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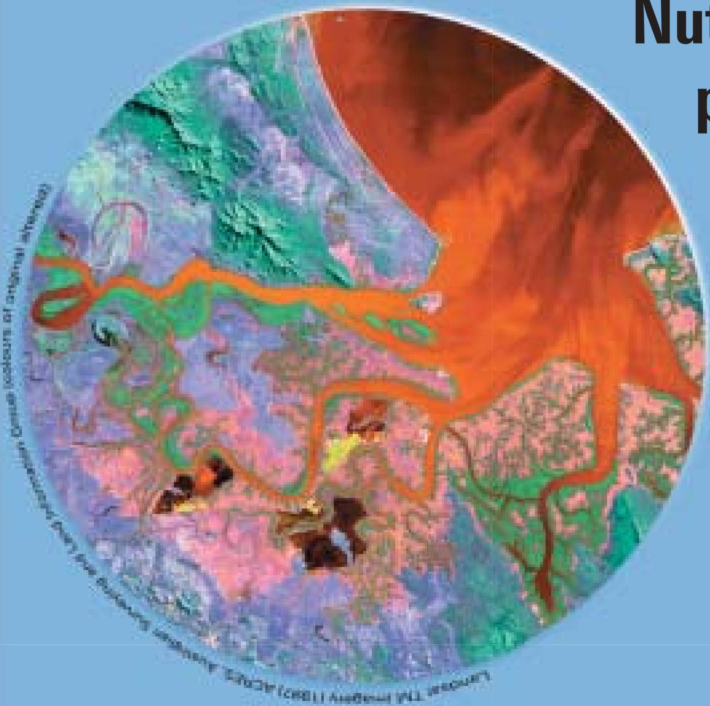

Nutrient dynamics and pelagic primary production in coastal creeks delivering into Keppel Bay

P.W. Ford
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May 2006

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

(in collaboration with Queensland EPA: A. Steven, J. Hodge, P. Thornton and J. Ferris)

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Acknowledgments

This milestone report describes work forming part of the much larger and integrated Fitzroy Agricultural Contaminants project of the Coastal CRC. All members of the modelling and biogeochemistry tasks of that project contributed to the work described here through participation in fieldwork, data analysis, preparation of diagrams, preparation of this report, or through critical reviews of the draft report. The authorship of this report reflects the team's contributions. We are very grateful to Dr David Scheltinga of the Coastal CRC scientific staff for a very careful and constructive review of the draft report which improved it considerably.

We benefited greatly from the contributions of the Queensland Environmental Protection Agency staff: Jonathon Hodge and Philip Thornton carried out two sampling surveys in Casuarina and Connor creeks including numerous acoustic Doppler current profiler (ADCP) transects. Andy Steven and John Ferris were instrumental in making available the extensive chemical datasets collected in Casuarina, Raglan and Inkerman creeks by the Queensland EPA in the 1980s which were invaluable in understanding the seasonal behaviour of these systems.

Kirrad Broadhurst (Skipper of the RV 'Rum Rambler') and his crew are thanked for their skilful seamanship and persistence in the pursuit of the last observation.

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1 Introduction

As you fly over the mouth of the Fitzroy estuary, the strongest impression is of an intricate interlaced network of coastal creeks, saltflats and mangrove stands. Four major coastal creeks (Figure 1)—Casuarina Creek, Raglan Creek, Connor Creek and Deception Creek—all discharge into the south-western corner or along the southern edge of the Keppel Bay box. At the mouth they are of comparable size to the mouth of the Fitzroy which also enters the Keppel Bay box in the same vicinity. Because of their close proximity, water, nutrients, sediment particles and organisms are all exchanged between the various creeks as well as with the Fitzroy. Given these interchanges it is realistic to think of the creek system as a whole interacting with both the Fitzroy River and Keppel Bay. Under dry season conditions, the Fitzroy estuary can be regarded as merely another (albeit large) coastal creek.

Figure 1. Major coastal creeks debouching into Keppel Bay in the vicinity of the Fitzroy estuary

To model the biophysical and geochemical behaviour within the Keppel Bay box requires a quantitative characterisation of the inputs from the coastal creeks into Keppel Bay as well as the outputs from Keppel Bay into the coastal creeks. In addition, it is necessary to have an understanding of the transformations materials undergo while temporarily resident within the coastal creeks. Work carried out during the first phase of the Coastal CRC Fitzroy project (Douglas *et* *al.*, 2005) provides a good understanding of the various biogeochemical processes occurring within the Fitzroy, and the seasonal delivery of sediments, nutrients and water through the Fitzroy to Keppel Bay.

This report describes the investigations into the coastal creek system conducted within the Fitzroy agricultural contaminants project. Before this work started there had been only a limited data acquisition on the water quality parameters in several of the coastal creeks carried out by the Queensland Environmental Protection Agency (EPA). These data are a valuable augmentation to the data collected under Coastal CRC auspices. We briefly outline the consolidated dataset, draw qualitative conclusions from it, and develop a conceptual model reflecting the interacting processes. These analyses are then the starting point for the development of a quantitative characterisation of the role of the coastal creeks in the biogeochemistry of Keppel Bay.

2 Site description

The four major coastal creeks entering the south-west corner of Keppel Bay are (proceeding clockwise around the Bay): Deception, Connor, Raglan and Casuarina creeks (Figure 1). The most eastern creek, Deception Creek, has not been investigated and is not considered further in this report. Several pairs of these creeks such as Connor and Raglan creeks, or Casuarina Creek and the Fitzroy, are interconnected. Despite this interconnection it appears, based on post-flood event salinity changes along the various creeks and post-flood satellite images, that the interchange of water between the upper reaches of the creeks and the Fitzroy estuary is limited, and water exchange occurs principally through the mouths. To a first approximation these distal interchanges may be neglected and (especially in the dry season) the creeks regarded as separate entities interconnected to each other through the south-western portion of Keppel Bay.

The creeks share some common characteristics with the Fitzroy estuary proper. These similarities are greatest during the dry season when the flow of fresh water into the Fitzroy estuary from the Fitzroy River is minimal. (We differentiate between the Fitzroy River—fresh water upstream of the barrage, and the Fitzroy estuary—ranging from fully fresh to fully marine downstream of the barrage.) The evolution of the longitudinal salinity distributions in the creeks and estuary after a major flow event is determined by the interplay of four factors: tidally driven mixing of salt water up the creeks from the mouth; evaporation which raises salt and nutrient concentrations; freshwater inflows due to local rainfall events; and dispersion which operates to reduce salinity gradients. The speed of the mixing process depends on the characteristics of the individual creeks.

The differences between the various creeks and the Fitzroy estuary are greatest during the major wet season flows which are delivered into Keppel Bay by the Fitzroy River. Because of the small catchments of the coastal creeks any freshwater flows are small, driven largely by local rainfall and of short duration. In contrast, the Fitzroy drains four major catchments and responds to rainfall in the upper catchment hundreds of kilometres away from the coastal creeks. The Fitzroy flows persist for longer and generally involve a much larger discharge.

Generally, freshwater deliveries to the coastal creeks and to the Fitzroy estuary are rarely coincident. Furthermore, because of the differences in discharge volumes the interactions between the creeks and the estuary are asymmetric. In an average wet season, the Fitzroy River delivers enough fresh water to

Keppel Bay to completely fill the estuary with freshwater and to produce a 'pool' of very low salinity water in the southern portion of Keppel Bay. Tidally driven mixing moves this low-salinity water into the creeks producing inverse estuaries with the salinity increasing up the creek. Initial results of hydrodynamic modelling confirm this effect. The creeks, however, have much smaller wet season discharges and these flows produce, at most, a freshening of the upstream portion of the coastal creek and have only very minor effects on the salinity at the mouth of the Fitzroy estuary.

While the volume of any creek is less than that of the Fitzroy estuary the combined volume of the major creeks is comparable to that of the Fitzroy estuary (Table 1) and the calculated surface area is a little smaller. In addition, compared to the Fitzroy, there are many more runners (small tidal creeks which fill and empty every tidal cycle) branching off the main creeks. While each runner is relatively small, collectively they greatly increase the volume of water contained at any moment within the creek system. Furthermore, their large intertidal surface to volume ratio greatly increases the scope for microphytobenthos (MPB) production, sediment-water exchanges, and the alternating wetting and drying phases enhance nutrient processing (especially denitrification) within the sediments. Consequently the capacity for biogeochemical processing by the creeks will be at least comparable to the Fitzroy if not substantially larger.

Table 1. Volumes and surface areas of the major coastal creeks in the Fitzroy area

Creek name	Volume (1000 m^3)	Area (m^2)
Connor Creek and tributaries	120 708	13 062 900
Kamiesh Passage	7 460	768 000
Bob's Creek	4 880	640 000
Alligator Creek	1 144	320 000
Casuarina Creek	52 040	10 030 000
Raglan Creek (to Inkerman Creek junction)	29 255	4 420 000
Raglan Creek (from Inkerman Creek junction)	24 062	3 770 000
Inkerman Creek	6 368	2 555 000
Unnamed creek (branch of Raglan Creek)	2 550	555 000
TOTAL	248 476	36 121 000
Fitzroy (for comparison)	~250 000	~40 000 000

There are quite marked differences in the morphologies of the various coastal creeks. While the Fitzroy estuary in its mid-reaches has fringing mangroves, these are lacking from Casuarina and Raglan creeks where the creeks are quite steep-sided and mangrove growth is confined to the runners. In contrast, Connor Creek has much more gently sloping sides and is lined by mangroves. The Fitzroy estuary, Casuarina and Raglan creeks are of comparable depth while Connor Creek has almost twice the average depth of the estuary. These morphological differences arise from the creeks being located in different regions which represent different stages of infilling of the Fitzroy delta (Dave Ryan, pers. comm). They are discussed in greater detail in the report from the geomorphological task of the agricultural contaminants project (Ryan *et al*., 2005).

3 Data collection

Transects were made along Casuarina Creek (August–September 2003 and 2004) and chemical and physical parameters were measured at multiple sites (Figure 2) within the creek. In addition, a 24-hour long mooring was established at the mouth of Casuarina Creek in August 2004 and the water quality parameters measured over a tidal cycle. Most of these observations were made under pronounced dry season conditions (August–September 2003 and 2004) and the nominal wet season cruise which we refer to was made immediately after a relatively very small discharge (300 000 Ml) from the Fitzroy in February 2005.

