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Nutrient dynamics and sediment budgets in the Fitzroy estuary during a flood event

CRC for Coastal Zone
Estuary & Waterway Management

Managing riparian lands to improve water quality: optimising nitrate removal via denitrification

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Nutrient dynamics and sediment budgets in the Fitzroy estuary during a flood event.

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Many of the drawings and illustrations in this report were prepared by Peter Verwey. The overall experimental design was conceived by Phillip Ford and he was responsible for the preparation of this report.

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Non-technical summary

1. Changes in nutrient and sediment concentrations along the Fitzroy estuary were investigated during the passage of a flood event in February 2005. The flood event was relatively small and was the last member of a group of three minor floods ending a protracted dry period. The flood came mainly from the Connor catchment with a smaller component from the Comet. The total event volume was equal to the estuary volume, but due to the vigorous tidal mixing in the lower estuary, only the upper part of the estuary remained filled with fresh water for the duration of the investigations. The salinity of the lower estuary (Thompson's Point) reached a minimum of 3 briefly and was about 12 for most of the time.

2. The average nutrient concentrations measured during the event were consistent with data on earlier events. There was considerable variation in input sediment and nutrient concentrations at the upper station during the passage of the event however. Some of this variation is attributed to the displacement of sediment-depleted waters from upstream by the incoming flood. Changes in the concentrations of the incoming dissolved nutrients were observed and are attributed to changing local inputs as well as differences between the sources in the catchment.

3. The observations show that approximately 10% of the incoming sediment load and the particle associated nutrients were removed in the 6 km long "Loop" (created when the "Cut-through" was formed in 1991). There was some evidence for production of NO_x in the lower estuary and waters in the vicinity of Buoy 1 several days after the passage of the flood. This is attributed to nitrification in the lower estuary and Keppel Bay.

4. The flows in this event did not go over bank. To provide some guidance on the likely sediment losses in larger flood events where overbank flow occurs we applied a simplified analysis to the (major) 1991 flood. This showed that about 25% of the incoming sediment load in the over bank flow would be removed in transit across the lower flood plain. This estimate depends critically on the settling rate of the fine sediments in the waters entering the flood plain. It needs to be kept in mind that only a portion of the larger flood actually goes onto the flood plain with the remainder continuing in-channel. In the idealised case considered, the calculated amount deposited was 9% of the total load, corresponding to a uniform 1.6 mm thick layer of sediment. This result agrees reasonably well with geomorphological estimates of a 1 mm yr^{-1} average deposition rate based on the flood plain core measurements.

5. The overall conclusion is that the transit of **small** flood events (i.e. those that don’t lead to overbank flows) through the estuary is accompanied by minor losses (order of 10%) of sediments through deposition in the “Loop” and small losses of dissolved nutrients. A simple analysis of large overbank events suggests that an increasing amount of particulate material is deposited on the flood plain, however, for the example chosen (1991 flood), this is only about 10% of the total sediment load. Thus estimates of loads of dissolved and particulate nutrients, and suspended solids, based on measurements made at Rockhampton, provide a realistic (±10%) assessment of the material actually delivered into Keppel Bay.

6. The intrinsic variability of the concentrations of all species across the flood event requires multiple measurements to estimate reliably the total load. There is evidence for some changes in NO_x in the immediate aftermath of the flood in the immediate offshore area.

1 Introduction

The Fitzroy Basin is major source of water, nutrients, and sediments into the southern sector of the Great Barrier Reef lagoon. There have been long standing concerns about the possible negative impacts of these substances, together with potentially deleterious effects of agricultural chemicals contained in the water. The Federal Government has recently established the NAPSWQ program aimed at reducing the potential impacts through improved land use management in the catchments. This impetus for improved land management takes place at a time of regionalization of natural resource management within Queensland, where local/regional community organizations have overall responsibility for critical decisions for landscape management. In the specific context of NAPSWQ, regional natural resource management authorities are now charged with the identification of priority areas for amelioration, for the identification and financial support of best-practice land use management to produce the greatest beneficial effect, and for the definition of targets for reduced sediment deliveries.

These tasks are especially difficult in the Fitzroy catchment, which is very large (144,000 km^2), is drained by four major river systems and has a wide range of soil types and topographies. Differing land uses, and a highly episodic and spatially non-uniform rainfall, all combine to produce considerable variations in the amounts of sediment and nutrients leaving the catchment, and delivered into the Fitzroy estuary at Rockhampton. The floodwaters are then transported via a 60 km long estuary to enter Keppel Bay. There is considerable scope for the transformation and removal of sediments and nutrients as they progress along the estuary both by biogeochemical processes within the water column, and by deposition on the flood plain through overbank flow. Recent geomorphic investigations by the Coastal CRC (Bostock *et al.* 2005) have provided good evidence for significant sediment deposition on the flood plain. Investigations (Douglas *et al.* 2005; Webster *et al.* 2005) of nutrient transformations within the estuarine water column during the dry season show that the composition of dissolved nutrients changes and there is also scope for biological uptake. Thus, the quantities of sediments and nutrients measured passing Rockhampton (the freshwater “terminus”) may not correspond closely with the amounts of material which actually enter Keppel Bay, quite apart from the subsequent landward transport of proportion of the deposited sediments from Keppel Bay into the Fitzroy delta (Margvelashvili *et al.* 2006). These issues also impinge on the interpretation of the results of sediment models such as SedNet, which treat the barrage at Rockhampton as the final node in the sediment delivery system. If the measure of effectiveness of the catchment management work is the amount of material delivered into the Great Barrier reef lagoon via Keppel Bay, then it is important that we have at least a semi-quantitative understanding of the role of the estuary in modulating flood event delivery of sediments and nutrients. It is also important to understand how the significance of these processes changes as function of the size of the flood, especially the differences between within-channel and overbank flows.

Recognising the importance of having an understanding of these issues the FBA commissioned the Coastal CRC to carry out an investigation of the changes in sediment, and nutrient concentrations on transit of a flood flow through the Fitzroy estuary. This report presents the results of this investigation. In Section 2 we characterize the flood event in February 2005 which was investigated. Section 3 provides an account of the methods and data collection, and the data is analysed and the results discussed in Section 4. Section 5 contains the synthesis of the results and the conclusions.

2 Characterisation of flood event

Much of the Fitzroy catchment has been in drought since 2003 and, consequently, flows from the catchment have been relatively infrequent and limited. Thus, on a seasonal basis the maximum daily discharge of recent episodic flood events has been relatively small, and the number of individual flood events within a season has been limited –compare the “wet” year of 1998-1999 with the “dry year” of 2004 -2005 (Figure 1).

