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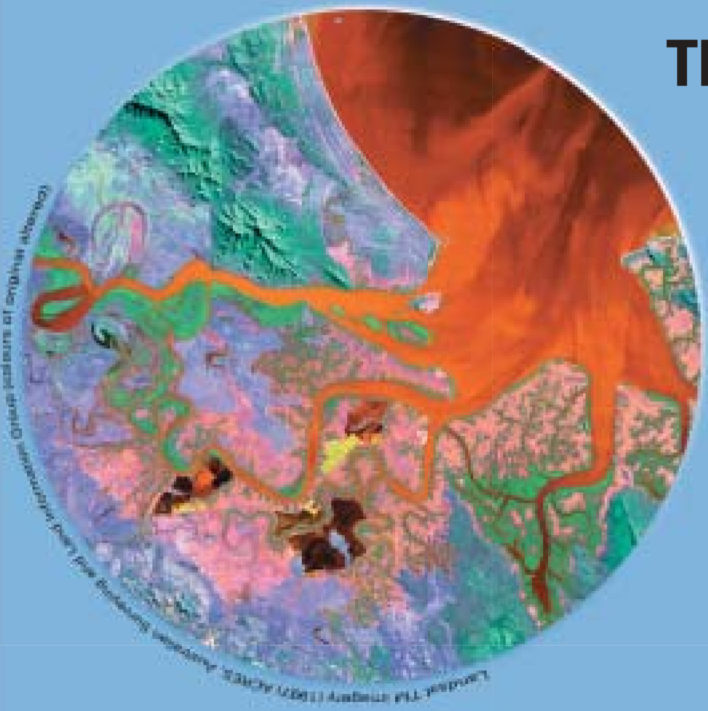

The Fitzroy contaminants project A study of the nutrient and fine-sediment dynamics of the Fitzroy Estuary and Keppel Bay

March 2006

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Ian Webster, Ian Atkinson, Helen Bostock, Brendan Brooke, Grant Douglas, Phillip Ford, Gary Hancock, Mike Herzfeld, Rhys Leeming, Charles Lemckert, Nugzar Margvelashvili, Bob Noble, Kadija Oubelkheir, Lynda Radke, Andy Revill, Barbara Robson, David Ryan, Christie Schacht, Craig Smith, Jodie Smith, Vicky Vicente-Beckett and Karen Wild-Allen

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The following persons comprised the project team for Project AC:

Ian Webster, Ian Atkinson, Helen Bostock, Brendan Brooke, Grant Douglas, Phillip Ford, Gary Hancock, Mike Herzfeld, Rhys Leeming, Charles Lemckert, Nugzar Margvelashvili, Bob Noble, Kadija Oubelkheir, Lynda Radke, Andy Revill, Barbara Robson, David Ryan, Christie Schacht, Craig Smith, Jodie Smith, Vicky Vicente-Beckett and Karen Wild-Allen.

This final report for Project AC represents a compilation of the findings of a suite of activities undertaken within Project AC and draws mainly from the final reports prepared for each activity. The contributions of the members of the team to these project activities and to the compilation of this report are outlined as follows:

Rhys Leeming, Andy Revill and Craig Smith investigated intertidal production in the Fitzroy Estuary; Bob Noble and Vicky Vicente-Beckett undertook pesticide and industrial chemical studies; sediment deposition and sediment origin in the Fitzroy Estuary–Keppel Bay region was investigated by Helen Bostock, Brendan Brooke, Grant Douglas, Gary Hancock, Dave Ryan and Jodie Smith; Charles Lemckert and Christie Schacht studied the dynamics of sediment resuspension in the Fitzroy Estuary; the biogeochemistry of Keppel Bay and the tidal creeks was investigated by Ian Atkinson, Lynda Radke, Phillip Ford and Ian Webster; modelling was undertaken by Mike Herzfeld, Nugzar Margvelashvili, Barbara Robson and Karen Wild-Allen. Remote sensing applications were completed by Vittorio Brando, Arnold Dekker and Kadija Oubelkheir as a separate project to Project AC but with strong cross-contributions. Thanks are due to Bob Noble for liaison with stakeholders and communications with the general public. The contribution of others to the successful completion of the project activities have been acknowledged in the individual activity reports.

Ian Webster was leader of Project AC and wrote most of this final report. Parts of the section on remote sensing were contributed by Arnold Dekker and Vittorio Brando. The section on pesticides, PAHs and metals was written by Bob Noble and Vicky Vicente-Beckett. Editing of the report was provided by Andy Revill, Phillip Ford, Nugzar Margvelashvili, Lynda Radke, Barbara Robson and Stephanie Butcher.

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Acronyms and abbreviations

As	Arsenic
BWZ	Blue water zone
CDOM	Coloured dissolved organic matter
Cr	Chromium
CTZ	Coastal transitional zone
DIN	Dissolved inorganic nitrogen
DO	Dissolved oxygen
DON	Dissolved organic nitrogen
DOP	Dissolved organic phosphate
FE	Fitzroy Estuary
Fe	Iron
GBR	Great Barrier Reef
KB	Keppel Bay
MPB	Microphytobenthos
MW	Molecular weight
N	Nitrogen
Ni	Nickel
NTUs	Nephelometric turbidity units
P	Phosphorus
PAHs	Polycyclic aromatic carbons
Sb	Antimony
TN	Total nitrogen
TOC	Total organic carbon
TSS	Total suspended sediments
ZMR	Zone of maximum resuspension

Executive summary

The Fitzroy catchment is the largest Queensland catchment discharging to the Great Barrier Reef (GBR) lagoon. Sediments and nutrients together with anthropogenic pollutants originating upstream in the catchment are discharged from the Fitzroy River via the Fitzroy Estuary (FE) and ultimately into Keppel Bay (KB). The estuary and the bay act as natural chemical reactors where the materials delivered undergo chemical and physical transformations before some are deposited and stored in the growing deltaic and beach areas, with the remainder transported eastward to the southern zone of the GBR lagoon.

The Reef Water Quality Protection Plan is a recent State–Commonwealth initiative which aims to improve land-use management practices within many Queensland catchments with the intent of reducing the loads of sediments, nutrients and other potentially deleterious substances entering the GBR lagoon. The background knowledge to make realistic predictions of the response of the FE and KB ecosystems to changed sediment and nutrient deliveries did not exist when this project started. The Agricultural Contaminants Project (Project AC) was developed to address these knowledge gaps and to produce a predictive framework to aid managers in the evaluation of various load reduction strategies.

The overall objectives of Project AC are to answer the following five questions:

1. How are nutrients and sediments transported, transformed and stored within FE and KB?
2. How are variations in nutrient and sediment delivery likely to impact on ecological function and primary production within the FE–KB system?
3. How are variations in riverine loads of sediment and nutrients likely to alter delivery of these materials to the GBR?
4. What pesticides and industrial contaminants are delivered to and remain in, the FE and KB and what is their potential impact?
5. How should managers monitor ecosytem health and function?

Project AC addresses these questions through a multidisciplinary study across the FE–KB system. It applied computer modelling of flow and mixing, of fine-sediment dynamics, of nutrient transformation and storage processes and of primary production. Knowledge of the transport and concentrations of fine sediments is important since most of the nutrients within the system are bound to sediment grains. Also, fine sediments effectively block the light necessary

for primary production in the water column and so have a direct impact on ecosystem function. The reliance on modelling in the project is in large part due to the enormous variability in the yearly discharge of the Fitzroy River. A project lasting only 3 years could not hope to experience the range of this variability, whereas model simulations can.

Project AC included a suite of data collection activities that were used in part to support the model development but also to provide further understanding of system behaviour. A major activity in the project was an extensive investigation of the rate of sediment deposition within KB and on the floodplain of the FE. A key result here is that perhaps less than a third of the fine sediment introduced to the system by the Fitzroy River is eventually transported beyond the bounds of KB to the GBR lagoon.

Another activity examined the role of primary production by microalgae on the extensive intertidal mudflats along the FE and tidal creeks. In these water bodies, primary production by phytoplankton in the water column is limited due to high suspended sediment concentrations and the consequent lack of underwater light necessary for their growth. The standing crop of the intertidal microalgae may not be large, but it is likely to be an important food source for prawns, crabs and other benthic feeding organisms.

The field investigation of the physical, chemical and biological properties of the water column and sediments showed how nutrients appeared to be generated by the bacterial decomposition of organic matter and dead phytoplankton. In the outer, well-lit parts of KB, these were consumed by phytoplankton as fast as they were generated. Conversely, in the inner parts of the bay where there were high concentrations of suspended sediments, primary production was almost certainly limited by light. It is likely that phytoplankton play a central role in the transport of nutrients between KB and the GBR lagoon. By comparing the nutrient content of incoming particles and the measured nutrient concentrations in sediment cores and using the measured sedimentation rate, we estimate that about half the input nutrient load was being stored in the Fitzroy floodplain, in the tidal creeks and in KB.

The Coastal CRC initiated a monitoring program in 2001 to quantify the concentration and loads of pesticides delivered to the FE from the Fitzroy River catchment. This monitoring has been extended during 2003–06 to include analysis for polycyclic aromatic hydrocarbons (PAHs) and metals in fine sediments and core samples from the FE and KB. This work adds to the very limited studies on PAH and metal contaminants, particularly in benthic sediments from the FE.

Measurements of pesticide concentrations in the summer inflows of the Fitzroy River into the estuary showed the presence of the herbicides Atrazine, Tebuthiuron, Diuron, Fluometuron, Hexazinone, Prometryn and Simazine. Atrazine and Tebuthiuron were detected in all the samples collected for the summer of 2004–05, illustrating the ubiquitous presence of these substances in the surface waters of the Fitzroy Basin. Their concentrations often exceeded ANZECC (2000) trigger values for protection of estuarine and inshore species.

PAHs are persistent organic pollutants that may enter the aquatic environment from natural and anthropogenic sources. In the Fitzroy Basin, potentially significant sources of PAHs arise from the disturbance of coal seams during mining operations and from the historic burning of vegetation. PAH analysis was undertaken on sediment samples collected throughout the FE–KB system. They were detected in most of the samples collected, but no concentrations exceeded the ANZECC trigger value.

Surface sediment and core slice samples from the FE were analysed for their metal content. Only concentrations of nickel (Ni), chromium (Cr), antimony (Sb) and arsenic (As) exceeded trigger values of the interim ANZECC sediment quality guidelines. Ni levels exceeded the guidelines most often, followed by Cr, Sb and in only one case, As. However, there are geological sources for both Ni and Cr in the basin.

Objectives 2 and 3 were addressed mainly using model simulation. Model predictions were obtained for low-, median- and high-flow years. The low- and median-flow simulations assumed modest but realistic inputs of fine sediments and nutrients and predicted small exports of fine sediments but a net influx of nutrients from the GBR lagoon. However, the high-flow year assumed much larger inputs and predicted significant exports of both nutrients and sediments to the lagoon. The freshwater inflow for the high-flow year used in the simulations (1999) was about one third of that discharged by the Fitzroy River during the major flood of 1991. This flood in 1991 is estimated to have delivered of the order of half of the total input of fresh water, fine sediments and nutrients for over the last 15 years.

Scenario modeling was undertaken to investigate the effects of two hypothetical land-use scenarios in the Fitzroy Basin on the primary productivity response of the FE–KB system and on the export of nutrients from the system to the GBR lagoon. The hypothetical scenarios were: (a) a reduction in vegetation cover to

30% of area from an assumed 55% cover at present and (b) an increase to 70% cover. The sediment and nutrient loads from the Fitzroy River corresponding to these scenarios were calculated in a separate modelling exercise. The calculated loads increased with decreasing vegetation cover and the resultant exports to the GBR lagoon followed suit. In the median-flow year, for the present condition of vegetation cover, the phytoplankton concentrations were predicted to be higher than for both reduced and increased cover. It appears that when cover is increased the supply of nutrients is decreased, resulting in more limited phytoplankton growth; but decreased cover increases the fine-sediment load that also reduces growth due to reduced light in the water column.

The fifth question asked of Project AC is ‘How should managers monitor ecosytem health and function?’ We suggest that the prime goal of a monitoring program would be to assess progress towards management objectives and to inform decisions on modification of management actions over time in response to system change. The chosen management objectives will determine what indicators of system behaviour and response need to be measured. Any monitoring program will necessarily be constrained by the resources available so the choice of indicators measured and the frequency with which they can be monitored is necessarily a compromise.

A dominant characteristic of the FE–KB system is its variability on time scales ranging from decadal, to interannual, to seasonal, to fortnightly and down to sub-daily. Variability on longer time scales is due to climatic and seasonal variations of the rainfall in the Fitzroy catchment which cause enormous variability in the discharge of the Fitzroy River, a major driver of system behaviour in the FE and KB. At the scale of weeks and days, the spring-neap cycle of high and low tidal ranges has a very large influence on suspended sediment concentrations as does the daily cycle of high and low tides. This variability makes the design of an effective monitoring program and the analyses of its results much more difficult than in most aquatic systems.

Only a monitoring program that lasts decades could account for discharge variablity directly. Assessing trends in system condition based on statistical analysis techniques is also likely to require decades of measurements before the analysis yields significant results. The analysis of monitoring information in the context of a modelling framework may be useful here. Models can readily accommodate changes in input conditions such as river discharge and system response could be judged against anticipated or modelled behaviour.

If such a monitoring-modelling strategy were to be adopted (and even if it were not), the highest priority of any measurement program should be the accurate assessment of the form and loads of nutrients and fine sediments discharged by the Fitzroy River into its estuary. In a system such as the FE and KB which have such large temporal variability, we would place a premium on employing automated measurement technologies and satellite remote sensing. Variability in the inherent optical properties of water and the very high concentrations of suspended sediments encountered in KB caused significant difficulties for the routine application of remote sensing. These difficulties are being overcome as they are encountered and we are confident that remote sensing will become a reliable and inexpensive tool for monitoring.

1 Introduction

The Fitzroy catchment is the largest Queensland catchment discharging to the Great Barrier Reef (GBR) lagoon and the second largest seaward-draining catchment in Australia next to the Murray-Darling Basin. Sediments and nutrients (both particulate and dissolved), together with anthropogenic pollutants originating upstream in the catchment, are discharged from the Fitzroy River via the Fitzroy Estuary (FE) and ultimately into Keppel Bay (KB). The estuary and the bay act as natural 'chemical reactors' where the materials delivered undergo chemical and physical transformations before some are deposited and stored in the growing deltaic and beach areas, with the remainder transported eastward to the southern zone of the GBR lagoon. There is growing evidence (summarised in Furnas, 2003) that sediments, pollutants and nutrients generated by human activities in tropical catchments and then transported by rivers into the GBR lagoon have the potential to exert a deleterious impact on reef ecosystems.

Substantial resources have been provided recently under the auspices of the Reef Water Quality Protection Plan (http://www.deh.gov.au/coasts/pollution/reef/) to improve land-use management practices within many of the Queensland catchments with the intent of reducing loads of potentially deleterious substances entering the GBR lagoon. The Fitzroy catchment and the adjacent Burdekin catchment are the largest two sources of sediments and nutrients to the GBR lagoon (Furnas, 2003). The background knowledge to make realistic predictions of the response of the FE and KB ecosystems to different sediment and nutrient loads and to evaluate the consequences of altered water deliveries to the GBR lagoon did not exist when this project started. The Agricultural Contaminants Project (Project AC) was developed to address these knowledge gaps and to produce a predictive framework to aid managers in the evaluation of various load reduction strategies and therefore of the various alternative proposed changes in catchment management.

The overall objectives of Project AC are to answer the following five questions:

1. How are nutrients and sediments transported, transformed and stored within FE and KB?
2. How are variations in nutrient and sediment delivery likely to impact on ecological function and primary production within the FE–KB system?
3. How are variations in riverine loads of sediment and nutrients likely to alter delivery of these materials to the GBR?
4. What pesticides and industrial contaminants are delivered to and remain in, FE and KB and what is their potential impact?
5. How should managers monitor ecosytem health and function?

This report addresses these questions through Chapters 2–8. Chapter 2 provides an overview of the physical geography of the Fitzroy River and of the FE–KB system including the nature of the flows in the river and the system's sedimentological history. Features of currents and mixing in the estuary and KB are outlined in Chapter 3. Chapter 4 describes how fine sediment that is delivered to the head of the estuary by the Fitzroy River is transported and stored within and exported from the FE–KB system. Similarly, transport, transformation, storage and export of nutrients introduced by the river are treated in Chapter 5. By providing a description of system function as it is, Chapters 3, 4 and 5 address Question 1. Since the system response to variability in loads is also treated in these three chapters, both in terms of primary productivity and export to the GBR lagoon, these chapters also address Questions 2 and 3.

As part of the development of the Reef Water Quality Protection Plan, the Fitzroy Basin Association has proposed a series of hypothetical land-use scenarios that have been evaluated for their likely impact on the delivery of nutrients and sediments by the Fitzroy River. In Chapter 6, we address specifically the likely impact of two alternative scenarios for land use in the Fitzroy catchment, one of which represents a significant increase in vegetation cover on grazing lands compared to the present condition and the other a significant reduction. Chapter 7 answers Question 4 by providing an analysis of the presence of pesticide and industrial contaminants in the FE–KB system and the significance of the concentrations found. Question 5 is addressed in Chapter 8, in which we describe some of the considerations surrounding the design of an effective sampling strategy including choice of appropriate indicators, sampling methodology and the timing and location of sample collection.

Project AC builds on previous projects undertaken by the Coastal CRC in FE (Currie & Small, 2002; Margvelashvili *et al*., 2003; Webster *et al*., 2004; Douglas *et al*., 2005) by extending the focus to include KB. It is complemented by two concurrent projects in the estuary, namely Environmental Flows (Project AF) and Floodplain Wetlands (Project AW). Project AC comprised a series of field-based measurement programs which were undertaken to develop an understanding of various facets of the system dynamics. These studies were also used to support the development of linked computer models of the hydrodynamics, fine-sediment dynamics and the biogeochemistry of the FE–KB system. The models provide a predictive framework as well as diagnostic support for the measurement-based studies. The final reports of the various activities that comprise Project AC are listed in the appendix together with a brief account of the nature of each activity.

2 Geography

The Fitzroy River, Fitzroy Estuary and Keppel Bay

The Fitzroy River has the largest Queensland catchment (143,000 km^2) draining to the GBR lagoon. Four major rivers (Connor-Isaacs, Nogoa, Comet and the Dawson) join to form the Fitzroy which discharges into its estuary through a barrage at Rockhampton (Figure 1). These rivers rise in the uplands of central Queensland and the Fitzroy itself falls to the coastal plain at Eden Bann Weir approximately 140 km upstream from the barrage. Land use in the Fitzroy Basin is dominated by grazing which covers 81% of its area, with 6% of the remainder being devoted to cropping. Extensive coal mining covers about 0.4% of the area but makes a large contribution to the region's economy.

Figure 1. The major rivers in the Fitzroy Basin

Rainfall in the catchments is highly episodic and is concentrated in the austral summer (December to March). Although there are numerous weirs on the various rivers draining the Fitzroy Basin, they are all small and essentially 'transparent' to large flow events. The only storage capable of retaining large water volumes is Fairbairn Dam on the upper reaches of the Nogoa. Large-scale events are relatively rare and consequently only one or two events per year are sufficiently large to produce major delivery of fresh water at Rockhampton. For most of the year, the only fresh water entering the estuary is a small discharge of treated waste water from Rockhampton and limited flows through the fishway at the barrage.

Between 1965 and 2005, the annual average discharge of the Fitzroy has varied by more than a factor of 100 (Figure 2) and deliveries of sediments and nutrients varied to a somewhat greater degree. Measurements made over studies lasting a few years can't represent the enormous variability in the yearly flows, but they can be used to validate numerical models of the system response. We then use the models to predict what would happen in flow conditions (and variations in sediment and nutrient and sediment delivery) for which we don't have measurements. This is the strategy that underlies the combined measurement-modelling approach undertaken in Project AC.

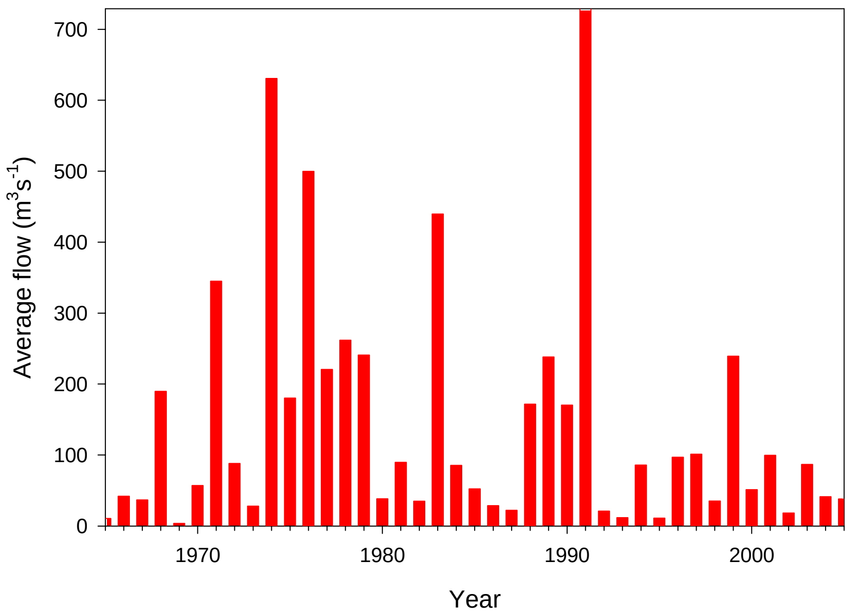

Figure 2. Yearly averaged discharge from the Fitzroy River measured at the Gap

The bar centred on the year 2000 represents the average discharge between July 1999 and June 2000, for example.

