Spatial and temporal patterns of flood plumes in the Great Barrier Reef, Australia

Thesis submitted by

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Papers arising from this thesis

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Abstract

This thesis considers the eutrophication of our coastal systems and the potential for anthropogenic driven change in these systems. The influence of river waters and plume driven nutrients and sediments into nearshore systems is also documented. Known changes in the Great Barrier Reef and associated Queensland catchments, including land use change, river water quality, flood plume extent and variation, coral cover, coral reef processes and any related changes are presented.

This research spans a number of large, long term data sets collected over the last 10 years, including long term chlorophyll *a* data set, and flood plume extents and water quality concentrations both in plumes and around inshore coral reefs. Modelling of all this data demonstrates that the inshore reef of the GBR is becoming more productive, with assessment of risk being highest for the inshore reefs adjacent to the Wet Tropics catchments.

This thesis outlines the potential changes in the nutrient availability by summarising a long term data set of chlorophyll *a*. The data collected in the seven years demonstrate persistent cross-shelf and regional differences in chlorophyll concentration. Seasonal trends are generally consistent between regions. There are pronounced gradients between inshore and offshore sites, indicating a strong terrestrial influence in the inshore lagoon of the GBR. Results from chlorophyll monitoring support the idea of an inner-shelf polluted zone adjacent to the developed catchments from Port Douglas to Harvey Bay (end of southern region), and relatively unpolluted zone on the inner-shelf north of Port Douglas and generally on the middle and outer shelf. The middle shelf between Cape Grafton and Cape Tribulation (central region) is also somewhat polluted due to its proximity to the coast and polluted rivers. In general, Coral Sea and outer shelf mean chlorophyll concentrations are close to 0.2 μg/L, areas of the GBR Lagoon without polluted river influence have mean concentrations near 0.3 μg/L, long-term mean concentrations in areas subjected to polluted river influence are near 0.6 μg/L while event concentrations in waters affected by flood plumes from polluted rivers are near 3 μg/L.

This larger part of this body of work has looked at the dispersal and extent of flood plumes, the importance of flood plumes as a source of nutrients and sediments and the

potential risk of riverine influence on the nearshore ecosystems of the GBR. Through the course of this work, I have monitored and measured flood plumes associated with cyclones from 1991 to 2000. The sampling events were Cyclone Joy (1991), Sadie (1994), Violet (1995), Ethel (1996), Justin (1997), Sid (1998), Rona (1999) and Steve (2000).

Plume distributions presented in chapter 4 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 greater 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 plumes 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 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 the Green Island Reef. Green Island Reef appears to 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 the 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.

Data presented in chapter 5 demonstrates 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 and duration and distribution of flow volume. The time lag difference is significant in the smaller Wet Tropic rivers (Herbert to Daintree) compared to larger Dry Tropic Rivers of the Burdekin and Fitzroy.

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

Modelling of the plumes associated with specific weather conditions has demonstrated that inshore reef 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. Chapter 4 presents a summary of the frequency and distribution of the all flood plumes mapped in the GBR over the last 10 years.

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 baseline 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 was 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 distribution 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. The hindcasted model provided 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.

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Russell- Mulgrave plume (1998)

Chapter One: The mechanism and transport of flood plume waters into the Great Barrier Reef.

1.1 Introduction

The Great Barrier Reef is as one of the most complex and unique ecosystems in the world, supporting a diverse of biota, coral reefs, intertidal areas seagrass beds and other habitats. It also supports a commercial fishing and shipping industry and is internationally known as an iconic tourist destination. The Great Barrier Reef runs parallel from Torres Strait to the south of Gladstone on the Queensland coast, and stretches from the coast to offshore reefs systems, which can be located within a 40 km zone from the shore (Cairns) or out to hundreds of kilometres offshore (Swains) (Figure 1). A diverse and well utilised environment such as the GBR requires a multidisciplinary approach to its management and protection, which is received through federal, state and local guidance (Anon, 2003). However, until recently, management and protection of the GBR has focused on understanding and managing the ecosystems contained within the GBR boundaries, with limited understanding of how the adjacent catchments and rivers can impact on the GBR ecosystem. There has been concern for some time now about increasing nutrient loading to the Great Barrier Reef (Bell, 1991, 1992; Moss *et al*., 1992; Brodie and Mitchell, 2005, 2006; Haynes et al., 2001). This growing concern has been based on a number of factors including: (i) continuing intensive agricultural development (ii) increasing urbanisation along the Queensland coast from the 1980's, (iii) rapid increases in the number of tourists visiting the Great Barrier Reef and (iv) loss of coastal wetlands (Hutchings and Haynes, 2000).

Terrestrial runoff to the GBR is largely influenced by the catchment activity and the threat from terrestrial runoff on GBR ecosystems has emerged as one of the key issues in GBR management (Baldwin, 1990; Brodie, 1995; 2002a, Haynes and Michalek-Wagner, 2000). The principal land uses in northern Australia contributing to this potential change are rangeland beef grazing and cropping, with lesser contributions from industrial, mining and urban development (Brodie and Mitchell, 2005). Runoff of sediments, nutrients and pesticides is increasing and for most pollutants the load is estimated to be many times the natural amount discharged 150 years ago (NLWRA, 2001, Brodie *et al*., 2003; Furnas, 2003).

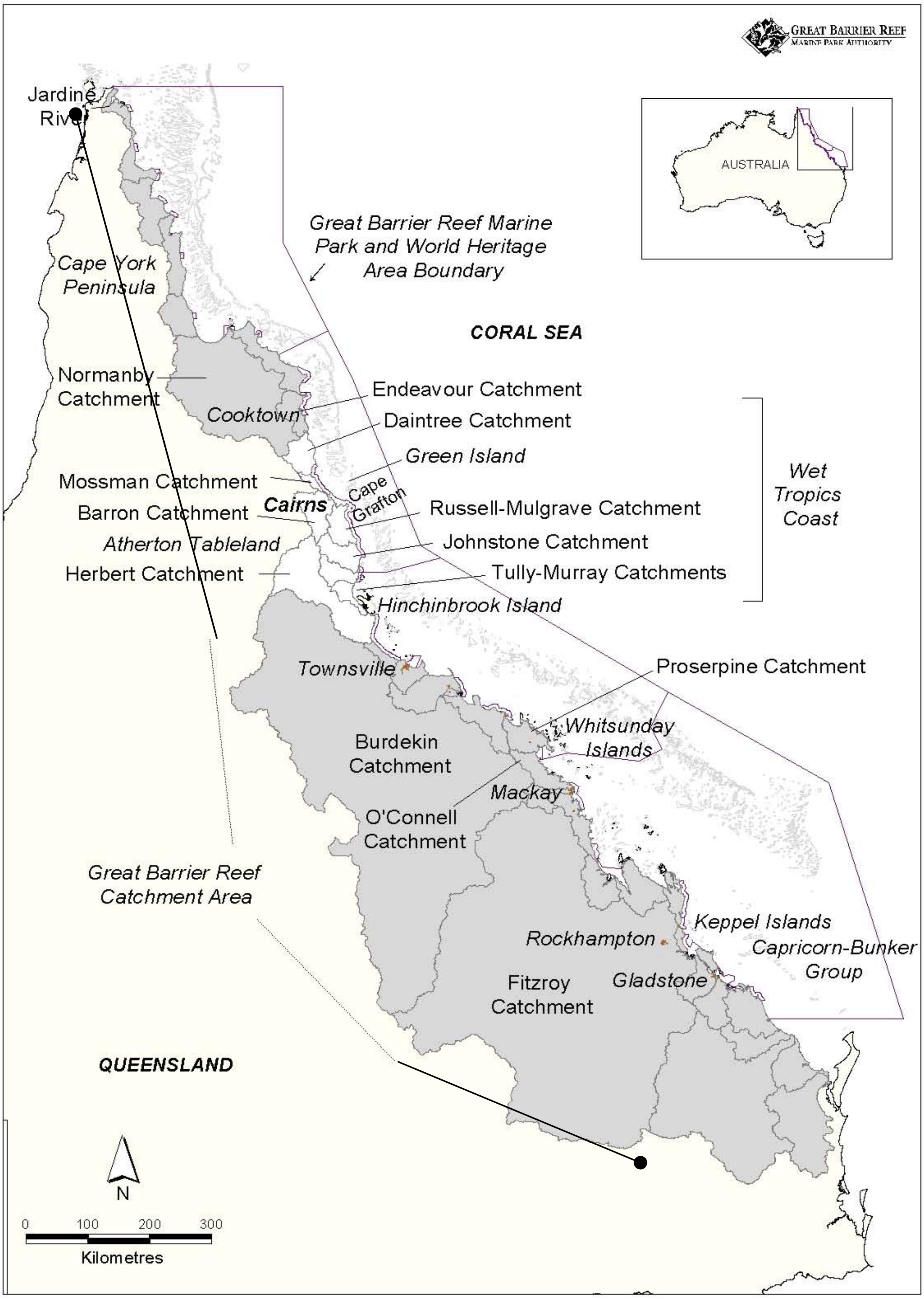


Figure 1: The boundaries of the Great Barrier Reef, outlining the extent of the Great Barrier Reef catchments.

This work is driven by the concerns about the increase of nutrients and sediments discharging to the GBR waters. Nutrient enrichment of our marine waters and associated consequences is seen as a world wide environmental problem. To study the impact and effect on the GBR, a number of research questions must be considered.

- Have marine phytoplankton community (being the primary producers and most likely to respond to increased nutrient availability) changed within the GBR waters?
- Input from rivers is one of the primary sources of new nitrogen, phosphorus and particulate matter into GBR lagoon. Riverine plumes are the main mechanism for transport of these constituents. What governs the movement of plumes into the GBR, and controls the extent and duration of the plume waters? Are inshore areas of the GBR more likely to experience plume waters?
- How are constituents driving the change delivered or to what extent do they move, and how do they impact on the GBR ecosystems?
- Can actual thresholds of nutrient and suspended sediment loads affecting GBR ecosystems be identified
- Finally, if we can define the delivery mechanism of increased nutrients into GBR waters, demonstrate evidence of nutrient enrichment and production and it can be successfully modelled, is it possible to estimate areas of “risk” from increasing nutrient and sediment delivery into GBR waters?

1.2 Research question 1: Is there any evidence of nutrient enrichment in the GBR lagoon?

Increasing nutrient supply to coastal and marine ecosystems is recognised as a major source of pressure to the ecological health of these systems, including intertidal areas, mangroves, wetlands and coral reefs (Bradbury *et al*., 1992; Smith *et al*., 1981; Koop *et al*., 2001; Haynes and Michalek-Wagner, 2000). However, the natural spatial and temporal variability of these systems, the definition of an undisturbed state, and the variable process of defining disturbance from nutrient enrichment makes it difficult to ascertain the level of anthropogenic impact from small and large scale processes driving natural variability in the GBR system. In the Great Barrier Reef, clear long-term and regional-scale effects from increased nutrient and sediment delivery is further confounded by the frequent natural disturbances by cyclones and floods (Finlayson and McMahon, 1988; Junk *et al*., 1989), a relatively short period of monitoring observations (Brodie, 2002) and the lack of definition or evidence on what constitutes a pristine environment.

Eutrophication is variably defined but one of the most commonly accepted criteria (Malcolm *et al*., 2001; Bricker *et al*., 1999) states that eutrophication is diagnosed by a demonstrated increase in nutrient concentrations, an accelerated growth of algae leading to an undesirable disturbance to the balance of organisms. A number of recent studies do document an undesirable disturbance to the balance of organisms in coral reefs related to nutrient enrichment, including decreases in coral diversity due to terrestrial run-off (Van Woesik *et al*., 1999, Fabricus *et al*., 2005, Fabricus, 2006; Devantier *et al*., 2006), increased competition by turf algae and macro algae (Smith *et al*., 1981; Walker and Ormond, 1982; Tomascik and Sander, 1985; 1987; Edinger *et al*., 1998; McCook, 1999); decreased efficiency of corals in removing suspended sediment (Fabricius and Wolanski, 2000) and the increased bio-erosion of coral structure by the dominance of filter feeders (Lapointe,1999). It is not the intention of this study to resolve the question of whether an “undesirable impact” has occurred in the Great Barrier Reef, but whether conditions now support the potential for an impact. Detection of nutrient enrichment in the water column associated with inshore coral reefs requires a focus on the establishment and subsequent analysis of data from long-term monitoring programs in order to separate anthropogenic impacts from natural nutrient variability. Measurement of chlorophyll concentrations derived from phytoplankton biomass can be indicative of enhanced nutrient inputs in many circumstances (Spencer, 1975; Furnas *et al*., 2005) and can provide a simple, reliable indicator of water column nutrient status in the absence of high frequency water column nutrient concentration measurements (Yunev et al., 2002; Harding and Perry, 1997). This study will use long term records of phytoplankton biomass to investigate if nutrient enrichment and increased algal production has occurred in any areas of the Great Barrier Reef.

1.3 Research question 2: What governs the movement and extent of riverine plumes in the GBR

The catchment area adjacent to the GBR measures over 423,000km^2 and approximately 380km^3 of rain falls on the catchment area annually. Of this an average of 70km^3 runs into the GBR, carrying particulate and dissolved nutrients, sediments and other materials (Furnas, 2003; Brodie *et al*., 2003). These materials have the potential to degrade water quality and the ecology of GBR ecosystems. Nutrient loadings to downstream environments are dominated by storm flows (Furnas and Mitchell, 2001). Rainfall and runoff are highly seasonal, with two-thirds occurring during the summer (December – April) wet season. Rainfall and runoff also varies greatly from year to year under the influence of summer monsoon, the occurrence of El Nino events and the unpredictable occurrence of cyclones (Devlin *et al*., 2002, Furnas, 2003, Brodie *et al*., 2003). The majority of runoff of water, sediments and nutrients to the GBR occurs during these short-lived flood events, discharging riverine plumes into the near shore GBR waters (Steven *et al*., 1996; Taylor and Devlin, 1998).

In times of high flow conditions, which can vary between catchments, riverine waters move into the marine environment as a freshwater plume, influencing a wide range of chemical, geological, biological and physical conditions in the adjacent coastal waters. Riverine plumes are biologically rich, spatially complex water masses characterised by strong horizontal and vertical salinity gradients (McManus and Fuhrman 1990; McKee *et al*., 2004; Dagg *et al.*, 2004) and can be recognised in surface waters through the sharp colour change and accumulation of foam and flotsam at the interface of the riverine plume and oceanic waters (McManus & Fuhrman 1990; Brodie & Furnas 1996). The movement and extent of these plumes into a complex region such as the GBR is influenced and controlled by physical forcing and oceanographic conditions. Previous work and modelling studies (Wolanski and Jones, 1981; Wolanksi and van Senden, 1983; King *et al*., 1997, 2001, 2002) suggest plumes are constrained close to the coast by oceanographic conditions imposed by Coriolis forces and the prevailing wind regime producing a net northerly water movement (Burrage *et al*., 1997). It is thought that overall forcing components generally drive the river plumes northward and towards the coast in GBR waters (Wolanski and Jones, 1981; Gagan *et al*., 1987), primarily influencing the reefs and coastal systems that lie within the inshore coastal system. However, there is evidence that plumes have been measured offshore in rare circumstances (Gagan *et al*., 1987; Brodie and Mitchell, 1992., Devlin *et al*., 2001) and plumes can potentially reach midshelf reefs which lie closer to the coast line, such as reefs in the Cairns area (Furnas *et al*., 1995).

Extrapolating how and where the increased nutrient and sediment are delivered to GBR waters warrant a greater understanding of the processes that drives the spatial and temporal extent of the plume itself. This study will report on the areal extent of nine flood plumes, and correlate spatial extent with concurrently measured physical factors, including river flow and rainfall, prevailing wind conditions and sea state. These primary factors driving plume extent will be combined in a simple model for the prediction of plume distribution for a selected catchment.

1.4 Research question 3: What are the biogeochemical processes in riverine plumes discharging into GBR waters.

The input of high concentrations of terrestrially derived material is part of a natural process, in which the complex physical structure of the buoyant freshwater leads to a strong gradient in concentrations of and transformations among biogeochemical constituents (nutrients and sediments) in plume environments (Dagg *et al*., 2004). There are a number of processes that occur in the mixing interface between the rivers and the oceans, most commonly linked to a simple conservative dilution curve, where the constituent is diluted linearly as the river water moves into the adjacent coastal zones. However, water in the estuary or plume can act independently of the dilution process, when biological and chemical removal takes places, substantially reducing the concentration of the constituent that reaches the open ocean. Potentially land use changes on GBR catchments have lead to increases in the magnitude and concentrations of nutrient and sediments delivered into GBR waters.

Fifteen major rivers drain directly into the GBR lagoon. Their catchments support a range of land use activities and are unique in their low human population densities, low rates of river regulation and long-term variable climates. Rivers flowing through these catchments experience highly variable flow regimes following high inter- and intra-annual rainfall variability (Finlayson and McMahon, 1988; Puckridge *et al*., 1998), regularly flushing fresh to the sea (Eyre, 1998), and “non-normal” estuarine behaviour (compared with temperate rivers) with rivers injecting freshwater and contained materials directly onto the adjacent continental shelf where "estuarine" mixing takes place (Dagg *et al*., 2004). As a result of high freshwater discharge rates typically linked to storm flows "estuarine" processes in the GBR associated with major rivers primarily take place on the adjacent coastal shelf within the constraints of a heterogeneous river plume instead of in a physically confined estuary.

This research question aims to explore the transport and transformation of dissolved and particulate constituents in freshwater plumes discharging into GBR waters, examining the mixing processes for a selected number of GBR catchments. The shape of the mixing curves over a number of measured plumes will define the movement of the sediment and nutrient inputs into GBR waters and will be used to investigate the extent and scale of biogeochemical processes over for individual catchments and flood plumes associated with that catchment.

1.5 Research question 4: What is the extent of variability in nutrient and sediment transport in GBR waters

Currently there are significant gaps in the knowledge of the interactive effect of the three main components of flood plumes (nutrients, sediments and low salinity water) on coral reefs. The assumed effects of flood plumes are:

(i) immediate effects, such as the mortality of some groups (e.g. corals killed by low salinity water, Van Woesik *et al*., 1995) and the proliferation of others (e.g. diatoms; Relevante and Gilmartin, 1982);

(ii) medium-term effects, such as the increased growth of macro algae in response to nutrient spikes (Schaffelke and Klumpp, 1998a, Schaffelke, 1999, Russ and McCook, 1999; McCook, 1999)

(iii) long-term effects, such as the replacement of sediment- or freshwater sensitive assemblages by more persistent taxa (Fabricus *et al*., 2005; Fabricus, 2006; Devantier *et al*., 2006).

The ecology of corals and coral reefs is directly influenced by the "quality" of the water they live in. Waters washing over and around reefs deliver and remove dissolved and particulate nutrients, sediments, prey and propagules and generally protect reef organisms from extreme fluctuations in dissolved gases, temperature and salinity. Under natural conditions, a wide range of GBR coral species live or once lived on nearshore and coastal reefs along the NE Queensland coast (Veron, 1995), in low nutrient environments, but possibly still fairly turbid conditions. One of the major problems, eutrophication or overgrowth of corals by fleshy algae has been attributed to excessive seawater nutrients by some scientists (Bell, 1991, 1992; Littler, and Littler, 1993; Bell & Elmetri, 1995, Lapointe, 1997; 1999). A wide variety of anthropogenic and natural causes have been implicated, but verification of the major causes has been limited by insufficient data (Fabricus, 2006). Elevated nutrient loading in coastal waters is thought to stimulate the large blooms of algae, which smother corals (Dubinsky & Stambler, 1996; Mundy and Babcock, 1998; Babcock and Smith, 2002). At present there is unequivocal evidence that high, chronic input of terrestrial sediment, organic matter and inorganic nutrients (Eyre and Davies, 2000, Brodie and Mitchell, 2005; Mitchell, 1997; Mitchell *et al*., 2001) are being delivered to GBR waters, but the link between this increased delivery and known impacts on GBR ecosystems is contentious (Larcombe and Woolfe, 1999; Fabricus and De'arth, 2004; McCook *et al*., 2001; Fabricus *et al*., 2005). Correlation of the maximum nutrient and sediment concentrations measured in GBR waters and known coral impacts from increased nutrient and sediments could be a first step in identifying water quality thresholds in the GBR waters (Moss *et al*., 2005)

Threshold values of nutrients and sediments can be difficult to identified, as responses tend to be dose-dependent or specific to local conditions. Therefore acceptable concentrations of "water quality" parameters and ecosystem properties require careful local definition before guidelines can be set at local or regional scales. However, some tentative sedimentation tolerance limits of 10 - 30 mg dry weight sediments deposited have been proposed (Rogers 1990, Pastorok and Bilyard 1985), but as acceptable levels will depend on hydrodynamic conditions, organic loading, and background turbidity, thresholds need to be adjusted to local conditions. Studies establish maximum nutrient threshold concentrations for healthy reefs at 0.105μM phosphorus, and 0.196μM nitrogen (Bell, 1992; Lapointe, 1999, Moss *et al*., 2005) - trace amounts far below the standards for drinking water. This study will not present concentrations that could be applicable to thresholds for "healthy reefs" as the lack of baseline data precludes establishment of reference conditions. However, it will describe a range of minimum and maximum water quality conditions that are found at catchment, water column and reef scale; and relates concentrations to known coral reef impact in other reef systems in order to develop ranges of concentrations most likely to impact on some aspect of the biology around GBR reef systems.

1.6 Research question 5: Identification of areas of risk from increasing nutrient and sediment delivery into GBR waters.

Predicting the effects of contaminant inputs on coastal marine ecosystems due to the increasing delivery of nutrients and sediments into coastal waters can indicate areas at risk from anthropogenic discharges. In order to assess the threat to coastal ecosystems from land based sources of pollution, catchment budgets, which determine the relative magnitude of the various sources of contaminants, are necessary. This sort of budgeting has now been carried out in great detail in Europe, North America and the Atlantic Ocean (Howarth *et al*., 1996; Nixon *et al*., 1996; De Wit, 2000; Alexander *et al*., 2002; Bricker, 2004). Some initial modelling of catchment budgets has been carried out on the GBR catchment (Moss *et al*., 1992; Furnas, 2003, Brodie *et al*., 2003; Neil *et al*., 2002; McKergow *et al*., 2005a, 2005b) which has led to comparisons of current and pre-European suspended sediment, nitrogen and phosphorus loads to the GBR lagoon from the individual catchments. Such an approach is needed to prioritise catchment management initiatives to manage high risk catchments.

This study extends this approach by aligning catchment budgets (Brodie *et al*., 2003) with modelled plume distributions from the catchments. A distance factor will be applied for each reef potentially impacted by that catchment, and applied to the overall catchment budgets and plume distribution models. A ranking system will be applied to each reef to determine an area of high, moderate and low “risk” for coral reefs in Great Barrier Reef waters.

1.7 Thesis outline

Chapter 1: General Introduction and thesis outline

Chapter 2: Evidence of nutrient enrichment in the Great Barrier Reef using chlorophyll concentrations

- Analysis of a chlorophyll data set from 9 areas of the Great Barrier Reef
- Data analysis of factors influencing the variability of the chlorophyll concentration across and along the Great Barrier Reef.
- Correlation of regional and cross-shelf differences of the chlorophyll

concentration to land use activity.

- Evidence on nutrient enrichment within central and southern inshore waters of the GBR.

Chapter 3: Mapping and distribution of flood plumes in the GBR

- Movement and mapping of flood plumes
- Weather and flow characteristics that influence the movement of plumes

Chapter 4: Transport and transformation of dissolved and particulate matter in flood plumes of the Great Barrier Reef

- Biogeochemistry of flood plumes
- Mixing profiles
- Spatial variability of nutrient concentrations
- Nutrient speciation

Chapter 5: Thresholds and concentrations. How do plumes affect the distribution and concentration of dissolved and particulate nutrients in the Great Barrier Reef?

- Reef water quality in flood plumes
- What do “reefs” experience in periods of flood plumes? Identification of spatial and temporal variability in extreme concentrations
- Cyclone Steve data from 2000 (specific reef sampling dataset)
- Insitu logger data (light climate influenced by plumes)

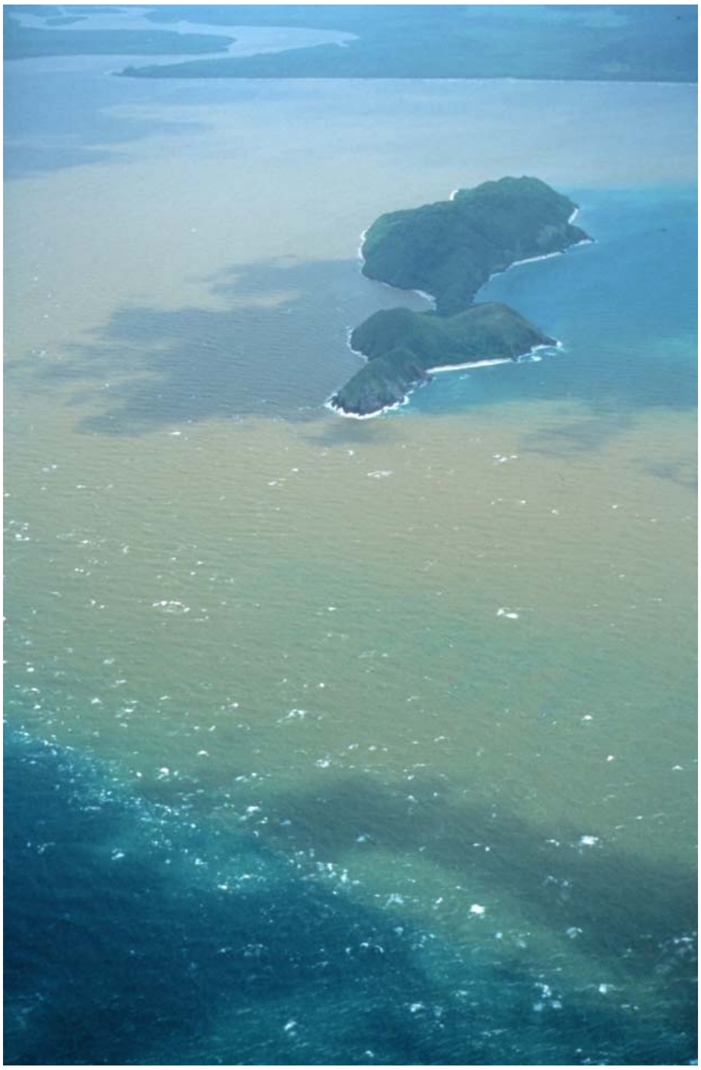
Chapter 6: Analysis of risk area related to catchment, nutrient delivery, plume movement and proximity of reef for the Great Barrier Reef.

- Identification of reefs “at risk” from inundation from flood plumes using plume movement and catchment characteristics and flood plume data.

Chapter 7: Conclusions

CHAPTER TWO:

Research question 1: Is there any evidence of nutrient enrichment in the GBR lagoon?



Plume surrounding the Frankland Islands, GBR

Chapter 2: Research question 1: Is there any evidence of nutrient enrichment in the GBR lagoon?

2.1. Introduction

Phytoplankton communities respond rapidly to increased nutrient availability resulting from events such as floods (Steven *et al*. 1996; Brodie and Furnas 1996, Devlin *et al*., 2000), upwelling (Furnas and Mitchell 1986, 1996) or resuspension (Furnas 1989). Any increase in nutrient inputs is rapidly taken up by phytoplankton communities which have the capacity to take up dissolved nutrients and scavenge nutrient concentrations to very low levels. Phytoplankton stocks respond quickly to changes in nutrient availability making measurement of the phytoplankton community a good indicator of nutrient status. Measurement of chlorophyll *a* concentrations is one of the most frequently employed techniques for assessing phytoplankton biomass (Monbet, 1992; Brodie and Furnas, 1994; Flindt, 1999) and variables such as chlorophyll *a* provide a reliable and integrative estimator of nutrient availability. There are five main advantages of monitoring chlorophyll *a* concentrations as compared with nutrient concentrations or species identification as a proxy indicator of nutrient availability.

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

Measurement of chlorophyll *a* concentrations derived from phytoplankton biomass have be shown to be indicative of enhanced nutrient inputs in many circumstances (Spencer, 1975) and can provide a reliable indicator of water column nutrient status in the absence of high frequency water column nutrient concentration measurements (Yunev *et al*., 2002; Harding and Perry, 1997). Monbet (1992) studied the relationship between the annual mean chlorophyll concentration (mg m^{-3}) and (i) the mean annual loading of dissolved inorganic nitrogen (DIN g m^{-2} y^{-1}) and (ii) the annual mean concentration of DIN (mmol m^{-3}). While there was a weak relationship between DIN loading and chlorophyll concentration the relationship between DIN concentration and chlorophyll concentration was much stronger. Harding and Perry (1997) concluded that between 1950 and 1994 there was a 5 to 10 fold increase in chlorophyll concentrations in the Chesapeake Bay system at the seaward region of the estuary and a 1.5 to 2 fold increase elsewhere which paralleled increases in nutrient loading over the same period.

Monitoring of chlorophyll concentrations in Great Barrier Reef waters has been successfully utilised as a proxy measurement of phytoplankton biomass and water column nutrient concentrations for a limited number of programs in the past (Gabric *et al*., 1990; Liston *et al*., 1992; Furnas and Mitchell, 1997; Brodie and Furnas, 1994; Brodie *et al*., 1997; Furnas and Brodie, 1996; Steven *et al*., 1998). These studies determined that a gradient of phytoplankton biomass and species composition exists across the Great Barrier Reef shelf and that inshore chlorophyll concentrations tend to be higher than in offshore areas (Furnas and Brodie, 1996). Chlorophyll concentrations are also higher in the central and southern Great Barrier Reef compared with sites located in more northern areas (Furnas and Mitchell, 1997). These studies also recognised a distinctive phytoplankton community gradient, with inshore diatom flora being replaced by a flora richer in dinoflagellates in open waters (Revelante *et al*., 1982). However, these studies were carried out in the period before the importance of marine picoplankton was recognized (e.g. Li *et al*., 1983), and it is now known that phytoplankton biomass in the Great Barrier Reef lagoon is typically dominated by phototrophic picoplankton (Furnas and Mitchell, 1997; Ayukai *et al*., 1997) and that nano- and micro plankton (including most diatoms and dinoflagellates) only become a dominant component of the plankton under conditions of significant nutrient enrichment. This current assessment builds on this earlier work on phytoplankton community and chlorophyll distribution in the Great Barrier Reef with a more comprehensive analysis of a long-term dataset of chlorophyll concentrations collected between 1991 and 2001.

2.2. Methods

2.2.1 Study area

Water samples were collected along the northern Australian eastern coast within the Great Barrier Reef region between 1991 and 2001. This region extends approximately 2000km parallel to the Queensland coast between 9^0 and 24^0S latitude and covers approximately 350,000 km^2 (Figure 2). The continental shelf in this region varies in width from 50 km in the north to over 200 km in the south and can be arbitrarily divided into three distinct cross-shelf areas. An inner shelf area with water depths of up to 20 m is immediately adjacent to the coast. This area contains coastal and island fringing reefs and intertidal and shallow water seagrass beds. The area is extensively affected by adjacent coast influences and its sediments are composed of predominantly terrestrial sourced material (Maxwell, 1968). The middle shelf area has water depths of 20 m to 40 m, fewer reefs and some areas of deep-water seagrass beds. The area is sediment starved. The outer shelf has water depths of 40 to 100m, has sediments dominated by carbonate materials and a majority of the Great Barrier Reef reefs are situated in this area. Sites were located along a cross shelf gradient at a number of regional areas within the Great Barrier Reef.

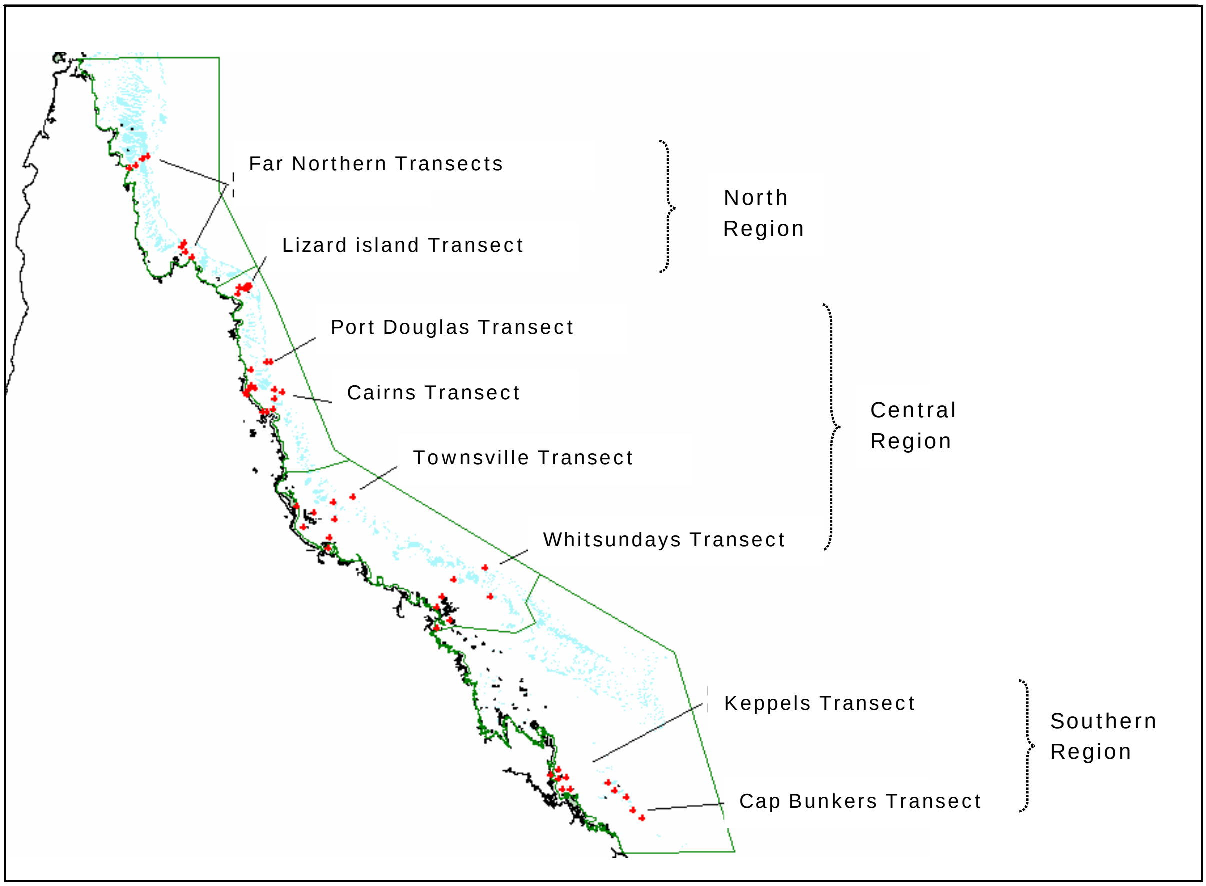


Figure 2: Latitudinal sampling transects for the Long term chlorophyll monitoring program. Transects were grouped into further divisions of north, central and south regions

2.2.2 Ambient water condition sampling sites

Chlorophyll monitoring stations were located in eight regional cross-shelf transects within the study area (Figure 3) The transects are Far Northern (13^{o}S); Lizard Island (14^{o}S); Port Douglas (15^{o}S); Cairns (16^{o}S); Townsville (18^{o}S); Whitsunday (21^{o}S) and Keppel Bay and the Capricorn Bunkers (23^{o}S). As the Keppel Bay sites are all situated inshore and Capricorn Bunkers all situated offshore, these two transects were combined into one transect called "Keppel Bay transect". Within each transect, between eight and fifteen fixed sampling stations were sampled at approximately monthly intervals from 1991 to 2001. The actual date for sampling within a calendar month was determined by logistics including boat availability and prevailing weather conditions. For ambient monitoring, cross shelf transects were sampled monthly at a fixed number of sampling sites. Replicate samples were taken at each sampling site. Duplicate samples were filtered from each sample. This sampling design is shown in Figure 3.

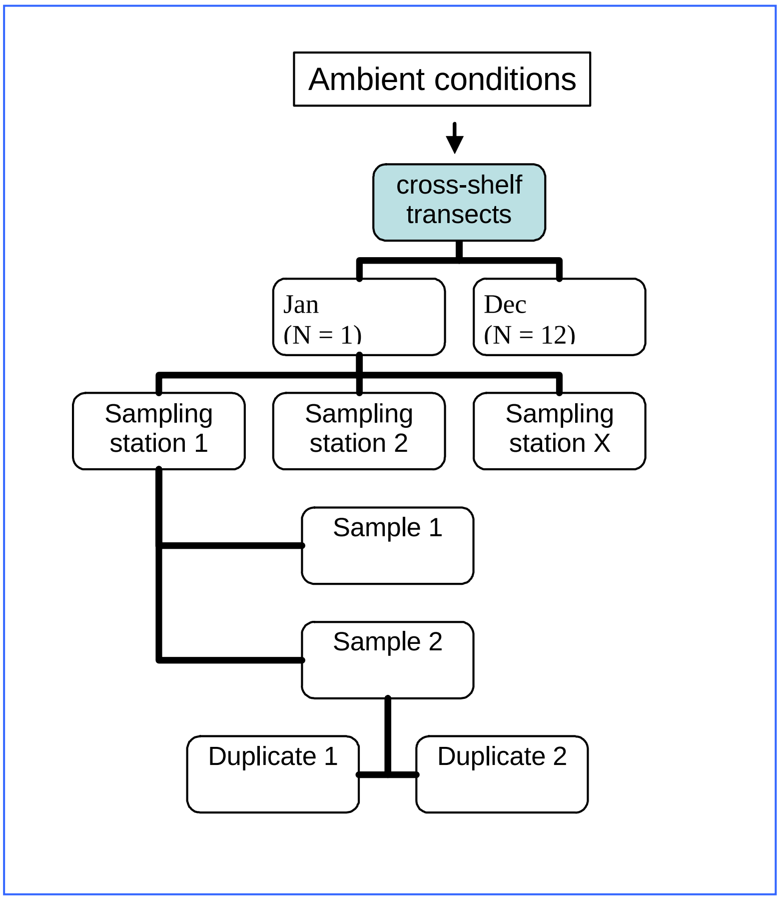


Figure 3: Design of sampling program for the ambient (baseline) conditions. Further details can be found in Steven *et al*., 1998 and Brodie *et al*., in press

2.2.3 High nutrient conditions (River plume sampling)

Riverine plumes are discharged into inshore Great Barrier Reef waters during flood events fed by cyclonic and monsoonal rains. Chlorophyll *a* concentrations within these plumes were sampled as part of the plume sampling program (Devlin *et al*., 2001). Plume water samples were collected from 9 wet season flood plumes that occurred between 1991 and 2000. Water samples were collected from multiple sites within each plume. Sample sites location was 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 to sea from the flooding river mouth, with additional samples collected in between river mouths if more than one river was in flood (Figure 4). Samples were collected along the plume salinity gradient, moving from the mouth of the river to the edge of the plume (Figure 5).

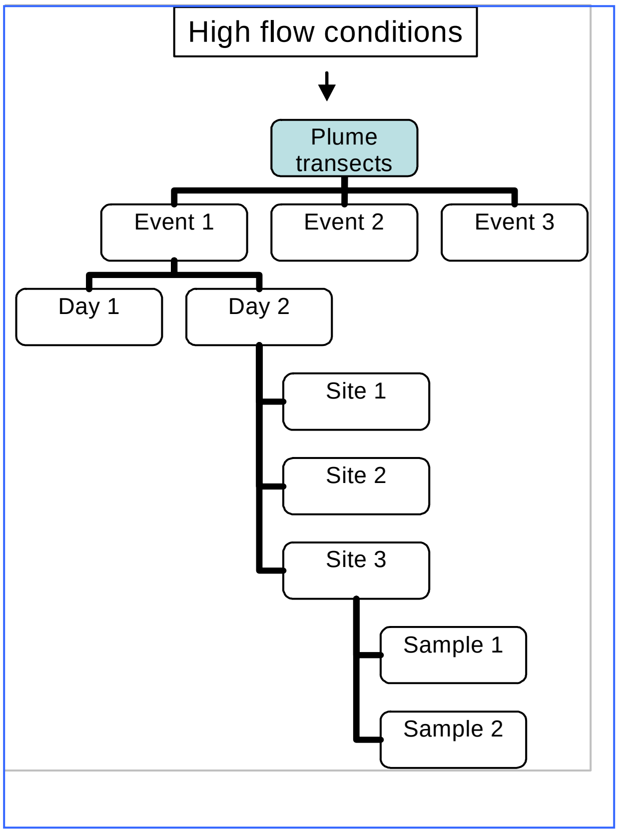


Figure 4: Design of sampling program for high flow conditions. Further details can be found in Devlin *et al*., 2002

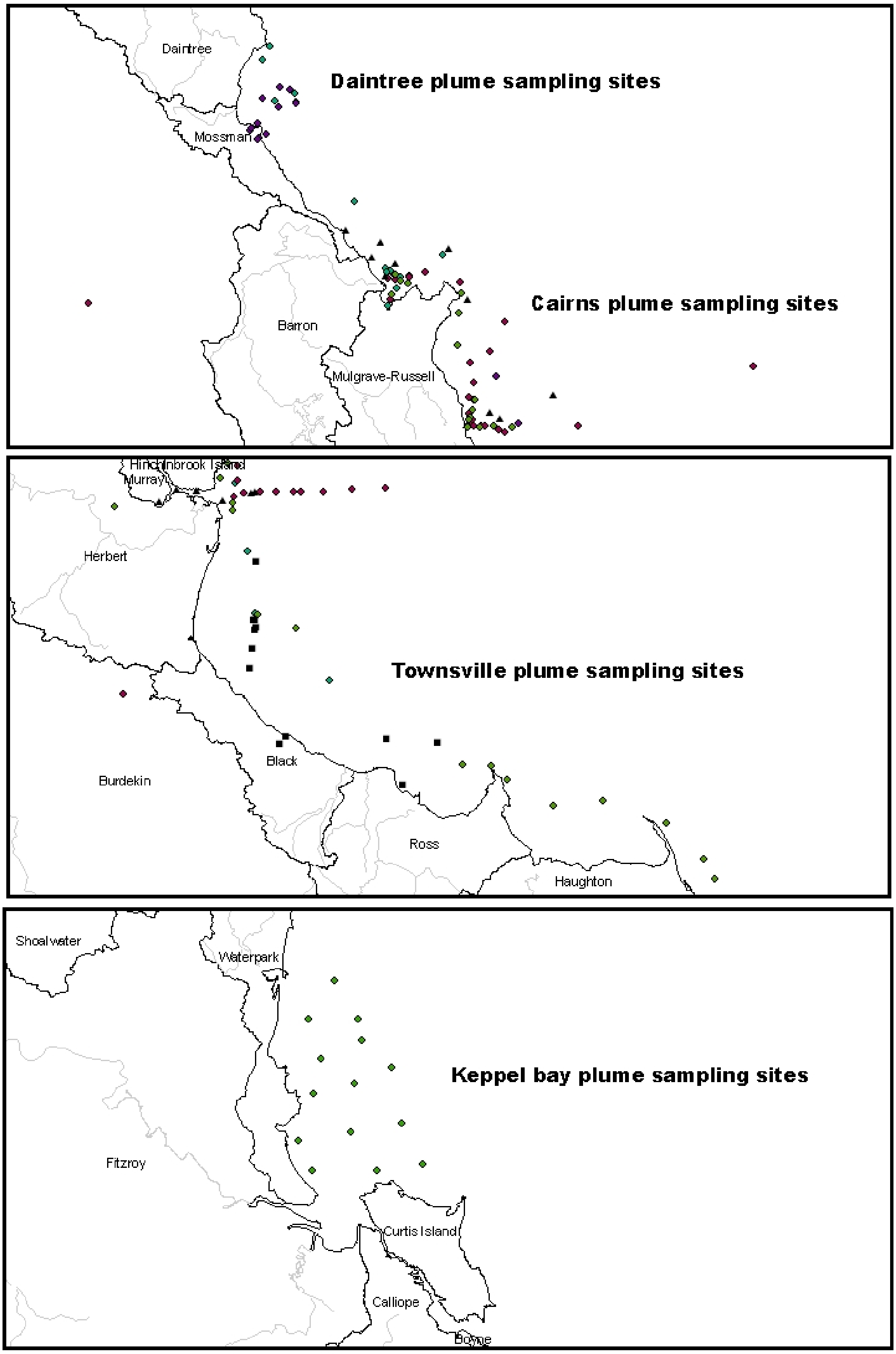


Figure 5: Location of plume sampling sites that correspond with location of ambient sampling sites.

