



Cooperative Research Centre for Coastal Zone Estuary and Waterway Management

Technical Report 8



Conceptual models of the hydrodynamics, fine sediment dynamics, biogeochemistry and primary production in the Fitzroy Estuary

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**Draft Final Report
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Executive Summary

The Fitzroy is a very large agricultural and coal mining catchment with an extensive wetland delta and estuarine area which is a major fisheries habitat in central Queensland. Significant loads of sediments and nutrients move through the Fitzroy Estuary and offshore during summer flow events. The impacts of these contaminants on the ecology of the estuary are largely unknown. With major water infrastructure development planned for the Fitzroy, there is an urgent need to how changes in flows and loads resulting from altered water and land uses in the catchments has the potential to impact on the estuarine systems. The Coastal Modelling project, CM-2, is one of a suite of CRC projects that address this need. Project CM-2 has developed conceptual and predictive models of the hydrodynamics, fine-sediment dynamics, biogeochemistry, and primary production of the Fitzroy Estuary. This report presents conceptual models for the estuary that are largely based on what has been learned in previous studies and from the computer modelling of the estuarine system.

Hydrodynamics is the study of water flow and mixing within an aquatic system. We need to know how material such as nutrients, fine sediments, and phytoplankton are transported along the estuary. The hydrodynamics of the Fitzroy Estuary are dominated by the tides and by the discharge of the Fitzroy River. The tides in the estuary have a large range and cause vigorous currents. These 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. In summer, monsoonal rains cause large discharges from the Fitzroy River into the estuary. Salt water is flushed from the estuary and the current associated with the river flow can combine with the ebbing tidal currents to scour accumulated fine sediments from the estuary seaward into Keppel Bay.

In contrast to coarse sediments, fine sediments tend to remain in suspension for periods of hours and perhaps days (or even much longer)

when they are lifted up off the bottom by currents. High concentrations of suspended sediments block out the light necessary for plant and phytoplankton growth in an estuary. Further, nutrients and agricultural chemicals can be fastened to fine sediments, so the fate of these substances may be partly determined by fine-sediment transport. From our modelling studies, we have determined that fine sediments tend to be transported up the estuary during times of low river discharge, but significant amounts may be scoured out of the estuary when river flows are high.

Biogeochemistry is the science of how nutrients are transformed and transported within an aquatic system. Nutrients are essential for primary production (plant and phytoplankton growth) which ultimately represents the foundation for the estuarine ecosystem including higher organisms such as fish, crustaceans, marine mammals and birds. When river flow is low, the majority of the nutrients delivered to the estuary derive from discharges from the Rockhampton sewage treatment plants and from the meatworks in the Lakes Creek and Nerrimbera areas. These nutrients sustain the phytoplankton growth in the water column in the upper half of the estuary where the water is relatively clear. It would appear that the consumption of phytoplankton by mussels and other grazers allows for elevated fish and crab catches in this part of the estuary.

In the lower half of the estuary, the tidal currents are stronger and suspended sediment concentrations are relatively high. Penetration of light into the water column is much reduced, causing phytoplankton growth to be severely inhibited. Algae grows on the surfaces of the intertidal mudflats in both the upper and lower parts of the estuary, but it is not known what contribution this growth makes to the overall productivity and ecology of the Fitzroy Estuary.

During times of high flow, the Fitzroy River discharges large amounts of nutrients into the head of the estuary. Our studies suggest that the majority of this input flows through the estuary and is discharged into Keppel Bay. During the summer of 2000/2001, the amount of nitrogen discharged by the

river into the estuary was estimated to be about 25 times larger than the input during the previous low-flow period from the sewage treatment plant and the meatworks taken together. A further scientific study undertaken by a team from the Coastal CRC which commenced in July 2003 aims to investigate the fate of nutrients and fine sediments discharged into Keppel Bay and to further refine our understanding of the fine-sediment dynamics, biogeochemistry, and primary production within the Fitzroy Estuary itself.

1 Introduction

The Fitzroy is a very large agricultural and coal mining catchment with an extensive wetland delta and estuarine area that is a major fisheries habitat for central Queensland. Significant loads of sediments, nutrients and unknown amounts of pesticides move through the Fitzroy Estuary and offshore during summer flow events. The impacts of these contaminants on the ecology of the estuary are largely unknown. There are potential impacts on National Estate listed wetlands, significant habitats for wading birds, dugong, dolphin and marine turtles and the southern lagoon of the Great Barrier Reef. With major water infrastructure development planned for the Fitzroy, there is an urgent need to relate flows and loads resulting from altered water and land uses in the catchment to potential impacts on the estuarine systems and nature-based tourism industries.

A number of regional planning activities are current within these catchments. This planning involves extensive stakeholder consultation through bodies such as the Fitzroy Basin Association. Strategic documents concerned with planning, management and evaluation of resource use options include the Draft "Water Allocation and Management Plan" and the "Central Queensland Strategy for Sustainability" for the Fitzroy. Within the regional planning processes for these catchments there has been ready acknowledgement that there were significant knowledge gaps concerning these important estuarine areas. Robust models which clearly link terrestrial activities and inputs to health of the estuarine systems are essential for the sustainable use of natural resources in catchments.

The Coastal Modelling project, CM-2, has the essential role of conceptualising and linking terrestrial and marine science and ecosystem health to the community and decision-making, policy and planning. Due to the limited time available between the project commencement (May 2002) and its end (June 2003), this project report presents a more limited set of outputs than initially anticipated from the full project CM-2. Completion of full model development and application will be undertaken in the follow-on project "Fitzroy Contaminants" which started in July 2003.

A key task for the CM-2 project has been the development of conceptual models of the hydrodynamics, fine-sediment dynamics, biogeochemistry, and primary production of the Fitzroy Estuary. This report, which represents one of three final reports for the project, describes these conceptual models. Another report details the development and application of pilot models of the hydrodynamics, sediment dynamics, and biogeochemistry of the Fitzroy Estuary ("Numerical Modelling of Hydrodynamics, Sediment Transport and Biogeochemistry in the Fitzroy Estuary" by Margvelashvili et al. (2003)). The development and application of a pilot model of the hydrodynamics of Port Curtis is the subject of the third report ("Numerical Modelling of the Port Curtis Region" by Herzfeld et al. (2003)).

The development of conceptual models for the Fitzroy Estuary is based heavily on the results of the three-year study of the Fitzroy Estuary funded by the CRC for Coastal Zone Estuary and Waterway Management that was undertaken between 2000-2003. This study is reported in "Carbon and Nutrient Cycling in Subtropical Estuaries" by Ford et al. (2003). The results of the numerical modelling studies for the Fitzroy were used to support the conceptual model development also.

This report is divided into four sections. The first three sections describe the conceptual models for the hydrodynamics, the fine-sediment dynamics, and the biogeochemistry. In these sections, the models are described in detail as are the bases for their formulation. In the final section, the conceptual models are summarised in point form and presented pictorially.

2 Hydrodynamics

Flow and mixing within the Fitzroy Estuary are most strongly controlled by freshwater flows mainly from the Fitzroy River discharging into the end of the estuary through the Rockhampton Barrage (Fig. 1) and by tides. Other potential influences on the hydrodynamics of such systems are wind, evaporation, and precipitation which affect the water balance of the system.

We first consider the major properties of the tides and river flows as drivers of the hydrodynamics of the system and then the response of the system to these drivers.



Figure 1. The Fitzroy Estuary.

2.1 Freshwater inputs

The dominant feature of the freshwater discharge from the Fitzroy River into the estuary is its seasonal and interannual variability. These are illustrated in the 11-year hydrograph from the Gap which is the gauged station furthest downstream on the Fitzroy River (Fig. 2). Flows tend to be highest in January through to March, but there are exceptions. Flows of over $4000 \text{ m}^3\text{s}^{-1}$ occurred in early September 1998. For the record shown, the median flow is $7 \text{ m}^3\text{s}^{-1}$ and the 25th percentile flow is $0.7 \text{ m}^3\text{s}^{-1}$, so most of the time flows in the Fitzroy are fairly modest and for a substantial proportion of the time they are small and sometimes zero. During times of zero or low discharge during the winter months, much if not most of the fresh water entering the upper end of the estuary is discharge from the Rockhampton Sewage Treatment Plant. There is some discharge through the fish ladder at the Barrage, but this is negligible.

Figure 3 shows the yearly average discharges for the Fitzroy River since 1965. Note that the discharge is averaged between July 1 in the previous year and June 30 in the nominated year. This ensures that the summer

rainfall period falls within one averaging period. What is evident in the record is the enormous amount of interannual variability in the annual discharges. The year 1991 had an average discharge of $730 \text{ m}^3\text{s}^{-1}$ whereas 1969 had an average discharge of only $4 \text{ m}^3\text{s}^{-1}$, more than two orders of magnitude smaller. The high average flows in 1991 were mostly due to a flood event with discharges of up to $15,000 \text{ m}^3\text{s}^{-1}$ which lasted about two weeks. A second major flood occurred a month after this one.

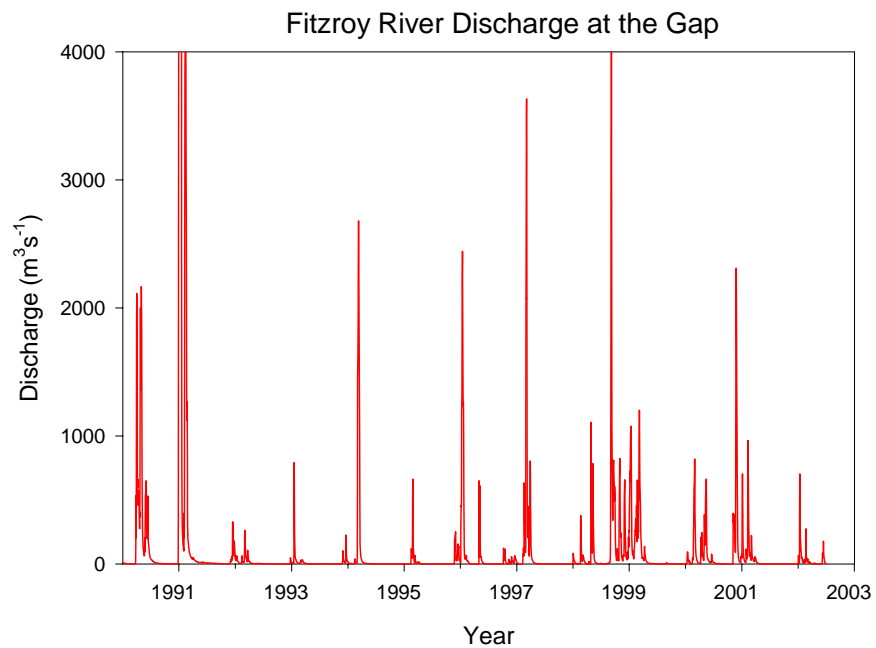


Figure 2. Daily discharge of the Fitzroy River at the Gap upstream of Rockhampton.

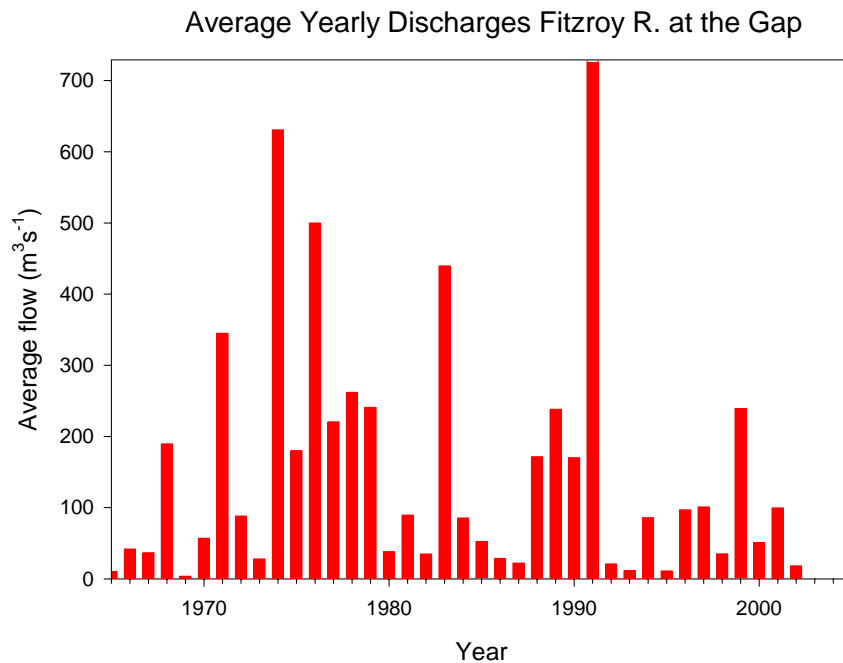


Figure 3. Annual average discharges of the Fitzroy River at the Gap.

