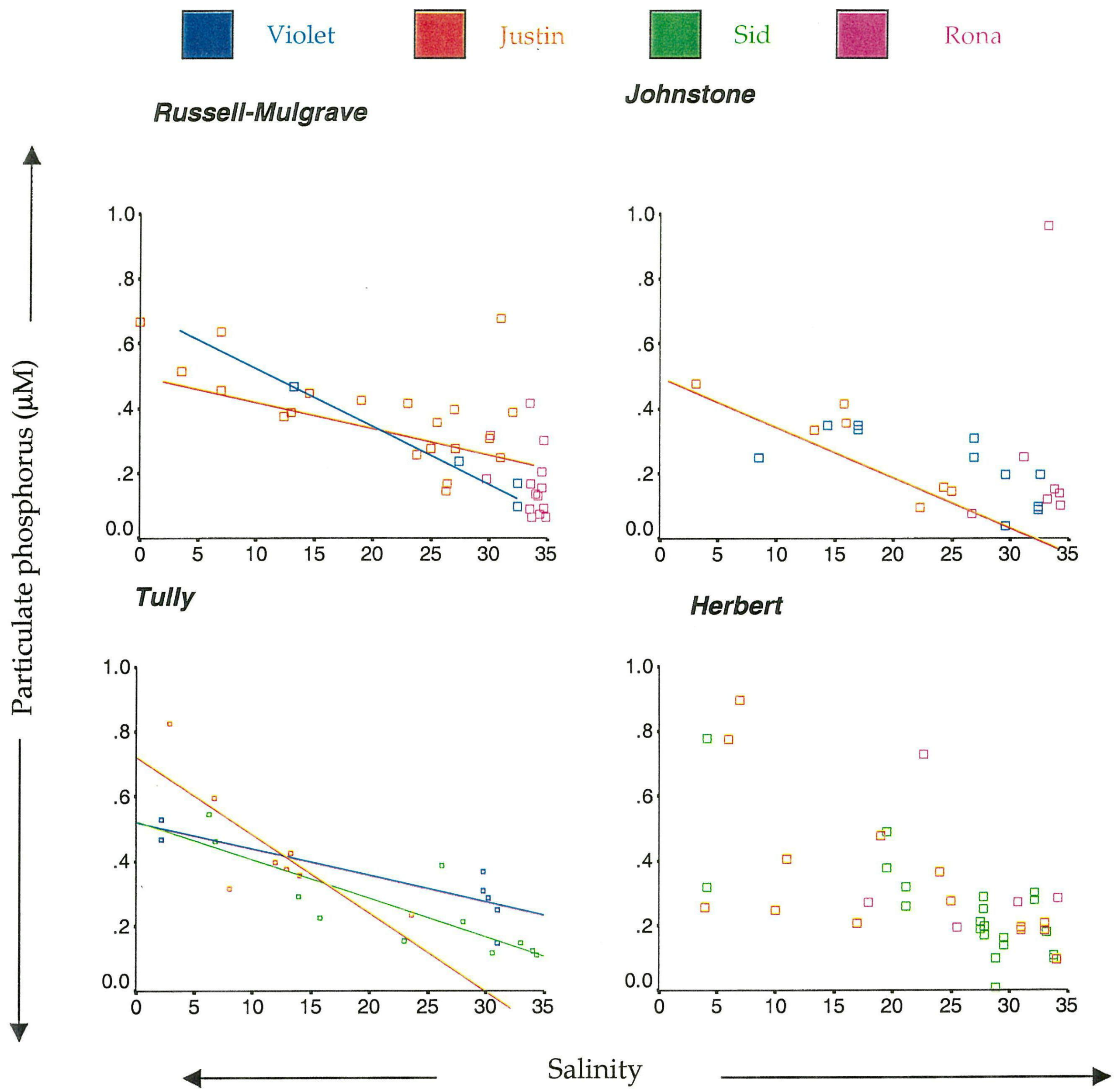


Figure 40. PP versus salinity from Wet Tropics river plumes associated with cyclones Violet, Justin, Sid and Rona. Lines of best fit have not been plotted for data sets where R^2 is less than 0.7.

NH_4, NO_3 and DIP concentrations measured in waters surrounding these inshore reefs during plume conditions ranged from 1 to 8 µM, 2 to 9 µM and 0.1 to 2.5 µM (figures 44–47). The long term ambient concentrations of these nutrient species in these areas are 0–0.01 µM, 0.1–0.4 µM and 0.1–0.15 µM respectively (Furnas & Brodie 1996). Concentrations measured in close proximity to reefs are 2–20 fold higher than ambient concentrations and above the trigger values set out in Brodie and Christie (forthcoming).

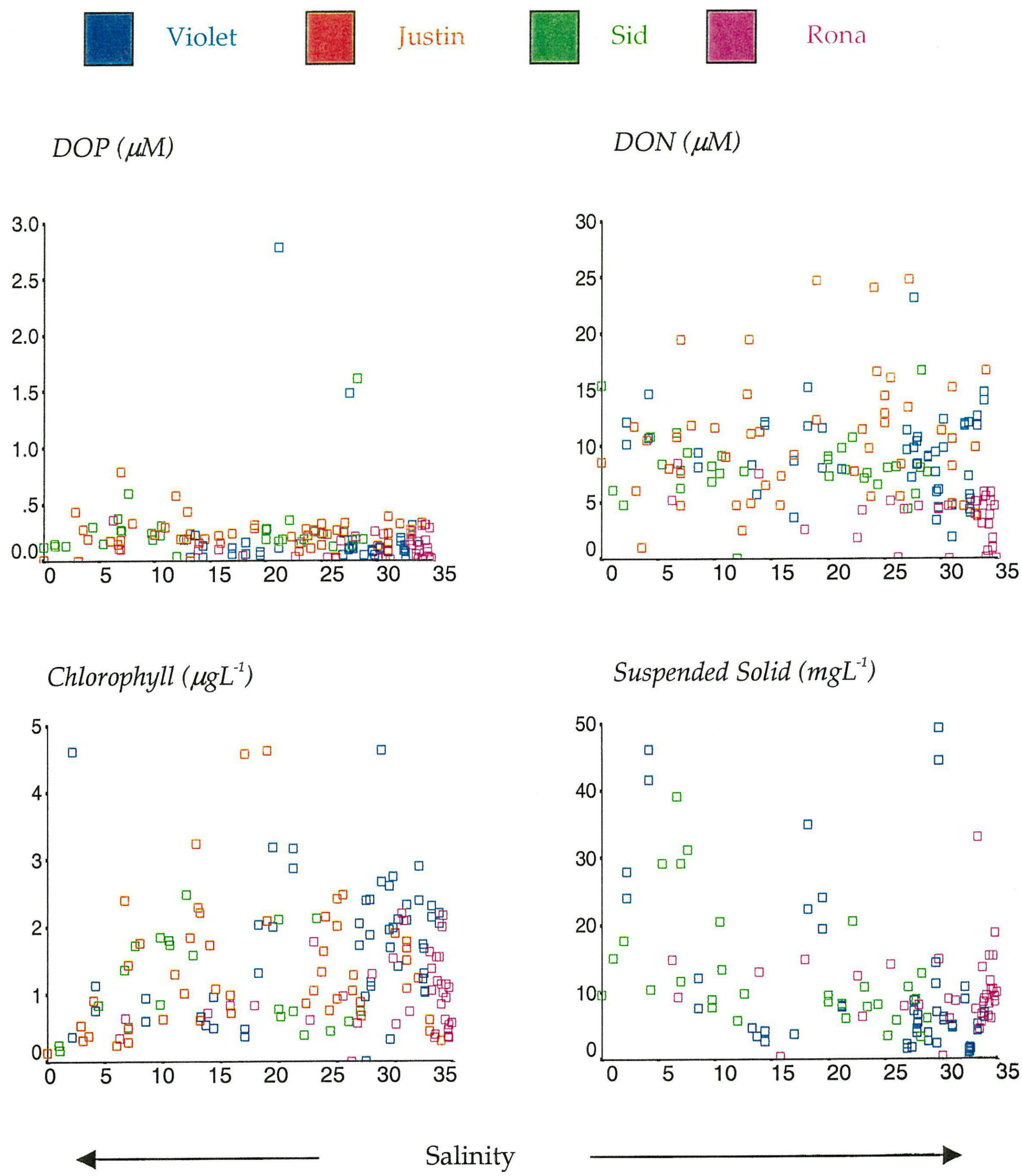


Figure 41. Water quality parameters versus salinity from Wet Tropics river plumes associated with cyclones Violet, Justin, Sid and Rona. Lines of best fit have not been plotted for data sets where R^2 is less than 0.7.