2.2.4 Sample collection

Surface water samples are collected using Niskin bottles for both programs and additional bottom water samples were collected as part of the flood plume sampling. Filtration of the water samples for chlorophyll and phaeophytin analysis was carried out within six hours of sampling, with the samples being kept under cool dark storage conditions before filtration. Chlorophyll and phaeophytin are routinely determined using a fluorometric method (Parsons *et al*., 1984) with periodic intercalibration against a high performance liquid chromatography (HPLC) absolute method. Weather conditions, physico-chemical measurements (salinity, temperature), secchi depth, and the presence of the blue green algae *Trichodesmium spp*. were also recorded at every site at time of water sampling.

2.2.5 Data analysis

For preliminary exploratory analyses stations were grouped by their regional transects and plotted individually over the sampling period They were also grouped into two distinct cross shelf transects with sites most likely to be influenced by terrestrial runoff described as inner sites (<25km from the coast) and sites unlikely to be influenced by terrestrial runoff, described as 'offshore' (> 25 km), sites.

Data were analysed using a general linear model, with chlorophyll as the response variables. (Chlorophyll was logged using a natural log function to reduce variability around the mean). The following explanatory variables were included in the models:

(1) *Regions* comprising Far North, Cooktown, Lizard Island, Port Douglas, Cairns, Townsville, Whitsundays, Capricorn Bunker & Keppels:

(2) *cross shelf* comprising inshore and offshore areas

(3) *season*, comprising a dry term (winter) (May to November) and a wet term (summer) (December to April).

(4) *time*, comprising temporal changes over each transect

Further grouping of the regions into three distinct geographical areas, north central and south, was related to land use activities on the adjacent catchments. Temporal information was also plotted out over the geographical areas.

2.3. Results

2.3.1 Spatial analysis of chlorophyll concentrations

Summary chlorophyll concentration statistics recorded over the ten-year sampling period are presented in Table 1, which include detailed descriptive statistics of the chlorophyll data in terms of their overall concentrations as well as their seasonal profiles. Statistical analysis of chlorophyll data obtained during the sampling period indicates strong seasonal and spatial variability with highest concentrations during the wet season and significantly higher concentrations (on average > 2 times higher) at inshore sites than at offshore sites (Table 1). The maximum concentrations of chlorophyll measured through the sampling period were taken in plume samples, linked to the nutrient enriched terrestrially derived plume waters (Table 1). Strong seasonal variation exists for all regional transects, though of lower magnitude for the Far Northern transects, with similar seasonal evolution patterns of: high levels of chlorophyll measured in the wet season, lower concentrations in the dry season, and the episodic maximum concentrations related to high flow events. Summary data indicates that concentrations measured in the central regions (Port Douglas, Cairns, Townsville and Whitsundays) and southern regions (Keppel Bay transects) are elevated in comparison to the northern region. Analysis of variance shows significant differences between regions, cross shelf and season. Cross shelf differences are more evident in some regions, as indicated by the significant interaction between cross shelf and transect (Table 2).

Table 1: Summary of chlorophyll concentrations for each transect in the study. Data was separated into summer (Nov – April) and Winter (May – Oct). Comparative data for flood plumes is also presented for the inshore summer period.

Program	Season	Area	Transect	Min	Max	Mean	SD	n
Ambient	**Winter**	**Inner**	**Far northern**					0
			Lizard Island	0.01	1.47	0.264	0.237	159
			Cooktown	0.07	0.56	0.231	0.1	94
			Port Douglas	0.03	3.97	0.509	0.431	527
			Cairns	0.01	3.61	0.649	0.548	772
			Townsville	0.06	2.97	0.494	0.464	228
			Whitsundays	0.03	1.24	0.352	0.156	196
			Keppels	0.01	4.99	0.527	0.55	1002
Ambient	**Winter**	**Outer**	**Far northern**					0
			Lizard Island	0.07	0.73	0.223	0.091	479
			Cooktown	0.01	0.47	0.156	0.074	180
			Port Douglas	0.02	0.74	0.211	0.108	567
			Cairns	0.02	1.62	0.209	0.182	887
			Townsville	0.01	0.46	0.163	0.104	240
			Whitsundays	0.06	0.32	0.156	0.066	24
			Keppels	0.06	9.05	0.448	0.747	939
Ambient	**Summer**	**Inner**	**Far northern**	0.09	0.8	0.296	0.148	83
			Lizard Island	0.1	1	0.309	0.148	184
			Cooktown	0.03	0.73	0.223	0.149	220
			Port Douglas	0.02	5.3	0.646	0.522	884
			Cairns	0.02	6.76	0.736	0.72	800
			Townsville	0.1	1.85	0.663	0.375	193
			Whitsundays	0.06	2.45	0.548	0.313	151
			Keppels	0.13	6.68	0.791	0.698	948
Ambient	**Summer**	**Outer**	**Far northern**	0.12	2.4	0.374	0.303	65
			Lizard Island	0.03	0.88	0.291	0.139	548
			Cooktown	0.06	0.83	0.231	0.14	140
			Port Douglas	0.02	2.44	0.346	0.229	966
			Cairns	0.01	1.64	0.305	0.251	984
			Townsville	0.03	1.72	0.222	0.206	192
			Whitsundays	0.01	0.29	0.157	0.102	12
			Keppels	0.01	9.18	0.588	0.713	1060
Flood	**Summer**	**Inner**	**Port Douglas**	0.28	5.30	0.81		38
			Cairns	0.18	6.89	1.18		176
				0.03	3.81	1.17		228
			Townsville	0.42	2.01	1.09		65
			Whitsundays					0
			Keppels	0.46	20.1	5.71		63

Table 2: Two-way analysis of variance (ANOVA) of transect chlorophyll a concentrations (Chlorophyll a concentrations $\log_{10}$ transformed prior to analysis). Explanatory variables include (a) regional transect, (b) cross shelf area, (c) interaction between transect and area and (d) season.

Source	SS	df	MS	F-ratio	P
(a) Transect	121.513	6	20.252	239.527	<0.001
(b) Area	67.991	1	67.991	804.142	<0.001
(c) Interaction	70.508	6	11.751	138.987	<0.001
(d) Season	57.748	1	57.748	682.997	<0.001
Error	1146.587	13562	0.085		

(a) Regional areas

Concentrations of chlorophyll *a* are consistently lower in the northern transects, with mean chlorophyll concentrations ranging from 0.23 to 0.31 μg/L inshore and 0.16 – 0.37 μg/l offshore in contrast to mean chlorophyll concentrations in the central and southern transects ranging from 0.35 – 0.79 μg/l inshore and 0.16 to 0.59 μg/l offshore.

(b) Cross shelf

Chlorophyll *a* concentrations are higher at all inshore sites in the wet and dry seasons excepting the Far northern transect where inshore and offshore samples were of similar magnitude (Table 1). There is significant variation in concentrations measured across the shelf for all transects within the central and southern section (Port Douglas, Cairns, Townsville and Whitsundays, $p<0.01$ and Keppel-Capricorn, $p<0.05$).

In comparison, there is negligible difference across the shelf in the northern regions, with mean summer concentration of 0.22 - 0.3 μg/l in the Far Northern and Cooktown Osprey inshore sites, compared to 0.22 - 0.37μg/L offshore. Mean winter concentrations in the Cooktown Osprey transect from 0.23μg/l inshore to 0.16μg/l offshore. The smaller variation across shelf for Keppels and Capricorn Bunker transects is due to the intermittent high chlorophyll values measured at the outer sites potentially linked to resuspension events or Coral Sea upwelling. For all other transects, monthly averaged chlorophyll concentrations measured at inshore sites ranged from 0.23 to 0.64μg/L in summer and 0.22 to 0.79μg/L in winter. In comparison, average concentrations measured at offshore sites ranged from 0.16 to 0.45μg/L in winter and 0.16 to 0.56μg/L in summer. Transects which do record the greatest variation between inshore and offshore sites (Table 1) in both wet and dry are Port Douglas, Cairns and Townsville. The exception to this is the high offshore concentrations measured in the Keppels in both summer and winter.

The significant interaction between transects and cross shelf areas indicate that the differences are not consistent across all transects, which is supported by plotting average chlorophyll concentration across transect and area (Figure 6). The variation in cross shelf concentrations support the idea that northern sites demonstrate little variability in their inshore and offshore sites, indicating a more constant delivery of nutrients across the shelf. The significant variation across shelf for Port Douglas, Cairns, Townsville and Whitsundays indicates favourable conditions for phytoplankton growth in these inshore areas, most likely related to increased nutrient delivery during the extreme flow events.

(c) Season

Seasonal variation is also significant across the geographical transects for all areas ($p<0.01$), with chlorophyll concentrations peaking in the wet season due to high river flow and enhanced nutrient availability, though this can be confounded by a number of high biomass values being measured in the winter in the Keppels and Capricorn Bunker transects. The seasonal pattern is evident in all regions, though the scale of seasonal variation is not consistent through transects. Central and southern regions support higher peaks of wet season biomass and northern transects supporting smaller changes in chlorophyll concentrations during the wet season.

Seasonal patterns in the chlorophyll concentrations show persistent summer maxima and winter minima. Higher values of biomass were recorded at all sites in the summer months (November to April) most likely related to this episodic river flow related to the wet monsoon season. The majority of the nutrient load to GBR coastal waters is through river runoff (Furnas *et al*, 1996). Annual loading from river runoff is highly variable and reflects the pulsed nature of hydrological events in the area with the high river flow being associated with pulsed nutrient loading supporting phytoplankton blooms (new production).

2.3.2 Land use activity

Further grouping of the sites into broad geographical areas related to land use activities (north, central and south GBR) demonstrate these significant differences are related to broadscale differences with the GBR (Figure 6). Central and southern regions demonstrate higher inshore chlorophyll *a* concentrations than the northern region. Mean distance from shore for inner and outer stations is not significantly different between the broad geographical areas ($p<0.01$), suggesting that the variation in biomass across shelf for central and southern transects may be influenced by the potentially higher nutrient inputs into these inshore coastal areas.

The significant variation within the broadscale regions (north, central and southern regions) demonstrates a pronounced regional difference in chlorophyll concentrations from the inner and outer sites (Figure 6). These differences could be attributed to the diverse geographic structure of the GBR shelf at the regional scale and could be relatively natural. However, land use activities over the three regions are markedly different and is likely to be a factor in driving this regional difference. The GBR river catchment area of the northern regional cross-shelf transects (north of Cooktown) is typically an undisturbed area with limited cropping activities and cattle grazing characterised by low stocking rates. The GBR River catchment areas of the Central regional cross-shelf transects are characterised by intensive cropping activities in the lower catchment areas. The cropping activities, primarily sugar cane cultivation, are concomitant with high fertilizer application rates and higher nutrient delivery in the rivers (Mitchell and Furnas, 2002, Eyre and Davies, 2000). Even in recent decades the concentrations and fluxes of nutrients in central and southern GBR Southern regional cross-shelf transects historically have had large proportion of clearing and are now characterised by high stocking rates for cattle grazing and intensive cropping activities in the lower catchment areas. River nutrient discharge has risen sharply as agricultural development continues (Brodie and Furnas, 2003). In the Tully River nitrogen concentrations have risen significantly in the period 1987 – 2000 (Mitchell *et al.*, 2001). Particulate nitrogen concentrations have doubled and nitrate concentrations increased by 16% over this period (Mitchell *et al.*, 2001).

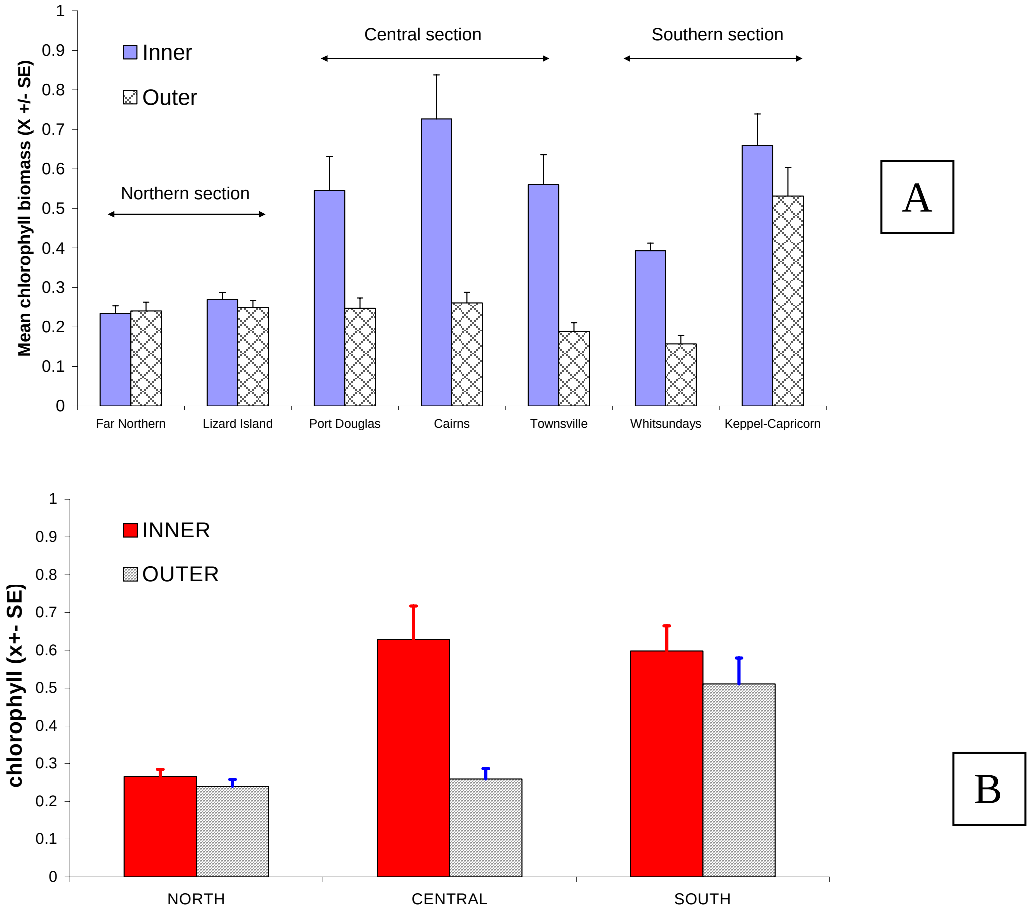


Figure 6: Mean chlorophyll concentrations (µg/l) measured across the geographical transects separated into inshore and offshore area (a) and regional areas grouped into broad geographical regions (north, central and southern areas of GBR) (b).

2.3.3 Contribution of high flow events to the phytoplankton biomass

It is important to distinguish water quality in flow-event conditions, identifying the flood pulse (Junk *et al*., 1989; Eyre and Davies, 1996) from ambient (baseflow) conditions. Comparative analysis of phytoplankton biomass measured in plume conditions with ambient (low flow) conditions are used to report on the response of phytoplankton standing stock to the input of nutrient rich flood waters. Mean concentrations of chlorophyll measured in the flood plumes were higher than those recorded in the water column in non-flood conditions and ranged from 0.03 to 20.1 µg/l. Concentrations of chlorophyll measured in flood plume conditions were generally an order of magnitude greater than in non-plume periods. A comparison of Barron River flow with measurements of chlorophyll *a* concentrations for the period 1992 and 2002 shoes peaks in river flow are highly correlated temporally with elevated chlorophyll concentrations are linked strongly with river flow (Figure 7). Peaks in concentrations of suspended sediments, nutrient materials and other chemical compounds coincide with peaks in flow rates as soil and associated soluble materials are washed off the land and into the rivers. Dilution of specific nutrient or ion concentrations in river waters can occur when watershed stocks are limited or have been washed out in floods earlier in the wet season.

2.3.4 Temporal patterns in chlorophyll biomass

Monthly averaged chlorophyll concentrations are plotted out for each regional transect are presented as monthly means from 1991 to 2001 (Figure 8). No significant change is measured in chlorophyll over the time of the sampling period (1991 – 2001). Seasonal patterns are observed in all regions, though greater peaks and periodicity are demonstrated in the central and southern regions. Northern sites are characterised by smaller seasonal variation between the inshore and offshore sites in contrast to the central and southern regions with the highest inshore seasonal fluctuations in chlorophyll *a* concentrations.

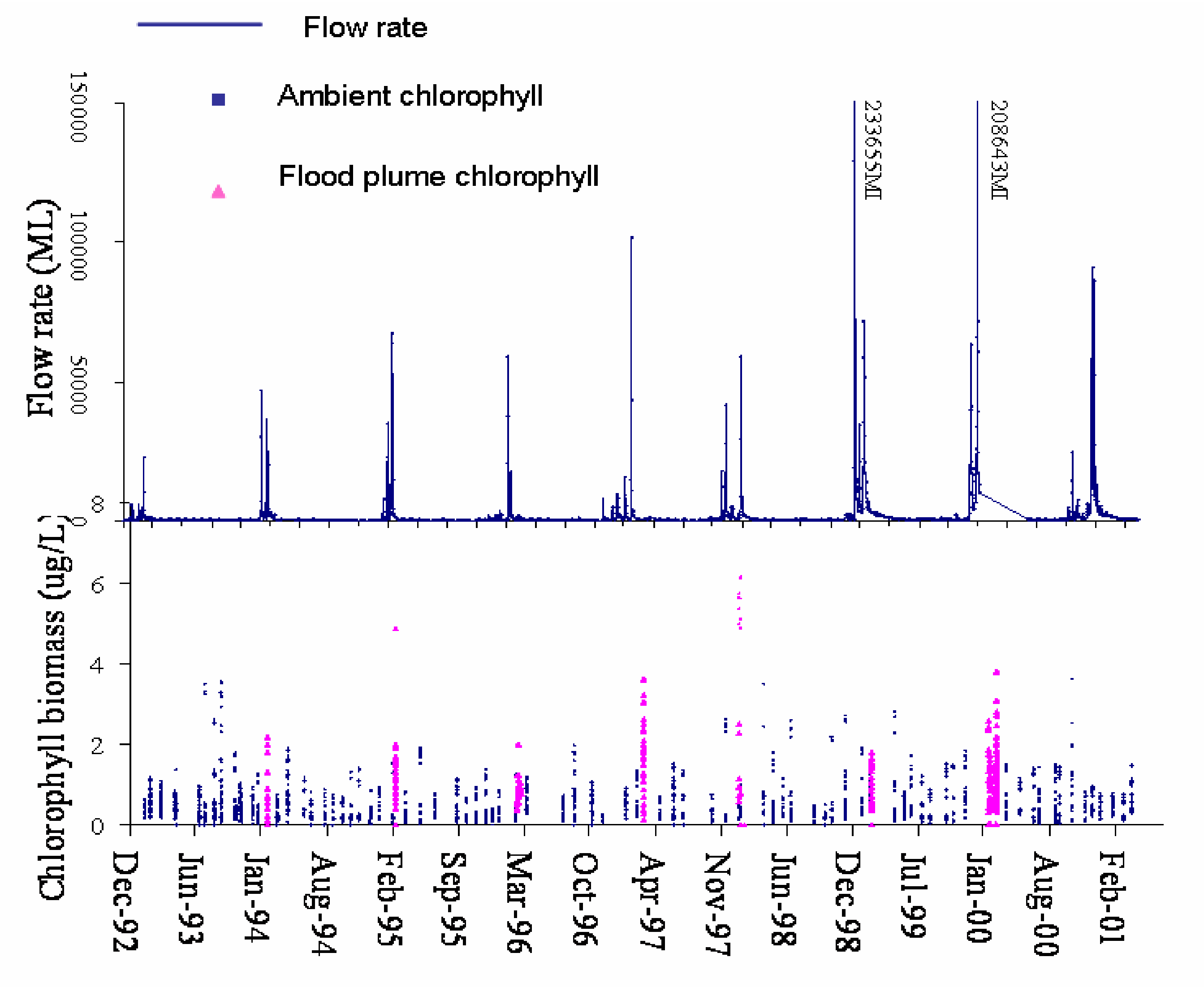


Figure 7: Mean average chlorophyll values over sampling period (1991- 2000). (a) Long term inshore chlorophyll data (blue) is compared with chlorophyll values taken in flood plumes (pink) from the inshore areas of the Cairns transect (b) Concurrent flow rates for the Barron River are reported (blue line).

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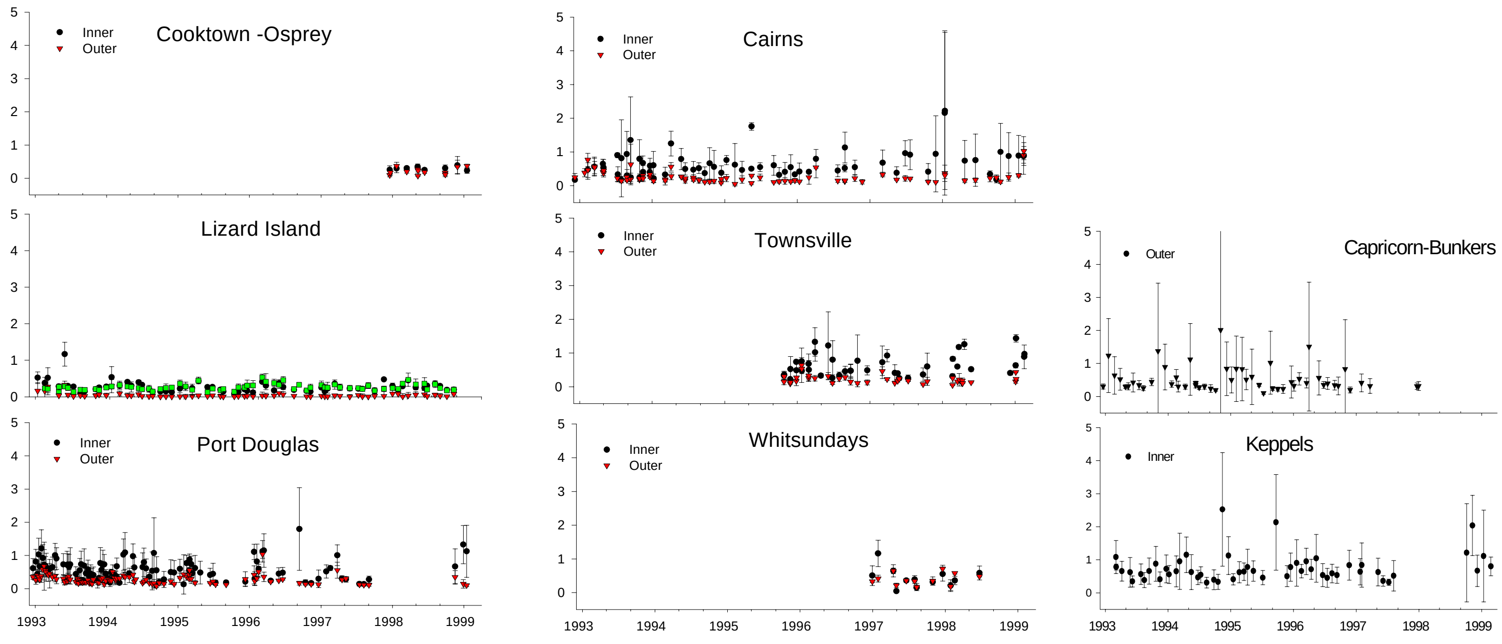


Figure 8: Mean monthly chlorophyll data (with SE) for the 8 transects on the Great Barrier Reef. Transects are placed in a north to south gradient. Data are grouped into inner (up to 20km off coast) and outer (> 20km off coast) cross-shelf areas)

2.4. Discussion

2.4.1 Spatial concentrations of chlorophyll biomass

Broadscale repetitive chlorophyll sampling throughout the Great Barrier Reef reveals significant regional differences in chlorophyll concentrations. The greatest degree of variability within the sampling design relates to the cross shelf differences, with inshore sites in the central area having consistently higher chlorophyll concentrations. Southern sites also have higher inshore chlorophyll concentrations, but more variable, with intermittent high offshore concentrations. Seasonal and inter-annual trends are generally consistent between regions.

(a) Regional differences

This study supports previous work which shows geographically distinct areas in GBR waters supporting variable phytoplankton communities (Furnas and Mitchell, 1986, 1987; Furnas and Brodie, 1996; Steven *et al*., 1998).Distinct geographical areas can be seen in lower chlorophyll concentrations measured at the northern sites, compared to the higher values measured at the central and southern regions. This spatial difference is most likely related to land use characteristics of adjacent catchments. The Great Barrier Reef river catchment areas north of Port Douglas are relatively undisturbed area with limited cattle grazing characterised by low stocking rates. This is in contrast to catchments south of Port Douglas which are characterised by intensive cropping (sugar cane) activities in the lower catchment areas. The cropping activities are concomitant with high fertilizer application rates and higher nutrient delivery in the rivers (Eyre and Davies, 1996; Mitchell and Furnas, 2002,). Rivers running through catchments dominated by agriculture typically have, for example, dissolved inorganic nitrogen (nitrate and ammonia) concentrations in flood flow 30 times that of rivers with undeveloped catchments (Mitchell *et al*., 2005; Brodie and Mitchell, 2005). Water discharged from these polluted rivers in flood flow covers the inshore part of the GBRWHA, but rarely the mid- or outershelf (Brodie and Furnas, 1996; Devlin *et al*., 2001, 2002, 2004). Concentrations of pollutants, such as dissolved inorganic nitrogen, in these river plumes which reach the inshore reefs and seagrass beds are typically 10-50 times higher than ambient concentrations in non-flood periods (Devlin *et al*., 2001) and exceed the 'effects levels' for biological action on corals (eg Koop *et al*., 2001; Moss *et al*., 2005), seagrasses and algae (Schaffelke and Klumpp, 1998).

(b) Cross shelf differences

Other studies have reported on the cross shelf variation of biomass concentrations in the GBR with Furnas and Brodie (1996) noting the cross shelf gradient in chlorophyll in the central GBR (Cairns and Innisfail) area with values ranging from 0.7μg/L to 1.3μg/l inshore falling to 0.3μg/l at the outermost sites, corresponding well to values measured in this study. Values of chlorophyll for the central section are similar to recent concentrations reported for coastal locations in the Townsville, Cairns and Shelburne Bay regions (0.59 – 0.68μg/L, 0.46 – 0.71ug/l) (Furnas, 1991; Muslim *et al*., 2003). High chlorophyll values (0.5 to 0.8μg/l) were also reported by Furnas and Brodie (1996) in the far southern GBR (Capricorn Bunkers) similar to those found in the present study. The northern section has limited historical data, though Furnas and Brodie (1996) reported inshore concentrations in their northern transect of 0.4ug/l and increasing across the shelf to 0.7μg/l. Ayukai *et al*. (1997) reported a mean chlorophyll concentration of 0.41μg/L in the Cairns region during summer sampling over the years 1992 to 1995.

Regional and cross shelf differences indicate increased nutrient delivery into coastal areas, which support enhanced rates of plankton growth and/or production.

(c) Season

Lacking a well defined seasonal cycle, biological variability in tropical ecosystems is more closely related to disturbance events and oceanographic processes such as upwelling (Furnas & Mitchell 1986), floods (Brodie & Mitchell 1991), tidal mixing (Holloway et al. 1985) and cyclones (Furnas 1989). The overall productivity of temperate Australian continental shelf waters is restrained by the poleward transport of low-nutrient tropical waters along the continent's eastern and western margins by the East Australian Current (Nilsson & Cresswell 1980) and Leeuwin Current (Godfrey & Ridgeway 1985). There are no large seasonal blooms producing surpluses of organic matter. As a result, Australia lacks the large demersal fisheries that characterise northern hemisphere continental shelf systems. Offshore sites have restricted, if any, effect from riverine discharge, and can be nutrient limited for much of the year, limiting primary productivity. Sources of nutrients to the Great Barrier Reef include inputs from land via river discharge (Mitchell *et al*, 1996) and urban runoff (Brodie, 2001b), atmospheric inputs including rainfall and nitrogen fixation by cyanobacteria and from the adjacent Coral Sea from the surface currents (nutrient poor) and deep water upwelling (nutrient rich). Many of these inputs are highly episodic in nature, occurring over short periods during and after cyclones (resuspension of bottom sediments, flooding of rivers) and during seasonal periods (upwelling). Furnas *et al*, (1995) determined that the most significant proportion comes from recycled material within the system and that the new inputs, from river discharge, atmospheric sources and upwelling, provide a much smaller proportion of total Great Barrier Reef nutrient inputs.

2.4.2 Influence of plume waters on chlorophyll concentrations

Concentrations of chlorophyll measured in flood plume conditions are generally an order of magnitude greater than in non-plume periods (Table 1) with concentrations in the range 0.5 – 16 $\mu g\ l^{-1}$ in low salinity waters (<30ppt). Comparisons of Barron River flow with chlorophyll concentrations reveal that intermittent elevated chlorophyll concentrations are linked strongly with river flow, demonstrating that plume events can be a main source of nutrient delivery and correlate with increases in chlorophyll concentrations. Australian tropical rivers have episodic flows, with most material transport occurring during large flow events (Devlin *et al*., 2001, 2003). Because of the small size of most catchments, flood events are usually of short duration, often lasting only a few days. These high flow periods are closely coupled to local rainfall patterns. In the monsoonal climate of northern Australia, significant flow into and nutrient discharge from rivers is restricted to the summer wet season and is highly variable between and within years (Isdale 1984). Major flood events are typically related to the activity of monsoonal depressions or tropical cyclones.

Plume measurements have usually been taken in the central region and are discharged from rivers with elevated concentrations of nitrogen and phosphorus. These values may not be representative of plumes from rivers of the northern GBR (Cape York), for which no plume water quality data is available, or the rivers of the central and southern GBR catchment in their ‘pristine’ conditions before agricultural development began circa 1850. Even in recent decades the concentrations and fluxes of nutrients in central and southern GBR Catchment Rivers have risen sharply as agricultural development continues (Brodie and Furnas, 2003). In the Tully River nitrogen concentrations have risen significantly in the period 1987 – 2000 (Mitchell *et al*., 2001). Particulate nitrogen concentrations have doubled and nitrate concentrations increased by 16% over this period (Mitchell *et al*., 2001). Chlorophyll concentrations related to phytoplankton communities

Simple measures of chlorophyll can demonstrate the variable parameters of seasonal change and geographical location and the influence of extreme flow events on this community; though it is more difficult to speculate on the nature of change in the phytoplankton community as the biomass fluctuates. However, previous work supports the smaller size fractions dominating offshore and in the Coral Sea (Furnas and Mitchell, 1985) with bloom concentrations (>2μg l^{-1}) supporting a larger proportion of phytoplankton (>10μm). This current work has been able to look at the consistency of this pattern over the length and breadth of the Great Barrier Reef demonstrating that the cross shelf differences, most significant in the central and southern area, is most likely to be influenced by increasing nutrient delivery into these coastal zones. Low nutrient concentrations tend to support a plankton community dominated by picoplankton giving low biomass readings (chlorophyll <0.5μg l^{-1}) (Tado *et al*., 2003), where the larger phytoplankton species are at a competitive disadvantage under low nutrient conditions. Previous work has shown the GBR has a phytoplankton community (>70%) dominated by the picoplankton (0.2 – 2μm) (Relevante and Gilmartin, 1982, Furnas, 1991). As nutrient concentrations increase, so do the proportion of larger size plankton (Furnas and Mitchell, 1985). Ayukai *et al.* (1997) demonstrated in periods of high nutrient inputs in the Great Barrier Reef waters, with increases in the phytoplankton biomass (>1 μg l^{-1}), there has been a measurable shift from a picoplankton dominated community to one dominated by nano (2 – 20μm) and microplankton (20 – 200μm). Relevante and Gilmartin reported on the ability of the diatom microplankton to dominate during nutrient pulses, indicating that diatoms can compete effectively with the nanoplankton during periods of high nutrient input. The implications of a shift in phytoplankton species composition from predominant picoplankton to a more significant nano and microplankton population on GBR ecosystem needs further study, as a correlation with crown of thorn juvenile populations has been postulated (Brodie *et al*., 2005).

1.5 Is there evidence of nutrient enrichment in the GBR?

Simplistic indices of phytoplankton biomass, as measured by chlorophyll *a*, may not be able to provide a detailed examination of phytoplankton communities, but the ease of sampling and reduced costs associated with the measurement of chlorophyll *a* can support a more detailed spatial and temporal sampling program which in turn, can give relevant information on broad-scale changes within the Great Barrier Reef lagoon. Knowledge of broad-scale changes can act as a baseline for further investigations into the immediate and long-term impacts of increasing nutrient discharges into the Great Barrier Reef lagoon.

Using relatively simple indices, collected at monthly intervals for 10 years, through a number of geographically distinct regions the data analysis has been able to support evidence of a strong latitudinal trends from north to south. There has also been considerable evidence to support a cross shelf gradient, most pronounced adjacent to the central regions, adding support for concerns of increasing nutrient delivery to the central coastal regions. However, the long-term nature of the signal is more difficult to assess, with no significant change over time for any region. Thus, either the program is not powerful enough to pick up on temporal changes, or assessment of temporal change has come too late. Work by Pulsford (1996) indicates a rise in fertiliser usage up to the 1980's where a levelling of use has been documented. Clearing and grazing peaked 50 years ago, with again some levelling of land use change (McColloch *et al.*,2003; McCulloch, 2004). Thus it may be difficult for the program to detect temporal change in biomass if nutrient delivery from the catchment has reached an upper threshold. However, the ability of the program to detect spatial differences potentially related to catchment land use, which can be detected in the data, provides a good background to areas of the reef which are experiencing nutrient enrichment and increased phytoplankton production.

Biological demand for nitrogen and phosphorus, by autotrophic organisms such as phytoplankton is high, resulting in low concentration of these nutrients in the water column. Therefore increases in nitrogen and phosphorus availability, either through 'new' inputs or recycling of nutrients, stimulate the primary productivity of all autotrophic organisms in the GBR lagoon. Eutrophication is the sustained increase of organic production by autotrophic organisms, resulting from increases in nitrogen and phosphorus availability. One of the first signs of eutrophication is an increase in the biomass of phytoplankton as they are better able to assimilate higher availability of nutrients than benthic, autotrophic organisms.

The 1993-1998 chlorophyll time series illustrates local variability in chlorophyll concentrations under non-disturbed conditions as concentrations of the phytoplankton are representative of the higher concentrations present inshore of the lagoon. Generally, short-term phytoplankton blooms rapidly follow changes in salinity resulting from either rainfall or riverine discharge (Devlin *et al*., 2001), resuspension of benthic sediments during cyclones (Furnas, 1989) or during strong south-east winds (Walker and O'Donnell, 1981) or from intrusions of upwelling water masses (Andrews and Furnas, 1986; Furnas and Mitchell, 1996).

The data collected in the seven years demonstrates persistent cross-shelf and regional differences in chlorophyll concentration. Seasonal trends are generally consistent between regions. There are pronounced gradients between inshore and offshore sites, indicating a strong terrestrial influence in the inshore lagoon of the GBR. Introduction of agriculture, primarily fertilised cropping, has increased nutrient inputs to the central catchments and consequently increased concentrations of dissolved and particulate nutrients in rivers draining agricultural dominated catchments (Brodie and Mitchell, 2005, Eyre and Davies, 1996).

Results from the chlorophyll monitoring support the idea of an inner-shelf polluted zone adjacent to the developed catchments from Port Douglas to Harvey Bay (end of southern region) and relatively unpolluted zone on the inner-shelf north of Port Douglas and generally on the middle and outer shelf. The middle shelf between Cape Grafton and Cape Tribulation (central region) is also somewhat polluted due to its proximity to the coast and polluted rivers. In general, Coral Sea and outer shelf mean chlorophyll concentrations are close to 0.2 $\mu g\ l^{-1}$, areas of the GBR Lagoon without polluted river influence have mean concentrations near 0.3 $\mu g\ l^{-1}$, long-term mean concentrations in areas subjected to polluted river influence are near 0.6 $\mu g\ l^{-1}$while event concentrations in waters affected by flood plumes from polluted rivers can be greater than 3 $\mu g\ l^{-1}$.

Results in this study indicate an inner-shelf zone supporting higher production and possible trophic shift in the phytoplankton community in areas adjacent to the developed catchments from Port Douglas to Harvey Bay in comparison to a relatively low production zone on the inner-shelf north of Port Douglas and the middle and outer shelf, supporting a phytoplankton community dominated by the picoplankton.

Chapter Three: The extent and duration of plume waters in the GBR (mechanism for transport of new material)

Edge of plume in contrast to blue oceanic water – Cyclone Sid, 1998

Chapter 3: The extent and duration of plume waters in the GBR (mechanism for transport of new material)

3.1 Introduction

Discharge of terrestrial material to the GBR occurs predominantly during the major river floods generally associated with cyclonic rainfall events between November and May. The resultant outputs are described as riverine plumes which extend into the GBR lagoon varying according to size and typology of the adjacent catchment. River inputs are important both in terms of the physical structure of they systems and as a source of nutrients and sediments to coastal waters (Jickells, 1998). The delivery of these plumes is one of the main mechanisms for new input into the GBR. Understanding of where they go, how far they go and what drives their dispersal is important in the understanding of nutrient and sediment delivery to GBR.

3.1.1 Great Barrier Reef catchment and rivers

The coast adjacent to the Great Barrier Reef consists of a large number of individual catchments (Figure 9) mostly small (<40,000km^2) but also two of Australia's larger catchments, the Burdekin (133,000km$^{2)}$ and Fitzroy (143,000km^2). Rivers draining these catchments discharge into the GBR with event frequencies ranging from annual, such as the Herbert River to decadal, such as the Fitzroy River.

Northern Australian catchments are different from most around the world (Harris, 1995), with unusual species composition and biogeography (Harris, 2001), low human population densities, low rates of river regulation, regular high turbidity, long-term variable climate and highly variable flow regimes following high inter- and intra-annual rain fall variability (Finlayson and McMahon, 1988; Puckridge *et al*., 1998). Australian catchments regularly flush fresh to the sea (Eyre, 1998) and exhibit "non-normal" estuarine behaviour (compared with many temperate rivers) with rivers injecting fresh and contained materials directly onto the adjacent continental shelf where "estuarine" mixing takes place (Dagg *et al*., 2004).

Discharge of both water and sediment is dominated by large flood events associated with tropical cyclones and monsoonal rainfall (Mitchell and Furnas, 1997; Furnas and Mitchell, 2000). The output from individual rivers varies from those such as the Tully which have multiple major flows each year, to those such as the Herbert and Pioneer which generally have one major annual flow, and finally, the Burdekin and Fitzroy in which major flows are separated by periods of 4 to 10 years (Figure 10). The Burdekin and Fitzroy rivers are characterised by floods where discharge increases by two to four orders of magnitude typically in less than 24 hours. A clear distinction divides the large dry catchments rivers such as the Burdekin (catchment area, 133,000km^2, annual mean discharge, 11 million ML) and wet tropics rivers such as the Tully (catchment area, 2,850km^2, annual mean discharge, 5.3 million ML) and the Johnstone (catchment area 2330km^2, annual mean discharge 4.7 million ML) (Figure 10).

Flow variability is an important controlling factor for river ecological processes (Puckridge *et al*., 1998). In waterbodies in Northern Australia it is important to distinguish water quality in flow-event conditions, the flood pulse (Junk *et al*., 1989), from ambient (baseflow) conditions. Nutrient loadings to downstream environments are dominated by storm flows, however flow events in even the largest of the northern Australian rivers (e.g. the Burdekin) are short and energetic, with flood-pulse periods of less than one month and water residence times in the river of approximately one week (Prosser *et al*., 2001a; 2001b). This is in contrast to other rivers (e.g. Murray-Darling) where flood pulses move down the system slowly and residence times can be many months.

This makes the process of delivery to GBR waters a short lived, but important event in driving offshore processes. Studies have shown a distinct gradient in water column and benthic sediment properties across the GBR shelf (Furnas *et al*., 1995, Brodie and Furnas, 1996, Gagan *et al*., 1987), which indicates that material exported from the land will most strongly affect the ecosystems of the coast itself and the nearshore reefs. Runoff collects a variety of substances as it moves through the river’s catchment-lands and waterways including nutrients, sediments and contaminants depending on the catchment characteristics and land-use practices. Upon reaching the sea at the river’s mouth, the runoff drives a buoyant plume into coastal and shelf water, interacting and impacting on the nearshore GBR waters. Understanding of how river discharge into the GBR, and the extent and influence of this riverine water can identify the land based constituents that can potentially impact on the GBR ecosystems.

The spatial extent of freshwater plumes in the GBR over the last ten years was correlated with weather and flow conditions. Since 1991 plume movement has been mapped by aerial flyovers, geographically referencing the extent of the plume. GIS coverages were created and combined to illustrate the general plume movement in the GBR lagoon. Plume distribution and pollutant concentrations are controlled by a number of factors, particularly wind direction and speed. Southeasterly winds dominant, typically pushing plume waters north and close to the coast.

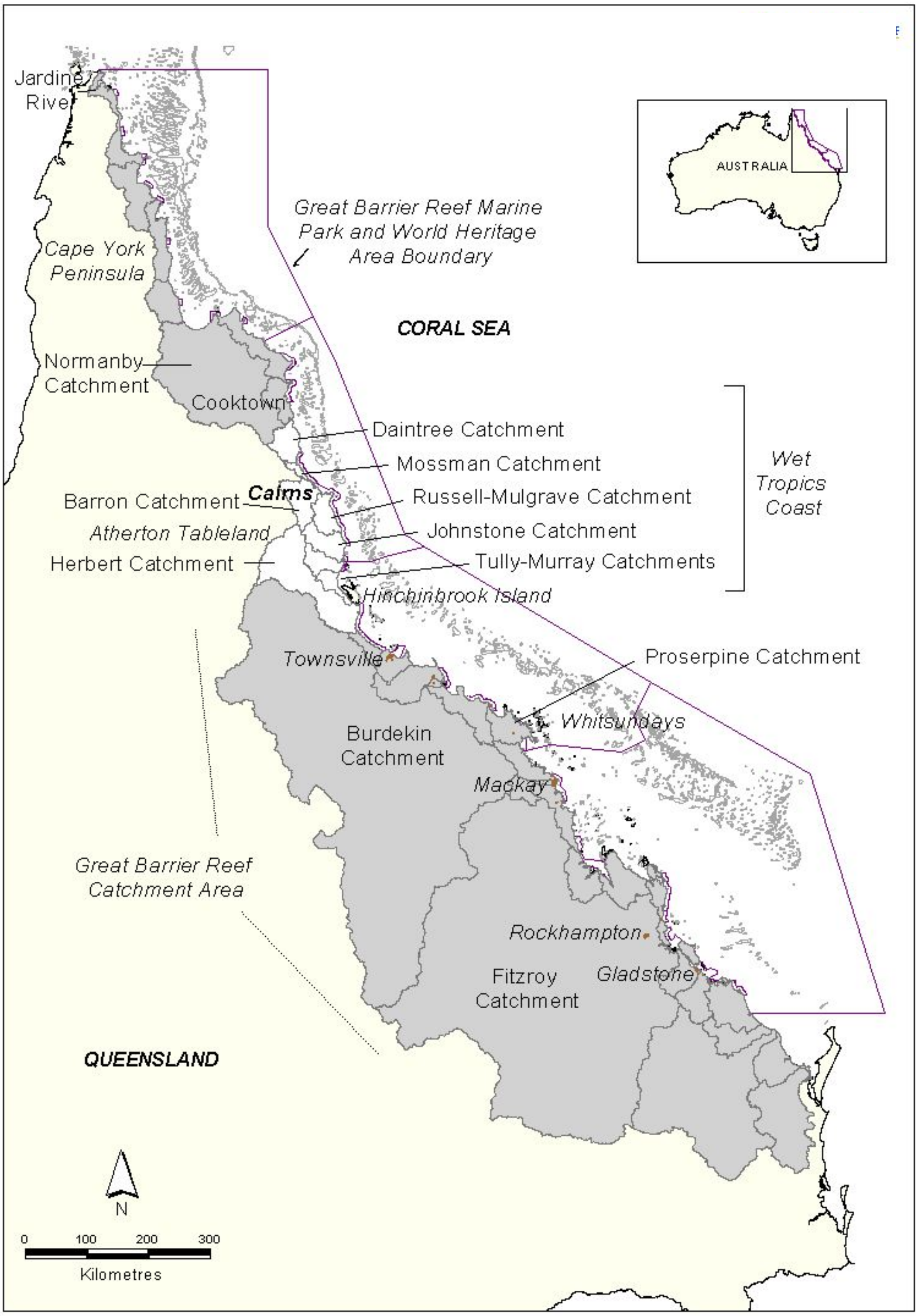


Figure 9: Map of the Great Barrier Reef Catchment and major rivers draining into the Great Barrier Reef lagoon.