2.2 Tides

The tides in the Fitzroy Estuary are of the mixed, dominant semi-diurnal type meaning that there are two high and two low tides per day with one of the high tides being significantly larger than the other for most of the time. The tides undergo a two-weekly cycle of spring tides and neap tides. A one-month long tidal record measured at Port Alma near the entrance of the estuary is shown in Fig. 4 which illustrates these features. During spring tides, the daily tidal excursion is about 5m which reduces to about half this range during neap tides.

Figure 5 compares water level measurements made over an 11-day period at Port Alma and at Lakes Creek which is about 12km from the Barrage at Rockhampton. Note that the bottom of the Lakes Creek record is truncated due to the emergence of the sensor from the water at sufficiently low tides. The relative height of the Lakes Creek record has been adjusted so that the two records would have about the same mean water level if the Lakes Creek record had not been truncated. The record shows that the tidal

amplitude is amplified at Lakes Creek by up to ~20% from the tidal amplitude close to the mouth of the estuary. Further, there is a significant phase lag along the length of the estuary. During spring tides, water level variations at the two ends of the estuary have approximately opposite phases, but the phase difference decreases during times of neap tides.

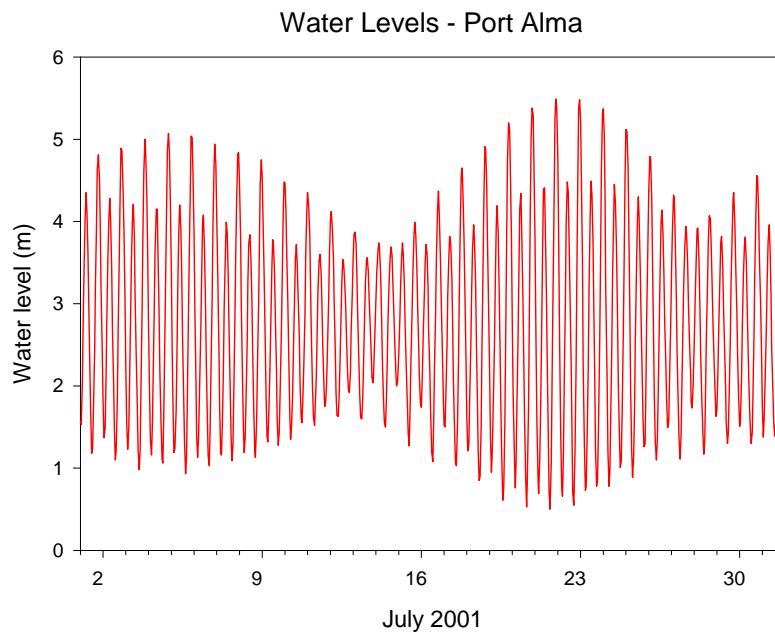


Figure 4. Measured water levels at Port Alma illustrating the diurnal variation and the spring-neap tidal cycle.

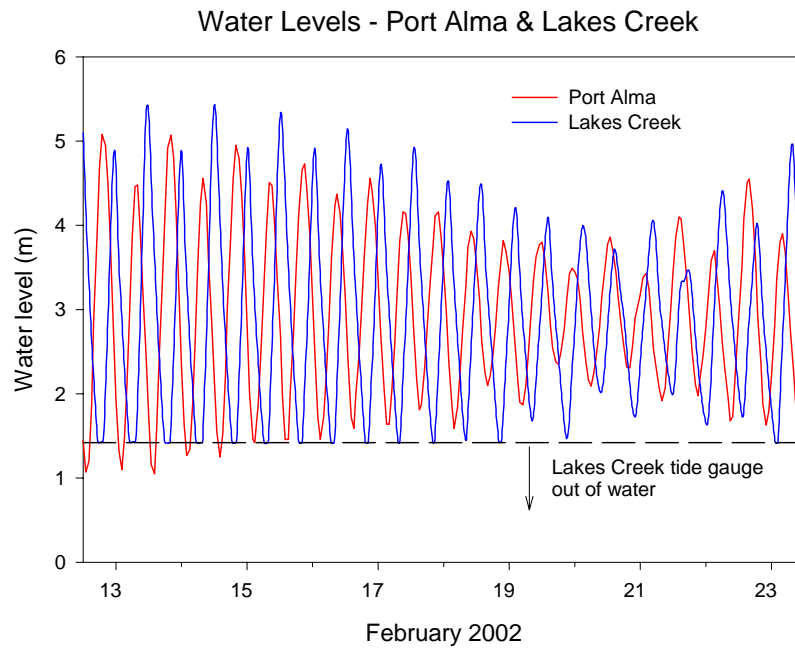


Figure 5. Comparison between water levels measured at Port Alma and at Lakes Creek. Note the phase shift and up-estuary amplification. The bottom of the Lakes Creek tidal record has been truncated due to the instrument emerging from the water.

2.3 Winds

The wind climate over the Fitzroy Estuary and the nearby coastal region is dominated by the Southeast Tradewinds which result in the dominant wind directions being south easterly and easterly. Some variation in wind direction results from the passage of troughs over the Australian continent. Winds measured by the Bureau of Meteorology at Yeppoon over the period July 1, 1998 to June 30, 2002 had an average direction of ESE and a speed of 4.6ms^{-1} (17kmh^{-1}). Wind speeds are on average ~20% higher than this average in mid-afternoon due to a sea breeze effect.

Water levels measured at Port Alma demonstrated fluctuations of amplitude $\pm 0.10\text{m}$ having periods longer than a few days. Some of these fluctuations appear to be related to the wind. In particular, some wind pulses towards the northeast were associated with elevated water levels at Port Alma. Such a response is consistent with longshore wind stresses causing a

piling up of water against a coast to the left of the wind direction (in the Southern Hemisphere) due to the Coriolis force. Other fluctuations in measured low-frequency water levels were not so obviously associated with the wind. Presumably, the water level response is associated with wind forcing over the whole of the Great Barrier Reef Lagoon and the continental shelves of eastern Australia to the south of the Fitzroy Estuary and the propagation of the oceanic response past the Fitzroy by continental shelf waves.

There will be a tilting of the water surface within the estuary due to the wind blowing along its length. Using the winds measured at Yeppoon, we can calculate that the winds blowing along the estuary would cause water level fluctuations at Rockhampton of only $\pm 0.03\text{m}$.

2.4 Salinity

The salinity regime within the Fitzroy Estuary is largely determined by the elapsed time since the previous flow event in the Fitzroy River. During flow events, salt water is flushed out of the estuary to be replaced by riverine fresh water. The relationship between estuarine salinity and discharge is well illustrated in Fig. 6 which shows the salinity at three sites along the estuary as a function of time. The station 59.6km from the estuary mouth is only 0.3km downstream from the barrage at Rockhampton. At this site and at the mid-estuary site (33.8km from the mouth), elevated discharges cause the salinity to diminish to close to zero. Also, the salinity at 2.5km from the mouth was reduced to less than half that of seawater (~ 35 PSU) following the summer 2000/2001 flow event. Following the cessation of flow events, the salinity along the estuary gradually increases as seawater is mixed towards its head by the tides.

The rate of increase of salinity after the flow events that occurred during the summers of 1993/1994, 1994/1995, and 2000/2001 is consistent with an exchange time for the water near the head of the estuary of 100 days. At the mid-estuary site (33.8km from the mouth), salinity rose to almost 40 PSU during the low-flow period in late 1994. This is substantially above the salinity of seawater and is probably due to evaporation from the water

surface concentrating the salt in the water column. If we assume a nominal evaporation rate of 7mm per day and if the estuary is assumed to have a mean depth of 5m, then evaporation from the water surface acting for a period of 100 days will concentrate any dissolved substance in the water column by 14%. This increase would account for a large part of the observed elevation of the salinity in mid estuary above that of seawater.

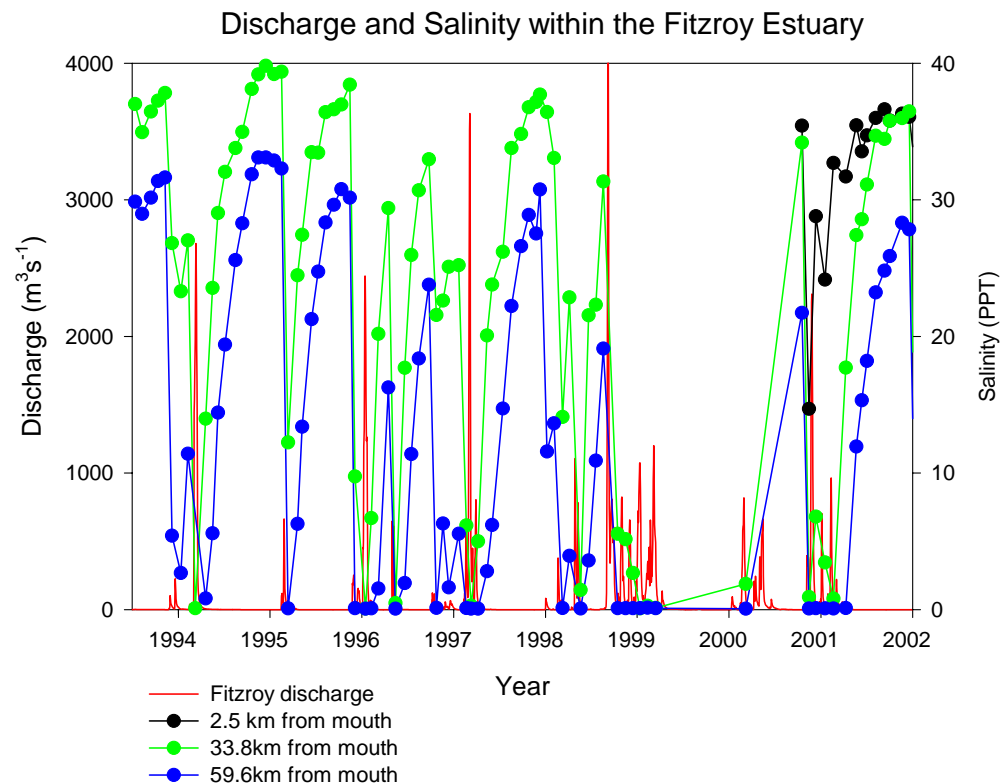


Figure 6. Salinity measured at three sites along the Fitzroy Estuary by the Queensland EPA (1994 – 1999) and by the CRC Coastal Zone Project FH–1 (2000 - 2002), and daily discharges from the Fitzroy River.

2.5 Currents

During periods of low discharge from the Fitzroy River, the currents within the estuary are dominated by tides. Figure 7 shows the results of model simulations for the current velocity and water level at a location 26km upstream from the mouth. This site is just upstream of the “Cut-through”

(see Fig. 1) about halfway along the main stem of the estuary. The model showed a good calibration against measured water levels within the estuary at Lakes Creek so we expect that the currents are also an accurate reflection of reality. The three days of the simulation shown represent a period of spring tides when we expect the tidal currents to be near their maxima.