Implications of these higher concentrations reaching inshore ecosystems are that inshore reef and seagrass beds off the developed Wet Tropic catchments (Port Douglas to Ingham) are now seeing above effect levels of nitrogen and phosphorus species for periods of days to several weeks in the wet season. The relative abundance of inorganic nutrients, particularly nitrogen to phosphorus (and silicon) ratios, exerts a strong influence on phytoplankton communities and trophodynamic processes, and therefore has been recognised as one of the critical aspects in marine science management (Akuyai et al. 1997). There is considerable evidence to support that inshore areas, both coral reefs and seagrass beds are being negatively impacted by changes in the plume water composition.

ENCORE results have shown reef organisms and processes investigated *in situ* were impacted by elevated nutrients, even at relatively low dosages (nutrient pulse = 11.5 μM NH_4 and 2.3 μM PO_4 resulting in initial concentrations of 10 μM NH_4 and 2 μM DIP). Coral reproduction was affected in all nutrient treatments (Koop et al. 2001). At higher loadings (11.5 μM NH_4 and 2.3 μM PO_4), which resulted in sustained elevated concentrations of 20 μM NH_4 and 4 μM PO_4 throughout the ponding period, there was significant biotic responses, include coral mortality, stunted coral growth with increase nitrogen and reduced skeletal density with increase P.

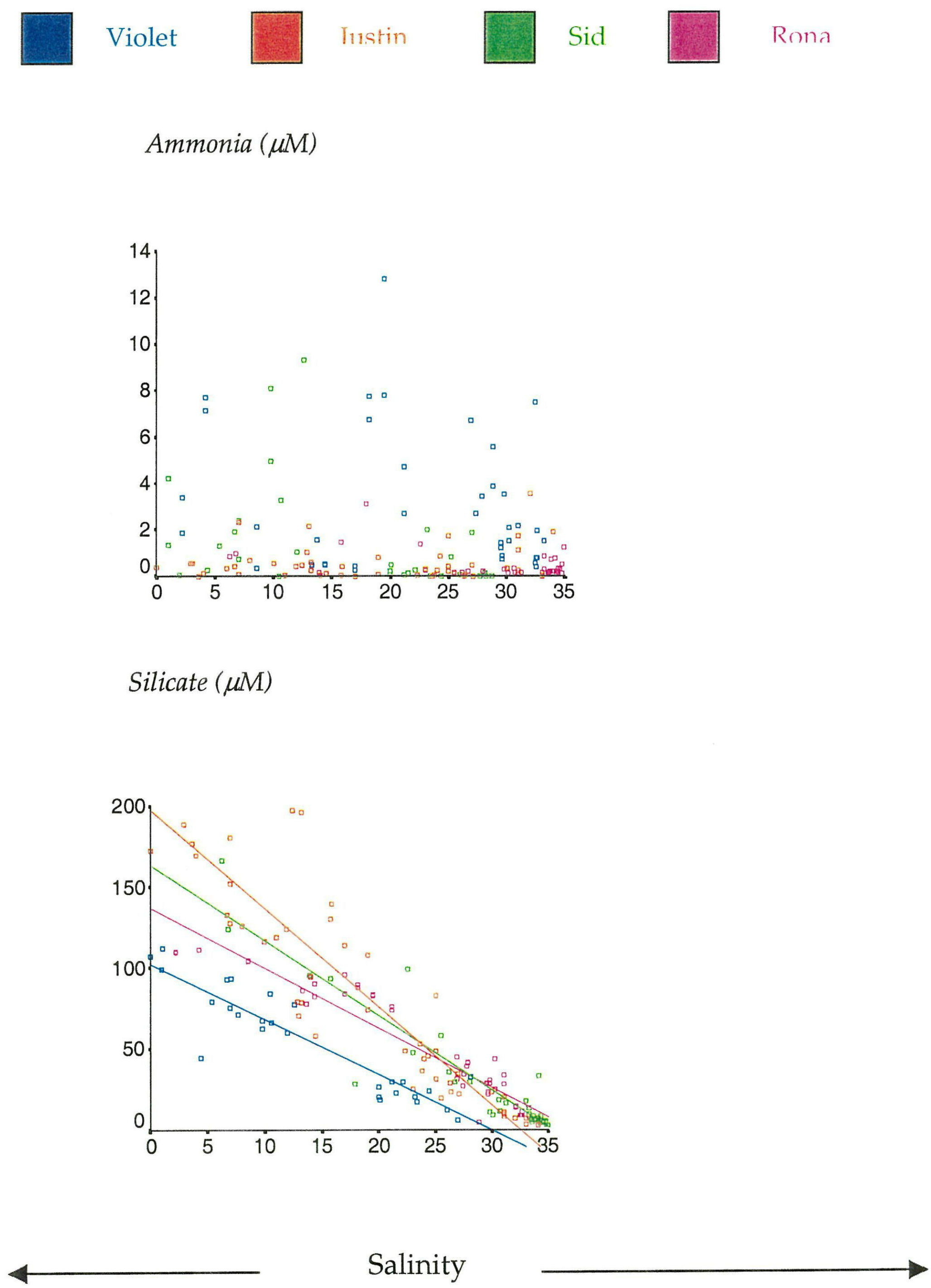


Figure 42. Various water quality parameters versus salinity from Wet Tropics river plumes associated with cyclones Violet, Justin, Sid and Rona. Lines of best fit have not been plotted for data sets where R^2 is less than 0.7.