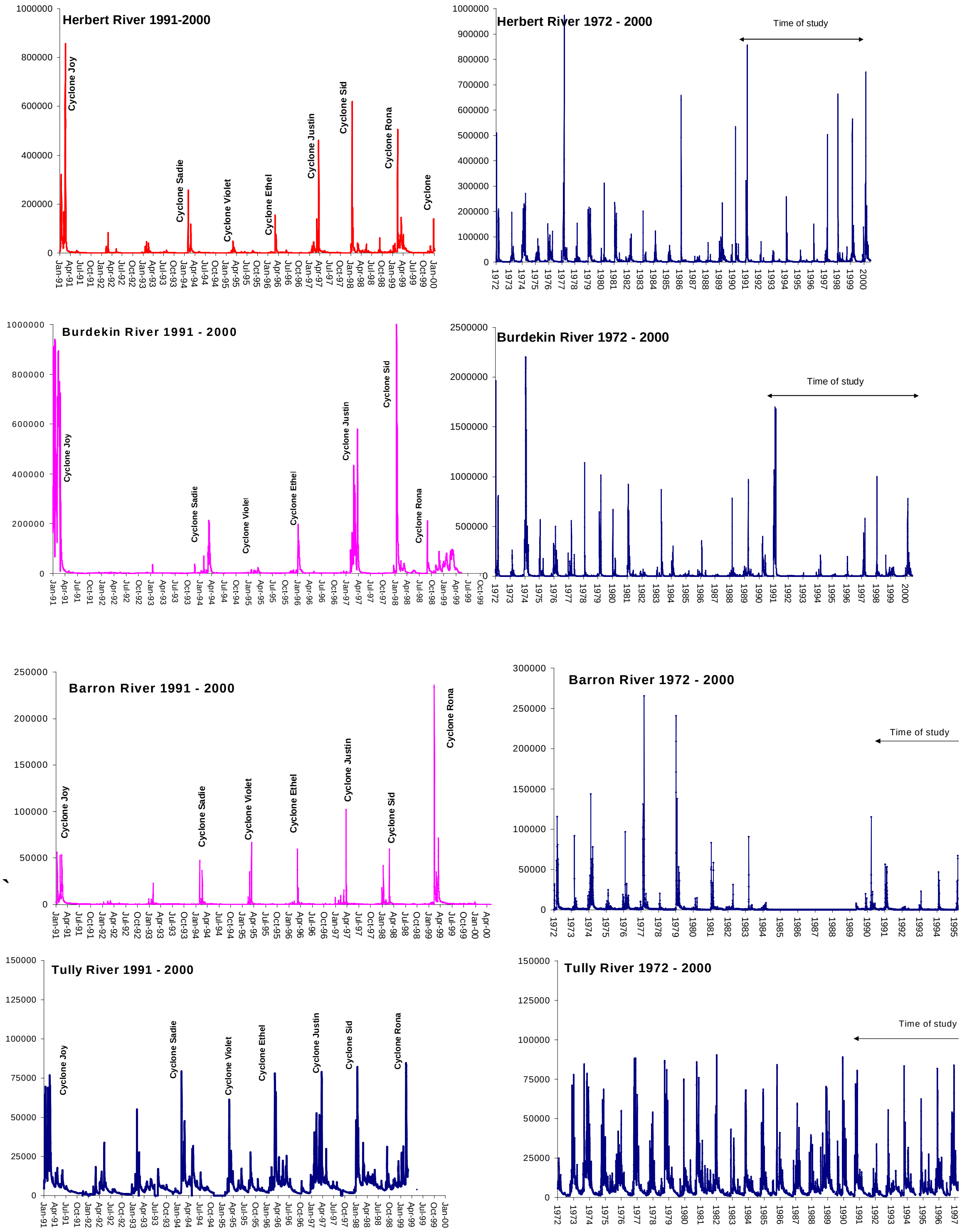


Figure 10: Historical flow rates in comparison to the study period for Tully (Wet Tropics), Herbert (intermediate) and the Burdekin River (Dry Tropics)

a) b)

Figure 11: (a). 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)*

3.2 Materials and Methods

3.2.1 Aerial mapping of flood plumes

Over the Queensland summer monsoon season, weather reports were monitored closely, specifically any low-pressure rain depressions. Within the first 24 to 48 hours after the onset of a flood event, river plumes were mapped primarily using aerial survey "snapshots" with confirmatory water sampling from vessel cruises where possible. 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 or weeks. Nine Great Barrier Reef flood plumes have been mapped (1991 – 2000).

The cyclone-associated plumes and the main areas of impact included in this study 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
- Steven (2000) Wet Tropics coast

Flood plumes associated with these weather systems were mapped on flights along and outwards from the coast. Plumes were readily observable as brown turbid water masses contrasting with cleaner seawater. All plumes mapped in this study were associated with cyclones and/or an associated monsoon trough. While plumes have been associated with a particular cyclone for convenience, in some cases, the main rainfall event was separated by some time from the actual cyclone. In these cases, the monsoon trough rainfall associated with the cyclone (e.g. Cyclone Sadie 1994) generated the plume. The locations of the plume fronts were fixed with geographic positioning systems (GPS) and loaded into a geographic information system (GIS). Wind direction and speed are presented for the day(s) that the extent of the plume was mapped.

3.2.2 Frequency of plume distribution

Plume extents and corresponding weather conditions demonstrates the variable nature of flood plumes and the range of conditions that give rise to their development. 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. A summary of plume behaviour is demonstrated by overlying all measured plume extents. The size and location of flood plumes associated with each monitored event were compared to identify areas within the GBR that experience a high frequency of plume inundation.

3.2.3 Hindcasting of plume distribution based on current knowledge of plume extent and shape

Using current knowledge on factors that control plume extent between the 1991 and 1999 period, a hindcast model was used to predict spatial extents of plumes from 90 years of weather and river flow data. Formulation of expected plume distributions allows for the identification of reefs that have been subjected to plume innundation and an estimate as to the frequency of impact over a longer time period than the current study.

The extent of a plume is calculated by relating the timing and force of river flow, wind direction and strength with plume extent and shape. The theoretical extent may, however, be influenced by fixed factors such as bathymetry, Coriolis effect, shape of the coast and catchment size and hydrology. To reduce the effect of the fixed variables in the model, hindcasting will be limited to one catchment area of the GBR where all fixed factors are taken as constant.

Relationships between the discharge criteria (river flow) and wind conditions experienced between 1994 and 1999 period were documented to ascertain the extent of the plumes with respect to these variables including the dates of discharge exceeding the set criterion, the date that the flood plume was primarily determined and the wind speed and direction measured before, after and during the event. Variables are correlated with known plume extents.

Study area

The study area was located between Barron and Russell-Mulgrave Rivers, where the one dimensional risk map (Figure 12) indicated high frequency of plume inundation within the inshore area.

Area of study is contained within the Wet Tropics region (Figure 12), and is adjacent to the Wet Tropics catchments, and is characterised by the highest rainfall in Australia, with frequent major rivers and subsequent plume formation. The catchments have high agricultural usage, with fertilised agriculture dominating the low-lying catchment area (Brodie and Mitchell, 2005).

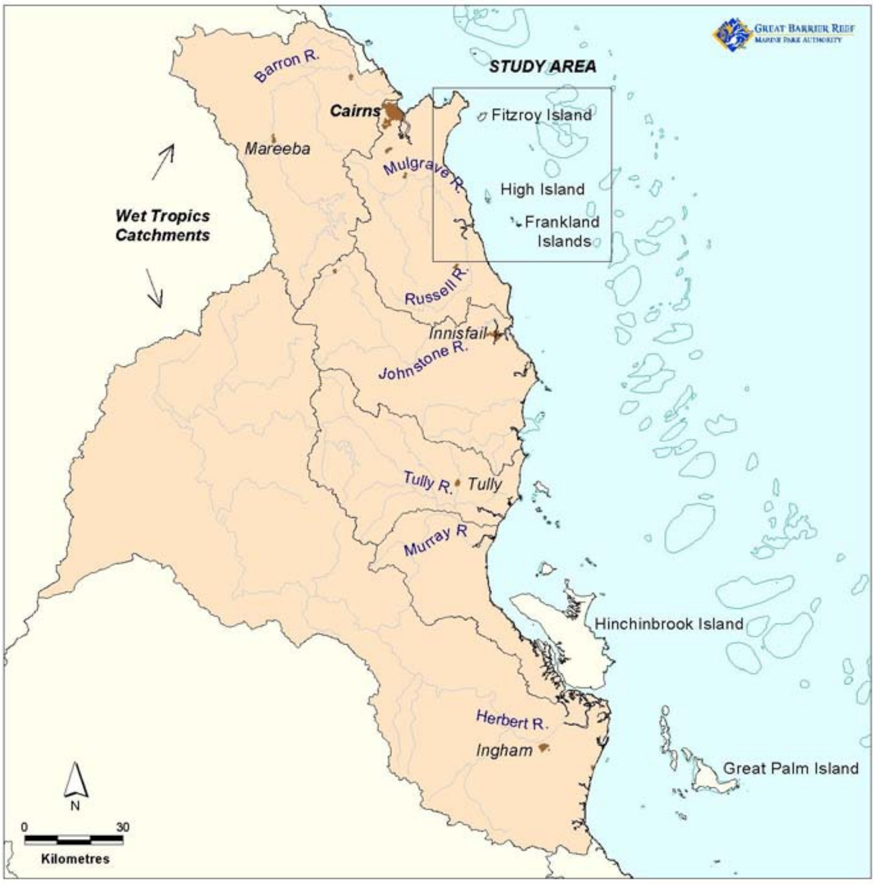


Figure 12: Area selected for modelling of hindcasting plume conditions

3.3 Results

3.3.1 Aerial mapping of plumes

The main driver of riverine plumes in the Great Barrier Reef are low pressure systems, usually (not always) leading to the formation of a cyclone. Flooding of Queensland Rivers usually occurs as the low pressure system/cyclone moves over land, resulting in heavy rainfall over a number of days. Cyclones can impact on one or more areas of the GBR, as evident by Justin, which existed as a cyclone for 23 days, moving inwards from the Coral Sea across the GBR, making land fall just north of Cairns and finally crossing back out to sea near the Burdekin. All the cyclones sampled within this study had unique and different tracks which can lead to different areas of the Queensland coast being affected (Figure 13)

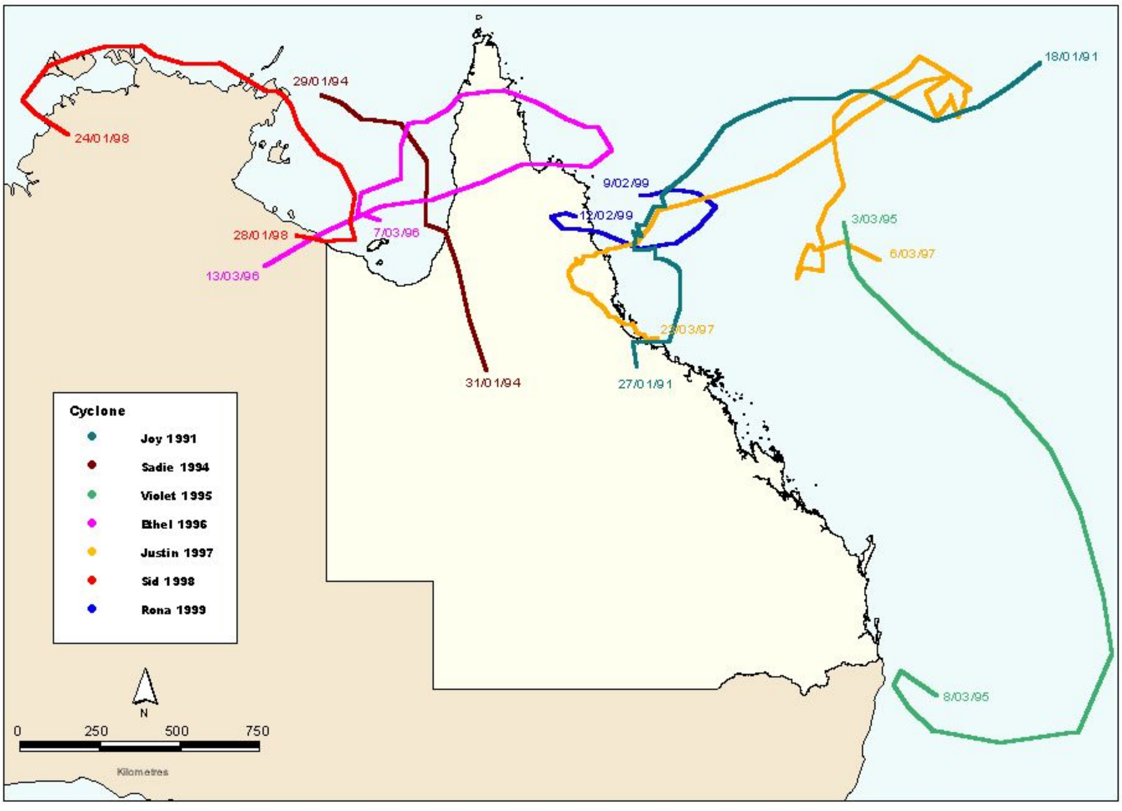


Figure 13: Tracks of cyclones over the Queensland coast from 1991 to 2000

Table 3: Weather and flow conditions for each sampling period

Year	Cyclone	Flooding rivers	Total flow (Megalitres)	Average flow/day	Wind Speed[2] (knots) and direction	Aerial flyover
1991	Joy	Fitzroy Burdekin	1 7148 000		< 5 NW/NE	12/1/91 19/1/91 23/1/91
1994	Sadie	Wet Tropics[1]	808 929	134 821	< 10 NW/NE < 10 NW/NE	1/2/94–2/2/94
1995	Violet	Wet Tropics	794 766	132 461	10 SE/S	28/2/95
1996	Ethel	Wet Tropics	1 827 959	304 659	10–15 S/SE 5–10 SE	6/3/96
1997	Justin – 1	Pioneer Burdekin	59 433 805 683	9906 134 280	10–15 SE	4/3/97
1997	Justin – 2	Wet Tropics Burdekin	1 040 203 2 102 423	173 367 350 403	10–20 N/NW	25/3/97
1998	Sid	Wet Tropics			10 SE	13/1/98
1998	Sid	Burdekin			15–25 E 5–10 NE	21/1/98
1999	Rona	Wet Tropics			10 NE-SE 10 SE	14/2/99
2000	Steven	Wet Tropics				

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. The majority of river plumes impacted on the Wet Tropics, with buoyant plumes recorded from Sadie, Violet, Ethel, Justin, Rona and Steven flood events. In contrast, a significant flood plume was recorded only once out of the Fitzroy (Cyclone Joy) and three times out of the Burdekin, including Joy, the early stages of Cyclone Justin and the later stages of Cyclone Sid (Table 3). Prevailing wind conditions tend to be southeasterlies, though moderate northerlies were experienced in Joy, Sadie and Justin.

The results of each mapping exercise are shown in Figure 14 to Figure 23 and describe the nine plumes mapped over the time of this study. Figure 14, Figure 19 and Figure 20 show individual plumes from large rivers (Burdekin and Fitzroy in the 'dry' catchment areas) while all other figures show the combined plumes typical of rivers within Wet Tropics region (Herbert, Tully, Johnstone, Russell-Mulgrave, Barron and Daintree Rivers) and the Mackay/Whitsunday region (Plane Creek / Pioneer / O'Connell /Proserpine Rivers). Plumes in the Wet Tropics region normally merge into a continuous area. However the individual river contributions can generally be distinguished visually through differences in colour and turbidity (as shown in Figure 23)

(i) 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 and Pioneer river catchments. 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).

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.

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 14) 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 (Figure 14). 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 terrestrial detritus. 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 27pppt at the Capricorn reefs (Prekker 1992).

(ii) 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 15) 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 (Table 3). Plumes associated with cyclone Sadie from Wet Tropics Rivers were also unusual among those documented in this report, with weak northwesterly and northeasterly winds allowing the plume to move offshore (Devlin *et al*., 1997).

(iii) 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 southeasterly direction down the coast. Moderate south-easterlies following the cyclone constrained the resulting plume to within 10 km of the Queensland coastline (Figure 16). 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 (Steven *et al.*,1996)

(iv) March 1996 – Cyclone Ethel

Cyclone Ethel formed as a weak tropical cyclone in the southeastern 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 (Figure 17). Moderate south-easterlies constrained the plume to within 15 km of the coast, and an aerial flyover was undertaken on 6 March 1996 (Figure 17).

(v) March 1997 – Cyclone Justin

Cyclone Justin developed in the Coral Sea on 7 March 1997, approximately 800 km east of Cairns. 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. Cyclone Justin was associated with high flow from the Wet Tropics Rivers as well as substantial flow from the Pioneer River and Burdekin River.

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. The first part of cyclone Justin resulted in flooding in the Pioneer and Burdekin Rivers in early March 1997. The plume from the Burdekin River moved south, directed by northeasterly winds. This resulted in a plume that moved in a southeasterly direction and covered a number of inshore Whitsunday reefs (Figure 18). 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 (Figure 19) along the coast in a similar pattern to Ethel and Rona.

(vi) 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 (Devlin, 1997).

Cyclone Sid, similar to Justin the previous year, was associated with high flow from the Wet Tropics Rivers as well as substantial flow from the Burdekin River.

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 (Figure 20). 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. Burdekin Plumes associated with Sid were relatively long lasting and still visible after two weeks (Figure 21).

(vii) 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. The flood plume associated with cyclone Rona was similar to cyclone Violet and Ethel 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 (Figure 22).

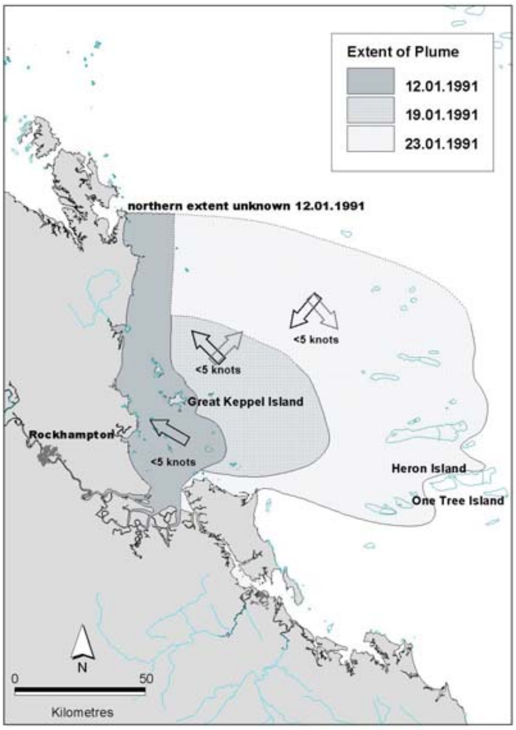


Figure 14: Flood plumes associated with Cyclone Joy, 1991

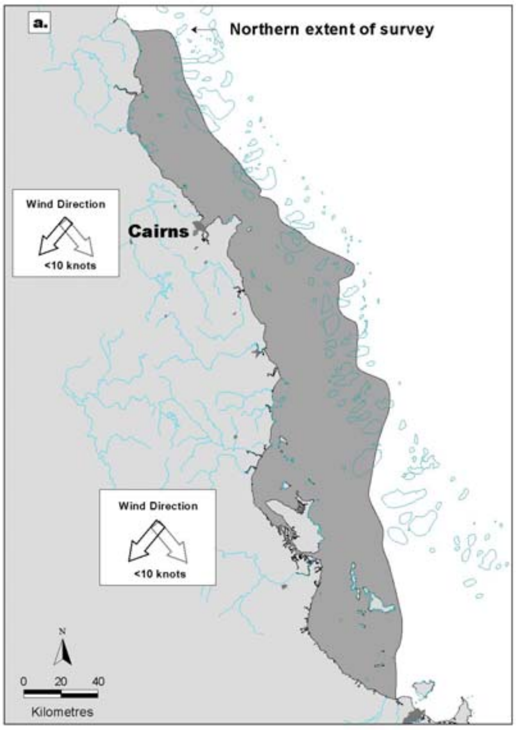


Figure 15: Flood plumes associated with Cyclone Sadie, 1994

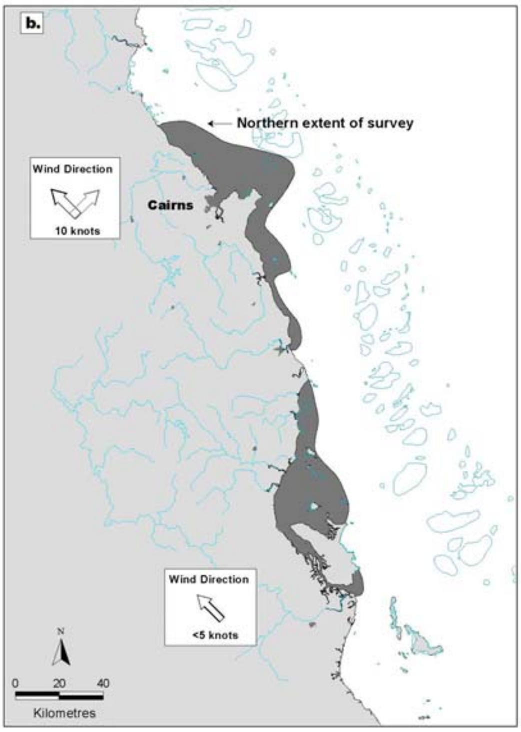


Figure 16: Flood plume associated with Cyclone Violet, 1995

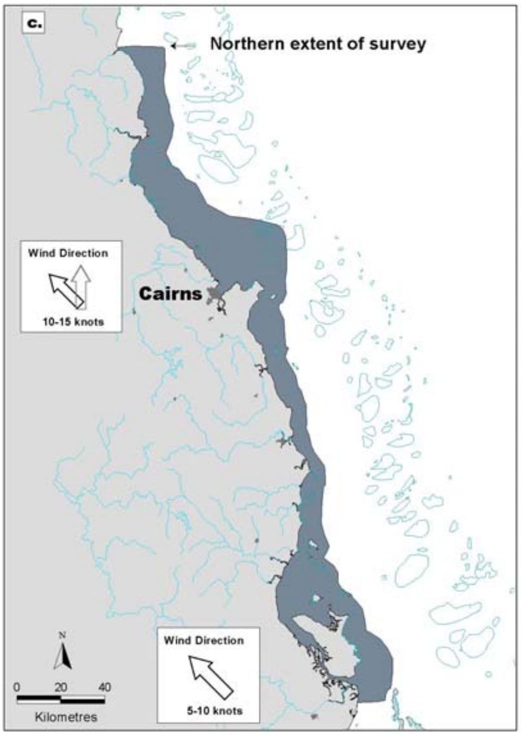


Figure 17: Flood plume associated with Cyclone Ethel, 1996

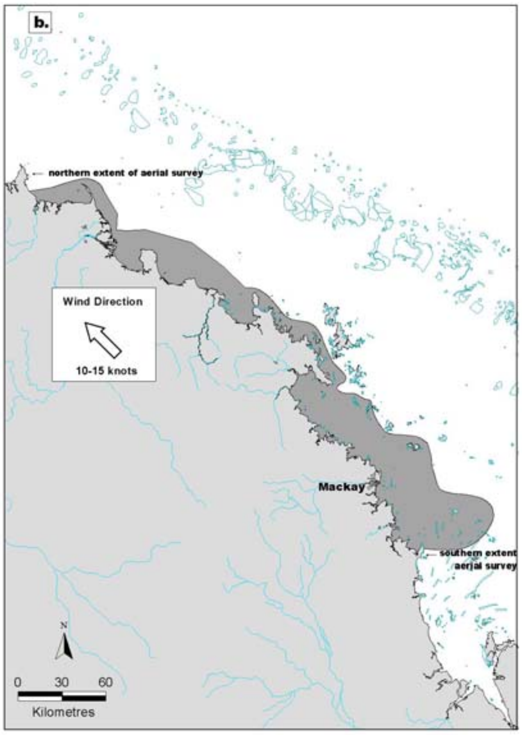


Figure 18: Flood plume associated with Cyclone Justin, 4th March 1997 – Southern Rivers

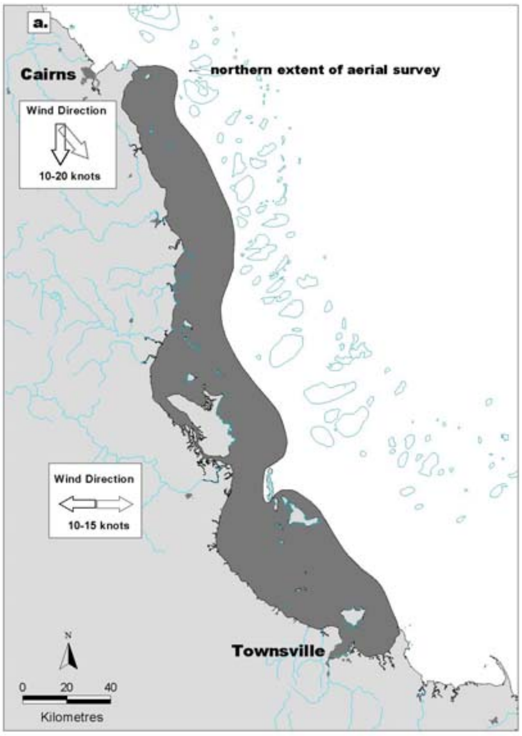


Figure 19: Flood plume associated with Cyclone Justin, 25th March, 1997, Wet Tropics River

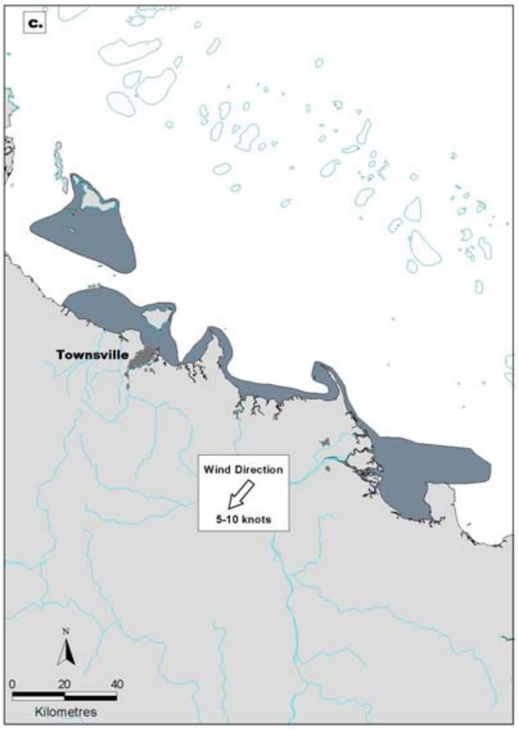


Figure 20: Flood plume associated with Cyclone Sid, 23rd January 1998, Burdekin River

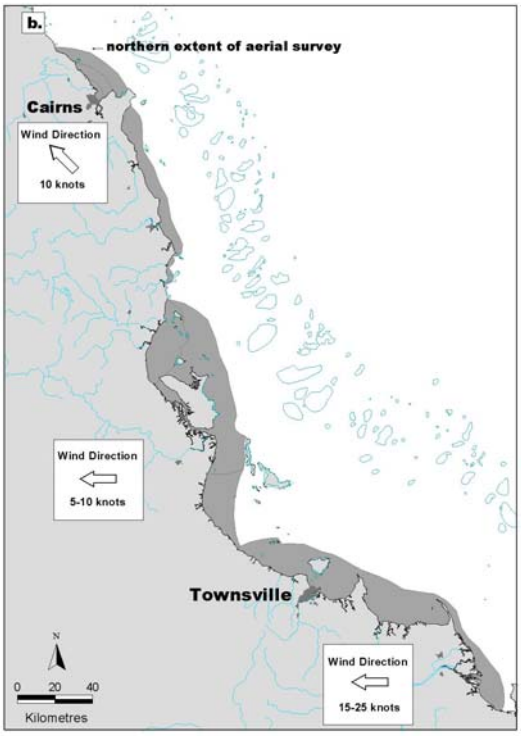


Figure 21: Flood plume associated with Cyclone Sid from Wet Tropics and Burdekin River

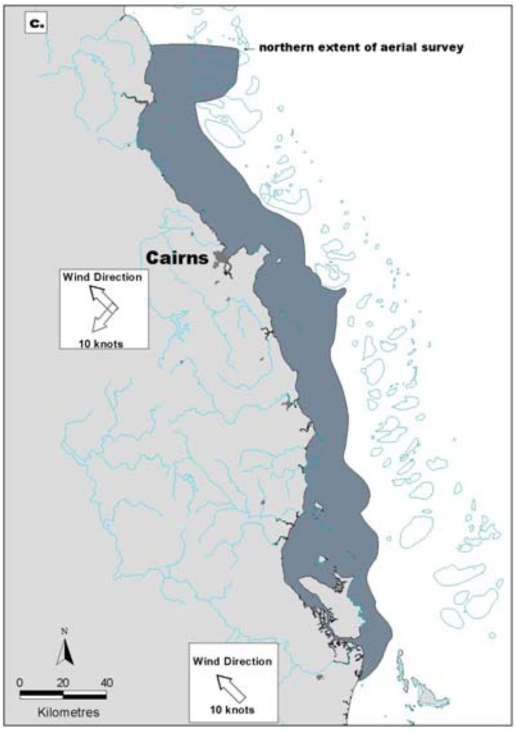


Figure 22: Flood plume associated with Cyclone Rona, 14th February, 1999

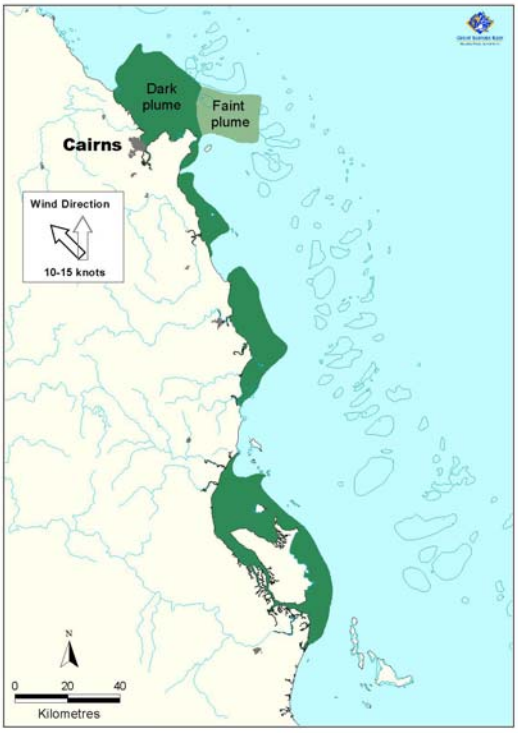


Figure 23: Flood plume associated with Cyclone Steve, 2000

3.3.2 Preliminary assessment of risk area for GBR

Areas with a high occurrence of buoyant plumes are identified by the darker colours, with gradients of colour identifying areas with limited occurrences of buoyant plumes (Figure 24). This two dimensional map is a first step in defining areas most likely to experience plume waters. It is important to note that the areas of influence are limited to GBR waters south of Cooktown as plume waters were not mapped north of Cooktown.

Plumes most commonly extend into the GBR lagoon to a distance of about 20km perpendicular to the coastline i.e.: over the inner shelf. Plume inundation most commonly occurs in the inner shelf of the Wet Tropic Region, including areas that lie between Townsville and Cairns. Wet Tropics Rivers that flow into this area experience flooding conditions at least once or twice a year, leading to the increased formation of plumes in this coastal area.

Of the nine plumes mapped in the present study, only two (Joy and Sadie) spread significantly beyond this distance onto the mid-shelf region and thus may have had direct effects on these reefs. In contrast to other mid- shelf reefs, Green Island Reef, off Cairns, was covered by plume water in 5 occasions of the 6 plumes, which occurred in the Wet Tropics during this study. This high frequency appears due to the steering effect of Cape Grafton. Plume water from the Johnstone and Russell-Mulgrave Rivers moving north is steered offshore by the prominent Cape Grafton (Wolanski, 1994). The plume then intersects and covers Green Island Reef and frequently parts of Arlington, Upolu, Oyster and Vlassof Reefs as well. These reefs are the only mid-shelf reefs in central and southern GBR observed in this study to regularly and directly experience river influence. Figure 24 presents the selected study area between Barron and Russell-Mulgrave area.

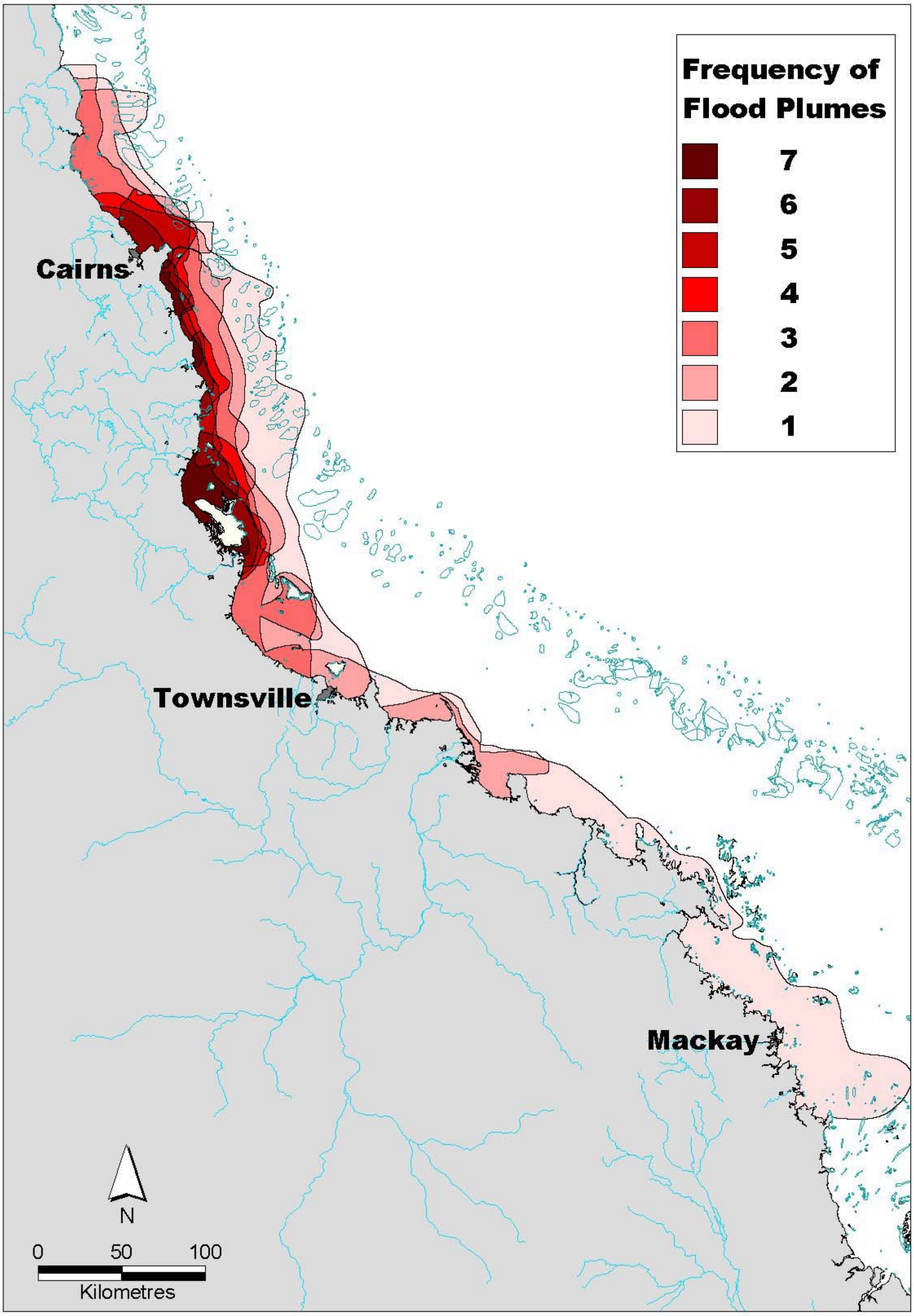


Figure 24: Frequency of plume formation from 1991 - 2000

3.3.3. Hindcasting of plume distribution based on current knowledge of plume extent and shape

Data sources

Historical records of river flow was obtained from Department of Natural Resources. Data was extracted from the historical river discharge from Myola and wind data available from Cairns Airport. Records of wind data for Cairns commenced in May 1941, therefore, the hindcasting analysis commenced with first event with >30 000 ML day^{-1} in the Barron River, which is in February 1943.

Flow (rainfall)

Observations demonstrated that flood plumes from the Barron River could be visually apparent with discharges in the order of 30 000 to 40 000 ML day^{-1} (data for Myola gauging station). Based on this information a figure of 30 000ML day^{-1} was assigned to historical flow data as a primary variable that needed to be exceeded for a plume to develop. Each incidence of flow greater than established threshold (30,000 ML day^{-1}) was examined to see if factors corresponded to the required conditions for the formation of the six plume distributions. Extreme flow of greater than 100, 000 ML day^{-1} was noted as producing greater extent of plume inundation.

Period of discharge

Variables observed during the study period were indicative of either wet or dry tropic rivers. Generally wet tropic rivers had flow events exceeding the peak flow (30,000) lasting 2 to 5 days. In contrast, the dry tropics rivers experience high flow events lasting days to week. The events observed in the Wet Tropics Rivers differed by either being very short and sharp (< 2 days) or prolonged (> 3days)

Wind speed

Wind speed factors include cyclonic (>50 knots), or trades (10 – 30 knots) or light (<10knots).

Wind direction

The prevailing wind situation for the monsoonal year tends to be south –southeasterlies, constraining plume extents to the coast. Rarely winds are reported as north/north east which, as reported for Cyclone Sadie, can push plume waters offshore.

Plume extents

An empirical model was constructed using the physical parameters measured during the plume (Table 4). Spatial extents within the study area were correlated with six qualitative fields of plume distribution: inner1, inner2, inner-mid, mid, mid-outer, and outer (Figure 25). Characteristics of flow and wind conditions that determine the extent and distribution of plume waters are presented for each qualitative field.

Variables used in the model to estimate the qualitative spatial extent of plumes and hindcast the frequency of plume inundation over the last 60 years were river flow (Department of Natural Resources), wind direction and wind speed (Australian Bureau of Meteorology). Based on information from the Barron and Russell-Mulgrave Rivers for the last 10 years, and correlated with known plume distributions, a figure of 30,000MLd^{-1} for flow was calculated as a primary variable that needs to be exceeded for a significant plume to develop. Wind conditions determined the direction of the plume water. Records of wind data for Cairns commenced in May 1941, therefore, the hindcasting analysis commenced with first event with >30,000MLd^{-1} in the Barron River, which is in February 1943. Based on the information from the known plume distributions (1991 – 2000), flow rates of greater than 30,000ML.d^{-1} result in a visible plume in the study area. Flow rates for the last 60 years that exceeded this daily rate were used in the modelling of spatial extent for the study area. The application of the model in defining the type of plume is illustrated in Figure 27. Hindcast modelling of weather conditions and flow rates over the last 60 years for the Barron and Russell-Mulgrave river catchment consequently shows the number of times a certain distribution has been experienced in this area.

The six fields were combined to give an approximate coverage for only three extent types, inner, mid and outer plumes. Figure 26 distinguishes these three different plume fields for the study area, including inner, mid and outer plume distributions.

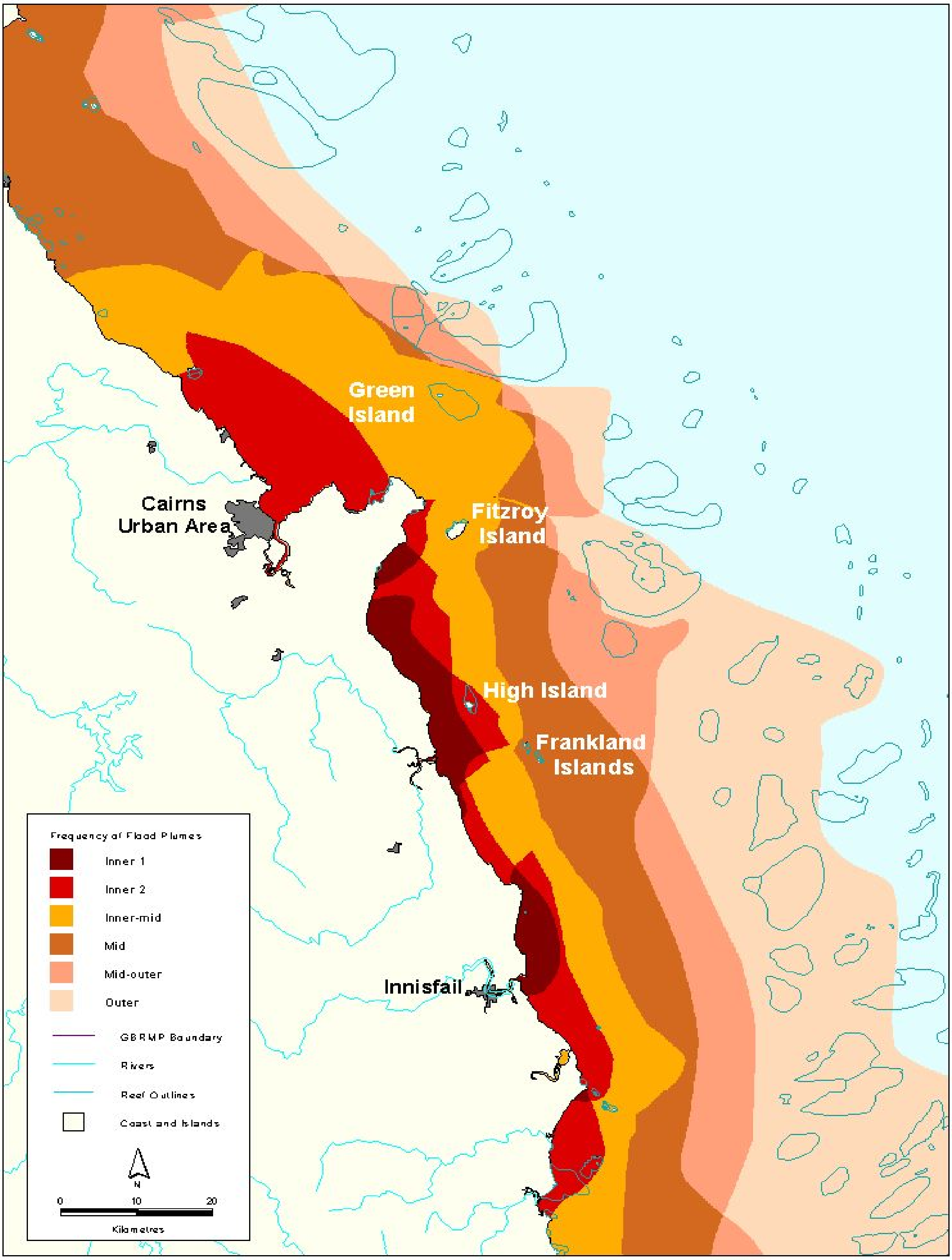


Figure 25: Plume distribution for the Wet Tropics area, between and including Johnstone and Barron Rivers

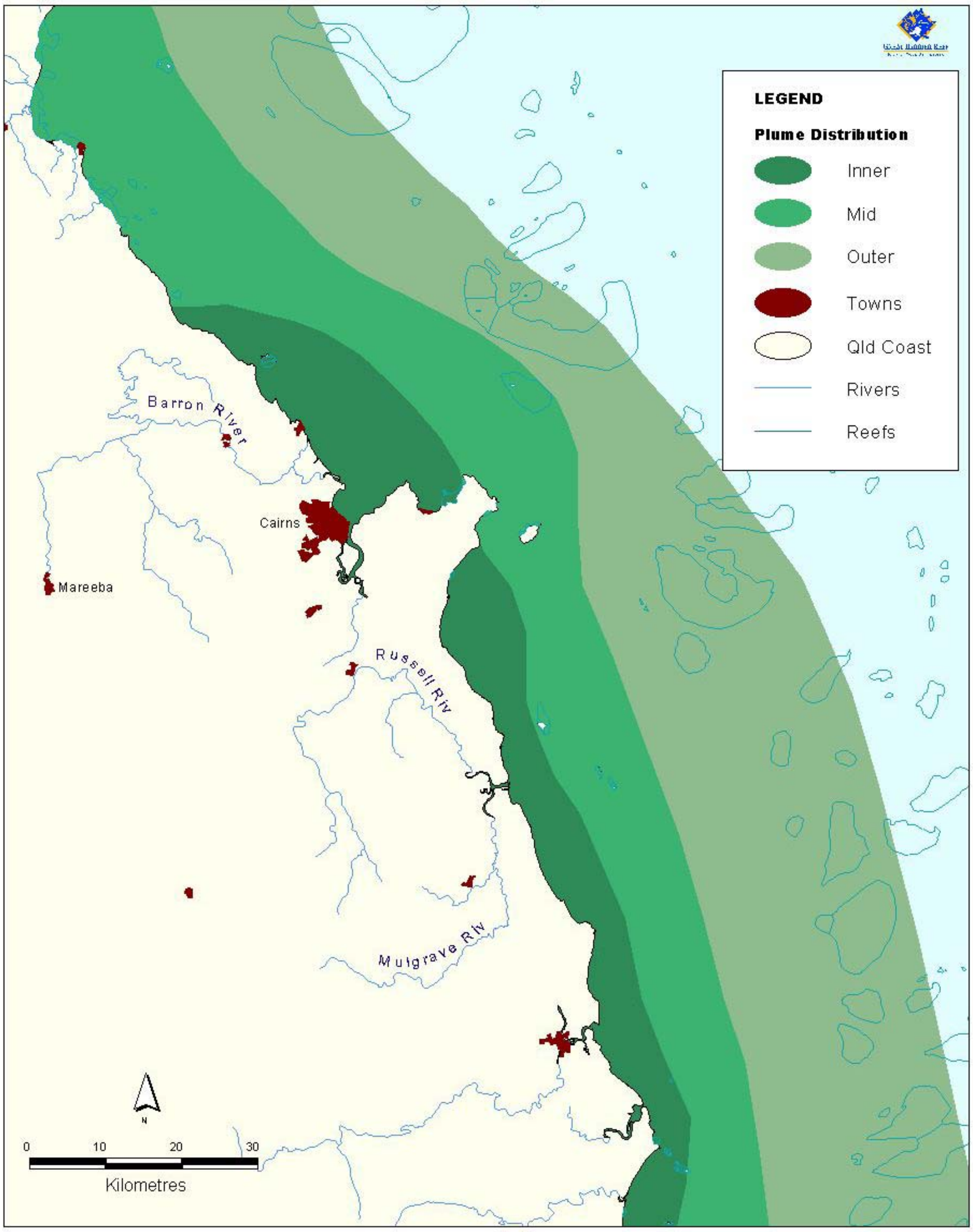


Figure 26: Integrated plume distributions for study area between Barron River and Russell-Mulgrave rivers. (Classes of plumes were combined to give an approximate coverage for three types of plume extents, inner, mid and outer)

Table 4: Idealised plume distribution based on the observed events 1994 – 1999 for the Barron and Russell-Mulgrave River section.