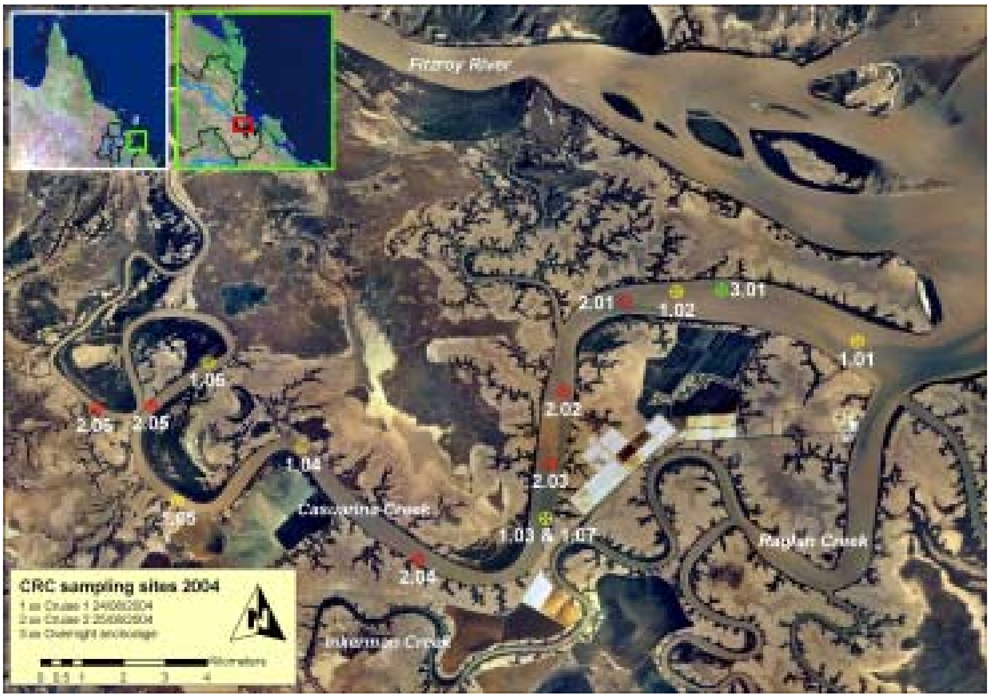

Figure 2. Location of Coastal CRC sampling sites in Casuarina Creek, together with the location of an overnight mooring near the mouth of the Creek (green marker '3.01')

Note the obvious differences in vegetation (mainly mangroves) along the Fitzroy, visible upper centre and left, and the saltflat-dominated areas surrounding Raglan, Inkerman and Casuarina creeks, and the numerous mangrove lined 'runners' crossing the saltflats

In collaboration with the Queensland EPA, we measured water quality parameters at multiple locations in single transits along Casuarina Creek and Connor Creek, on successive days in August–September 2004. The same suite of water quality parameters was collected at these sites (Figure 3) as during the Coastal CRC cruises.

In addition, the Queensland EPA had a monitoring program in the late 1980s which measured major water quality parameters monthly over an 18-month cycle at several sites in each of Casuarina Creek, Raglan Creek and Inkerman Creek (a tributary of Raglan Creek) (locations shown in Figure 3). We were generously granted access to this data which proved to be very useful in understanding the seasonal variation of salinity within the coastal creeks. Tables 2 –5 provide a consolidated overview of all the data collected for the major creeks (Casuarina, Raglan, Inkerman and Connor creeks). Note that there are some variations in the frequency of the data collected at the EPA sites from July 1988 to June 1990.

Table 2. Details of water quality data collection in Casuarina Creek

Dates of sampling	Details of data collected
EPA monthly sampling July 1988 to June 1990	Longitudinal profiles of surface salinity, dissolved oxygen (DO), temperature (T), total nitrogen (TN), total phosphorus (TP), Kjehldahl nitrogen (TKN), and dissolved nutrients (ammonia and nitrogen oxides (NO_x), Secchi depth. Sampling sites 7.01 to 7.06 located at 3, 6, 11, 14.5, 22.5 and 29 km adopted mean thread distance (AMTD) respectively (see Figure 3).
CRC cruise 1 August 2003	Longitudinal and vertical profiles of salinity, DO, T, turbidity, TN, TP, total dissolved nitrogen (TDN), and total dissolved phosphorus (TDP) and dissolved nutrients [filterable molybdate-reactive phosphorus (FRP) and NO_x], chlorophyll *a* (chl *a)*, total organic carbon (TOC) and dissolved organic carbon (DOC), total suspended solids (TSS), Secchi depth and inherent optical properties. Sampling sites 1.01 to 1.07 (see Figure 2).
CRC cruise 2 August 2004	Static overnight mooring in mouth; measured currents continuously with an upward-looking acoustic Doppler current profiler (ADCP), plus vertical profiles of nutrients etc. as above. Sampling site 3.01 (Figure 2).
CRC cruise with EPA 31 August 2004	Longitudinal and vertical profiles of salinity, DO, T, turbidity, total and dissolved nutrients, chl *a*, TOC and DOC, TSS, Secchi depth. Continuous logging of surface physical parameters plus turbidity and fluorescence. Integrated discharge at various cross-sections using on-board ADCP. Sampling sites 2.01 to 2.06 (see Figure 2).
CRC cruise 3 February 2005	Mooring overnight at station near entrance—continuous record of T, DO, S and turbidity plus ADCP profile.

Table 3. Details of water quality data collection in Raglan Creek

Date of sampling visit	Data collected
EPA monthly sampling July 1988 to June 1990	Longitudinal profiles of surface salinity, DO, T, TN, TP, total organic nitrogen (TON) and dissolved nutrients (ammonia and NO_x), Secchi depth. Sampling sites 6.01 to 6.05 located at 1, 7, 11.2, 33 and 39.5 km AMTD, respectively (see Figure 3).
CRC cruise 3 February 2005	Three stations in the mouth, profiles of physical properties, nutrients and chl *a* inclusive.

Table 4. Details of water quality data collection in Connor Creek

Date of sampling visit	Data collected
Cruise with EPA 1 September 2004	Longitudinal and vertical profiles of salinity, DO, T, turbidity, total and dissolved nutrients, chl *a*, TOC and DOC, TSS and Secchi depth. Sampling sites 5.01 to 5.09 (see Figure 3). Continuous logging of surface physical parameters plus turbidity and fluorescence. Integrated discharge at various cross-sections using on-board ADCP.

Table 5. Details of water quality data collection in Inkerman Creek

Date of sampling visit	Data collected
EPA monthly sampling July 1988 to June 1990	Longitudinal profiles of surface salinity, DO, T, TN, TP, TOC, and dissolved nutrients (ammonia and NO_x) and Secchi depth. Sampling stations 8.01 and 8.02, at 2.5 and 12 km AMTD (see Figure 3).

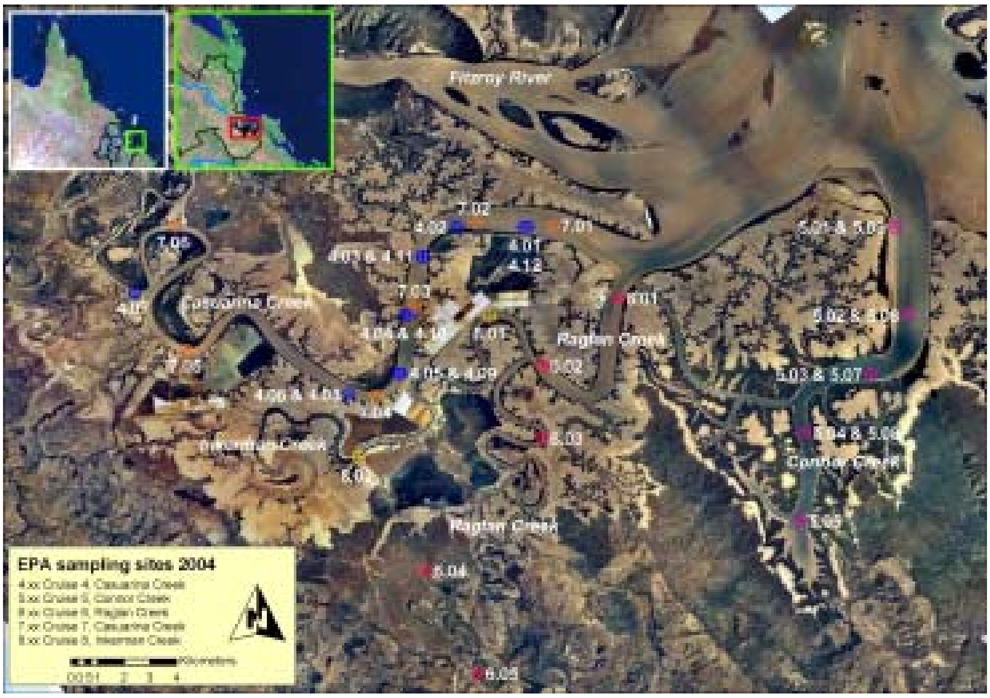

Figure 3. Location of sites in Casuarina Creek (orange markers) and Connor Creek (purple markers) sampled in 2004 where sampling was undertaken in collaboration with the Queensland EPA

In addition the sites of Queensland EPA monthly monitoring program during 1988 to 1990 are shown (blue, yellow and red markers). Note the changing proportion of saltflats to mangroves on moving from east to west.

4 Data analyses and results

The most striking aspect of the coastal creeks is the marked differences they display among themselves. We first discuss the various sets of observations of the qualitative characteristics of each creek with a view to developing an understanding of their behaviour on various time scales—from the seasonal to tidal scale. Based on this conceptualisation we go on to develop a quantitative analysis of the biogeochemical functioning where the data permits this.

4.1. Qualitative analysis: Casuarina Creek

Casuarina Creek has the most extensive dataset of all the coastal creeks. The EPA monthly observations cover a full annual cycle from July 1989 to July 1990. The two CRC cruises in August 2003 and 2004 provide a detailed view of the spatial distribution of physical and chemical properties along the creek, while the 24-hour mooring near the mouth explored the variation of physical and chemical properties over a tidal cycle.

4.1.1. Conductivity

The EPA data for 1988 to 1990 shows considerable changes in surface salinity (Figure 4) at both ends of the system, as well as changing gradients of salinity. The summer (February and March 1989) upstream variations, reflected in diminished salinity, arise from wet season inputs of freshwater.