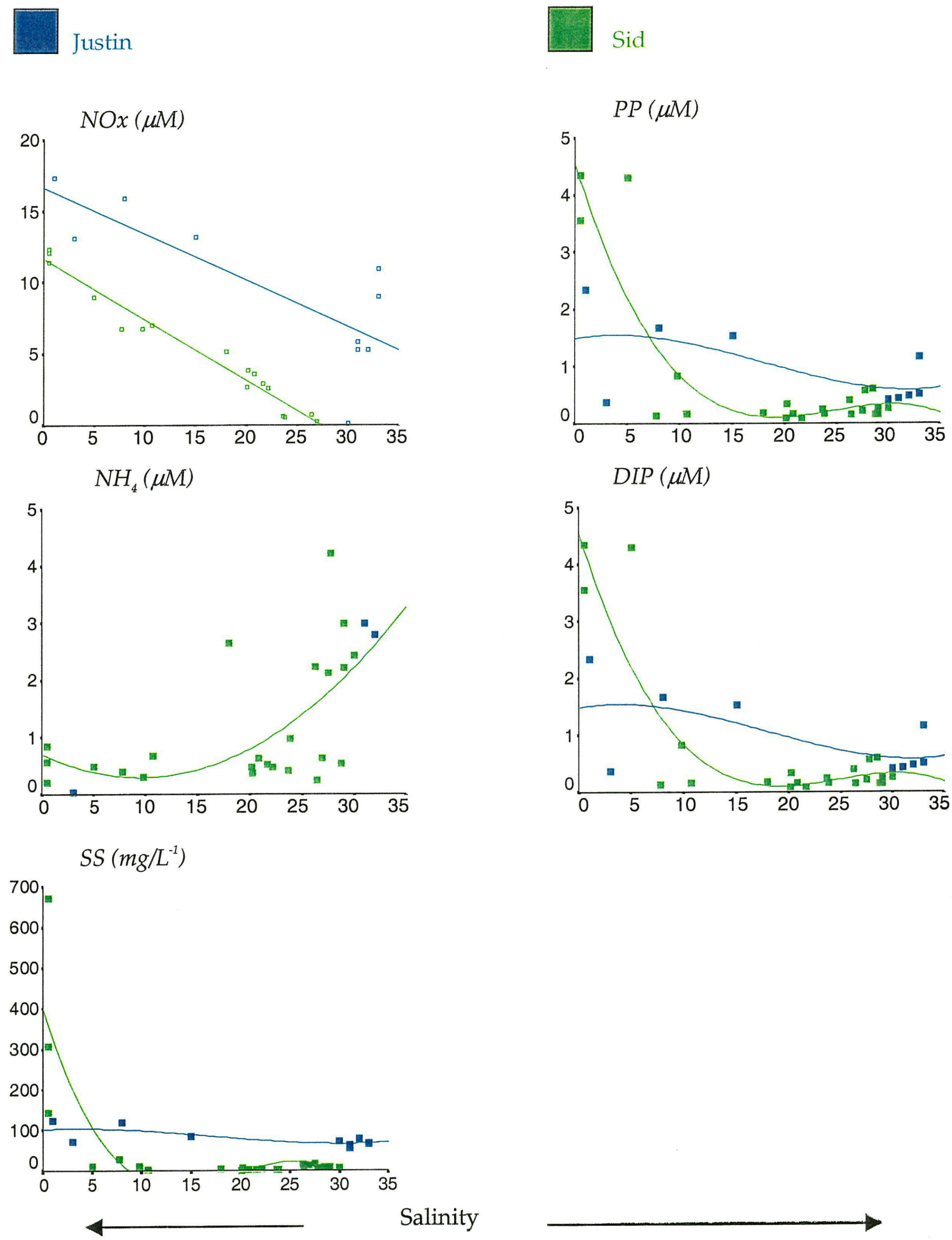


Figure 43. Water quality parameters versus salinity measured in river flood plumes from the Burdekin associated with cyclones Justin and Sid. Lines of best fit have not been plotted for data sets where R^2 is less than 0.7.

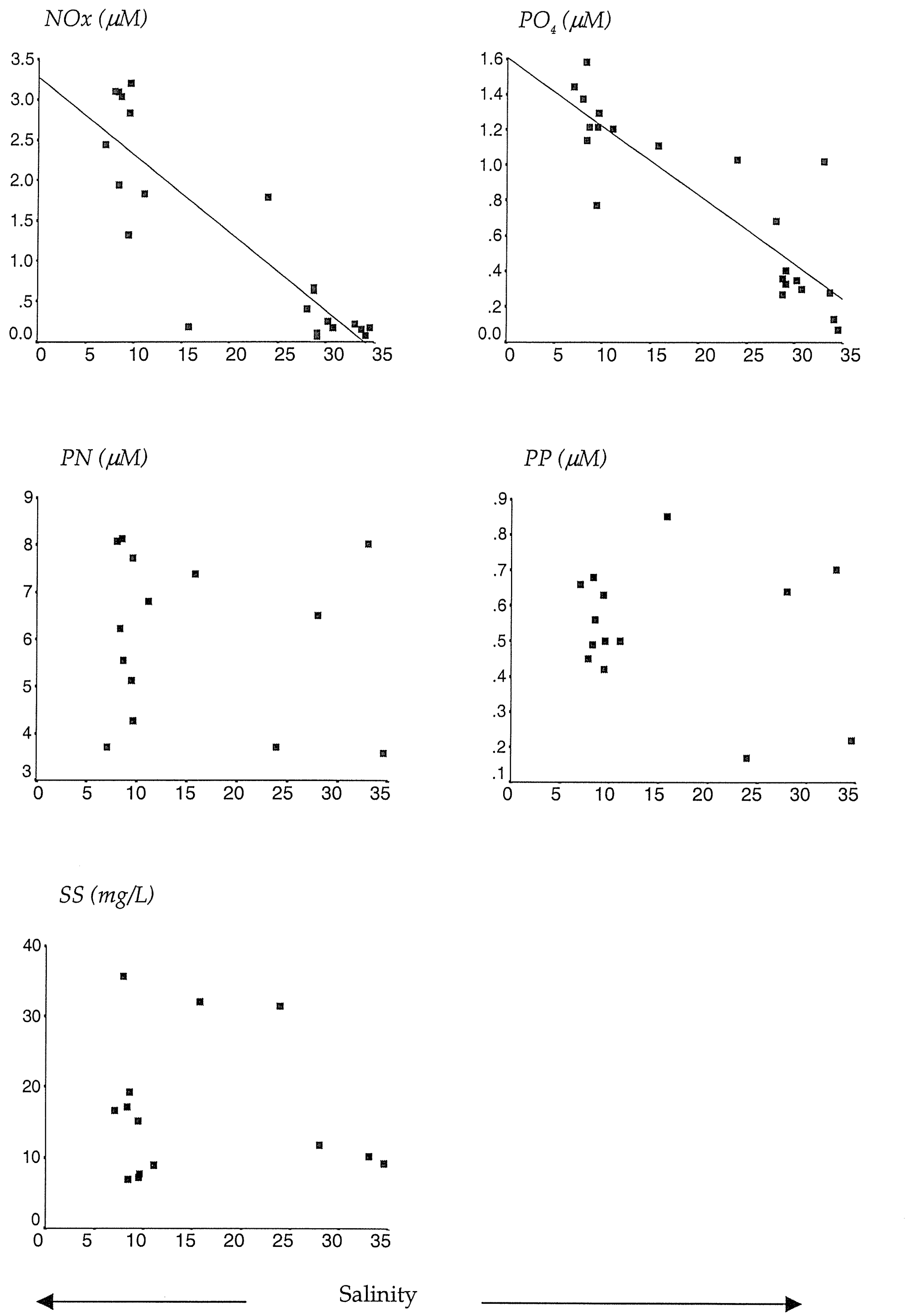


Figure 44. Water quality parameters versus salinity measured in river flood plumes from the Fitzroy associated with cyclone Joy. Lines of best fit have not been plotted for data sets where R^2 is less than 0.7.

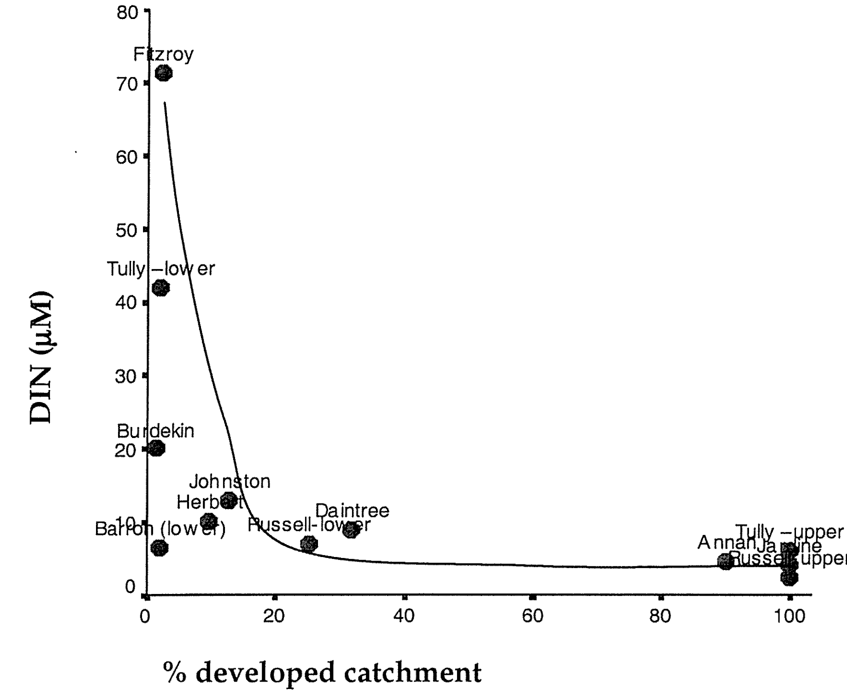


Figure 45. Relationship between DIN concentrations and area of developed catchment within the GBR catchment. (Source: Wachenfeld et al. 1998)