Types of Plume Distribution	**Observed Plume**	**Wind Direction (8pt)**	**Wind Speed (knots)**	**Flow rate (ML/d)**
Inner	Violet Sid/Katrina	Independent	10 or less	>30 000 for 1- 2 day
Inner	Un-named March 1997	S - SE	<12	> 30 000 for 3 consecutive days
Inner - Mid	Ethel	S – SE	>12	> 30 000 for 3 consecutive days
Mid	Justin	NW - N	≥10	> 30 000 for 2 consecutive days
Mid - Outer	Rona	SE - NE	¬10	> 30 000 for 4 consecutive days
Outer	Sadie	NW - NE	≥10	> 30 000 for 2 consecutive days

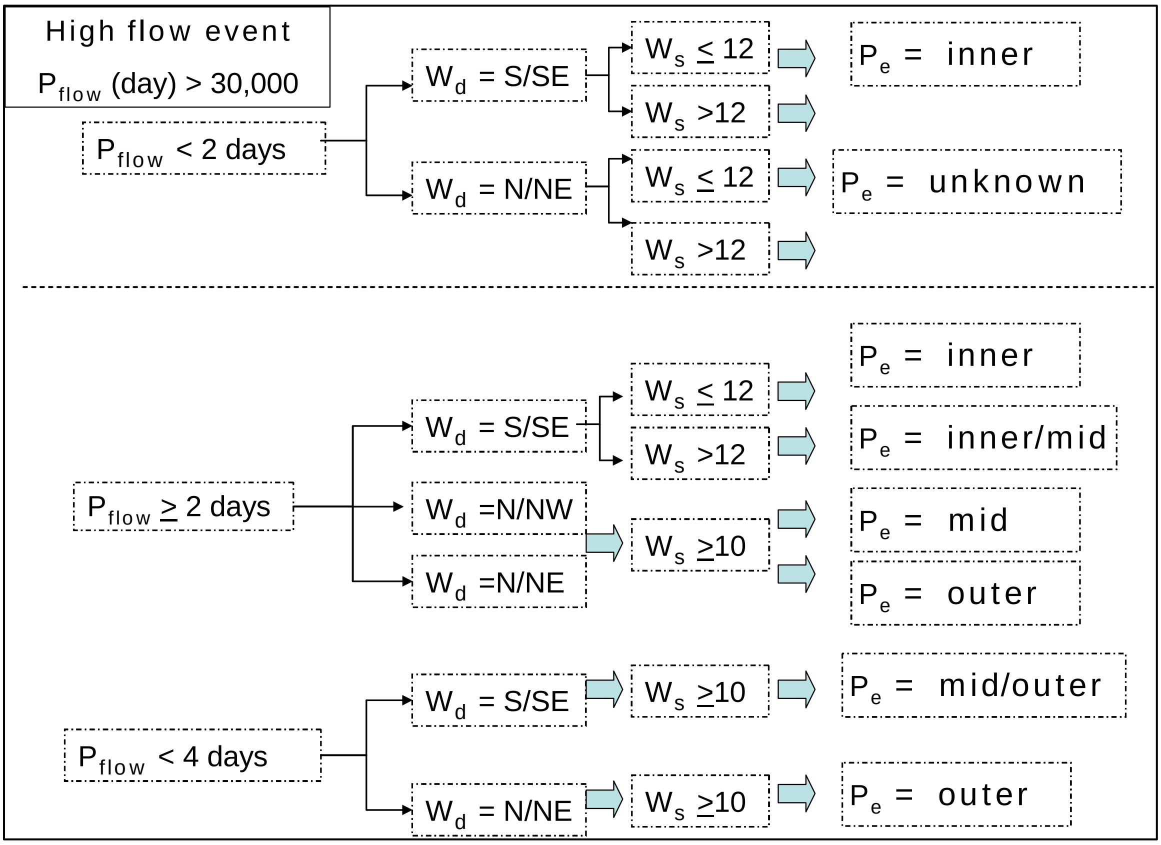


Figure 27: Conceptual model of plume movement in response to variable weather conditions

Characteristics of model

The "hindcast" plume extent for each flood event of the last 70 years ,was calculated as follows.

Where R_f > P_{flow} then

P (fl) = Σ [W_d + W_s + R_f]……………………. *Equation 1*

P(fl) represent the plume extent on any given flood event. W_d is the wind direction, W_s is the average wind strength, and R_f is river flow and strength,

Event 31/01/94 – 01/02/94

$W_{d:}$ [North/north eastt - (W_d = 6)

$W_{s:}$ [light (<10knots)] - (W_s = 1)

$R_{f:}$ [31/01/94 = 46905ML /day and 01/02/94= 30296 ML/ day] – ($R_{f:}$ = 1)

=OUTER PLUME DISTRIBUTION

The wind and discharge data was integrated with the mapped plume extents to develop a matrix that produces set criteria for a predicted plume distribution based on similar historical conditions. The determination of flood plume extent into 3 observed categories (inner, mid and outer) are 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 measured between 1994 - 1999.

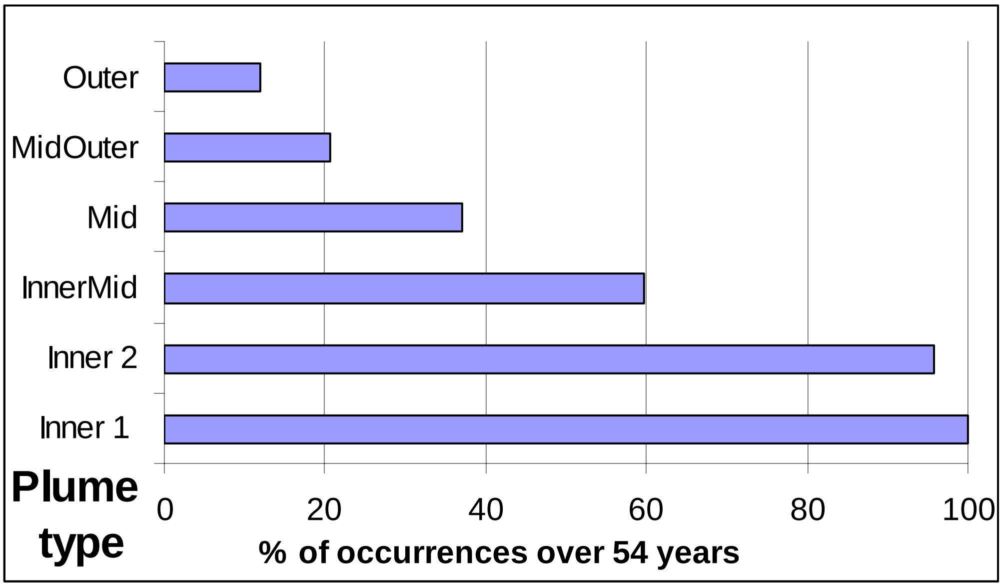
Figure 28 provides a summary of the events that have exceeded the river discharge criteria with estimates of plume extent ascribed based on the predicted distributions (defined in d and flow rate) are reported for the 6 types of plume distribution.

The hindcasted plumes provide a preliminary estimate of how frequently plumes extend to a particular area of the GBR. For example, 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.

Based on this data for the study area it is estimated that in the past 58 years, the Wet Tropics region experienced inner shelf plume waters on a very frequent basis, i.e. 1- 2 times per year. Plumes reached the inner category (as defined in Figure 2) 92 times, the inner-mid 52 times, the mid 34 times, the mid-outer 19 times and the outer 11 times.

This basic empirical modelling shows the potential to hindcast plume occurrence over a small area of the GBR. This type of information can be included into a more detailed risk analysis, where hindcasting from known spatial plume distributions and historical weather conditions can create a more detailed risk area within the whole of the GBR.

Figure 28: Predicted plume distribution based on the flow rates and wind data for the Barron River section for the period 1943 to 1999. Extreme events can not be predicted by the model as those series of variables have not been measured over the study period**.**



3.4 *Discussion*

3.4.1 Plume extent and direction

On the basis of river flow analysis (Figure 10) the 9 years of this study are thought to be representative of the types and frequency of flooding into the GBR. Figures 18, 19, 20, 22 and 24 show the combined plumes typical of the situation in the Wet Tropics (Herbert, Tully, Johnstone, Russell-Mulgrave, Barron and Daintree Rivers) and Plane Creek / Pioneer / O'Connell / Proserpine Rivers area. The importance of wind and wind direction as a factor in the distribution of a flood plume is established in addition to a number of other primary factors such as river flow rates and catchment rainfall, which can impact on plume extent and coverage

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. Under relatively calm conditions such as those following Sadie, light offshore winds pushed the plume 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 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 extreme flow conditions 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 (Devlin et al., 1997; Taylor and Devlin, 1997). The plume may have been more extensive had the rainfall been sustained in the upper catchments of the Wet Tropics Rivers.

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. Headland steering of low salinity water has been previously reported off Cape Kimberly by Ayukai *et al*., (1997).

The area of the shelf covered by plume water and its spatial distribution pattern is governed by river discharge volume, coriolis forcing and wind stress. In the absence of wind stress, plumes move in a northerly direction from the river mouth. In times of low wind stress the plumes also spread well offshore and can reach beyond the main barrier reefs on the outer shelf into the Coral Sea, such as Cyclone Sadie.

In periods of stronger winds, wind stress may be a greater forcing function than the Coriolis effect (Wolanski, 1994). If the wind forcing is opposed to the Coriolis effect in direction, i.e.: north or north east winds, the overall plume movement may be to the south, e.g. the Burdekin plume associated with Cyclone Justin (Figure 12). However the most common situation from the data sets presented in this study are when winds are from the southeast. Southeasterly trade winds dominate for most of the year in the GBR and produce a strong northwest longshore movement of inner shelf waters (Wolanski et al., 1981). Under these conditions, wind and Coriolis effect act in the same direction to drive plumes to the north (ie: Figure 10 - 13). In addition, plumes tend to be held closer to the coast in these conditions than in periods of light winds or north/north-east winds (Figure 13). These observations are in agreement with the modelling studies on the Burdekin plume of King *et al.*, (1997, 2001, 2002), which also show the northern movement, and coastal nature of the plume.

3.4.2 Plume frequency

Plume distributions measured in this study illustrate a number of different distributions in relation to variable weather conditions. 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, and wind strength and direction. The greater number of plumes mapped over this study (Cyclones Violet, Ethel, Justin, Sid and Rona) were restricted to a shallow nearshore northward band by strong south-easterly winds. However, under relatively calm conditions such as those following Cyclone Sadie, light offshore winds pushed the plume 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 from the Fitzroy River influenced by light northerly winds late in the event also moved offshore, eventually impinging on Capricorn Island group reefs.

Overlaying the extent of all measured plume demonstrates that some reefs in the GBR experience river waters annually, some episodically, some rarely and some never at all. Flood plumes evolve over time in response to a number of factors, however the frequency with which inner shelf ecosystem experiences plume water is linked intrinsically to the flow regime and hydrology of the adjacent catchment. The frequency observed is a direct function of prolonged, high intensity rainfall frequency on the adjacent coast, which corresponds to flow. Plumes occur in inner shelf waters of the Wet Tropics coast (Herbert to Daintree Rivers) at least annually and often twice a year. Flow rates for the Tully River detailed annual flow conditions sufficient to drive a buoyant plume into GBR waters at least once, and usually a number of times per year. Plumes occur in inner shelf waters from Mackay to the northern Whitsundays (Pioneer to Proserpine Rivers) approximately once very two years while the Burdekin River produces a significant plume approximately 3 – 4 year intervals and the Fitzroy River on average at 10-year interval. The intervals for the Cape York Rivers is thought to be every 3 – 4 years but plumes in this area have not been studied by changes in river and plume water composition.

Most flood plumes in the GBR spread to the north of the river mouth for distances of up to 200km, but not more than approximately 20 km from the coast. Material from the plume will, initially be deposited within this zone either directly as particulate material from the river, or, if dissolved, eventually as organic particulate matter after uptake into biological organisms. Other studies (Johns *et al*., 1994; Brady *et al*., 1994; Risk *et al*., 1994; Gagan *et al*., 1987) have shown this evidence of terrestrial material in benthic sediments in a band along the coast on the inner shelf. In addition, Haynes *et al.,* (2000a, 2000b) showed residues of pesticides in intertidal and subtidal sediments, primarily in a band close to the coast and adjacent to those catchments with a history of use of the particular pesticide.

3.4.3 Hindcasting of plume distribution

Hindcasting plume behaviour based on historical weather conditions allows an estimate of the frequency of plume inundation and movement in the GBR lagoon. Using current knowledge on factors that control plume extent between the 1991 and 1999 period, we can correlate weather variables over the last 90 years with predicted spatial extents of plumes. Formulation of expected plume distributions, over a longer time period than individual observations, allows for the identification of reefs that have been subjected to plumes and an estimate as to the frequency of impact over a longer time period than the current study for one area of the GBR

Spatial distribution of the frequency of plume coverage delineates the inshore area of the GBR that is annually inundated by flood plume waters. From this information, an assessment of the area of risk from river runoff has been developed. Inshore reefs and seagrass beds within this high frequency area and adjacent to agricultural catchments, are seen to be at the highest risk from catchment activities. 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.

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Chapter 4: Transport and transformation of dissolved and particulate matter in flood plumes of the Great Barrier Reef

Chapter 4: Transport and transformation of dissolved and particulate matter in flood plumes of the Great Barrier Reef

4.1 Introduction

The distribution of flood plume waters in the GBR has been studied opportunistically over the last 30 years in some detail but observations of river water in the GBR lagoon have been noted and documented at many times earlier in the 20th century. For example low salinity water was recorded at Low Isles (16 km offshore) during the 1928/29 British Museum Great Barrier Reef Expedition coinciding with flooding in the adjacent Barron and Daintree Rivers (Orr, 1933). The effects of low salinity water on the reefs of the Whitsundays, associated with major cyclones near Mackay in 1918 were reported by Hedley (1925) and Rainford (1925). In the 1960s low salinity water was noted in the wet season well offshore in the Cairns area (Pearson and Garrett, 1978). Davies and Hughes (1983) noted terrigenous sedimentation in 1982 at Boulder Reef (15 km offshore) associated with flooding in the Endeavour River. Wolanski and associates led a period of more detailed study of flood plumes in the 1978 – 1983 period focussed on the Burdekin River. Plumes were tracked using salinity measurements in both the 1979 (Wolanski and Jones, 1981) and 1981 Burdekin floods (Wolanski and van Senden, 1983). Burdekin plume water was shown to move north from the river mouth and was detectable up to 300 km from the mouth (Wolanski and van Senden, 1983). Plume water distribution was governed by geostrophic forces – particularly the wind regime and Coriolis effect (Wolanski, 1994).

The effects of the 1991 Fitzroy River flood on reefs impacted by the river plume were dramatic. Low salinity, high suspended solids and nutrient-rich water surrounded reefs of the Keppel Islands group (20 km offshore) for a period of three weeks (Brodie and Mitchell, 1992; O'Neill et al., 1992) and reached the northern reefs of the Capricorn-Bunker group (75 km offshore) for a few days (Devlin *et al*., 2001). Coral mortality in the Keppels was high (van Woesik *et al*., 1995) with some mortality in the Capricorn-Bunkers (Devlin *et al*., 2001). In the same cyclonic rainfall the Burdekin River plume was detected 30 km off Townsville (100km from the river mouth) with a frontal area of high productivity and larval fish abundance (McKinnon and Thorrold, 1993; Thorrold and McKinnon, 1995). Low salinity water containing elevated nutrient concentrations have also been recorded during long-term biological oceanographic studies of the GBR lagoon (Brodie and Furnas, 1996). In recent studies the increase in suspended sediments discharged from the Burdekin River due to the effects of beef grazing on the catchment has been measured. Elevated barium concentrations in corals from reefs almost 200 km from the river mouth were used as a signal for increased sediment discharge (McCulloch *et al*., 2003). Studies of the evolution and dynamics of the Herbert River flood plume using an airborne salinity mapper have shown how the plume developed in response to tidal currents, the wind and boundary current forcing (Burrage *et al*., 2002). Modelling of river plumes from the Burdekin, Herbert, Tully and Johnstone Rivers has recently shown how inner-shelf reefs in this area are exposed to low salinity water on a regular basis (King *et al*., 2002).

Following the 1991 Fitzroy flood, a more formal investigation of flood plumes in the GBR lagoon was instituted (Steven *et al*., 1996; Devlin *et al*., 2001) with the objective of mapping the spatial limits of the influence of river water, quantifying the concentrations of key parameters in plume water at various times in the life of the plume and determining the fate of materials discharged from the rivers. Results reported in this thesis focus on the spatial extent of plumes in the period 1991 – 2000 and the processes which occur in the plumes. The results are compared to evidence from benthic sediment chemical composition and isotope signatures in corals and sediments to confirm the spatial extent of direct terrestrial runoff influence in the GBR.

Rivers discharging into the GBR lagoon are one of the main mechanisms for inputting new sources of nutrients and sediments into the reef, though the actual distribution and movement of the individual constituents varies considerably between the wet and dry tropic rivers. Wet Tropic Rivers have limited freshwater and saline mixing in the dry season with little input into the GBR and high freshwater flow in the wet season with rapid flushing times. The consequence of this is predominately freshwater flow to the mouth of the river, where the riverine waters discharged over and into the adjacent coastal seawater. Dry Tropics Rivers have negligible or no flow during the dry season and can act as tidal bay with tidal intrusions from the seawater end.. Flood plumes move in response to prevailing weather conditions over the coastal shelf with the plume waters acting as an estuary itself with mixing processes from the freshwater end (mouth of the river) to the seawater end (end of plume). Constituents act differently within the plume water. For some constituents the plume water is a simple mixing interface between the rivers and the lagoon. For others, the river and the corresponding plume acts as an open end system in which biological and chemical removal takes place, substantially reducing the amount of constituent that reaches the reef (Loder and Reichard, 1981; Dagg *et al*., 2004). Cycling processes within plumes for different constituents are markedly different and hence plume cycling can not only change total nutrient loads but also modify ratios of one nutrient to another, which holds implications for the biological responses to plume waters. A major tool which has been used to study the mixing processes in estuaries is the mixing plot in which a known chemically conservative property, generally salinity, is plotted against the constituent of interest (Loder and Reichard, 1981). If the plotted data fall on a straight line, the constituent is said to mix conservatively. If the curved line results, then either several water masses with different constituent concentrations are mixing or an internal source or sink is present. Processes occurring in addition to mixing i.e. non-conservative behaviour can include, the biological uptake from dissolved to a particulate stage, sedimentation of particulate matter and the mineralisation or desorption of particulate to dissolved species (Dagg *et al*., 2004). In this chapter, these standard estuarine techniques are used to further examine the processes occurring in the flood plume.

4.3 Methodology

4.3.1 Sampling design

Flood plumes vary in extent and distribution (Devlin *et al*., 2001), and promotes the need for a flexible sampling design to account for plume timing, structure and duration. The sampling strategy targeted the extent and duration of the associated flow event with time and location of sampling dependent on which rivers were flooding and the areal extent of the plume. Once the general area and location of plume extent was decided, 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.

Nine plume events were sampled over the extent of this study from 1991 to 2001. Sampling usually took place over one to three days, with the exception of Cyclone Ethel in 1996 which had repeated sampling over a 13 day period, Cyclone Sid in 1998 which had repeated sampling over 10 days and Cyclone Steve which had repeated sampling for 24 days. Details of sampling and timings are shown in Table 6. Surface water samples were taken in cyclonic flood plumes over a period of three to five days. The objective was to sample 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.

All data collected over a single event was presented for Violet and Justin as representative of the type of data collected over each plume event. Data is then presented as independent constituent behaviour for each parameter listed in Table 5.

4.3.2 Analytical Methods

Dissolved and particulate nutrients, suspended particulate matter and chlorophyll were measured throughout all plume samples. Acronyms and measurement units for each parameter are described in Table 5. 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.

Not all parameters were measured in all plumes, due to laboratory or sampling error, or time constraints. The full range of analyses and the parameters measured in the plumes are presented in Table 7.

Table 5: Acronyms and symbols for nutrient and other water quality parameters collected in the plume waters.

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	μM (μmol/litre)
DON	Dissolved Organic Nitrogen	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	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)
SPM	Suspended Particulate Matter	mg L^{-1} (mg/litre)
S	Salinity	psu = ‰ = g L^{-1}

Table 6: Details of water sampling for each plume event.

Year	Cyclone	Duration of flooding	Major flooding rivers	Wind Speed[2] (knots)	Wind direction	Sampling areas	Sampling dates	Additional comments
1991	Joy		Fitzroy Burdekin	<5	NW-NE	Inshore and offshore Fitzroy R.	17-18/1/1991	
1994	Sadie	30/1/94 – 4/2/94	Wet Tropics[1]	<10 <10	NW-NE NW-NE	(1) Barron mouth-Fitzroy (2) Offshore Herbert–Tully	1/2/94 4/2/94-5/2/94	A transect was sampled from the Brook Islands to the Russell-Mulgrave River with further sampling being concentrated around the Barron River
1995	Violet	25/2/95 – 2/3/95	Wet Tropics	10 <5	SE-SW SE	Wet Tropics (2) Offshore Herbert–Tully	1/3/95-2/3/95 2/3/95	Water sampling of the plume during cyclone Violet was pre-planned and undertaken as co-ordinated effort between a number of agencies. Water samples were collected within and adjacent to five rivers at 33 stations on 1 and 2 March 1995
1996	Ethel	5/3/96-10/3/96	Wet Tropics	10-15 5-10	S-SE SE	(1)Barron mouth-Green Is. (2)Daintree mouth – Snapper (3)Tully-Herbert	5/3/96-6/3/96 7/3/96 18/3/96	Sites were opportunistically sampled transects within the Ethel plume from south of Cairns to north of the Daintree River.
1997	Justin 1		Pioneer Burdekin	10-15	SE	Burdekin mouth-south of Townsville	4/3/97-5/3/97	Water samples were collected from multiple sites from

Year	Cyclone	Duration of flooding	Major flooding rivers	Wind Speed[2] (knots)	Wind direction	Sampling areas	Sampling dates	Additional comments
1997	Justin 2		Wet Tropics Burdekin	10-20	N-NW	Wet Tropics	24/3/97- 27/1/97	plumes originating from the Herbert, Tully, Johnstone, Russell-Mulgrave and Barron rivers on 2 sampling dates (4 and 25[t] March)
1998	Sid		Wet Tropics Burdekin	10 15-25 5-10 10	SE E NE SE	Wet Tropics Burdekin Magnetic Is. – Pandora Russell-Mulgrave mouth-Franklins reef	13/1/98- 14/1/98 15/1/98- 16/1/98 22/1/98- 23/1/98 27/1/98	Water samples were collected from multiple sites from plumes originating from the Burdekin, Herbert, Tully, Johnstone, Russell-Mulgrave and Barron rivers. 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.
1999	Rona		Wet Tropics	10 10	NE-SE SE	(1) Wet Tropics (2) Offshore Herbert–Tully	16/2/99- 19/2/99	Sampling was undertaken in the plume from the Barron River to south of the Herbert River 16–19 February 1999 . Sampling was initiated in the north adjacent to the Barron River and continued down the coast.

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).

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 (650ºC) and secondary combustion (1050ºC), 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 deionised 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 60ºC. Wet filter salt blanks were subtracted from the resulting weight.

Table 7: Water samples and associated analyses for each plume event

CYCLONE	**Joy**	**Sadie**	**Violet**	**Ethel**	**Justin**	**Sid**	**Rona**	**Steve**
Salinity	Profile	profile	profile	profile	profile	profile	profile	profile
Temperature	Profile	profile	profile	profile	profile	profile	profile	profile
Water samples	Profile	profile	profile	surface	surface	surface	Surface	Surface
Water analyses								
DIN	√	√	√	√	√	√	√	√
DIP	√	√	√	√	√	√	√	√
DON	√	√	√	√	√	√	√	√
PN	√				√	√	√	√
PP	√				√	√	√	√
SPM	√	√	√	√		√	√	√
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.

4.3.3 Data analysis

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.

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 29). 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).

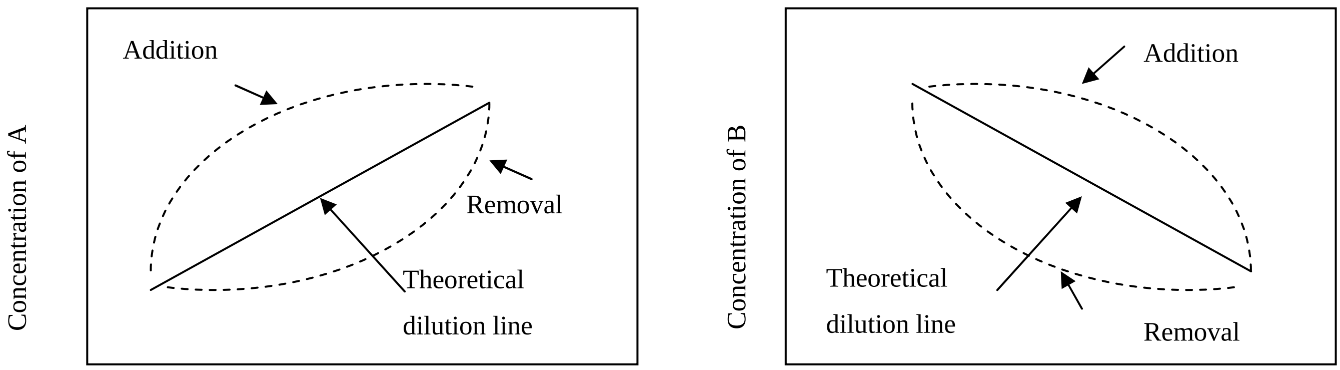


Figure 29: Idealized representation of the relationship between concentrations of a dissolved component and a conservative index of mixing for an estuary where there are single sources of river and seawater. For a component (A) is greater in seawater than in river water and (B) for a component whose concentration is greater in river water than in seawater (Chester 1990).

Variability between events and catchments

Each plume event varies in both space and time. Full sampling strategies are presented for these events only as representative of the different types of events that can occur, including a small wet tropics merged plume (Violet – Figure 32), a mid/outer wet tropics plume (Justin- Figure 34), and dry tropics plume (Joy – Figure 37) associated with Fitzroy River. Sites associated with the Barron, Russell-Mulgrave, Johnstone, Tully-Murray and Herbert plumes are illustrated with plume shape and extent. Mixing curves of the main constituents are presented for each of the catchment areas sampled in the plume.

Constituent behaviour

The behaviour of each constituent was examined by mixing curves for each of the plume events. Events were selected if there were sufficient points along the salinity gradient. Points are differentiated by location of adjacent catchment (Figure 30). Mixing profiles for SPM, NO_x, NH4, DIP, DON, DOP, PN, PP and Chlorophyll *a* are presented in Figure 32 to Figure 36. Selected mixing profiles for individual events are presented for SPM (Figure 39), NO_x (Figure 41), DIP (Figure 46), chlorophyll *a* (Figure 50)

The salinity gradient was divided into four ranges, including 0 to 10, 10 – 20, 20 – 30 and 30 to 35. Constituent concentrations are averaged over each salinity break for all catchments with 95% confidence limits for DIN (Figure 44), DIP (Figure 47), chlorophyll (Figure 49). For DON, DOP (Figure 51), PN and PP (Figure 48), only salinity averaged concentrations are presented due to the limited number of samples taken through the plumes .

Conceptual mixing curves for dissolved and particulate constituents are constructed as a summary of the behaviour of individual constituents over the salinity ranges.

Nutrient ratios

DIN:DIP ratios were also calculated through the plume samples. DIN:DIP ratios can be used as a measure against the Redfield ratio of 16:1 (Redfield, 58). This ratio is derived from the average elemental composition of marine organisms and is the standard ratio used by biologists. The amount of deviation from the Redfield ratio can be used to infer changes in the nutrient present within a water body which is likely to become limiting to algal growth first when nutrient concentrations decline to growth rate limiting concentrations.

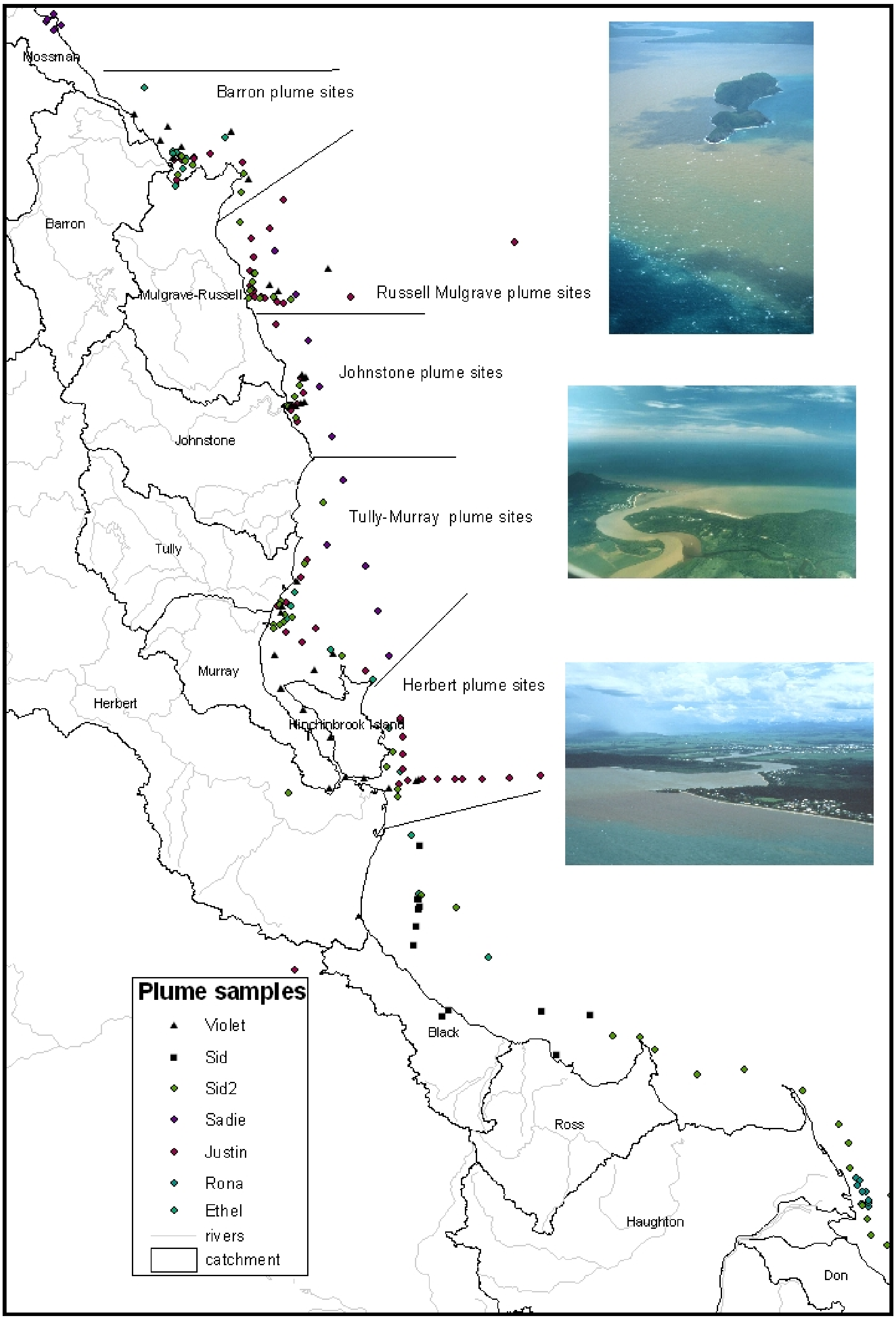


Figure 30: Sampling sites within each plume event.

4.4 Results

4.4.1 Variability between events and catchments

The distribution of dissolved and particulate within the plume is a function of riverine inputs, mixing and biological activity which adds or removes nutrients. Plume extent and sampling sites within the plume are presented for Cyclone Violet, Justin, Sid, Rona and Steve. Mixing graphs for each constituent are presented adjacent to each catchment. Mixing profiles for Barron, Russell-Mulgrave, Tully and Herbert plume waters are reported only for Wet Tropic plumes. Plumes measured in the dry tropics are reported for either the Burdekin or the Fitzroy.

Full sampling events are presented for Violet, Justin (Wet Tropics) and Fitzroy (Figure 31 to Figure 37) which demonstrate the variability of constituent concentrations over the salinity ranges, catchments and events. 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 over one to several days whereas concentrations of dissolved components vary greatly during flooding in the river, e.g. first flush. This would affect the mixing curves.

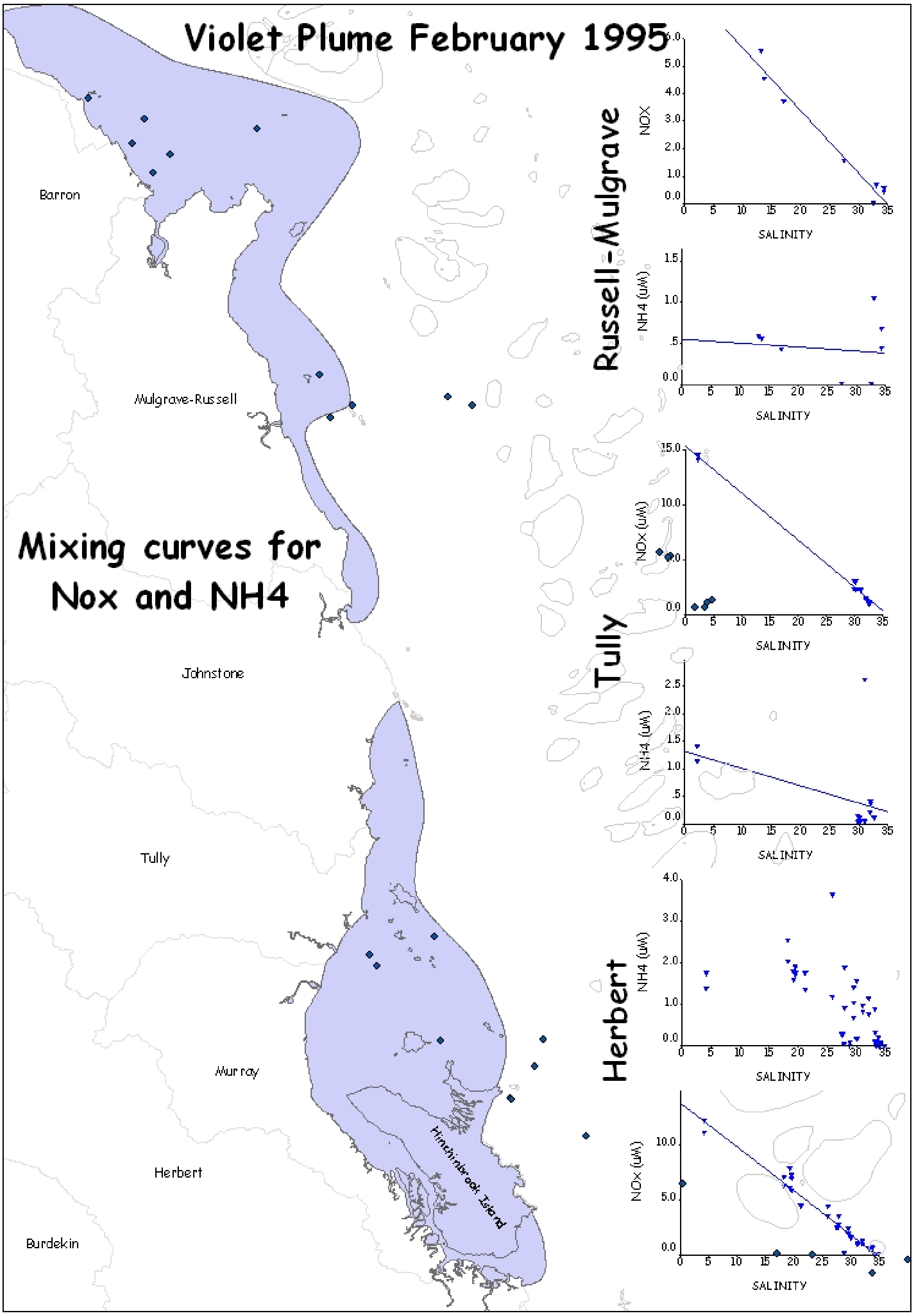


Figure 31: Mixing curves for dissolved nitrogen species for Violet Plume for Wet Tropics catchments. Triangles show nutrient concentrations and diamonds denote sites.