Logistic and financial constraints limited us to sampling only one flood event. Throughout 2004, sampling was deferred as the events were quite infrequent and very small, and our strategy was to attempt to capture a big and more typical (see discussion below) event. This did not arrive. So with time running out we sampled the next event which was a small flood which arrived in Rockhampton about 30 January 2005. This event was preceded by two even smaller events in December 2004 and early January 2005 (Figure 2). While this event was the largest of the three events the interpretation of the data was somewhat complicated by the new floodwaters entering an estuary where effects of the two antecedent floods had not been totally eliminated. The total volume delivered by the three events was 920,000 Ml. This is about a quarter of the mean annual runoff (5.6 million Ml (Kelly and Wong, 1996); 4.6 million Ml (DNRM)). It is also only about three times the total estuarine volume (~250,000 Ml at mid-tide). With the flows being spread over three months and no individual flow greatly exceeding the estuarine volume, the estuary did not flush fully fresh to the sea throughout 2004-2005. The sequence of relatively small flows leads to the second and latter flows being preceded by remnant water from the first flow which has been stored upstream of the barrage. The incoming new, catchment-generated flow acts as a piston pushing this “old” water before it. There are also potential chemical differences between waters derived from the different catchments and landuses. Thus, the initial stage of the second flood event consists of water atypical of the actual flood. While stored upstream of the barrage, particles settle out and biological uptake of dissolved nutrients occurs. The volume of this stored water is about 120,000 Ml based on the volume of the barrage (60,000 Ml) and of the numerous other storages upstream (B. Packett, pers. comm.).

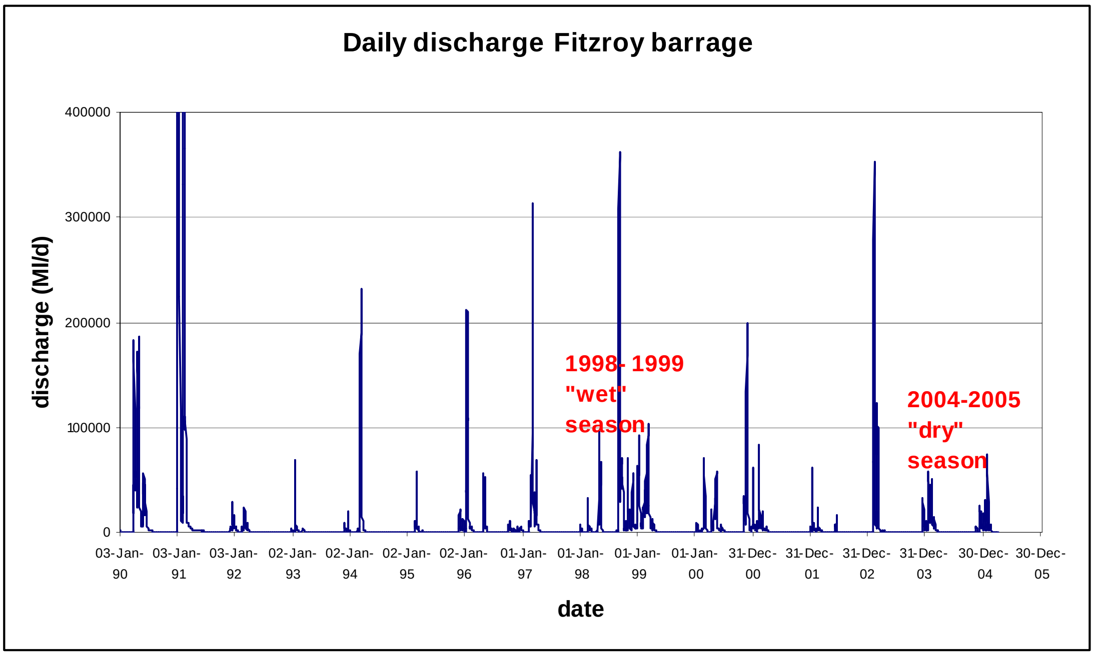

Figure 1: Daily discharge of the Fitzroy 1990 to 2005 (measured at the Gap) showing the episodic and highly seasonal character of the flows, the large inter-annual variability, and the differences in the number of individual flow events between the 1998-1999 "wet" season and the 2004-2005 "dry" season.

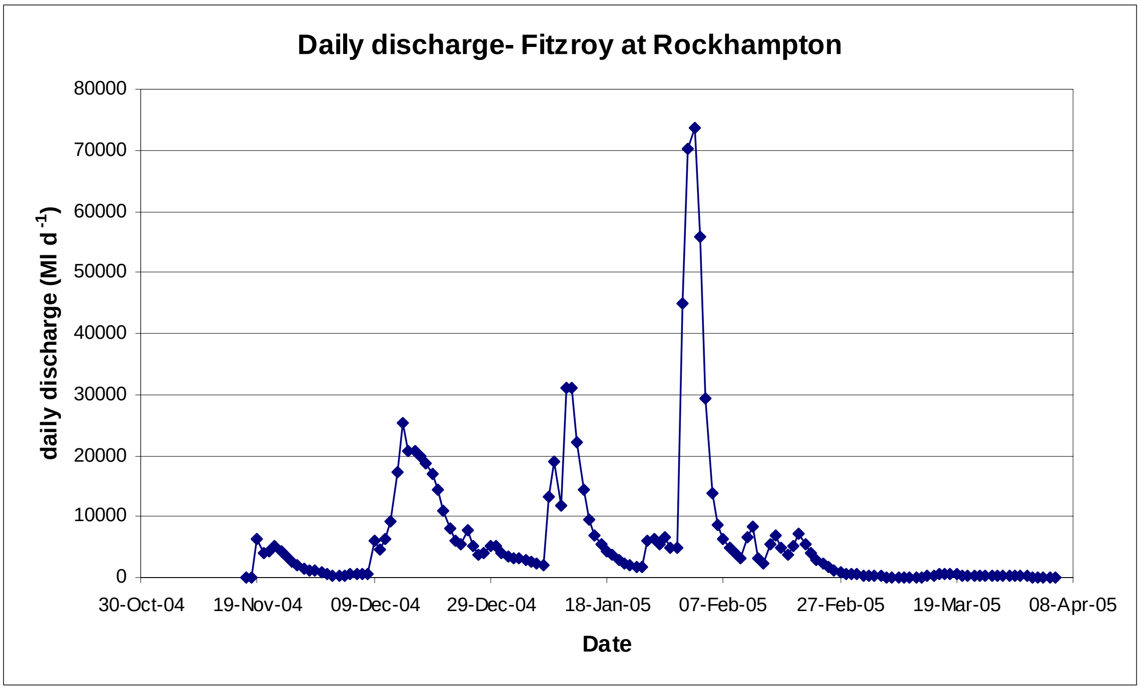

Figure 2: Daily discharge at Rockhampton showing the three flood events potentially available for sampling. (Discharge data at the Gap: DNRM; corrected for transit time from The Gap to Rockhampton (Packett, pers. comm.)).