Furnas (1989) and Brodie and Mitchell (1992) demonstrate that increased nutrient supply during a flood plume enhances the growth of phytoplankton, leading to plankton blooms. Long term increases in phytoplankton can lead to a higher abundance of non-reef building filter feeders, such as tubeworms, sponges and bivalves (Smith et al. 1981). Excessive phosphorus concentrations can weaken the skeleton of reef builders (hard coral, coralline algae) and make the reef structure more susceptible to damage from storm action (Bjork et al. 1995; Rasmussen et al. 1992). Increased concentrations of dissolved inorganic nutrients decrease the recruitment success of hard corals (Ward and Harrison 1997) and support the growth of macroalgae (Grigg & Dollar 1990; Smith et al. 1981). Some macroalgal species, which are abundant on GBR nearshore reefs, efficiently use pulses of dissolved nutrients at concentrations similar to those observed in flood plumes (Schaffelke 1999; Schaeffelke & Klumpp 1998a, b).

Scleractinian corals exhibit a variety of reactions to stress including sublethal responses ranging from mucus and zooxanthellae discharge through to a reduction in reproductive output or success (Ward & Harrison 1997; Harrison & Wallace 1990). Reproduction is generally more sensitive to stress that other life functions such as growth or survival, hence successful reproduction occurs over a relatively narrow range of environmental conditions (Begon et al. 1986). Larval recruitment by corals can be negatively impacted by rise in nutrient and turbidity levels. Reductions in larval recruitment can be due at least in part to competition with algae, which can reduce access to light and pre-empt space required by juvenile corals. Ward and Harrison (1997) demonstrated that experimentally elevated nutrient levels, present during a five-day larval settlement period, reduced settlement rates of *Acropora lngicyathus* at One Tree Reef, GBR. Significantly less recruits survived in conditions of elevated phosphorus levels of 0.2 μM and in elevated levels of 2 μM nitrogen. Nutrient concentrations measured at inshore reefs in the GBR (figures 44–47) demonstrate 5–10 fold higher concentrations of these elevated nutrient conditions have been measured for periods of 3–14 days after peak flow conditions.

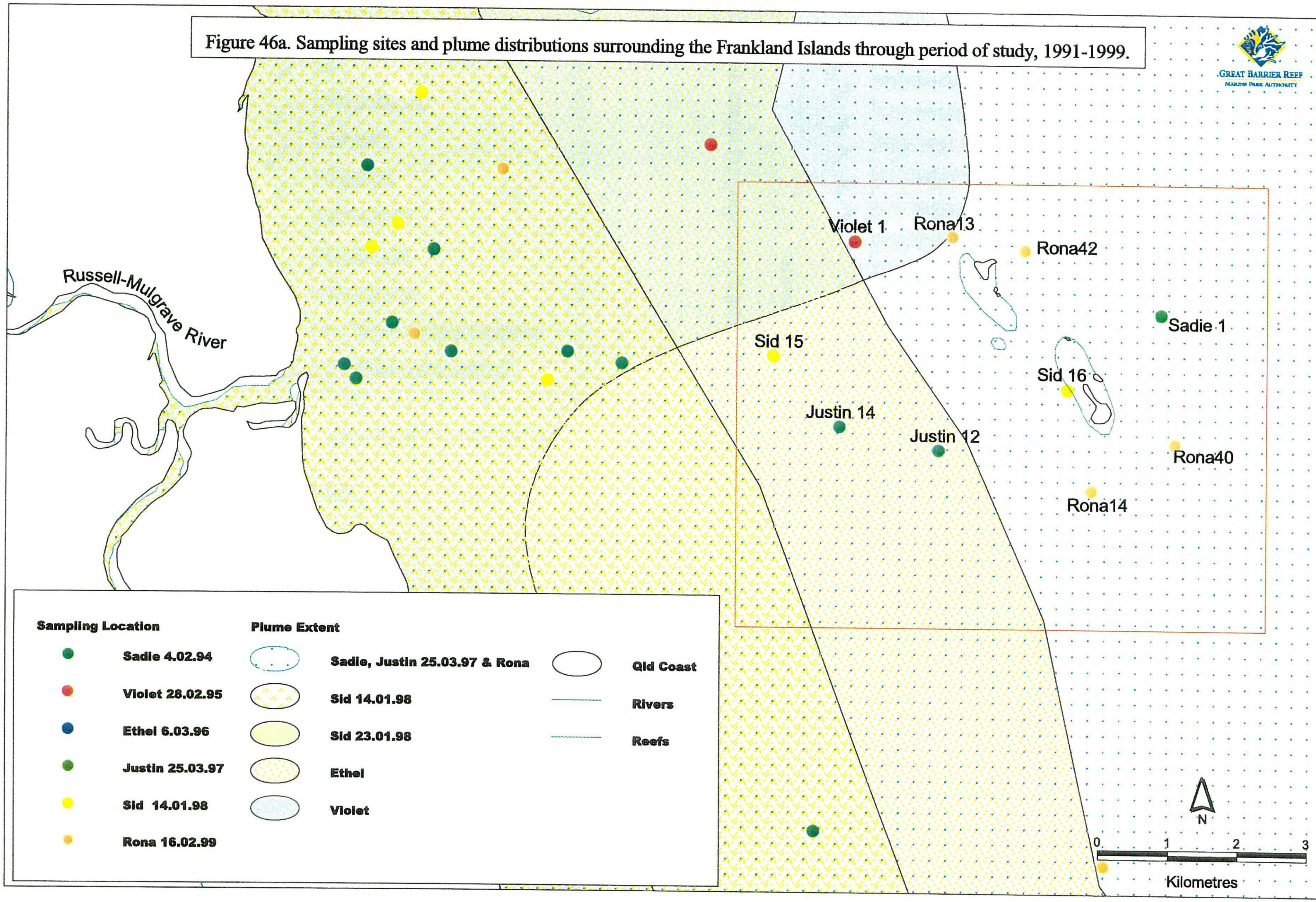
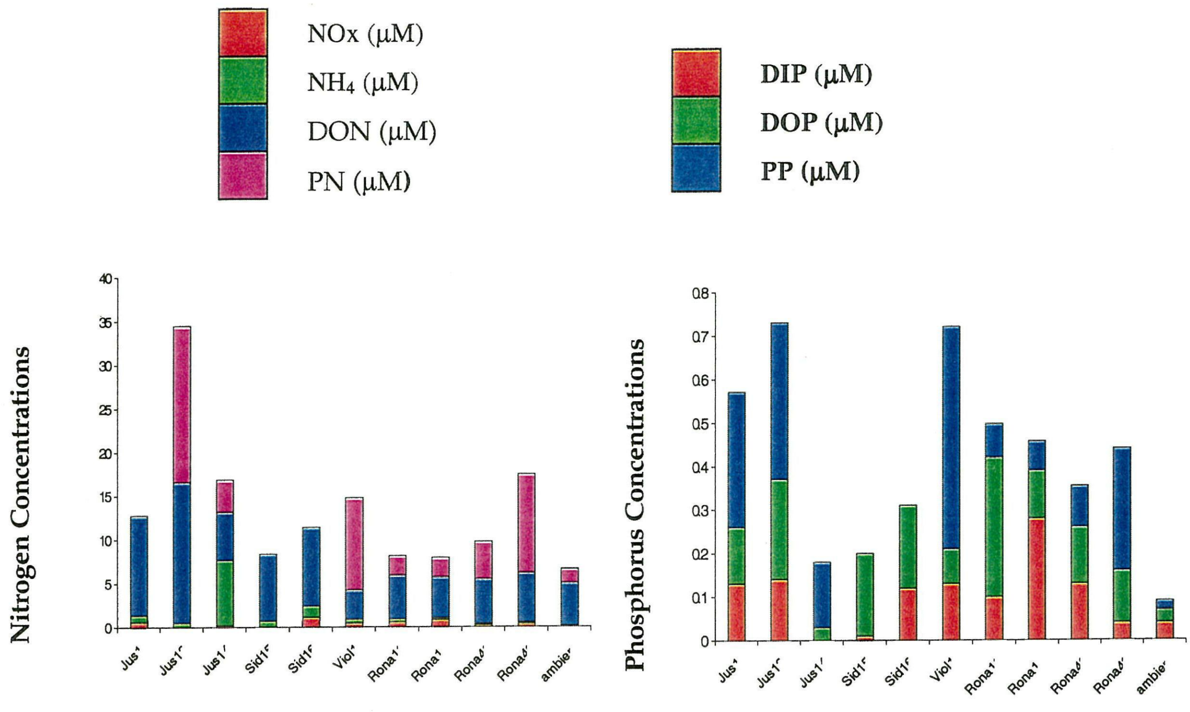
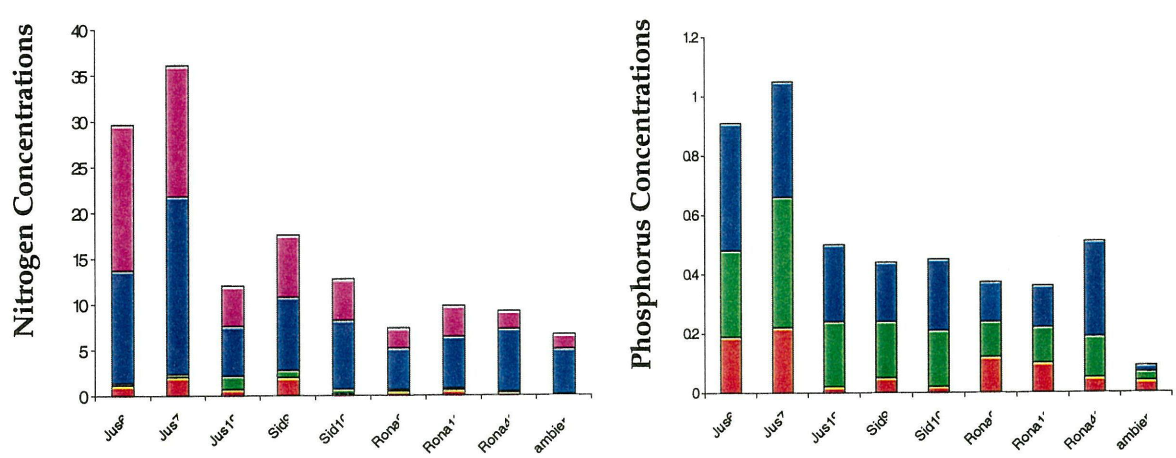