The rainfall run-off into the Fitzroy and its tributaries carries sediments and nutrients with it. Due to its increased capacity to transport particulate material, heavy run-off carries proportionally more sediment than does smaller run-off. Thus, doubling run-off results in more than a doubling in the amount of sediment that flows into and down rivers. The total volume of water estimated to have been discharged by the Fitzroy River in 1991 was 230 billion cubic metres. This was mainly due to a flood lasting about two weeks—the third largest last century.

There were even bigger floods in 1918 and 1954. These floods were due to the passage of tropical cyclones. The total discharge in the 16 years between 1990 and 2005 was 580 billion cubic metres; that is, the 1991 flows accounted for about 40% of this total by themselves. However, of the fine sediment delivered to the estuary between 1990 and 2005, 60% of it is estimated to have been delivered during the floods of 1991. The delivery of fine sediments by the river is dominated by flood events that occurred only several times in a century. Since the majority of the nutrient load carried by the river during flow events is in the form of either organic particles or as material attached to sediment particles, flood events also account for a disproportionately large fraction of nutrient delivery to the estuary.

The upstream limit of the FE is defined by the Barrage across the Fitzroy River at Rockhampton, 54 km from KB (Figure 3). At its coastal end, the estuary connects to the south-western corner of KB in the vicinity of the major tidal creeks. Between Rockhampton and the sea lies a deltaic (estuarine) floodplain which is excised by the main channel of the estuary. This channel is ~200 m wide at Rockhampton but widens to ~3 km near the estuary mouth. Depths along the channel tend to increase towards the mouth with a median depth of ~10 m. The main channel of the FE has an estimated volume of 250 million cubic metres at mid tide. The estuarine floodplain is ~20 km wide and is constrained by ranges of hills on its northern and southern sides.

Figure 3. Satellite photo of Fitzroy Estuary and Keppel Bay

In most years, flow in the estuary remains within the confines of the estuarine channel, but when river flow volumes exceed ~8,000 m^3s^{-1}, the channel overflows and water spreads out over the adjacent floodplain (Peter Voltz, pers. comm.). Some of the sediments carried with this overbank flow remain behind when the floods recede and have caused a gradual build-up of the floodplain over time.

KB is a relatively shallow embayment (Figure 4) with water depth slowly increasing seaward. Its offshore extent is ~20 km and the distance between its southern end near the mouth of the FE to Great Keppel Island is ~40 km. Depths near the offshore boundary are ~15 m.

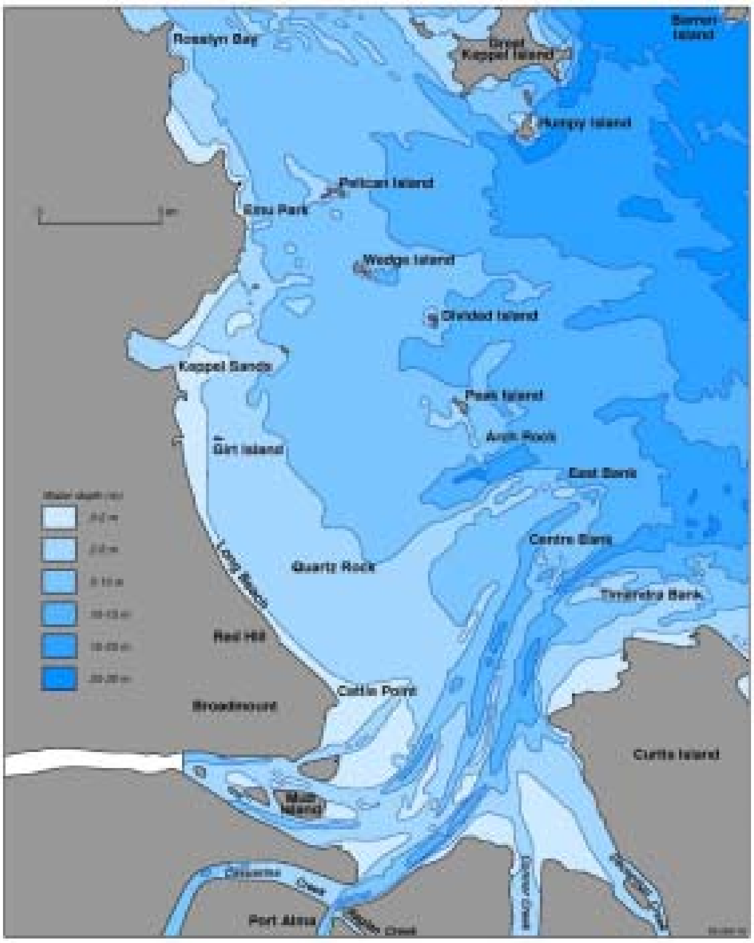

Figure 4. Bathymetry of Keppel Bay (modified after Ryan *et al*. (2006)

Extending from the mouth of the FE towards the north-east are three relatively deep channels with depths ~10 m or more. One of these is the main shipping channel into Port Alma and is dredged. The largest three coastal creeks (Casuarina, Raglan and Connor Creeks) together are of comparable size to the FE and all enter KB in close proximity to the estuary. The other, more northerly, coastal creeks entering directly into KB are all small and ephemeral with very small catchments. The nutrient load delivered by them is assumed to be small relative to the load from the Fitzroy River via the estuary.

History of deposition and estuary formation

The stratigraphy and age of recent sediments that make up the FE floodplain downstream from Rockhampton, tidal creeks and KB were examined to reveal the evolutionary history of this large coastal sedimentary basin and identify the quantity and rate of the sediment accumulation. The results of this study are reported in more detail in a series of reports by Bostock *et al*. (2006a,b), Brooke *et al*. (2006a,b), Ryan *et al*. (2006) and by Smith *et al*. (2006). Cores collected as part of this study, core logs provided by past drilling programs and acoustic sub-bottom profiles of KB were used to build a depositional history of the basin. The arrangement of floodplain sediments, channel deposits and various shallow-marine sediments record the rise and then stabilisation of sea level over the last 10 000 years (Figure 5). As sea level rose, the former floodplain of the Fitzroy River was flooded to form KB and the mouth of the river moved inland towards Rockhampton. Sea level stabilised around 7000 years ago and since that time the estuarine basin between Rockhampton and the coast has been filling with shallow-marine, estuarine and floodplain deposits.

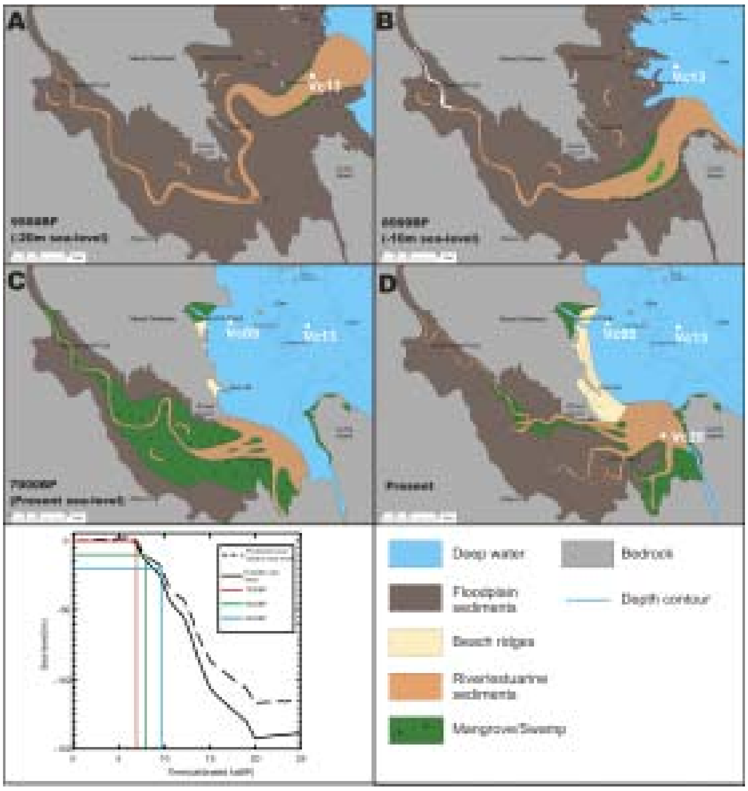

Figure 5. The evolution of the Fitzroy Estuary and Keppel Bay over the last 10 000 years

Relict channels of the Fitzroy River are preserved in the outer section of KB and even further out into the lagoon of the GBR and indicate relatively little river-derived sediment has accumulated there. Relict river-mouth channels are preserved in the bay just to the north of Curtis Island (Figure 4). Some of these channels have been maintained by strong tidal currents while others are partially filled with sediment. In contrast, sediments from the Fitzroy River have accumulated in the inner bay to the north of the estuary mouth and filled in and covered relict river channels. Sand from the Fitzroy River deposited in KB has also been reworked onshore to Long Beach. Over the last 2000 years, these sands have accreted to form a beach-ridge plain approximately 3 km wide between Cattle Point and Keppel Sands.

The course of the Fitzroy River across its estuarine floodplain is undergoing continuing evolution. The Loop, an 8 km long channel feature about halfway between Rockhampton and the mouth of the FE (see Figure 3), was a meander in the main channel of the river until the flood of 1991 when large flows broke through the banks between its two sides. Now, the main channel short-circuits the Loop and the reduced flows within the Loop are causing it to gradually fill with sediment. A previous loop section that has since mostly filled with sediment is the large horseshoe-shaped lagoon to the north of the main channel on Fitzroy Vale.

3 Currents and mixing within the FE–KB system

Hydrodynamics – Fitzroy Estuary

Hydrodynamics is the study of water flow and mixing within an aquatic system. We need to know how materials such as nutrients, fine sediments and phytoplankton are transported through the FE–KB system. The hydrodynamics of the FE are dominated by the tides and the discharge of the Fitzroy River and are described in more detail by Webster *et al*. (2004). The hydrodynamics of KB and regions of the GBR lagoon near KB are reported by Radke *et al*. (2006).

Tides in the Mackay region (19.5–25°S) are dominantly semi-diurnal (two high tides and two low tides per day), with marked inequality between the high tides, but little between the low tides. These features are evident in the 20-day record of predicted water levels for Port Alma (southern KB) shown in Figure 6. The tidal range in KB also undergoes a pronounced 14-day cycle of spring-neap tides which can also be seen in the figure.

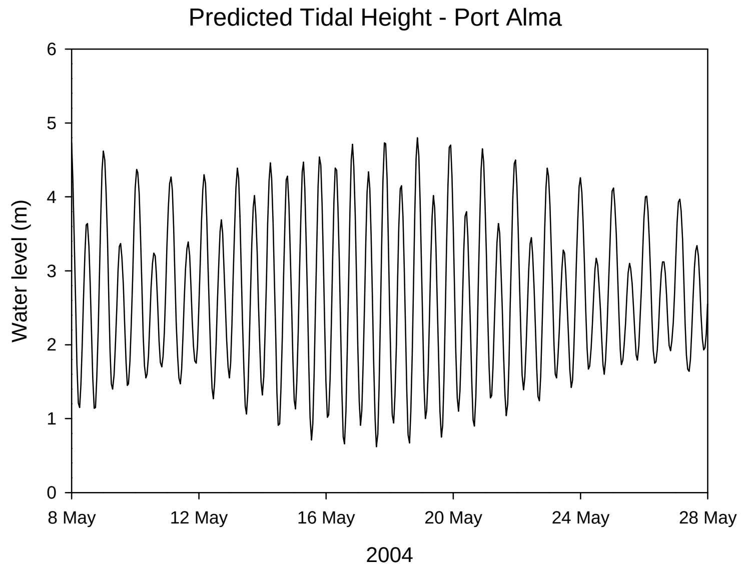

Figure 6. Predicted tidal heights at Port Alma

The large tidal ranges in the region cause vigorous currents in the FE. Spring tides at Port Alma have a maximum range of ~5 m and neap tides about half this range. The tidal range increases with distance up the estuary. At Lakes Creek, ~7 km down-estuary from the Barrage, the tidal range is about 20% larger than it is at the mouth of the estuary. Tidal currents act to mix material along the estuary and are strong enough, particularly in the lower half of the estuary, to resuspend settled sediments. For most of a typical year, the discharge of the Fitzroy River is small and the hydrodynamics of the estuary are dominated by these tidal currents.

The summertime discharges of the Fitzroy River into the FE flush salt water from the estuary, rendering it fresh all the way to its mouth in most years. In a median year, the river discharge is approximately ten times the volume of the estuary. For 1991, the flow volume would have been sufficient to fill the estuary's channel over 150 times, whereas in 1969 there was insufficient flow to fill the channel even once. Following the cessation of significant flows in the Fitzroy River at the end of summer, the back and forward currents due to tides mix sea water back up the estuary so it gradually becomes saltier along its length. At Rockhampton, it takes about three months for the salinity of the water in the estuary to approach that of sea water.

Hydrodynamics – Keppel Bay

For most of the year, currents in KB are also dominated by tides. Figure 7 shows the direction and amplitude of the average flooding tide obtained from measurements taken during Project AC. Peak currents, which occur in late February and August, would range up to 2.5 times the speed of these average currents. That is, peak currents in the channels approaching the mouth of the FE, where the largest currents occur in the bay, would be expected to almost reach or exceed 1ms^{-1} (~2 knots) at these times.

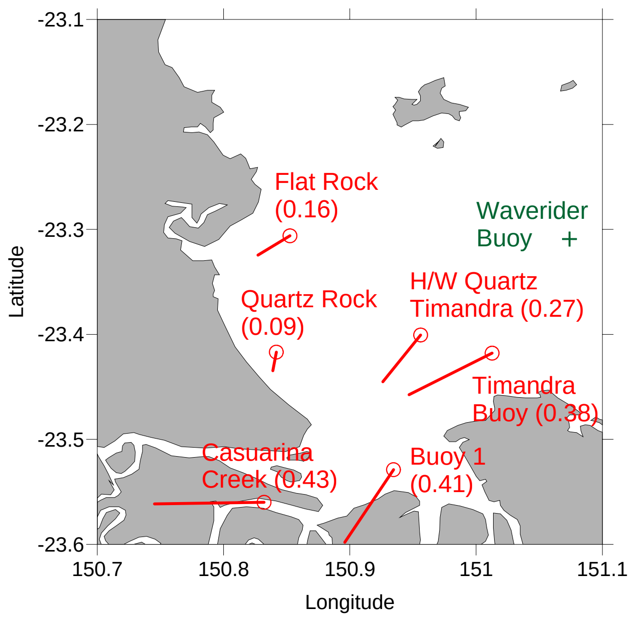

Figure 7. Calculated average tidal currents plotted for a flooding tide at the sites of current meter deployments

The numbers in brackets are the current amplitudes in ms^{-1}. Relative amplitudes are indicated by the length of the red lines and the direction of currents on a flooding tide is along the line away from each marked point.

During times of high Fitzroy River discharge, salinity within KB is reduced to a degree that depends on the volume of fresh water discharged. Large discharges cause a brackish plume to spread out from the mouth of the estuary over the top of more saline water underneath (see conceptual model, Figure 12). The fresh water discharged into KB during the flood of 1991 produced a surface plume approximately 3 m thick (O'Neill et al. 1992) that extended at least as far as the Keppel Islands (Figure 4). The direction of spread of the plume and therefore its zone of impact depends on the direction and strength of the wind at the time.

Measurements obtained in KB following the flood of January 1991 showed the plume to spread northwards along the coast initially under the influence of south-east winds. Later, the wind switched to more northerly directions causing the plume to be blown southwards and eastwards, impinging on the Capricorn-Bunker group of coral atolls. Turbulent mixing caused by energetic tidal currents would gradually erode brackish plumes from below, causing their salinity to gradually increase and the thickness of the fresher water layer to decrease as salt water from below was mixed into it. The longevity of the plume is very much affected by the state of the spring-neap tidal cycle and the volume and rate of freshwater delivery.

Following the cessation of river flow, tidal mixing and wind currents gradually cause the riverine water in KB to be dispersed and replaced with sea water from further offshore. Later on in the dry season during the dry winter-spring months, with no further input of fresh water, evaporation in the relatively shallow water along the western side of KB, in the tidal creeks and in the FE causes salinity to increase to slightly above that of sea water (~5% increase). From this increase and from an assumed evaporation rate, we can estimate the time taken for water within western KB to exchange with offshore water as ~20 days. Modelling of the hydrodynamics of the FE and KB is described in the report by Herzfeld *et al*. (2006).

Hydrodynamics – Great Barrier Reef lagoon

A major feature of the oceanography of the GBR coastal region is the East Australian Current (EAC) which flows southward along the seaward edge of the GBR (Figure 8). Measurements in the inshore region of the GBR lagoon near KB are limited. Griffin *et al*. (1987) report on the results of an oceanographic study which was undertaken in the region between Capricorn Channel and Fraser Island over a period of six months starting in June 1983. Analysis of measurements from a current meter off Curtis Island shows that the currents were very well correlated with the wind over the region. Winds from the south-east tended to produce a current towards the north-west, a tendency that has been observed in the lagoon of the GBR off Townsville. Thus, we can use wind direction and strength as a means of estimating the direction and magnitude of the current running along the coast. Current estimated from wind in this way is a 'proxy' current.

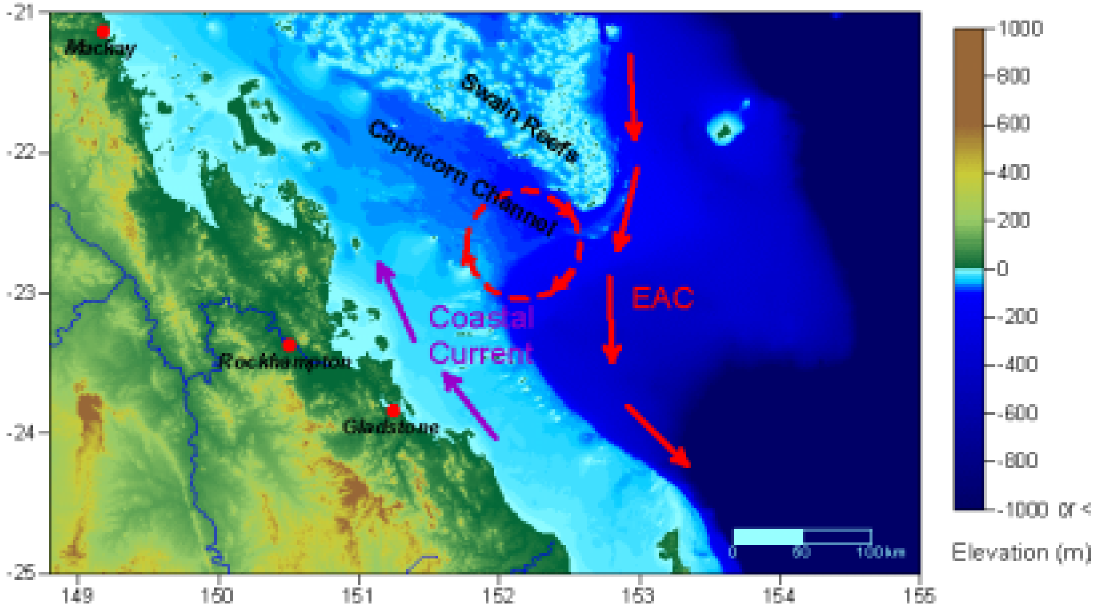

Figure 8. Currents in the Capricornia region of the GBR (Map courtesy of P. Briggs, CMAR)

Figure 9 shows monthly longshore proxy currents estimated from a 21-year record of winds. The proxy current flows for most of the year towards the north-west, reflecting the dominance of the south-east trade winds in the region, particularly during the summer months. Thus, nutrients and fine sediments from the Fitzroy River that are mixed beyond the limits of KB will tend to be carried north-westwards along the coast. Satellite images of surface water temperature and some current measurements show that a clockwise rotating eddy associated with the EAC sometimes occurs in the Capricorn Channel (Figure 8). Fine sediments from the Fitzroy have been found in Capricorn Channel and we can postulate that their presence is due to the interaction between the generally north-westwards coastal current and the EAC eddy.

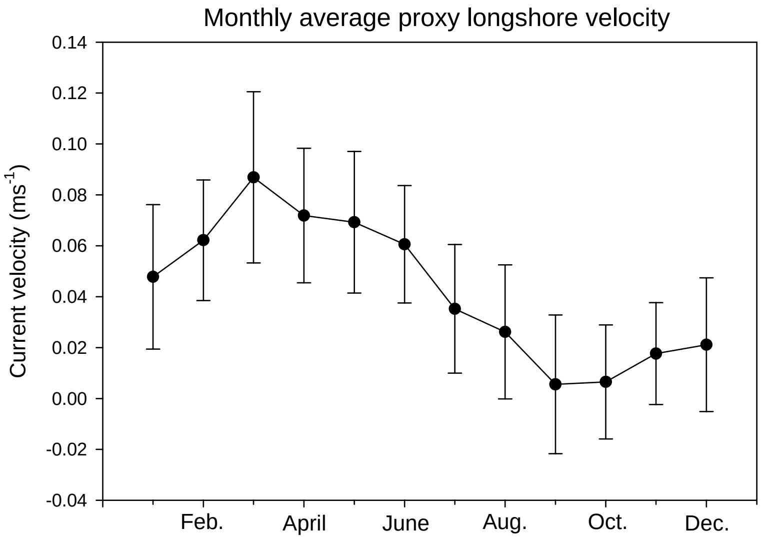

Figure 9. Proxy longshore current velocity averaged monthly for the period 1982–2004

A positive current is towards the northwest. The vertical bars show ± the standard deviation of the monthly averages.