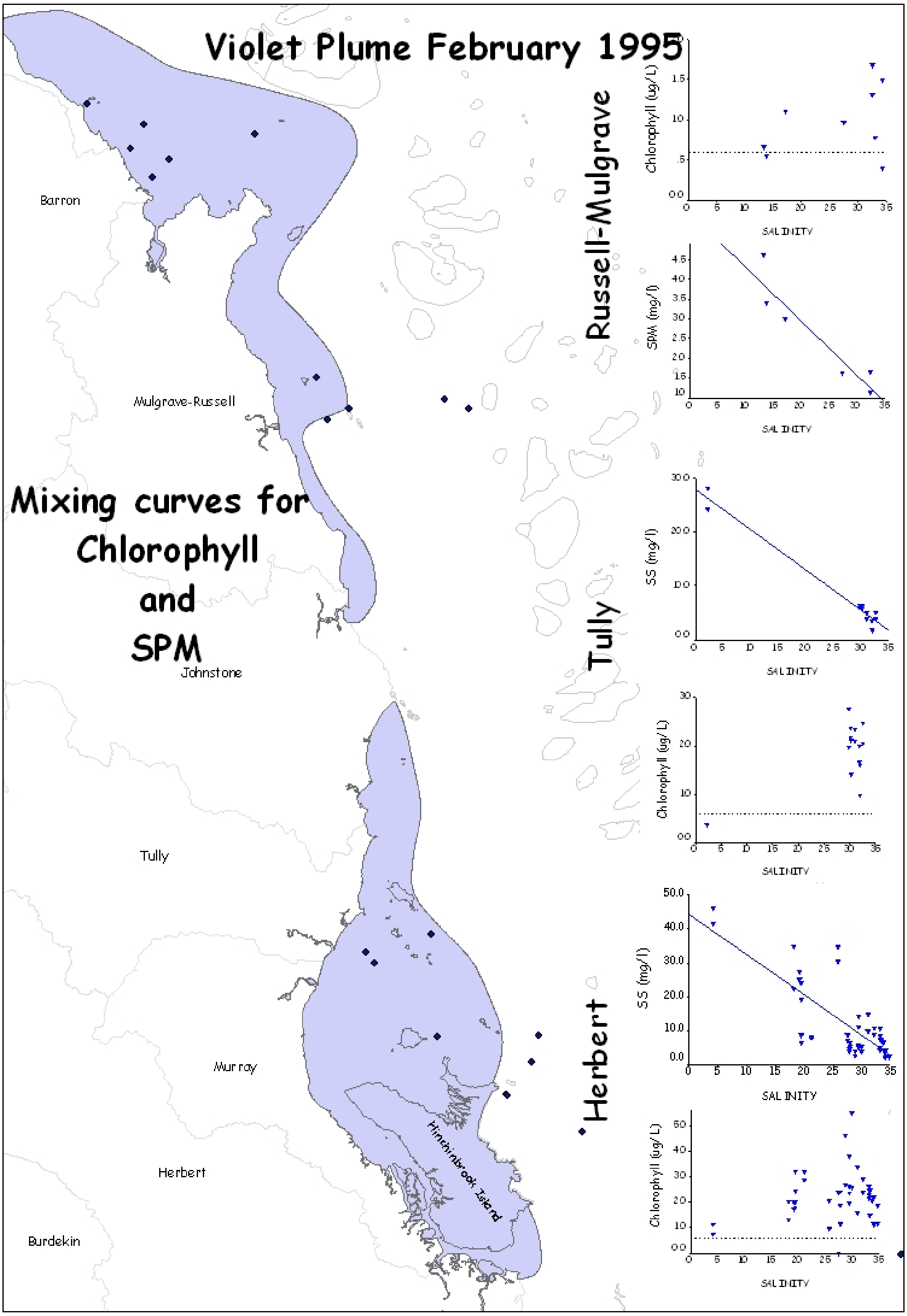


Figure 32: Mixing curves for dissolved nitrogen species for Violet Plume for Wet Tropics catchments

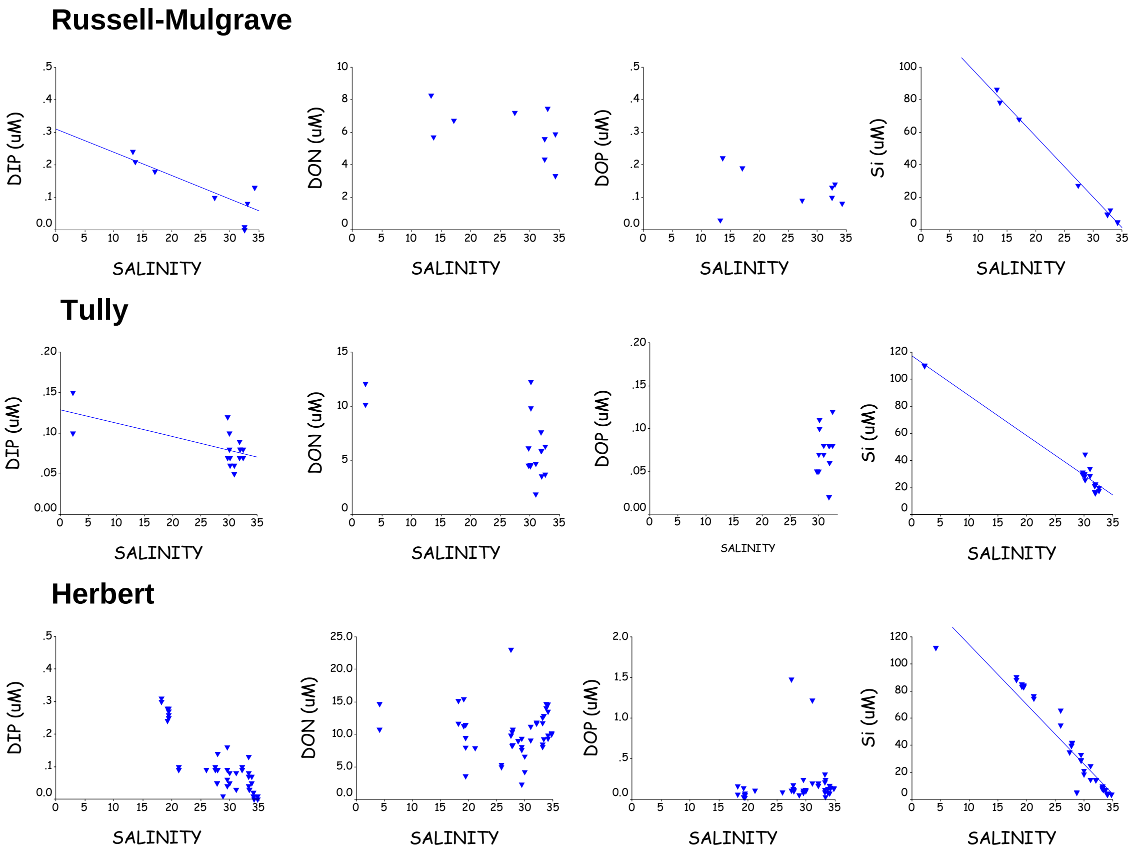


Figure 33: Mixing curves for Cyclone Violet for DIP, DON, DOP and SiO4 for three Wet Tropics catchment

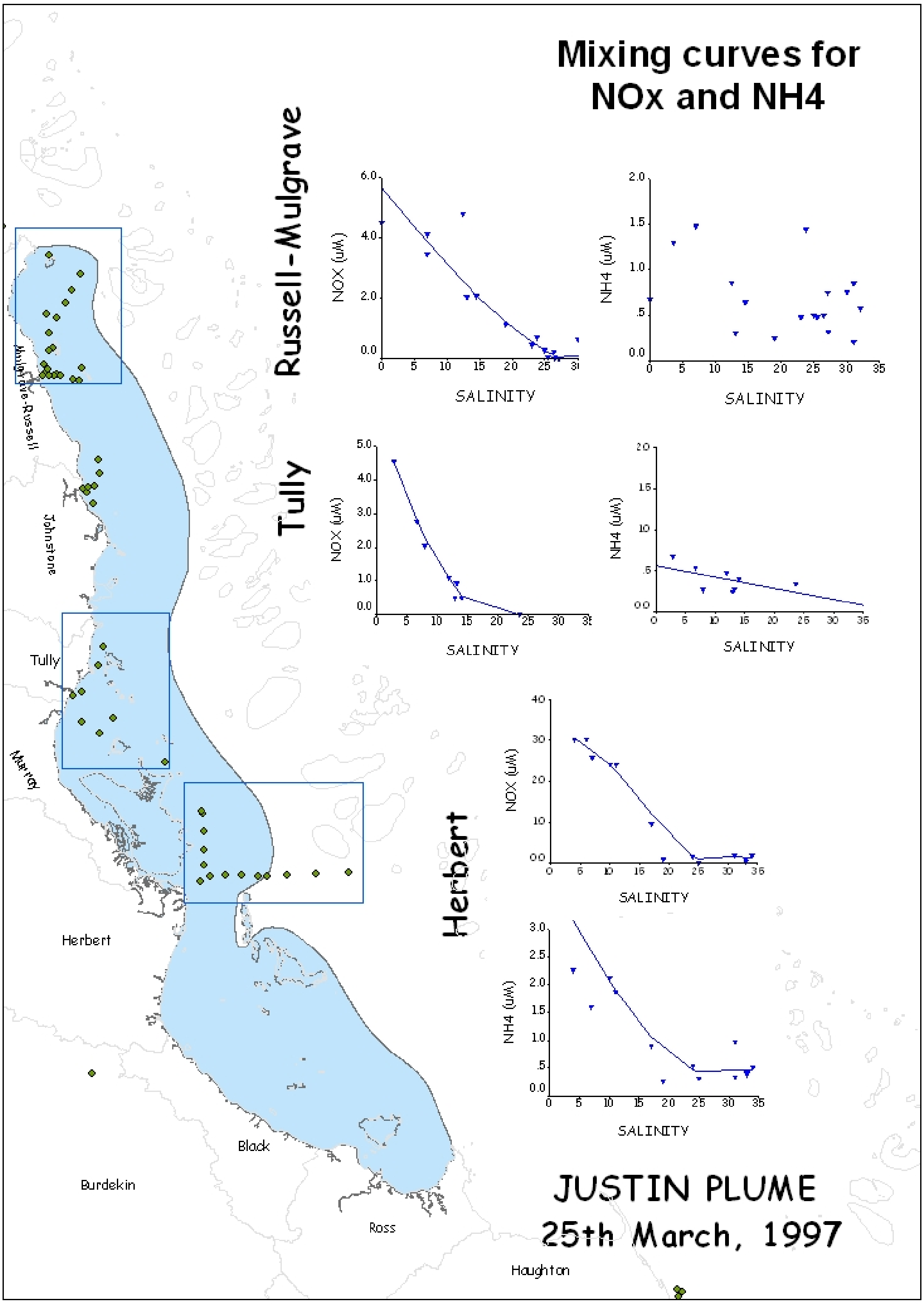


Figure 34: Mixing curves for dissolved nitrogen species for Justin Plume for Wet Tropics catchments

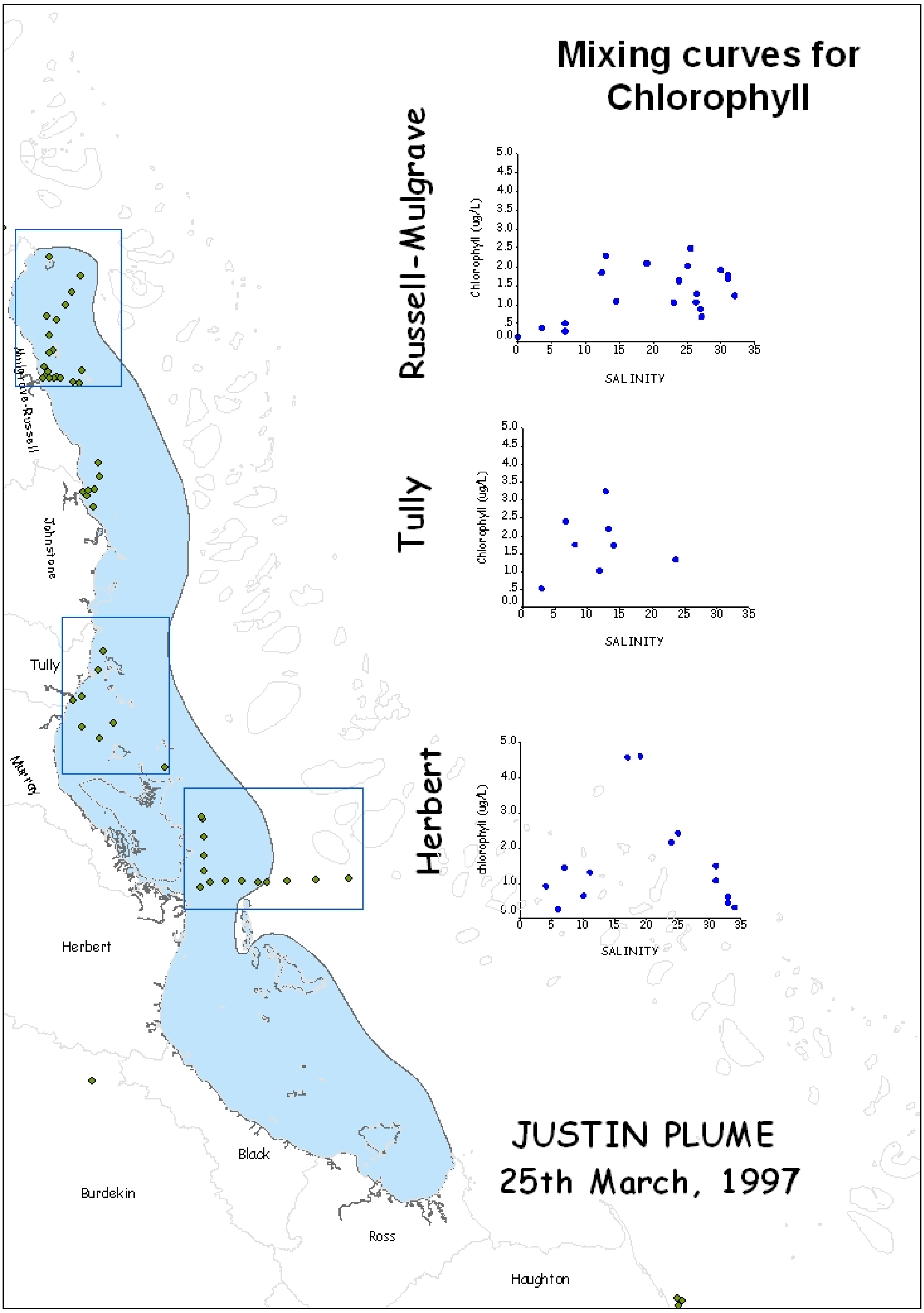


Figure 35: Mixing curves for chlorophyll for Justin Plume for three Wet Tropics catchments

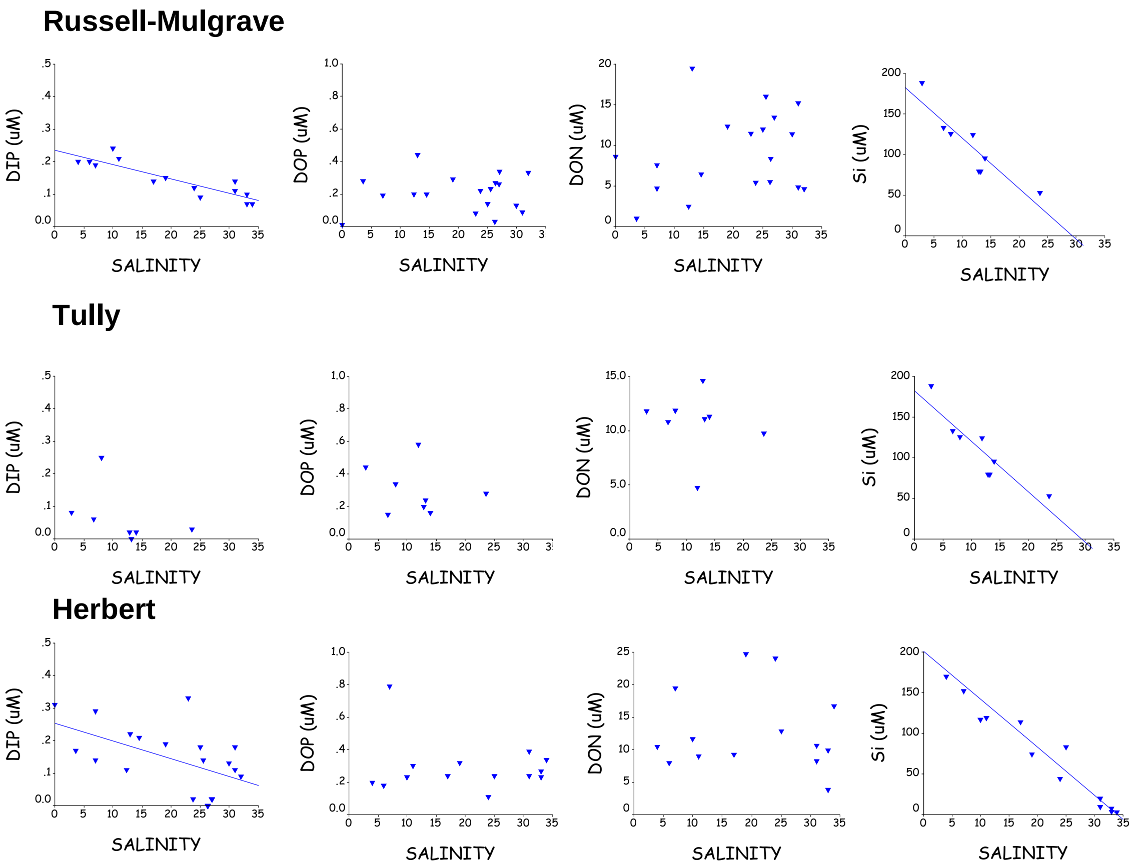


Figure 36: Mixing curves for Cyclone Violet for DIP, DON, DOP and SiO4 for three Wet Tropics catchment

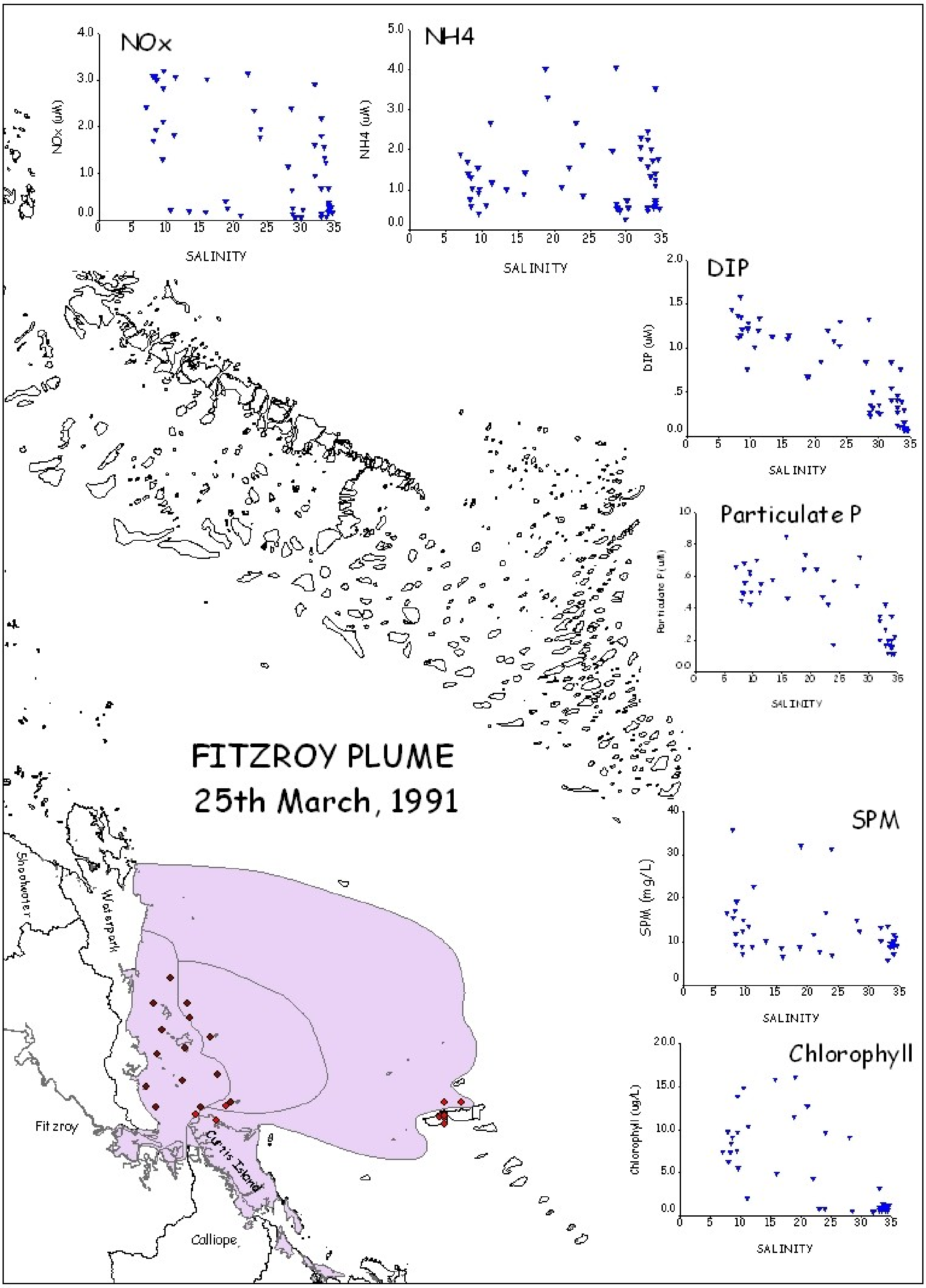


Figure 37: Mixing curves for all constituents in the Fitzroy Plume for a Dry Tropics catchments

4.4.2 Constituent behaviour

Suspended particulate matter (SPM)

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 38) where suspended solid and particulate phosphorus concentrations drop to very low levels close to the river mouth at salinities of less than10. Reductions in the suspended sediment in the lower salinity plumes is shown in other events, though this is (Figure 39) complicated by the resuspension of the plume in strong wind conditions on these occasions.

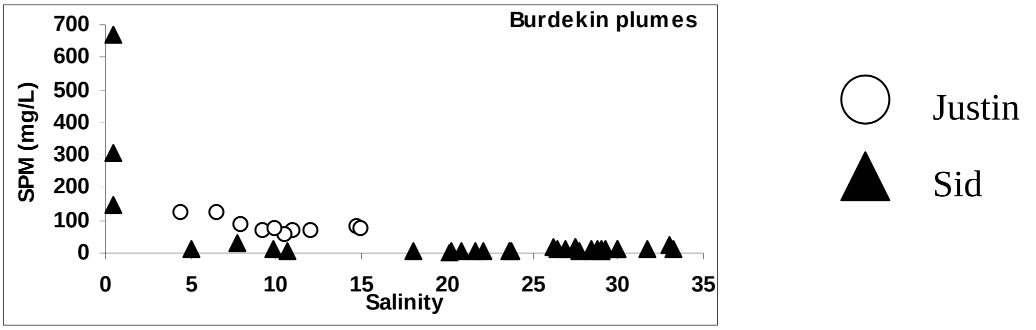


Figure 38: Mixing curves for SPM sampled in the Burdekin plumes. Events included Justin (1997) and Sid (1998)

SPM is lower in the higher salinity plume waters in comparison to the Dry Tropics plume corresponding to reported values for SPM in the rivers (Devlin *et al.*, 2001; Mitchell and Furnas, 2001; Mitchell *et al.*, 1997). Wet Tropics rivers have SPM concentrations averaging 200mg/L at 0 salinity for both Russell-Mulgrave (Devlin *et al.*, 2001), Tully (Mitchell and Furnas, 2001) and the Herbert (Mitchell *et al.*, 1997) in comparison to the Burdekin which has reported average SPM concentrations at 0 salinity of 400mg/L (Devlin, 1998; Devlin *et al.*, 1998; Devlin, 2001). This demonstrates the higher loads of SPM which move out of the Dry Tropics regions, however SPM drops out rapidly through the plumes in both regions, reducing SPM concentrations to approximately 10 to 20mg/L in the higher salinity plume waters (Figure 38 and Figure 39). There are some instances of higher SPM concentrations at higher salinities, such as the Barron plume from Cyclone Rona which is likely caused by resuspension of the particulate matter, related to the prevailing weather conditions.

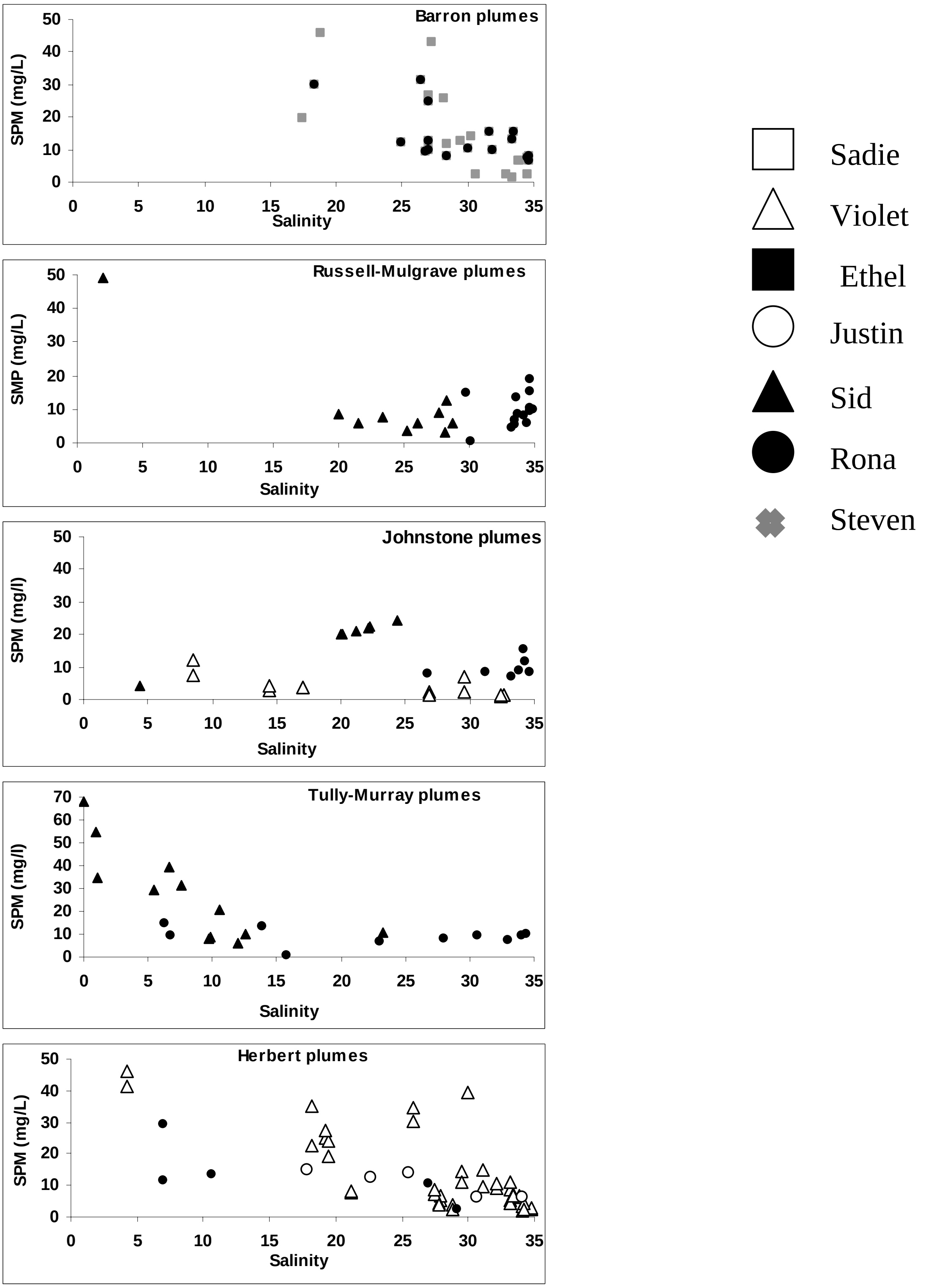


Figure 39: Selected mixing profiles for SPM (suspended particulate matter) for the Wet Tropics catchments

NO_x (nitrite and nitrate)

NO_x generally follows a conservative mixing process, with a strong linear pattern in relation to the salinity gradient (Figure 40 and Figure 41). Source and end concentrations are variable between catchment and as a result, there are different slopes to the lines in relation to catchment. These linear relationships indicate the NO_x may not be utilised or released by any chemical or biological processes in the lower salinity ranges. However, there is some scattering of data at the higher salinity ranges, indicating non-conservative mixing. Non-conservative mixing processes of the inorganic nutrients in the higher salinity ranges could indicate processes, other than dilution, occurring in the plume. Plumes generally 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 as turbidity falls to levels which allow sufficient light availability (i.e. < 10mg l^{-1}).

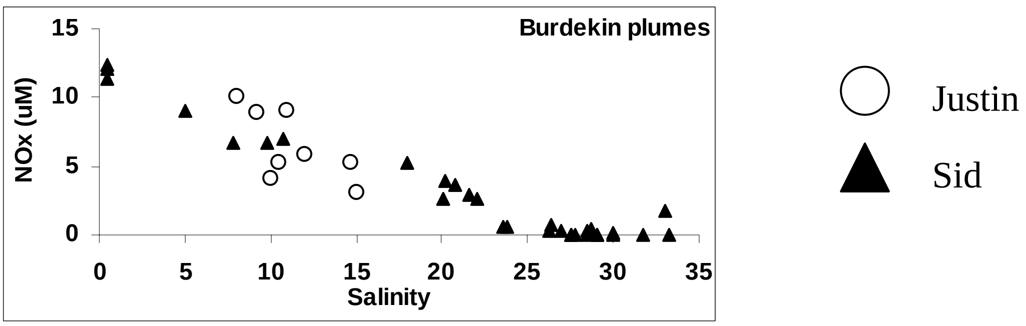


Figure 40: Mixing curves for NO_x sampled in the Burdekin plumes. Events included Justin (1997) and Sid (1998)

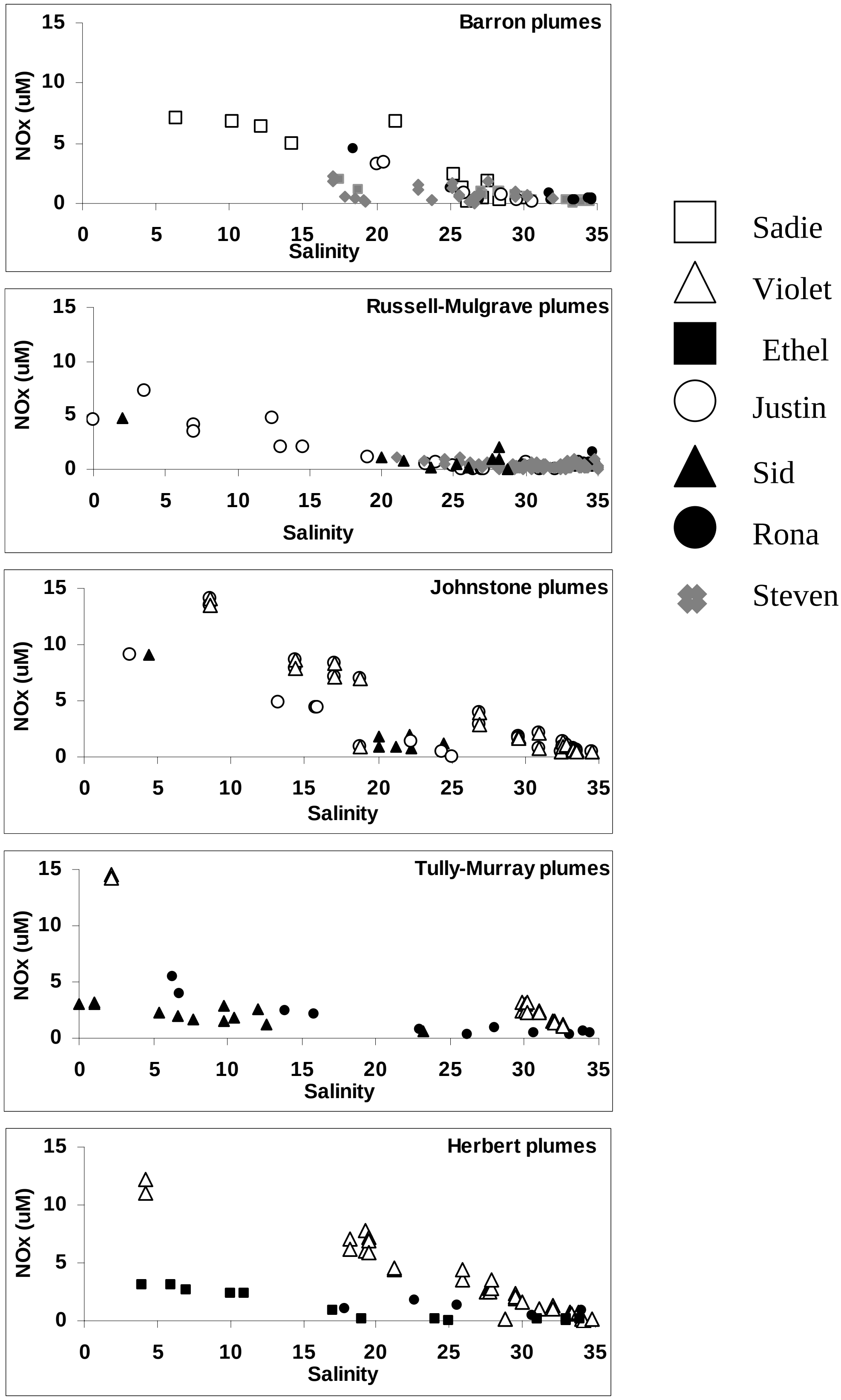


Figure 41: Selected mixing profiles for NO_x(nitrate and nitrite) for the Wet Tropics catchments

NH_4 (ammonia)

Ammonia concentrations are far more scattered reflecting both variations in supply, uptake and production from biological processes in the plume (Figure 42 and Figure 43). 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.

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.

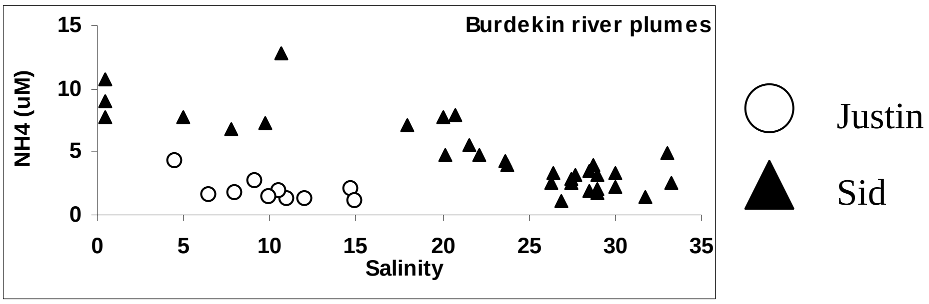


Figure 42: Mixing profiles for NH_4 (ammonia) sampled in the Burdekin plumes. Events included Justin (1997) and Sid (1998)

Separation of the dissolved nitrogen species into salinity ranges (Figure 44) indicate that NO_3 is primarily influenced by dilution and is the primary forcing species for the NO_x mixing patterns. NO_2 forms a small fraction of the total dissolved concentration and has little influence on NO_x concentrations. Concentrations are reduced by approximately 1 to 1.5µM every 10 units of salinity. However, there is significant variability at the 15 to 20 range, indicating that biological processes are starting to occur at this salinity range. For NH_4, there is no clear pattern of dilution, and concentrations are seen to increase between the 15 to 25 salinity ranges.

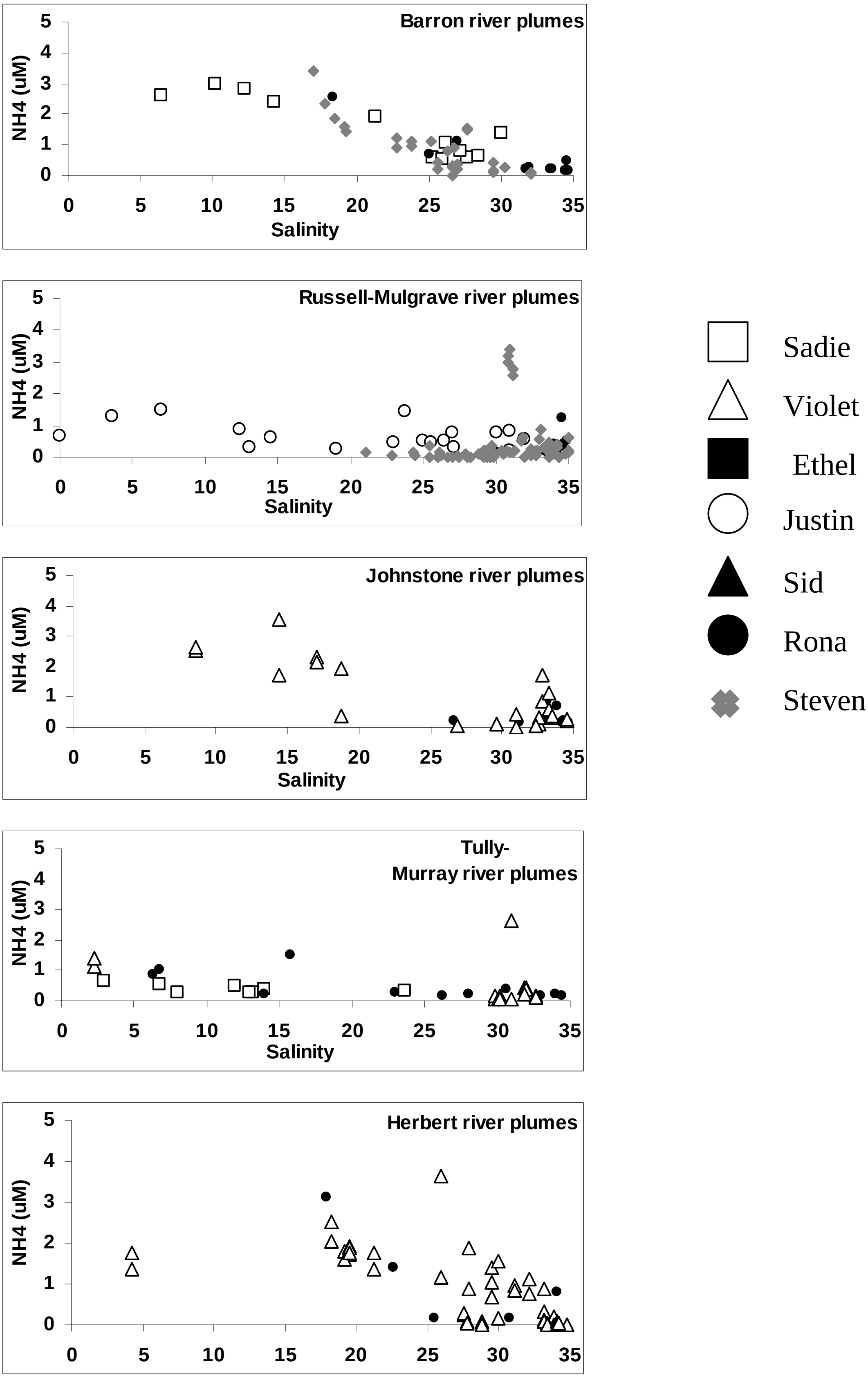


Figure 43: Selected mixing profiles for NH_4 (ammonia) for the Wet Tropics catchments

Dissolved Inorganic Nitrogen – movement and dispersal

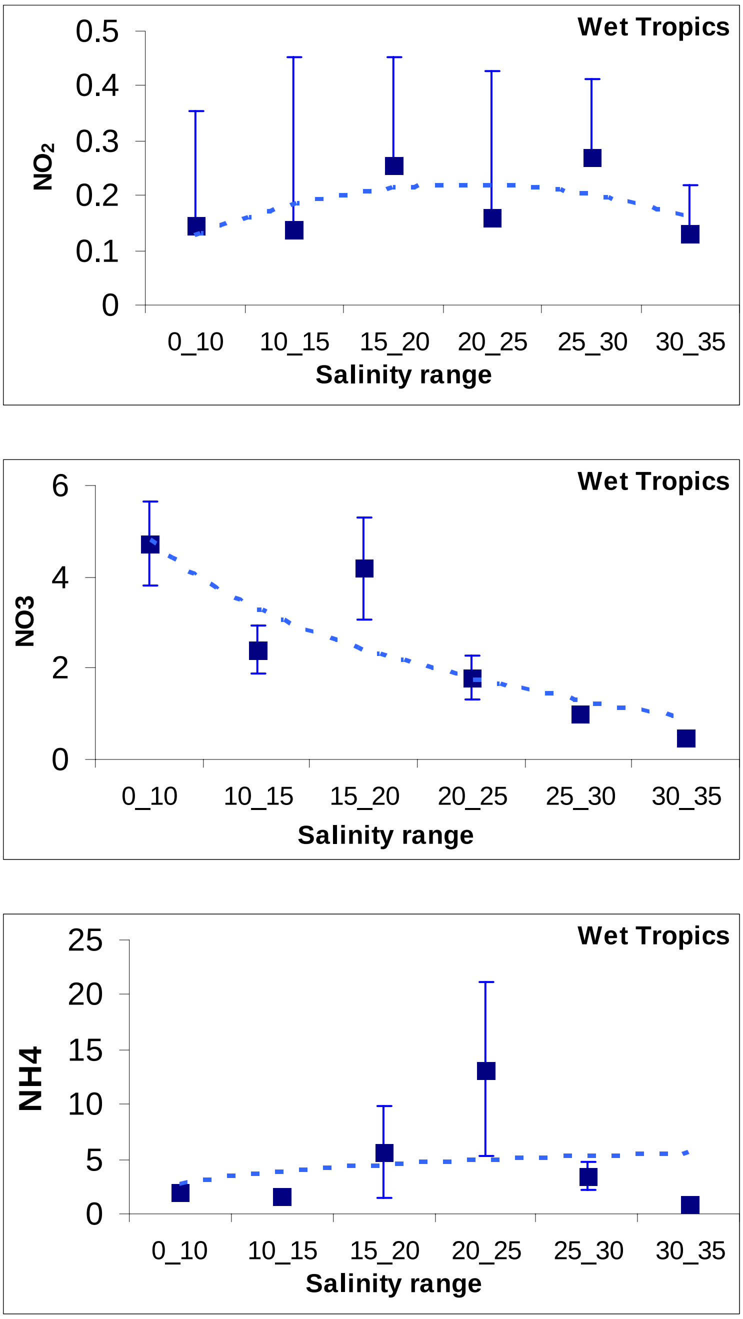


Figure 44: Rate of change in dissolved inorganic nutrient species through salinity gradient. Data is averaged over salinity range. Error bars represent 95% confidence limits.

DIP

Dissolved inorganic phosphate (DIP concentrations are elevated in the majority of samples (Figures 45 and 46). Concentrations are variable through the salinity range, however conservative mixing is evident in the Burdekin (Figure 45). Wet Tropics mixing curves suggest a flattening out of DIP at the higher salinities and it is difficult to model the dilution line due to the lack of samples taken at low salinities (Figure 46). However both the Barron and Tully samples suggest some activity at the lower salinities with sporadic higher concentrations around salinities of 20 to 25. This could reflect the transition of p between the dissolved and particulate stage. A proportion of the DIP measured in the plume waters could be sourced from particulate material. However, concentrations of DIP approach detection limits at salinities greater than 30 suggesting biological mediated depletion.

Studies by Cosser (1988, 1989), Pailles & Moody (1995, 1996) and Mitchell *et al.* (1996, 1997) 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 plumes 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. 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.

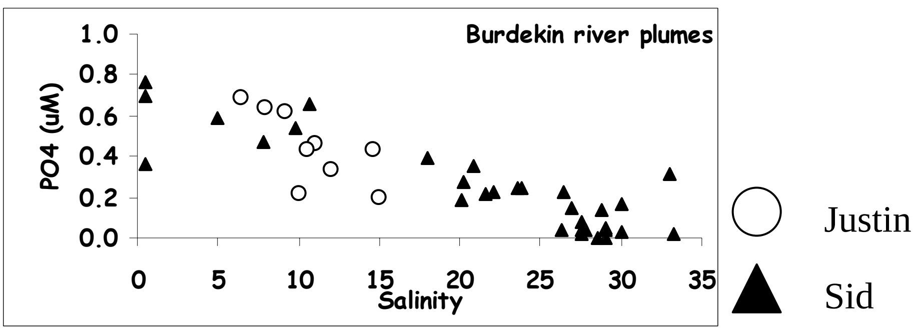


Figure 45: Mixing profiles for DIP (dissolved inorganic phosphate) for the Burdekin catchment

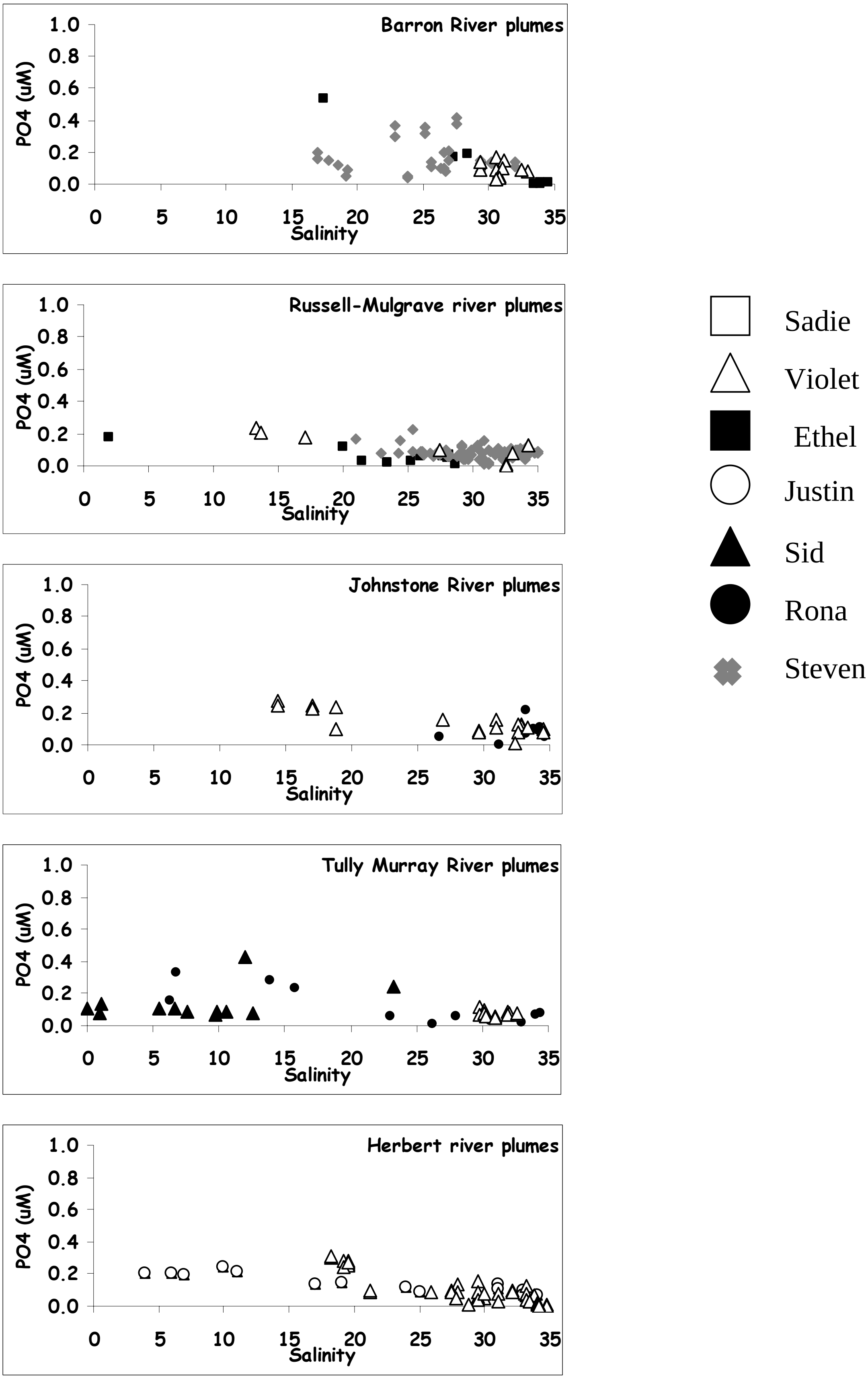


Figure 46: Selected mixing profiles for DIP (for the Wet Tropics catchments).

Combing the DIP concentrations for all plumes and separating into salinity bands does suggest a slightly conservative mixing curve (Figure 47). However, dilution does not seem to count for all the removal of DIP, with processes of adsorption and desorption most likely controlling the concentration measured in the plume waters. In low salinity, turbid regions, P is dominated by abiotic particles – water interactions, moving seaward, the relative importance of these processes declines in comparison to cycling through the water column in coastal waters. Once again, as turbidity drops to below 10mg l^{-1} , there is enough light for growth and P is taken up by the phytoplankton. However, the abiotic processes (adsorption and desorption to particles) also continue to play an important role in the coastal mixing zone.

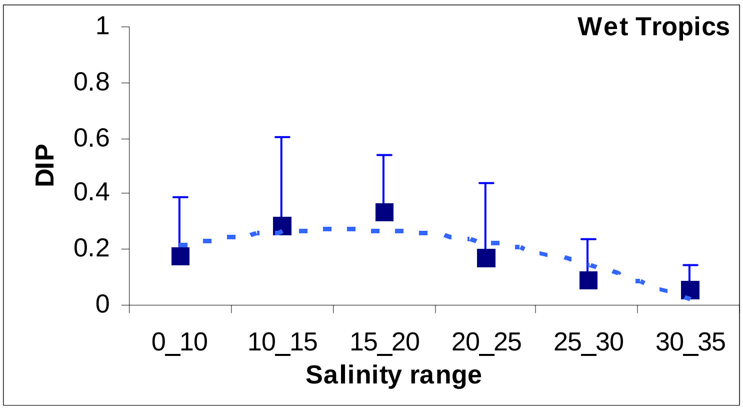


Figure 47: Mean and standard error along salinity gradient for DIP in plume waters

Particulate phosphorus and nitrogen

Particulate nutrients were higher than ambient conditions with peak concentrations measured adjacent and north of the flooding rivers. Particulate nutrients (Figure 48) 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 and generally were higher than 15 μM at low salinity levels. Concentrations of 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 coastal surface waters, however the finer fractions, which may contain considerable PN and PP, can be transported further. PN and PP can be a source of continually desorbing nutrients over long periods and the resulting dissolved nutrients can serve as a nutrient source for phytoplankton growth. Concentrations of PN and PP vary directly with river flow (Furnas & Mitchell 1997) and can peak during major seasonal flood events (Mitchell *et al*. 1997), reflecting the transport of organic matter and soil particles through the watershed. 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

Studies on 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).