Figure 46a. Sampling sites and plume distributions surrounding the Frankland Islands through period of study, 1991-1999.



Sampling sites around the Frankland Islands

Figure 46b. Water quality concentrations (nitrogen and phosphorus species) taken near Frankland Islands



Sampling sites around High Island

Figure 47b. Water quality concentrations (nitrogen and phosphorus species) taken near High Island

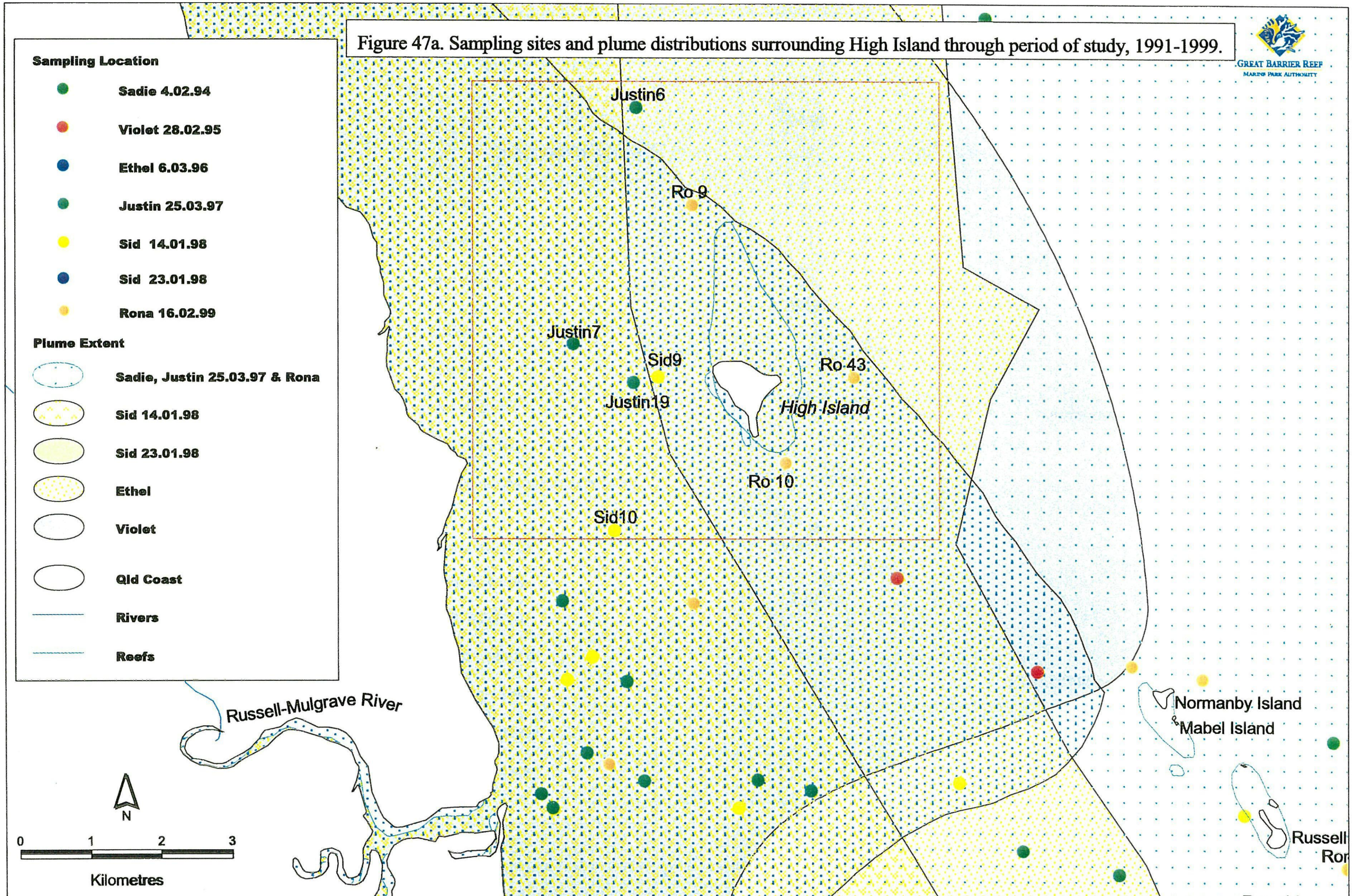
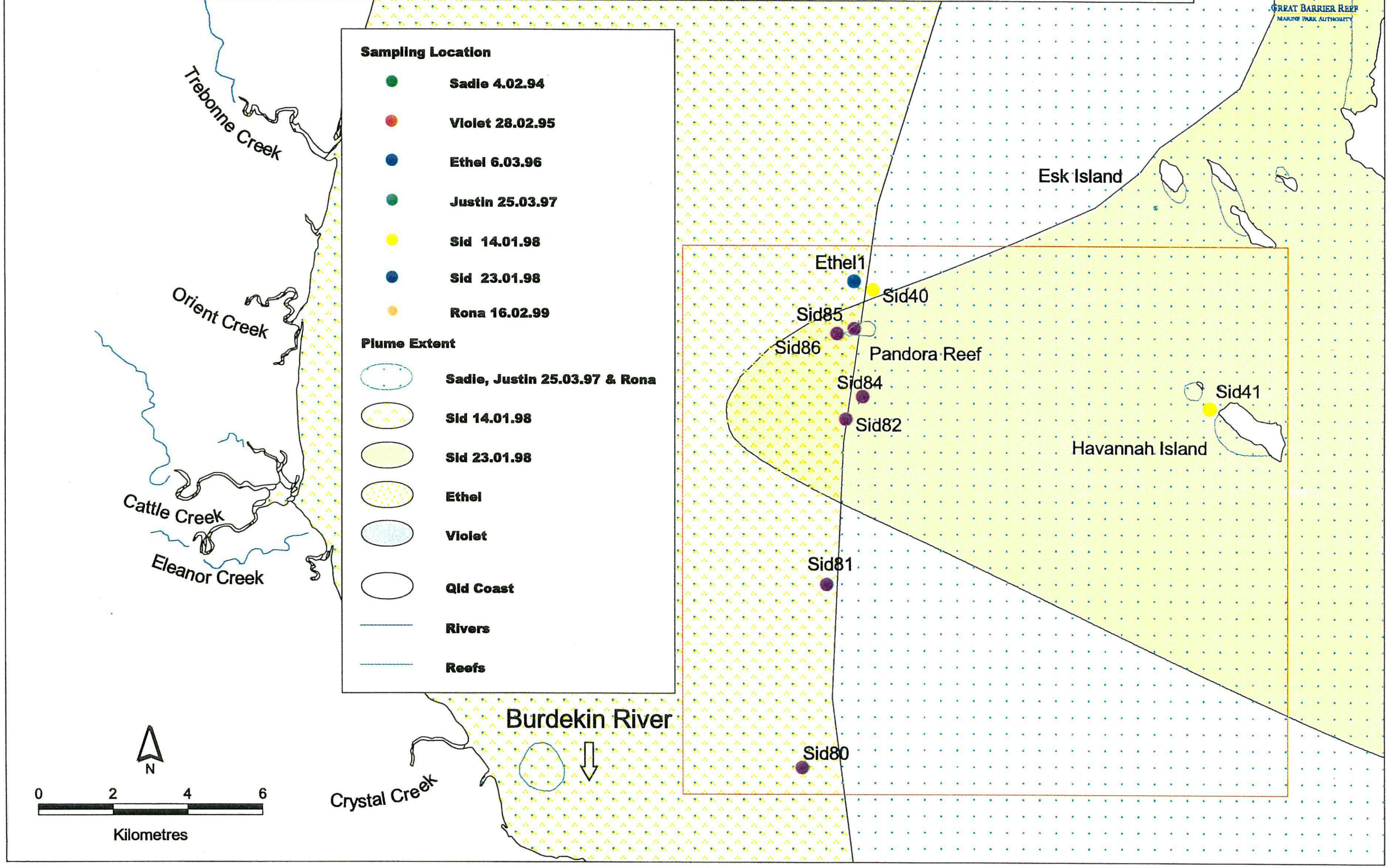