4 Transport and fate of fine sediments

Physical properties of fine sediments

The fine sediments we consider here have particle sizes less than 63 µm and represent the major part of the sediment load carried by the Fitzroy River and discharged into the FE. They are transported through the estuary and eventually some of them are deposited in KB where they comprise a large component of the seabed over much of the bay. Fine sediments are readily suspended by the currents within the bay and, due to their relatively slow sinking rates, can remain in suspension for some time before settling back to the bottom. Transport of fine sediments is dominated by cycles of resuspension, transport in the water column by the current, and by deposition. Coarse sediments such as sands tend to saltate (bounce along the bottom). The muddy sediments in KB had median grain sizes that were measured to be less than 10 µm. The estimated sinking rate for a 10 µm grain is ~10 m day^{-1}, whereas a grain of size 1µm would sink at a rate of ~10 m day^{-1}. It would take the smaller grain approximately 50 days to settle through a water column of 5 m depth.

High concentrations of sediments in the water column lead to high turbidity and a consequent reduction in light, which is necessary for photosynthesis by benthic plants and microalgae and by phytoplankton. Further organic material adsorbs to the surfaces of the sediment particles in sufficient amounts that the transport of these sediments represents a major pathway for the movement of organic materials from one part of the bay to another. Thus, the behaviour of fine sediments is an important determinant of the biogeochemistry of KB both through its potential impact on primary production and on nutrient cycling. Radke *et al*. (2006) report in more detail on this behaviour and on the relationship between fine sediments and nutrients in KB. Modelling of the resuspension, settling and transport of fine sediments is treated in a report by Margvelashvili *et al*. (2006).

Delivery of fine sediments to the Fitzroy Estuary

The delivery of suspended sediment by the Fitzroy River to the FE is very much dominated by the flow events that typically occur during the summer months. There have been a number of estimates of the average yearly delivery of fine sediments to the estuary by various investigators ranging from 1861 kt yr^{-1} to 10 466 kt yr^{-1} depending on assumptions made about flow–sediment concentration relationships and averaging period. Annual loads vary greatly from year to year, partly due to interannual variations in discharge and partly to variation in the concentration of suspended sediment in the river flow. Joo and Yu (in prep.) note that if flows in the Fitzroy River are primarily due to flows in the Isaac River, then the suspended concentration for a given discharge is lower than it would be if the Nogoa and Comet Rivers were to contribute higher proportions of the total flow. They also note that care needs to be exercised in defining the period over which the average is calculated. They suggest 30 years is a suitable averaging period as it would be expected to account for decadal variations in rainfall. For example, the 1970s was a relatively wet decade, but the last 10 years has been relatively dry with relatively lower river discharges.

Using monitoring data collected in the Fitzroy catchment between 1974 and 2003, Joo *et al*. (2005) have developed ratings curves which can be used to estimate the relationship between discharge and sediment concentration. For the Fitzroy, this analysis reveals that the sediment concentration increases as the 0.39 power of the discharge. Using their calculation, a medium discharge rate in the Fitzroy River of 1000 m^3s^{-1} would have a total suspended sediment (TSS) concentration of ~420 g m^{-3}. A large flow of 10 000 m^3s^{-1} would have an estimated TSS concentration of ~1030 g m^{-3}. Thus, the interannual variation in the delivery of fine sediments to the FE can be expected to be somewhat larger than the variation in flow illustrated in Figure 2.

The dynamics of fine sediments within the Fitzroy Estuary

Fine sediments discharged into the head of the estuary during floods are carried along the estuary by the freshwater inflow. The mean particle size in the river water is of the order of 1µm and a significant fraction of the particles are much smaller. Such particles sink slowly and the TSS concentration in the estuary is augmented by sediments delivered previously and resuspended by the vigorous tidal currents.

In the months following the cessation of the summer inflows, the salinity of the estuary gradually increases. When the suspended sediments encounter salt water, they flocculate into larger particles which sink much more rapidly (Figure ***10***). Flocculation is a phenomenon that fundamentally alters the fine-sediment dynamics within the FE and also in KB. Flocculation appears to occur when salinity increases to 1–2 (parts per thousand) or equivalently when the salinity increases to about 3–6% of sea water (seawater salinity ~35).

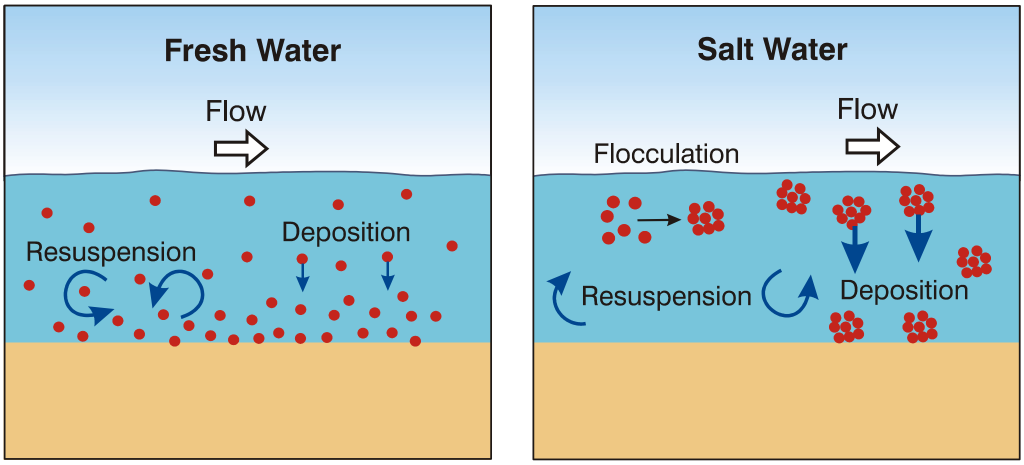

Figure 10. Factors controlling the concentration of fine sediments in the water column in the Fitzroy Estuary and Keppel Bay

When salt water reaches the upper half of the estuary, flocculation enhances sediment sinking rates and causes the water column to clear. Closer to the mouth, the much more vigorous tidal currents maintain active sediment resuspension and suspended sediment concentrations remain high year-round. The relatively high clarity of the water in the upper reaches of the estuary allows for vigorous phytoplankton production, which in turn supports large populations of mussels and other organisms. In the lower part of the estuary, TSS concentrations remain high, rendering the water column highly turbid with little light penetration so that there is not much primary production in the water column. We speculate that most of the primary production in this part of the FE occurs as coatings of algae living on the intertidal mudflats. Part of Project AC addressed this topic and we return to it later.

During low river discharges, the upstream and downstream transports of water along the estuary during the flooding and ebbing phases of the tidal cycle are approximately balanced. However, due to tidal asymmetry, maximum velocities developing during the flooding phase tend to exceed velocities developing during the ebbing phase, resulting in a net upstream pumping of sediments in the estuary. When river discharges to the estuary are appreciable, ebbing tidal currents may exceed flooding currents so more resuspension and higher concentrations occur during the ebb. When river discharge is sufficiently large, the currents associated with this flow may be comparable to the amplitude of the tidal current. Under this circumstance, river flow would add to the ebbing tide to produce very strong currents in the estuary and very active resuspension of settled sediments on the falling tide. Such flow events would export both the suspended sediment that was introduced by the river during the event and sediment that had accumulated within the estuary sediment between events.

The dynamics of fine sediments within Keppel Bay

In most years, the volume of water during a summer flow event was large enough to fill the estuary. If the volume exceeds the estuary volume significantly, then one would expect that a large quantity of suspended fine sediment would be discharged directly into KB in unflocculated form. In the summer of 1990–91, the discharge volume during a seven-day period exceeded the estuary volume by more than a factor of 30. With such high delivery rates, the transit time of suspended sediment in the estuary will be small. Large floods will exceed the flow capacity of the estuarine channel and much of the fresh water and the sediment delivered by the river will spread out over the estuarine floodplain.

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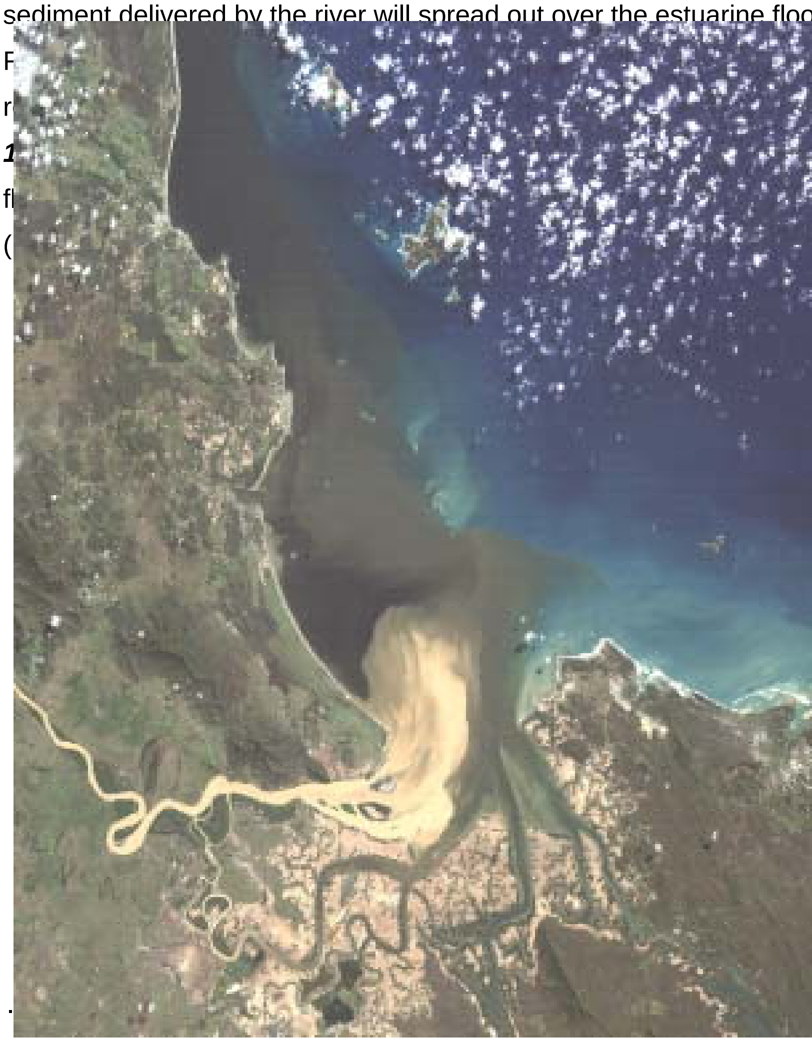

Figure 11. Landsat image of Fitzroy Estuary and Keppel Bay showing the plume of turbid water resulting from the 1989 flow event

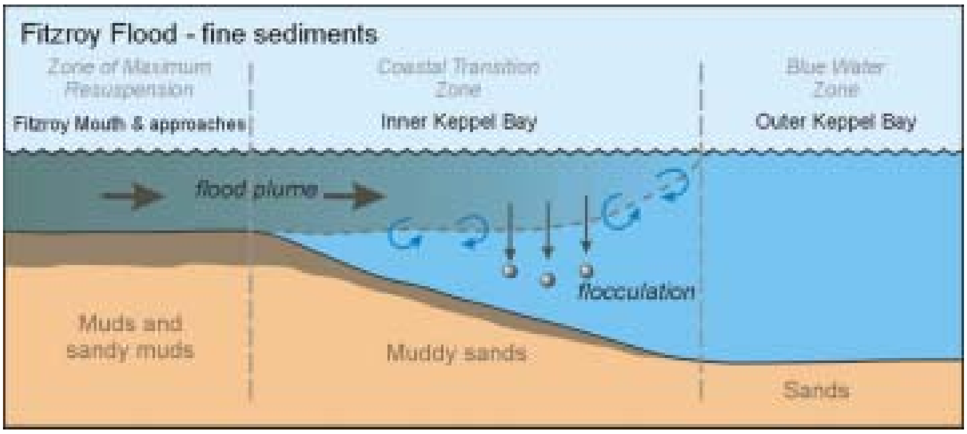

Figure 12. Conceptual model of Fitzroy flood plume penetrating into Keppel Bay showing flocculation of fine sediments

Sinking rates of flocculated sediments in KB have been estimated to be ~1–2 m day^{-1} which is many times faster than the sinking rates of unflocculated river sediments. A sampling cruise through the plume of the 1990–91 summer flood showed a shallow brackish surface layer with sediment concentrations between one-twentieth and one-fortieth of the TSS concentration measured at Rockhampton (Brodie & Mitchell, 1992). It would appear that most of the suspended sediment flocculates and deposits within a few kilometres of the mouth of the FE.

Following the cessation of flows, deposited sediments undergo a cycle of resuspension, transport by currents and deposition which gradually causes them to disperse throughout KB away from their initial deposition site. Resuspension of bed sediments occurs because of the interaction of the mean flow and turbulent eddies with the bed that can dislodge settled particles. Fine sediments in the bed tend to stick together due to electrostatic forces, creating a network of particles which may be more resistant to resuspension than the individual grains. The cohesiveness of such networks is a property of the sediment mineralogy and can be increased by the presence of biogenic films. Such cohesive sediments do not resuspend until a critical flow speed is exceeded, which may be much higher than for coarser particles. Once the critical flow speed is exceeded, resuspension rates increase with flow at a rate that is much greater than the rate of increase of flow speed. Ultimately, the concentration of sediments suspended in the water column depends on the balance between resuspension, deposition and horizontal transport.

Resuspension occurs most vigorously in the channels approaching the mouth of the FE where there is a supply of deposited fine sediments and where current speeds are highest. The relatively high concentrations of TSS in the approaches to the mouth can be seen as turbid water in the satellite image shown in Figure

3. From satellite imagery, we can estimate the concentration of TSS near the water surface. Figure 13 shows the TSS concentrations estimated for 7 September, 2003. Over the southern part of the bay around the estuary mouth, TSS concentrations mostly exceeded 5 g m^{-3}.

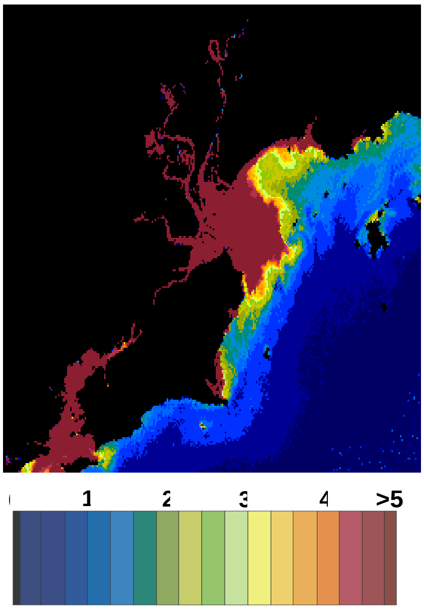

Figure 13. TSS concentrations inferred from the Meris satellite overpass on 7 September 2003. Concentrations are in g m^{-3}

There is a second zone of relatively high TSS concentration along the western side of KB (see Figure 3 and Figure 13). This region is relatively shallow (<5 m) and is subject to waves approaching from the east and south-east, the two dominant wave directions in the region. Wave currents are high where the waves start to shoal as here, and wave currents combined with background wind or tidal currents are effective agents for resuspension. A second source of turbid water (high TSS) observed in western KB might be water which is blown by the prevailing south-east wind from the zone of highest TSS concentration near the estuary mouth.

The distribution of water column zones with relatively high TSS concentrations tends to follow the distribution of bottom sediments with a relatively high proportion of mud. Further, the geochemical properties of the suspended sediments mostly reflect those of the muddy fractions of the underlying bed sediments, although the spatial variation of these properties was small within KB.

Time series of turbidity were measured at Buoy 1 near the mouth of the FE and at Timandra Buoy off the north end of Curtis Island (Figure 14). Measurements at Buoy 1 were obtained 1 m below the surface every 10 minutes for a month starting in mid-February 2004 just as Fitzroy River flows were diminishing and resumed in mid-August 2004. The later deployment started in the dry season at least five months after the cessation of summer flows in the Fitzroy.

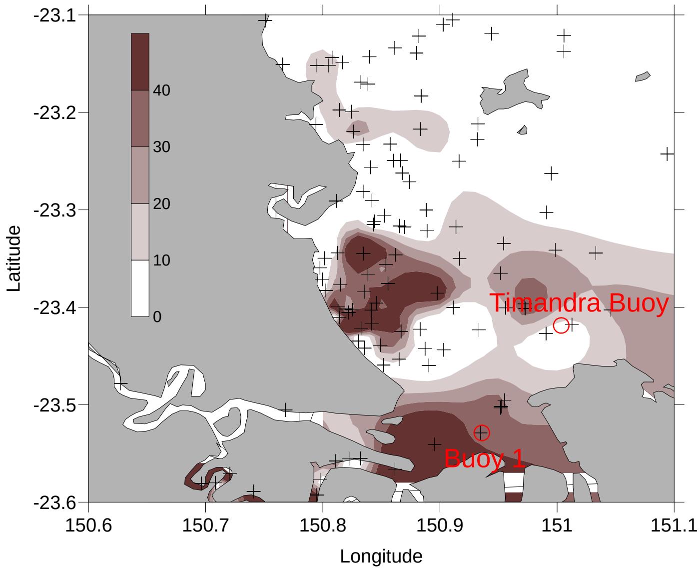

Figure 14. The percentage of mud in bottom sediments across Keppel Bay

The plus signs show the locations from which bottom samples were obtained for analysis. Also shown are the locations of Buoy 1 and Timandra Buoy.

Figure 15 shows the turbidity record from the second Buoy 1 deployment. Most of the turbidity in the inner parts of KB is due to fine suspended sediment. In fact, a comparison of measured turbidity and TSS concentration shows these to exhibit close to a 1:1 relationship. That is, 1 NTU (turbidity unit) is approximately equivalent to a TSS concentration of 1 g m^{-3}. Turbidity in all three time series undergoes a very pronounced semi-diurnal variation whose amplitude varies over the 14-day spring-neap tidal cycle.

The highest turbidity in a semi-diurnal cycle occurs 1–2 hours before low tide at Port Alma. This is consistent with the majority of the semi-diurnal turbidity variation being due to the tidal oscillation of offshore water (low turbidity) and water from the estuary mouth (high turbidity) past Buoy 1 (Figure 3). If this were the total explanation, then high tide would have the lowest turbidity at Buoy 1 and low tide the highest. However, active resuspension of muddy bottom sediments also causes turbidity to increase in the water column when currents are strongest at mid-tide. This effect is a likely cause of the apparent phase shift between maximum turbidity and low tide.

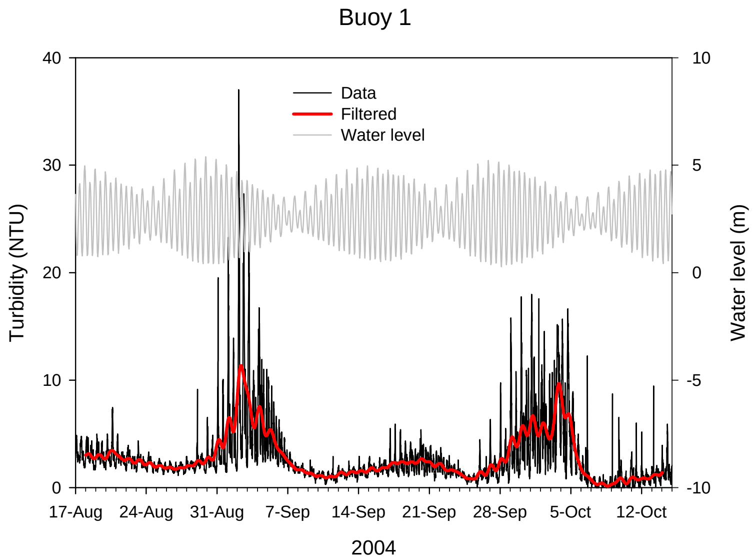

Figure 15. Time series of measured turbidity for the second turbidity meter deployment at Buoy 1. Also shown are this time series low-pass filtered and the time series of predicted water levels at Port Alma

When short-term fluctuations are filtered out to show background trends (Figure ***15***), maximum turbidity occurs a day or two after the peak tidal range (and peak currents) during spring tides. Turbidity during the neap tides is many times lower than the turbidity maximum even though neap tidal currents have amplitudes that are about half of those occurring during spring tides. This illustrates how resuspension of sediments from the bottom does not simply increase in proportion to current speed, but tends to be much more effective as current speeds increase beyond their critical values that initiate resuspension.