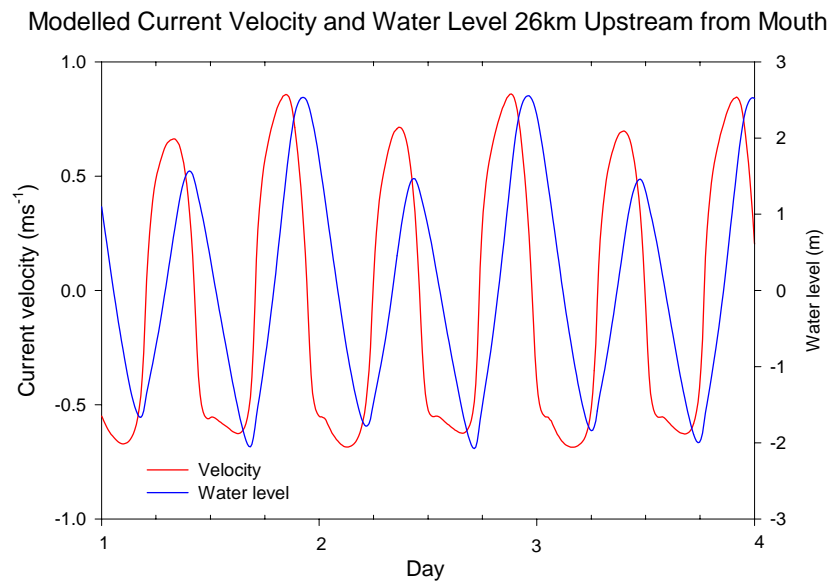


Figure 7. Modelled current velocities and water levels 26km from the mouth of the Fitzroy Estuary.

The currents at this site are large and show maximum current speeds of $\sim 0.9\text{ms}^{-1}$ on the flood tide and $\sim 0.7\text{ms}^{-1}$ on the ebb tide. To compensate for their smaller magnitudes and to conserve the volume of water within the estuary, the ebbing current flows for longer. This asymmetry in the tidal currents is commonly observed in estuaries when the tidal range is only several times smaller than the mean water depth. The asymmetry of the tidal currents is expected to have a profound influence on the transport of sediments within the estuary which will be discussed later. In general, tidal currents diminish as one proceeds from the mouth of the estuary towards its head. Constrictions in the channel where it is relatively narrow or shallow points may cause the currents to be elevated locally above those that would have occurred if the channel width and depth changed uniformly

along its length. During the period of neap tides, flood tides are reduced to maxima of $\sim 0.5\text{ms}^{-1}$ and ebb tides to maxima of $\sim 0.4\text{ms}^{-1}$.

As the tide floods and ebbs within the main channel, parcels of water move up and back along its length. The excursion distance of a water parcel decreases from the mouth of the estuary to zero at its head. For water which has an average position 10km upstream from the estuary mouth, its longitudinal excursion during the cycle of a spring tide is modelled to be $\sim 15\text{km}$. At the mid-estuary distance of 26km from the mouth, the excursion reduces to 11km during spring tides.

During the times of floods, a significant portion of the flow within the Fitzroy is due to freshwater discharge. The average cross-sectional area of the estuary is $\sim 3000\text{m}^2$, so that a discharge of $2000\text{m}^3\text{s}^{-1}$ would cause a flow of $\sim 0.7\text{ms}^{-1}$. Discharges of this size or larger were experienced on a number of occasions in the record shown in Fig. 2. Under these circumstances the flow would be similar to or larger than the tidal flow speeds. Of course, the addition of large amounts of fresh water discharging into the head of the estuary would alter the hydrodynamics in ways that would differ substantially from what one would experience if the effects of freshwater discharge and the tides were simply added together. The volume of the main channel is $\sim 2.5 \times 10^8 \text{m}^3$. We can consider how many times the channel would be filled by the flows in different years. 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 (Fig. 3). During the flood events of 1991, the freshwater discharge was sufficiently high to overflow the banks of the estuarine channel. This stage represents a discontinuity in the behaviour of the estuary as exchanges of dissolved and particulate nutrients between the extensive flood plains and the floodwaters now becomes possible. Once overbank flow occurs there will be extensive deposition of sediments on the flood plain.

3 Fine sediments

Fine sediments are defined here as sediments that have a grain size of $\sim 100\mu\text{m}$ or less. These sediments are liable to be suspended in the water column by currents and settle relatively slowly to the bottom. The settling rate in still water varies as the square of the grain size; a grain of $100\mu\text{m}$ diameter would sink at a speed of $\sim 0.01\text{m s}^{-1}$, whereas a $1\mu\text{m}$ grain would sink at a speed of $\sim 10^{-6}\text{m s}^{-1}$. Thus, the $1\mu\text{m}$ grain would take $\sim 60\text{d}$ to settle through a 5m water column. Transport of fine sediments is dominated by cycles of suspension, transport in the water column by the current, and by deposition. Coarse sediments such as sands tend to saltate (bounce along the bottom).

Fine sediments are significant to the ecology of rivers and estuaries in a number of ways. For a given concentration of suspended sediment in the water column, the efficiency of blocking the penetration of light by absorption or by scattering increases as the inverse of grain size. Thus suspensions of fine silts or clays can be very effective at reducing the light necessary for the growth of phytoplankton or benthic primary producers (microphytobenthos, macroalgae, sea grass). Nutrients (phosphorus) and pesticides adsorb to the surfaces of mineral particles. Having a larger surface area to volume ratio, fine particles can adsorb much larger concentrations of these contaminants than suspensions of particles having greater grain sizes. Transportation of nutrients and pesticides in adsorbed form is regarded as likely to be a major delivery mechanism for these substances between the catchment of the Fitzroy River and the mouth of the estuary.

3.1 Delivery of fine sediments to the estuary

The delivery of suspended sediment by the Fitzroy River to the Fitzroy Estuary is very much dominated by the flow events that typically occur during the summer months. Limited data (Taylor and Jones, 2000) indicate high annual delivery of river sediments to the Fitzroy Estuary ($\sim 4\text{ MT/year}$

on average), but these loads vary very much 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. Figure 8 shows concentrations measured in the Fitzroy River by the Queensland Department of Natural Resources and Mines (DNRM) and by Queensland Environmental Protection Authority (EPA) since 1990 for discharges exceeding $10\text{ m}^3\text{s}^{-1}$. Also, shown are measurements made by the EPA at a location 0.3km downstream from the Rockhampton Barrage. The latter concentration measurements would be expected to reflect concentrations in the discharge from the Barrage under these flow conditions. What is evident in the graph is that although TSS concentrations generally increase with discharge, the relationship between TSS concentration and discharge is highly irregular and variable. It is well known that TSS:discharge ratios change with the stage of the hydrograph and with the catchment in which the flow event originates. Consequently, it is probable that the relative interannual variation in suspended sediments delivered to the Fitzroy Estuary is even greater than the variation in annual discharge shown in Fig. 3. Our analysis of TSS delivery to the Fitzroy Estuary (Ford et al. 2003) undertaken on measurements obtained between October 2000 and July 2002 estimates 0.23 MT and 0.13 MT of suspended sediment delivered to the estuary in the summers of 2000/2001 and 2001/2002, respectively. These sediment loads are an order of magnitude less than the estimated mean delivery of 4MT per annum.

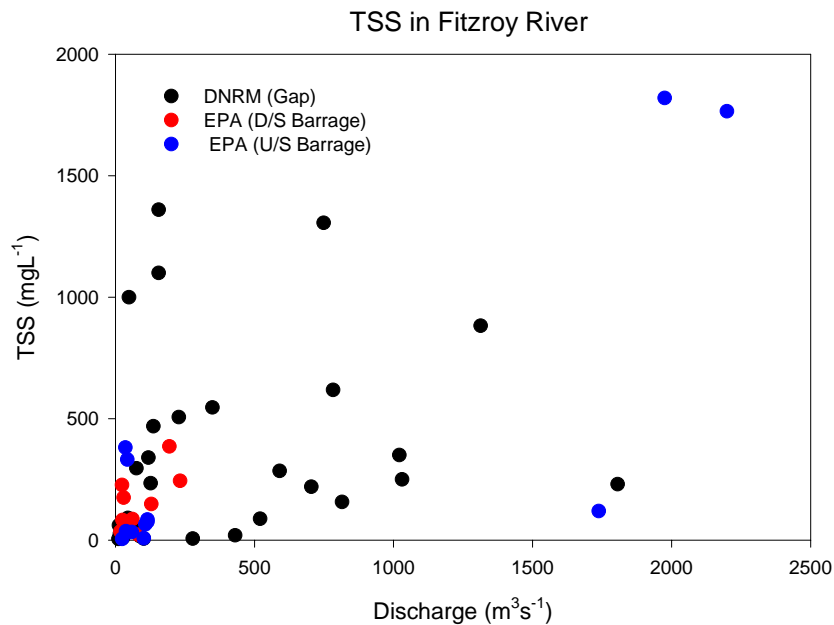


Figure 8. Concentrations of TSS measured in the Fitzroy River for discharges $>10\text{m}^3\text{s}^{-1}$.

3.2 The transport of fine sediments within the Fitzroy Estuary

Fine sediments discharged into the head of the estuary downstream from the Rockhampton Barrage are redistributed through the system by the hydrodynamic processes of suspension, transport in the water column and deposition. The mean particle size is of the order of $1\mu\text{m}$ and a significant fraction of the particles are much smaller (Fig. 9). Such particles sink slowly, but when they encounter salt water they flocculate into larger particles which can sink much more rapidly. Flocculation is a phenomenon that fundamentally alters the fine-sediment dynamics within the estuary. It is enhanced up to specific shear rates but, at high shears, the aggregated particles are broken into smaller particles. Thus there is a complicated interplay between particle size, salinity, and tidally generated currents.

The factors which control the concentration of suspended sediment are schematised in Fig. 10. 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. The cohesiveness is a property of the sediment mineralogy and also whether the sediment surface is covered by biogenic films or not. Such cohesive sediments may not resuspend until a critical flow speed is exceeded, which may be much higher than for coarser particles. In typical model formulations of the resuspension process, resuspension rates scale as the square of the flow speed so that doubling of flow speeds would quadruple resuspension rates.

The deposition rate of particles is the product of the concentration of particles in the water column and the particle sinking speed. The particle sinking speed can be greatly increased by flocculation causing deposition rates to increase in proportion. Ultimately, the concentration of sediments suspended in the water column depends on the balance between resuspension, deposition, and horizontal transport. High concentrations tend to occur in the water column when resuspension is active as during times of high currents. On a sandy bed, an equilibrium distribution of sediments in the water column tends to be established, with the resuspension and deposition fluxes cancelling each other. On a cohesive bed, the erosion process might be irreversible because, once eroded, the cohesive sediment cannot be reconstituted in its consolidated form in the energetic estuarine environment. Therefore the erosion rate is not balanced by an equal rate of deposition. The eroded fine sediments are winnowed, carried, and deposited in still water.

Erosion and sedimentation at the sediment-water interface are functions of the bed shear stress τ_b , the critical shear stress of deposition τ_d and the critical shear stress of erosion τ_e . If $\tau_b > \tau_e$ erosion occurs from the top of the bed downward until the shear stress applied to the bed is equal to the bed shear strength. If $\tau_b < \tau_d$ the sediment will be deposited. The deposited mass of sediment forms a bed with increased values of void ratio. Due to the self-weight of the sediment mass, consolidation begins and the bed properties change. When $\tau_d < \tau_b < \tau_e$, the applied stress is high enough to prevent any deposition from occurring, but not high enough to

erode the top bed layer. This situation occurs when the bed has been eroded to a layer that is sufficiently hard to resist further erosion. Neither erosion nor deposition occurs during this time step, and only consolidation takes place.

On a mixed bed consisting of fine and coarse particles, the presence of the coarse fraction can limit the depth from which finer grains are available. The finer grains are winnowed from the bed and the remaining grains soon form a layer that shields the grains below and thus arrests further entrainment.