Figure 47a. Sampling sites and plume distributions surrounding High Island through period of study, 1991-1999.

Figure 48a. Sampling sites and plume distributions surrounding Pandora Reef through period of study, 1991-1999.



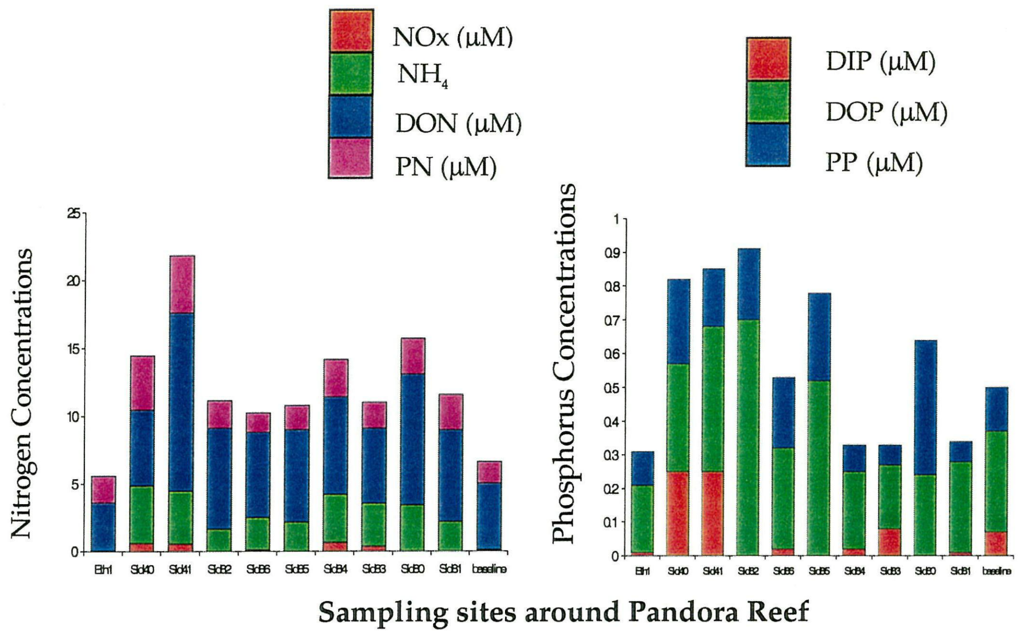


Figure 48b. Water quality concentrations (nitrogen and phosphorus species) taken near Pandora Reef.