Measurements at Buoy 1 for the month following the inflows in February 2004 showed peak TSS concentrations to be twice as high during spring tides as those observed later in the year during the dry season (Figure 15). We suggest that the higher TSS concentrations in the earlier period were due to the continued resuspension of fresh sediment recently deposited by the summer inflows. The persistence of elevated TSS concentrations even after the freshwater plume had dissipated is a feature also simulated by the model of fine-sediment dynamics discussed later.

Transport of fine sediments within Keppel Bay

Fine-sediment model description

The previous section has shown that the concentration of TSS in the water column is highly variable both in space and in time. A measurement program that made measurements at a sufficient number of locations and sufficiently frequently to resolve how sediment moves around in the system would be prohibitively expensive. Here we describe the use of a computer model of the fine-sediment dynamics to illuminate the processes at work during the flood times and during the dry season. This application is described in more detail by Margvelashvili *et al*. (2006).

The fine-sediment model includes the processes of sediment resuspension, deposition, flocculation, sediment consolidation and horizontal transport by currents. Thus, it relies on the simulation of currents from throughout the FE–KB system obtained from the simultaneous application of the hydrodynamic model (Herzfeld *et al*., 2006). Three sediment classes are included, namely fine silt and clay (grain size <10 µm), coarse silt (grain size 10–63 µm) and sand (grain size >63 µm). The two silt sizes sink at different rates and prove to move through the system in different ways. The sand fraction may not be important for transporting nutrients or increasing turbidity, but when it is mixed with the mud fractions it restricts the resuspension of the latter.

Figure 16 shows simulated shear velocity during an ebbing tide. Bottom shear stress, which is the force exerted by flowing water on the bottom, is proportional to shear velocity squared. The figure shows that the areas of high shear velocity (and high shear stress) are concentrated in the southern part of KB near the mouth of the FE. Accordingly, the model treats this zone as one of active resuspension. This zone appears to coincide reasonably well with the parts of KB where satellite imagery shows TSS concentrations to be highest (see Figure ***3*** and Figure 13).

The model also replicates other major features of the fine-sediment behaviour in KB such as the daily cycle of TSS concentrations and their spring-neap cycle. In other cases, the model did not simulate measurements so well. It did not represent the appearance of parts of the river plume at Buoy 1 very well. Due to computational and data limitations, the hydrodynamic and fine-sediment models can't represent much detail in the bathymetry of the channels leading to the mouth and we expect this is part of the explanation of the discrepancy between simulation and measurements at this time.

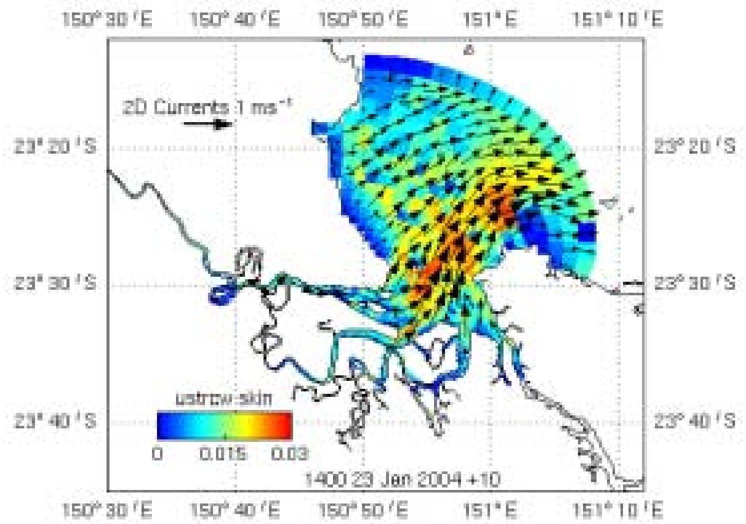

Figure 16 Simulated bottom shear velocities (colours) during an ebbing spring tide

The arrows show the depth-averaged current velocities simulated by the hydrodynamic model.

Model transport predictions

The model has large computational requirements which restrict the length of time that it can simulate the response of the FE–KB system to input loads from the Fitzroy River. Accordingly, we chose to run the model for a selection of three single-year periods representing a dry year with low inflows, a median year and a year with relatively high inflows. The characteristics of these flows are listed in Table 1. See also Figure 2. The yearly flow volume simulated varies by a factor of 20 and represents volumes that range from less than two estuary volumes to 30. The wet year had a yearly flow volume about one-third of 1991. It was not feasible to run the model with 1991 discharges due to model stability reasons.

Table 1. Characteristics of flows used for model simulations

Type	Year	Average flow (m^3s^{-1})	Percentile (1965–2005)	Estuary volumes
Dry	1993	11.7	8	1.5
Medium	2003	86.7	53	11
Wet	1999	239.4	83	30

Figure 17 shows the simulated mass balance of fine silt and clay after a one-year model run for the three flow years considered. The high flows in the wet year cause a large amount of fine silt and clay to be discharged into the head of the FE. Some of this is deposited within the estuary while the majority flows through the estuary and into KB. Following the cessation of the flows, much of the fine silt and clay is redistributed through KB by tidal and wind-driven currents. Some of this is transported beyond the boundaries of KB into the GBR lagoon through the dry season, but even after a year, the total mass exported is estimated to be about one-third of that input during the flow event. In the years following a wet year, we would expect export of fine silt and clay to the GBR lagoon to continue—perhaps for a number of years following a very large flow event such as the flood of 1991. In all three flow scenarios, accumulation of fine silts and clays tends to occur on the north-west coast of Keppel Bay, in the tidal creeks and in the Narrows (leading to Port Curtis).

The mass of fine silt and clay input by the Fitzroy River during the simulated dry- and median-flow years is very much smaller than that input during the wet year. During the wet year, there is net deposition within the FE, but this is gradually eroded from the estuary during the dry and median years so that the export of fine silt and clay during these years to KB is predicted to be greater than that which came down the river. Some of the sediment exported to KB is deposited within the bay and tidal creeks and the rest is exported to the GBR lagoon. This export to KB is relatively modest: ~0.1–0.2 Mt yr^{-1}.

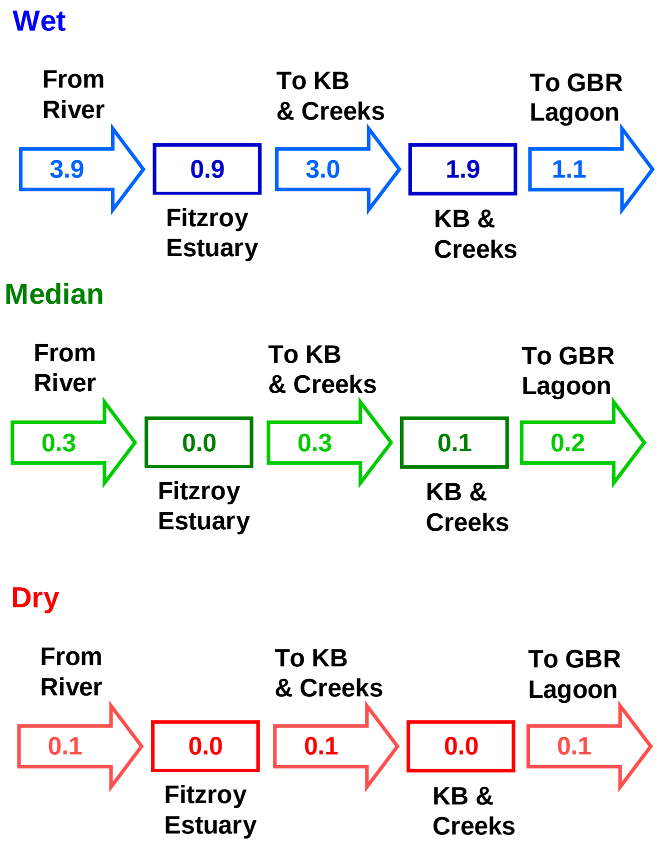

Figure 17. Schematic showing modelled transport (arrows) and stores (boxes) of fine silt and clay for wet-, median- and dry-flow years for the Fitzroy River

The results shown are the increase in the stores and the total transport between stores after 1 year of simulation. Units are Mt.

Transport estimated from measured deposition rates

Bostock *et al*. (2006a,b) describe how sedimentary records have been used to estimate the rate of deposition of silts and clays (>63 μm) through the FE–KB system. Deposition in the FE and on its estuarine floodplain is estimated to be 0.86 Mt yr^{1}, in the tidal creeks to be 1.95 Mt yr^{-1} and in KB including on the beaches and sand bars on its western side to be 0.47 Mt yr^{-1}.

These deposition rates can be used to develop sediment budgets for the system and particularly to develop an estimate for the export of sediment from KB into the GBR lagoon. The net export rate is calculated as the difference between the assumed average load of silts and clays delivered by the Fitzroy River and the measured total rate of accumulation of sediment throughout the system. Dougall *et al*. (2005) cite a number of studies by various investigators which estimate the average load as being as little as 1.86 Mt yr^{-1} and as much as 10.47 Mt yr^{-1}. Accurate estimation is difficult due in large part to the enormous episodicity in the hydrograph and variation in the source of river water in the catchment. Dougall *et al*. (2005) used the catchment delivery model SedNet to estimate an average load of 4.58 Mt yr^{-1} whereas a second recent estimate of 3.65 Mt yr^{-1} was obtained by Joo *et al*. (2005) who used an entirely different (sediment rating curve) method. Both these estimates are in the middle of the range reported by others.

Figure 18 shows the fine-sediment budgets inferred from accumulation rates and for these two values of the estimated average load of the Fitzroy. Both budgets show that the majority of the input load is trapped within the FE–KB system, but whereas ~1.30 Mt yr^{-1} is exported for L = 1.30 Mt yr^{-1}, only 0.37 Mt yr^{-1} is exported when L = 3.65 Mt yr^{-1} is assumed. For both loads, the majority of input sediment is stored within the FE–KB system and most of this storage occurs within the tidal creeks.

Most of the average load is delivered by the relatively rare large flood events—in the last 30 years most of the load would have been attributable to the 1991 flood. Sediment delivery would have been at least five times larger than the wet year modelled. Because of this very large contribution from 1991, it turns out that the wet year modelled has an input load that is similar to the average Fitzroy load estimated by Joo *et al.* (2005). The loads stored in the FE predicted by the wet-year simulation (0.89 Mt yr^{-1}) are similar to the measured accumulation rate in the FE and floodplain (0.86 Mt yr^{-1}). Likewise, the storage in KB and in the tidal creeks are not dissimilar, being 1.86 and 2.42 Mt yr^{-1}, respectively.

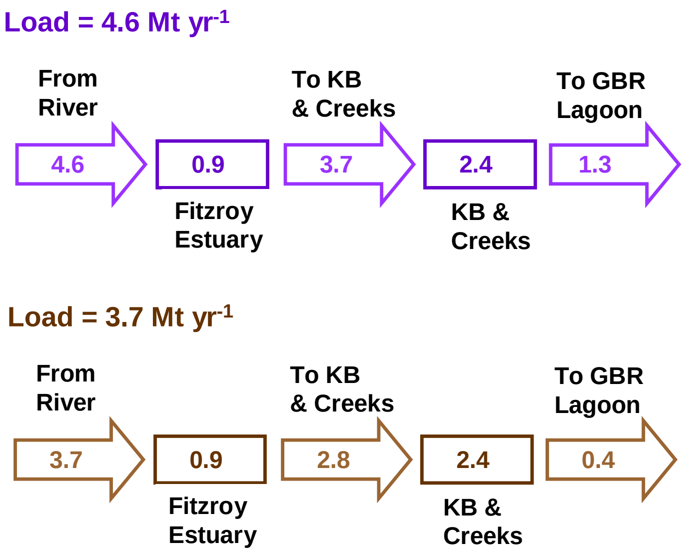

Figure 18. Sediment budgets for the FE–KB system derived from measured sediment accumulation rates and for two assumed values for the average load of fine sediment in the Fitzroy River

The boxes are measured deposition rates and the arrows are calculated transport.

Note that the model does not include storage on the floodplain, whereas the accumulation rates for the FE do include sedimentation there. Further, the model simulations are for the fine silt and clay fraction whereas the budgets derived from the accumulation data refer to the total silt component of transported sediment. The proportion of very fine material in the load of the Fitzroy (clay) is estimated to be over 95% (Horn *et al*., 1998) so that total silt and clay load and fine silt and clay load are not much different to one another.

The 'measured' sediment budgets shown in Figure 18 represent transport and accumulation rates averaged over decades. Due to computational limitations, the sediment model could not be run over similar time periods or even over a limited sequence of years so that model-predicted and measured storages are not determined on the same basis. Nevertheless, the predictions and the measurements are consistent to the extent that storage within the FE–KB system appears to be a large fraction of the total input load.

5 Transport and fate of nutrients

Delivery of nutrients to the Fitzroy Estuary

Nitrogen (N) and phosphorus (P) are the nutrients that are most commonly associated with water quality problems in water bodies. These nutrients are transported by the Fitzroy River during floods in both dissolved and particulate forms. Most of the latter is attached or adsorbed to suspended sediment. Measurements of nutrient concentrations in the Fitzroy River at various times over a number of years show that concentrations vary considerably presumably as a consequence of the stage of the hydrograph, the antecedent rainfall conditions and the catchment source.

Furnas (2003) provides estimates of the average annual delivery of nutrients to the FE. His total estimated loads of N and P are 5100 t and 1000 t respectively, of which 60% and 79% respectively occur in a particulate phase associated with suspended sediments. Average annual nutrient loads estimated recently by Dougall *et al*. (2006) using an approach based on a derivative of SedNet are 8900 t of N and 3200 t of P, which are substantially larger. The discrepancy is somewhat consistent with the difference in the estimated suspended sediment loads. SedNet estimates an annual sediment delivery of 4.58 Mt yr^{-1}, which is twice as large as the 2.23 Mt yr^{-1} estimated by Furnas. As with the delivery of water and of suspended sediments to the FE already described, the delivery of nutrients is expected to have a high interannual variability, with the majority for the last 15 years being delivered during the 1991 flood.

Nutrient dynamics within the Fitzroy Estuary

Webster *et al*. (2004) have described the transport and fate of nutrients within the FE and we summarise the main points here. For flows that have a larger volume than the FE, the estuary is completely filled so river water and the nutrients it carries are discharged directly into KB in more or less unmodified form. For lesser flow volumes, river water may not reach the estuary mouth by the end of the flow period and the river nutrients are retained within the estuary until tidal mixing gradually causes the fresh water to be replaced by sea water in the months following cessation of the flow.

Figure 19 shows the import and export results for total nitrogen (TN) during the Coastal CRC study of 2000–2002 (Webster *et al*., 2005). Each bar represents the import/export calculated between successive pairs of surveys undertaken at approximately monthly intervals. Through the first summer of the study, October 2000 to April 2001, the total input by the river to the estuary is estimated to be 2 520 t of which 2 420 t was exported out of the estuary. Almost half of this input load in the first summer was delivered to the estuary over a 10-day period near the end of November 2000. The following summer the total input is calculated to be 600 t which is smaller by more than a factor of four. The export during this second summer was 320 t. Apparently, most of the TN was carried straight through the estuary by the higher flows during the first summer, whereas during the second summer the flow event was barely large enough to fill the estuary. A series of flow events in the first summer had a combined volume that would fill the estuary 13 times, whereas in the second summer it would have been filled less than twice.

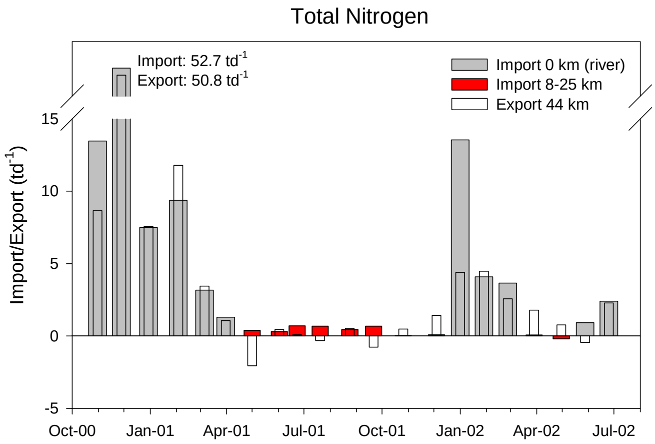

Figure 19. TN imports and exports from the Fitzroy Estuary

Imports are shown as river inputs for discharge >5 m^3s^{-1} and for input between 8–18 km for discharge <5 m^3s^{-1}.

Our analyses show that there is a net input of N into the water column in the upper part of the estuary during the dry season. Some of this is due to the decomposition of organic matter on the bottom introduced by the flows in the previous summer, but discharges from the Rockhampton wastewater treatment plants and the meatworks would appear to contribute significantly also.

Nutrient dynamics in Keppel Bay

Radke *et al*. (2005) and Radke *et al*. (2006) report on the field investigation of the biogeochemistry and primary production within KB and the tidal creeks undertaken as an activity in Project AC. The following interpretation of their study results is supported by the biogeochemical modelling of the FE–KB system described by Robson *et al*. (2006a).

Dissolved and particulate nutrients reach KB either directly through the penetration of the river plume into the bay during flood events or later during the dry season when fine sediments and water are exchanged between the bay and estuary by oscillatory tidal flows. Nutrient dynamics in KB under low-flow conditions reflect the interplay of internal biogeochemical processes, biological utilisation and hydrodynamic factors which govern the distribution and concentrations of dissolved nutrients, of the nutrients associated with the fine-grained sediments in the seabed and overlying water column, and of phytoplankton and biological detritus.

KB can be divided into three biogeochemical zones based on the nature of the underlying sediment (percentage fine sediments, see Figure 14), TSS concentrations and the behaviour of dissolved inorganic nutrients. Accordingly, the conceptual model of dissolved nutrient dynamics (shown in Figure 20) under low flow conditions is divided into three segments based on these zones; that is: the zone of maximum resuspension (ZMR), the blue water zone (BWZ) and the coastal transitional zone (CTZ).

Ultimately, these zones derive from the hydrodynamics of the bay. The ZMR, encompassing the approaches to the FE and tidal creeks, has high tidal currents causing active resuspension of fine particles and high turbidity. The CTZ, which covers most of the western side of KB, is characterised by smaller tidal currents, but being relatively shallow is subject to some resuspension due to the combined effects of tidal currents and waves. In the deeper BWZ further offshore, the effects of waves on resuspension is diminished. Water in this zone is subject to exchange with clearer water from across the seaward boundary of KB.

About two-thirds of nutrients are delivered to KB in particulate form, mainly as organic constituents on soil particles, while the remainder is in dissolved forms (Douglas *et al*., 2005). The dissolved materials move with the plume and are mixed into the saline waters as the plume dissipates. We have estimated that it takes about 20 days for a large part of the water within western KB to exchange with the GBR lagoon waters further offshore. Two months after the cessation of flows in the Fitzroy River (three mixing times), one might expect that the dissolved nutrients introduced to KB by the plume would be mostly mixed out of the system even if they were not consumed by phytoplankton.

Phytoplankton are unicellular plants (algae and blue-green algae) that may stick together as colonies. They are found in the water column and tend to slowly float or slowly sink depending on whether they contain gas vacuoles within their bodies or not. Microphytobenthos (MPB) are similar to phytoplankton except that they live on the bottom. Usually about 10 days after the end of a flood event, the water clears sufficiently for a phytoplankton bloom to occur, consuming the available dissolved nutrients (Brodie & Mitchell, 1992). Presumably at least some of the organic matter associated with the sediments deposited by the flood is consumed by bacteria, a process that releases dissolved nutrients to the water column. These nutrients allow further phytoplankton growth. In the BWZ, the water is clear and there is sufficient light for the phytoplankton and the MPB to grow as fast as nutrients become available, resulting in complete utilisation of the released nutrients.

When the phytoplankton and MPB are eaten by other organisms or die in some other way, the nutrients they contain in their bodies are released to the water column by digestion or bacterial degradation and are again available to fuel further primary production. In the BWZ, the phytoplankton and MPB consume the dissolved nutrients as fast as they are released, so that concentrations of dissolved nutrients in the water column are usually too low for analytic detection.

This cycle of nutrient utilisation also occurs in the CTZ and in the ZMR, although in the latter zone we have observed that large concentrations of suspended sediment limit the extent to which primary producers can utilise the available nutrients. Consequently, in the ZMR particularly, phytoplankton do not consume all the released nutrients and the nutrients occur in measurable quantities.
The important conclusion from this is that the cycle of nutrient uptake by phytoplankton and MPB is an important factor in determining the fate of nutrients in KB and in the upper half of the FE. In effect, the nutrients contained within the cells of phytoplankton are transported as the cells are dispersed by currents. This is an important nutrient exchange mechanism in KB. Our conceptual model of nutrient dynamics is illustrated in Figure 20.