PN and PP can be a source of continually de-sorbing nutrients over a large time period, contributing to the dissolved component. This decline in nutrients within the particulate matter may be related to desorption of nutrients from surface particulate nutrients and could serve as a food source for phytoplankton growth (McCulloch *et al*., 2003). 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.

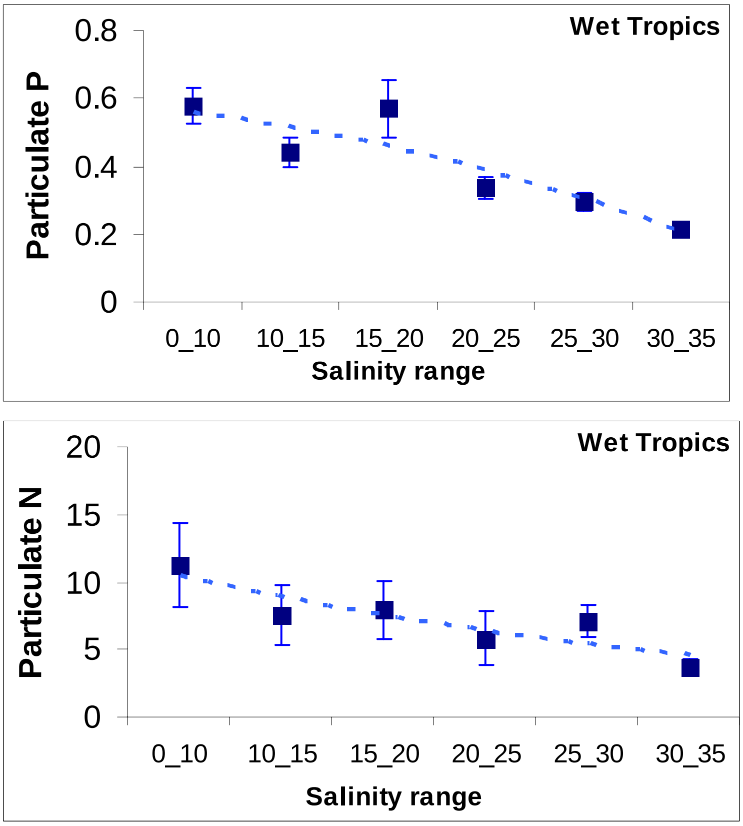


Figure 48: Mean and standard error along salinity gradient for Particulate N and P in Wet Tropics catchments

Chlorophyll *a*

Chlorophyll *a* concentrations have an inverse pattern of increasing concentrations to distance from the river mouth. Figure 50 indicates that there are low concentrations for chlorophyll a in the immediate mixing zone (salinity less than 5), and increasing through the salinity range of 10 to 20. Once in the higher salinities, the chlorophyll biomass starts to drop off again, most likely due to a combination of grazing pressure and light availability. This is seen as a common pattern throughout all the plumes as illustrated in Figure 49. Chlorophyll *a* concentrations are most likely to be influenced by the length of time which water column phytoplankton have been exposed to flood generated nutrients and the increasing light availability as the heavy suspended matter drops out of the plume. 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 (Figure 37), generally 20 times ambient (non-flood) inshore values, indicating an extensive phytoplankton bloom within the plume. 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).

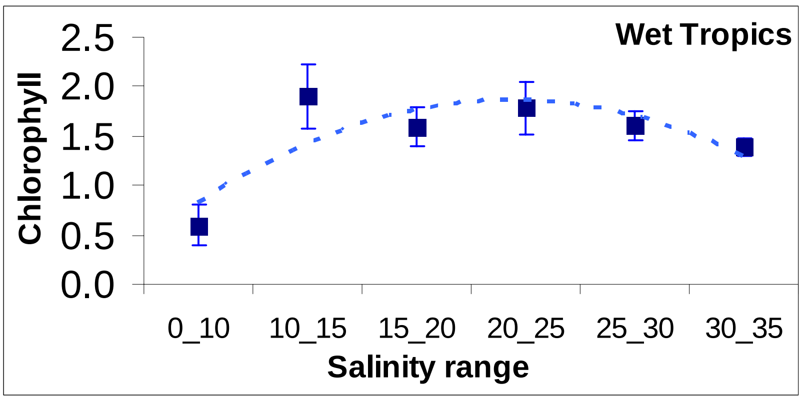


Figure 49: Mean and standard error along salinity gradient for chlorophyll *a* in Wet Tropics

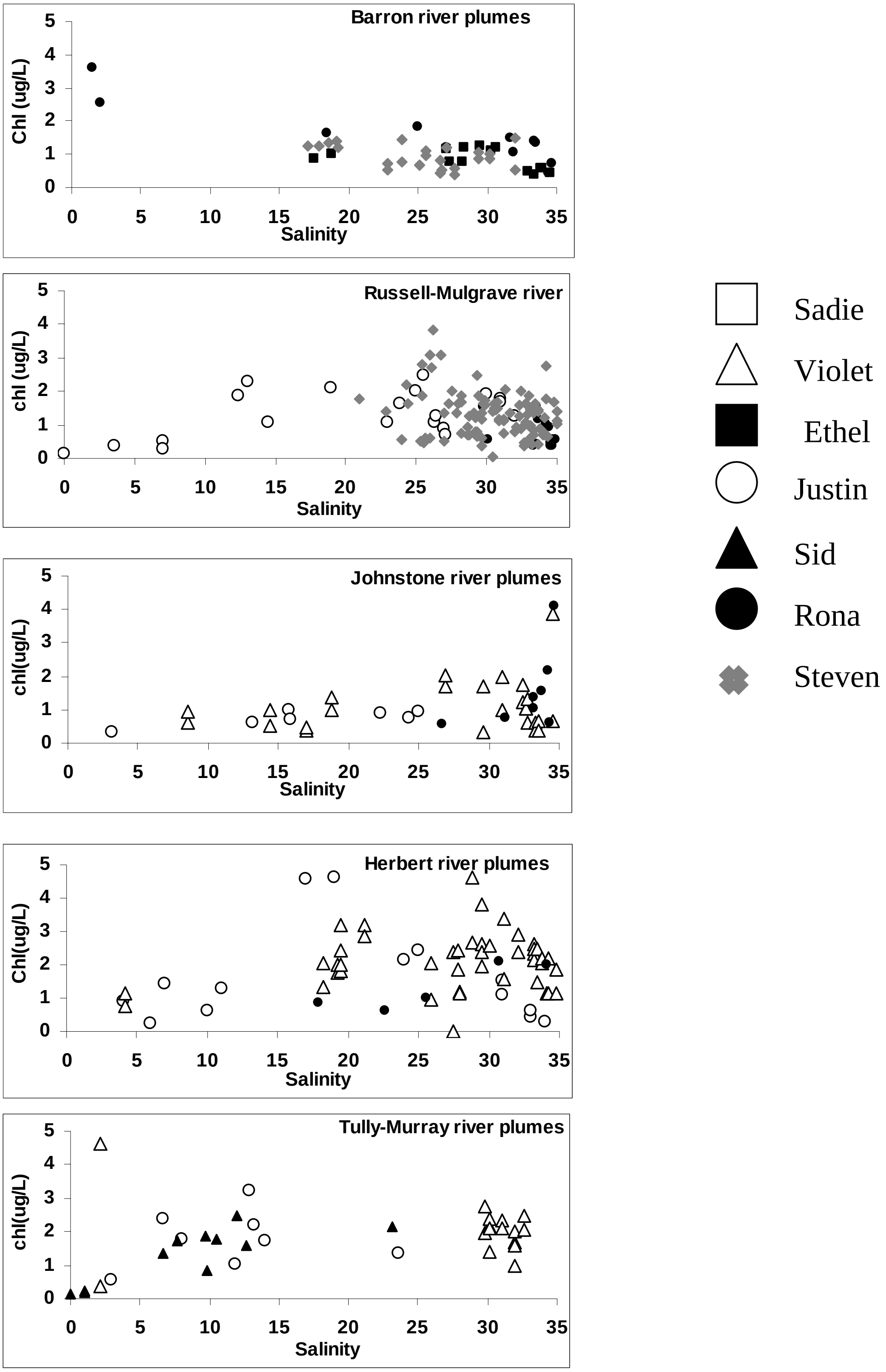


Figure 50: Selected mixing profiles for chlorophyll a (for the Wet Tropics catchments)

Dissolved organic nitrogen and phosphorus

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.

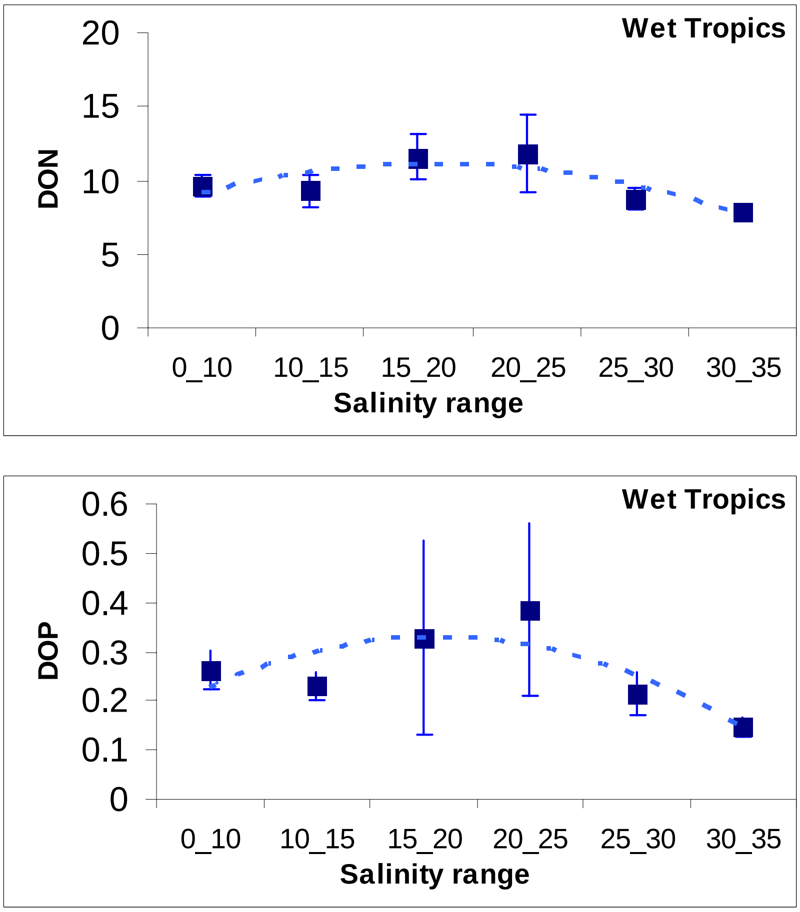


Figure 51: Mean and standard error along salinity gradient for DON and DOP in Wet Tropics

Change in nutrient ratios

In coastal marine waters of the GBR, the immediate bioavailable forms of nitrogen (NO_x ,NH_4) and phosphorus (PO_4) are observed at similar magnitude, in low but detectable concentrations during the dry season (Furnas, 2003). This ratio fluctuates during plume events, creating a non limited environment for phytoplankton growth. The Redfield ratio states algal growth requires 16 times more N than P (Redfield, 58), the growth of phytoplankton in shelf waters appears to be generally constrained by N availability rather than phosphorus or silicate (Furnas and Mitchell, 97). Ratios in plume waters are highly variable reflecting the different abiotic and biotic processes influencing the N and P concentrations. There is some evidence that the plumes tend to become P limited at higher salinities, indicating the higher sources of N availability.

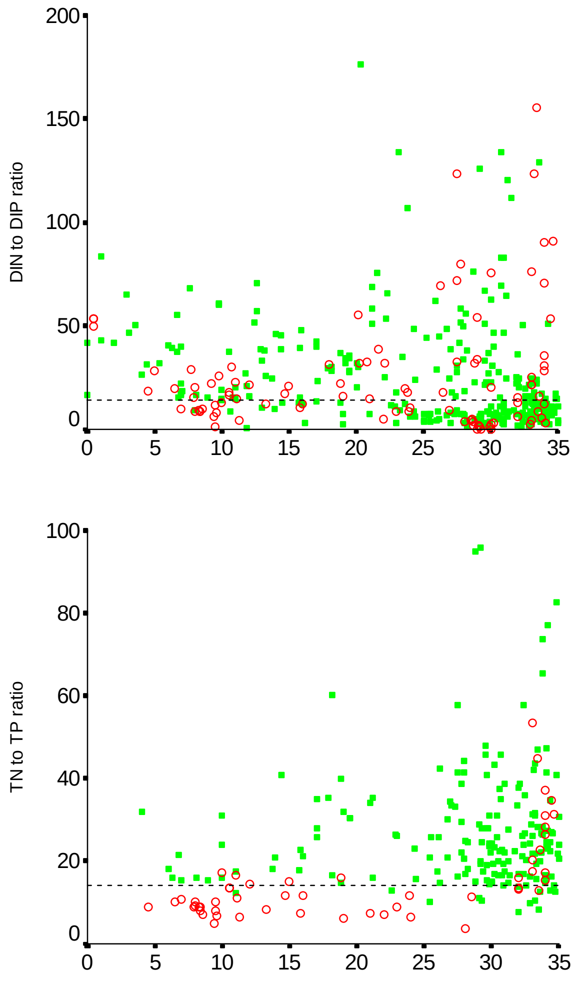


Figure 52: Nitrogen and Phosphorus ratios (DIN:DIP and TN:TP) against salinity. Circle denotes Dry Tropics samples and square denotes Wet Tropics.

4.5 Discussion

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. Mixing profiles demonstrate initial high concentrations of all water quality parameters, with the exception of chlorophyll *a*, 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 processes can be identified for each individual constituent.. 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 at any time.

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. The higher salinity range represents the area of highest productivity with the 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.

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, 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 (Woolf and Larcombe, 1998).

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 NO_x and DIP 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.

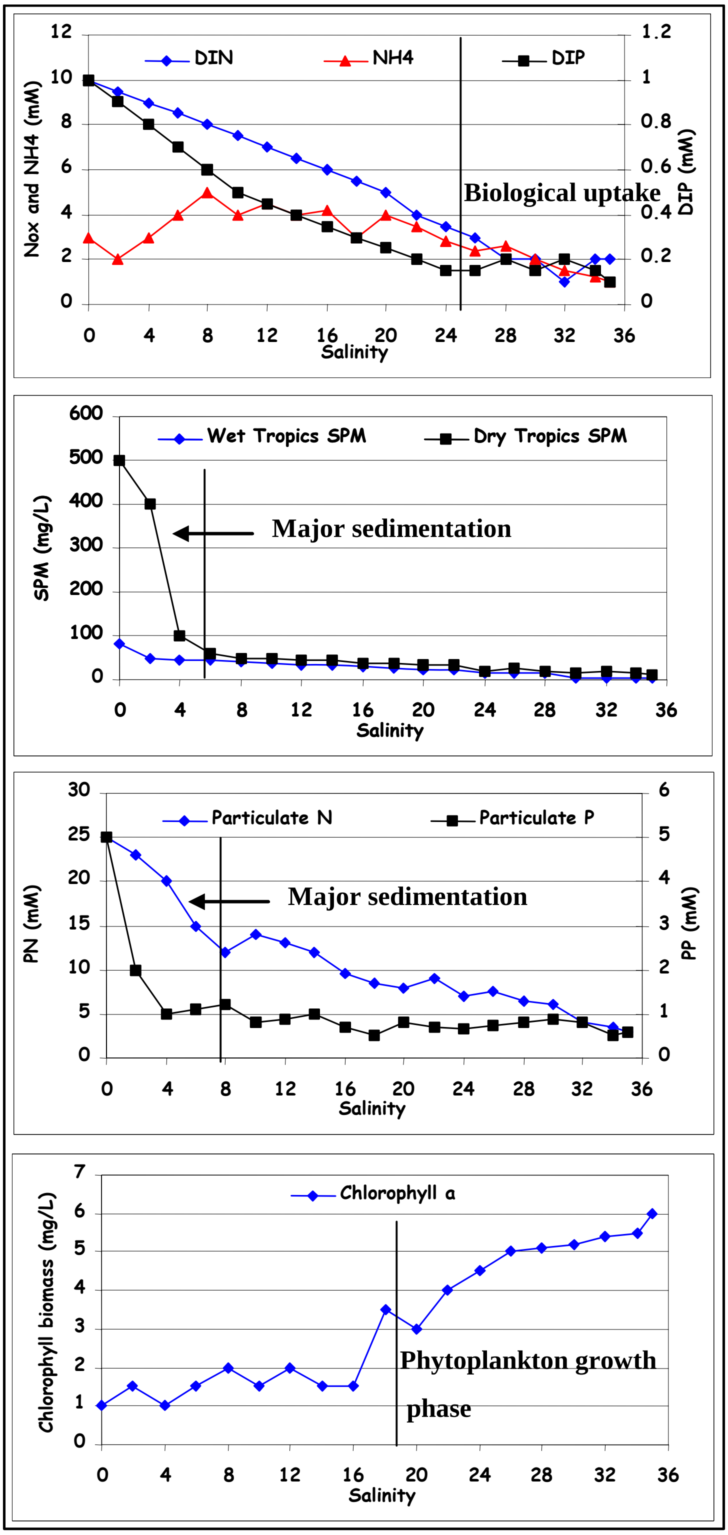
Changing land practices associated with loss from grazing lands and fertilised cropping has resulted in increases in inorganic nutrients in north Queensland rivers. This has resulted in inshore coral reefs experiencing higher concentrations of nutrients than in past years. Reefs offshore of the Wet Tropics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

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 reduce rapidly. DIN can reach 17 μM with a decline to 0.5 μM across the plume boundary. Conversely dissolved inorganic phosphorus (DIP) can fall from 0.4 μM to low ambient levels of 0.05 μM across the plume interface. Patterns of mixing vary for each flow event. River waters also contain high levels of PN and PP, which reduce longitudinally through the plume due to mixing dilutions.

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



Typically dilution (conservative) is main cause of removal at lower salinities though some loss and addition evident

Non conservative behavior at higher salinities

Figure 53: Representation of constituent behaviour for dissolved and particulate nutrients, SPM and chlorophyll a.

dependent on particular events, between days and through a single event, depths and catchments. It should be noted that the data collected in this thesis does not cover all variations of the different events and some generalisations have been made to provide general trend for entire regions. Due to the nature of flood plume sampling, it is difficult to sample all events and all catchments equally in time and space. For example, data frequency is higher off the Barron and Russell-Mulgrave rivers, both because of the frequency of plume inundation and the ability to move quickly out of the Cairns harbour. In contrast, the Tully-Murray river has limited sampling due to the difficulties in getting to the plume in the early stages. However, constituent behaviour is still reported for both regions, and care needs to be taken in considering catchment specific differences. The other limiting factor of the data is that not all events were sampled in the lower salinities due again to the logistics of sampling in the plumes in both the early stages and in being able to move the boat close to the river mouth. Thus approximations of the mixing curves have been made for all the catchments, and further work is required in defining catchment specific mixing curves.

The fate of materials suspended or dissolved in plumes can be partially understood from studies of the concentration changes occurring in the plume as mixing with seawater progresses (Dagg *et al*., 2004). Generally most suspended solids and the associated particulate nutrients and pesticide residues sediment from the plume quickly and are deposited within a few kilometres of the river mouth. This process is common in many large rivers e.g. the Mississippi (Trefry *et al*., 1994). In the salinity mixing diagrams of the Burdekin plume suspended solids concentrations drop from > 1000 mg L^{-1} in the river at zero salinity to < 50 mg L^{-1} at salinities near 5 – 10 $^{0}/_{00}$. The zone of salinity 5 – 10 $^{0}/_{00}$ occurs about 5 km from the river mouth in active large plume conditions. This fine benthic sediment is then continuously resuspended, as it has been deposited in depths of generally less than 10 metres, by the prevailing south east wind regime and transported north along the coast (Larcombe *et al*., 1995; Woolfe and Larcombe, 1998; Lambeck and Woolfe, 2000). This behaviour of initial short-term deposition of fine sediments near the river mouth and final deposition in a different area as the result of wind-driven resuspension and transport over a longer time period is characteristic of many global river systems. A well-studied example is the Atchafalaya River, a distributary part of the Mississippi system, and its discharge to the Gulf of Mexico (Allison et al., 2000). The final fate of sediment from most GBR rivers is to be trapped in northward facing bays where the south east wind regime is attenuated and minimal further resuspension occurs (Larcombe and Woolfe, 1999). Dissolved fractions in the plume are transported far further than the suspended solids and particulate fractions. Dissolved inorganic nutrient concentrations are relatively high in peak flow conditions in the rivers involved in the present study. Typically DIN (mostly nitrate) concentrations lie in the range 300 to 1000 μg L^{-1} (20 – 70 μM) and DIP in the range 5 to 40 μg L^{-1} (0.15 – 1.3 μM) in flood conditions in rivers such as the Burdekin, Herbert, Tully and Johnstone (Furnas, 2003). This can be compared to the large rivers and their plume behaviour reviewed by Dagg *et al*. (2004) where three temperate rivers (Changjiang, Mississippi and Huanghe) have DIN concentrations in the range 40 – 134 μM and DIP, 0.6 – 3 μM but three tropical rivers (Amazon, Zaire and Orinoco) have much lower concentrations in the range 6 – 12 μM for DIN and 0.2 – 0.8 μM for DIP. High concentrations of dissolved nutrients, 10 to 100 times non-flood ambient concentrations, are measurable in the plumes in the GBR at distances of ten to two hundred kilometres from the river mouth. Dissolved nutrients move conservatively through the estuarine plume in the lower salinity ranges, indicating very little biological uptake in the initial stages of the plume. However, in the higher ranges of salinity (25 – 36 $^{0}/_{00}$), there is increased biological processing. Nutrient levels stay elevated throughout the plume, with dissolved inorganic nutrient levels exceeding ambient concentrations through all salinity ranges. Dissolved inorganic nutrients are not taken up in the early stages possibly due to light limitations on phytoplankton growth due to plume turbidity. This effect has been commonly observed in many rivers including the Amazon (Smith and DeMaster, 1996), Mississippi (Lohrenz *et al*., 1999), Changjiang (Tian *et al*., 1993), Pearl (China)(Cai *et al*., 2004) and Brantas (Indonesia) (Jennerjahn et al., 2004). Suspended matter concentrations appear to need to be reduced below 10 mg L^{-1} to allow sufficient light for strong phytoplankton growth (Turner *et al*., 1990). This lack of uptake allows the inorganic nutrients to be transported away from river mouth, exposing inshore reefs to high inorganic nutrient concentrations. Coupled with this, inshore reefs are exposed to elevated concentrations of fine particulate matter, both river-derived clay materials and phytoplankton. After the large initial sedimentation stage there is little sedimentation at higher salinities with suspended particulate matter concentrations averaging between 10 to 30 mg/L in the higher salinity levels (26 – 35 $^{0}/_{00}$). The particulate matter concentrations are reduced in the higher salinity ranges, but the variability suggests that resuspension of the finer particulate matter may be occurring. Concentrations in the later stages of the plume are still elevated and may suggest an increase in fine colloidal matter as the larger particulate matter sediments out of the plume.

The high variability between catchments is due to the different source concentrations in the different rivers, the different stages of sampling through the existence of the plume and flow variability. 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 and resuspension processes resulting from rough weather conditions.

Most flood plumes in the GBR spread to the north of the river mouth for distances of up to 200 km but not more than approximately 40 km from the coast. Material in the plume will initially be deposited within this zone either directly as particulate matter from the river or, if dissolved, eventually as organic particulate matter after uptake into biological organisms. Thus, if little further transport of the terrestrial material in an offshore direction occurs, we could expect to see evidence of the material in benthic sediments in a band along the coast on the inner shelf. Further offshore, on the middle and outer shelf, we would expect to see little terrestrial derived material in benthic sediments. With a few exceptions this pattern has been verified in studies of benthic sediment and biota composition. In transects across the GBR, terrestrial biomarker chemicals (Currie and Johns, 1989; Johns *et al*., 1994), higher plant materials (Shaw and Johns, 1985), land-sourced trace metals (Brady *et al*., 1994), $\delta^{13}C$ in corals (Risk *et al*., 1994) and sediments (Gagan *et al*., 1987), $\delta^{15}N$ in corals (Sammarco *et al*., 1999) and coral skeletal densities (Risk and Sammarco, 1991) change from a terrestrially influenced signal inside 20 km to almost no terrestrial influence beyond 20 km. On the other hand evidence of movement of fine sediment as a nepheloid layer from inshore to almost 30 km offshore in strong wind conditions has been reported near Cairns (Wolanski and Spagnol, 2000). Pesticide residues, particularly of the herbicide diuron and the insecticide dieldrin, are also found in intertidal and subtidal sediments, primarily in a band close to the coast (Haynes *et al*., 2000) adjacent to those catchments with a history of use of the particular pesticide. The effects of variability in river influence on inner shelf ecosystems is not well understood. However correlations between relative distance from the coast or relative distance across the shelf and diversity and/or abundance in taxa such as soft corals (Alcyonaria)(Fabricius and De'ath, 2001a) and crustose coralline algae (Fabricius and De'ath, 2001b) are known. Such correlations are attributed to turbidity, sedimentation and nutrient gradients with distance across the shelf (Fabricus and De'ath, 2004; Fabricus *et al*., 2005)**.**

Chapter 5: Terrestrial discharge into GBR (b) Maximum thresholds of nutrients and chlorophyll biomass in GBR waters

Chapter 5: Terrestrial discharge into GBR (b) Factors that drive variability in plume concentrations

5.1 Introduction

Coral reef systems are complex and it is difficult to assess how a input variable such as dissolved nutrients can impact on the “health” of the system. Assessment is hindered by the (nearly always) simultaneous impact of coincident high seawater temperatures in the summer/wet season period and of low salinity, high turbidity and high nutrient concentrations caused by flood plumes. Tracing the change in time and space for constituents in plumes allows some estimate of the concentrations experienced by inshore ecosystems of the GBR, particularly reef systems. Modified landuse, vegetation clearing and agricultural practices on GBR catchments (Pulsford, 1996; Mitchell *et al*, 1997; Eyre and Davies, 1997) result in higher loads and concentrations of nutrients discharging into plume waters. Inshore ecosystems, inshore reef and seagrass beds off the developed Wet Tropic catchments are now potentially experiencing above effect levels of nitrogen and phosphorus for periods of days to several weeks in every wet season. The relative abundance of inorganic nutrients in these inshore areas, particularly nitrogen to phosphorus ratios, potentially exerts a strong influence on phytoplankton communities and trophodynamic processes (Akuyai *et al*, 1997) and can impact on ecological health of coral reefs.

The mechanism of mixing, dilution, uptake and sedimentation are the main processes involved in the dispersal and extent of nutrients and sediments in plume waters. Delivery of the terrestrially derived nutrients and sediment into GBR waters is primarily related to the transfer and transformation of the constituents as they pass through the plume from a freshwater end to a saline end However a number of other factors can influence concentrations measured in plumes and affect the actual exposure concentration and duration that GBR ecosystems may experienced. Catchment usage effects the initial concentrations (source pressure) of dissolved and particulate matter in the river waters. This does not influence particulate matter, particularly SPM, as data (chapter 4.5) demonstrates that sedimentation occurs relatively close to the river mouth, and is not a direct source of increased turbidity on inshore reefs. However the highly developed agricultural catchments have reservoirs of dissolved nutrients, which can influence the actual concentrations measured around reef systems.

Concentrations of water quality parameters such as suspended sediment and nutrients measured in flow events can be used to quantify contaminant loads from catchments to receiving waters (e.g. GBR coastal waters) and may also give an indication of whole of catchment condition (McKergow *et al*., 2005a). However, by concentrating on samples taken earlier in the plume and close to the river mouth, the concentrations will be indicative of catchment activities.

- Distance from river mouth (catchment to reef)
- Timing of sampling (related to plume extent and duration)

This chapter looks at three mechanisms that will influence the transport of sediments and nutrients into the GBR. Firstly is there is a relationship between levels of agricultural use and human activity on the catchment and the concentration of dissolved and particulate nutrients in the early stages of the plume. Secondly, if high nutrient concentrations are exported into plumes adjacent to high agricultural use catchment, is this measurable at sites in close proximity to reefs. What are the main factors that influence nutrient concentrations within the plume waters, is it all related to catchment or are the processes of dilution, timing of sampling, and scale of event and weather conditions more important in constraining the influence of catchment? Figure 54 represents the interaction of these three factors in influencing the variability of plume concentrations.

This chapter presents a specific sampling event (Cyclone Steve – 2000) where fixed sites are located around three inshore reefs, with samples collected over five consecutive days. The information is extrapolated to calculate exposure and dosage and related to known information about impacts from current literature. Finally, I will sample, in detail, sites around an inshore reef system to develop potential exposure levels for reefs in high risk areas.

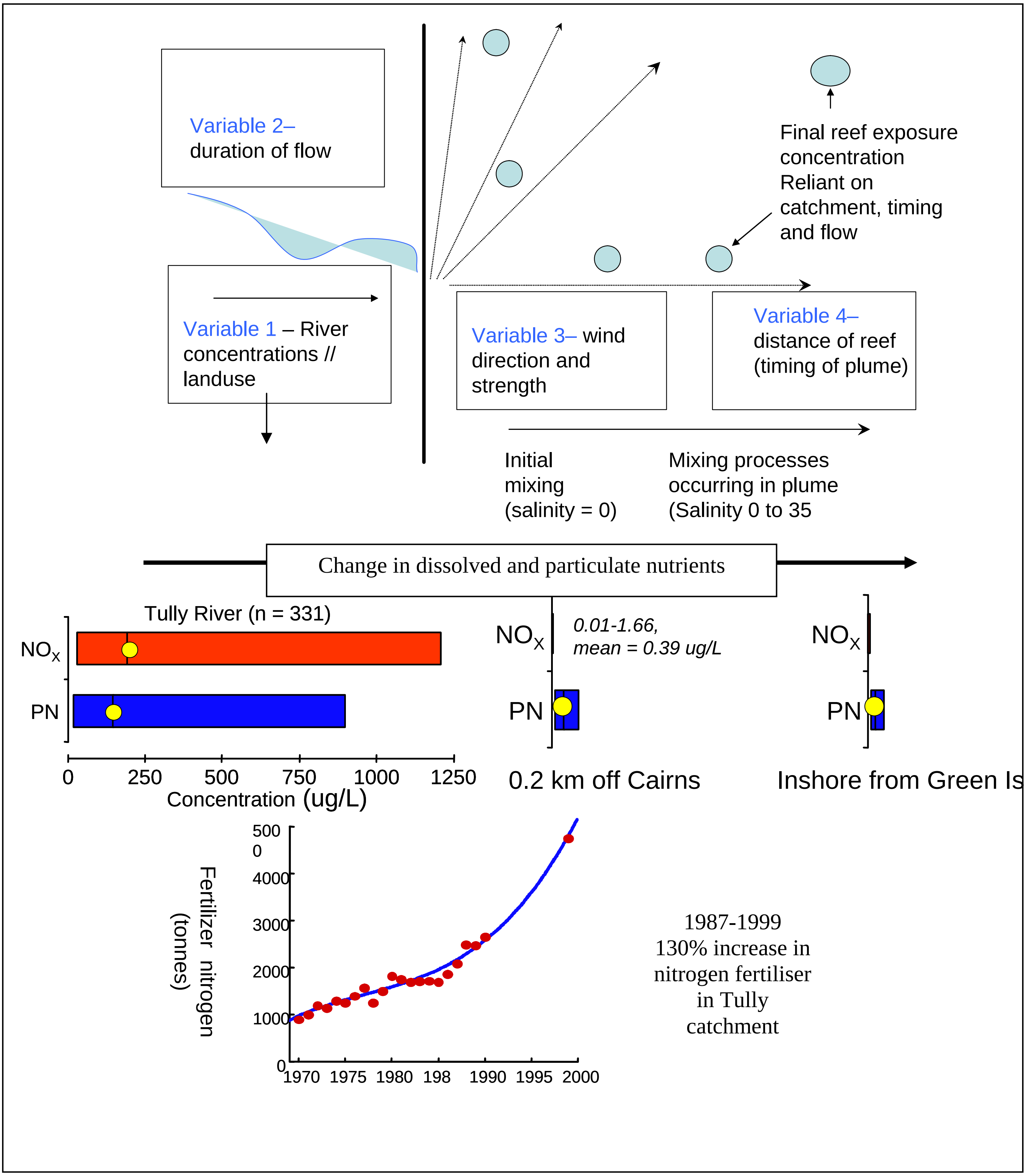


Figure 54: Conceptual diagram of variables which influence reef concentrations during plume events.

5.2. *Methodology*

5.2.1 Plume sampling

Sampling of plumes is described in the previous chapter. Sampling usually took place over one to two days, with the exception of Cyclone Ethel in 1996 which had repeated sampling in the Wet Tropics over a 13 day period and Cyclone Sid in 1998 which had repeated sampling in the Burdekin plume over 10 days Details of plume sampling is presented in **Table 9.**

5.2.2 Concentrations in plumes related to catchment

Sites selected to represent catchment processes were contained within the immediate plume discharging from each catchment. Sites were taken in a salinity gradient away from the river mouth, and excluded all sites within 500 m of any reef system. Sites were also excluded from areas where the water masses from individual plumes were merging. An example of the selection of plume sites representing individual catchments is shown in Figure 55. Plume waters were defined by the associated river discharging into the plume sampling area.

Water quality data (dissolved and particulate nutrient species, suspended solids and chlorophyll) was reported for each site. Mean minimum and maximum values and standard error associated with all constituents measured in flood plume waters, related to catchment are reported in Table 8

5.2.3 Concentrations in plumes related to distance (reef concentrations)

Selected samples collected within plume waters were identified as "reef" samples if they were collected at close proximity to an inshore reef. Reef sites were calculated as any site that was within 500m proximity of a reef. This is an arbitray selection, and was thought to represent water that was moving across a reef. Water quality data (dissolved and particulate nutrient species, suspended solids and chlorophyll) was reported for each site. Mean minimum and maximum values and standard error associated with all constituents measured in flood plume waters, related to catchment are reported in Table 9.

Comparison of concentrations related to inshore sites and reef sites from all years were grouped over catchment area (defined as the extent of primary plume from that catchment). Mean concentrations of NOx, DIP, chlorophyll a and suspended solids were plottted with 95% SE for both plume waters and reef waters against the ambient value of that parameter (as measured by Furnas *et al*., 2001) (Figure 58, 59 and 60).

A loss factor was applied to each inshore and reef sites relative to every catchment (Table 10). This is a very broad generalisation, but can give us some indication of the degree of loss of dissolved and particulate nutrients, SPM and chlorophyll.

5.3.4. Concentrations in plumes related to time (flow)

The influence of time and flow was examined by relating concentrations within the plume waters with day of sampling related to flow event. Water quality variables were plotted against time and correlated with catchment flow. Data is presented for plumes discharging from the Barron, Russell-Mulgrave, Tully, Johnstone and Burdekin Rivers over the sampling period (1991 – 2001). Rate of change in the dissolved nutrient concentrations, chlorophyll biomass and suspended particulate matter (SPM) were analysed by sampling in plume waters as close as possible to peak flow and comparing to samples taken after peak flow conditions.

it takes for the water to move past a reef system. Sites will be based on location of sampled plumes.

Example: Barron River in Cyclone Rona – Peak flow on 13/2/1999 (129338 ML)

Data collected on the 13/2/1999 – **Day = 0**

Samples from the Barron River plume were collected on the **16th (Day = 3)**

17th (Day = 4)

18th (Day = 5)

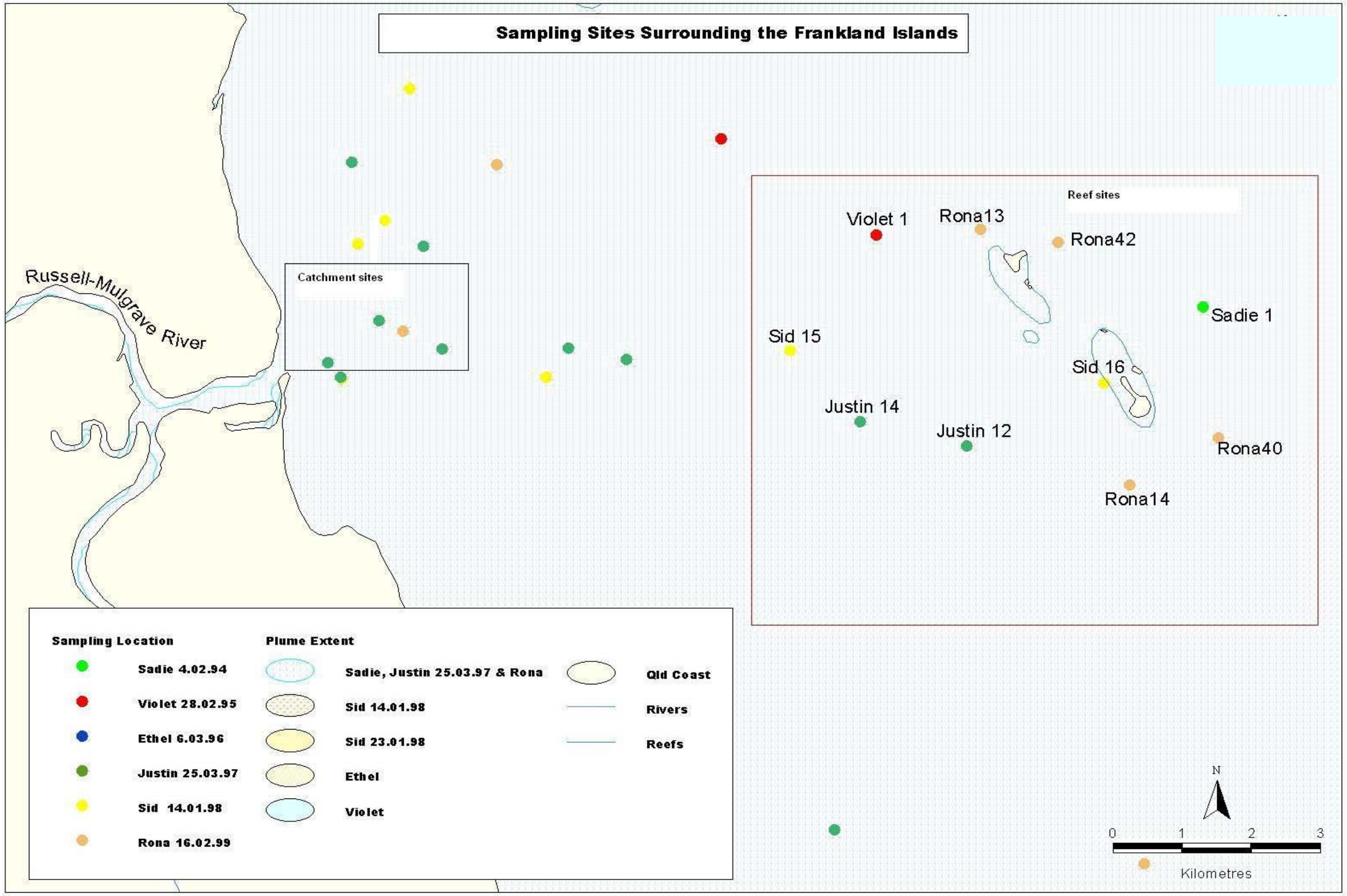


Figure 55: Selection of sites related to catchment and divided into inshore and reef sites

5.2.5 Calculation of variability related to catchment, timing and distance

Concentration of the constituent at a reef level will be influenced by all the factors and it is difficult to separate loss from any one factor to calculate an end concentration at distance from river mouth. Reef concentrations related to inshore reefs off the Wet Tropics central coast is investigated for one plume event. This event calculated initial catchment concentrations at the mouth of the Barron and Russell-Mulgrave River, then accounted for time (3 weeks) and distance, to estimate the exposure concentrations of dissolved nutrients, SPM and chlorophyll biomass for the three inshore GBR reefs.

5.2.5.1 Sampling sites

Sites were located in a gradient out from the Russell-Mulgrave River (Figure 57). Twelve sites were positioned around the Franklands Reef, High Island and Fitzroy Island in the central section of the GBR (Figure 58). Plume water sampling occurred during both the first flush event and the extreme flow event associated with Cyclone Steve in February and March, 2000. Nitrate + nitrite (NO_3+NO_2), ammonia (NH_4), dissolved inorganic phosphate (DIP) and chlorophyll concentrations were collected from surface and bottom samples.

5.2.5.2 Data analysis

Russell-Mulgrave flow rates were plotted over the extent of the sampling period for 2000 (Figure 56) This sampling event comprised of two seperate flow incidences, with sampling of plume waters just after first flush on the 9th February and again after the main flow event between the 1st and 6th March. Water quality sampling was iniated 24 to 48 hours after peak flow. Nutrient, chlorophyll and suspended sediment concentrations collected in the Cyclone Steven plume (including first flush samples) were averaged over all reef sites and plotted against Russell-Mulgrave flow. Data was plotted against days (0-26) with 0 being day just previous to first flush event, and 26th day being after return to ambient flow conditions. This allows a broad correlation of nutrient availability in the reef waters with flow.

The extent of variability between individual reefs and sites was investigated by measuring dissolved and particulate nutrients, SPM, and chlorophyll *a* concentrations over four reef sites during a first flush and flood event. Concentrations were plotted against sampling day (Figure 61). The first flush was measured on the 11th February

2000 and not all sites were sampled. The large flow event was associated with the movement of Cyclone Steve, and sampling commenced on the 3rd March 2000. Sampling was initiated two days after the heaviest flow. Dotted line is ambient (non flood) concentration.

In all cases, our examination of this data is restricted to when samples were taken. The first flush was measured with no expectation of another flow event. However, it remains an interesting comparison between values measured in first flush and less extreme flow rates and the main sampling event, associated with Cyclone Steve, which had highest flow of the year.

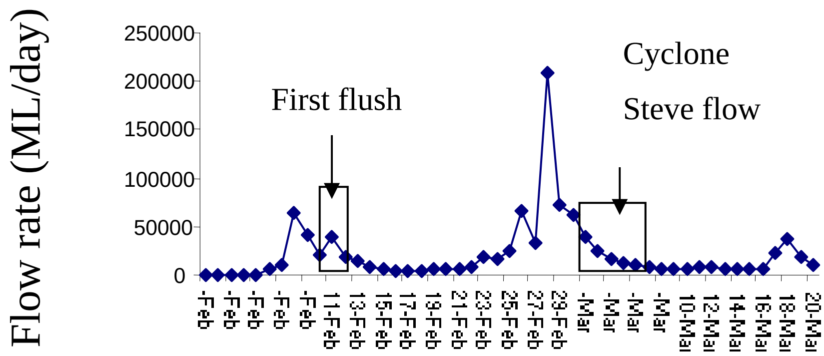


Figure 56: Flow rates associated with Russell-Mulgrave over February and March 2000.Sampling for water quality parameters was initiated during the first flush event and the extreme flow associated with Cyclone Steve (2000)

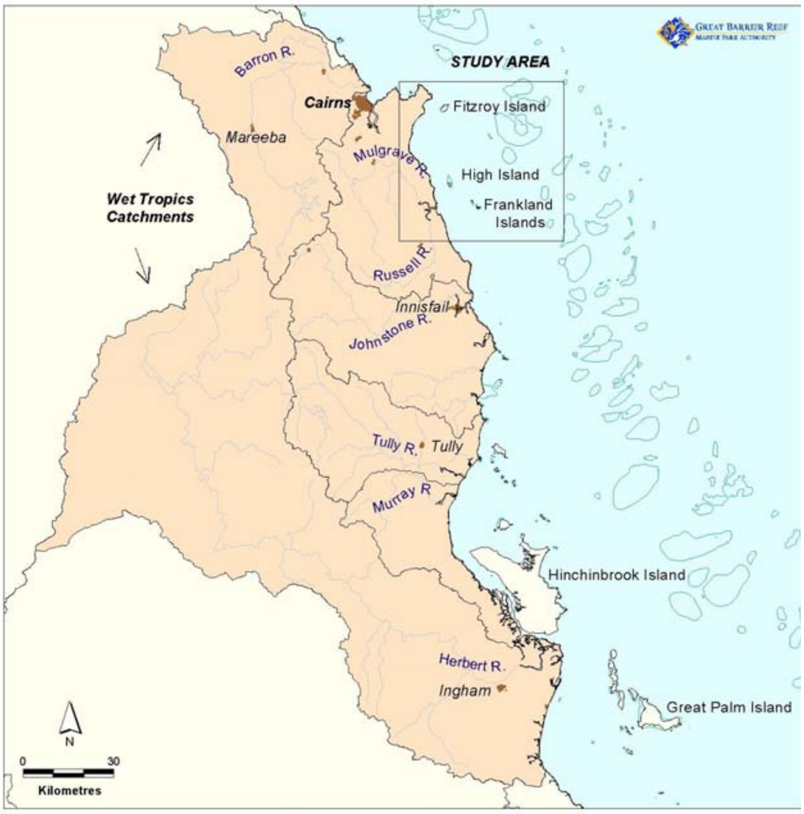


Figure 57: Map outlines Wet Tropics area which has detailed reef water quality sampling. Plume frequency and hindcasting were modelled in this area.