The maximum daily discharge for the February 2005 event was 73,800 Ml d^{-1}. This is, for the Fitzroy, quite a small daily maximum discharge. It is, for instance, only about 5% of the daily maximum during the 1991 flood. The event was also quite short lived with the flow returning to less than 10,000 Ml d^{-1} within seven days. It is illuminating to compare these “dry” year flow characteristics with those of the “wet” year of 1998-1999 (Figure 3 below). This had six separate flood events spread over seven months, each having a maximum daily flow larger than 70,000 Ml, and each event persisted for longer than the February 2005 event. The volume in each event was at least one estuary volume and the total annual runoff was 7.56 million Ml, which is almost twice the annual average runoff.

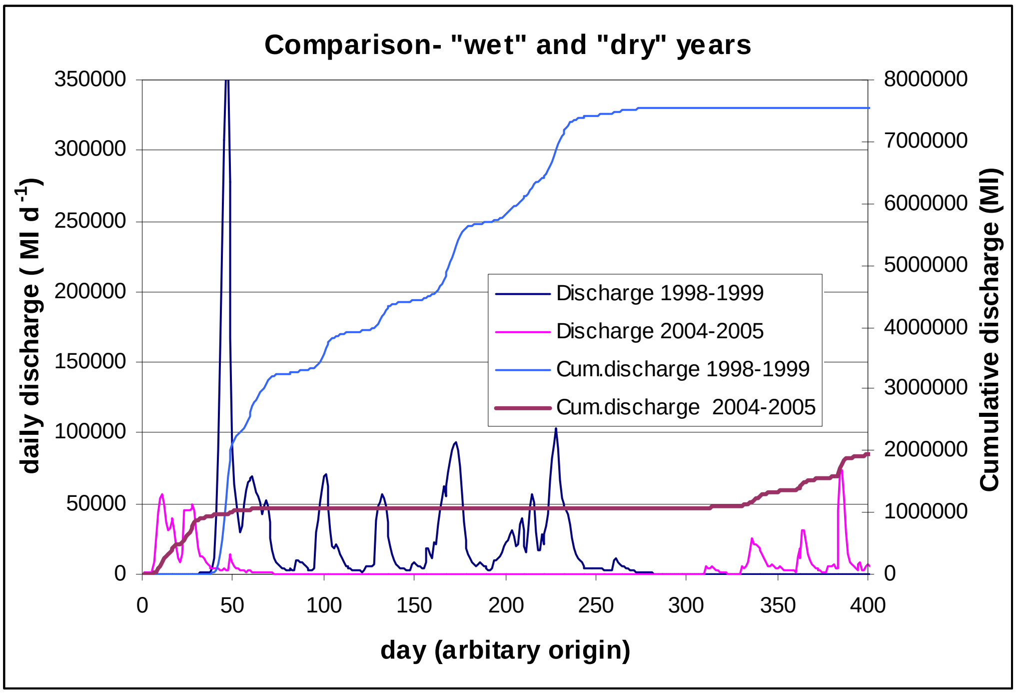

Figure 3. Daily discharges of the Fitzroy at the Gap during “wet” and “dry” year, together with the cumulative discharges for both years. Note especially the relative size of the event discharges “wet” (light blue) and the “dry” (dark red).

3 Data collection

To understand changes in the concentrations of suspended solids and dissolved nutrients, which occur in the flood event water as it passes through the estuary, it is necessary to sample the flood event at multiple locations within the estuary over the duration of the flood. Water samples were collected at two static sites: the Fitzroy Motor Boat Club (FMBC) located 5 km downstream of the barrage (55 km AMTD) starting 30 January 2005, and at Botany Point, 48 km downstream of the barrage (12 km AMTD), at daily intervals starting 31 January 2005 (Figure 4). Tidal resuspension has been shown to be a significant source of variability of Total Suspended Solids (TSS) at locations in the Fitzroy estuary (Douglas *et al.* 2005). Time of sampling relative to the local tidal phase is thus a potential confounding factor in TSS measurements and in the interpretation of such measurements. We attempted to minimize these effects at Botany Point by sampling at the same tidal phase (approximately 1 hour after the high tide), and by sampling on both the rising and falling tides at FMBC (Figure 5). While these measures reduce potential errors somewhat, interactions between the freshwater discharge and the tidal cycle lead to shifts in the timing of maximum discharge and of maximum resuspension (LeBlond, 1988) and are not simply compensated for.

Water samples (one litre) were collected, at least daily for the duration of the flood, in high-density polyethylene bottles and stored at 4^{o} C until suspended sediment concentration was measured by filtration (through 0.2 µm polysulfone filter paper and drying at 65^{o} C). Additional unfiltered samples were collected at the same time for Total Nitrogen (TN), Total Phosphorus (TP) analyses and Total Organic Carbon (TOC). Filtered (0.45 µm cellulose acetate syringe filters with GF/F glass fibre pre-filter) samples were collected simultaneously for analysis of ammonia (NH_4^+), Nitrate + Nitrite (NO_x), reactive phosphorus (FRP), and Dissolved Organic Carbon (DOC). Both suites of samples were stored frozen until analysed. An additional sample for Dissolved Silica (DSi) was collected also and stored at room temperature in the dark until analysed. Five-litre water samples were also collected for analysis of naturally occurring radio-nucleides. The suspended sediments were removed by flocculation with Polydadmac and allowed to settle overnight before siphoning off the supernatant liquid and drying the quantitatively recovered sediment.

In addition, the Queensland EPA carried out two cruises along the full length of the estuary on 2 and 3 February and measured water column physical properties (temperature, salinity, Turbidity, and Dissolved Oxygen) at specific stations established previously as part of the Coastal CRC's investigations (Douglas *et al*. 2005). Water samples for TN, TP, and NO_x (filtered) were collected at the same time and stored frozen until analysed.