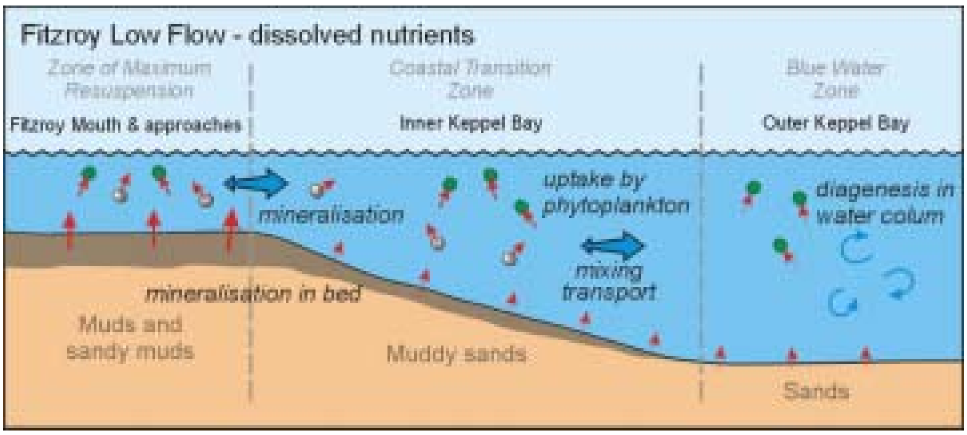

Figure 20. Conceptual model of dissolved nutrient dynamics under low-flow conditions in Keppel Bay

Although sand-to-mud ratios vary across KB, the geochemical and biogeochemical properties of mud fractions (of similar particle size ranges) throughout the CTZ and ZMR tend to be uniform. For example the phosphorus content to iron content ratios for suspended and bed sediments are indistinguishable within these zones. The active mixing of these fine sediments by tidal flows acts to homogenise them across the zones of active resuspension and transport.

Organic matter has distinctive properties that depend on its origin. One characteristic is the relative concentration of the carbon isotope ^{13}C to the most common isotope ^{12}C. A measure of the enrichment of ^{13}C is provided by the parameter $\delta^{13}C$. Another characteristic property of organic matter is the ratio of its total organic carbon content (TOC) to its total nitrogen content (TN). Figure ***21*** shows these two properties for the sediments in KB. These properties are most consistent with the organic matter having a bacterial and/or marine phytoplankton origin. The organic matter signatures are quite distinct from those of terrestrial plants and of catchment soils. The implication is that the organic matter that is associated with deposited and suspended sediments in KB has mostly been transformed by marine organisms after its arrival in the bay.

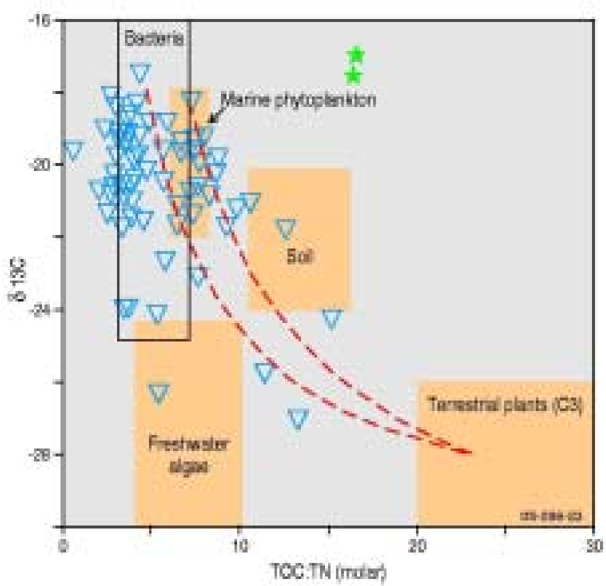

Figure 21. Characteristics of organic matter of the fine sediments in Keppel Bay

The shaded areas show the general characteristics of organic matter from various sources. The green stars are samples collected in the Comet and Bedford Rivers.

The fine sediments within KB contain a large amount of iron (Fe). Measurements show that the Fe content of particles per mass of sediment (the specific concentration) increases approximately linearly with the surface area of the sediment grains when the latter is expressed as surface area per gram of sediment; that is, the specific area (see Figure 22). This behaviour is consistent with most of the Fe being present as surface coatings on the sediment grains. The specific Fe concentration at zero area of ~20 mg g^{-1} likely reflects that portion of the iron that is incorporated within the mineral comprising the grains.

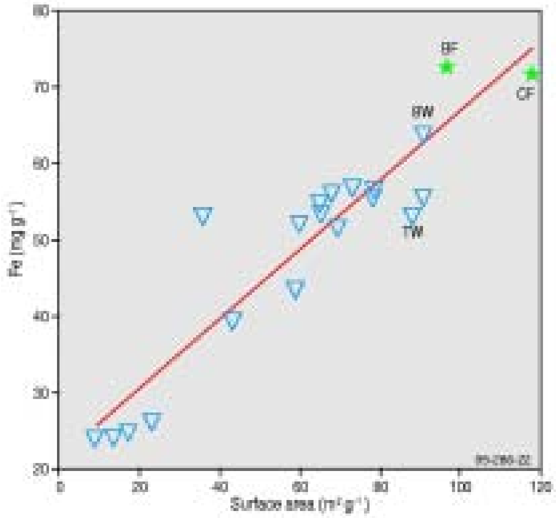

Figure 22. Specific iron concentration within sediment versus specific surface area

The labels are TW (Theodore Weir), BW (Bedford Weir), BF (Bedford River during flood) and CF (Comet River during flood).

Figure 23 shows total N and total P concentrations measured within sediments as a function of the specific Fe concentrations. For both N and P, concentrations increase approximately linearly with Fe indicating that both these nutrients also increase with specific surface area. For particles of the same shape (e.g. spheres for example), specific surface area increases in direct proportion to the inverse of particle size (e.g. diameter). Thus, the relationships shown in Figure 22 and 23 also demonstrate that the amount of nutrient per unit mass of sediment also increases as the inverse of particle size. Fine particles hold much more nutrient per unit mass than do large particles.

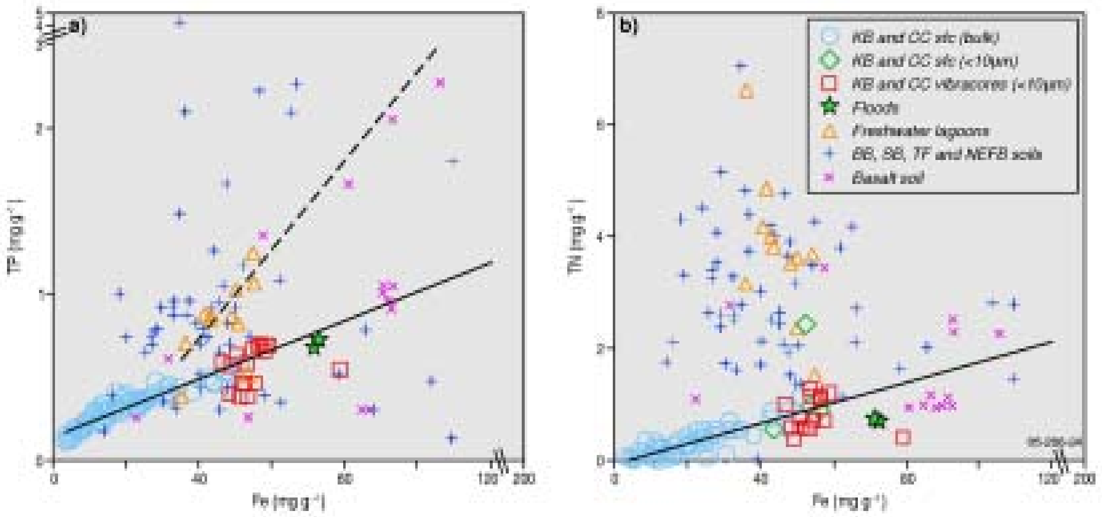

Figure 23. Total nutrient concentration in sediments versus specific Fe concentration: for total P (left) and for total N (right)

The solid lines show the best linear fit to the measurements obtained for surficial sediments in KB and Casuarina Creek (CC). The other abbreviations in the label are BB (Bowen Basin), SB (Surat Basin), TF (Thomson Fold Belt) and NEFB (New England Fold belt).

Figure 23 shows the concentrations of TN and TP vs. Fe down sediment cores collected from KB and Casuarina Creek (CC). Many of these concentrations cluster around the line characteristic of surficial sediments. At least in terms of their relationship with Fe concentrations, these sediments are similar to surficial sediments. If the organic matter in the buried sediments had undergone further significant degradation, one might expect that the relationships of TN and TP with Fe might alter also. That this has mostly not occurred suggests that the N and P associated with these sediments occurs in forms that are not very reactive. So, those nutrients that are exported as bound to fine sediments during the dry season may not be readily degradable to fuel primary production in other parts of the GBR lagoon. However, it is more likely that nutrients bound to sediments freshly discharged into the FE–KB system following a flood are more degradable.

TN and TP vs. Fe relationships from catchment soils in the Fitzroy catchment show a large degree of variability and reflect the different soil types and geological formations throughout the catchment. KB and CC sediments tend to have lower TN:Fe and TP:Fe ratios than most of those in the catchment, although the basaltic soils derived from the western side of the catchment draining into the MacKenzie River have properties that are similar to those in KB and CC. The sediments deposited within the freshwater lagoons exhibit ratios that reflect something like an average of those from the catchment. These are sediments that have not undergone marine transformations. One might assume that the mix of sediments delivered to the FE–KB system had properties that were an ‘average’ of those of the lagoon sediments and of those measured in catchment soils. If we further assume that no Fe was lost from the deposited sediments, it would appear that about two-thirds of the N and one-third of the P had been lost in the transformations of organic material in KB. Also, the analysis of a limited number of samples would suggest that a large amount of the P within the sediments has reacted with sea water and formed insoluble precipitates with calcium (apatite). This may account for the observation that more N is lost from the sediments than P.

We have suggested that the organic matter associated with the sediments in KB is fairly unreactive. Our modelling simulations which reconcile measured phytoplankton and nutrient concentrations within the water column of the bay suggest a decomposition time scale of 47 years for the old sediment-bound organic matter. Conversely organic matter freshly deposited by floods is much more reactive and has an estimated break-down time scale of 14 days. This new organic matter represents only a small proportion of the old, previously deposited material. For 2003 (a median flow year), we estimated a sediment delivery of ~0.26 Mt. Spread evenly over the area of KB (~600 km^2), this mass of sediment represents a layer only ~0.2 mm thick. For the major flood of 1991, the average deposition depth would be a few millimetres.

There are two other major factors that appear to have a significant impact on dissolved nutrient concentrations in KB. The first is the possibility of N fixation in the water column and in the sediments. Certain types of organisms can ‘fix’ dissolved nitrogen gas into forms that can utilised by phytoplankton. From experiments undertaken on sediment cores, we have developed a relationship between the rate of nutrient generation by this mechanism and the quantity of oxidised Fe (Fe^{3+}) in surficial sediments. In turn, from measured Fe concentrations in sediments over KB we can estimate the amount of nutrient (N) generated in this way by sediment N fixation to be 3200 t yr^{-1}. Fixation of N by certain species of phytoplankton can occur in the water column also, but this rate is calculated to be small considering the measured concentrations of the principal nitrogen-fixer, a blue-green algae of the genus *Trichodesmium.*

Secondly, dissolved organic nitrogen (DON) and dissolved organic phosphorus (DOP) represent a significant fraction of the dissolved nutrients that are discharged into the FE–KB system by the Fitzroy River. Dissolved organic material also seems to be excreted by primary producers on the intertidal areas and in the water column and is present in significant quantities throughout KB. The transport of DON and DOP represents a pathway for the exchange of N and P in or out of the FE–KB system, but the significance of these substances for fuelling primary production within the system is uncertain. Up to now, we have considered the nutrients in their dissolved inorganic N and P forms. DON and DOP come in many forms, some of which can be readily utilised by phytoplankton and bacteria and some much more unreactive. We have not differentiated these forms, but it is probable that if phytoplankton could readily utilise most dissolved organic nutrients to fuel growth, then their concentrations would be too low to measure, particularly in the well-lit BWZ of KB.

The major tidal creeks that connect to KB near the mouth of the FE (Casuarina, Raglan and Connor) have a combined surface area and volume that is similar to those of the FE itself. These creeks do not have large inflows of fresh water, but at times of significant floods in the Fitzroy River, we would expect that some fresh water discharged into KB does mix through the mouths of these creeks carrying with it dissolved and particulate nutrients and suspended sediments. During the dry season, the vigorous tidal currents in the region of the mouth of the FE and in the tidal creeks continue to exchange dissolved and suspended material between the creeks and KB.

Our modelling shows these tidal creeks to be net sinks of fine sediments. However, from measurements obtained during the dry season, Ford *et al*. (2005) determined that there was a net export of dissolved inorganic N and P from Casuarina Creek to KB. Conversely, there was a net import of these nutrients into Connor Creek of similar magnitude. For Casuarina Creek, we can presume that the dissolved nutrients that are exported derive from the decomposition of particulate organic matter (phytoplankton plus sediment-bound nutrients) within the creek. Connor Creek is deeper and clearer than either Casuarina or Raglan Creeks due to less effective tidal resuspension of bed sediments. One might suppose that the clearer conditions are more conducive to phytoplankton and MPB growth in Connor Creek and consequently to net nutrient uptake by these organisms. Whether Connor Creek acts as a net sink of dissolved nutrients over a full year of seasons is not known.

Primary production within the FE–KB system

In coastal water bodies, primary producers include phytoplankton, MPB, macroalgae and sea grasses. These groups form the base of the food chain on which higher aquatic organisms including crustaceans (crabs, prawns, etc.), molluscs and fish ultimately depend for their survival. All primary producers require light and nutrients in order to grow and the availability of these is a major determinant of the survival of particular types of primary producers. Seagrasses require a stable bottom and lots of light (clear, shallow water) in order to grow. This primary producer does not flourish in the FE–KB system. Macroalgae are the seaweeds which are typically red or brown in colour and are found on the bottom in the BWZ. Phytoplankton and the MPB both grow quickly and tend to be eaten at a similar rate and are usually considered the most important food sources for aquatic organisms even when macroalgae and seagrasses are present in abundance.

The clearing of the water in the upper half of the estuary due to sediment flocculation that occurs when salt water is mixed up the estuary during the dry season allows significant phytoplankton growth. Chlorophyll concentrations in the water column in this region have been measured to exceed 10 mg m^{-3} which is moderately high (ANZECC, 2000). There are large beds of small mussels that filter planktonic material out of the water column (Currie & Small, 2002). Schools of jellyfish have been observed in this section of the estuary which would also prey on the phytoplankton population. The nutrients required to foster phytoplankton growth in this part of the estuary during low flow times derive mainly from the decomposition of organic material deposited in this section of the estuary during the time of high flow. However, Webster *et al*. (2005) estimated that perhaps a quarter of the nutrient supply is discharge from Rockhampton's wastewater treatment plants.

In the seaward half of the FE, the water is too turbid due to active tidal resuspension of sediments to support primary production in the water column by phytoplankton. In the extensive intertidal areas along the sides of the estuary, extensive mats of MPB live on the sediment surface and receive the light they need to grow for at least the time that they are exposed at low tide. MPB can be filamentous algae, blue-green algae, diatoms or other types of microorganisms (see Figure 24).

A major activity in Project AC was the investigation of primary production in the intertidal areas along the sides of the FE. Its results are described in detail by Revill *et al*. (2006). Modelling of primary production in the intertidal areas was also undertaken by Wild-Allen *et al*. (2006).

Figure 24. Abundant diatoms (dark brown areas) on an intertidal bank in the Fitzroy Estuary

The growth of MPB on the intertidal areas underwent a seasonal cycle. When the estuary was fresh during and immediately following flows in the Fitzroy River, the amount of MPB was relatively low partly because the fresh water would not be a suitable environment for the species there. Nevertheless, the flows did introduce large amounts of nutrients into the estuary which led to high growth through autumn. Maximum concentrations of MPB occurred during the winter as a consequence of this growth. As summer approached but before summer flows began, the MPB population declined. It is thought that the decline at this time of the year is due to the intertidal sediments becoming overly warm (probably >50^{o}C), a condition not conducive for MPB growth.

It is certain that intertidal production of MPB also occurs along the extensive intertidal areas in the tidal creeks. A significant difference between these and the FE is that the estuary is subject to summertime flows of fresh water which replenish nutrients and fine sediments and which may reset the MPB populations. However, for flows which are large enough to penetrate into KB, fresh water appearing at the estuary mouth will mix up into the tidal creeks to some extent.

Figure 25 shows the measured concentrations of chlorophyll in the water column during a cruise to KB in September 2003. A similar concentration distribution was measured a year later also. Chlorophyll concentration is a measure of how much phytoplankton there is in the water. Over most of KB, concentrations are $<1\ \text{mg m}^{-3}$, but higher concentrations are found in the south-west corner of the bay near the mouth of the FE. Summer chlorophyll concentrations show a similar pattern, but are about twice as large.

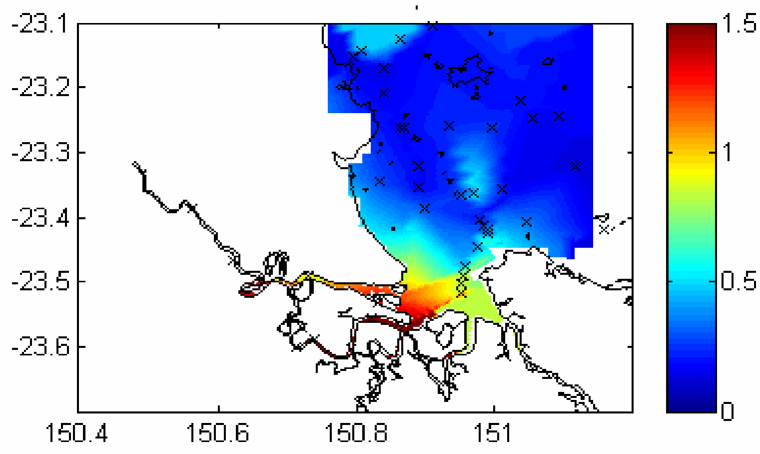

Figure 25. Chlorophyll concentrations measured in KB in September 2003

Concentrations are in mg m^{-3}

It is apparent that phytoplankton growth throughout most of KB is limited by the availability of nutrients. There, nutrient concentrations are below the limits of detection. As dissolved inorganic P was detectable in more samples than dissolved inorganic N in the CTZ, it is likely that nitrogen was the limiting nutrient in this zone. Phytoplankton grow in this zone, but losses must approximately balance growth. We hypothesise that it is mainly decomposition of dead phytoplankton cells and the resultant release of nutrients into dissolved forms that allows growth. Conversely, in the mouth region of the FE, concentrations of phytoplankton are higher, but there are also measurable concentrations of dissolved nutrients. In this highly turbid region, growth is limited by the availability of the light necessary for growth. Again, there must be an approximate balance between growth and loss. This time nutrients are supplied by the decomposition of deposited and suspended organic matter in the mouth region and in the tidal creeks. A conceptual model of primary production in KB is shown in Figure 26.

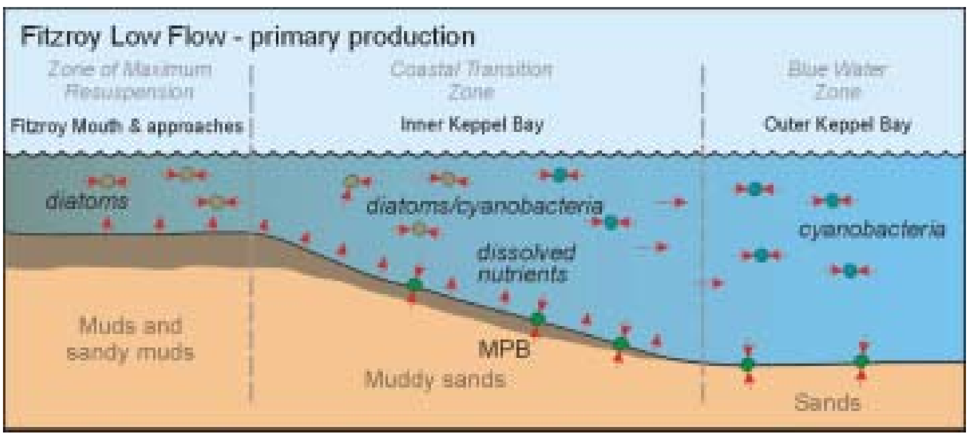

Figure 26. Conceptual model of primary production under low-flow conditions in Keppel Bay

The composition of phytoplankton within KB varies between its different zones. Diatoms were the main taxonomic group in the ZMR, also due to the energetics of the region. Because diatoms sink, they need to be actively resuspended and mixed through the water column in order to access the light near the water surface—light they need for photosynthesis. In the BWZ, cyanobacteria (both the filamentous *Trichodesmium* spp. and the smaller unicellular species) were the main phytoplankton groups present. These cyanobacterial species either have gas vacuoles that allow them to float or are small enough (unlike diatoms) that they sink through the water column very slowly. Thus, they do not rely on tidal resuspension to remain in the water column. Cyanobacteria have an additional advantage in KB because they can use dissolved nitrogen gas as part of their N supply and so have a competitive advantage over other phytoplankton types where the availability of N is very low. The CTZ is an intermediate zone characterised by a mixture of diatoms and cyanobacteria.

The cyanobacterium *Trichodesmium* spp. can be problematic in KB. While the individual *Trichodesmium* cell size is $<10\ \mu m$, it exists in the form of multicellular filaments that may be $200\ \mu m$ long. It tends to float on the surface and is sometimes blown ashore in spring and summer to form shoreline mats bordering KB, which may then rot. This shoreward movement of *Trichodesmium* spp. represents a transport of nutrients from offshore in the GBR lagoon into KB.