Figure 58: Individual water quality sites sampled in Cyclone Steve (2001) around three selected reefs.

5.3 Results

Table 8: Minimum salinities and maximum and mean (+SE) nutrients, chlorophyll and suspended particulate matter concentrations from the catchment plumes in GBR surface waters

Catchment	Daintree	Barron	Russell-Mulgrave	Tully - Murray	Johnstone	Herbert	Burdekin	Fitzroy
Sampling times over study period	18	176	228	115	96	109	65	63
Salinity	11.8 (26±9)	6.4 (29±6)	0 (30±6)	0 (26±10)	3.1 (29±8)	4 (28±9)	0.5 (21±10)	7 (24±10)
NH_4	1.1 (1.0±1.02)	9.31 1.2±1.8	7.5 (0.51±.87)	4.44 (0.95±1.1)	5.25 (1.0±1.2)	5.06 (1.0±1.0)	12.8 (3.6±2.8)	4.1 1.3±0.9
NO_2	0.13 (.06±0.03)	1.1 .15±0.18	0.31 (.09±0.07)	1.23 (0.25±.26)	0.28 .11±.07	0.96 .23±0.23	0.52 .12±0.14	1.35 .37±0.37
NO_3	2.9 (.78±1.1)	6.9 (.83±1.3)	7.23 (.61±1.2)	14.3 (1.9±2.7)	14.0 2.4±3.3	12.1 (1.9±2.5)	17.2 (3.3±4.6)	2.41 .76±.78
DON	9.7 (4.5±2.0)	27.1 (7.2±4.4)	24.8 (7.6±4.0)	17.8 (7.7±3.8)	16.6 (7.5±3)	40.4 (9.9±6.1)	28.9 (7.4±4.3)	-
PN		9.9 3.9±1.9	32.1 (4.3±3.9)					
DIP	1.4 (.13±0.34)	0.6 .14±0.11	0.33 (.1±0.06)	2.46 (.15±0.34)	0.27 .11±.07	0.56 .13±0.11	1.16 .24±0.26	1.58 .65±0.4
DOP	0.19 (.04±0.07)	2.67 (22±0.30	1.61 (.26±0.18)	0.60 (.18±0.14)	0.35 .12±.0.11	2.78 .23±0.39	0.93 .31±0.18	1.98 .42±0.4
PP		0.71 .26±0.18	0.34 0.16±.06					0.85 .43±0.2
$Si(OH)_4$								
Chl a	1.55 (.18±0.44)	4.89 1.2±0.77	3.81 (1.2±0.65)	4.61 1.5±0.9	2.18 96±0.5	5.49 (1.8±1.1)	2.01 (1.1±0.6)	20.1 5.7±5.5
SPM	62.0 (10.1±19)	150.1 18.7±22	590.1 (23.9±99)	191.2 20.6±31	33.0 7.4±7.1	80.7 15.7±17	672 (42.3±100	35.7 (13±6.8)

5.3.1 Concentrations in plumes related to catchment

Each plume 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. The movement and dispersal of plume waters in a generally northern direction eventually results in a heterogeneous water system composed of a number of distinct plume water masses. Concentrations of constituents in these distinct plume masses, in the early stages of the plume and in waters close to the river mouth, the concentration of constituents within the plume are indicative of the land-use activities on the adjacent catchment. Summary of concentrations for individual catchment plumes (Table 8) demonstrate variable concentrations for plumes related to proximity of catchment, for both wet and dry tropics. Measurements are taken in the freshwater end when salinity has been measured at 0, however for the Daintree, Barron, Johnstone, Herbert and Fitzroy; samples were never taken within freshwater, indicating some degree of mixing within the estuary. Plumes measured adjacent to Russell-Mulgrave, Tully and Burdekin completely flush fresh and mixing (dilution) occurs over the full salinity range.

Values for dissolved and particulate nutrients in the inshore plume waters are considerably higher than ambient concentrations, with the magnitude of increase for nutrient concentrations measured in flood plumes ranging from 5 to 100 fold greater than ambient water quality conditions. Nutrient concentrations averaged over each catchment in a south to north gradient (Fitzroy to Daintree River) show no particular pattern along the GBR coast but again with generally higher than ambient values for each plume area.

5.3.2 Concentrations in plumes related to distance (reefs)

Concentrations for dissolved and particulate nutrients and SPM decrease as they move away from the river mouth as would be expected from the mixing curves (chapter 5) and are two to five fold lower than concentrations taken within inshore plume waters. This natural process of dilution and advection and uptake contribute to reef concentrations being lower than initial concentrations. Values for NO_x remain elevated around reef sites, with mean values exceeding the ambient values (Table 9, Figure 58). DIP is elevated in plume samples, but approaches the ambient concentrations in water samples collected around inshore reefs (Figure 59). Chlorophyll *a* is higher offshore, reflecting an elevated phytoplankton signature related to increased nutrients and lower turbidity from sedimentation (Figure 60) Suspended solids is higher close to river mouths, falling out quickly as plume moves offshore.

Table 9; Mean and maximum values for reef samples associated with GBR catchments.

Constituent	DAINTREE	BARRON	RUSSELL-MULGRAVE	JOHNSTONE	TULLY-MURRAY	HERBERT	BURDEKIN
Mean Salinity	27.6	28.5	30.4	32.6	21.9	32.4	28.0
Min Salinity	16.2	19.1	13.0	31.0	7.6	30.7	21.0
Mean NOx	0.6 + 0.3	0.5 + 0.1	0.5 + 0.05	0.6 + 0.3	1.0 + 0.3	0.6 + 0.4	0.3 + 0.1
Max NOx	2.2	1.0	5.6	0.7	2.9	0.8	2.9
Mean NH4	0.8 + 0.3	0.4 + 0.1	0.4 + 0.1	0.3 + 0.2	1.4 + 0.4	0.5 + 0.3	3.0 + 0.6
Max NH4	2.1	1.6	3.4	0.4	4.4	0.9	5.6
Mean DIP	0.4 + 0.2	0.1 + 0.05	0.1 + 0.05	0.11 + 0.05	0.14 + 0.05	0.1 + 0.07	0.1 + 0.05
Max DIP	1.4	0.2	0.2	0.1	0.4	0.1	0.3
Mean Chl	0.9 + 0.5	1.0 + 0.2	1.2 + 0.1	0.9 + 0.5	1.6 + 0.5	2.2 + 1.3	
Max Chl	1.6	1.7	3.8	1.1	3.2	2.3	
Mean SPM	8.0 + 1.8	9.9 + 3.1	15 + 10	8.6 + 1	17.8 + 5	5.1 + 1	10 + 2
Max SPM	21.3	15.4	590.1	8.6	191.1	6.1	25.9
Mean DOP	0.1 + 0.07	0.2 + 0.1	0.3 + 0.1	0.1 + 0.04	0.2 + 0.05	0.2 + 0.1	0.3 + 0.1
Max DOP	0.1	0.6	0.8	0.1	0.6	0.3	0.7
Mean DON	3.6	8.0	8.0	4.3	6.9	8.1	8.4
Max DON	4.5	17.0	21.0	15.0	11.0	19.0	21.0
Mean PP		0.2	0.2				
Max PP		0.4	0.3				
Mean PN		3.4	4.3				
Max PN		8.8	32.1				

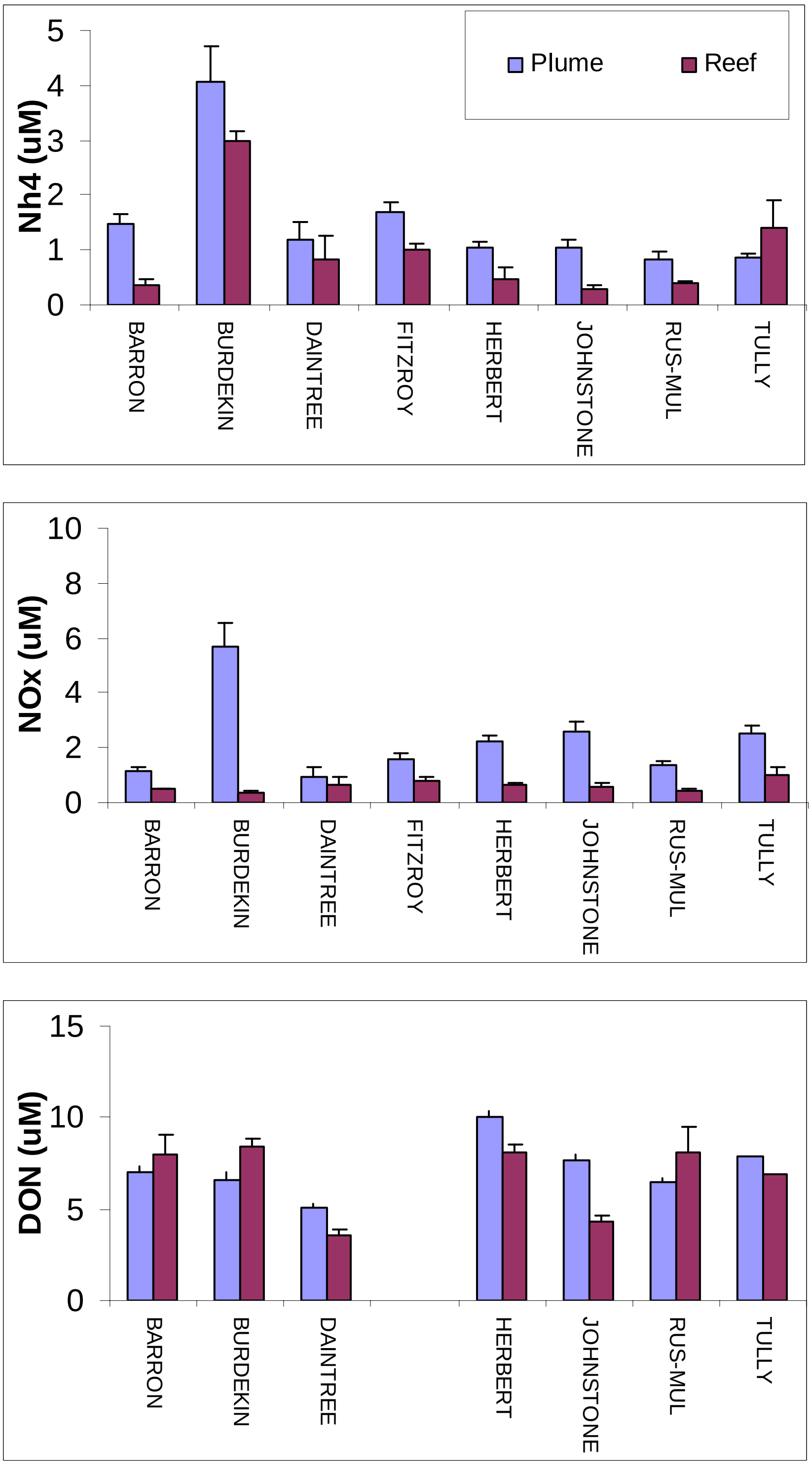


Figure 59: Dissolved nutrients (NH4, NOx and DON) concentrations for plume and reef waters for individual catchments.

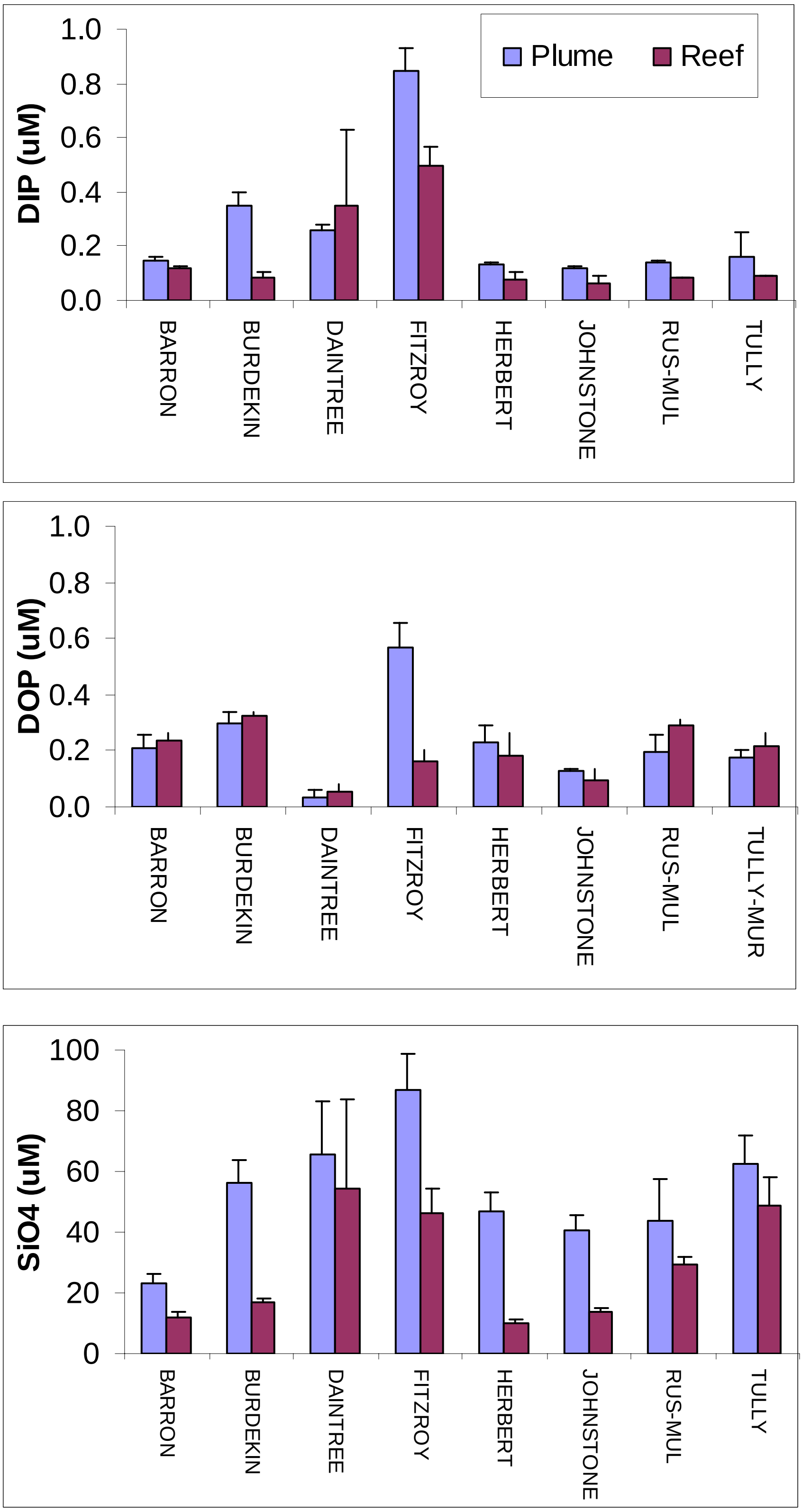


Figure 60: Dissolved nutrients (DIP, DOP and SiO4) concentrations for plume and reef waters for individual catchments.

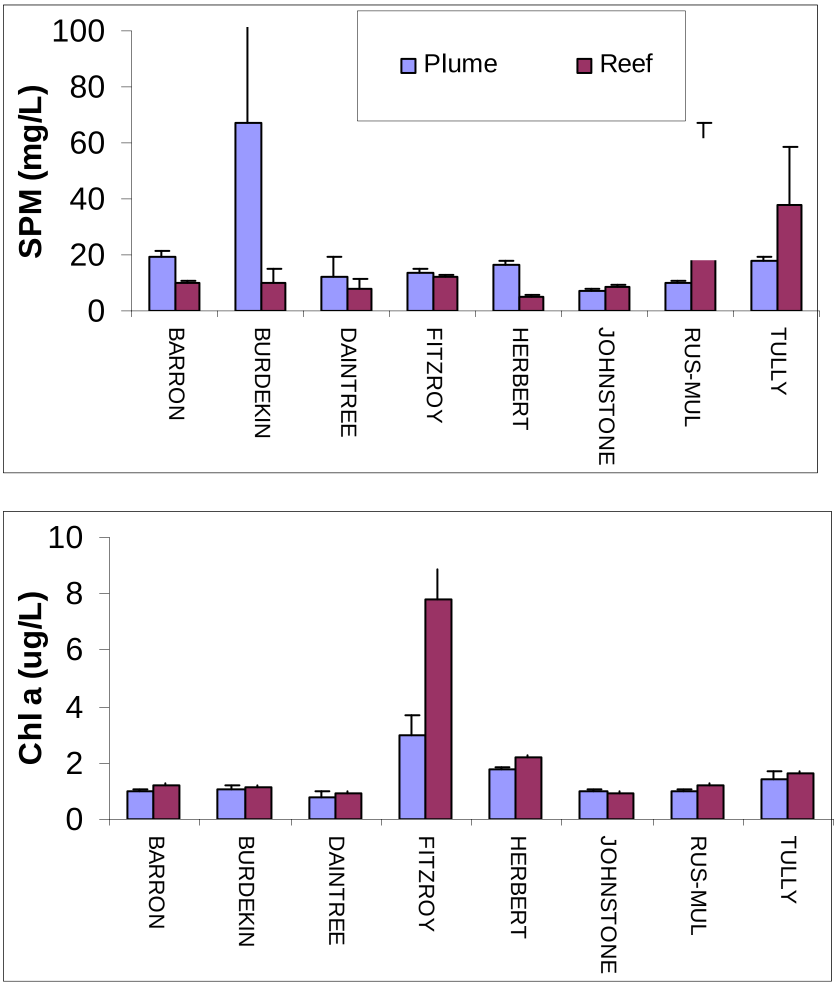


Figure 61: Chlorophyll and SPM concentrations for plume and reef waters for individual catchments.

Table 10: Calculation of change in mean concentrations of constituents for each catchment. –ve indicates a overall loss from inshore sites to reef sites and +ve indicates overall gain.

% loss	NOx	NH4	DON	DIP	DOP	SPM	CHL
BARRON	-59.4	-75.0	13.9	-21.7	11.0	-49.6	21.0
BURDEKIN	-94.1	-27.2	28.1	-75.5	7.7	-85.2	0.8
DAINTREE	-31.7	-30.2	-30.5	35.6	50.0	-36.1	21.0
FITZROY	-50.3	-40.7		-41.1	-71.5	-11.6	160.0
HERBERT	-71.6	-55.4	-19.2	-38.5	-22.3	-68.5	22.6
JOHNSTONE	-78.7	-71.3	-43.9	-48.9	-23.1	17.0	-3.9
RUS-MUL	-65.7	-53.4	24.8	-40.2	48.4	431.3	23.6
TULLY	-60.1	62.6	-12.1	-45.1	20.1	115.3	11.3

5.3.3 Concentrations in plumes related to time (flow)

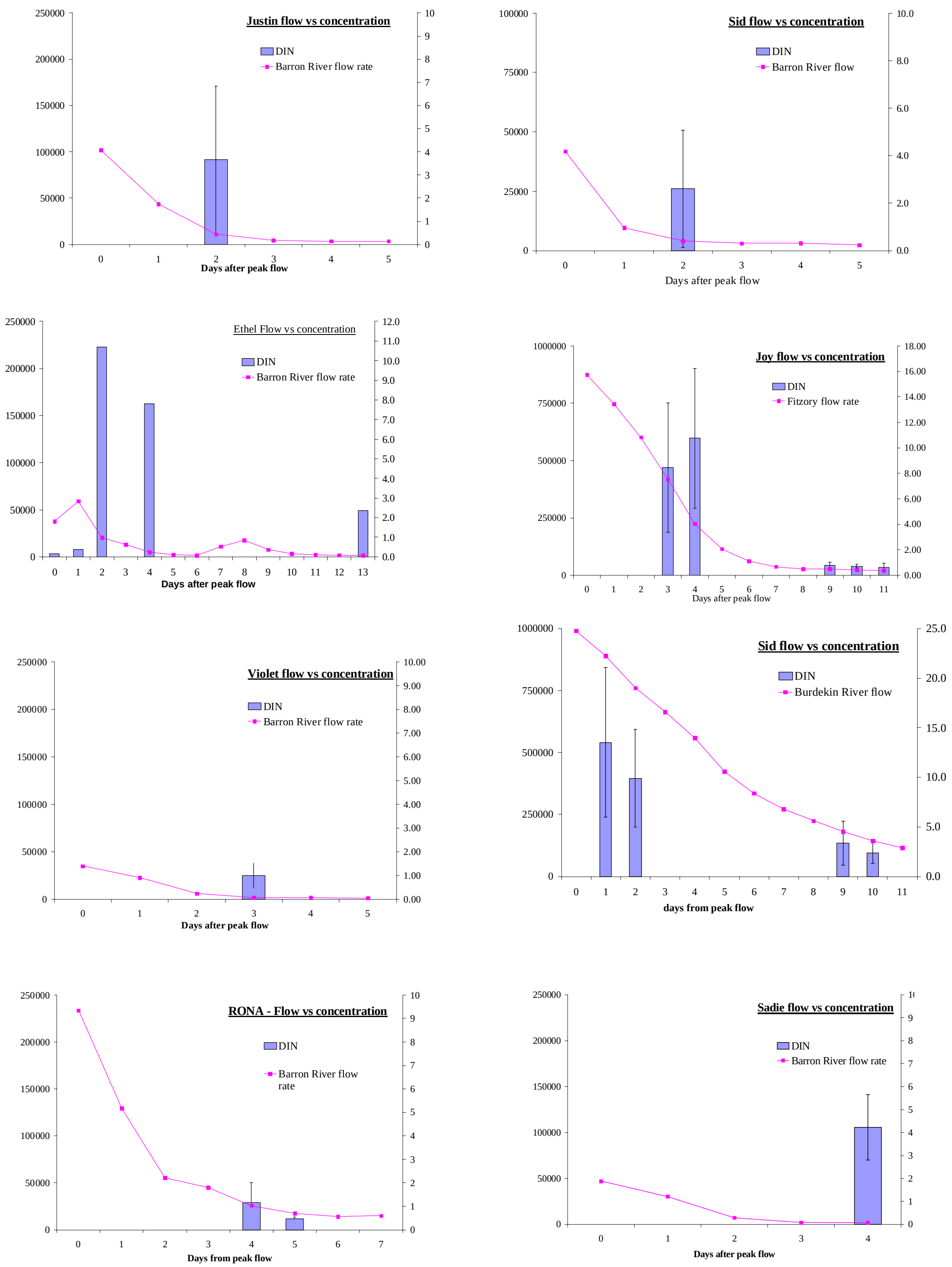


Figure 62:Flow vs concentration relationship between Wet Tropic catchment and DIN (NO_x +NH_4)

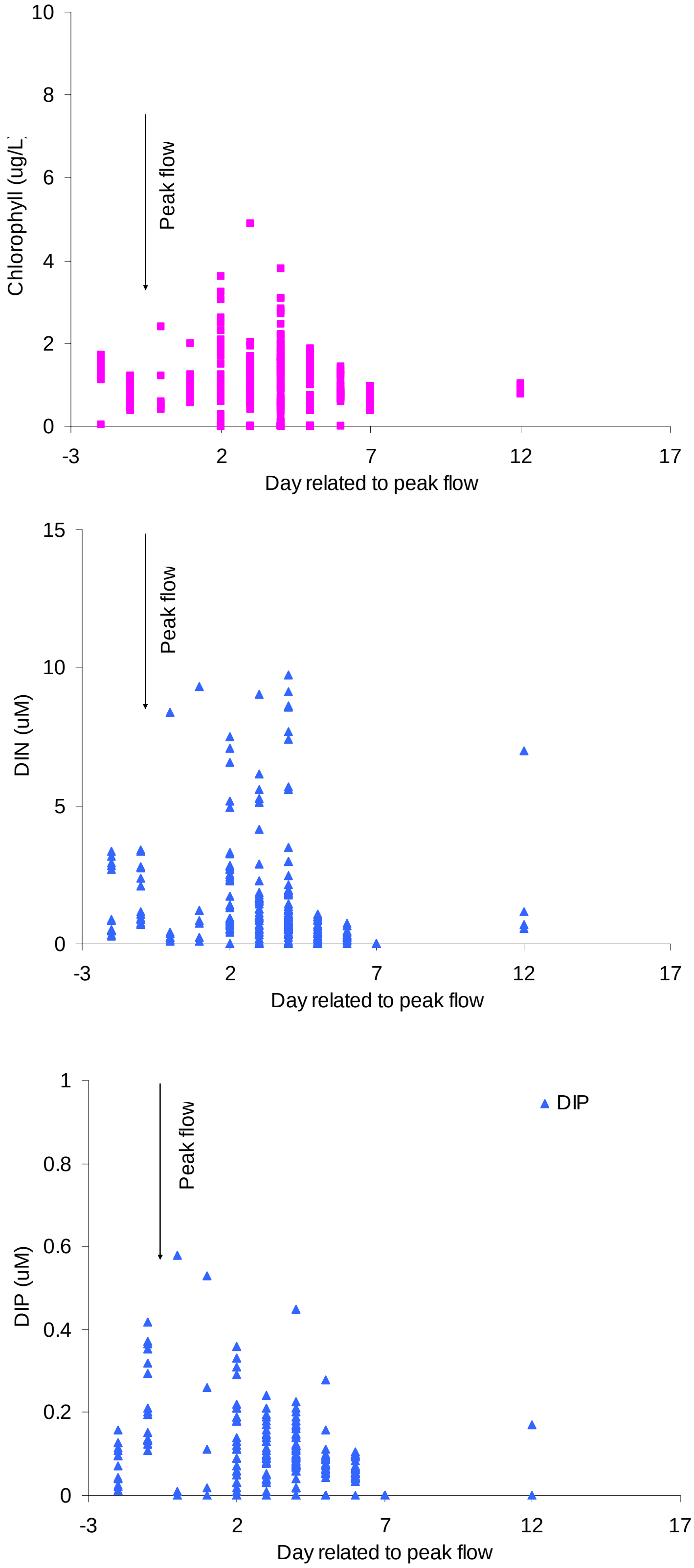
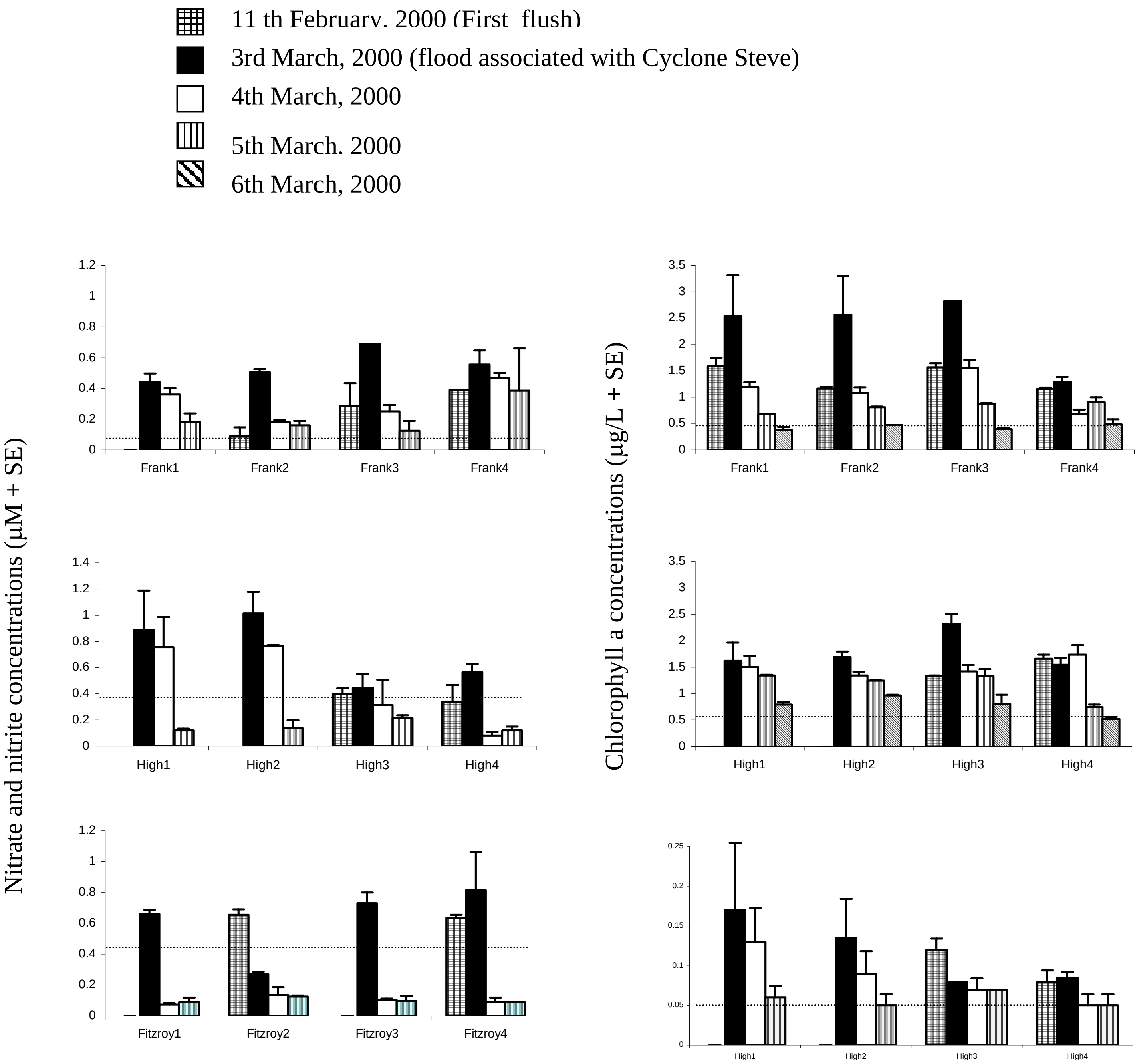


Figure 63: Concentration plotted against day. Day is measured against peak flow, where day = 0 is the highest flow measured for the catchment. Data is combined from all catchments and all plume samples.

5.3.5 Plume concentrations and reef exposure

NH_4, NO_3+NO_2 ,DIP and chlorophyll concentrations measured in waters surrounding these inshore reefs during plume conditions ranged from 0.2 - 3μM, 0.03 – 1.1μM, 0.1–2.5μM and 0.5 –2.6μg/L respectively. These concentrations are dependent on sampling time and location. Note that sampling in the Cyclone Steve flood event (March 2000) was initiated two days after peak flow, and concentrations measured are most likely not representative of the highest concentrations around these inshore sites (Figure 64). NH_4 and NO_x concentrations are very high, and remain elevated over all sampling days. PO_4 is slightly elevated in first flush and the first day of main flood, however concentrations fall back to ambient levels by the third to fourth day of sampling. This may suggest that nitrogen is the nutrient of most concern. Chlorophyll is high, but it is difficult to see a relationship with the nutrient species.

The long term ambient mean concentrations of NH_4, NOx, DIP and chlorophyll in these areas are 0.03 μM, 0.11μM, 0.07μM and 0.56μg/L respectively (Furnas and Brodie, 1996). Concentrations measured in close proximity to reefs during flood plumes are generally 2 to 20 fold higher than ambient concentrations. NH_4 concentrations measured around the Frankland Islands after the first flush (e.g. 3μM) reach up to 100 fold higher than ambient concentrations.


11 th February, 2000 (First flush)
3rd March, 2000 (flood associated with Cyclone Steve)
4th March, 2000
5th March. 2000
6th March, 2000
Nitrate and nitrite concentrations (µM + SE)
Chlorophyll a concentrations (µg/L + SE)
Frank1
Frank2
Frank3
Frank4
High1
High2
High3
High4
Fitzroy1
Fitzroy2
Fitzroy3
Fitzroy4

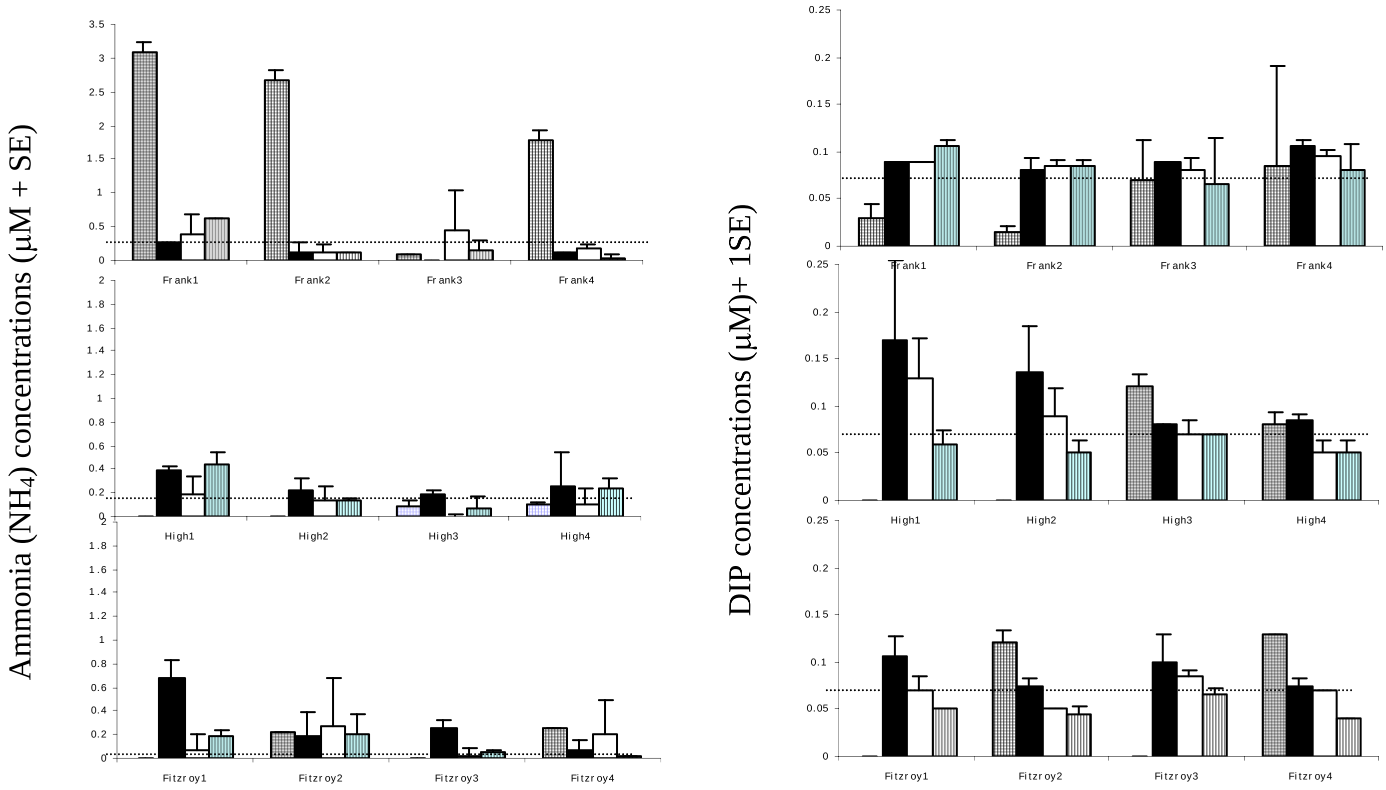


Figure 64: Nitrate+nitrite (NO_3 and NO_2), ammonia (NH_4), chlorophyll and DIP concentrations measured over four reef sites over a first flush and large flow event.

Concentrations are presented for 4 sites located on Franklins, High and Fitzroy reefs. Reefs are located on a gradient of distance from Russell-Mulgrave River. Sites were located around the perimeter of each reef and labelled accordingly (Frank1, Frank2, Frank3, Frank4, High1, High2, High3, High4, Fitzroy1, Fitzroy2, Fitzroy3 and Fitzroy4). Locations of reefs and sites are shown in Figure 57 and 58.

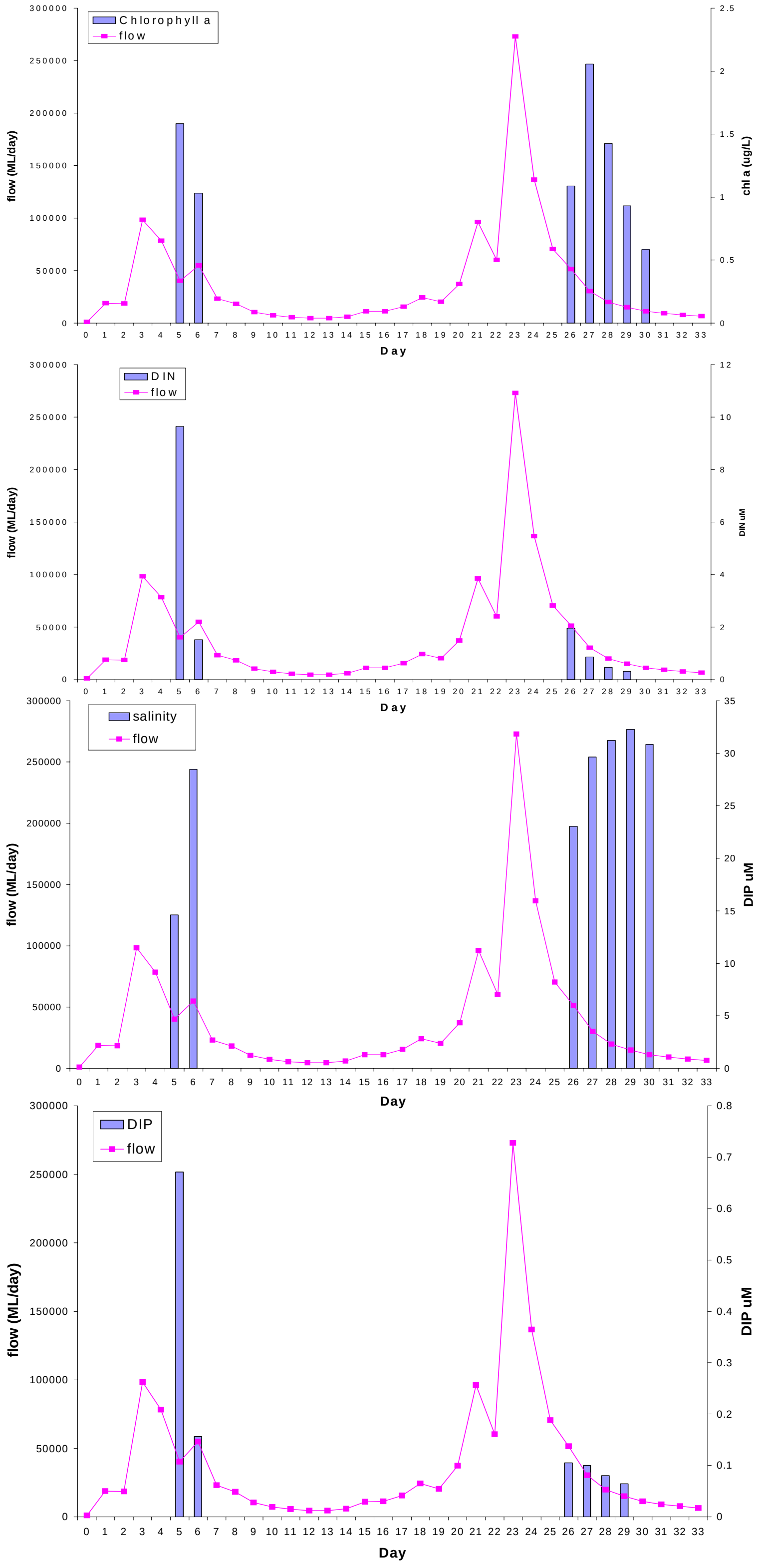


Figure 65: Correlation between flow and DIN, DIP, chlorophyll a and salinity for Cyclone Steve sampling. Flow is presented for Russell-Mulgrave river over high flow event associated with Cyclone Steve

NO_x concentrations averaged over reef sites plotted against day (0-26) showed a slight correlation with Russell-Mulgrave flow (Figure 65). An interesting observation is the very high NO_x concentrations measured directly after first flush, and the moderate concentrations measured after the main flow event. This is due to the mobilisation of the inorganic nutrient load off the catchment during the first flow event after ambient winter flow conditions and the exhaustion of the supply of NO_x.

It is also difficult to distinguish the effect from flow with no evident pattern between the flow volume and water quality concentration. Concentrations would be influenced by the timing of sampling but processes (biological uptake, remineralisation, coastal mixing) other than dilution make it difficult to link nutrients concentrations with instantaneous flow.

5.4 Discussion

5.4.1 Concentration related to catchment

Studies on north Queensland Rivers have described the movement and activity of particulate and dissolved nutrients in river water discharge into the GBR lagoon (Mitchell *et al*., 1997; Mitchell *et al*., 2005). 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 (Mitchell *et al*., 1997).

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 complex and related to wind forces, mixing associated with coastal geomorphology and bathymetry and biological processes in the water column. It can be difficult to assess which changes result from individual factors. Concentrations measured throughout plume waters over different events are highly variable. The magnitude of increase for nutrient concentrations measured in flood plume waters range from 5 to 100 fold greater than ambient water quality conditions. Concentrations measured in the plumes are of course related to the concentrations and loads in the rivers. Rivers on the GBR catchment have shown a strong correlation between the percentage of developed catchment and the concentration of dissolved inorganic nitrogen (DIN) (Wachenfield *et al*, 1998; Devlin *et al*., 2001). In general, concentrations of DIN increase by a factor of 3-50 times on rivers draining into the GBR from highly developed compared to undeveloped or lightly developed catchments (Brodie and Mitchell, 2005).

5.4.2 Concentration related to flow

Previous work has shown (Taylor and Devlin, 1997; Devlin, 1997; Brodie and Furnas, 1996) that the timing of sampling is critical to obtaining reliable estimates of nutrient concentrations in flood plumes. This seems evident in the flow and concentration correlation shown for samples taken in Russell-Mulgrave plume associated with Cyclone Steven (Figure 64). 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.

5.4.3 Plume concentrations and reef exposure

Concentrations measured in close proximity to reefs are 2–20 fold higher than ambient concentrations and above the preliminary water quality criteria for GBR waters (Moss *et al*., 2005). 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, under the project ENCORE (Koop *et al*, 2001). 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. Impacts on coral reef organisms and processes from nutrient loading vary in respect to dose level, whether nitrogen and/or phosphorus were elevated and are often species specific. Impacts have included coral mortality, stunted coral growth with increased nitrogen and reduced skeletal density with increased phosphorus (Ward and Harrison, 1997). Increased nutrient supply during a flood plume has been shown to enhance the growth of phytoplankton, leading to plankton blooms (Furnas 1989; Brodie and Mitchell, 1992; Rodhe *et al*., 2006). Increased concentrations of dissolved inorganic nutrients decrease the recruitment success of hard corals (Ward and Harrison, 1997) and support the growth of macroalgae (Smith *et al.*, 1981; Grigg and Dollar, 1990). 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 (Schaeffelke and Klumpp, 1998a, 1998b; Schaffelke, 1999).

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 (Rasmussen and Cuff, 1990; Rasmussen *et al.*, 1993; Bjork *et al.*, 1995). In general, prolonged exposure to concentrations of NO_3 or NH_4 above 5μM or PO_4 above 2μM lead to adverse impacts on corals summarised in Ferrier-Pages *et al* (2000).

As a result of the higher loads and concentrations of nutrients reaching inshore ecosystems, inshore reef and seagrass beds off the developed Wet Tropic catchments (Daintree to Herbert) are now experiencing above toxic levels of nitrogen and phosphorus for periods of days to several weeks in every wet season.