As part of the Coastal CRC's Project AC wet season cruise on the *Rum Rambler*, water samples were collected at four stations in the lower Fitzroy on the morning of Monday 7 February 2005, as the tide was running out. The following day (8 February 2005) the *Rum Rambler* was moored at Buoy 1 in the mouth of the Fitzroy and water samples were collected at approximately hourly intervals throughout the day.

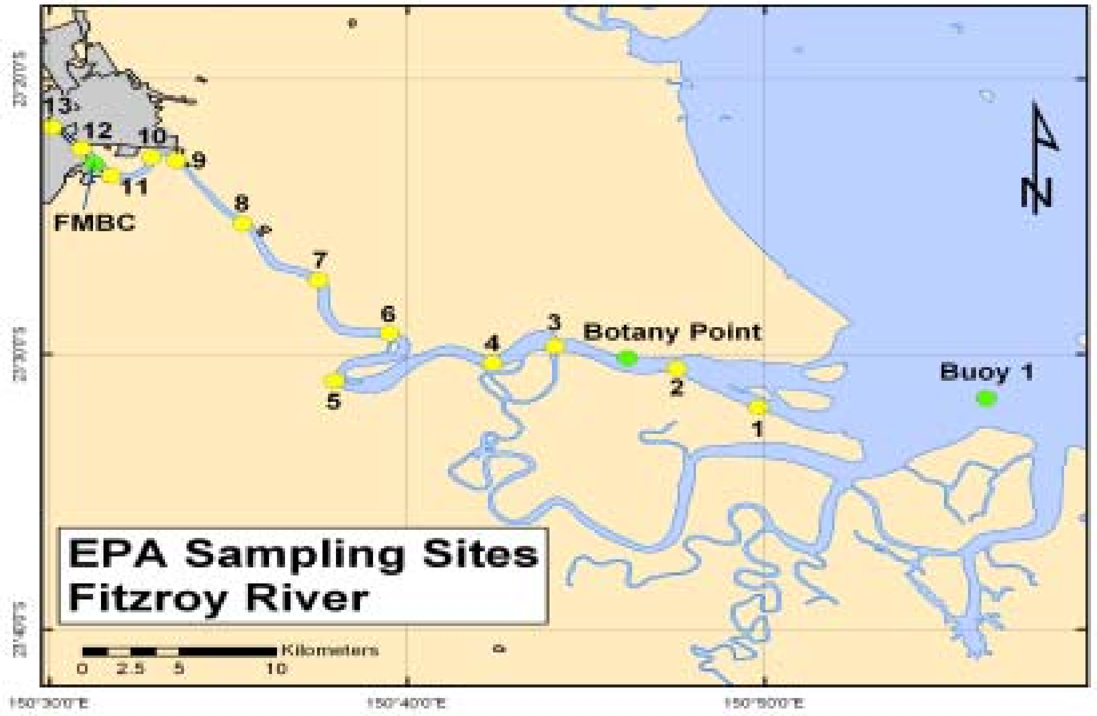

Figure 4. Fitzroy estuary showing EPA sampling sites (yellow circles) with distance scale. The FMBC sampling site is at 55 km AMTD and the Botany Point site is at 12 km AMTD. The numbers indicate EPA stations. The "Loop" station is number 5 (28.1 km AMTD).

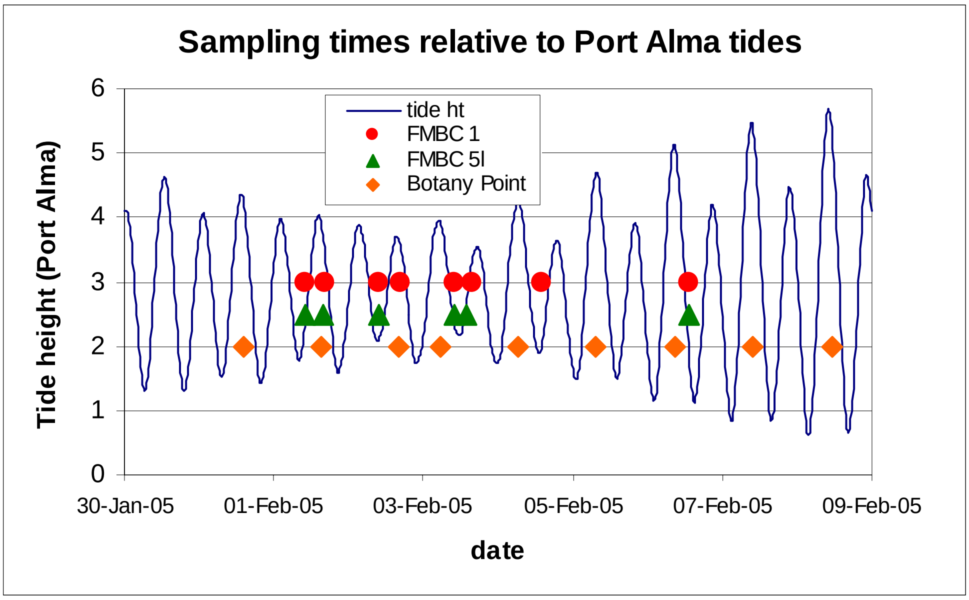

Figure 5. Sampling times at FMBC (red dots and green triangles), and at Botany Point (BP) (orange diamonds) relative to tide height at Port Alma. The tide height at Port Alma was calculated using the program wx32tide. Note that under no-discharge conditions the tidal maximum at FMBC is approximately 2.5 hours later than the maximum at Port Alma. The height of the markers as shown is purely arbitrary.

4 Results and discussion

Suspended sediment concentrations

Figure 6 shows the suspended sediment concentrations at FMBC and BP together with the daily discharge over the event. Before the flood arrives at FMBC, the TSS is relatively low (~200 mg l^{-1}) remains relatively low until approximately 120,00 Ml of water has passed over the barrage. This volume of water corresponds to volume of water from previous flood events stored upstream from which much of the particulate material has settled out already. After passage of this water the sediment concentration rapidly rises to ~1,000 mg l^{-1} as the new floodwater arrives and then slowly declines to about 200 mg l^{-1} over the next eight days. In contrast, the concentration at BP is initially low (~400 mg l^{-1}) and decreases with the arrival of the "older" floodwaters on 3 February. The salinity then is 3 indicating that there is only limited mixing with seawater, which would have a lower TSS. As the volume of the inflow up to the sampling time on 3 February at BP is ~250,000 Ml and is considerably greater than the volume of the estuary upstream of BP (133,000 Ml) than the TSS concentration there should be (assuming plug flow) ~1000 mg l^{-1}.