The transport of nutrients within the FE–KB system

Biogeochemical model description

As with the fine-sediment model, we develop a biogeochemical model for the FE–KB system to better understand the transport, transformation and storage of nutrients in a system subject to considerable temporal and spatial variability. The development and application of the biogeochemical model is fully described by Robson *et al*. (2006a). A summary is provided here.

Broadly, the model represents a set of pelagic interactions and a set of benthic interactions controlled by analogous sets of functional groups. The model may be conceptualised as a series of stores (boxes) and flows (arrows) of nitrogen, phosphorus or carbon. Figure 27 shows a schematic of the model structure as it applies to nitrogen. Similar structures apply to phosphorus and carbon. Nitrogen stores in the model include phytoplankton (diatoms and *Trichodesmium* spp.), zooplankton groups, MPB and nitrogen in various organic and inorganic forms including detritus. Some of the flows between stores represent biogeochemical transformations including uptake of nutrients by primary producers, consumption of phytoplankton by zooplankton and organic matter degradation.

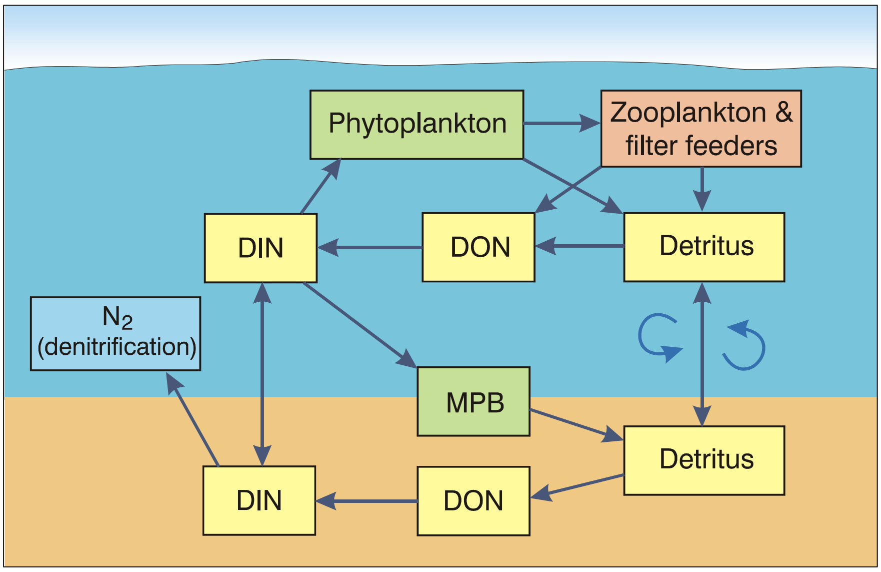

Figure 27. Schematic of biogeochemical processes and primary production in Fitzroy Estuary and Keppel Bay. Here the stores and transformations of nitrogen components are represented

The biogeochemical modelling scheme is implemented across the FE–KB region. This model is coupled to the hydrodynamic and fine-sediment models so that the physical exchanges—washout to the ocean, burial of organic matter, settling of detritus to the seabed, transfer to the tidal creeks, and diffusion of solutes between water column and sediments—are also represented. The modelled processes include benthic organic matter degradation, the return of nutrients to the water column from sediments.

Biogeochemical model transport predictions

As with the fine-sediment model, the biogeochemical model has large computational requirements and again, we chose to run the model for the dry, medium and wet years that are listed in Table 1. Figure 28 shows the simulated mass balance of the nitrogen after a one-year model run for the three flow years considered.

The high flows in the wet year cause a large amount of nitrogen to be discharged into the head of the FE primarily as organic matter associated with the suspended sediments. Some of this is deposited within the estuary while the majority flows through the estuary and into KB. Over the year, about a one-third of the input N is exported to the GBR lagoon mainly as phytoplankton and as dissolved N, but about a sixth of the input is exported as refractory N associated with suspended sediments. The remaining half of the N input by the river is deposited within KB and the tidal creeks. In a large flood such as that of 1991, we expect that the model would show an export efficiency of N to the GBR lagoon to be substantially greater than the 35% demonstrated for our wet-year simulation.

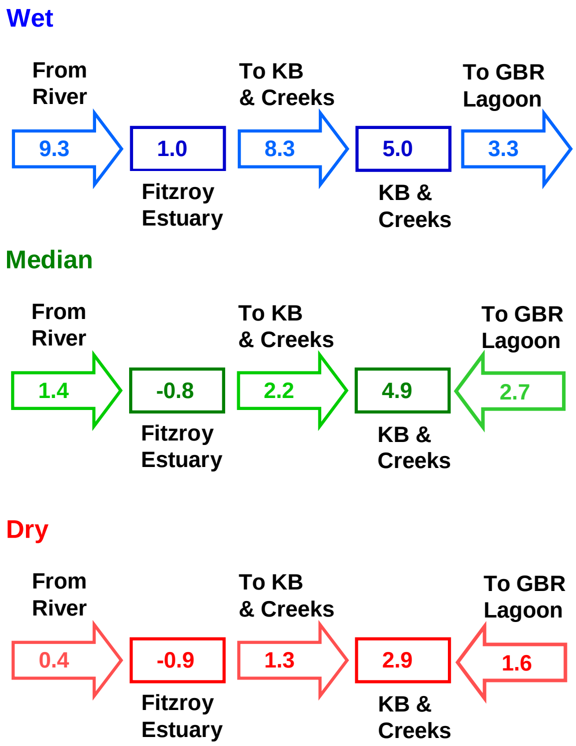

Figure 28. Schematic showing modelled transport (arrows) and stores (boxes) of nitrogen for wet-, median- and dry-flow years for the Fitzroy River

The results shown are the increase in the stores and the total transport between stores after one year of simulation. Units are kt.

The simulations for the median- and dry-season years show similar behaviour to one another. The model predicts an influx of N from the GBR lagoon into KB in both cases which is larger than the input by the river. Most of this input occurs as DON and a minor proportion as phytoplankton. There is a net loss of N from the FE. The tidal creeks and KB both act as major deposition zones for N. It should also be noted that by the end of the dry season in the wet-year simulation, the export flux between KB and the GBR lagoon has reversed to become an import flux for N.

One result that seems anomalous is the higher import of N from KB during the median-flow year than during the dry-flow year. Due to lower turbidity in the dry-flow year, phytoplankton concentrations are higher in outer KB than in the median year. Consequently, more N is mixed out of KB as phytoplankton during the dry year so the overall net import of N is reduced. This result illustrates how the system response is not simply proportional to loads of nutrients.

Nutrient transport estimated from measured deposition rates

During Project AC, we measured the nutrient content of deposited sediments. Combining this information with the estimated rates of sediment deposition (described previously in this report), we calculate an estimated rate of burial of nutrients within the FE–KB system. As with fine-sediments, the net export rate is calculated as the difference between the assumed average load of nutrients delivered by the Fitzroy River and the measured total rate of accumulation of nutrients within deposited sediments throughout the system. We present results for two estimates of the input nutrient loads, namely the estimated loads proposed by Dougall *et al*. (2006) and by Furnas (2003) (see Table 2).

Table 2. Estimates of nutrient loads proposed by Dougall *et al.* (2006) and Furnas (2003)

Export efficiencies are the proportion of the input load that is delivered to Keppel Bay. The negative efficiency represents import from Keppel Bay.

Nutrient	Load (t yr^{-1}) Dougall *et al*.	Load (t yr^{-1}) Furnas	Export efficiency Dougall *et al*.	Export efficiency Furnas
N	8,900	5,101	63%	36%
P	3,200	1,101	46%	-56%

The estimated nutrient transport pathways in the FE–KB system calculated using the sediment deposition measurements are presented in Figure 29 for N and in Figure 30 for P. For N, the results suggest that if the input load proposed by Dougall et al. is assumed, then 63% of the nitrogen input by the Fitzroy River passes through to KB (see Table 2), whereas the Furnas estimate of input load of N gives an export efficiency of 36%. The modelling results are at least superficially more consistent with the lower export efficiency.

For P, the export efficiencies are lower than they are for N. In fact, if the input load proposed by Furnas is correct, then KB imports P from the GBR lagoon. The difference in the export efficiencies of N and P is consistent with the concentrations of N and P measured in the sediment cores from KB and from CC (Figure 23). It was noted in the discussion surrounding this figure that compared to the concentrations in riverine sediments (expressed as mass of nutrient per mass of sediment), N appeared to be depleted by about two-thirds and P by about one-third relative to their concentrations on incoming sediments. That is, about twice as much N was lost from the sediments as P. In fact, if all fine sediment were deposited in KB and the tidal creeks, then these depletion rates would imply export efficiencies of ~65% and ~35% for particulate N and P respectively.

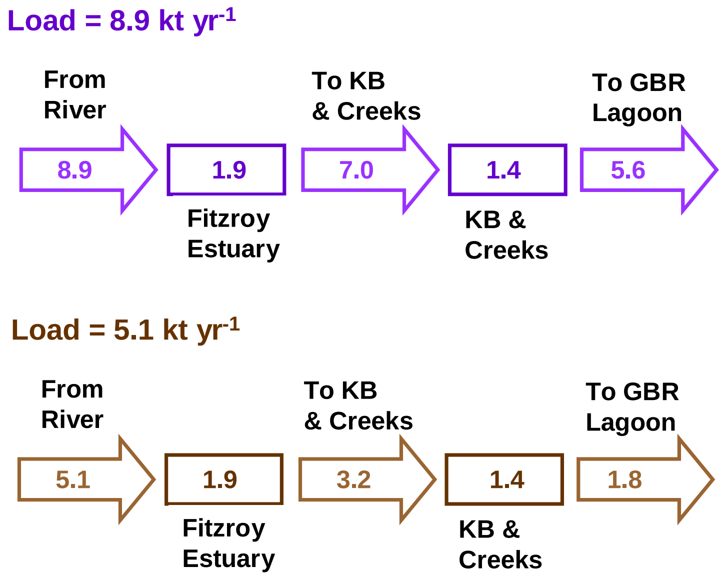

Figure 29. Nitrogen budgets for the FE–KB system derived from measured sediment accumulation rates and sediment nutrient concentrations

Results are shown for two assumed values of the average load of N from the Fitzroy River. The boxes are measured deposition rates and the arrows are calculated transport. Units are kt.

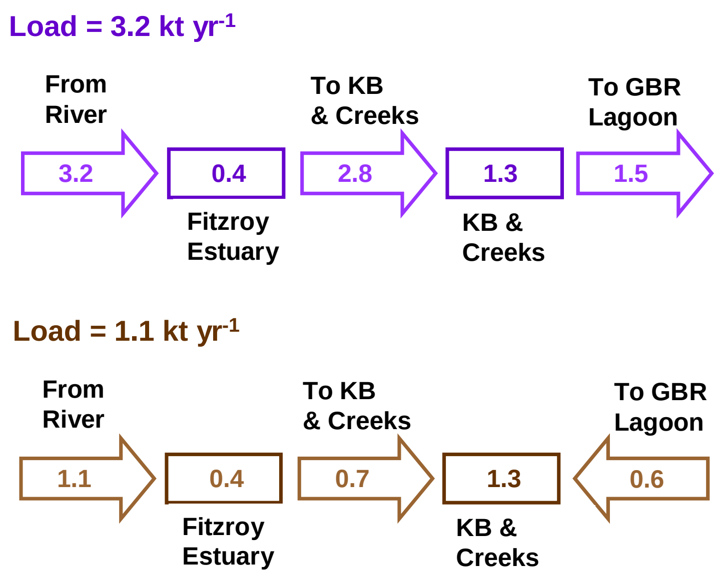

Figure 30. Phosphorus budgets for the FE–KB system derived from measured sediment accumulation rates and sediment nutrient concentrations

Results are shown for two assumed values of the average load of P from the Fitzroy River. The boxes are measured deposition rates and the arrows are calculated transport. Units are kt.

There are two other sources of nutrients in the FE–KB system that we have not included in this calculation. The loads from Rockhampton's wastewater treatment plants are ~75 t yr^{-1} and ~30 t yr^{-1} for N and P, respectively. These represent about 1% and 3% of the estimated average loads estimated by Furnas (2003). A potentially much more significant source of N is fixation in the bottom sediments in KB. Our estimate of 3200 t yr^{-1} for N fixation represents a very large fraction of both the estimated N loads to the FE–KB and their inclusion would add directly to the amount of N exported to KB. Adding this amount of N to the calculated export as shown in Figure 29 would result in the total export being very similar to the average river input of N. In effect, this amount of N closely balances the estimated burial of N in the FE and in KB and the creeks resulting in an export efficiency of the FE–KB system of close to 100%. That N fixation is really occurring at the rate estimated needs to be confirmed.

The export of dissolved inorganic N from Casuarina Creek during the dry season as a yearly rate is estimated to be 19 t versus -21 t for Connor Creek (an import). The corresponding export loads for P are 2.3 t and -3.7 t. These numbers are small compared to the overall budgets for N and P presented in Figure 29 and 30.

6 Scenario analysis for catchment modification

The Fitzroy Basin Association has proposed a series of hypothetical land-use scenarios. The evaluation of their effects on the delivery of sediments and nutrients is being used to inform the Assocation in developing their response to the Reef Water Quality Protection Plan. Dougall *et al*. (2006) have estimated the changed loads in the Fitzroy River through application of the catchment program SedNet coupled with the nutrient delivery algorithm ANNEX.

In Project AC, we used our suite of hydrodynamic, fine-sediment and biogeochemical models to predict the impact of two of the land-use scenarios and compare them to the third scenario which is current land use. The two ‘change’ scenarios are an increase in vegetation cover to 70% (graz70) and a decrease in vegetation cover to 30% (graz30). The current vegetation cover is assumed to be ~55%. In these scenarios, decreased vegetation cover results in increased loss of fine sediments and their attached nutrients from the landscape into rivers. The water delivery from the catchment to the rivers and the concentrations of dissolved nutrients will be assumed to be unaltered by changes in the vegetation cover although this is highly unlikely in reality.

In our analyses, we consider the impacts for all three scenarios (current, graz70, graz30) for both the median- and wet-flow years considered in the previous chapter (see Table 1). For the dry year, the loads were small and there was little difference in the model response to the three scenarios. Mainly, we consider two aspects of the impact of changed loads: how adoption of the scenarios would alter delivery of nitrogen to the GBR lagoon and, how primary production (phytoplankton chlorophyll) would respond. The latter provides some measure of the ecological response of the system. The application and results of this scenario analysis is described in more detail by Robson *et al*. (2006b).

The duration of the wet season in the FE–KB system varies from year to year according to the timing and magnitude of freshwater flows. However, here we shall report wet season results as pertaining to the period from December until April and the dry season, for the period from May to November inclusive.

Effect on export of nitrogen to the GBR lagoon

Table 3 details the loads used in the simulations and the export of N over a year to the GBR lagoon.

Table 3. Total annual freshwater inflow, sediment and nitrogen load for each scenario

Flow	Scenario	Sediment load (Mt)	Load N (kt)	Export N (kt)	% Export
Median flow	Current	0.3	1.4	-2.1	None
(86.7 m^3s^{-1})	Graz70	0.1	0.7	-1.4	None
	Graz30	0.5	2.2	-1.1	None
High flow	Current	3.9	9.2	2.8	30
(239.4 m^3s^{-1})	Graz70	2.6	6.2	1.8	29
	Graz30	7.8	18.5	5.6	30

During the wet season in the median-flow year, there is N export for both graz30 and graz70, whereas for the current case, a small import of N is predicted. However, over the year as a whole including the dry season, the model predicts a net import of N—largely in the form of DON—from marine sources, with the current case having the largest import. This result seems anomalous for graz70 since its load is smaller than the current load. For this scenario, phytoplankton concentrations in outer KB are predicted to be slightly higher than for the current case, resulting in increased export of N in this form offsetting the import of DON. The predicted change in TSS export across all scenarios was minimal, varying from an export approximately 9.6 kt day^{-1} during the wet season of the graz70 scenario to 9.8 kt day^{-1} during the wet season of the graz30 scenario. Predicted changes during the dry season were even smaller.

The results proved more sensitive to scenario choice over the course of a year for the high-flow year than for the median-flow year. Neither land-use change scenario greatly affected dry-season exports to the GBR lagoon; however, with greater wet-season loads expected during a high-flow year, the impact of changes on the total annual export to the GBR lagoon was substantial. During the high-flow year, doubling the N load to the FE (graz30) doubles the predicted export to the Great Barrier Reef lagoon, while reducing N loads by one-third (graz70) reduces predicted export to the GBR lagoon by a similar amount. The overall result is that the export efficiency of the FE–KB system to N loads during a high-flow year remains at about 30% across all three scenarios. For the high-flow year, reducing loads through catchment management is predicted to result in a proportional reduction in loads to the GBR lagoon. Since it is the high-flow years that are responsible for most nutrient export, we might expect that this result would apply approximately to loads averaged over a number of years.

Effect on chlorophyll *a* concentrations

Figure 31 shows the spatial distribution of chlorophyll *a* at the water surface on 5 February during the median-flow year simulation for each scenario. Doubling particulate nutrient and sediment loads (graz30 scenario) and reducing loads (graz70 scenario) both have the effect of reducing chlorophyll concentrations in KB. This will be shown to be due to the counteracting effects of increasing loads of nutrients and sediments.

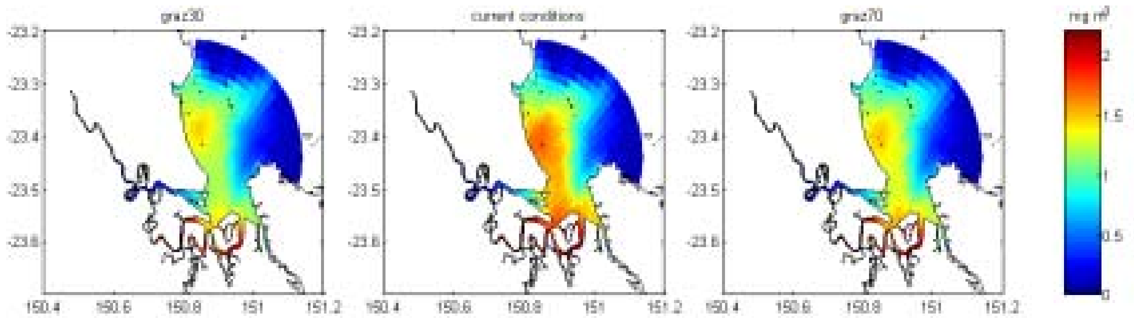

Figure 31. Snapshot of simulated chlorophyll *a* concentrations at the surface on 5 February (near the peak of the wet-season flood event) for each scenario in a median-flow year

A more quantitative picture of impact can be obtained by comparing the median concentrations in each scenario over the course of the wet season and over the course of the dry season at specified sites. For this analysis, we show results for five sites: one in Fitzroy Estuary downstream of the Loop (around 30 km down-estuary from the Barrage); one in the mouth of the estuary; one at a site in Deception Creek; one in inner KB; and one in the outer part of the model domain (the outer bay).

In general, the effects of changes in sediment and nutrient loads on sediment and nutrient concentrations in the water column are strong in FE, but much less so in outer KB. This behaviour is in large part due to the mixing of water relatively low in TSS and chlorophyll concentrations across the seaward boundary of KB. Most of the new sediment deposited by an inflow is initially deposited near the mouth of the estuary although it gradually disperses throughout the FE–KB system. Variation of the amount of this new sediment introduced by the river for the three scenarios causes a similar variation in the amount of suspended sediment. Further away from the mouth, larger proportions of the suspended sediments were deposited previously and derive from a benthic sediment pool that does not vary across the scenarios, so the impact of changes in sediment load on TSS concentrations is less there. The effect of changed wet-season sediment loads on TSS concentrations in and near the estuary is sustained throughout the year for the median- and high-flow years as sediments deposited during the flood event are continually resuspended and redeposited by changes in tidal currents.

In a median year, the concentrations of TN and TP in the FE and near the estuary mouth also increase with nutrient load (decreasing vegetation cover) during the wet season. Although the graz30 scenario does exhibit elevated nutrient concentrations over the other two scenarios in the dry season as well, this elevation would be ~50% higher in the FE and appears substantially less than this elsewhere within the FE–KB system. In fact, the model mostly predicts a slight increase in dry-season TN concentrations in the graz70 scenario, but this small change is well within the bounds of normal variability. Similar relative behaviour also occurs for dissolved inorganic nitrogen (DIN).

Predicted changes in chlorophyll *a* concentrations with land use are relatively small (Figure 32). However wet-season pelagic primary production (and hence chlorophyll *a*) is predicted to be slightly lower than the current case in both the increased vegetation cover and reduced vegetation cover scenarios for the median-flow year. In the graz70 scenario, primary production is constrained by the reduced N and P supply, which result in lower concentrations of dissolved nutrients in the coastal creeks and inner KB. In the graz30 scenario, nutrients are more plentiful; however, pelagic primary production is constrained by light, with higher total suspended solids concentrations and correspondingly increased turbidity. The dry season results are similar to the wet season results at most sites, except that a very small increase in chlorophyll *a* in outer KB is predicted during the dry season for the graz70 scenario. Chlorophyll *a* concentrations are consistently low across all scenarios and this is consistent with the limited field observations obtained during Project AC.