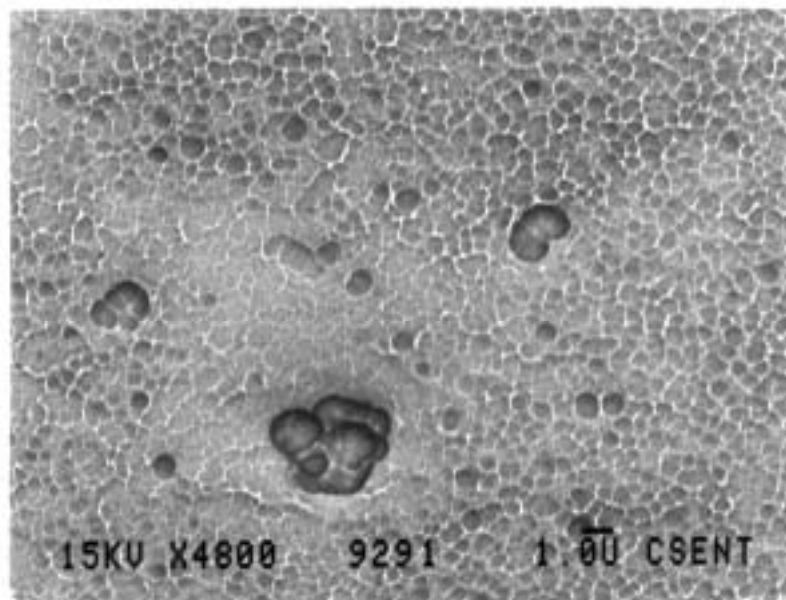


Figure 9. Electron micrograph of evaporated droplet of water from the Fitzroy River upstream of the Barrage showing an agglomeration of particles (lower centre) and presence of fine particles much smaller than $1\mu\text{m}$. Note the size of the $1\mu\text{m}$ bar. (Image courtesy of Eric Hines CSIRO Entomology).

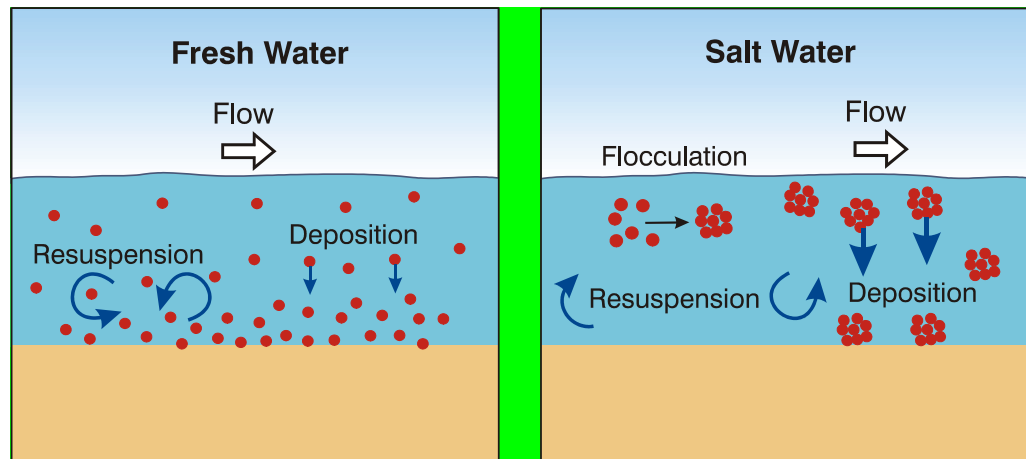


Figure 10. Factors controlling the concentration of fine sediments in the water column in the Fitzroy Estuary.

Because of the impact of salinity on flocculation and because of the impact of flow events on material transport within the estuary, we discuss the sediment dynamics during flow events and the more extended low-flow periods separately.

3.3 High-flow sediment dynamics in the Fitzroy Estuary

During flow events of sufficiently elevated discharge, salt water may be completely flushed out of the estuary rendering the estuary fresh along its full length. In this case, sediment flocculation and settling within the estuary would be minimal and one might expect the estuary to be a relatively efficient transmitter of fine sediments between the Fitzroy River and Keppel Bay. An estimate of when such conditions might occur can be obtained by comparing the volume of inflow during a flow event to the total volume of the estuary ($\sim 2.5 \times 10^8 \text{ m}^3$). We set the duration of a flow event to be 7 days and show the time series of the ratio of flow volume discharged during this time (as a running sum) to the estuary volume in Fig.11.

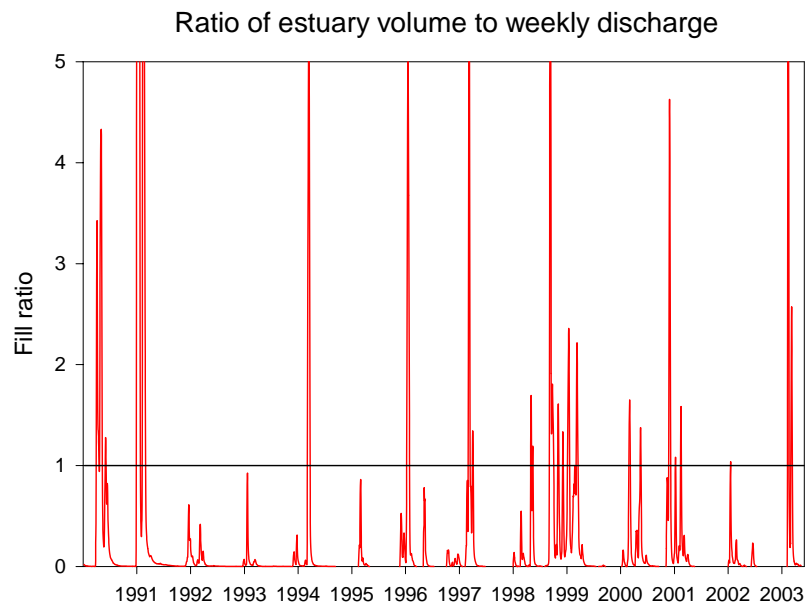


Figure 11. The ratio of the river volume discharged as a running 7-day sum to the volume of the Fitzroy Estuary.

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 Keppel Bay in unflocculated form. In the summer of 1990/1991, the discharge volume summed over 7 days 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, and we suggest that most of the TSS delivered down estuary from the Barrage would reach the estuary mouth. From there, the river water spreads out into Keppel Bay as a plume of relatively fresh water which floats on the more saline water of the Bay (Fig. 12). As this plume becomes more saline due to mixing with underlying water, flocculation would occur leading to enhanced deposition of the suspended sediments. A sampling cruise through the plume of the 1990/1991 summer flood showed a shallow freshwater surface layer with sediment concentrations between 1/20 to 1/40 of the TSS concentration measured at Rockhampton (Brodie and Mitchell, 1992). This result has significant implications for the delivery

of sediments to the Great Barrier Reef and is explored further in Ford et al. (2003).



Figure 12. Landsat image of Fitzroy Estuary and Keppel Bay showing the plume of turbid water resulting from the 1989 flow event.

3.4 Low-flow sediment dynamics in the Fitzroy Estuary

The predominantly fine particles brought into the estuary by the river during flow events are very slow to settle in fresh water. However, the ionic strength increases as the advancing seawater gradually mixes with the particle-laden fresh water and causes the particles to flocculate and settle more rapidly. In the lower energy environments towards the landward end of the estuary, the water clears. The relatively low concentration of sediment in the water in the upper estuary is seen in Fig. 13. The period shown in the Figure is a period of low discharge ($< 10\text{m}^3\text{s}^{-1}$).

Experiments by P. Ford on riverine sediments suggest that flocculation occurs between salinities of 1-2 PSU. There were a series of discharge events in the Fitzroy River between the beginning of November 2000 and the end of March 2001 (days 309 to 455). The first time shown plotted in Fig. 13 is for day 478 which is ~2 weeks after flows reduced to less than $10\text{m}^3\text{s}^{-1}$. At this time, the hydrodynamic model predicts the salinity to exceed 1 PSU so it would appear likely that significant flocculation has occurred causing the upper estuary to clarify.

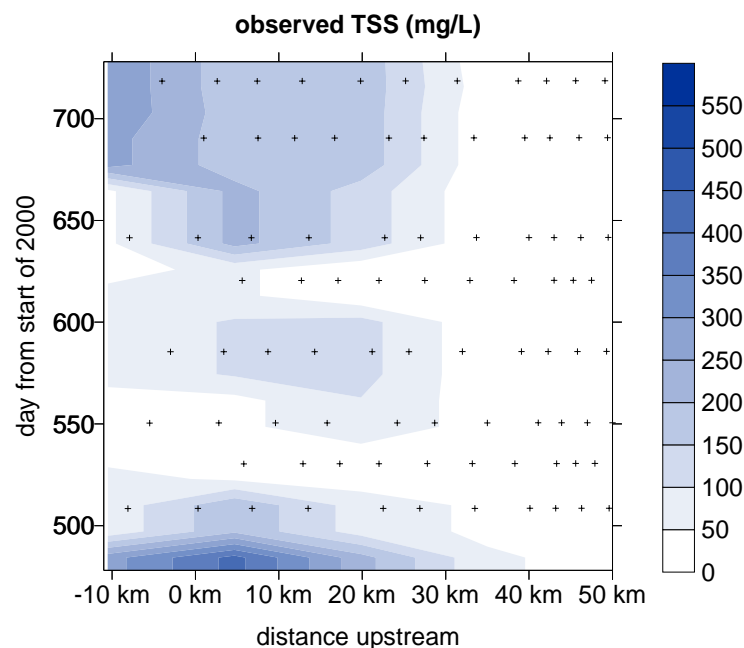


Figure 13. Contour plot of measured TSS along the estuary versus time. The dots represent measurement times and locations.

In the lower estuary, tidally driven resuspension and deposition appear to produce large and rapid changes in sediment concentrations. Figure 14 compares measured and modelled TSS concentrations at a location 33km down-estuary from the Barrage. The fine-sediment model has been developed by Margvelashvili et al. (2003). The thickness of the black line representing the modelled TSS concentrations indicates the range of diurnal TSS concentrations predicted by the model; that is, the lower and upper edges of the line are the minimum and maximum diurnal TSS concentrations. The highest TSS concentrations occur during times of spring tides and at these times the diurnal variation in concentration can be very large. On day 50 for example at $x = 33\text{km}$, modelled concentrations

vary from $\sim 50\text{mgL}^{-1}$ to more than 400mgL^{-1} over the diurnal cycle. The model shows and Figure 13 also suggests that the highest TSS concentrations tend to occur along the seaward half of the estuary where the currents have the largest amplitudes. This may very well be the case also for flow events that are large enough to flush the estuary of salt water during times of spring tides.

If the diurnal variations in TSS within the Fitzroy Estuary truly are similar to those that are modelled, then the use of measurements spaced at monthly intervals to define representative TSS concentrations is highly problematic. The measured concentrations are determined very much by the phase of the daily tide at the time of sample collection (Ford et al. 2003) as well as on the phase of the spring-neap tidal cycle. The survey undertaken on 13 June 2001 measured TSS concentrations of less than 50mgL^{-1} along the length of the estuary (Fig. 13), but the reason for these low concentrations appears to be that the time of this survey coincided with neap tidal ranges.