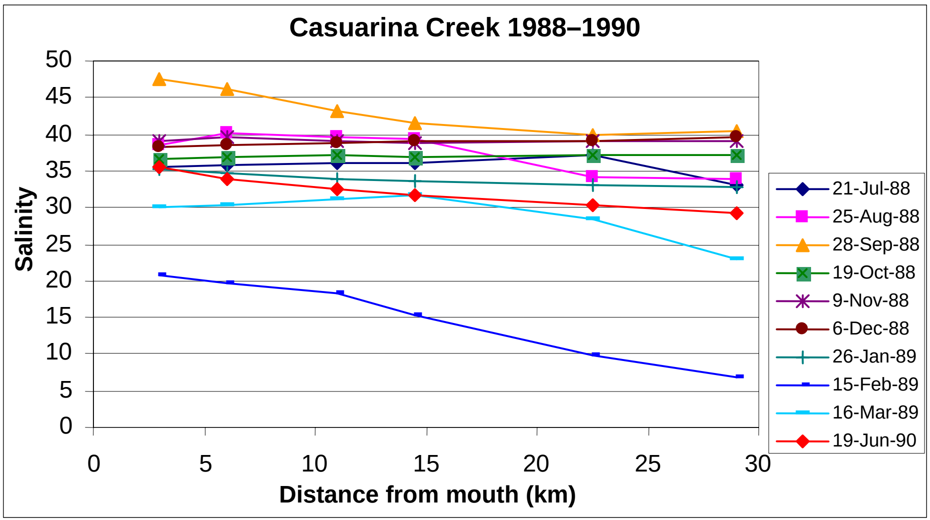

Figure 4. Salinity measured at 50 cm depth along Casuarina Creek, 1988–1990 (Data: EPA)

Water enters Casuarina Creek from both the upstream connection to the Fitzroy estuary and the mouth during a flood. These combined effects initially are seen post-flood in a reduction in salinity to about half sea water at the mouth, with the salinity decreasing moving away from the mouth of the creek. A month later (16 March 1989) the estuary is now at full seawater salinity, and the mouth is approaching this value. However, the upstream end remains substantially below full seawater salinity.

The persistence of this initial post-wet season gradient, with upstream salinity less than downstream (i.e. at the mouth), suggests that the entry of Fitzroy estuary water after elevated flood flows into Casuarina Creek through the upstream connection is now quite limited. As the dry season progresses the salinity gradient diminishes until there is no difference between the two ends. The conductivity of the distal end continues to increase due to evaporation while the seaward end tracks the salinity of Keppel Bay.

The 'final' dry season state is clearly demonstrated in the vertical profiles collected along Casuarina Creek in both 2003 and 2004 (shown in Figure 5). These show that the salinity increases from 36.8 close to the mouth to 37.8 at the site 28.4 km upstream—more than a 2% difference.

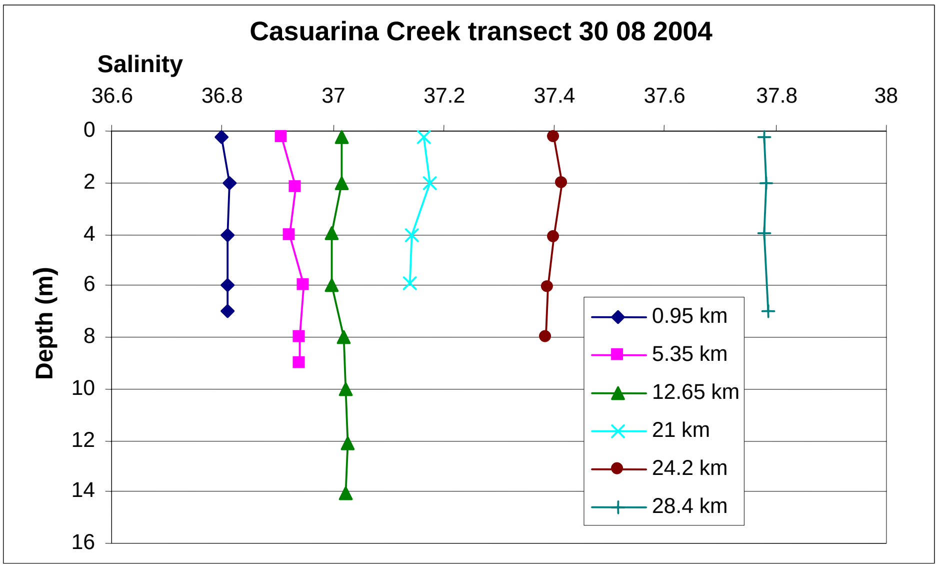

Figure 5. Vertical profiles of salinity along Casuarina Creek

Note that salinity increases upstream with distance of each profile given in legend

From Figures 4 and 5, it can be seen that the downstream–upstream measurement, that is, the salinity gradient, changes direction over an annual cycle. Note also from Figure 5 that there is only a slight vertical gradient of conductivity/salinity at any location, indicating that the creek is relatively well mixed vertically. The longitudinal gradient in salinity during the dry season arises from evaporation from the surface of the creek.

Evaporation occurs uniformly along the creek, but the water at the mouth is immediately replaced by water from Keppel Bay. Consequently, during a tidal cycle the outgoing creek water is slightly more salty than the incoming water. The upstream water can only be removed by dispersive mixing downstream. In the rain-free conditions maintained for much of the year, a steady state is reached where the loss of water by evaporation within the creek is balanced by an inflow of salt water through the mouth, while the upstream increase in salt content (due to evaporation) is balanced by a dispersive flux of salt down the creek (Smith & Atkinson, 1983).

4.1.2. Temperature

The surface water temperature shows a clear annual cycle with a minimum of 20°C in July and a maximum of 28°C in February. The mouth is slightly warmer than upstream and a very weak vertical temperature gradient exists. This gradient persisted over both the initial upstream and subsequent downstream legs of the transect and reflects the solar heating of the shallower water upstream, and not an artefact of the time/tidal differences in sampling the different locations.

4.1.3. Dissolved oxygen (DO)

There is very limited seasonal DO data but what is available from the EPA surveys suggests that DO concentration decreases going upstream. The Coastal CRC data provides a snapshot which supports this assessment. It shows (Figure 6) a vertical gradient of DO indicative of a DO sink in the bottom sediments or alternatively a surface source. A potential surface source is microphytobenthos.

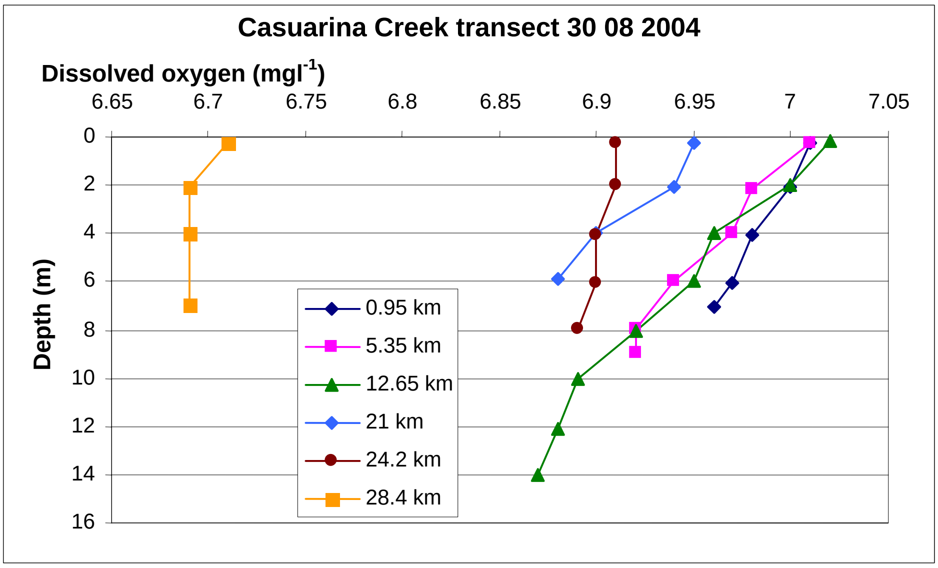

Figure 6. Dissolved oxygen concentration profiles in Casuarina Creek

4.1.4. Turbidity and suspended solids

Surface turbidity increases markedly in going upstream, from ~100 NTU to ~350 NTU at the upstream station (Figure 7), where the Secchi depth is 0.2 m. The TSS concentration parallels the turbidity, ranging from 115 mg/L at the mouth to 350 mg/L at the most distant station. There is a clear gradient of increasing turbidity with depth indicating resuspension of fine sediments from the bottom. The transect shown was undertaken on a flooding tide with the tidal velocity decreasing going upstream, suggesting that the observed turbidity gradient is real rather than an artefact of observations occurring at different stages of the tidal cycle. Repeat observations of turbidity made at the same point on both the upstream and downstream traverses were similar, reinforcing our confidence that the gradient of turbidity (and TSS) is a genuine phenomenon.

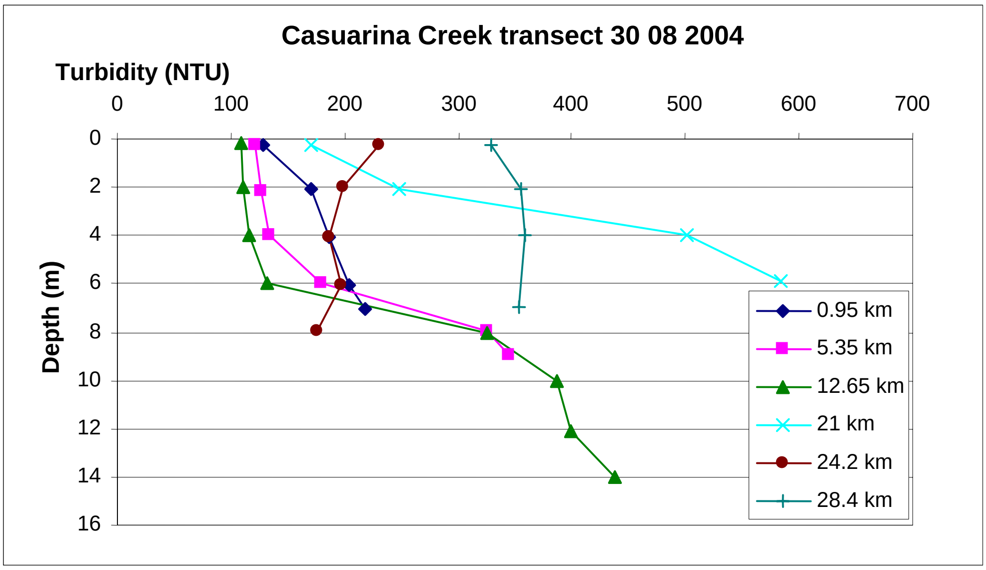

Figure 7. Vertical profiles of turbidity along Casuarina Creek

4.1.5. Total nutrients

Total nitrogen (TN) and total phosphorus (TP) in the EPA dataset both increase going upstream, with the gradient of TP being much more clear-cut than the TN gradient. This may, however, merely reflect the effect of tidal forcing and observations being made at different sites at different parts of the tidal cycle. A further confounding effect is that TN and TP reflect both particulate and dissolved components and, as we show later (Section 4.1.6), there are clear gradients in both the major dissolved species, filterable molybdate-reactive phosphorus (FRP) and nitrogen oxides (NO_x).