The high-flow year scenarios show a different chlorophyll *a* pattern during the wet season (Figure 33), with predicted chlorophyll *a* and primary production lower than in the median-flow year at all sites for all three catchment land-use scenarios due to the increased turbidity of the water column. Nutrient loads are higher for all land-use scenarios in the high-flow year than in the median-flow year, so primary production in the inner bay is not nutrient-limited even in the graz70 scenario. Hence, chlorophyll *a* concentrations respond to the increased light availability associated with reduced sediment loads from the graz30 scenario to current conditions to the graz70 scenario.

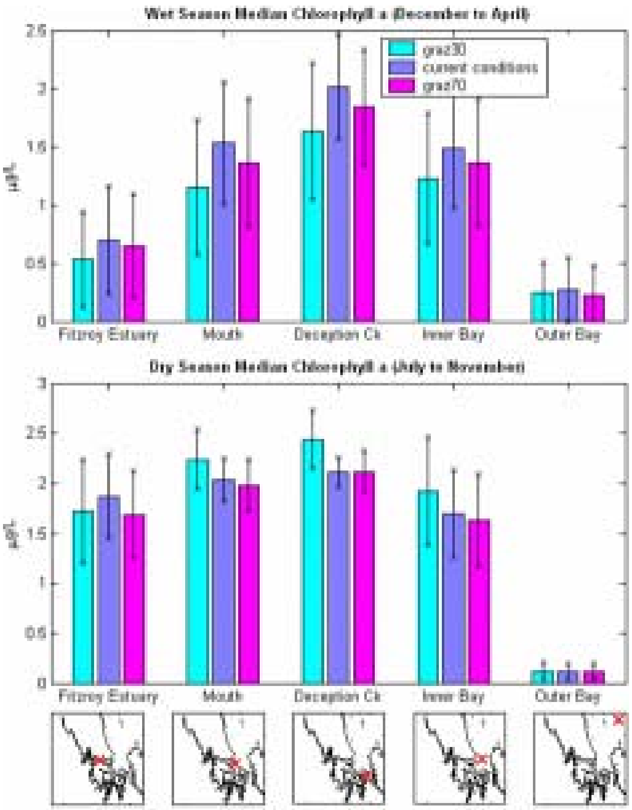

Figure 32. Effect of catchment change scenarios on median chlorophyll *a* concentration at five sites (median-flow year simulation)

Error bars give an indication of variance, with the standard error shown defined here as the standard deviation of simulated concentrations in daily model output, divided by the square root of the number of days in the sample.

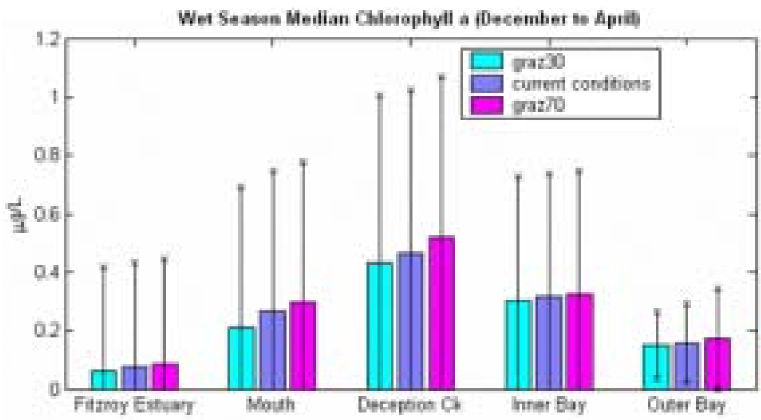

Figure 33. Effect of catchment change scenarios on median chlorophyll *a* concentration at five sites during the wet season (high-flow year simulation)

Error bars give an indication of variance, with the standard error shown defined here as the standard deviation of simulated concentrations in daily model output, divided by the square root of the number of days in the sample.

Effect on fisheries and ecology

The models developed during this study do not directly simulate fish, prawns or other higher-level ecosystem components. However, we can speculate on the possible impacts of the changes predicted. Under the increased vegetation (graz70) scenario, both loads of organic materials from the catchment and *in situ* primary production are reduced and hence the food supply to fish and prawns, particularly in their juvenile forms, is likely to be slightly reduced. Hence, fisheries production may be slightly reduced. Loads of suspended solids reaching the GBR lagoon were found not to be strongly affected during a median-flow year simulation, so this potential loss of production in the FE and KB may not be countered by improved habitat status for adult fish further out. It is possible, however, that the health of seagrass beds in KB will be somewhat improved in the scenario.

The implications of the reduced vegetation cover (graz30) scenario results are difficult to predict: although *in situ* primary production may be lower due to increased turbidity, the load of organic material from the catchment may be increased considerably. Hence, there may be a net increase in potential food for fish and prawns in the system, but a change in food quality and location. More particulate organic material is expected to be available in the estuary and tidal creeks which provide habitat for juvenile barramundi and crabs, but the food supply in the outer bay (habitat for adult barramundi and prawns during the wet season) is not substantially increased. Changes in turbidity might also have more direct effects on fish and fisheries and increased export of sediments to the GBR lagoon would be expected to result in a reduction in habitat further out.

7 Pesticides, polycyclic aromatic hydrocarbons and metals

The Coastal CRC initiated a monitoring program in 2001 to quantify the concentration and loads of sediments, nutrients and pesticides delivered to the FE from the Fitzroy River catchment and results for pesticide monitoring to 2003 have been reported by Noble *et al*. (2005). This monitoring has been extended during 2003–06 to include analysis for PAHs and metals in fine sediments and core samples from the FE and KB. There have been very limited studies on PAH and metal contaminants particularly in benthic sediments from the FE. This later set of sample collection and analysis comprises an activity within Project AC. The results of this activity are reported fully by Vicente-Beckett *et al*. (2006) and are summarised here.

Pesticides

Background

The term pesticide includes insecticides and herbicides and covers a range of agricultural products for controlling floral and faunal pests. Considerable quantities of pesticides are applied for agricultural production in the Fitzroy Basin. Run-off from intensive summer rainfall in the catchments can carry a portion of these materials into rivers and thence into the estuary transported on suspended solids or in solution. A number of previous studies have identified the presence of pesticide residues in the freshwater sections of the basin and limited reports of residues in estuarine benthic sediments (Haynes *et al*, 2000). Recent studies into the effects of pesticides on corals and seagrasses have highlighted the potential for these agrochemicals to impact marine organisms at relatively low concentrations (Jones *et al*., 2003; Haynes *et al*., 2000).

The herbicide Tebuthiuron is widely used to control woody regrowth in the grazing areas of the Fitzroy Basin. Herbicides including Atrazine are commonly used in dryland cropping which covers about 3% of the basin. In the fairly restricted irrigated cropping areas of the basin mostly along the Dawson and Nogoa Rivers, more intensive usage of both insecticides and herbicides is common. Appreciable quantities of herbicides are also used for weed control along roadways and rail lines and in urban areas. Summer is the peak time for application and detection occurs mostly during the summer growing season or shortly after. Most insecticides have a short half-life but residues of a number of herbicides are commonly found in areas downstream from the irrigated cropping areas.

Measurements of pesticides obtained during this study

Pesticide concentrations were measured in water samples collected from the Fitzroy River near Rockhampton and in the FE during the summers of 2003–04 and 2004–05. Samples were also collected from a Rockhampton stormwater drain during January 2005. Rainfall mostly in the western areas of the Fitzroy Basin in the summer of 2003–04 produced a moderate discharge of about 880 gigalitres past the Barrage. Analysis of water samples taken across the hydrograph at Rockhampton and lower in the estuary for this minor flood gave estimated loads of herbicides: Atrazine, 330 kg; Tebuthiuron, 150kg; and Diuron, 50 kg. Concentrations of Atrazine and Tebuthiuron exceeded trigger values for protection of 99% of estuarine and inshore species (ANZECC, 2000). Pesticides were monitored entering KB from the mouth of the FE near the peak discharge for this event. Maximum concentrations of pesticides entering KB (and therefore the GBR lagoon) for the event were Atrazine 0.3 μgL^{-1}, Diuron 0.02 μgL^{-1} and Tebuthiuron 0.15 μgL^{-1}. This work confirms for a relatively small summer flood the movement of considerable loads of a number of herbicides from the upper catchments of the Fitzroy Basin into the FE and KB.

From mid-December 2004 to early February 2005, rainfall across the Fitzroy Basin produced minor discharges (about 280 gigalitres total) in the lower Fitzroy River with different contributions from each catchment for the December, January and February flows. Herbicides (and loads) detected include Atrazine (55kg), Tebuthiuron (90kg), Diuron (3kg) and lower loads of Fluometuron, Hexazinone, Prometryn and Simazine. Of these, Atrazine and Tebuthiuron were detected in all 23 samples collected, while the other chemicals were detected in some of these samples. These results clearly illustrate the ubiquitous nature of residues of Atrazine and Tebuthiuron in surface waters of the Fitzroy Basin.

Flows from the Dawson and to a lesser extent the Nogoa and Mackenzie made important contributions to the December and January flows to the estuary. In samples from these flows, residues of Diuron and Fluometuron were also detected. A major use of these herbicides is in the irrigated agricultural areas of the Dawson and Nogoa catchments. Where values have been assigned, the concentrations of most of these herbicide residues (except Tebuthiuron) were below the trigger values for 99% ecosystem protection of tropical estuaries and inshore regions (ANZECC, 2000). However the concentrations of Tebuthiuron are of concern. Since more than 80% of the basin is used for grazing the ubiquitous detection of Tebuthiuron is not surprising. Tebuthiuron is highly toxic to woody plants and its presence in floodwaters and thus estuarine waters and potential impacts on marine flora warrant investigation.

Analyses of three stormwater samples collected from drains flowing into the estuary at south Rockhampton on 7 January 2005 showed residues of Atrazine, Hexazinone and of Total Petroleum Hydrocarbons but not organochlorine or organophosphorus insecticides or PAHs. However, the volume of this urban stormwater runoff flowing into the estuary at Rockhampton will mostly be insignificant compared with the input from the three wastewater treatment plants (~20 $MLday^{-1}$) and summer flows from the upper catchment.

Polycyclic aromatic hydrocarbons in sediments

Background

Polycyclic aromatic hydrocarbons (PAHs) are persistent organic pollutants that may enter the aquatic environment from natural sources (e.g. oil shales and natural forest fires) and from various anthropogenic sources such as oil spills, stormwater, atmospheric deposition and combustion processes including coal-fired electricity power plants, internal combustion engines and incineration and burning of wood and coal. In the Fitzroy Basin, potential significant sources of PAHs arise from the disturbance of coal seams during mining operations and from the historic burning of vegetation. Some PAHs may be mutagenic or carcinogenic and are of concern because of their known and potential toxicity. There is still very limited information on their ecotoxicity, but toxicity of low-molecular weight PAHs to aquatic organisms have been reported and uptake by many aquatic organisms such as mussels, crabs and fish have been demonstrated.

Measurements of PAHs obtained during this study

PAHs are mostly non water-soluble (except naphthalene) and, being hydrophobic, often attach to particulate matter such as fine sediments. Consequently, we analysed for PAHs in surface sediment samples from the FE and KB as well as in slices from a deep core from KB. Of the nine surface samples from KB, PAHs were detected in only three and concentrations were low. More than 15 PAHs were detected in all 17 surface samples collected from the Narrows and from the lower Fitzroy above and below the Barrage. None of the detected PAHs exceeded the ANZECC (2000) trigger value, although some sediments immediately upstream and downstream of the Barrage had much higher total PAHs compared to the other samples. There are no interim guidelines for some high molecular weight (MW) PAHs such as perylene (or its derivatives).

PAH ratios have been used to infer sources of PAHs in sediments. For example, for PAHs of MW = 178, a concentration ratio of anthracene to the sum of anthracene and phenanthrene <0.10 is taken as an indication of petrogenic sources (e.g. fossil fuels), while a ratio >0.10 indicates a dominance of pyrogenic sources (PAHs from high-temperature and incomplete combustion of biomass or fossil fuels). A third source category is diagenetic; that is, derived from the transformation of organic matter in sediments.

A comparison of the calculated ratios with reported values indicate that some of the detected PAHs were largely from pyrogenic sources and that perylene was from a diagenetic source. The PAHs detected in slices of the 2.6 m sediment core from KB were all below ANZECC (2000) trigger values. Perylene was the dominant PAH in all slices, representing 64% of the total PAHs at 61 cm depth and up to 98% of the total PAHs in the two deepest slices analysed. Ratios of PAHs throughout the core indicated sources similar to those of the surface samples.

The surface sediments and sediment cores indicate generally low levels of PAHs. This is consistent with the Fitzroy Basin not being highly industrialised or urbanised. PAHs found in the Fitzroy cores appear to be largely of natural origin. In contrast, many more types of PAHs and higher concentrations were detected in the benthic muds of Port Curtis (a fairly industrialised area) including some PAHs that are potentially carcinogenic. PAHs within the FE–KB system should be monitored if industrialisation increases in the region as they may have impacts on aquatic flora and fauna.

Metals

Background

There are many agricultural and mining activities within the Fitzroy Basin which can contribute to metal pollution. Some fertilisers include metal contaminants such as cadmium in phosphate salts. In the past, there were cattle dips that used arsenic compounds as pesticides for cattle ticks. Several past and present mining activities for copper, gold and coal result in disturbance of the earth’s surface, leading to exposure of minerals such as pyrite, which produce acid and sulphate upon air oxidation, contributing to acid mine drainage and mobilisation of metals. There is also current exploration for nickel in the region.

Measurements of metals obtained during this study

For 73 surface sediment and core slice samples from the FE analysed for their metal content, only concentrations of the elements Nickel (Ni), Chromium (Cr), Antimony (Sb) and Arsenic (As) exceeded trigger values for either the low or high interim sediment quality guidelines (ANZECC, 2000). Ni levels exceeded the guidelines most often, followed by Cr, Sb and in only one case As. The highest mean Ni levels were found in sediment grabs from the FE, followed by those from upstream of the Barrage and in slices of a core from Raglan Creek. The highest mean Cr levels were found in sediment grabs upstream of the Barrage, followed by those from the FE. The highest mean Sb concentrations were found in the slices of a KB core near the mouth of the FE, followed by the FE samples. Sediment samples from KB near the coast gave the lowest mean concentrations for all ANZECC-regulated metals except As, mercury (Hg) and Sb.

There appears to be no clear evidence of accumulation in the upper layers of the two cores analysed, except for As and Sb in the core collected from Raglan Creek (Figure 34). Also, Sb had highly variable content in the slices of the KB core. A comparison of metal concentrations observed for Port Curtis with those for the Fitzroy in the present study showed that the mean levels for Cr, Ni and Sb in the FE were higher than those found in Port Curtis, while levels for the other metals were reasonably similar. The highest enhancements compared to natural levels in the sediments were exhibited by Sb, Ag, Ni and Hg. The observed behaviour of Cr and Ni are consistent with the presence of geological sources for these metals in the Central Queensland region, but the behaviour of Ag, Sb and Hg is not explained and would require further study.

The relative ratios of the four stable lead isotopes ^{206}Pb, ^{207}Pb, ^{208}Pb and ^{204}Pb can be used to determine the likely source of the lead. The mean Pb content in the 23 core slices analysed from a core near the mouth of the river was 15.0 ± 1.0 mg per kg of sediment (dry weight). The mean measured ratio $^{208}Pb/^{206}Pb = 2.07 \pm 0.01$ of these slices from the KB core is comparable to the value of 2.06 measured for near-pristine estuarine and marine tropical northern Australia and to modelled present-day average crustal values, indicating little anthropogenic contamination by this metal.

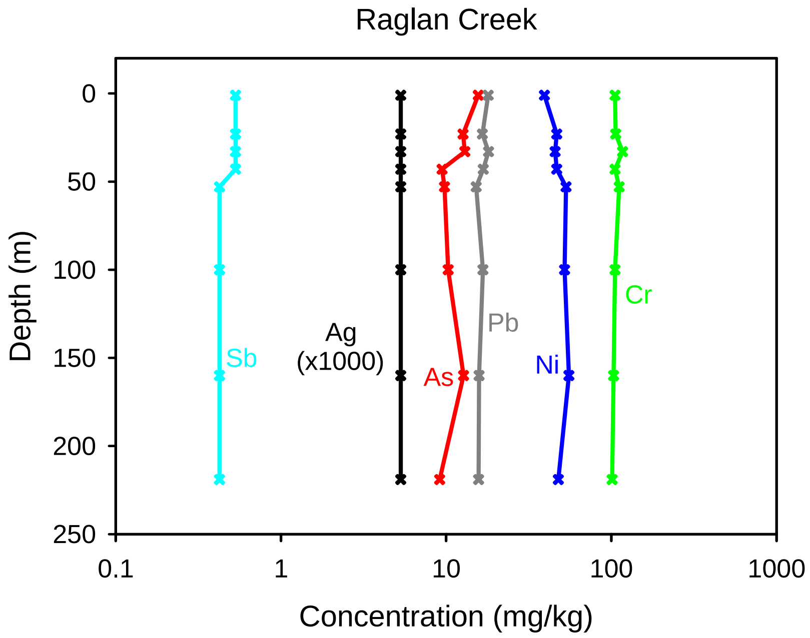

Figure 34. Concentrations of metals down a core collected from Raglan Creek. Concentrations of Ag are µ*g kg*$^{-1}$

Mean metal concentrations in sediments and estimates of background levels in the FE were similar to levels found in Port Curtis estuarine and intertidal sediments, except for higher concentrations of Ni, Cr and Sb. Levels of Ni and Cr approached or exceeded the low ANZECC sediment quality guidelines. The number of sediment samples used in the multivariate analysis is relatively limited and more samples, particularly from mangrove sites and tidal creeks, would improve the predictive models for metal concentrations and identify metal enhancements in the FE more accurately. As well, sediment cores from less disturbed muddy sites would provide further insight on metal accumulation.

8 Considerations for monitoring the FE–KB system

One question asked of Project AC is 'How should managers monitor ecosytem health and function?' We suggest that the prime goal of a monitoring program would be to assess progress towards management objectives and to inform decisions on modification of management actions over time in response to system change. The issue of what the management objectives are will inform what indicators of system behaviour and response need to be measured. Any monitoring program will necessarily be constrained by the resources available so the choice of indicators measured and the frequency with which they can be monitored is necessarily a compromise. There is no single correct design for a monitoring program. Rather, we present in the following some general considerations for guiding the development of a monitoring program.

Time and space scales

A dominant characteristic of the FE–KB system is its variability on time scales ranging from decadal, to interannual, to seasonal, to fortnightly and down to sub-daily. The variability on longer time scales is due to climatic and seasonal variations of the rainfall in the Fitzroy catchment which cause enormous variability in the discharge of the Fitzroy River, a major driver of system behaviour in the FE and KB. At the scale of weeks and days, the spring-neap cycle of high and low tidal ranges has a very large influence on suspended sediment concentrations as does the daily cycle of high and low tides. This variability makes the design of an effective monitoring program and the analyses of its results much more difficult than in most aquatic systems.

Only a monitoring program that lasts decades could account for discharge variability directly. Assessing trends in system condition based on statistical analysis techniques is also likely to require decades of measurements before the analysis yields significant results. The alternative is to evaluate response in a particular year against the volume of discharge. The analysis of such data would need to extend beyond the application of statistics and would involve considerations of the biophysical and ecological processes that are involved. The analysis of monitoring information in the context of a modelling framework may be useful here. Models can readily accommodate changes in input conditions such as river discharge and system response could be judged against anticipated or modelled behaviour.

For example, suppose a management action resulted in a decrease in load by a few percent per year; then the models would predict a particular response for the yearly median chlorophyll concentrations (say) that would inherently include the effects of interannual variability manifest through their forcing by loads, freshwater inflow and meteorological conditions. A comparison between trend analyses undertaken on measurements and on model predictions would aid in establishing how much of the measured trend was due to statistical uncertainty arising from natural temporal variability in the FE–KB system and how much was due to an underlying change in its condition.

If models are to be used as a tool for supporting ongoing assessment of system condition and response, then it is important that the uncertainty in model simulations be reduced as much as possible. An ancillary purpose of the monitoring program could be to support ongoing calibration, validation and improvement of the models so that their effectiveness as management tools is enhanced

Key considerations for the design of a monitoring program are the choice of indicators, the choice of sampling frequency and location and the manner in which the results are to be interpreted. The suggestions for a monitoring program presented here are designed specifically to support the ongoing assessment of the effects of management actions on key indicators of the biogeochemical function of the FE–KB system that might combine with the diagnostic use of the hydrodynamic, fine-sediment and biogeochemical models.

The development of a monitoring program to address ecological function is problematic in the context of this study. The presence of phytoplankton is an important indicator of ecological system function as it represents the main food supply for higher organisms. However, the study did not address how food webs in the system were constructed in the FE–KB system. Specifically, we did not investigate how the presence or absence of particular phytoplankton groups or other food sources might impact on the response of the higher trophic levels of the system including invertebrates, fish, birds and marine mammals. Accordingly, we do not make any further recommendations on how ecosystem function might be monitored beyond recommending that phytoplankton type and concentrations be monitored.

Monitoring parameters

Riverine loads

Accurate evaluation of riverine loads of nutrients, fine sediments and suspended particulate matter has the highest priority in our proposed monitoring strategy. It is absolutely essential for the direct assessment of the effectiveness of strategies that might be implemented for reducing loads from the catchments. It is also fundamental for the interpretation of observed changes in the FE–KB system, including the diagnostic use of the models. Management of loads requires knowledge of where they are coming from and what factors determine their composition. The acquisition of this knowledge is a major undertaking by itself and warrants significant investment of effort.