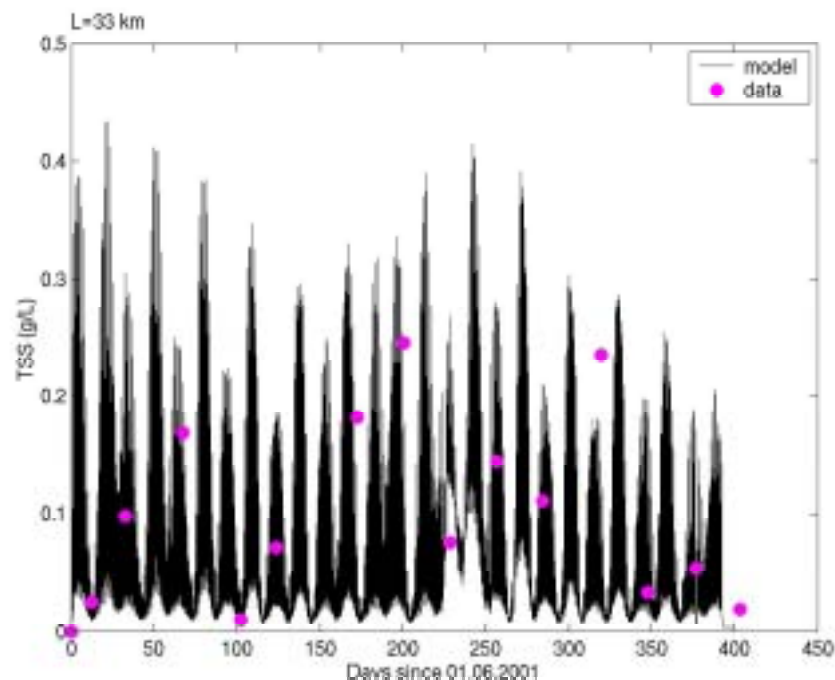


Figure 14. Time series of modelled TSS concentrations at $x = 33\text{km}$. Also shown are the TSS concentrations measured at this site during the monthly sampling EPA sampling program.

3.5 Sediment transport within the estuary

During low or zero river discharges, the upstream and downstream transport of water along the estuary during the flooding and ebbing phases of the tidal cycle are approximately balanced. However, sediment transport depends on the amount by which the velocity exceeds the threshold velocity necessary to initiate sediment resuspension and motion. In asymmetric flow, sediment fractions, with a critical resuspension velocity greater than the ebb velocities, but less than the flood velocities, are resuspended during the flood and remain settled on the bottom during the ebb. In the section on hydrodynamics, we discussed the asymmetry of the tidal currents in the Fitzroy Estuary which demonstrate larger flow amplitudes on the flood than on the ebb (see Fig. 7). The net result of such asymmetry would be up-estuary pumping of sediments with subsequent deposition of particles in the upper estuary. Deposition would occur preferentially in areas of relatively low current such as the Loop or in sections of the estuary channel that are wide and deep.

When river discharges to the estuary are appreciable, then the ebbing tidal currents may exceed the flooding currents so that more resuspension and higher concentrations occur during the ebb than during the flood. When the river discharge is sufficiently large, the currents associated with this flow may be comparable to the amplitude of the tidal current. Then the 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. Thus, under low flow conditions and over the annual time scale, the net balance between river loads, sediment discharge to ocean, and upstream pumping, is likely to be accumulation of sediment in the estuary. However, this gradual accumulation of sediments over the annual time-scale is probably balanced by the rapid and large discharge of sediment to the ocean during the episodic, high river flow events.

The Fitzroy Estuary and Keppel Bay are closely interactive estuarine and coastal zones and sediment dynamics in the estuary are sensitive to hydrodynamic and transport conditions in the coastal waters outside the estuary. Because of upstream pumping, the time-varying concentrations of suspended solids in the mouth of the estuary and in Keppel Bay could have a direct impact on the sediment composition and accumulation rates in the upper estuary. This interaction between Keppel Bay and the Fitzroy Estuary is a central issue in the investigations of the Phase 2 Fitzroy Contaminants Project.

4 Biogeochemistry

This section develops conceptual models of the biogeochemistry of the Fitzroy Estuary. It is primarily concerned with the input and fates of the two nutrients nitrogen and phosphorus, and with primary production in the estuary. As with the hydrodynamics, and with the dynamics of fine sediments, the biogeochemical behaviour of the system has two phases connected with the low-flow and high-flow regimes of the Fitzroy River.

4.1 Nutrient Loads and Export

By far the greatest input of the nutrients nitrogen and phosphorus to the Fitzroy Estuary derives from the Fitzroy River during high flow events. Figure 15 shows the import and export results for Total Nitrogen (TN) during the CRC study of 2000-2002 (Ford et al., 2003). Each bar represents the import/export calculated between successive pairs of surveys undertaken at approximately monthly intervals. In combination with simulations of the mixing behaviour of the estuary deduced from a hydrodynamic model, these data are used to infer the transport pathways of nutrients in two sections of the estuary. These are the “up-estuary box” (the section 8 - 25 km from the Barrage), and the “down-estuary box” (the section 25 - 44 km from the Barrage). The Loop is not considered explicitly and has been included in the down-estuary section.

River imports are shown for river discharges (averaged between surveys) $> 5\text{m}^3\text{s}^{-1}$ since it is only for these discharges that the river dominates inputs of TN. 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 2,520T of which 2,420T was exported downstream of $x = 44\text{km}$. 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 600T which is a factor of more than 4 smaller. The export during this second summer was 320T.

Figure 15 shows that the export of nitrogen during the first flows of each summer is significantly less than the import during this time. This is consistent with the first flows of the summer acting to 'fill up' the estuary before export can occur through the mouth. Further, it is apparent that the export efficiency for TN is a lot higher during the first summer (96%) than during the second (53%). During the first summer, most of the TN would have been carried straight through the estuary by the higher flows, whereas during the second summer the flow event was barely large enough to fill the estuary (Fig. 11). Based on the study of 2000-2002, approximately half the input load is Dissolved Organic Nitrogen (DON); Dissolved Inorganic Nitrogen (DIN) and Particulate Nitrogen (PN) each comprise about a quarter of the load.

The effective TN concentrations in the river inflow measured during the 2000-2002 survey varied between $0.5 - 1.5\text{mgL}^{-1}$ so that most of the variation in riverine load shown in Fig. 15 is due to variation in average discharge between surveys. Concentrations of TN in the river measured by DNRM at the Gap and by the EPA upstream from the Barrage over the last 13 years for discharges $> 10\text{m}^3\text{s}^{-1}$ varied between $0.4 - 3.5\text{mgL}^{-1}$, but most measurements fell in the range $0.5 - 1.5\text{mgL}^{-1}$. Using the average river concentration of 1.1mgL^{-1} measured over this time, the median yearly total nitrogen load to the Fitzroy Estuary since 1965 would be 3,020T with a maximum of 25,300T in 1991. Thus, the TN load delivered to the estuary

during the summer of 2000/2001 is similar to the median load. The estimate of the maximum yearly load is probably too low since it would appear that for the highest flows the TN concentration is larger than the nominal average.

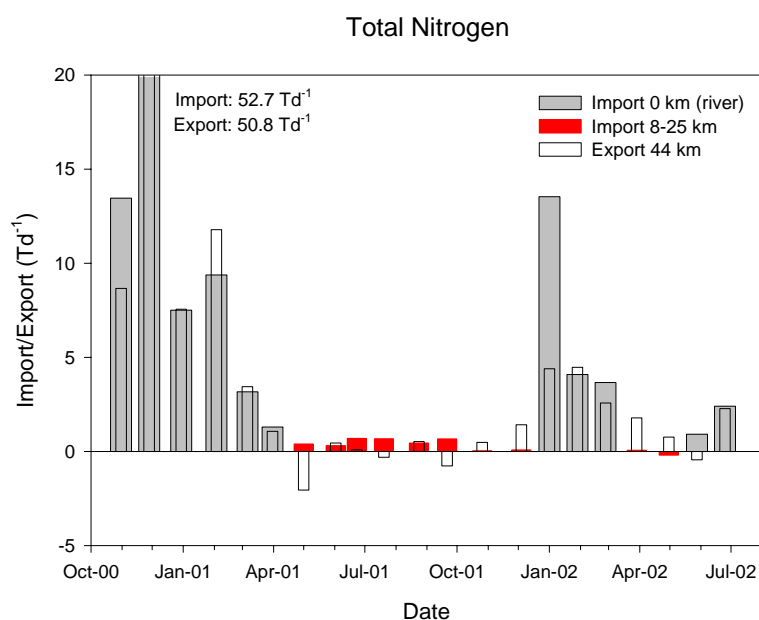


Figure 15. TN imports and exports from the Fitzroy Estuary. Imports are shown as river inputs for $\bar{Q} > 5 \text{ m}^3 \text{ s}^{-1}$ and for input between 8 -18km for $\bar{Q} < 5 \text{ m}^3 \text{ s}^{-1}$.

For river discharges less than $5 \text{ m}^3 \text{ s}^{-1}$, it seems that the dominant source of nitrogen to the estuary is discharge from the Rockhampton STP and the meatworks downstream from Rockhampton at Lakes Creek. These inputs (shown as the red bars in Fig. 15) are comprised mainly of nitrate and ammonia. In the low-flow period between April 2001 and January 2002, these inputs were estimated to deliver 95T of TN to the estuary or 4% of the TN input during the previous summer.

Like nitrogen, most of the phosphorus input to the estuary is delivered during the high flow events. During the summer of 2000/2001 it is estimated that 980T of total phosphorus (TP) was delivered to the estuary of which

760T was exported. The following summer, 200T was input of which only 60T was exported. It would seem that the transmission efficiency for TP is less than that for TN, but like TN the efficiency is higher for larger discharges. Total phosphorus in the river inflow for discharges $>10\text{m}^3\text{s}^{-1}$ varied between $0.02 - 0.9\text{mgL}^{-1}$, with a tendency for higher discharges to have higher concentrations. Compared with TN, TP river concentrations showed greater relative variability. The ratios of the standard deviation in concentration to the mean are 0.56 and 0.67, for TN and TP respectively. Most of the TP in the river flow appears to be associated with suspended sediments. On average, 26% of the TP on riverine suspended sediments is Filterable Reactive Phosphorus (FRP) for discharges $>10\text{m}^3\text{s}^{-1}$. Further, there appears to be a distinct relationship between TP and TSS in the river (Fig. 16). Total Phosphorus concentrations increase approximately proportionally with TSS for TSS concentrations $< 500\text{mgL}^{-1}$, but for higher TSS concentrations, TP concentrations are approximately constant.

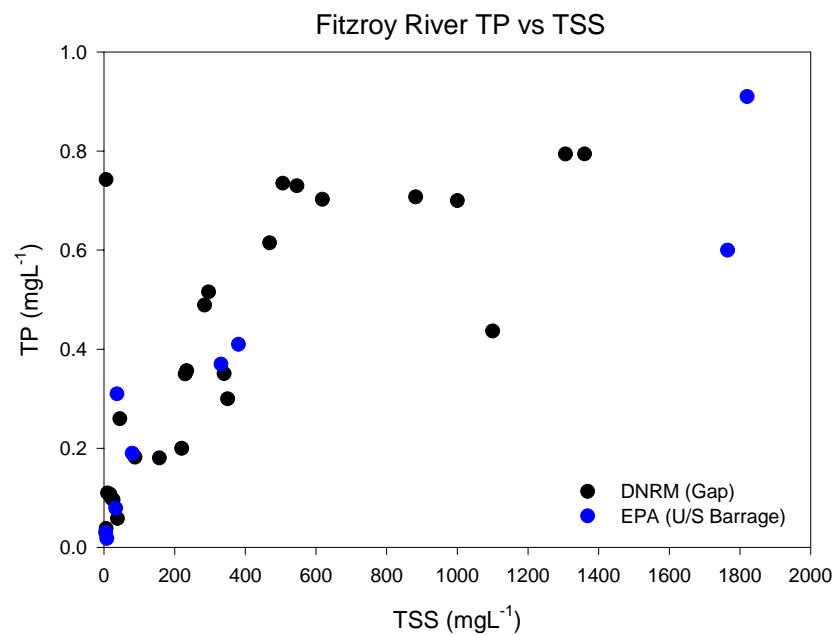


Figure 16. Concentrations of TP plotted versus TSS measured in the Fitzroy River for discharges $>10\text{m}^3\text{s}^{-1}$.