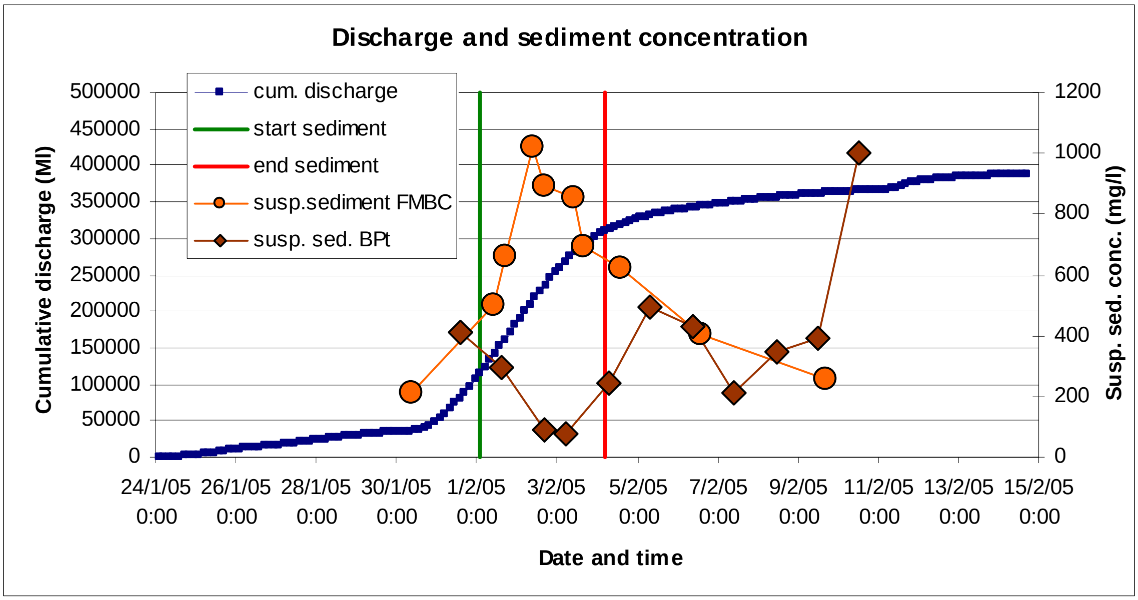

Figure 6. Daily discharge at FMBC (blue diamonds), sediment concentrations at FMBC (orange circles) and BP (brown diamonds) over the February 2005 flood event.

This is not the case suggesting that there has been extensive mixing between the "old" and "new" freshwater. The BP TSS concentration rises to a maximum of 500 mg l^{-1} on 6 February well after the maximum should have reached this site. However, the salinity of the water at BP then is 12. The Salinity at buoy 1 is 24 at this time and the TSS is estimated to be 50-100 mg l^{-1}. Mixing between the incoming sediment laden freshwater (TSS~900 mg l^{-1}) and these marine waters

(TSS~100 mg l^{-1}) will produce a TSS concentration close to what is observed. These results suggest that the assumption of plug flow within the estuary is invalid and that extensive dispersion of the high TSS concentration pulse is occurring. As long as the rate of inflow of freshwater remains high, the mixing zone is well below the lower station, and we observe high TSS concentrations and low salinity there. However, as the freshwater flow declines the zone of mixing with seawater moves upstream, the salinity rises and the TSS declines. In this particular event, the salinity at BP never fell below 3 and at this concentration flocculation of particles will be relatively rapid with higher settling velocities. Consequently some sediment deposition will be occurring and contributing to the reduction in sediment concentration. The maximum sediment concentration at BP was on 11 February well after the passage of the floodwaters. This date coincides, however, with the highest Spring tide and these results suggest that sediments recently deposited in the lower estuary during the flood have been remobilised as the tidal range increases.

Sediment Budgets

Constructing a short-term sediment budget for the estuary provides a way of examining the relative sizes of the various processes adding and removing sediment. We use the flows and measured sediment concentrations at FMBC from the start of the event, up to the end of 2 February and 3 February, to calculate the total incoming sediment load over these two time periods. The EPA longitudinal surveys on 2 and 3 February (Figure 7) are used to estimate the total amount of sediment in the estuarine water column.

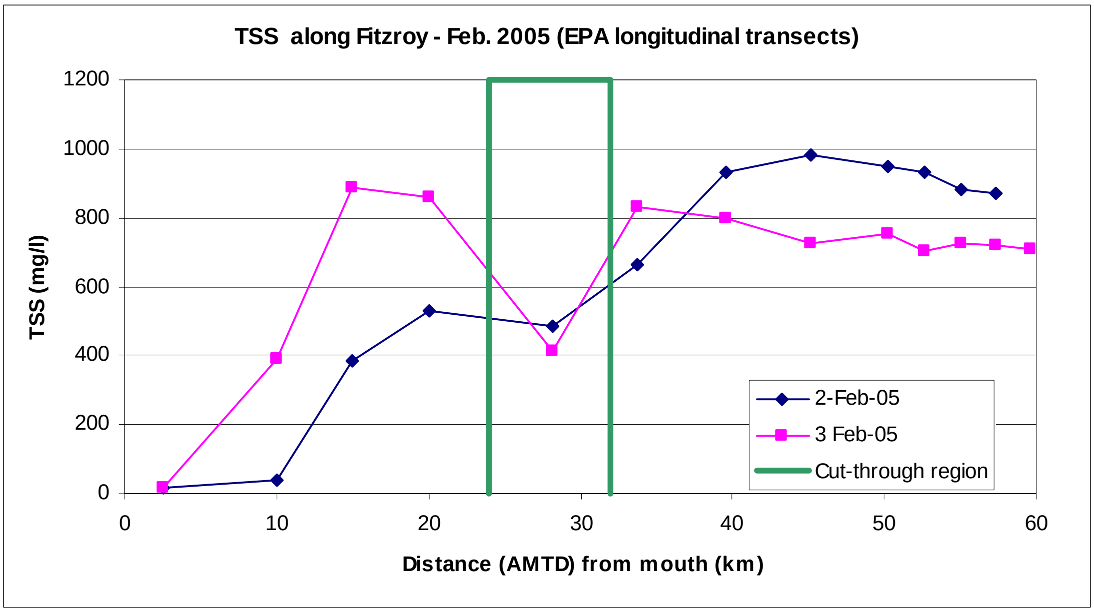

Figure 7. Sediment concentration at EPA sampling sites along the Fitzroy estuary on 2 and 3 February 2005. The outlined region indicates the "Loop" portion of the estuary.