Flow events deliver most of the annual loads of nutrients to the FE and it is imperative that loads from these events, which may only last a week or two, are estimated accurately. It is important that the composition of the loads be determined, as this strongly affects their ecological impact. It has been shown that different methods of estimating loads from the currently available data can yield quite different results and it is difficult to know which is most accurate without more measurements during flow events. Parameters to be measured would include dissolved inorganic nutrients (N and P), TSS concentrations organic nutrients (both dissolved and particulate), total N, total P and mineral P. Organic N has different levels of reactivity depending on its composition. We need to develop methods for assessing the reactivity of this component of the riverine load.

Salinity

Salinity is a major indicator for flushing and stratification and will be affected by changes in river discharge and exchange. It can be used by models as a means for assessing the presence or absence of river water in KB and as a diagnostic measure of exchange rates in KB both in the wet and dry seasons. Spot salinity measurements as with all other forms of spot measurements suffer from the problem of spatial aliasing due to tidal motions. Parcels of water move considerable distances over the tidal cycle due to tidal currents. In principle, water parcel position can be corrected for the tidal displacement using model simulations of tidal currents. Otherwise, the interpretation of spatial patterns of salinity (or any other spot measurement) needs to be undertaken with care.

During high flows of fresh water into KB, there may be a large degree of stratification, with brackish water floating over saltier more marine water with different physical and chemical properties underneath. Monitoring all water properties in KB may have to consider the collection of samples for analysis from near the surface as well as near the bottom during high flows.

During freshwater discharge into KB, the distribution of salinity in the surface layer especially is likely to display considerable spatial and temporal heterogeneity. The temporal variability can be accommodated by making measurements with automatic recording instrumentation located on buoys for example. Satellite remote sensing can be used to estimate the spatial distribution of coloured dissolved organic matter (CDOM). CDOM is discharged with river water and can so be used to infer the distribution of salinity in the river plume in KB. The application of this analysis technique for the waters of KB is not yet fully developed.

Dissolved oxygen

Dissolved oxygen (DO) is a critical water quality indicator if it becomes so depleted in the water column that the lives of marine organisms (especially fish) are endangered. DO also affects rates of processes that affect nutrient cycling, such as nitrification and denitrification. Although our studies have not shown significant oxygen depletion in either the FE or KB, depletion may be more significant when larger amounts of organic matter are discharged by the Fitzroy River under higher flows than we experienced. DO is a parameter that is usually measured anyway with salinity, water temperature and turbidity using profiling equipment.

Chlorophyll *a* and phytoplankton

Chlorophyll *a* is an indicator of the presence of phytoplankton and so comprises an indicator for water quality in its own right. We have measured chlorophyll concentrations in KB which are not suggestive of a water quality problem of concern. It is likely that phytoplankton concentrations show considerably more temporal variability than was evident from our limited measurements. High concentrations (blooms) may be missed or poorly sampled by monthly sampling. Temporal variability of chlorophyll concentrations can be addressed using moored fluorometers. Blooms can also show considerable spatial heterogeneity. Remote sensing techniques using aircraft or satellites have major potential for estimating the spatial distribution of near-surface chlorophyll concentrations. We discuss the opportunities for the application of remote sensing below.

The behaviour of different phytoplankton types and their significance to the ecology varies considerably. For example, some phytoplankton types fix N and their presence may indicate a relative shortage of this element as a nutrient.

Samples need to be collected during blooms particularly for the analysis of the phytoplankton species composition.

Fine sediment concentrations

The dynamics of fine sediments within the FE–KB system are a major determinant of the biogeochemical and (presumably) ecological responses to input loads of nutrients and sediments from the Fitzroy catchment. The interplay between settling and resuspension determines concentrations of particulate material in the water column. In the zone of maximum resuspension (the FE and its mouth region, the tidal creeks and southern part of KB), tidal resuspension and horizontal advection of fine sediments cause TSS concentrations to vary enormously over the spring-neap cycle and over the daily cycle of high and low tides. This behaviour would render a spot measurement of TSS concentration meaningless unless it were placed in the context of a model simulation or some other time-dependent framework. As with the measurement of chlorophyll, the techniques of remote sensing and auto-measurement of turbidity as a surrogate for TSS concentration have the potential to overcome some of these sampling problems.

Nutrients

As key determinants of phytoplankton growth, the concentrations of nutrients in the FE and KB should be included as part of a monitoring program. Changes in water column nutrient concentrations (TN and TP, ammonium and oxidised nitrogen, dissolved inorganic P and organic N and P) with time may be an indicator of the impact of adopted management strategies. The sampling program should measure dissolved inorganic N and P concentrations on time and space scales that resolve their principal temporal and spatial variations. Temporal variations in concentration at tidal time scales will occur due to aliasing arising from tidal motions. Unlike TSS concentrations, the concentrations of dissolved nutrients within a parcel of water are not expected to change much over a tidal cycle. This may not apply to the concentrations of particle-bound nutrients as sediments settle and are resuspended.

Pesticides, PAHs and metals

Input of a range of possible contaminants from anthropogenic activities in the basin to the estuary and KB is likely. Potential impacts of these contaminants on the coastal ecosystem are still unclear. The current studies concentrated on pesticides loads in flows of freshwater entering the estuary and on PAH and metal concentrations in benthic and core samples from the estuary and KB.

Results for pesticides confirmed previous data showing significant loads of several herbicides (Atrazine, Tebuthiuron and Diuron) and lower concentrations of several others entering the estuary in summer flows from the basin. While related studies have shown the presence of residues of persistent organo-chlorine pesticides in crocodile eggs from the estuary, the environmental fate and possible impact of these herbicide loads on coastal and marine flora is unclear. Monitoring should include further evaluation of these residues and their impacts and hopefully record decreasing loads of herbicides entering the estuary in the future as improved land management practices are implemented in the Fitzroy Basin.

For PAHs, in contrast to the higher levels and wider range of compounds found in Port Curtis, concentrations in the Fitzroy samples were low and probably from natural sources. Monitoring for PAHs in the Fitzroy should perhaps be considered on a 5–10 year scale.

For metals, levels of Ni, Cr, As and Sb exceeded trigger values and those of Hg were also elevated. While geological sources for Ni and Cr are likely, the sources and potential impact on the ecosystem of the other elements warrant investigation and inclusion in a monitoring program.

Monitoring locations

The number of locations that can reasonably be monitored will depend on resource constraints. The present work shows the existence of a number of distinct zones which show different chemical and physical properties: the highly turbid, fine-sediment dominated water near the mouth of the FE and coastal creeks (the zone of maximum resuspension, ZMR); the clearer, often fresher water of the FE near the barrage; a coastal transition zone between the mouth area and the deeper water of KB and along the coast to the north (the CTZ) and the clear, low-nutrient marine water of outer Keppel Bay (the BWZ). The coastal creeks account for a significant area in their own right and it has been shown that Connor and Casuarina Creeks differ substantially in their function. Ideally, sites located within each of these zones would be included in a monitoring program.

Collection of cores

Useful insights into temporal variations in sediment load and quality can be derived from the analysis of sediment cores collected in depositional zones within the Fitzroy River floodplain and estuary. Sediment cores provide a record of the rate of accumulation and geochemical character of sediment that has been deposited during flood discharge events. In essence, these data provide the ability to 'retrospectively' monitor catchment-derived sediment that is reaching the coastal zone. These types of data may be especially useful for gauging the effectiveness of new land-use management practices. Sediment cores can also provide data that extend further back in time, beyond the historical period, to provide insights into the character of floods that have occurred prior to European settlement. These data are important for better understanding the natural variability of sediment load and character and for comparison with modern data. The length of these records varies between depositional setting and the resolution of the data is dependent on the rate at which sediment has accumulated as well as the core sample interval. For example, the sediment record from Crescent lagoon shows how source areas of catchment-derived sediment and the geochemical character of the sediment have changed over the last 70 years.

Remote sensing

Application to the FE–KB system

Remote sensing from aircraft or from satellites can provide detailed images of near surface concentrations of total suspended sediment (TSS), chlorophyll and coloured dissolved organic matter (CDOM) over large areas. High levels of CDOM are dissolved in river water and its concentration provides us with an estimate of how much the river water has been diluted; that is, of the salinity. It is likely that the most cost-effective opportunities for remote sensing of water quality parameters for the FE–KB system lie with satellite remote sensing. Suitable sensors overfly the region twice per day and each image covers an area that includes significant parts of the catchment, captures the entire Fitzroy River to the KB area and extends right across the GBR lagoon.

A Coastal CRC remote sensing activity undertaken in parallel with Project AC aimed to investigate the potential use of remote sensing for estimating surface water concentrations (Brando *et al*., 2006). Such data can be interpreted in their own right but could also be used to validate and calibrate our hydrodynamic, fine-sediment and biogeochemical models of the system. As part of the remote sensing activity, surface water samples were collected and analysed for their optical properties to develop the relationships between optical behaviour and constituent concentrations. Unfortunately, we were not able to use remote sensing in a routine sense to calibrate and validate our models due to unanticipated difficulties with the calibration of the algorithms used to infer concentrations from images. The optical complexity of the FE–KB system necessitated the development of a new generation of computational methods for producing remote sensing images.

Figure 35 shows that concentrations of chlorophyll derived from the biogeochemical model with those estimated from remote sensing imagery for 27 June 2004 are in good quantitative agreement with one another. Similarly, good agreement was obtained between TSS simulated concentrations and those derived using remote sensing. Considering that these are two fully independent methods for estimating these concentrations, these are exciting results as they indicate that *in situ* sampling independent assessment and modelling are possible even in such a complex system as the FE–KB where *in situ* sampling is logistically difficult.

Although Figure 35 shows comparisons for one date only, an analysis of the more than 40 images over 2004 with the simultaneous output of the biogeochemical model showed overall agreement in the range of concentrations for chlorophyll and TSS.

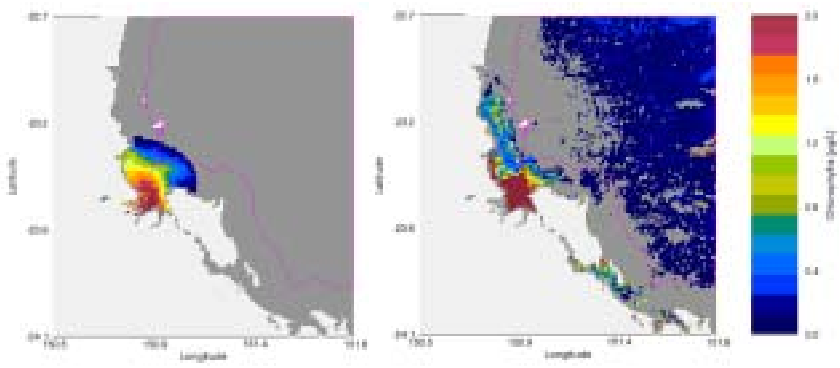

Figure 35. Comparison of model-predicted concentrations of chlorophyll over Keppel Bay with those estimated using the analysis of a satellite image for the same time on 27 June 2004

Both the model and the remote sensing chlorophyll image show a sharp transition between the zones of high and low chlorophyll concentration. The remote sensing image covers a much larger area than the model domain which is restricted to KB and so the former is able to show the FE–KB system in the context of the contiguous waters of the GBR lagoon. Remote sensing images have shown the limitations of model assumptions, particularly of the boundary conditions. In other images, strips of moderately high chlorophyll concentrations extend northwards along the coast, which is counter to the model assumption of low concentrations all along the outer edge of the model domain. On the other hand, the strength of model applications is that they provide full 24-hour coverage of concentrations, function independently of clouds and storms (unlike satellite data) and provide three-dimensional results (which can be important when flood plumes extend over the surface).

The potential application of satellite remote sensing for monitoring

There are a number of satellites whose imagery is potentially useful for our applications. Satellite imagery gives complete spatial coverage at specific times of the day, but only under cloud-free or partially cloud-free conditions, so all images are not useful. We estimate that on average the two MODIS satellites provide more than 100 images per year. The SeaWiFS satellite would provide another 60 or so images per year and the MERIS satellite 20–30. The model will give permanent output at virtually any time period and has hindcasting and predictive capabilities.

If modelling is to be used to support the long-term monitoring of the FE–KB system, then its utility and accuracy will be greatly enhanced at relatively low cost by incorporating remote sensing data products on an ongoing basis. Due to the large geographical area, data collection to support ongoing model development, calibration and validation is expensive and could be supplemented by maps of surface concentrations of chlorophyll, TSS and CDOM derived from satellite images. The distribution and transportation paths of these materials in KB immediately after a major flood could be effectively determined using remote sensing. Remote sensing is essential for understanding the boundary conditions used in the models and in understanding the context of material transport and phytoplankton growth between KB and the GBR lagoon.

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Appendix

Activity reports for Project AC

The following reports are the final reports for the series of activities that were undertaken during Project AC. During the course of the project, there were a series of milestone reports also compiled.

Report 32: ***Nutrient dynamics and pelagic primary production in coastal creeks delivering into Keppel Bay***

By Ford, P. W., Radke, L.C., Webster, I.T., Robson, B., Atkinson, I., Tindall, C. & Verwey, P.

This investigation combined the detailed, but temporally limited, water column physical, biological and chemical measurements in Casuarina and Connor Creeks (described in Report 34 below), with the more extensive monthly survey data conducted by the EPA in 1988 to 1990 in Casuarina, Raglan and Inkerman Creeks. Fluxes of dissolved nutrients to/from Keppel Bay were derived from the data.

Report 34***: Keppel Bay: Physical processes and biogeochemical functioning***

By Radke, L.C., Ford, P.W., Webster, I.T., Atkinson, I. & Oubelkheir, K.

This activity investigated the hydrodynamics, biogeochemistry and primary production of Keppel Bay and the tidal creeks. It was centered on the collection and interpretation of data from two trips to the study area in the dry season and one in the wet season. Measurements were obtained on currents, salinity, water temperature, suspended matter, nutrients and chlorophyll in the water column. Additional samples of bottom sediments were collected for geochemical analysis.

Report 35: ***Fitzroy River: intertidal mudflat biogeochemistry***

By Revill, A., Leeming, R. & Smith, C.

This study was a field and laboratory based activity that investigated primary production on the intertidal mudflats of the Fitzroy Estuary. Samples were collected for pigment analysis through the seasons to aid in the assessment of the form of the primary production that was occurring. Additional incubation experiments were undertaken to assess rates of primary production and of nitrification/denitrification.

Report 36: *Fitzroy Estuary mudflat model*

By Wild-Allen, K., Herzfeld, M., Margvelashvili, N., & Rosebrock, U.

> This model investigated the interaction between primary production and the tidal flooding and ebbing on a hypothetical mudflat similar in dimensions to those found along the Fitzroy Estuary and the tidal creeks.

Report 37: *Contaminants in the Fitzroy Estuary – Pesticides, polycyclic aromatic hydrocarbons and metals*

By Vicente-Beckett, V., Noble, R., Verwey, P., Packett, R., Ruddle, L., Munksgaard, N. & Morrison, H.

> This activity investigated the extent of pesticides contamination of the water column in the Fitzroy estuary during the summer flows of 2003–2005 covering a limited number of sites. Estimates of the pesticide load were calculated from the concentrations and the known water flows. Sediment samples for polycyclic aromatic hydrocarbons (PAHs) and metals analysis were also taken at a number of locations throughout the FE–KB system.

Report 38: *Numerical hydrodynamic modelling of the Fitzroy Estuary*

By Herzfeld, M., Andrewartha, J.R., Sakov, P. & Webster, I.

> A three-dimensional hydrodynamic model was developed for the Fitzroy Estuary, Keppel Bay and tidal creeks as a connected system. It was run over a period of 18 months using measured river inputs and winds and simulated currents, salinity and temperature over this time. These simulations were used for model calibration and verification. The model was later used to predict currents and mixing for the sediment and biogeochemical models.

Report 39: *Modelling of fine sediment transport in Fitzroy Estuary and Keppel Bay*

By Margvelashvili, N., Herzfeld, M. & Webster, I.

> This model simulated the transport, resuspension and deposition of fine sediments throughout the FE–KB system. It relied on the previous application of the hydrodynamic model and its predictions were used by the biogeochemical model as fine sediments are an important agent for nutrient transport as well as being the major determinant of the underwater light climate. After calibration and validation, the model was run for three years having a low, median and high discharge to illustrate how river discharge affects the sediment dynamics.

Report 40: ***Biogeochemical modelling and nitrogen budgets for the Fitzroy Estuary and Keppel Bay***

By Robson, B.J., Rosebrock, U., Webster, I.T., Herzfeld, M. & Margvelashvili, N.

A biogeochemical model was developed for the FE–KB system to simulate the fate and transport of nutrients in the system as well as primary production of phytoplankton and MPB. The biogeochemical model relied on the hydrodynamic model to simulate currents and the sediment model to simulate fine sediment transport. It was calibrated and validated using data collected during Project AC and was used to simulate biogeochemical and primary production responses to low, median and high flow years and to facilitate the calculation of nutrient budgets.

Report 41: ***Scenario modelling: Simulating the downstream effects of changes in catchment land use***

By Robson, B.J., Webster, I.T., Margvelashvili, N. & Herzfeld, N.

Scenario modelling was undertaken to investigate the effects of two hypothetical land-use scenarios in the Fitzroy catchment on the primary productivity response of the FE–KB system and on the export of nutrients from the system to the GBR lagoon. The hypothetical scenarios were: (a) a reduction in vegetation cover to 30% of area from its present 55% cover and (b) an increase to 70% cover. These scenarios were implemented by changing the sediment and nutrient loads from the Fitzroy River accordingly. Each of the scenarios was simulated for a low, medium and high flow years.

Report 47: ***Geomorphology and sediments of the Fitzroy River coastal sedimentary system – Summary and overview***

By Brooke, B., Bostock, H., Smith, J. & Ryan, D.

This report provides an overview of the geomorphic and sedimentary characteristics of the FE and KB. We show how riverine and shallow-marine processes that occurred thousands of years ago affect the present day structure of the coast and the distribution of modern sedimentary environments. The rates of sediment accumulation over the last several thousand years and during the last one hundred years are identified to provide a better understanding of coastal landform development and an indication of the potential physical impacts on the coast of changes in catchment land use.

Report 48: ***Sediment accumulation and Holocene evolution of the Fitzroy River lower floodplain, south-east Queensland***

By Bostock, H., Ryan, D. Brooke, B., Packett, R., Hancock, G., Pietsch, T. Moss, P. & Harle, K.

Sediment cores and surface sediments were collected from the floodplain below Rockhampton during two field surveys. Stratigraphic information provided by the analysis of the cores and existing borehole data allowed the development of an evolutionary model of the Fitzroy River estuary that spans the last 8000 years. The stratigraphic data also enabled the calculation of the mass of sediment that has been trapped in the floodplain and estuary during this period. In addition, cores obtained from two of the freshwater lagoons near Rockhampton have provided new insights into changes in the physical characteristics of sediments deposited during floods of the last 50 years.

Report 49: ***Geomorphology and sediment transport in Keppel Bay, south-east Queensland, Australia***

By Ryan, D.A., Brooke, B.P., Bostock, H., Collins, L.B., Buchanan, C., Siwabessy, J., Margvelashvili, N., Radke, L., Skene, D. & Hamilton, L.

A suite of grab samples were collected from Keppel Bay and the lower estuary. The sediments were classified into five classes based on grainsize, chemical composition and associated wave and tidal currents. These results were compared with high-resolution acoustic images of the seafloor topography to provide a better understanding of sediment transport within Keppel Bay.

Report 50: ***Holocene evolution and modern sediment accumulation on a macro-tidal coast – Keppel Bay, south-east Queensland, Australia***

By Bostock, H., Ryan, B., Brooke, B., Skene, D., Hancock, G. & Pietsch, T.

Sub-bottom profiles and vibracores collected in Keppel Bay were used to examine the temporal evolution of the Fitzroy Estuary and Keppel Bay as they evolved from when sea levels were more than 20 m lower than at present and as sea level rose between 9000 and 6000 years ago. Based on stratigraphic data and accumulation rates measured in sediment cores we have calculated the amount of Fitzroy River sediment that has been trapped in the bay during this period.

Report 51: ***Records of changes in sediment accumulation, sea level and land-use over the last 2000 years preserved in beach deposits at Keppel Bay, Queensland, Australia***
By Brooke, B., Ryan, D., Radke, L., Pietsch, T., Douglas, G., Flood, P. & Packett, R.

In this activity, the depositional history of the beach-ridges inland from the western coast of Keppel Bay is examined. A series of techniques are used to date these parallel ridges and to demonstrate that their formation occurred in short episodes up to a few decades long. The analysis of the trace element composition of the deposits shows that changes in the regional origin of sediments have occurred in the last 230 years.

Report 52: ***Identifying sources of catchment-derived sediment to Keppel Bay and the Fitzroy River floodplain in tropical Queensland, Australia***
By Smith, J., Douglas, G., Radke, L., Palmer, M. & Brooke, B.

In this report, Keppel Bay sediments are compared to catchment soils through a combination of geochemical techniques and statistical modelling and the major source areas in the catchment are delineated.