The impacts from this prolonged exposure to higher inorganic nutrients can be two pronged. This research was set up to define short-term peaks during the plume, and to relate these values to inshore coral reef processes. However there is considerable evidence to support that inshore areas, both coral reefs (Van Woesik *et al*, 1999; Fabricus and De'ath, 2001a; 2001b; Fabricus and De'ath, 2004; Fabricus *et al*., 2005) and seagrass beds are being negatively impacted by changes in river and plume water composition from a long-term change in the nutrient composition. (Fabricius and Wolanski, 2000, Wolanski and Duke, 2002) show that in areas of high nutrient enrichment there is the development of marine snow (sticky nutrient particles colonised by mucopolysaccharide diatoms and bacteria) which leads to the flocculation of amorphous aggregates. These flocs can sink to sea floor, leading to smothering, or rise to surface, reducing available light. Small filter feeding organisms tend to have expended more energy in removing the larger stickier “snow” flocs and this can be detrimental or lethal to small benthos animals (Fabricus and Wolanski, 2000). This research tends to support the idea that long term nutrient enrichment in the inshore lagoon, related to increases in the nutrient inputs from flooding rivers, can be detrimental to ecological health. Previous work in this thesis defines the inshore coastal area adjacent to the Wet Tropics catchments as an area of elevated chlorophyll a, which supports this idea of increasing long term nutrient enrichment for certain areas of GBR. Further research is required on the impacts of short term pulses of nutrients and sediment on the long term health of the inshore reef system.

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.

Chapter 6: Analysis of exposure from terrestrial runoff for the Great Barrier Reef

Chapter 6: Analysis of exposure from terrestrial runoff for the Great Barrier Reef

6.1 Introduction

Coastal areas such as the Great Barrier Reef are particularly vulnerable to eutrophication, and there are a number of recognised pressures on the Great Barrier Reef, which can potentially lead to a nutrient enriched coastal system (Brodie *et al*, 2005). As previously shown (2.4.1, 5.4.1) the quality of riverine waters discharging into the GBR has deteriorated in recent years as human population and catchment activities have increased along coastal regions. However, our conceptual model of eutrophication is still evolving, hampered by the non linear relationship between nutrient enrichment and production in marine systems and can be difficult to model, monitor and manage in realistic time scales (Cloern, 1998, Meesters *et al*. 1997). Our understanding of the complex relationships between variables and processes occurring on coral reefs is limited, and it can be difficult to link a pressure (i.e. nutrient enrichment) with a direct biological response. Simulation of potential impact or the assessment of risk from nutrient enrichment based proxy variables on the GBR may provide another mechanism of managing the effects of coastal eutrophication.

In this chapter a model is developed to predict areas within the Great Barrier Reef most exposed to risk of terrestrial discharge. The simplest models for eutrophication aim only to predict the value of an easily observed variable, such the biomass of phytoplankton. These models are referred to as screening models, as they are used to screen ecosystems for actual or potential eutrophication. There are many models, indicators and indices of eutrophication to predict or calculate the risk or impact of nutrient enrichment. The USA based model (Bricker *et al*., 1999) uses a scoring system of disturbances related to overenrichment, such as increased chlorophyll biomass, submerged aquatic vegetation (SAV) and dissolved oxygen. Nixon (1995, 1996) based his assessment on a calculation of phytoplankton primary production, related to trophic status. Nixon (1992) showed a strong relationship between areal nutrient load and primary production in a wide variety of ecosystems, including marine coastal waters. There are models (Painting *et al*, 2006) for assessing susceptibility to nutrient enrichment based on areal nutrient loads and light climate related to the potential of primary production. The European Water Framework

Direction, classifies estuarine and coastal waters on a combination of phytoplankton indices, nutrient enrichment and susceptibility (light climate) (Devlin *et al*, 2006). All these models and indices predict the susceptibility of a system to be negatively impacted by anthropogenic inputs, either from nutrient enrichment, contaminants, suspended sediment or a combination of all three.

6.2 Components of the model

Diversity in the catchment (due to factors such as topology, landuse) and their watersheds results in different types of inputs into the GBR. Numerous similarities exist between all catchments, but there are also basic differences. Indicators of ecological health or susceptibility to nutrient over-enrichment are different for these two types of systems. However, many of the same biological or ecological attributes may work as indicators in these different systems. Any monitoring and management efforts to restore systems affected by nutrient enrichment should be underpinned by knowledge of the physical environment and the undisturbed ecosystem condition. The results from the previous chapters have elucidated a number of factors which can correspond to a measured disturbance associated with eutrophication and are associated with a higher degree of risk for a possible effect from nutrient enrichment.

6.2.1 River concentrations

Contaminant and nutrient loads in river discharge vary accordingly to the extent of agricultural and urban usage on the catchment**.** Rivers such as the Normanby, with relatively undeveloped catchments, have low dissolved inorganic nutrient fluxes (Furnas, 2003) while the Herbert, Tully and Pioneer, with extensive cropping on the catchment have high dissolved inorganic nutrient fluxes (Mitchell *et al*, 1997; 2001, 2005). River discharge from catchments dominated by agriculture typically have dissolved inorganic nitrogen (nitrate and ammonia) concentrations in flood flow 30 times that of rivers flowing through undeveloped catchments (10–100 μM compared to 1–5 μM) (Eyre and Davies 1996; Faithful and Brodie, 1990; Mitchell and Furnas, 1997; Hunter *et al* 1996; Noble *et al* 1997; Mitchell *et al*. 1997). Flood waters from rivers where the upper catchment is undeveloped, lightly developed or used for rangeland grazing have low concentrations of dissolved inorganic nutrients (e.g. 1–10 μM for nitrogen). In contrast, waters discharging from the same catchment, after passing through cropping-dominated lower catchment and floodplain, have high concentrations of dissolved inorganic nutrients (e.g. 10–100 μM for nitrogen, Brodie and Mitchell; 2005). In rivers with large areas of rangeland beef grazing, concentrations of suspended sediments and particulate nitrogen and phosphorus are high compared to rivers with limited catchment development. In general suspended sediment concentrations measured in dry tropic rivers are higher than those measured in wet tropical rivers (Furnas and Mitchell, 2001).

Pesticide residues and dioxins have been detected in GBR coastal sediments, seagrasses and dugongs (Muller *et al*., 1998; 1999; Haynes *et al*., 2000a). Of the pesticides still in common use on the GBR Catchment, the herbicide diuron, widely used in sugarcane cultivation, is most commonly found in subtidal and intertidal sediments (Haynes *et al.*, 2000a). The concentrations of diuron found are at or above the concentrations assessed to cause damage to seagrasses (Haynes *et al*., 2000b).

6.2.2 Delivery of nutrient and sediments during flood events

Concentrations of suspended sediments, particulate and dissolved nutrients and pesticide residues in east coast Queensland rivers reach peak values during flood events, typically associated with tropical cyclone and monsoon rainfall (Chapter 4, 5). These extreme flow conditions deliver high concentrations of nutrients and sediments into the inshore regions of GBR lagoon. Factors which will affect the delivery of sediments and nutrients include the total discharge; big rivers such as Fitzroy and Burdekin have a more extensive influence and present a higher risk than the smaller Wet Tropics rivers. However, it is also the frequency of discharge and plume formation where rivers which have frequent significant discharges, such as the Tully River, can apply a higher risk to the nearshore ecosystems.

6.2.3 Fluxes of nutrients and sediment

The fluxes of the most important river borne pollutants, suspended sediment, nitrogen, phosphorus and diuron are particularly important in assessment of risk and can act as a proxy to the extent and change in land use of the catchment. Simply the greater the flux the greater the risk. Previous chapters have demonstrated that there is a higher flux of nutrient delivery in plume waters adjacent to agricultural catchments, though it is difficult to define the exact increase due to lack of plume data from pristine catchments. Increased phytoplankton biomass in coastal areas adjacent to Wet Tropics catchments with high agricultural usage (Chapter 2).

6.2.4 Nitrogen

Dissolved inorganic nitrogen (DIN) is an additional risk to the total nitrogen (TN) flux. The greater the proportion of DIN (the bioavailable component) in the TN, the greater the risk.

6.2.5 Distance and direction of ecosystem from river mouth

Some rivers, such as the Fitzroy and Daintree, have significant reef areas within the plume extent area, while for others, such as the Burdekin, reefs only occur at a considerable distance from the mouth. Mixing processes in the plume waters can lead to strong gradients in concentrations of, and transformations among, biogeochemical constituents in the plume environment (Devlin *et al*, 2001). Predominately, the dissolved inorganic fraction dilutes linearly though the salinity gradient. River plumes generally move to the north of the river mouth driven by south-east winds and Coriolis forcing (Wolanski, 1994; Devlin *et al*, 2004). The northward zone of influence from each river mouth is also detectable in benthic sediment composition (Lambeck and Woolfe, 2000). In considering these factors, a simple inverse distance factor was used in the risk analysis for reefs to the north of river mouths.

6.2.6 Combined factors of model

The model will estimate the concentrations of contaminants in river discharge (eg Furnas and Mitchell, 2001), or modelled concentrations for rivers with little known data (Prosser *et al*, 2001a; 2001b; Brodie *et al*., 2003) to calculate a river pollution index. This river pollution index will be combined with our knowledge on the spatial and temporal patterns of flood plume distribution in the Great Barrier Reef (Devlin *et al*, 2001), and the proximity of reefal area to river plumes to assess risk to GBR ecosystems from contaminated terrestrial runoff.

6.3 Methods

6.3.1 Study area

124 reefs were selected throughout the GBR reef system to represent good spatial coverage of the reef system, from inshore to offshore and north to south. The movement of plume waters was calculated from the river mouth to the inner reef edge. Distance

was not calculated in a direct line, but as the plume moves, so that distance around headland and reefs were included in the calculation.

6.3.2 Model

An Ecosystem Risk Index (ERI) has been developed based on indices of river concentrations, frequency of delivery, dissolved nitrogen, distance from river sources and direction from river mouths.

The model will use a three-stage approach,

- Defining the pressures from terrestrial discharge into the coastal system and ranking them accordingly **– River Pollution Index**
- Defining the area within the Great Barrier Reef most likely to be impacted by riverine plumes **– Plume direction factor**
- Combing state of river (River pollution index), area of influence and potential on inundation from riverine plume (plume direction factor) to estimate **Ecological Risk Index (ERI)**

6.3.3 River Pollution Index

The River Pollution Index measures the relative pollution of the major rivers discharging to the GBR. The index includes components of mean annual discharge, discharge variability, total suspended sediment including particulate nitrogen and phosphorus load, dissolved inorganic nitrogen (DIN) load, diuron load and urban discharge load (Equation 1). Description of each factor and data sources are listed in Table 11. Calculated river pollution indices for the 25 major rivers are listed in Table 12.

River Pollution Index. = *f* (Ad) + *f* (F) + *f* (TSPM) + *f* (DIN) + *f* (D) + *f* (U) ……..Equation 2

where *Ad = Mean annual discharge,*

F =River variability,

TSPM = total suspended solids flux,

DIN = (dissolved inorganic nitrogen),

D = Diuron load and U = Urban load.)

Table 11: Description of data sources and factors used in calculation of River Pollution Index

Factor		Description	Period	Data sources	Analysis
Mean annual discharge	***f(Ad)***	Mean annual discharge of river flow (km^{3})	1968 – 1994	Department of Natural Resources flow network (gauging stations).	Values for 25 rivers were evenly distributed into 11 classes and assigned a scale of 0 to 10
Variability in flow	***f(F)***	This measure was derived from the number of days with flow exceeding the mean daily flow for each river	1968 - 1994	Department of Natural Resources flow network (gauging stations).	Values for 25 rivers were evenly distributes into 11 classes and assigned a scale of 0 to 10
Total Suspended Solid	***f(SPM)***	TSPM was calculated using SedNet (Brodie et al, 2004)			These values (averaged as tonnes/year) were scaled evenly into a 0 – 10 range to give the final function value.
Dissolved Inorganic Nitrogen loading.	***f(DIN)***	DIN loading was calculated using SedNet (Brodie et al, 2004)			Scaled 0 – 10
Diuron	***f(D)***	Diuron flux was derived from a proxy value – diuron use per hectare on the 26 catchments (Hamilton and Haydon, 1996).		Diuron concentrations in GBR sediments (Haynes et al, 2000a).	Validated by data showing highest values of diuron in coastal sediments adjacent to those catchments with the highest diuron usage Scaled 0 – 10.
Urban	***f(U)***	A measure of urban discharge, incorporating some element of industrial discharge, was developed based on catchment population numbers		Population landuse patterns (Gilbert and Brodie, 2001).	This measure was scaled evenly into a 0 – 4 range thus giving less weight to this factor than the others making up the RPI.

Table 12: Calculated River Pollution Indices for GBR Rivers.

River	Export		Rating (scaled from 0 to 10)							
	Total sed export (kt/yr)	DIN export (t/y)	Annual Discharge	River variability	Fertilizer	Total sed (TSPM)	DIN	Diuron	Urban	RPI
Normandy	1169	950	4.8	4.5	0	4.0	4.9	0	0	18.2
Endeavour	244	220	1.7	2	0	0.8	1.1	0	1	6.7
Daintree	182	184	1.2	7.2	0.4	0.6	1.0	0.5	0.5	11.0
Mossman	52	52	0.6	8.4	3.9	0.2	0.3	3.4	1	13.8
Barron	76	222	0.8	5.1	2	0.3	1.2	0.1	4	11.4
Russell-Mulgrave	290	1031	3.5	8.7	3.7	1.0	5.3	1.2	2	21.7
N&S Johnstone	440	1649	4.6	9.1	10	1.5	8.5	3.6	3	30.4
Tully	240	950	3.2	10	5.4	0.8	4.9	0.8	3	22.7
Murray	62	242	1.1	8.4	6	0.2	1.3	0.6	1	12.6
Herbert	694	1027	3.9	6	2.7	2.4	5.3	0.8	3	21.4
Black	165	53	0.4	3.3	0	0.6	0.3	0	4	8.5
Ross	82	64	0.5	2.4	0	0.3	0.3	0	4	7.5
Haughton	294	140	0.7	3.1	8.7	1.0	0.7	0.5	1	7.0
Burdekin	2816	1922	10	4.3	0.1	9.7	10.0	0	3	37.0
Don	455	71	0.7	3.5	0.7	1.6	0.4	0.1	2	8.2
Proserpine	362	250	1.1	2.7	3.3	1.2	1.3	1.8	3	11.1
O'Connell	811	418	1.5	3.8	3.3	2.8	2.2	4.9	1	16.1
Pioneer	409	389	1.2	3.7	7.5	1.4	2.0	7.3	3	18.6
Plane Ck	602	429	1.5	3.2	6.8	2.1	2.2	10	3	22.0
Fitzroy	2915	1251	5.8	4.1	0.1	10.0	6.5	0	4	30.4
Calliope	220	43	0.3	2.9	0.1	0.8	0.2	0	3	7.2
Boyne	45	73	0.3	3.2	0	0.2	0.4	0	2	6.0
Baffle Ck	321	178	0.8	4	0.2	1.1	0.9	0	1	7.8
Kolan	63	109	0.4	3.6	1.1	0.2	0.6	0.3	1	6.1
Burnett	474	473	1.1	4.6	0.3	1.6	2.5	0.1	4	13.9

6.3.4 Plume direction factor

Spatial distribution of dissolved nutrients is based on the linear movement of dissolved inorganic nutrients through the plume waters and the proximity of the reef to the river mouth. A simple inverse distance factor was used in the risk analysis for reefs to the north of river mouths. To calculate the probability of a reef being inundated by plume water moving out from the river mouth, a plume direction factor (PDF) was applied to each ecosystem and reef combination (Figure 66).

The Plume Direction Factor (PDF) is based on our knowledge of the spatial distribution of plume water in the GBR (Devlin *et al*, 2001, 2005; King *et al*, 2001) and calculates how often the reef was likely to be inundated by plume waters based on the frequency of plume extent (Chapter 4). The location of the reef in relation to plume movement and distance away from the river mouth was designated a category type, based on the angle of sight from the river mouth.

Category 1 events: This is where plume waters spread commonly to the north and northwest driven by the prevailing southeast wind regime and Coriolis effects and constrain close to the coastline (Category 1 events). Thus ecosystems at an angle of 180^0 – 360^0 to the river mouth are placed in Category 1 with a PDF of 1.

Category 2 events: Plume waters move to north and northwest with a slight offshore movement, driven by weaker southeasterly winds. Headlands and Coriolis effects can also attribute to plume moving slightly offshore. Thus ecosystems at an angle of 0^0 – 30^0 to the river mouth are placed in Category 2 with a PDF of 0.8.

Category 3 events: Similar to Category 2 but more offshore movements, influenced by intermittent wind direction to the north and northeast. Thus ecosystems at an angle of 30^0 – 45^0 to the river mouth are placed in Category 3 with a PDF of 0.6.

Category 4 events: Movement offshore and to the east is less common and requires northerly winds. Thus ecosystems at an angle of 45^0 – 90^0 to the river mouth are placed in Category 4 with a PDF of 0.4.

Category 5 events: Movement of plume waters to the south of the river mouth is least likely to occur (Category 5 events). Thus ecosystems at an angle of 90^0 – 180^0 to the river mouth are placed in Category 5 with a PDF of 0.2.

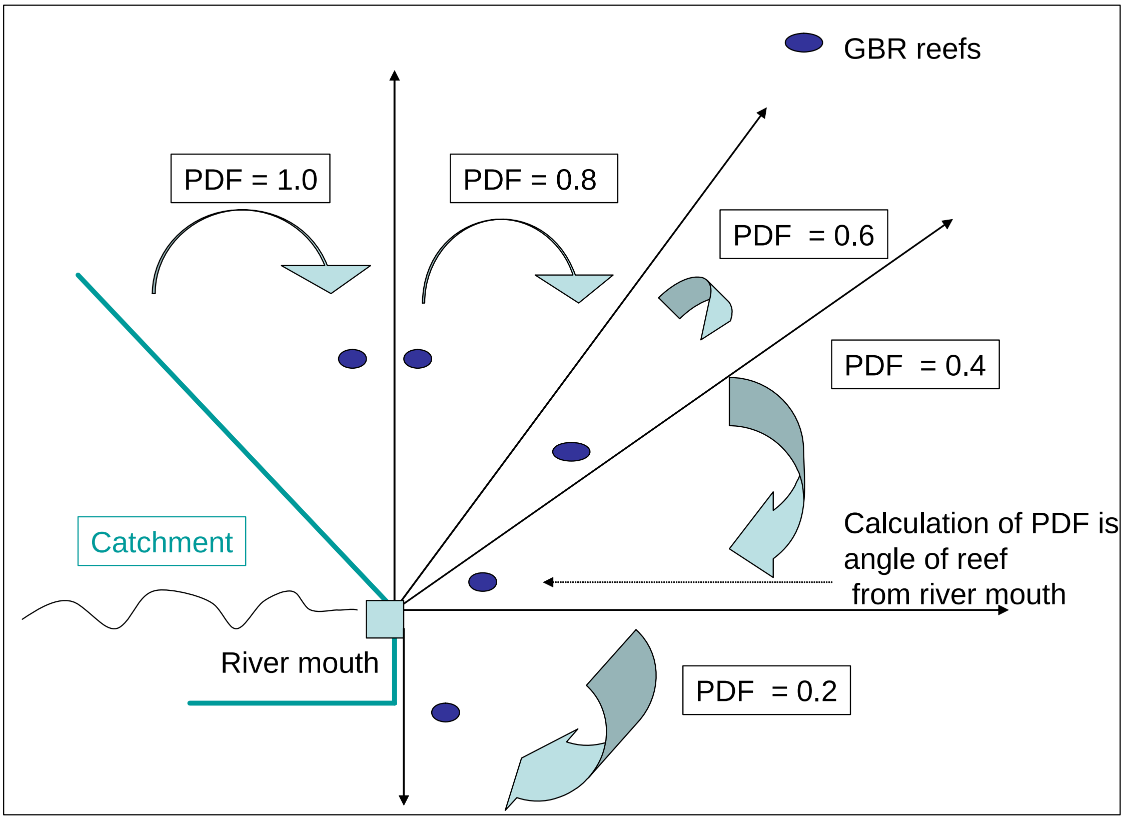


Figure 66: The Plume direction factor. Location of the reefs in relation to the river mouth is how the PDF is calculated.

6.3.5 Ecosystem Risk Index

The Ecosystem Risk Index (ERI) was formulated as a function of the RPIs, the distance of the ecosystem to each relevant river and the direction of the ecosystem to each relevant river mouth (Equation 2). In the present study only coral reefs were considered in the risk analysis and a selection of 148 were assessed. In future, assessments of the other ~3000 reefs of the GBRWHA will be carried out, as well as other ecosystems such as seagrass meadows. The number of rivers considered in the ERI analysis (n) was determined on an individual ecosystem basis from our knowledge of the distribution of river plume water in the GBR lagoon (Devlin et al, 2001).Examples of calculation of ERI for 5 selected reefs is shown in Table x.

Ecosystem Risk Index =

$$\mathbf{(R.P.I_1 \times (\mathit{PDF}_1) \times 1/d_1^{*}) + (R.P.I_2 \times \mathit{PDF}_2 \times 1/d_2) + \ldots\ldots + (R.P.I_n \times \mathit{PDF}_n \times 1/d_n)}$$

-- Equation 3

RPI	**River Pollution Index**
***PDF**.	**The Plume Direction Factor (PDF)**
***d**.	**The distance from each ecosystem to the relevant river mouth.**
n	**Number of rivers used in the analysis**

A 1/d function is used which assumes linear dilution of pollutants in the plume with distance from the river mouth. This is approximately correct for many parameters, suspended solids being the exception where dilution (as sedimentation) occurs at a greater than linear rate (Devlin *et al*, 2001). However, for this calculation of the risk all parameters are assumed to decrease linearly with distance.

Table 13: Example of Ecosystem Risk Index (ERI) calculation for two reefs (Round-Russell Reef and Tobias Spit).

These two reefs can potentially be impacted by a number of riverine sources and individual ERI are calculated for every river. Total ERI is a sum function of all the individual ERIs.

Reefs	Associate Rivers	RPI*	PDF*	distance by sea	1/d	Individual ERI	TOTAL ERI
Round - Russell Reef	Barron	14.6	0.2	54	0.02	0.05	1.8
	Russell-Mulgrave	19.9	0.4	13	0.08	0.61	
	Johnstone	31.2	0.8	32	0.03	0.78	
	Tully	22.8	0.8	90	0.01	0.2	
	Herbert	18.8	1	146	0.01	0.13	
	Burdekin	20.9	1	325	0.00	0.06	
Tobias Spit (High Island)	Barron	14.6	0.2	52	0.02	0.06	3.0
	Russell-Mulgrave	19.9	0.8	9	0.11	1.77	
	Johnstone	31.2	1	42	0.02	0.74	
	Tully	22.8	1	106	0.01	0.22	
	Herbert	18.8	1	160	0.01	0.12	
	Burdekin	20.9	1	319	0.00	0.07	

6.5 Results

The calculated Ecosystem Risk Indices for 154 selected reefs are listed in Table 14 and reefs that fall into the high-risk category are ranked in Figure 67. From these ERI values, a risk assessment map (Figure 68), delineating area of risk from terrestrial influence has been constructed. Risk areas around each selected reef were extrapolated to give an overview of the whole reef system.

The risk predictions resulting from this assessment are based on our broad understanding of the distribution of risk within the GBR, and are not intended to define areas of impact, but more to delineate areas which can potentially be affected by anthropogenic inputs. Outputs from the risk model predicted 30 reefs at high risk, with

Tobias Spit and Snapper Island being at highest risk. This illustrates that the main contributors to risk from terrestrial discharge in the Great Barrier Reef are close proximity to river mouths and frequent coverage of plume discharging from agricultural catchments. Biological end points most likely to be at risk are the inshore reefs captured in the high-risk category and the intertidal areas, including seagrass beds and intertidal areas. On the opposite end of scale are 90 reefs, which are at minimal, or no risk from terrestrial discharge. The no-risk scenario is driven by distance away from river mouth, or plumes discharging from pristine or low cropping catchments, or located away from the expected plume distributions. These results do demonstrate that the majority of the Great Barrier Reef areas are at minimal risk from terrestrial discharge. From this preliminary risk analysis, inner-shelf reefs in the Wet Tropics region and Whitsundays are considered to be at highest risk from contaminants in river run-off in the GBR. Moderate risk reefs are found between inshore and midshelf areas between Cape Upstart and the Daintree River. Moderate to low risk reefs are primarily in midshelf areas, with some inshore reefs within Princess Charlotte Bay. Minimal risk area from terrestrial runoff are the northern reefs and the outer shelf reef area.

Table 14: Summary of ERI calculation for the 154 reefs included in the analysis.

High Risk (<1.0)	Moderate risk (0.7 - 0.9)	Low Risk (0.5 - 0.69)	No Risk (<0.5)	
Tobias Spit	Split Rock Reef	Low Islands Reef	Brampton Reef	Hope Reef
Snapper Island	Magnetic Island Reef	Humpy Reef	Darley Reef	Middle Island Reef
Victor Reef	Gibson Reef	Smith Bowden Reef	Gubbins Reef	Prudhoe Island Reef
Flat Top Reef	Green Reef	Defiance Reef (South)	Barron Reef No 1	Cairns Reef
Round -Russel	Rocky Island Reef	Garden Reef	Cape Rock Reef	Dawsons Reef
Highwater Reef	Green Island	Coombe Reef	Old Reef	Shaw Island Reef
Normandy	Virago Shoal	Magnetic Island #6	Broadhurst Reef #2	Shaw Island Reef #4
Hay Reef	Bald Reef	Curtis Island #2	Bailey Reef	Phillips Reef
Stingaree Reefs	Gould Reef	Defiance Reef (North)	Bare Reef	Dingo Reef #3
Fitzroy Reef	Salamander Reef	Wedge Island Reef	Centipede Reef	Dingo Reef #2
Middle Reef	Rattlesnake Island	Howie Reef	Keswick Island #1	Coppersmith Reef
Magnetic Is # 1	Herald Island Reef	Hudson(Coolah) Reef	Keeper Reef	Pickersgill Reef
Scott Reef	Stanley Island Rf	Pearl Reef	Agincourt No 1	Creech reef (Nth)
WheelerIsland	Bay Rock Reef	Unity Reef	Nares Reef	St Helen Reef
(Bedarra) Reef	Bray Reef	Lake Reef	Ripple Rocks Reef	Wilkie Reef
Struck Reef	Magnetic Island Reef	Brook Shoal	Lodestone Reef	Fairlight Reef
(Timana) Reef		Bowden Reef	Boulder Reef	Egret Reef
Flat Rock Reef		Brook Islands Reef	Holbourne Island Reef	Osterland Reef
Haycock Reef		White Topped Reef	Arlington Reef	North Head Reef
Cockle Bay Reef		Great Keppel Is. No 5	Upotu Reef	Hope Island West
Double Island		Korea Reef	Hitchinbrook Reef	Hope Island East
Freshwater Point		Conical Rocks	Long Rock Reef	Gloucester Reef
Sudbury Reef		Eva Reef	North Repulse Reef	South Repulse Reef
		Allonby Reef	Oyster Reef	Pelorus Reef
		Twenty Foot Reef	Irving Island Reef	Orpheus Island 5
		Batt Reef	Flat Island Reef	Temple Island Reef
		Egg Reef	Charity Reef	Evening Reef
		Taffy Reef	East Repulse Reef	Stone Reef
			Great Palm Island Reef #2	Cow Reef
			Lindeman Island Reef #4	Orpheus Island Reef #1
			Long Island Reef #5	Anchorsmith Reef
			Endeavour Reef	Silversmith Reef
			Barber (Boodthean) Reef	Sidney Reef
			Four Foot Reef	Tryon Reef
			Long Island Reef #6	Seaforth Reef
			Prawn Reef	Brush Island Reef
			Long Island Reef #3	Williamson Reef
			Faith Reef	Stanley Reef
			Long Island Reef #2	Lark Reef
			South Overfall Reef	Knight Reef
			Long Island Reef #1	Thomas Reef
			Dingo Reef #1	Waratah Island Reef
			Mast Head Reef	Pool Reef
			Heron Reef	Renow Reef
			Tiger Reef	Blacksmith Reef
			Wallaby Reef	Hammer Reef
			Goldsmith Island Reef #3	Minster Reef
			Passage Isle Reef	Bellows Reef
			Manta Ray Reef	Kangaroo Rf (West)
				Forge Reef

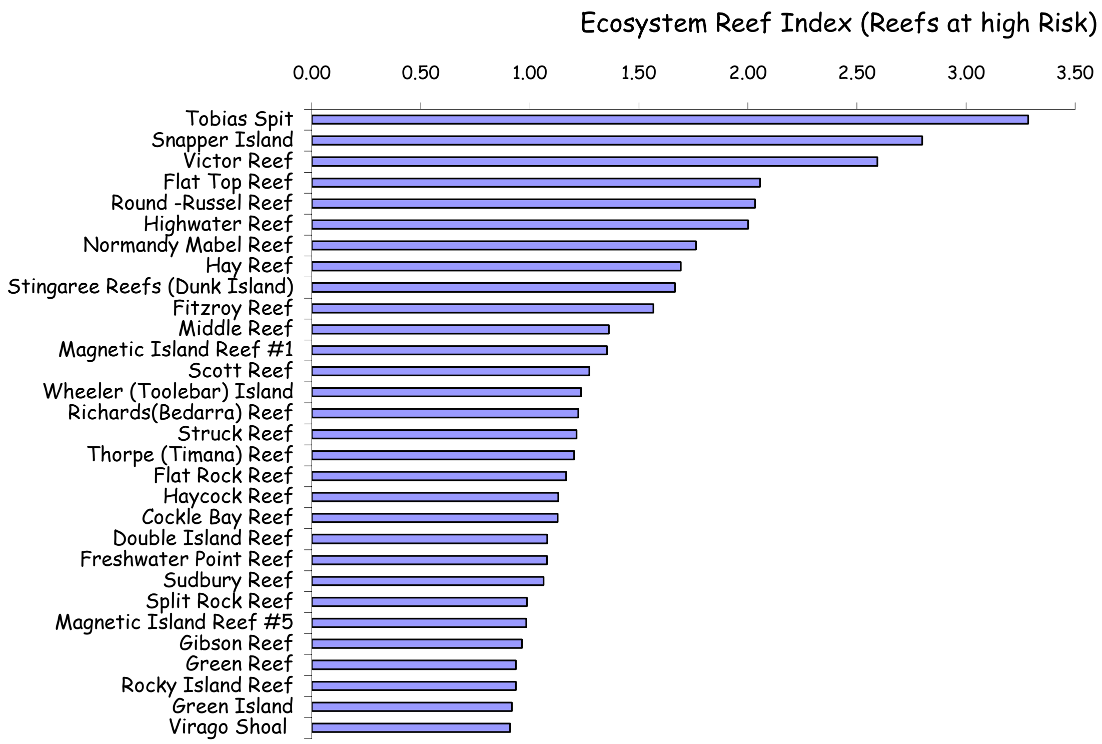


Figure 67: Rating of risks at high risk as calculated by the ERI model. High risk was denoted as total ERI being greater than 0.9.

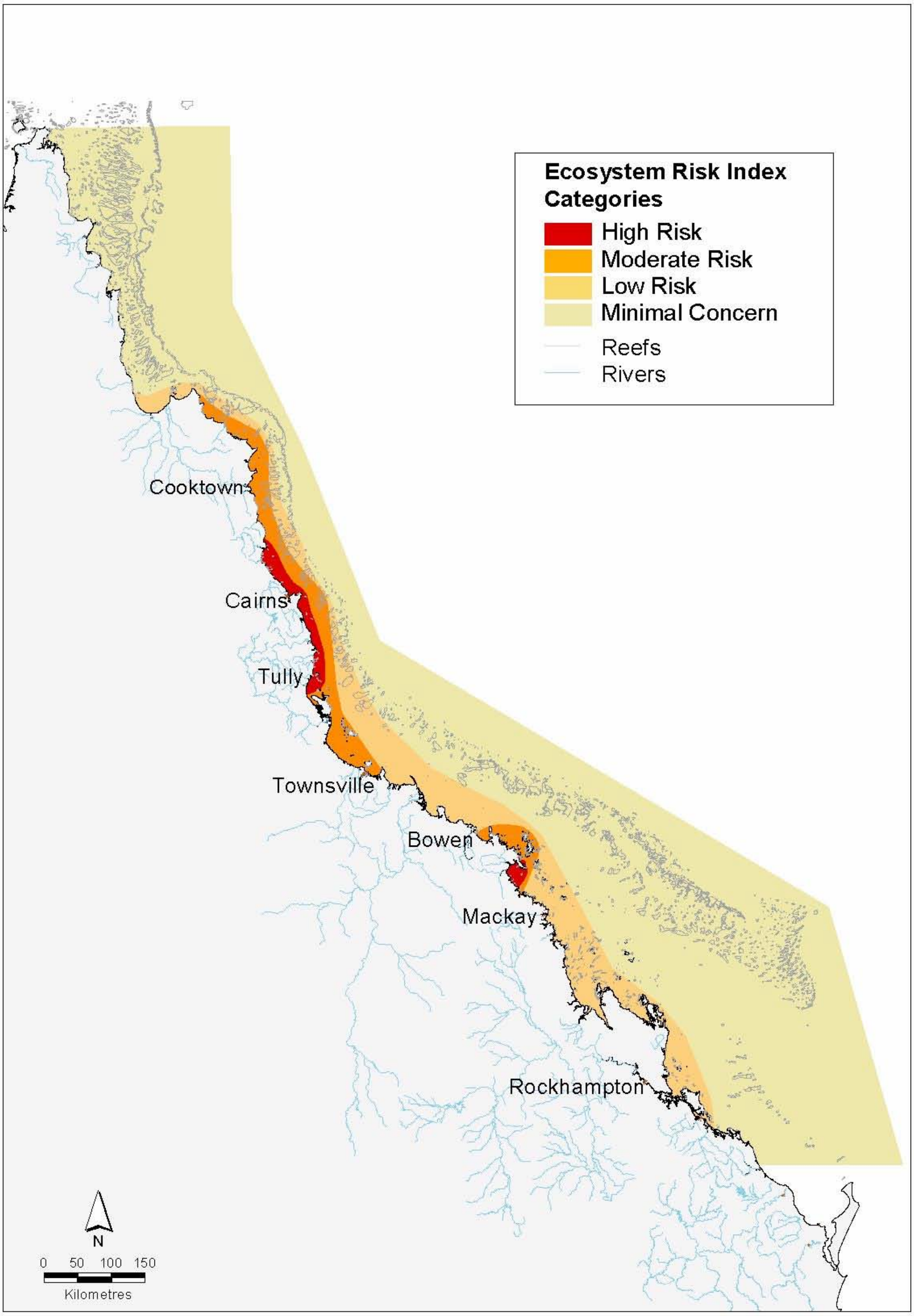


Figure 68: Estimation extrapolation of Ecosystem Risk Index categories for the Great Barrier Reef.

6.5. Discussion

6.5.1. Implications for the GBR

Reefs with the highest ERI ratings are also the reefs where evidence for reefal damage associated with terrestrial discharge is strongest (van Woesik *et al*, 1999; Fabricius and De'ath, 2001a, 2001b; Fabricus and De'ath, 2004; Fabricus *et al*., 2005; Devantier *et a*l., 2006). In the Whitsundays, a nutrient/suspended sediment gradient from the Proserpine River has been correlated with reduction in coral cover, species richness and abundance combined with increased coral recruit mortality (van Woesik *et al*., 1999). Green Island Reef and Sudbury Reef have the highest risk indices of the mid and outer shelf reefs assessed. At Green Island off Cairns, the large expansion in the area of seagrass meadows on reefal areas normally without seagrass has been shown to be a result of increased nutrient supply from mainland river discharge (Udy *et al,* 1999; Fabricus *et al*., 2005).

Proper catchment management is essential for the long-term health of these high-risk areas. The pre-eminent risk to inshore coral reefs and seagrass communities in the Great Barrier Reef is posed by water quality degradation resulting from pollutants contained in land run-off. If fundamental changes in land-management in Queensland do not occur (including minimisation of vegetation clearance, erosion and responsible use of pesticides and fertilisers), the health of the inshore ecosystems of the Great Barrier Reef World Heritage Area is likely to continue to decline.

6.5.2 Limitations of the model

The model does not include small rivers, which may be locally important when their discharge point (mouth) is very close to a reef. An example is Maria Creek on the Wet Tropics coast, which discharges 2 km from the southern part of King Reef. Inclusion of small streams in the risk analysis will improve its accuracy at such locations.

As treated in the model some catchments are actually basins and consist of many small streams all discharging into the sea separately in widely different locations. Systems like this distort the model through an imprecise value of the distance and direction factors for each reef and river.

Using a 1/d function assumes all pollutants reduce in concentration (and influence) in a linear fashion with distance from the river mouth. This is generally true for species such as nitrate, however the relationship for others, particularly suspended solids, is probably $1/d^x$ where $x>1$. A more complex model could take the different relationships for different parameters into account. In future a risk model including all of these more exact analyses will be developed.

The analysis only takes into account direct influence of rivers in the GBR Lagoon. After the initial physical and biological trapping of river-borne material from a plume the material and its derivatives are transported further on the shelf over periods of months and years by physical and biological processes. Primary methods of redistribution include wave resuspension of sediments and northward transport in longshore currents (Larcombe *at al*., 1995; Lambeck and Woolfe, 2000), bioturbation of sediments and movement of biological material in the water column. The influence of material transported to ecosystems in the long-term has not been included in the model.

Finally, the model gives each of the parameters that calculate the River Pollution Index equal weight. This approach does assume that diuron has the same relative effect as total sediment and dissolved inorganic nitrogen, without any identification of a species specific effect. Obviously the impact and consequences of each parameter would vary between the individual GBR ecosystems and the ratio and absolute amounts of each parameter would have varying consequences. It is difficult to define impact relative to cause, and thus the model is simplified into an exposure model, where only the concentration and extent of each parameter is accounted for. Further work is required on defining impact and consequences to futher develop the model into a risk based model, where delivery and fate is linked to a biological consequence for each parameter.

Chapter 7: Conclusions

This thesis presented the outcomes of 9 years of plume study within the GBR. Distribution and extent of plumes and the variability in nutrient and sediment concentrations is important in understanding the complexities of GBR inshore communities. Identifying areas of high plume inundation linked to catchment activities is also important in the overall assessment of risk for GBR communities.

Data presented in this thesis 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

Most SPM deposits from the plume close to the river mouth, often within a few kilometres of the mouth. Thus most of the particulate nutrient material will also be lost from the water column in this zone and not transported any great distances in the plume. In contrast there is almost no loss of dissolved nutrients, except by dilution, in the plumes until salinities rise to above 25 $^0/_{00}$ which is generally 50 to 200 km from the river mouth. The main reason for lack of biological uptake and phytoplankton growth appears to be the elevated turbidity in the early stages of the plume and the consequent light limitation. The implications of the contrasting behaviour of particulate nutrients and dissolved nutrients are that nutrients discharged from rivers in dissolved form are transported great distances in the plume. They thus have the ability to influence biological activity on much of the inner-shelf of the GBR. Nutrients discharged in a particulate form are trapped near the coast and probably do not have a major influence on, for example, most of the inner-shelf coral reefs. These results have important implications with respect to the degree of exposure of inner-shelf ecosystems to river-sourced nutrients and suspended particulate matter. As different forms of nutrients are exported from different land uses on the catchment the results can also help decide on priorities for management to reduce export from specific land uses. In general it is very clear that the primary area where flood plumes are common is the inner shelf and that ecosystems in this area are at most risk from pollutants contained in river discharge (Brodie *et al.*, 2001a; Brodie, 2002; Furnas, 2003; Fabricius and De'ath, 2004; Fabricus *et al.*, 2005).

Long-term effects of eutrophication on some inner shelf coral reefs of the GBR are now evident. In the Whitsundays, a nutrient/suspended sediment gradient from the Proserpine River has been correlated with reduction in coral cover, species richness and abundance combined with increased coral recruit mortality (van Woesik *et al.*, 1999). Synergistic effects of nutrients and sediment (Fabricius and Wolanski, 2000) in association with the acute effects of cyclones, bleaching and crown of thorns starfish (Fabricius and De'ath, 2004; Brodie *et al.*, 2005) are the cause of the widespread reef degradation in inner shelf areas of the central GBR. At Green Island off Cairns the large expansion in the area of seagrass meadows on reefal areas normally without seagrass has been shown to be a result of increased nutrient supply from mainland river discharge (Udy *et al.*, 1999). Knowledge of the transport of land-derived materials on the GBR shelf and hence the exposure of GBR ecosystems to this material allows us to better understand the changes which are occurring in these ecosystems.

7.1 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 (Peierles *et al.*, 1991). A similar correlation has been demonstrated for rivers on the GBR Catchment (Wachenfeld *et al.* 1998). Brodie and Mitchell (2005) demonstrates 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 (Moss *et al*., 2006; 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; Mitchell *et al*., 2001) and levels of 4–10 μM in the nearshore environment.

7.2 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 (Kinsey 1991; Bennell 1979; Baldwin, 1987, Bell, 1991,1992, Bell and Gabric, 1991, , Brodie, 1991, Brodie and Mitchell, 1991, Furnas *et al*., 1995, Jones and Tirendi, 1989, Rassmussen and Cuff, 1992, Walker, 1991a, Walker, 1991b and Yellowlees, 1991]). Some published material claims that the system is already eutrophic (Bell 1991, 1992) and that the available water quality data for the GBR support the hypothesis that the nutrient pool, and hence fertility of the water column, has now reached a critical level for the survival of fringing coral reefs in some regions of the GBR. Other work demonstrates increases in the nutrient discharge to the GBR from rivers over the last 150 years (Moss *et al*., 1992, Mitchell *et a*l, 2001). 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; McCook, 1997). 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 *et al*. 1999; Rogers 1990; Smith *et al*., 1981; Brodie *et al*., 2005) 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. Nutrient concentrations associated with reef waters give some indication of the extreme concentrations inshore reefs experience during a river plume. 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.

Sustained algal blooms on coral reefs may be generated by nutrient enhancement (Lapointe 1999; Smith et al. 1981; Schaeffelke, 1997; 1998; 1999), by a reduction in the number of herbivores (Hughes *et al*., in press) 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 a*l. 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 (Brodie et al., 2007). 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.

Recent publications support the idea of a degraded inshore reef system linked to the higher nutrient runoff from the central catchments adjacent to the GBR (Devantier et al., 2006; Brodie et al., 2006; Fabricus et al., 2005; Fabricus, 2006). Evidence of a lag in species diversity in the 400km section adjacent to the northern Wet Tropics coast, which was respectively 67% and 41% lower in site richness that the adjacent Far Northern and Central GBR areas indicates that the higher productivity within the nearshore areas adjacent to agriculturally dominated catchments do impact on the survival of inshore coral reefs. Brodie et al. (2006) reports on the incidence of crown of thorn outbreaks directly linked to the high nutrient pulses from the adjacent Wet Tropics catchments. Recent work by Fabricus et al. (2005) and Devantier et al. (1998) support the suggestion that turbid shallow inshore reefs can represent highly diverse coral reef habitats. The inshore reefs of Princess Charlotte Bay that have remained relatively undisturbed by terrestrial runoff and other anthropogenic influences were particularly rich, both in ecological and aesthetic terms. In comparison, other reefs which are closer to human influences appear depauperate. Fabricus and De'ath (2004) and Fabricus *et a*l., (2005) propose that the both regional differences in water quality and assesmblages, and the existence of ecological gradients along the water quality gradients add evidence that many of the biological responses are related to differences in water quality. Fabricus (2006) reviews that changes along the water quality gradients in the Great Barrier Reef is consistent in direction with other studies (decreasing corals and increasing algae) that the inshore reef assemblages are strongly shaped by current water quality conditions.

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 thesis demonstrates movement of nutrients and sediments from the river mouth to the inshore reef systems. It unequivocially shows that terrestrically derived, high nutrients and sediments discharge from rivers and spread widely at appreciable concentrations over large areas of the GBR. High concentrations (effect levels) of nitrogen and phosphorus are being measured at inshore reefs for a period of days and weeks in concentrations far above ambient concentrations and most likely far above what they were pre European settlement. Higher nutrient availability in the Central GBR relates to a residual signal of higher chlorophyll a concentrations persisting in the Central and Southern GBR compared to the Northern GBR. 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. These conclusions are documented in peer review papers as set out in Appendix One.

7.3 Further Research

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. 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 ; Fabricus, 2006). 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.

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, 2004). 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. A joint, co-ordinated approach to managing the GBR and adjacent catchments is needed to establish an integrated catchment-to-reef water quality strategy that promotes sustainable land use practices at regional and local levels. This joint approach is being achieved through the establishment of the Reef Water Quality Protection Plan (RWQPP), a joint Commonwealth and Queensland initiative (Anon, 2003). The goal of the RWQPP is the halting and reversing the decline of water quality entering the Reef within 10 years. The two objectives which will support the achievement of this goal are the reduction of diffuse sources of pollutants in water entering the reef and to rehabilitate and conserve the areas of the Reef catchment that have a role in removing water borne pollutants.

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Appendix One: Peer reviewed outputs supporting thesis

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