A more thorough approach which makes clear the existence of systematic differences (if any) between the upstream and downstream sites is to plot the difference: downstream–upstream observations of the analyte across the season. Consistently negative values indicate that the upstream value is higher than downstream value and a persistent concentration gradient exists. We apply this technique throughout this report.

In the Casuarina Creek case (Figure 8) we see that downstream–upstream NO_x has predominantly negative values throughout the year. The existence of this gradient is supported by measurements made during the 24-hour mooring. These show that NO_x (as well as TP and TN) concentrations during the inflow phase are clearly higher than during the outflow suggesting that particulate material is being pumped upstream due to the tidal asymmetry. The particulate component for both analytes is large, and DON and NO_x make up a relatively small fraction of the TN and TP. The TN:TP ratio is in the range of 4–6.

The Casuarina Creek transect, when the measurements allowed calculation of the particulate N:P, showed that this ratio was lowest at highest salinities, that is, mostly upstream. This suggests that these particles, which had been resident in the system longest, had undergone proportionately greater nitrogen mineralisation of particulate N and thus were depleted in N relative to P. The particulate organic phosphorus had also undergone mineralisation but its abundance was controlled by the particle surface area.

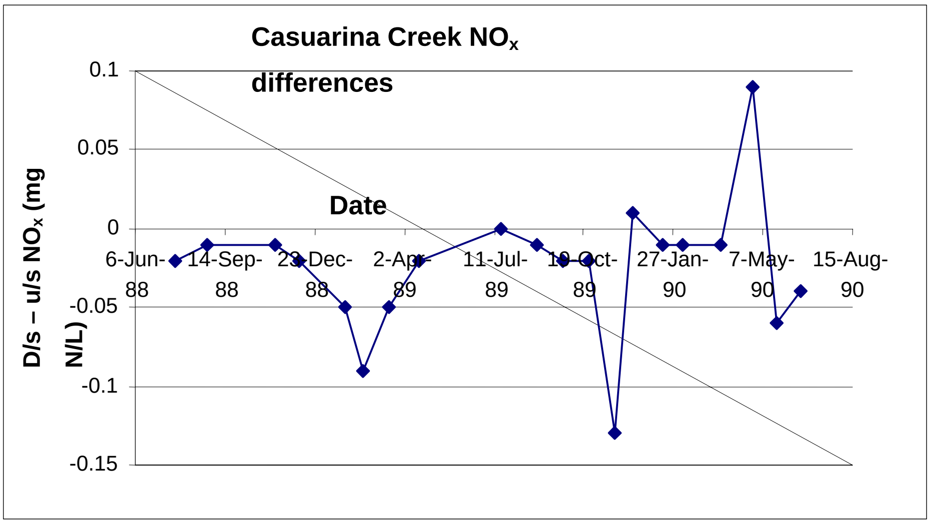

Figure 8. Downstream (d/s)/upstream (u/s) concentration differences for NO_x in Casuarina Creek, 1988–1990 (Data: EPA)

4.1.6. Dissolved nutrients

The monthly data shows that NO_x (see Figure 8) and FRP both increase on going upstream. This observation is supported by the more detailed longitudinal profiles collected by the agricultural contaminants project in August 2004 which show (Figure 9) that FRP and TDP both increase in going upstream also. Total dissolved nitrogen (TDN) seems to be constant along the length of the creek. Dissolved silica (DSi) is highest at the distal end and decreases towards the mouth (Figure 10). The variation in DOC along the length of the creek shows no such pattern and seems to oscillate about the mean (Figure 10).

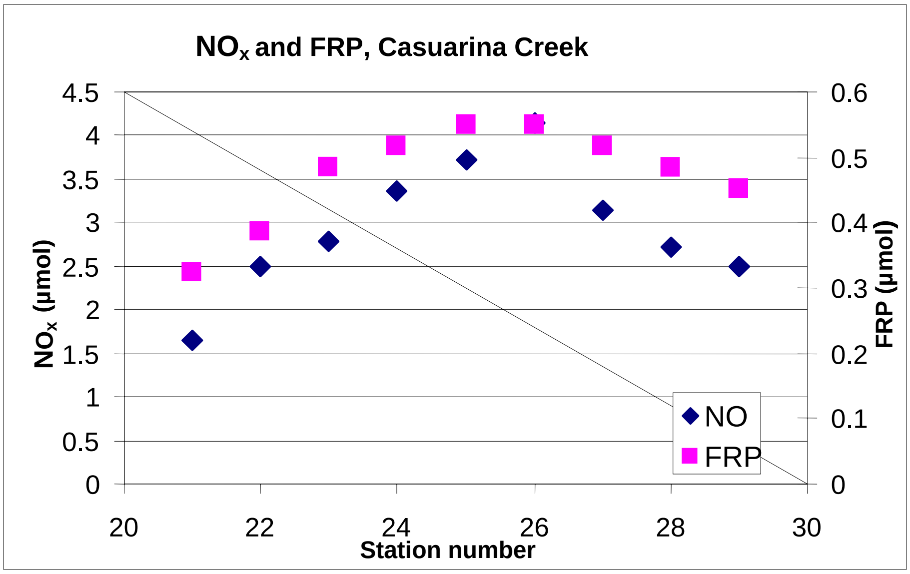

Figure 9. Spatial distribution of dissolved nutrients NO_x and FRP along Casuarina Creek

Stations 21 to 26 correspond to travel up the creek, while stations 27 to 29 are travel down the creek to the mouth.

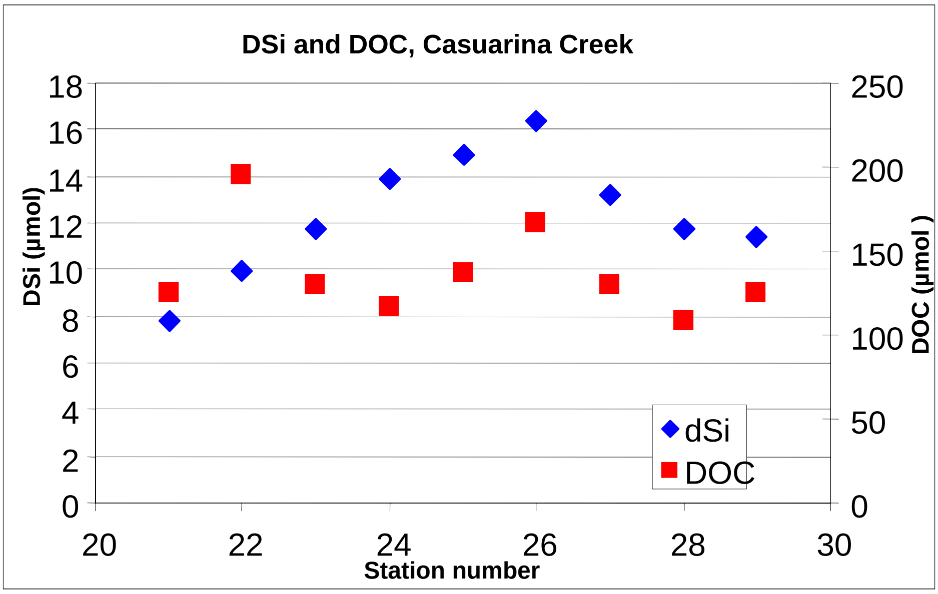

Figure 10. Spatial variation of DSi and DOC in Casuarina Creek

Stations 21 to 26 correspond to travel up the creek, while stations 27 to 29 are travel down the creek to the mouth.

4.2. Qualitative analysis: Raglan Creek and Inkerman Creek

Raglan Creek and its main tributary, Inkerman Creek, were monitored monthly by the EPA from July 1988 to June 1990. In addition, spot measurements were made in February 2005 at three locations in Raglan Creek.

4.2.1. Conductivity

Salinity distribution in Raglan Creek (Figure 11) shows considerable spatial and temporal variation with the mouth always relatively close to seawater concentration while the most upstream station varies between fresh water and about half sea water, suggesting both very limited longitudinal mixing in the upper portions and a continuous input of freshwater which varies over the seasons. The persistence of moderate salinity throughout the dry season is in marked contrast with the behaviour of Casuarina Creek (see Section 4.1) which is at least fully saline along its whole length by early summer.

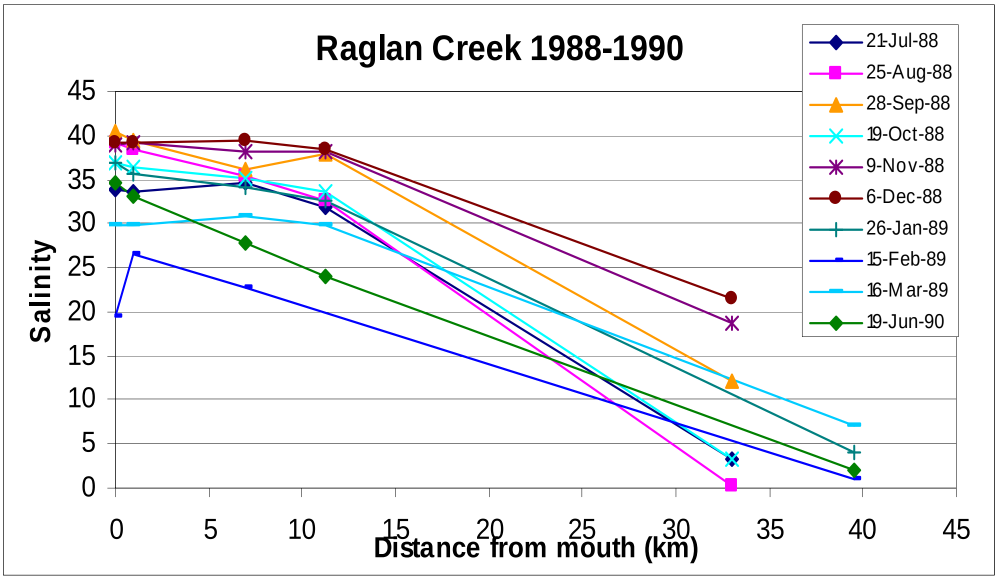

Figure 11. Longitudinal conductivity in Raglan Creek, 1988–1990 (Data: EPA)

Only two stations were monitored in Inkerman Creek. The salinity in Inkerman Creek (Figure 12) varies from three-quarters sea water to full sea water at the mouth, while the second station (11 km upstream from its junction with Raglan Creek) is generally at the same concentration or just slightly more (note especially the 6 December 1988 observation in Figure 12), indicating the formation of an inverse estuary where evaporation has proceeded faster than the replacement of the water by dispersive mixing.