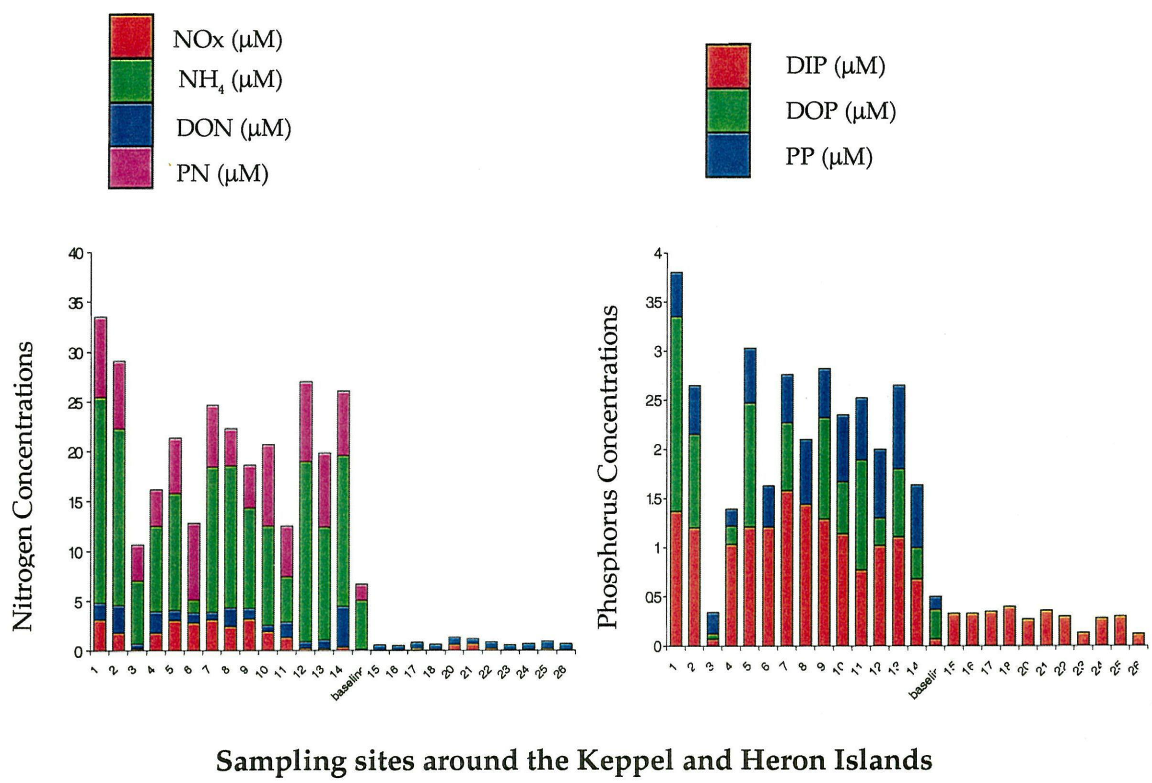


Figure 49b. Water quality concentrations (nitrogen and phosphorus species) taken near Keppel Islands on 17–18 January 1991 and surrounding Heron Island on 23–24 January. Heron Island samples were measured for PO_4, NO_x, and NH_4 only (Prekker pers comm).

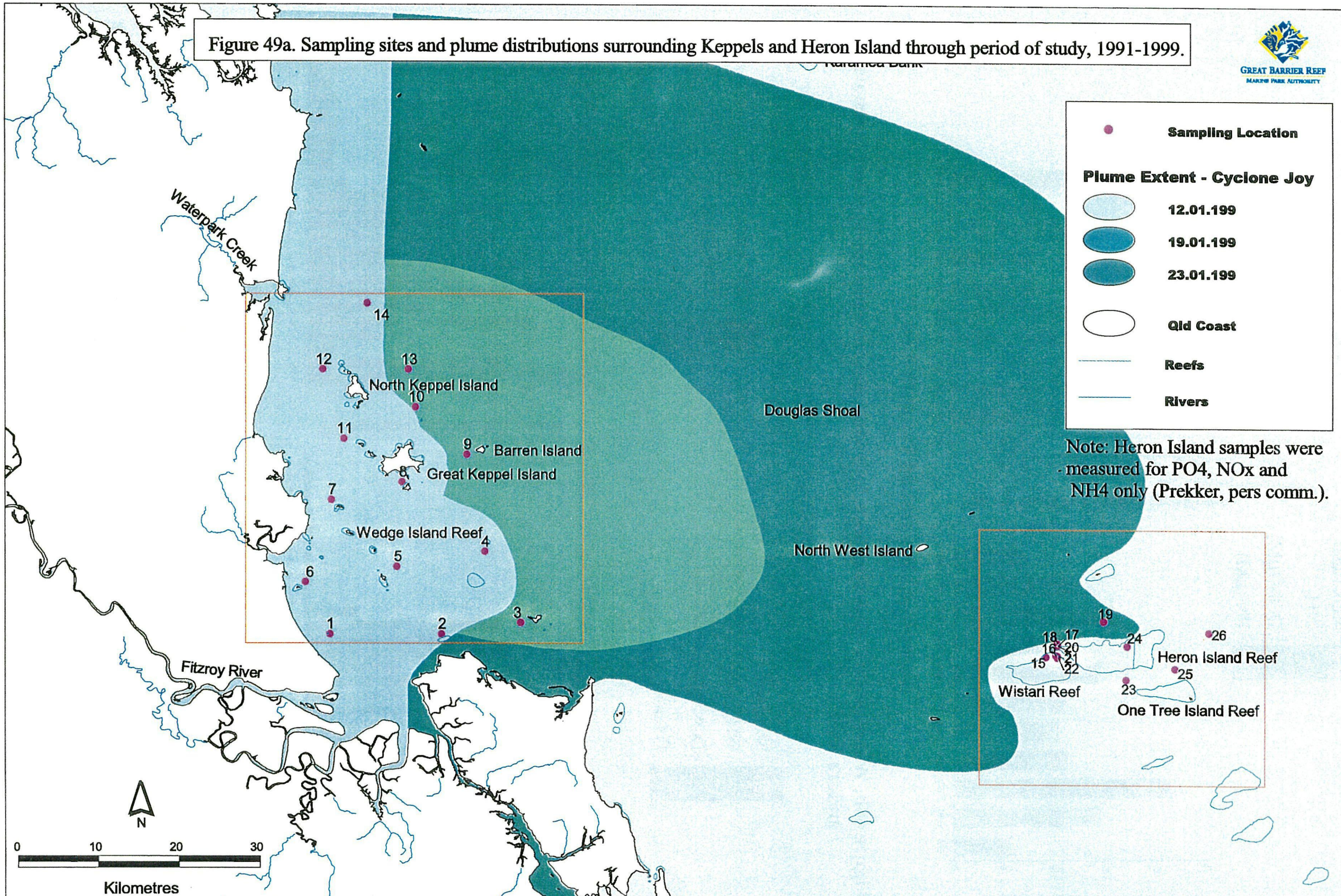


Figure 49a. Sampling sites and plume distributions surrounding Keppels and Heron Island through period of study, 1991-1999.

Older corals can be affected by changes in the physio-chemical regime. Hughes (1996) demonstrates that the longer-lived corals can have significant mortality due to the many colonies being gradually reduced in size due to partial smothering by macroalgae. This loss of corals can continue as surviving colonies will continue to shrink into smaller, more vulnerable size-classes. Reduced fecundities of diminishing adult coral stocks are another negative impact. As a consequence of recruitment failure and the accelerating depletion of adults, coral abundance can decline substantially. The most significant effects of the reef fertilization experiment (ENCORE) were reduced coral reproduction capacity (Ward & Harrison 1997).

Sustained algal blooms on coral reefs may be generated by nutrient enhancement (Lapointe 1997; Smith et al. 1981), by a reduction in the number of herbivores (Hughes 1994) or a combination of both (Lapointe 1997). Higher concentrations of nutrients on coral reefs also promote filter-feeding benthic organisms through phytoplankton blooms. For example, the biomass of sponges on numerous Caribbean reefs has been directly related to the amount of land-derived nutrients (Wilkinson 1987). Urban run-off and sewage outfalls into Kaneohe Bay, Hawaii supported a sponge-dominated assemblage of suspension feeders on reef slopes and flats as well as macroalgal blooms for several decades, which decreased by 60% within two years of sewerage diversion (Smith et al. 1981).

While there has been considerable debate regarding the current nutrient status and the actual/potential impacts on the GBR ecosystems, there is evidence that eutrophication has occurred in some inshore areas of the GBRWHA. Increases in local and/or regional nutrient levels have led to increased seagrass biomass and distribution at Green Island (Cairns regions) (Udy et al. 1999) and around Palm Island (Klumpp et al. 1997). Anecdotal evidence suggests that some nearshore fringing reefs in the central section of the GBRWHA are now muddier and have less coral and more algal cover. The comparison of historical photographs of reef flats prior to 1950, with the current status, revealed signs of degradation on some reefs (Wachenfeld 1997). Analyses of coral cores from the Queensland coast suggest that coral growth conditions did change significantly about 50 years ago, which has been correlated with land use changes on the adjacent coast (Rasmussen et al. 1992). van Woesik et al. (1999) documents a reduction in relative abundance of coral cover and decline in recruitment and growth in relation to proximity to a river mouth in the Whitsunday inshore region. Long term water quality monitoring programs in the GBR demonstrate regional differences in the chlorophyll *a* concentrations in the inshore lagoon areas. Central and Southern regions have significantly higher inshore chlorophyll a concentrations than the northern region (Devlin et al. in review). The GBR river catchment area adjacent to the northern regional cross-shelf transects is typically an undisturbed area with limited cropping activities and low stocking rates. The GBR river catchment areas adjacent to the Central and Southern regional cross-shelf transects are characterised by high stocking rates and intensive cropping activities in the lower catchment areas.