The results (Table 1) show that for 2 February 2005 there is good agreement between the incoming load and the amount of material present in the estuary. Moreover, the lower concentrations at the seaward end (i.e. 10 km AMTD) and the higher concentrations at the landward end (i.e. 55 km AMTD) are consistent with the concentrations measured at the corresponding static sites (BP and FMBC respectively) (see Figure 6). However, the disparity between the total incoming load (30 January to 2 February), and the amount of suspended sediment in the estuary one day later on 3 February, is quite marked (the difference is about 10% of the total incoming load). The flood discharge was insufficient to completely prevent tidal exchange with waters in the ”Loop”. Loss of suspended particles here would have occurred due to the reduced velocities. There is a marked decrease in suspended sediment concentrations (Figure 7) in this region relative to the adjacent sites on both the up- and down-stream sides.

Table 1. Loads of sediment entering the Fitzroy estuary 30 January to 2 February, and 30 January to 3 February together with sediment load in the estuary based on EPA cruises on 2 and 3 February 2005.

Time span/location of load estimate	TSS load (tonnes)
Incoming load FMBC 30 Jan. – 2 Feb.	113,700
Incoming load FMBC 30 Jan. – 3 Feb	161,000
Estuary load-10 to 60 km AMTD – 2 Feb.	112,000
Estuary load-10 to 60 km AMTD – 3 Feb.	145,500

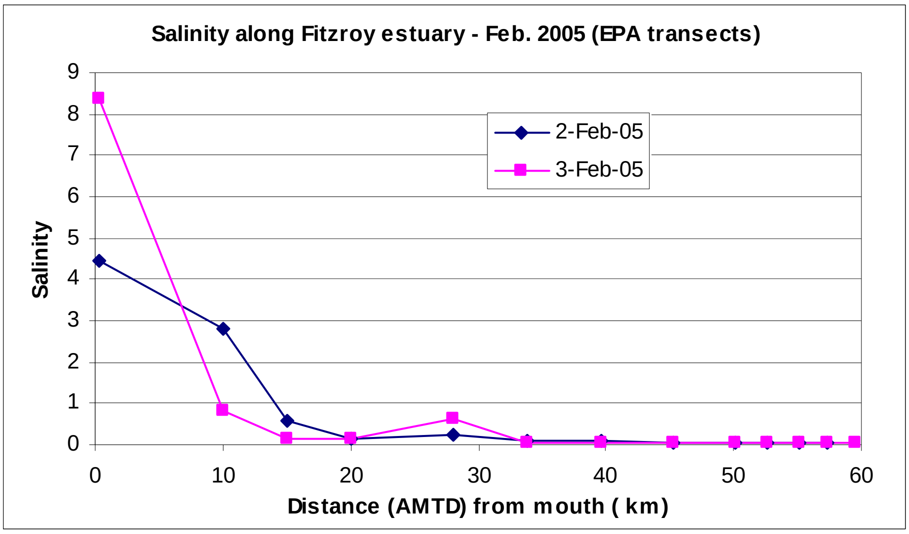

Figure 8. Salinity along the Fitzroy estuary on 2 and 3 February 2005.

The inflow of water with a lower TSS concentration, together with dispersive mixing has led to a spatially uniform decrease in the TSS concentration over the upper half of the estuary. Flow, together with dispersive mixing has moved more material downstream and the sediment concentration has increased in the lower estuary. The salinity in this region (Figure 8) has increased since the previous day indicating that the increase in sediment concentration due to the advection of sediment from upstream has been somewhat attenuated by mixing with seawater.

Subsequent evolution of the salinity at the lower station is shown in Figure 9. After an initial decrease in salinity due to the arrival of the flood peak, the salinity rises as the freshwater flow decreases, reaching a relatively constant value corresponding to about 1/3 seawater, as the tidally driven mixing of seawater upstream is balanced by the continuing inflow of freshwater and mixing with lower salinity water further upstream.

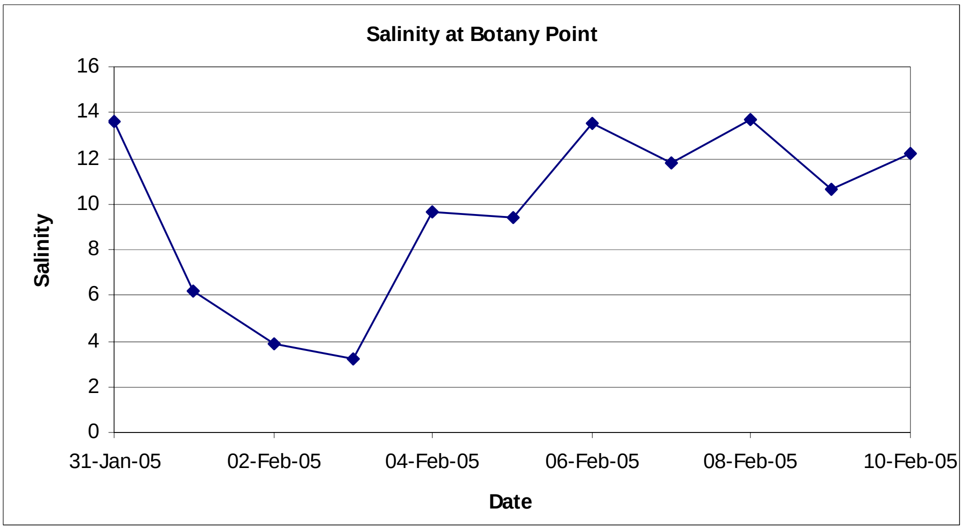

Figure 9. Salinity at Botany Point showing the decrease due to the initial floodwater inflow followed by a rough balance between further inflows and tidal mixing.

Nutrients

Both dissolved and particulate nutrients are delivered into the Fitzroy estuary by the flood event. Details of the average concentrations (standard deviation) and the proportions of the major components at FMBC and BP are set out in Table 2.

The average concentrations of both the dissolved and particulate species conform closely to the average values reported for the Fitzroy (Furnas, 2003). There are, however, quite marked changes in concentration of many of the individual species across the event. This is reflected in the relatively high standard deviations (Table 2). We consider the particulate and dissolved nutrients in subsequent sections.

Table 2. Average concentrations (µM) of the major nutrient components (standard deviation) at the FMBC and BP stations.