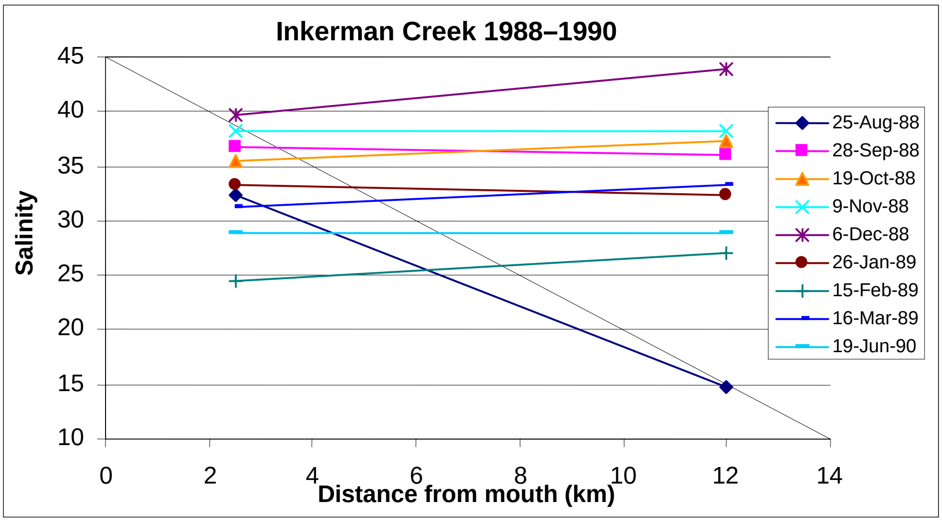

Figure 12. Longitudinal variation in conductivity in Inkerman Creek, 1988–1990

Distance is measured upstream from the junction with Raglan Creek (Data: EPA)

4.2.2. Temperature

A clear seasonal variation of surface temperature of the same size and synchronous with that noted in Casuarina Creek is observed. Vertical temperature structure is very weak.

4.2.3. Dissolved oxygen

Only one set of surface measurements are available for the whole observation period 1988–1990. Inkerman Creek was not investigated further during the CRC project. It shows a decrease in DO concentration going upstream.

4.2.4. Turbidity and suspended solids

There are only very limited measurements of these parameters. Secchi disk observations in Raglan Creek were generally in the range 0.1 to 0.6 m, suggesting relatively turbid waters with a high suspended solids load comparable to Casuarina Creek. Secchi disk depths were less in Inkerman Creek.

4.2.5. Total nutrients

Total nitrogen (TN) and total phosphorus (TP) both increase going upstream in Raglan Creek (Figure 13). With only a few exceptions, the upstream TN and TP concentrations are higher than the downstream concentrations measured on the same day. The values for the various species seem to be positively correlated. The average TN:TP ratio is 2, indicating a system which is strongly N limited. There is insufficient data to define the nutrient gradient in Inkerman Creek.

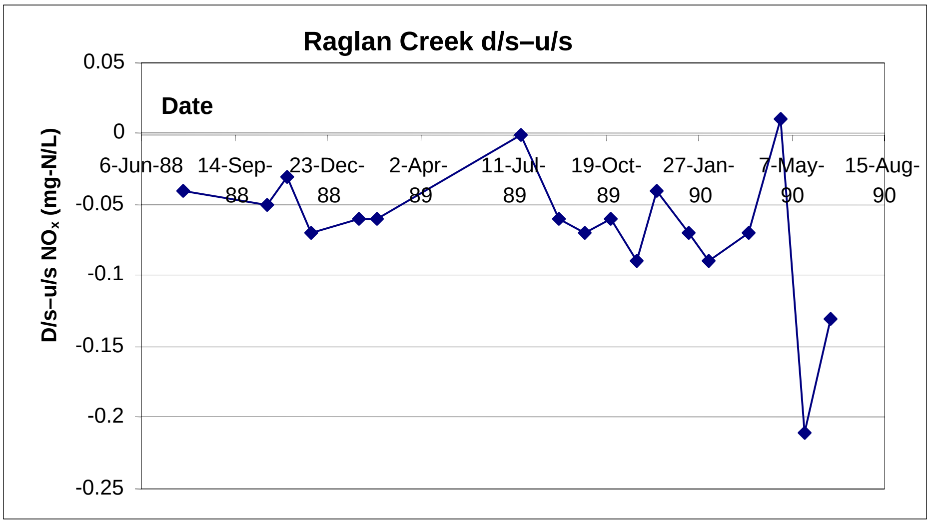

Figure 13. Concentration difference for NO_x between downstream (d/s) and upstream (u/s) stations in Raglan Creek, 1988–1990 (Data: EPA)

4.2.6. Dissolved nutrients

The downstream–upstream difference is negative except for two occasions where it is ~0. Thus NO_x concentration increases on going upstream in Raglan Creek (see Figure 13).

4.3. Qualitative analysis: Connor Creek

The available data on Connor Creek is limited to a single 1-day cruise made in the dry season in August 2004. Thus we cannot comment on the seasonal variation.

4.3.1. Conductivity

Salinity increases monotonically upstream from 36.5 near the mouth to 37.55 at 14.6 km upstream (Figure 14), with a very slight increase in salinity with depth.

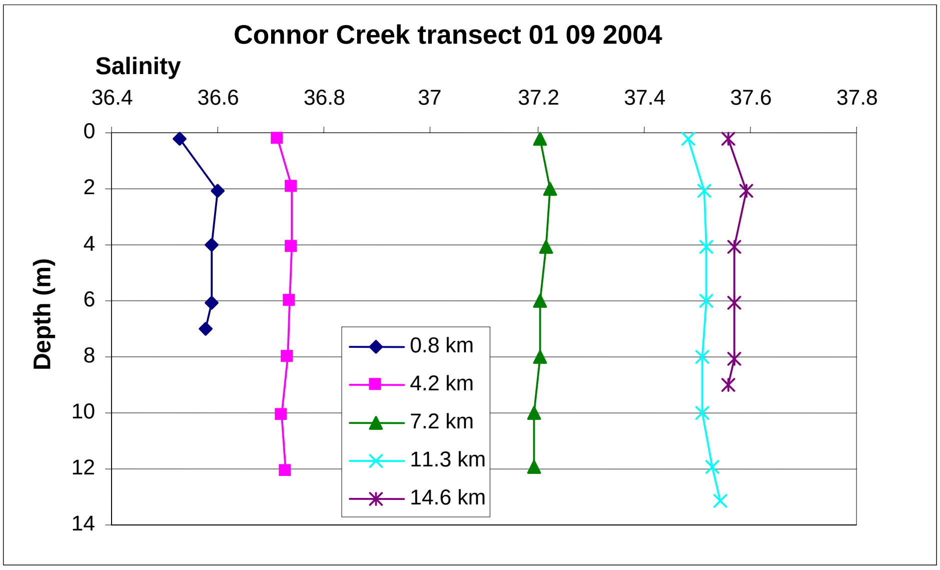

Figure 14. Longitudinal profiles of salinity in Connor Creek, 1 September 2005

4.3.2. Temperature

As with Casuarina Creek the mouth of Connor Creek is slightly warmer than further upstream and there is a very weak vertical temperature gradient.

4.3.3. Dissolved oxygen

There is a clear decrease in DO from 6.54 mg/L to 6.00 mg/l going upstream (Figure 15). A vertical gradient of DO is discernible and the DO concentrations are about 0.5 mgl^{-1} less than those measured in Casuarina Creek on the previous day.

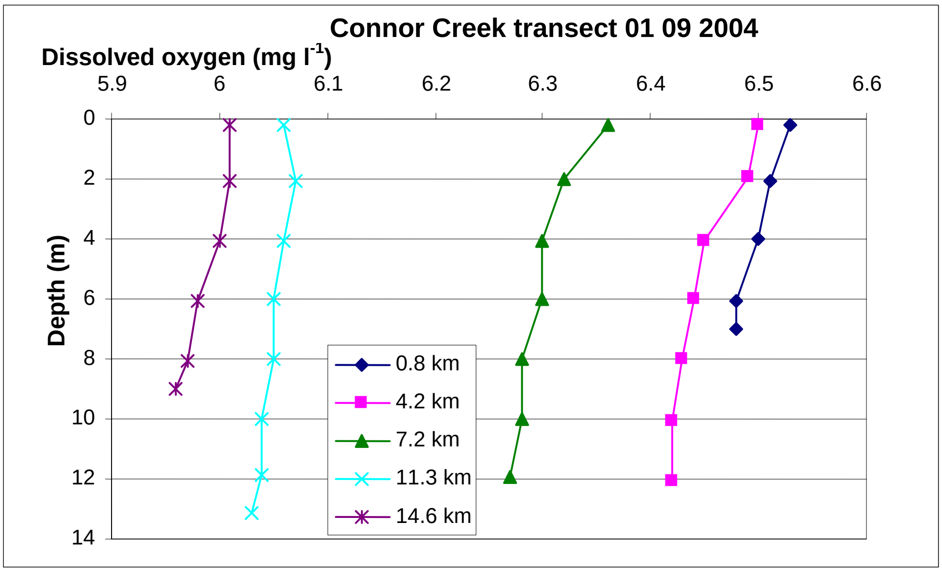

Figure 15. Longitudinal profiles of DO in Connor Creek, 1 September 2005

4.3.4. Turbidity and suspended solids

Surface turbidity declines markedly (Figure 16) in going upstream; from ~100 NTU to 13.5 NTU at the most upstream station where the Secchi depth is 0.65 m. The TSS concentration parallels the turbidity ranging from 115 mg/L at the mouth to 16 mg/L at the most distant station.