From the measurements obtained during the study of 2000-2002, the internal inputs of TP could be calculated for the low-discharge period. Between June-December, 2001, the net input of TP into the section of the estuary between $x = 8 - 25$ km from the STP and meatworks is calculated to be 8T and most of this phosphorus is FRP. The molar ratio of the inputs of TN to TP in this upper section of the estuary during the low-flow period is 26:1 compared to a ratio of 6:1 for the TN:TP ratio in the inflow during elevated discharges. The TN:TP ratio in the low-flow input is higher than one would expect if the input were due to a STP discharge or to waste from a meatworks. It is possible that considerably more than 8T of phosphorus was discharged, but a major proportion of it was adsorbed to bed sediments in this section of the estuary. The average FRP concentration in the inflow during elevated flow events is 0.08 mgL^{-1} and we might assume that within benthic sediments this would be the equilibrium concentration associated with adsorption-desorption process between porewaters and sediment particles. For an effluent containing an FRP concentration greater than this, some of the 'excess' FRP would be adsorbed to sediments at rates that would be in part limited by transport rates within interstitial waters.

4.2 Transport of nutrients within the estuary

During times of high river discharge, it would appear that nutrients discharged into the head of the Fitzroy Estuary are carried through the estuary by the mean flow. If the flow volume during a discharge event is several times larger than the estuary volume, then we might expect that the transmission efficiency approaches 100% and that the composition of the exported water is similar to that of the river discharge. Though if the discharge is so large that it goes over bank, then it is likely that the suspended load will be different from the up-estuary value. During lesser flow events, more of the discharge volume is retained within the estuary, which is then subject to transport processes associated with low river discharges. Since these transport processes are less efficient at transporting nutrients along the estuary than is a uni-directional flow, the

opportunity for biogeochemical processes to store, remove and transform input nutrients before export to Keppel Bay is greater.

Under low-flow conditions, transport along the estuary is dominated by the back and forth motion of the tidal currents. The oscillatory motion of the tides causes mixing in both directions along the estuary. We have already shown how salt is gradually mixed back up the estuary after the cessation of a freshwater inflow event by this process. For dissolved nutrients, long-estuary transport occurs in the same way. For both these nutrients concentrations tend to be higher in the landward half of the estuary than they are in Keppel Bay so that this transport mechanism would tend to transport dissolved forms down the estuary.

For both nitrogen and phosphorus, some of the total nutrient concentration is in particulate form. In the section on fine-sediment transport, we have suggested that during low-flow periods, fine sediments are transported up-estuary due to the asymmetry of the tides. It is likely that negatively buoyant particulate nutrients would also have a tendency to be transported up-estuary. Conversely, if there is a significant gradient in particulate nutrients in the water column such that concentrations decreased in the down-estuary direction, mixing processes in the water column would tend to transport these particulates in a down-estuary direction.

4.3 Biogeochemical transformations

Figure 17 schematicises the likely major biogeochemical transformations in the Fitzroy Estuary for nitrogen during low-flow conditions in the Fitzroy Estuary. The transformations include changes in the chemical form of the nitrogen as well as uptake and release by primary producers and grazers. We suggest that the interaction between water column processes and processes in the sediments are likely to be important determinants of the overall cycling of nutrients in the system.

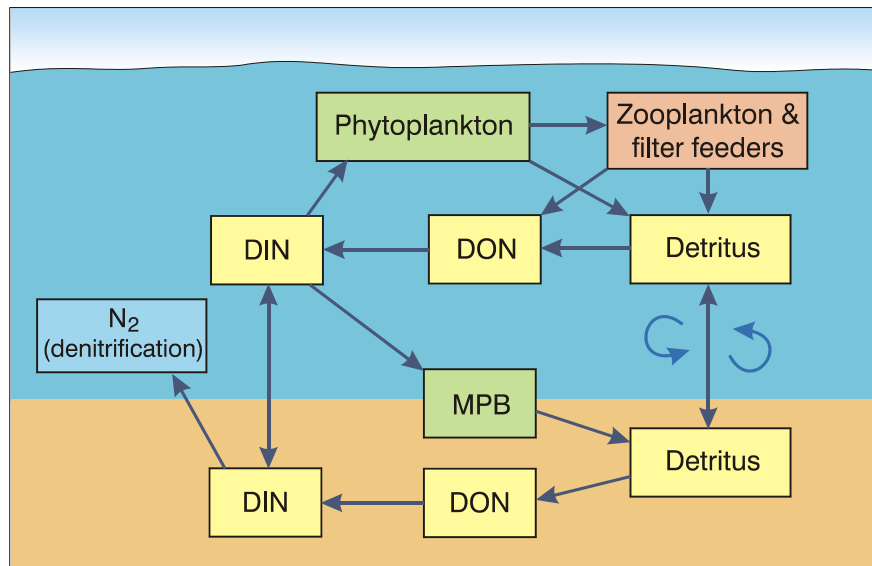


Figure 17. Schematic of biogeochemical processes and primary production in Fitzroy Estuary during low-flow periods.

Primary production occurs as plants take up nutrients and photosynthesise. Primary producers require light for growth and in the Fitzroy there does not appear to be enough light on the bottom to support the growth of seagrass or macroalgae even during low-flow times when the water column is relatively clear. Strong currents in the estuary also mitigate against the establishment of these plant groups. However, phytoplankton in the upper half of the estuary during low-flow periods do experience enough light as they are mixed through the water column to sustain growth, although this does not appear to be the case in the lower estuary. Turbidities in the lower estuary are much higher than in the upper estuary and an analysis of the chlorophyll budget for the estuary suggests that the chlorophyll that is seen in the lower estuary derives from phytoplankton that are mixed seaward from the more productive upper estuary and also from Keppel Bay. The numerical biogeochemical model supports this conclusion, with the majority (60%) of phytoplankton production occurring in the upper half of the estuary.

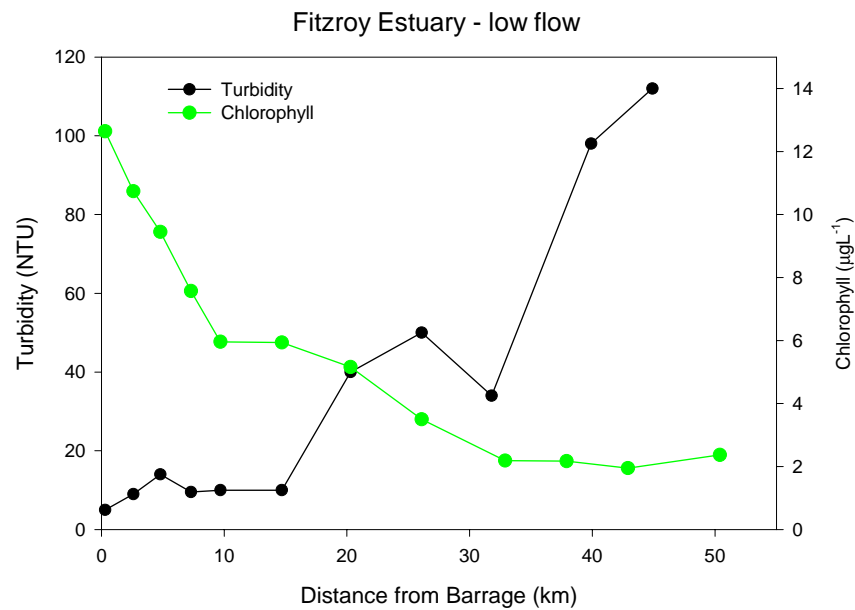


Figure 18. Median turbidities and average chlorophyll concentrations measured along the estuary during the low-flow period April-December 2001.

During the low-flow period, phytoplankton concentrations in the estuary were quite variable; between 8 – 25km downstream from the Barrage, average concentrations varied between $1.1\mu\text{g L}^{-1}$ and $14\mu\text{g L}^{-1}$ with an average of $5.2\mu\text{g L}^{-1}$. An average irradiance through the water column can be calculated from the average daily irradiance (light strength) at the water surface and the light-absorbing properties of the water column estimated from measured Secchi depths. Figure 19 shows that a large part of the variation in chlorophyll concentration is associated with the availability of light. The two highest chlorophyll concentrations occurred in months having high irradiances due mainly to the water column being relatively clear at these times.

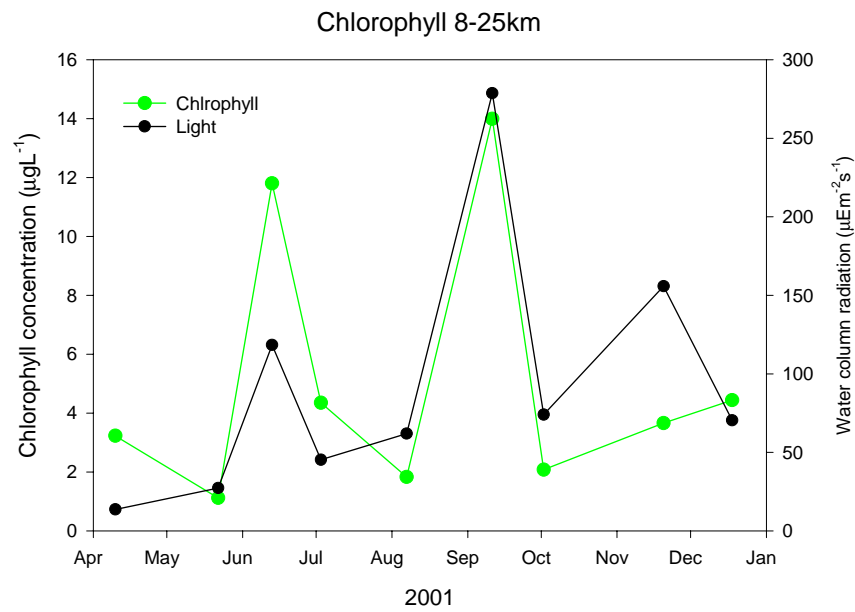


Figure 19. Time series of chlorophyll and average water column irradiance for $x = 8 - 25\text{km}$ measured at approximately monthly intervals.

Phytoplankton takes up dissolved inorganic nitrogen and phosphorus for growth (Fig. 17). Figure 20 shows the flows of the nitrogen species DIN and DON as well as chlorophyll through the upper and lower sections of the Fitzroy Estuary determined from measurements made during the low-flow period April-December 2001. The results are expressed as the equivalent Tonnes of nitrogen exchanged over this 220-day period. Thus, chlorophyll nitrogen is the mass of nitrogen contained within the phytoplankton having the measured chlorophyll concentrations.

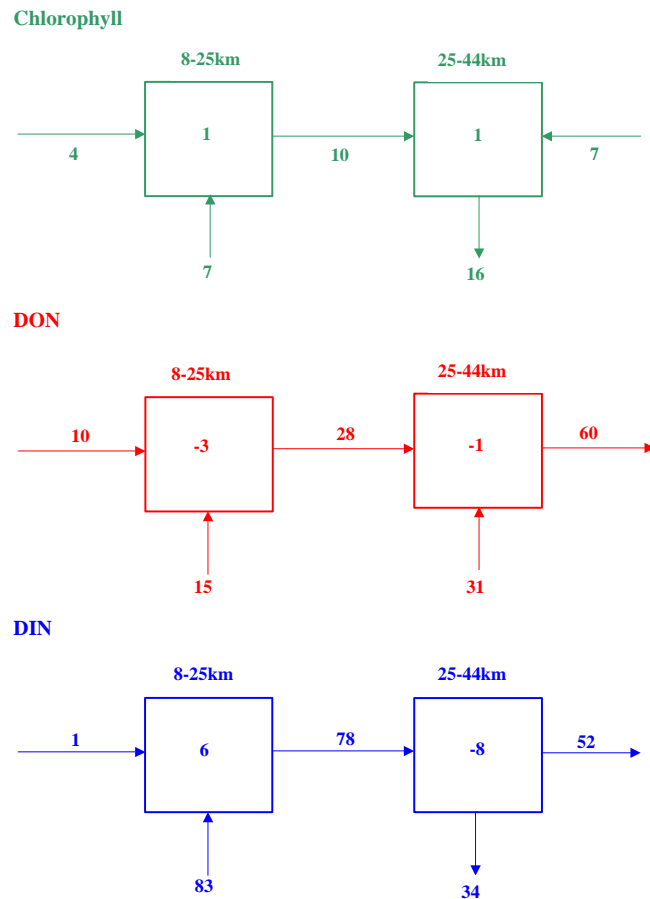


Figure 20. Nitrogen budgets for low-discharge period April-December 2001. Units are tonnes of nitrogen. The numbers within the boxes are the changes in the water column 'store' over this time.