Multiple stressors often have significant effects on recruitment and regenerative processes of assemblages. These impacts are much less obvious than catastrophic or chronic mortality, but they play a crucial role in community dynamics over longer time scales. Importantly, chronic anthropogenic impacts can impede the ability of coral assemblages to recover from natural disasters, even when there is little detectable effect on rates of adult mortality. Once a reef has been degraded, it is usually impossible to ascertain retrospectively the precise mechanisms that were involved or the relative importance of different events.

High concentrations of nutrients and sediments are being measured in our river catchments, and through the movement of flood waters, these pollutants are moving into the inshore areas of the GBR. This report demonstrates movement of nutrients and sediments from the river mouth to the inshore reef systems. High concentrations (effect levels) of nitrogen and phosphorus are being measured at inshore reefs for a period of days and weeks. While high nutrient concentrations in river plumes are transient and quickly reduced by biological uptake, it is probable that long-term increased nutrient availability in inshore waters of the GBR from increased terrestrial fluxes may have occurred. Diffuse source pollutants, specifically high levels of nitrogen, originating from agricultural lands are considered to be the greatest chronic pollutant source to the GBRWHA, and management of these inputs, both point source and diffuse, are essential in the long term management and sustainability of the GBR.

5.5 Further Research

While increasing nutrient loads have been recognised as a major threat to reefs, the actual way in which reefs respond to these increases is poorly understood. (Koop et al. 2001; Hatcher et al. 1989). Understanding how changes occur in the species composition of a coral reef is a major ecological and management goal. Changes in the inshore coral reefs can be caused by a number of interacting physical, biological and anthropogenic processes that vary in intensity, frequency and spatial scale (Hughes 1996). Scientific knowledge of the catchment to reef processes is essential in any management strategy, and research and monitoring programs need to target the movement, source and fate of pollutants in the GBR, and to document changes occurring in the nearshore environment. Knowledge of the physical environment and the extreme water quality concentrations that reefs 'experience' will help in the understanding of any changes within and between the selected inshore reefs.

Further study areas in this program includes deployment of data loggers around three inshore reefs. These loggers record turbidity, salinity, temperature, depth, direct and scattered light and transmission. This ongoing data collection will measure the conditions that are experienced by the inshore benthic communities over the wet season, including plume events.

A second part of this study will be the assessment of the potential impacts of extreme water quality conditions on the inshore reef communities. Identification of changes in the benthic communities will involve linking the coral reef community with water quality patterns. This will involve a three year project looking at coral composition and size distribution, recruitment and juvenile survival rates on three selected inshore coral reefs. Data from this project will be presented in a later research publication. Specifically the aims of this component are to:

- Link concentrations of materials in the plume (water quality regime and physio-chemical characteristics) and plume duration at inshore reefs to the survival of benthic communities.
- Investigate whether water quality regimes and physio-chemical characteristics of inshore reefs are reflected in the coral composition, recruitment success and juvenile species composition and survival at these reefs. These objectives are being implemented through a research program targeting the survival and growth of juveniles on inshore reefs impacted regularly by flood plumes. Flood plumes carrying large loads of sediment are unlikely to effect all coral colonies to the same degree. Some species are sediment tolerant, while others are highly susceptible. Furthermore, small coral colonies can be easily smothered by sediment settling out from the water column, while larger colonies are more likely to escape. Studies have been set up to follow individual coral colonies over time at a number of inshore reefs to assess if or how impacts from flood plumes can be quantified, and whether impacts can be related to water quality within the plumes. The study sites are located in the Cairns inshore areas, and are set up in a

northerly direction away from the mouth of a Wet Tropics river flood. In assessment of extreme water quality concentration on an inshore reef, the processes that may lead to changes in the adult coral community structure within these reefs must be clarified.

5.6 Management Implications

Data presented in this report demonstrate that the GBR lagoon has an inter-dependent relationship with the adjacent coastal catchments. The water quality and ecological integrity of the GBR lagoon is affected by material originating from a range of land-based activities predominated by agricultural activities.

Measurements taken in the plume allow the relationship to be established between instantaneous changes to long term patterns. Patterns that have been demonstrated in sediment movement (Woolfe et al. 1998; Woolfe & Larcombe, 1998), coral coring (McCulloch et al. 1996) and large plume modelling (Wolanski & van Senden 1983) are supported by the results in this report. This type of sampling gives us 'snapshots' of what is happening in the marine environment and how these short-term events drive the long-term patterns. Final outcomes of the flood monitoring program will contribute to understanding the impacts of land based pollutants on the GBRWHA.

A number of land management strategies have been initiated over the last 10 years in the GBR Catchment. These include an Integrated Catchment Management (ICM) program, based on the premise that management of land and water resources mush be co-ordinated as well as the recognition of economically sustainable development principals at the farm level through the use of property management plans and development of industry codes of sustainable practice (Johnson et al. 1998). Whilst some notable achievements have been made by the Queensland agricultural industry (e.g. widespread adoption of sugar cane trash blanketing and fencing off stream banks), the fact remains that appropriate land management in Queensland had not eventuated (Haynes & Michalek-Wagner, in press). Vegetation clearing in Queensland agricultural lands is still being carried out at rates that are up to an order of magnitude higher than any other Australian State (Queensland Environmental Protection Agency 1999) with fertiliser application rates still increasing over the GBR Catchment.

This has serious management implications for GBRMPA, particularly when considering the limited jurisdiction of the Authority over land use activities. Use of any federal legislation in this regard encompasses constitutional issues between the State and the Commonwealth. The *Great Barrier Reef Marine Park Act 1975*, created to protect the Marine Park, provides little scope to control land-based activities which produce damaging run-off (Wachenfeld et al. 1998). However, establishment of the *Environment Protection and Biodiversity Conservation Act 1999* provides scope to recognise the potential impacts of these activities on areas of national environmental significance, including the GBRWHA. Close links with state environmental agencies provide the structure to manage land based impacts. Furthermore, local governments are also involved in water quality management with respect to urban planning and drainage and the licensing of industrial sources of pollution. A major review of the multi-Authority complexities involved in the management of the GBR has highlighted these jurisdictional difficulties and recommended stronger collaboration between Commonwealth and Queensland State Authorities and Agencies in order to achieve effective co-management of the region (Sturgess 1999). A joint, co-ordinated approach to managing the GBR and adjacent catchments is what is needed to establish an integrated catchment to reef water quality strategy that promotes sustainable land use practices at regional and local levels.

GLOSSARY

Acronyms and symbols for nutrient and other water quality parameters used in this report.

	Parameter	Units
NH_4/NH_3	Ammonium/ammonia	μM (μmol/litre)
NO_2	Nitrite	μM (μmol/litre)
NO_3	Nitrate	μM (μmol/litre)
NO_x	Nitrite + Nitrate	μM (μmol/litre)
DIN	Dissolved Inorganic Nitrogen DIN = NO_2+NO_3+NH_4	μM (μmol/litre)
DON	Dissolved Organic Nitrogen DON = TDN - DIN	μM (μmol/litre)
PN	Particulate Nitrogen	μM (μmol/litre)
TDN	Total Dissolved Nitrogen	μM (μmol/litre)
PO_4	Phosphate, ortho-phosphate	μM (μmol/litre)
DIP	Dissolved Inorganic Phosphorus DIP = PO_4	μM (μmol/litre)
DOP	Dissolved Organic Phosphorus	μM (μmol/litre)
PP	Particulate Phosphorus	μM (μmol/litre)
$Si(OH)_4$	Silicate	μM (μmol/litre)
Chl *a*	Chlorophyll *a*	μg L^{-1} (μg/litre)
Phaeo	Phaeophytin	μg L^{-1} (μg/litre)
SS	Suspended Solids	mg L^{-1} (mg/litre)
S	Salinity	psu = ‰ = g L^{-1}

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