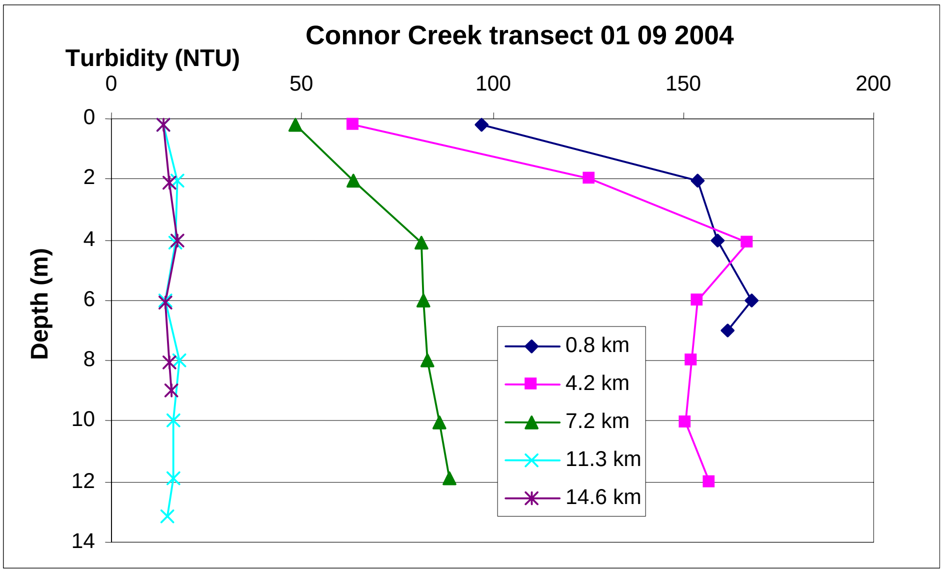

Figure 16. Longitudinal profiles of turbidity (NTU) in Connor Creek, 1 September 2005

Note that in contrast to Casuarina Creek (Figure 7) the turbidity decreases on going upstream

There is a clear gradient of turbidity with depth at the three downstream stations, while at the two upstream stations there is no vertical gradient. There was considerable flotsam, exclusively mangrove leaves, in the upper part of Connor Creek. Similar accumulations were not seen in any of the other creeks.

4.3.5. Total nutrients

Total nitrogen (TN) and TP (Figure 17) both decrease going upstream. The particulate component for both analytes is small, however, with DON and NO_x making up most of the TN and FRP being the dominant component of the TP. The TN:TP ratio is in the range of 15–20.

4.3.6. Dissolved nutrients

Oxides of nitrogen (NO_x), FRP and TDP all decrease on going upstream (Figures 17 and 18). This is the reverse of the trend seen in Casuarina Creek (see Section 4.1.6). In contrast DSi is highest at the upstream end and decreases towards the mouth.

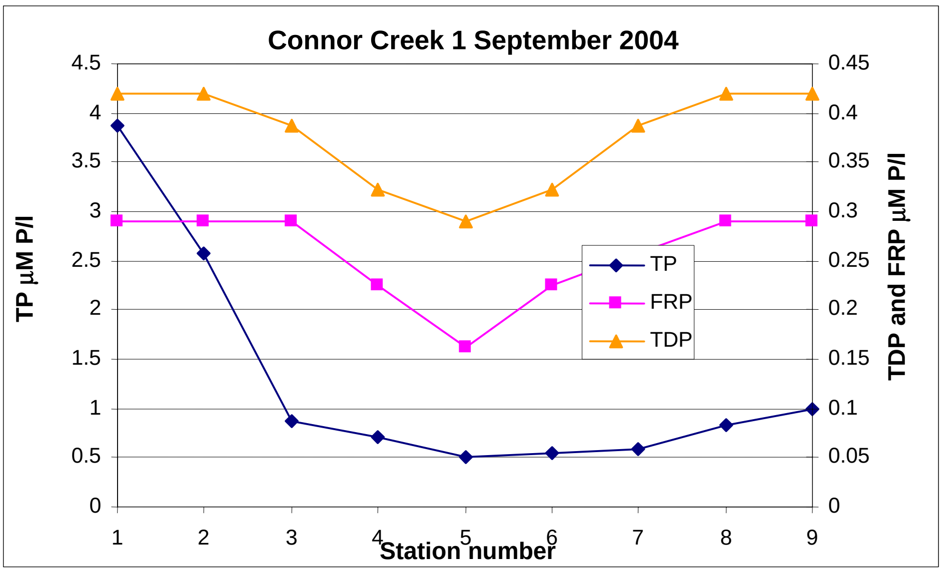

Figure 17. Spatial variation in concentration of TP, TDP and FRP in Connor Creek, September 2004

Stations 1 to 5 correspond to increasing distance up the creek, while stations 6 to 9 are for passage down the creek to the mouth

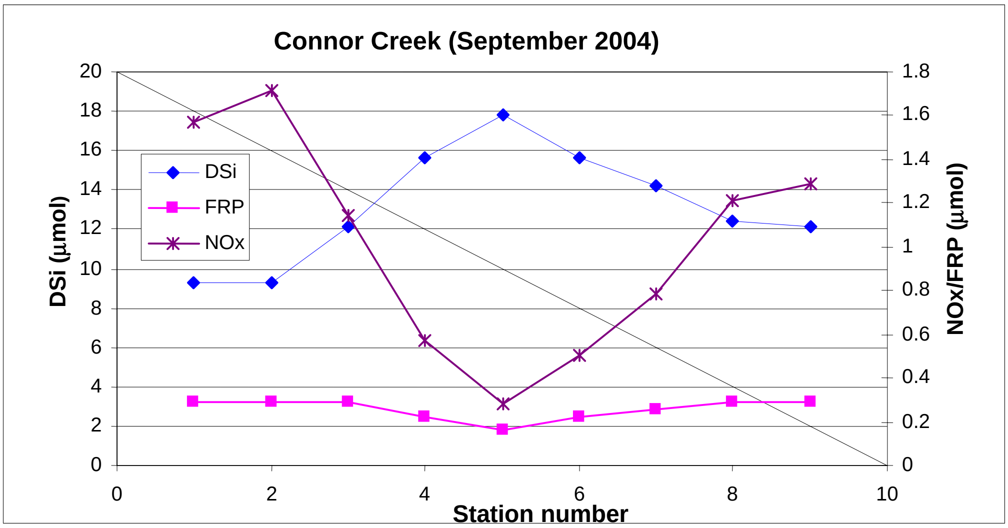

Figure 18. Spatial variation in concentration of DSi and NOx in Connor Creek, September 2004

Stations 1 to 5 correspond to increasing distance up the creek, while stations 6 to 9 are for passage down the creek to the mouth

4.4. Statistical analysis of data

While the illustrative figures showing the spatial distribution of the various nutrients within Casuarina, Connor and Raglan creeks along with the plots of downstream–upstream differences are good evidence for the claimed concentration gradients, statistical analysis adds considerable rigour to this conclusion. Fortunately, we have an extensive suite of observations in Casuarina and Raglan creeks made at well-separated upstream and downstream locations in each creek.

If there was no intrinsic difference between the sites (null hypothesis) then we would expect that there should be an equal number of occasions when the concentration difference between the sites was greater than zero or less than zero. The mean of the observations should be zero. Data of this type (numbers of positives, negatives and zeros) is termed dichotomous data and can be examined by well-established techniques (Dixon & Massey, 1957). Tables 6 and 7 show the results of such an analysis applied to the 1988–1990 data from Casuarina and Raglan creeks.

Table 6. Analysis of differences in nutrient concentration between upstream (u/s) (29 km AMTD) and downstream (d/s) (11 km AMTD) in Casuarina Creek 1988–1990

	NH4+ (mgN/L)	DON (mgN/L)	NO_x (mgN/L)	TN (mgN/L)	TP (mgP/L)
Number of negatives (d/s–u/s)	4	7	17	11	13
Number of positives (d/s–u/s)	3	8	2	9	4
Number of zeros (d/s–u/s)	13	5	1	0	3
Mean (s.d.)	-0.002 (0.008)	-0.01 (0.22)	-.024 (0.04)	-0.034 (0.25)	-0.43 (0.08)
Z (parameter)	0.378	-.258	3.44	0.447	2.18
Significance	—	—	Sig 1%	—	Sig 5%

Table 7. Analysis of differences in nutrient concentration between upstream (u/s) (11.2 km AMTD) and downstream (d/s) (1 km AMTD) in Raglan Creek 1988–1990

	NH_4^+ (mgN/L)	DON (mgN/L)	NOx (mgN/L)	TN (mgN/L)	TP (mgP/L)
Number of positives (d/s–u/s)	5	3	1	3	1
Number of negatives (d/s–u/s)	2	9	16	15	14
Number of zeros (d/s–u/s)	11	6	1	0	3
Mean (s.d.)	-0.004 (0.04)	-0.07 (0.2)	-0.07 (0.05)	-0.14 (0.2)	-0.05 (0.06)
Z (parameter)	-1.13	1.732	3.638	2.828	3.357
Significance	—	—	Sig 1%	Sig 1%	Sig 1%

The analysis in Tables 6 and 7shows that the probability of there being no significant difference between the upstream and downstream concentrations of NO_x in Casuarina Creek is less than 1 in 100, while the corresponding probability of there being no upstream/downstream difference for TP concentrations is less than 1 in 20. In Raglan Creek, the probability that there is no difference between the upstream and downstream concentrations of NO_x, TN and TP is less than 1 in 100.

We are thus justified in concluding that there are concentration gradients in NO_x and TP in both systems, with the upstream site having a higher concentration, and in Raglan Creek there is also a gradient in TN concentration. The mean concentration differences for all the nutrient species considered are negative in all cases providing further evidence of the higher concentrations upstream even if these are not statistically significant.

5 Synthesis of qualitative results and conceptualisation

The qualitative analysis of the extant physical and chemical data for the various coastal creeks has identified some common characteristics as well as some marked differences. Raglan, Inkerman and Casuarina creeks are in one group, while Connor Creek falls in a separate group with markedly different behaviour (based on the qualitative process understanding which has emerged from this work, it is probable that Deception Creek functions in a dissimilar fashion to both other groups).

The concentration of dissolved nutrients, DOC and DSi are higher in Casuarina and Raglan creeks than in areas of Keppel Bay close to the mouth of the Fitzroy River. Furthermore the concentrations of these species are higher at the upstream sites than at sample sites near the mouths of these creeks. Species such as TN, TP which have a high component of particulates, and TSS and turbidity follow the same general pattern with concentrations higher upstream than downstream. In marked contrast, in Connor Creek, both the dissolved nutrients (apart from DSi) and particulate species concentrations decrease on going upstream. Concentrations of dissolved species (FRP and NO_x) are lower in Connor Creek than in the immediately adjacent areas of Keppel Bay

In addition, the behaviour of the creeks differs from the Fitzroy estuary in significant ways arising primarily from the volume of the estuary relative to freshwater discharge, and the way episodic flood events completely fill the estuary with fresh water. In contrast, the catchments of the coastal creeks are limited to the coastal plain and, relative to the volume of each creek, are much smaller. Thus the coastal creeks are much less likely to be flushed fresh to the mouth by local rainfall events. Only in major flood events, when the Fitzroy breaks its banks and spreads across the floodplain would the coastal creeks such as Raglan, Inkerman and Casuarina creeks be filled with fresh water to the mouth. Even in these circumstances it is doubtful that Deception and Connor creeks would be filled with fresh water.