For chlorophyll, it is apparent that during this low-flow period 7T of nitrogen was taken up by phytoplankton in the section of estuary between 8 – 25km and this was supplemented by a further 4T mixed downstream from the section of estuary between 1 – 8km . From the light available in the water column and from measured phytoplankton concentrations, we estimate the maximum potential phytoplankton production during this low-flow period as 1080T (or ~150 times larger than the inferred production of 7T from the budget) if production is limited only by the availability of light. The 83T of DIN input to the upper estuary is insufficient to support 1080T of production. Nutrients are available in sufficient concentrations to maintain phytoplankton growth. DIN concentrations were mostly greater than

100 µg L⁻¹ during the low-flow period and FRP concentrations were mostly greater than 50 µg L⁻¹.

Rather, net phytoplankton assimilation is likely to be limited by losses due to sinking to the bottom and by predation by zooplankton. In the upper part of the estuary, there are large beds of small mussels (*Amygdalum* cf. *glaberrima*) that would filter planktonic material out of the water column (Currie and Small, 2002). Also, schools of jellyfish have been observed in this section of the estuary which would also predate on the phytoplankton population. The bacterial decomposition of dead phytoplankton cells, dead predators, and other detritus such as the waste products of predation return inorganic DIN to the water column where it can fuel further phytoplankton growth as shown in Fig. 17. Thus, it is likely that this cycling of nutrients is associated with a gross phytoplankton production within the upper estuary which is many times larger than the net production of 7T (of nitrogen). Results from the biogeochemical model suggest that gross phytoplankton production is approximately 21 times net production during the low-flow period.

Figure 20 shows that during the low-flow period chlorophyll is lost from the lower part of the estuary between 25 – 44 km downstream from the Barrage. Net phytoplankton production is negative there and this part of the estuary acts as a sink for phytoplankton mixed down-estuary from the upper part of the estuary and up-estuary from Keppel Bay. We have speculated that the lack of light limits phytoplankton growth. Interestingly, beds of the mussel *Amygdalum* were not found in the lower estuary indicating either a lack of suitable food such as phytoplankton, the presence of an undesirable habitat such as high concentrations of suspended mineral matter, or the lack of suitable substrate. However, primary production may still be maintained by the microphytobenthos (MPB) living on the intertidal mud flats along the sides of the estuary. The MPB are microscopic algae that live on the surface of sediment. By being exposed on low tide, they obtain the light necessary to grow even if conditions in the water column nearby are not conducive to phytoplankton growth. As with phytoplankton, they participate in nutrient cycling (Fig. 17)

by taking up DIN from the water column and surficial sediments to support their growth. They are predated upon by crustaceans, molluscs, and fish and their sequestered nutrients ultimately returned to the water column. In the lower estuary (and in the upper estuary), primary production by MPB is likely to be large and an essential component of the ecosystem that supports fish and prawn production. A key component of the CRC project on contaminants in the Fitzroy Estuary is the investigation of primary production by the MPB.

During the low-flow period, the budget calculation suggests that there was an export of 78T of DIN and 28T of DON to the lower part of the estuary between $x = 25 - 44$ km. In the lower estuary, 34T of DIN is lost internally, whereas there is an input of 31T of DON. We might speculate that some of the lost DIN is taken up by the MPB and that the DON is a return of some of this nitrogen as one of the decomposition products (Fig. 17). The budget for Total Nitrogen calculates a TN loss in the lower estuary of 157T during the low-flow period. Most of this loss appears as particulate material with about 10% comprising phytoplankton. If this loss of TN were ultimately due to denitrification, then the average denitrification rate through the low-flow period would be $\sim 50 \text{ mg(N)m}^{-2} \text{d}^{-1}$ (or $\sim 3 \text{ mmolm}^{-2} \text{d}^{-1}$) which is a moderately large denitrification rate for a coastal zone (Seitzinger, 1988). Of course, because of the difficulty in estimating fluxes of particulate material, it is not at all certain that the estimated loss of TN in the lower estuary is accurate. Preliminary results from the dynamic biogeochemical model suggest an average denitrification rate of only $3 \text{ mg(N)m}^{-2} \text{d}^{-1}$ over the low-flow period.

Phosphorus transformations in estuaries such as the Fitzroy are mostly similar to those for nitrogen. An important difference between phosphorus and nitrogen cycling is that there is no equivalent of denitrification for phosphorus. Also, phosphate adsorbs to suspended and benthic sediments. The total pool of phosphorus that is available to support phytoplankton growth includes the phase that is dissolved in the water column (FRP) as well as the phases that are adsorbed to sediments and

that will be released to the dissolved if FRP concentrations are reduced (Fig. 21).

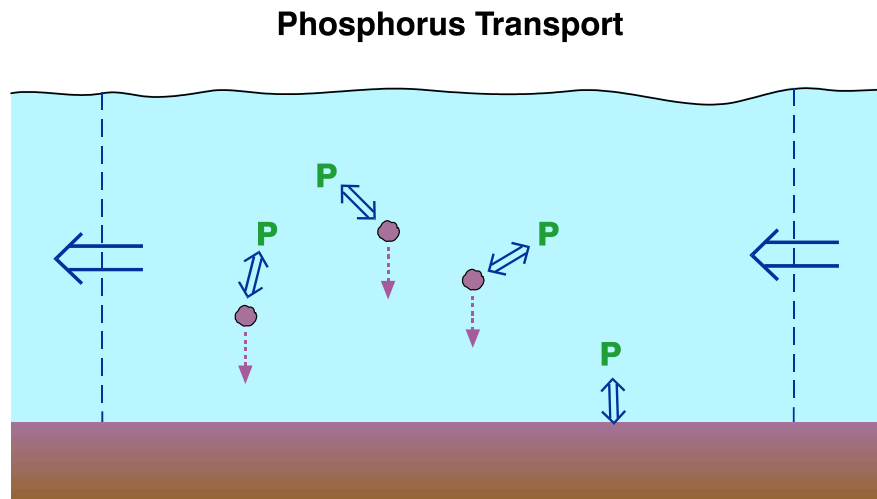


Figure 21. Schematic showing the interaction between dissolved phosphorus (P) and suspended and benthic sediments.

We calculate the molar ratios of the concentrations of the bio-available forms of nitrogen and phosphorus namely FRP and DIN. In the upper (8 – 25km) section of the estuary the ratio of the average concentrations is 5.1 and 9.7 in the lower 25 – 44km section of the estuary. Since the uptake ratio of nitrogen molecules to phosphorus molecules by phytoplankton is ~16 (Redfield ratio), then this would suggest that nitrogen is the most likely nutrient limiting growth of phytoplankton if nutrient limitation were to occur.

5 Summary – conceptual models

The following section summarises and presents in graphical form the conceptual models for the hydrodynamics, fine sediment dynamics, nutrient transport and transportation, and for primary production in the Fitzroy Estuary. In view of the large differences in the physical environment and transport conditions in the estuary under high and low-flow conditions, separate conceptual models are presented for each.

5.1 Hydrodynamics

5.1.1 High flow

- a) The freshwater input to the estuary occurs during high-flow events that occur mainly during the summer. The annual discharge is highly variable from year to year.
- b) The estuary is macro-tidal with large tidal ranges and strong tidal currents. The tides are dominantly semi-diurnal with a pronounced spring-neap cycle of tidal range.
- c) During times of high discharge, the currents due to the freshwater flow-through within the estuary and the tides 'add' together. For very large river discharges, the flow-through currents may be strong enough to prevent the reversal of flow direction on the flooding tide.
- d) High flow flushes salt from estuary and estuary becomes fresh from the Barrage to the mouth.
- e) Once the flow goes over bank the water velocity within the estuary will only increase very slowly.

5.1.2 Low flow

- a) Water motion in the Fitzroy Estuary is dominated by the tides during times of low river discharge.
- b) The oscillatory motion of the tides causes mixing along the estuary.
- c) The hydrodynamic model predicts asymmetric tidal currents with the peak velocity during the flood higher than that during the ebb.
- d) Following a high-flow event, the estuary gradually becomes more saline as seawater is mixed up-estuary from Keppel Bay towards the Barrage.

5.2 Fine-sediment dynamics

5.2.1 High flow

- a) During high flow, the river discharges elevated concentrations of suspended sediments into the head of the estuary downstream from the Barrage.
- b) The particle size of the riverine sediments is small and these sediments settle slowly.
- c) The currents associated with the through flow and the tidal currents combine to ensure that most of the suspended sediment remains in suspension and is exported through the mouth of the estuary. Additional sediment that was deposited previously may be scoured from the bottom to augment the exported load.
- d) The annual load of fine sediment is highly variable and largely reflects changes in river discharge.

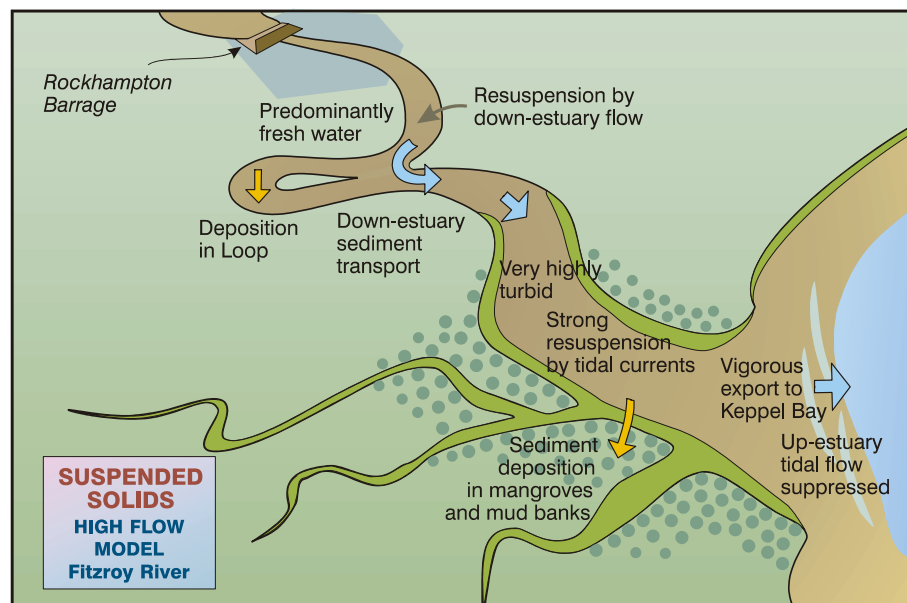


Figure 22. Conceptual model of fine-sediment dynamics in the Fitzroy Estuary during high-flow events. Blue arrows represent internal transport and yellow arrows represent net losses.

5.2.2 Low flow

- a) The elevated salinities within the estuary that develop during low-flow periods cause the suspended sediments to flocculate into larger particles

that settle quickly. Suspended sediment concentrations in the landward half of the estuary reduce and the water clears, but where tidal currents are more vigorous in the lower part of the estuary resuspension remains active and the water column retains elevated suspended sediment concentrations and the water remains turbid.

b) In the lower estuary, there are major variations in the suspended sediment concentration associated with the diurnal changes in the strengths of the tidal currents.

c) Due to the asymmetry of the tidal currents on the ebbing and flooding tides, the fine-sediment model predicts that sediment transport is up estuary during times of low river discharge.