Parameter	FMBC	BP
Total Nitrogen (TN)	106 (19)	78.5 (20)
Particulate Nitrogen (PN)	44 (22)	26 (18)
PN/TN %	40 (16)	32 (18)
Total Phosphorus (TP)	13 (3)	9.3 (4)
Particulate Phosphorus (PP)	11 (3)	7.4 (4.4)
PP/TP %	85 (6)	73 (17)
Total Dissolved Nitrogen (TDN)	62 (15)	52.6 (22)
Dissolved Organic Nitrogen (DON)	30 (14)	30 (22)
NO_x	31 (6)	20 (6)
Ammonia	1.5 (0.3)	2.2 (1.3)
Total Dissolved Phosphorus (TDP)	1.8 (0.5)	2.0 (0.60)
Dissolved Organic Phosphorus (DOP)	0.2 (0.1)	0.4 (0.4)
Filterable Reactive Phosphorus (FRP)	1.6 (0.5)	1.6 (0.3)
Dissolved Silicon (DSi)	N/A	95 (25)

Particulate Nutrients

A convenient, and frequently made, assumption is that the nutrient content of the particles is constant and that the measured TSS concentrations can be used as a reliable predictor of particulate N and P content of the floodwaters. The data collected over this event allow us to test this assumption. The particulate phosphorus (PP) concentrations at both FMBC and at BP are well correlated ($R^2 = 0.52$ and 0.62 respectively) with the TSS concentrations at the respective sites. Particulate nitrogen concentrations (PN) at these two sites are poorly correlated with TSS suggesting either, that *in situ* transformations are changing the nitrogen content of the particles, or that there is a population of particles with different N contents, which are selectively removed.

Particulate N and P make up a significant fraction of TN and TP respectively. Thus removal of particulate material by settling in the “Loop” region as suggested above should also lead to decreases in the concentration of these two analytes in the same region. In contrast, dissolved nutrients will not be removed in the same region. The data (Figure 12) is consistent with these inferences. TN and TP both decline in the “Loop” region, but NO_x remains constant.

Dissolved nutrients

The dominant dissolved inorganic nitrogen species entering the Fitzroy just above the Fitzroy Motor Boat Club (FMBC) sampling site is NO_x. Ammonia, the only other inorganic nitrogen species, is only a small fraction (5 to 10%) of NO_x. NO_x and ammonia retain the same relative proportions but concentrations are slightly lower at Botany Point (BP) than at FMBC, suggesting that there has been mixing with low nutrient freshwaters left in the upper estuary by the last flood, together with the some nitrification (conversion of ammonia to NO_x) and removal of NO_x by bacterial consumption or denitrification. The high water turbidity rules out pelagic primary production as a sink for either NO_x or ammonia.

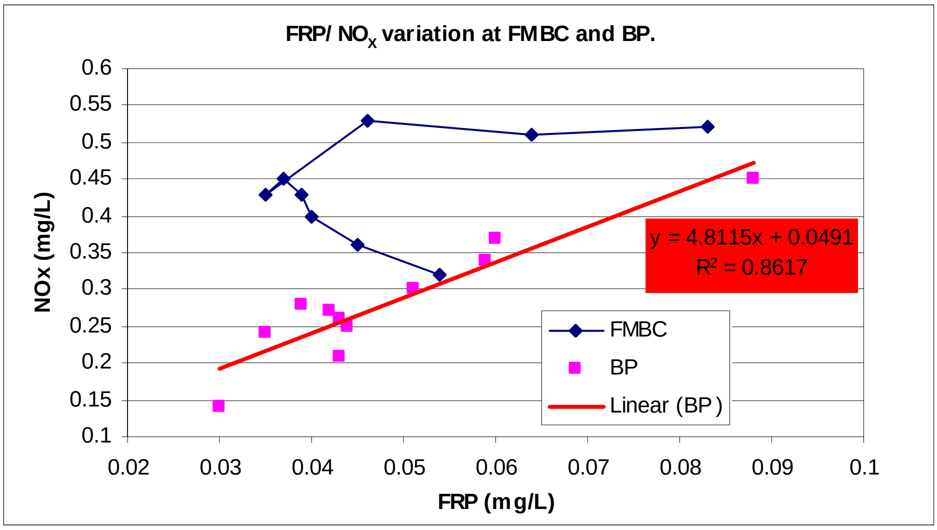

Figure 10. Covariation of FRP and NO_x at upstream (FMBC) and downstream (BP) stations.

FRP concentrations are slightly higher at FMBC than at BP. FRP and NO_x are strongly correlated (Figure 10) at BP ($R^2 = 0.86$; N=10), but poorly correlated at the upstream FMBC station ($R^2 = 0.1$). Only one of the FMBC points lies on the same line as all the BP data (Figure 10), and the NO_x curve is hysteretic with two differing values of NO_x corresponding to the same value of FRP. These results suggest that there is an intermittent source of NO_x upstream of the FMBC station. The possibilities include resuspension of oxic sediments with high pore water NO_x concentrations, stormwater inputs or, inputs from different upstream tributaries. Instream mixing, including transit through the “Loop” has mixed the different waters by the time they reach BP.

The temporal variation of concentration of NO_x at FMBC is considerably less than at BP and its general decline over time appears to “lag” the NO_x concentration change at the downstream BP site (Figure 11). There are, however, irreconcilable differences between the NO_x concentration measured on the samples from the static sampling sites (Figure 11) and the data collected on 3 February during a transit up the estuary (Figure 12). From the transect, the downstream NO_x is higher than the upstream, but the time series data shows the upstream NO_x concentration as being higher on the same day. This dichotomy may arise from the hysteretic effects noted above, as the samples were not collected at the same time in the same place in the two approaches. The differences may also reflect the different sampling times relative to the local tidal stage at the two stations and arise from tidal driven nitrification/denitrification as well as resuspension and deposition. Whatever the cause of the disparity it underlines the desirability of having some redundancy in the sampling of dissolved nutrients.