Catchment flows do, however, produce a discernible impact on Raglan Creek. It appears, from the EPA data (and Department of Natural Resources and Water gauging data), that there is a continuous inflow of fresh water at the landward end of this creek, maintaining the creek there in a fresh-to-brackish state. The implications for fish ecology are discussed later (Section 8). This demonstrates a general principle that if the creek is long enough, and the inflow of fresh water big enough (or the tidal mixing at the head of the creek is small enough), then a steady state condition of longitudinally varying salinity can be achieved. This steady state has marine conditions at the seaward end, slightly hypersaline conditions in the middle region, and fresh water at the upstream terminus. Importantly, there is free passage for motile organisms between these different environments. There will be numerous permutations of creek length and freshwater inflow which can produce this equilibrium state. The periodicity of coastal rains is the major determinant of achieving this state. Frequent rains with increases in freshwater flows will prevent equilibration. However, the prolonged dry and brief wet season characteristic of semi-arid catchments such as the Fitzroy predisposes them to reaching this dynamic steady state.

Under dry season conditions which characterised most of the observations, all estuaries displayed a slight reverse salinity gradient. This arises from evaporation. Additional sea water is then mixed in from the seaward end (in relatively small quantities) to replace the evaporated water, while salt is transferred downstream by dispersion driven by the tidal mixing processes. The system approaches a steady state where dispersive dilution balances evaporative concentration. We return to this point in the quantitative analysis (see Section 7).

The tidal action not only causes dispersion of dissolved substances but also produces resuspension of fine particles. The extent of sediment resuspension depends on the shear at the sediment–water interface. The shear is a non-linear function of the velocity and scales as the square of the velocity once the critical shear has been exceeded. Thus, the higher the velocity of the water moving in and out of the estuary, the greater the resuspension.

All tidal creeks are subject to the same tidal forcing at their mouth. Within any creek the velocity will depend on the ratio of the tidal prism to the total volume of water contained within the creek. At any measuring point the tidal out flow is ξA where ξ is the height of the tidal prism and A is the surface area upstream of the observing point. In time $T/2$ where T is the tidal period, this volume of water flows through the cross-sectional area wh, where w is the width and h the depth at the observation site. The tidal velocity is then approximately $2A\xi/(whT)$. For shallow and relatively narrow creeks such as Casuarina and Raglan creeks where ξ and h are of comparable size, the velocities will be much higher than in the much broader and deeper Connor Creek where $h > 2\xi$. Consequently, resuspension will be much greater in these shallower creeks. This is consistent with our observations; that Connor Creek has a much lower TSS and turbidity, as well as a greater fraction of the TN and TP in the dissolved phase compared to the shallower creeks.

Due to the reduced turbidity in Connor Creek, the light penetration is better, and as the ratio of tidal prism to total volume is reduced the residence time becomes longer. There is thus greater scope for pelagic primary production in the deeper coastal creeks. The chlorophyll *a* concentration in Connor Creek is approximately double that in Casuarina creek. There is also more favourable conditions for growth of attached algae on the gently sloping intertidal areas.

The only other example of extensive growth of attached algae seen was at the mouth of Raglan creek where the bank has a gentle slope also. Thus, due to phytoplankton uptake, Connor Creek acts as a sink for NO_x and FRP, converting the dissolved nutrients into pelagic primary production. Some of this material is exported by tidal action while a proportion of the enhanced primary production settles generating a considerable oxygen demand, hence the lower DO in Connor Creek compared to the other creeks, as well as providing a substrate for denitrification further consuming NO_x.

Despite the better light climate in Connor Creek, the much greater water depth ensures that much of the deeper areas are out of the euphotic zone. Sediment diagenesis produces dissolved inorganic nitrogen (DIN), principally NO_x and DSi, and while some of the DIN is taken up in the pelagic the calmer conditions do not keep heavier diatoms in the euphotic zone. Thus much of the DSi is exported into Keppel Bay. In the shallower and much more turbid creeks the reduced light and shorter residence time lead to much lower primary productivity. This production is concentrated in the microphytobenthos (MPB) in the intertidal area as this is the zone which is least subject to the light constraints. Without the pelagic phytoplankton nutrient draw-down, these creeks act as sources of dissolved nutrients. The light-limited MPB growth cannot remove all the DSi which is thus exported to the sea where the light conditions are more favourable for its uptake.

5.1. Cautionary remark

In this report we have concentrated on what we may infer about the biogeochemical functioning and the interplay between physical and biological processes of the coastal creeks from a dataset which is temporally and spatially limited. The observations of concentration changes are all made on the scale of the major creeks. The ‘coastal creek system’ really consists of the saltflats, the numerous small creeks which discharge into the major creeks and the creeks themselves. What we have is a study of total system behaviour, not of the individual elements.

The reader should be aware that there are some major areas of ignorance in our understanding of how the various components interact and integrate. We lack any detailed understanding of the episodic inputs to/outputs from, and biogeochemical transformations occurring on saltflats which are inundated only periodically. The biogeochemical functioning of the mangrove ‘runners’ is another significant knowledge gap. Here the extent of inundation and water exchange with the major coastal creek, and the character and extent of the biogeochemical processing, depends on the highly variable tidal cycle.

6 Conceptual synthesis

Combining all these qualitative inferences leads to separate and distinct conceptual models for the various creeks. These are presented below.

6.1. Connor Creek

Connor Creek has a relatively deep marine embayment with a longer water residence time and a better light climate than do the other coastal creeks. Pelagic primary production is highest here, and there are attached algae in the gently sloping intertidal zone. Connor Creek acts as a sink for dissolved nutrients DIN and FRP and as a source of DSi to Keppel Bay. Tidal resuspension is weak and limited to the mouth area. There is close coupling between the extensive fringing mangroves and the water body. There is considerable scope for denitrification to occur and this is likely to be an N limited system.

6.2. Casuarina Creek

This creek is a shorter and more uniform version of the Fitzroy estuary in the dry season. Fresh water entering Casuarina Creek during floods is rapidly displaced post-flood. Strong tidal resuspension in this relatively shallow creek leads to a high TSS and very poor light climate. Pelagic primary production is very tightly constrained and MPB is also limited due to the small area on the steeply sloping banks and the frequent resuspension. The asymmetric tides pump particulate nutrient material upstream where it is mineralised and DIN, FRP and DSi are exported into Keppel Bay.

6.3. Raglan and Inkerman creeks

Although Inkerman Creek is a tributary of Raglan Creek it has its own characteristics which differentiate it from its parent. It has a relatively short length and terminates in saltflats. Freshwater inputs are thus quite limited and it is marine to hypersaline for its full length. The available nutrient data is insufficient to define its biogeochemical function. By analogy with Casuarina Creek it is likely to be a sink for particulates and a source for dissolved nutrients. Primary production will be limited to intertidal MPB.

Raglan Creek, because of its length and the apparent continuing input of fresh water from the upper coastal catchment, has the strongest salinity gradient of all the creeks. It is marine at the mouth except immediately post-flood, the intermediate region is moderately hypersaline, and the upper reaches brackish to fresh. The lower reaches are highly turbid and have low pelagic primary production. Apart from the mouth where the bank slopes are gentle and attached algae grow, the bank slopes are relatively steep and there are only limited intertidal areas for MPB. There are strong gradients of TN, TP and NO_x decreasing downstream, suggesting that the creek is a source of dissolved nutrients derived from particulate matter pumped in through the mouth of the estuary.

7 Quantitative analysis

As noted in the discussion of the experimental results, for much of the dry season Casuarina, Raglan and Connor creeks all have increasing salinities moving upstream. In our conceptual model we attribute this to evaporative losses from the creeks. These losses are balanced by the inflow of sea water of lower salinity from Keppel Bay. The higher salt concentration upstream is dissipated downstream by tidally driven dispersion.

If we assume that the system has achieved steady state (and the close similarities of the monthly longitudinal salinity observations over several months (see Figures 4, 11 and 12) offer reassurance on this point and we examine this assumption further in the Appendix), then we can apply the analysis of Smith and Atkinson (1983) to calculate the fluxes of dissolved nutrients into/out of the various coastal creeks. Briefly the method requires that the system be at steady state with upstream evaporative salt concentration balanced by downstream dispersion. Then the source/sink strength (B_Y) of a non-conserved species Y is given by:

$$B_Y = E * (S_0 * dY/dS - Y_0) \qquad \text{(Eqn 1)}$$

where:

E is the net water loss/gain (i.e. evaporation minus rainfall, and groundwater inputs—we set these two components to zero in this analysis);

S_0 is the salinity at the seaward boundary of the system;

Y_0 is the concentration of the non-conserved species at the seaward boundary; and

dY/dS is the concentration gradient of species Y with respect to the salinity.

The flux B_Y is the sum of all processes affecting the concentration of Y, excluding advection and mixing with ocean water. Note that by using the concentration gradient with respect to salinity (dY/dS) rather than the spatial gradient (dY/dz, where z is distance along the creek), this analysis obviates the need to take account of displacement effects due to making measurements at different stages of the tidal cycle.

As first stage of the application of this analysis we have replotted the longitudinal concentration for data for Casuarina and Connor creeks (Figures 19–22) against salinity. Note especially that the directions of the gradients for DIN and DIP (but not DSi) are of opposite sign for Casuarina and Connor creeks.

In addition, we have applied the same analysis to the nutrient concentration and salinity data from the 24-hour mooring at the mouth of Casuarina Creek. This is essentially of the same character as the longitudinal profiles of salinity and concentration. The only difference in this case is that the boat is stationary, with the water moving past it, while in the longitudinal profiles the boat is moving relative to both the water and to the bank.