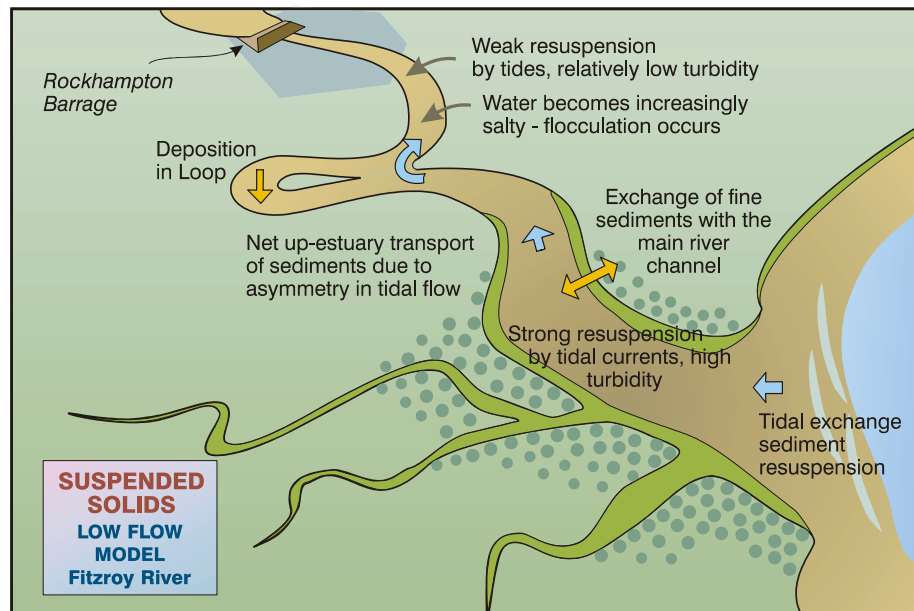


Figure 23. Conceptual model of fine-sediment dynamics in the Fitzroy Estuary during low-flow periods. Blue arrows represent internal transport and yellow arrows represent net losses.

5.3 Nutrient transport and transformations

5.3.1 High flow

a) Most of the dissolved and particulate nutrient introduced into the estuary during high river flows is transported through the mouth and exported to Keppel Bay in unaltered form

- b) The transmission efficiency of nitrogen species through the estuary may be significantly higher than for phosphorus particularly for discharge volumes that are not much greater than the volume of the estuary.
- c) Inorganic phosphorus is transported through the estuary as a dissolved phase and adsorbed to suspended sediments.
- d) The annual load of nutrients is highly variable and largely reflects changes in river discharge.

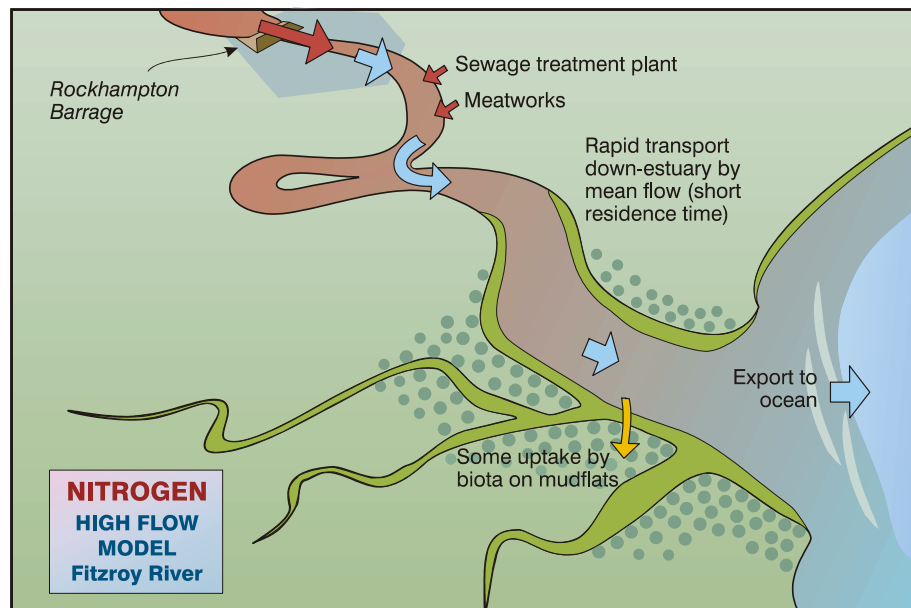


Figure 24. Conceptual model of nitrogen dynamics in the Fitzroy Estuary during high-flow events. Red arrows represent inputs, blue arrows represent internal transport, and yellow arrows represent net losses.

5.3.2 Low flow

- a) Most of the nutrients input to the estuary under low-flow conditions derive from the Rockhampton Sewage Treatment Plant and the meatworks. Their total annual input is small compared to the riverine input of nutrients, but is certain to be very important for the ecology of the estuary
- b) There is a net export of dissolved nitrogen and phosphorus species to Keppel Bay, but there may be an import of particulate species through the mouth. The export of nutrients during low-flow periods is many times smaller than that during high flows.
- c) The transport of nutrients along the estuary is dominated by tidal mixing.
- d) Nutrients are cycled between biotic and abiotic forms.

- e) Phosphorus adsorbs to suspended and benthic sediments which influences its dissolved concentrations and transport within the system.
- f) Denitrification removes nitrogen from system.

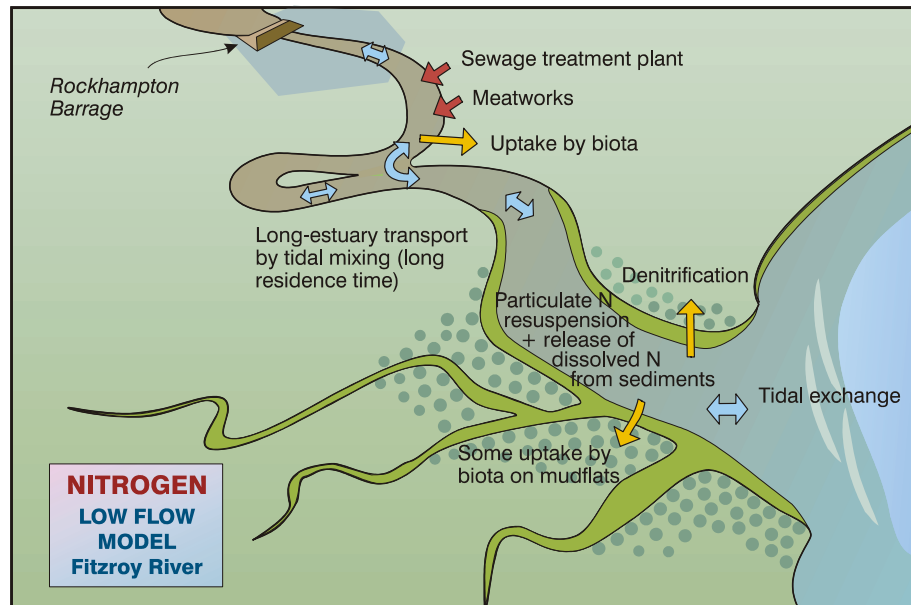


Figure 25. Conceptual model of nitrogen dynamics in the Fitzroy Estuary during low-flow periods. Red arrows represent inputs, blue arrows represent internal transport, and yellow arrows represent net losses.

5.4 Primary production

5.4.1 High flow

- a) Due to highly turbid conditions and to phytoplankton being swept down estuary and out through the mouth, primary production in the water column is likely to be negligible.
- b) Primary production by the microphytobenthos may occur on the intertidal areas along the sides of the estuary channel.

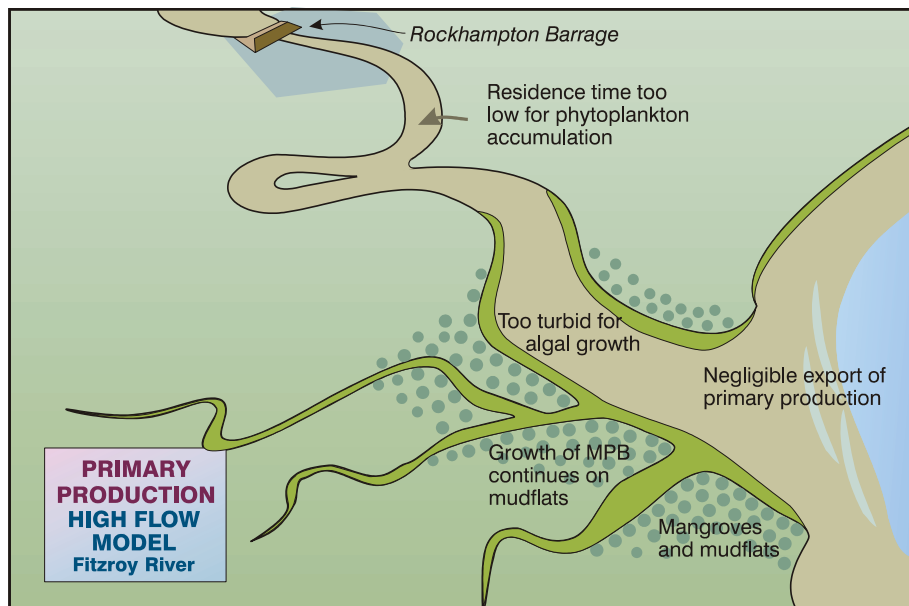


Figure 26. Conceptual model of primary production in the Fitzroy Estuary during high-flow events

5.4.2 Low flow

- a) Medium levels of phytoplankton occur in the water column in the upper part of the estuary where the water column has reduced turbidity and there is access to a ready supply of bio-available nutrients from the STP and meatworks. Variations in production are associated in turbidity changes in the water column.
- b) There is active recycling of the nutrients through the water column and sediments so that the net phytoplankton production over the low-flow period is much less than the gross production.
- c) In the lower half of the estuary, water column primary production is limited due to lack of light caused by active sediment resuspension. The lower estuary acts as a net sink for phytoplankton biomass mixed down-estuary and mixed up-estuary through the mouth from Keppel Bay.
- d) It is likely that there is considerable primary production and nutrient cycling by the microphytobenthos on the intertidal areas along the length of the estuary, but the magnitude of this production is not known.

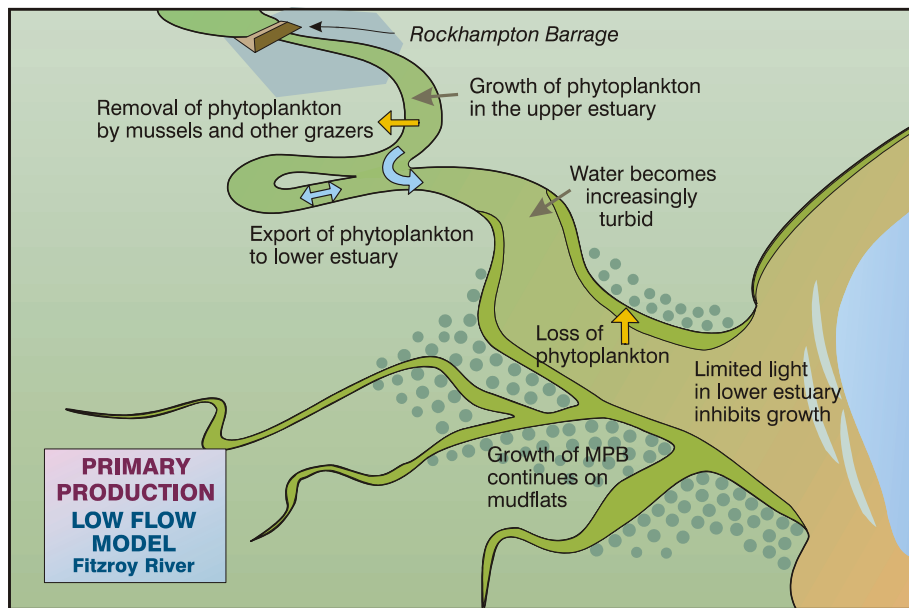


Figure 27. Conceptual model of primary production in the Fitzroy Estuary during low-flow periods.

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