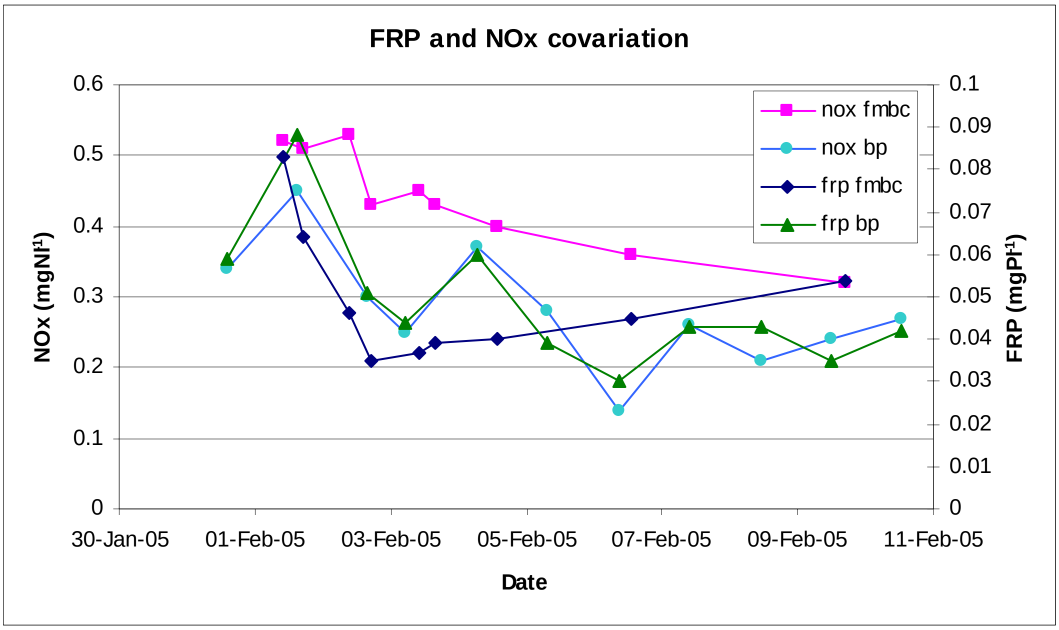

Figure 11. Temporal variation of NO_x and FRP at both FMBC (Rockhampton) and BP (Botany Point) stations.

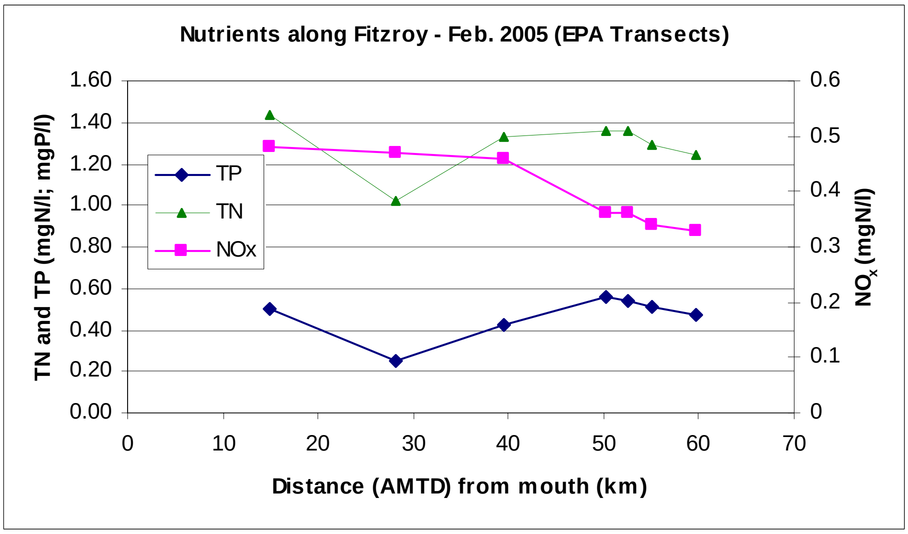

Figure 12. TP, TN, and NO_x concentrations in the Fitzroy estuary 3 February 2005. The "Loop" extends from approximately 23 to 32 km AMTD.

These problems highlight also questions of optimal sample location: to choose an upstream location where the flow is unidirectional, tidal effects are smaller, and estuarine sources and sinks are neglected, or a site as close as possible to the mouth of the estuary. Such a downstream site could, in principle, yield more realistic estimates of actual estuarine deliveries to coastal waters. However, this option requires a much more extensive sampling regiment to disentangle the tidal modulation (LeBlond, 1978) of the discharge to calculate the load.

As noted earlier, Figure 12 provides further support for removal of particulate matter in the “Loop” region with both TN and TP having their lowest concentration in this region (the distant end of the “Loop” is at 28.1 km).

The average NO_x concentration at FMBC is higher than that at BP (). This reflects, in part, the dilution of the high–NO_x freshwater by marine waters with a low concentration of NO_x (the wet season cruise which was conducted at the same time as the flood event found that the NO_x throughout Keppel Bay was below detection limits). When the NO_x concentrations at BP are extrapolated to zero salinity, then the extrapolated NO_x concentration is 0.364 mg l^{-1}, and although this is still beneath the FMBC value the difference is not statistically significant. NO_x concentrations were sampled further downstream on 7 February as part of the wet season cruise and the estuary outflow was again sampled across a tidal cycle at Buoy 1 on 8 February. NO_x concentrations at both of these sites were very strongly linearly correlated with salinity ($R^2 = 0.98$, n = 4; and $R^2 = 0.95$, n = 9). The extrapolated NO_x concentrations (0.663 mgl^{-1} and 0.546 mgl^{-1} respectively) are slightly higher than the concentrations measured 4 days earlier at BP and suggest that there has been generation of additional NO_x on passage of the floodwaters further downstream.

Dissolved Silicon concentrations at these various sites estimated by the same procedures are in very close agreement supporting the proposition that nitrification is occurring in these waters.

5 Analysis of flood plain deposition

The concentration (C) at time (t) of suspended particles in a turbulent suspension of height (H) is (Martin and Nokes, 1988):

$$C = C_0 \exp(- v^*t/H)$$

where v is the settling velocity. We apply this analysis to the 1991 flood taking the discharge to be 14,000 cumecs for 14 days with 5,000 cumecs travelling across the flood plain of area 700 km^2. Anecdotal accounts of the flow (P. Voltz, pers. comm.) indicate that the floodwaters were approximately two m deep across the flood plain. This leads to an estimated transit time of 3.2 days for each parcel of water. If we take the settling velocity of the particles to be 0.2 md^{-1} then the initial concentration of sediment, taken to be 1,500 mg l^{-1} on entry is reduced to 1,090 mg l^{-1} on exiting from the flood plain. This corresponds to a 27% reduction in concentration, but it needs to be kept in mind that only a proportion of the total discharge travels across the flood plain and experiences this loss of material. Considering the whole flood event the reduction is 10 % and the deposited sediment corresponds to a uniform layer 1.6 mm layer across the flood plain. As such a deposition event does not occur every year the long-term average deposition rate calculated for flood plain deposition by this method is somewhat below the deposition rate of 1 mm yr^{--1} inferred from the cores and adopted in the calculation of the sediment budgets (Bostock *et al.* 2005; Webster *et al.* 2006). The results of these two independent approaches are, however, sufficiently close to suggest that they are in “the right ballpark”.

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