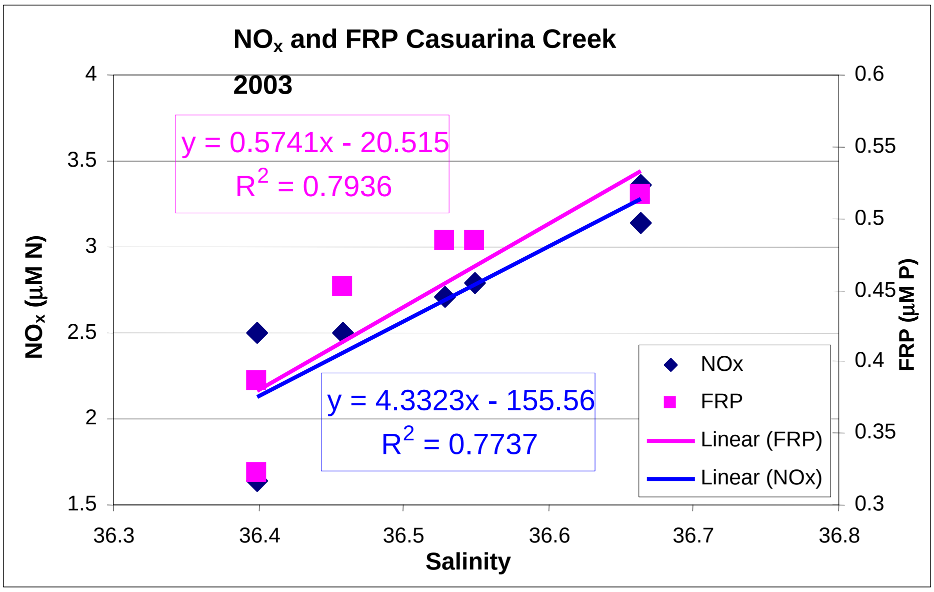

Figure 19. NO_x and FRP as functions of salinity in Casuarina Creek, August 2003

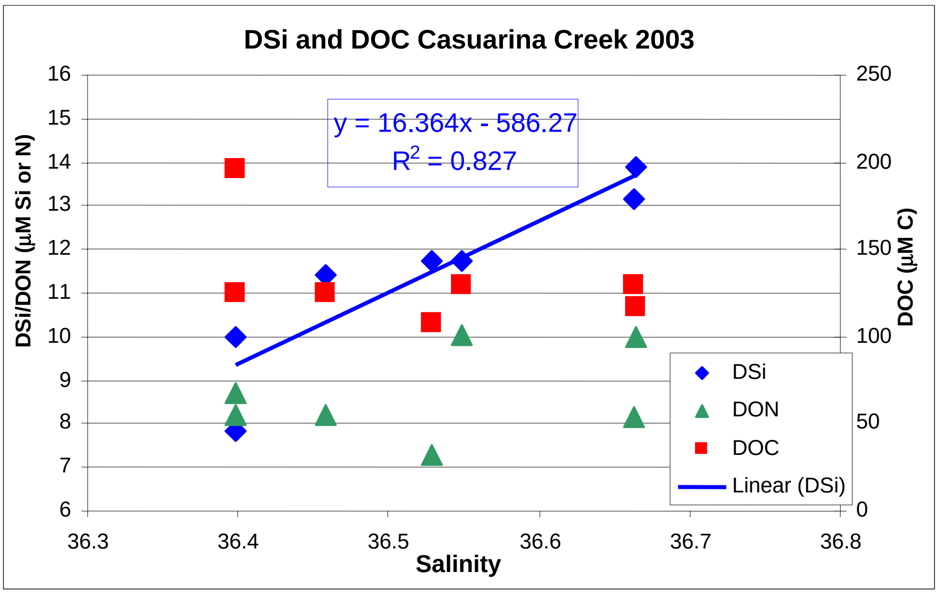

Figure 20. Dissolved silica, DOC and DON as functions of salinity in Casuarina Creek, August 2003

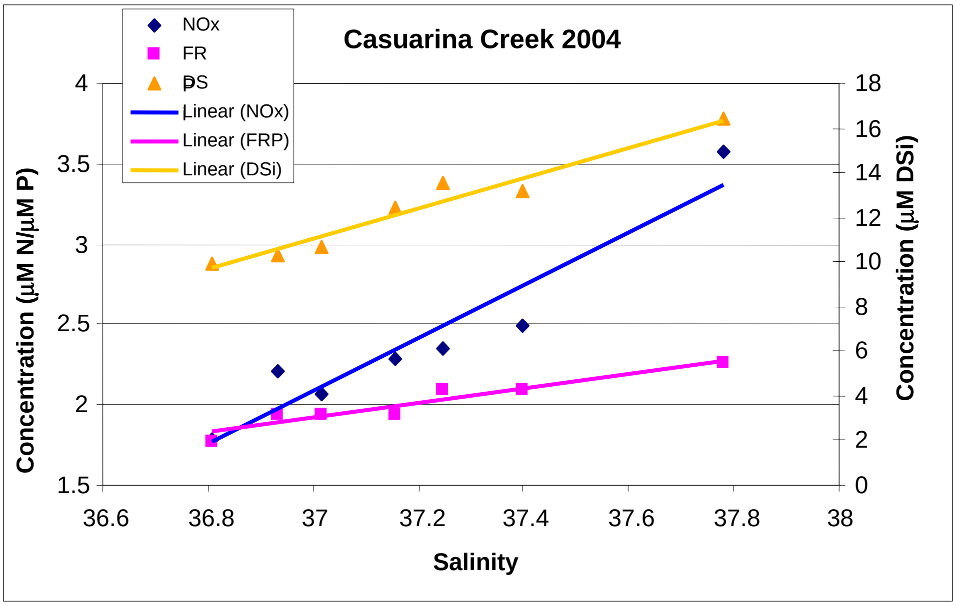

Figure 21. Dissolved silica, NO_x and FRP in Casuarina Creek, August 2004

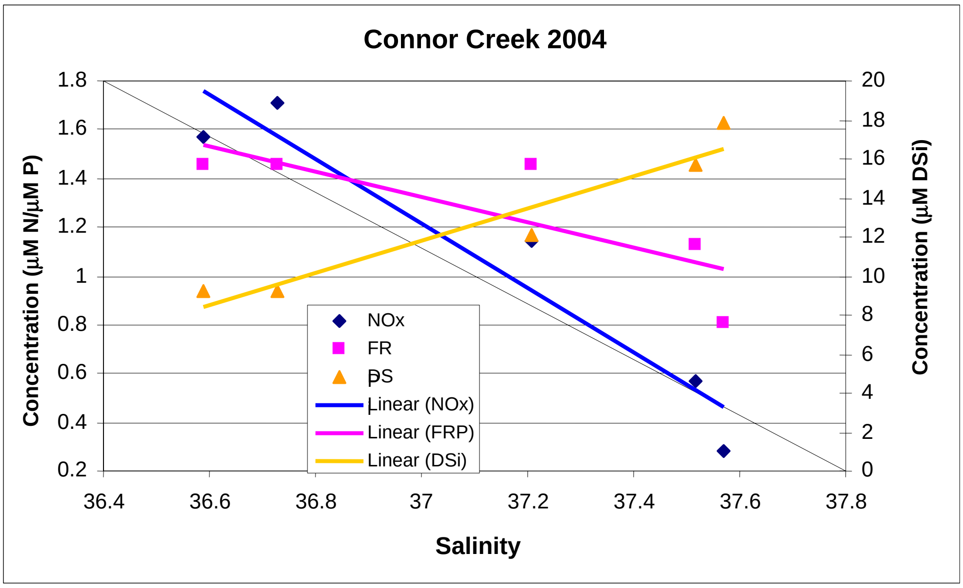

Figure 22. Dissolved nutrient concentrations as functions of salinity in Connor Creek, EPA cruise August 2004

Note that FRP concentration has been multiplied by 5 to make gradient discernible and that gradients for NO_x and FRP are opposite to those in Casuarina Creek (Figures 19 and 20).

Using Equation 1 and the best fit lines for the various nutrient species shown in Figures 19–21, we have calculated the net fluxes of different species into Keppel Bay together with the annual loads based on a 300-day dry season. The results are shown in Table 8. The largest contributor to the uncertainty in these calculations is the evaporation rate which leads to a relative error of approximately ± 10%. In addition DO concentration in both systems shows a clear decrease on going upstream. The gradient is approximately linear with salinity and we have applied the same technique to calculate the net flux of DO into the system. This is also shown in Table 8.

Table 8. Calculated fluxes and loads (based on a 300-day dry season) of dissolved nutrients into Keppel Bay from Casuarina and Connor creeks. Note that a negative sign indicates a flux from Keppel Bay into the coastal creek

Creek	Species			
	DSi	NOx	FRP	DO
Casuarina				
Flux (mM m^{-2} d^{-1})	1.58	0.37	0.02	-0.73
Load (kgMole)	4770	1132	61	-2180
Connor				
Flux (mM m^{-2} d^{-1})	1.86	-0.32	-0.03	-2.55
Load (kgMole)	7300	-1241	-98	-7700

The results of the quantitative approach are consistent with the fluxes inferred from the longitudinal concentration profiles for the dissolved nutrients. While both creeks are sources inputs of DSi to Keppel Bay, Casuarina and Connor creeks function in different ways. The areal fluxes are comparable for the two systems but of different sign and the overall effect is that they partially cancel each other out. The other two creeks (Inkerman and Raglan) have similar characteristics to Casuarina Creek and the overall effect of the complex of coastal creeks is to be a source of nutrients to Keppel Bay. Other species such as DOC (see Figures 19 and 20) do not show any systematic variation with salinity within the creeks which leads to the conclusion that their net rate of transformation within the creeks is slow on the time scale of exchange between the Creek and Keppel Bay proper.

It is noteworthy that the atomic ratios of the DIN and FRP fluxes are not far removed from Redfield ratio. In Connor Creek the DIN:FRP ratio is 18.5 and suggests that that the nutrient uptake is consistent with phytoplankton production. Analogously, the dissolved nutrient ratio in Casuarina Creek (11) is consistent with the breakdown of phytoplankton.

8 Possible ecological significance of the Fitzroy estuary coastal creeks

The complex of coastal creeks in the vicinity of the Fitzroy mouth is somewhat unusual in the juxtaposition of a number of large creeks to a macrotidal estuary which has very large flows relative to the combined volume of the main stem of the estuary and the coastal creeks. As the preliminary results of the hydrodynamic modelling and the qualitative analysis of the EPA data show, fresh water is pushed into the mouths of coastal creeks at times of major flood flow.

The salinity declines markedly and the lower reaches of the creeks become brackish-to-fresh with the distance of penetration of the brackish water, determined by the hydrodynamics of the particular creek and the meteorological and tidal conditions. This effect will persist longer than the less than full seawater salinity conditions at the mouth because of the finite exchange time between the creeks and Keppel Bay proper. The creeks thus provide an environment for species, especially the larval and juvenile forms, attuned to less than full salinity. The apparent unique character of Raglan Creek, where an especially wide range of salinities exists over the whole seasonal cycle, makes the conservation of this creek especially important.

The coastal creeks are also subject to freshwater inflows from rainfall in their relatively small catchments. This has the effect of flushing the coastal creeks from the distal end and changing what is, after the prolonged dry season, a hypersaline environment to a brackish or fully fresh environment. This again provides a more hospitable environment for salt-sensitive species. The changes in salinity at the mouth and distal ends of each creek are driven by different processes and do not necessarily coincide.

9 References

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Appendix 1 Validity of steady state approximation and the relative magnitude of errors

The flux of nutrients to and from the coastal creeks reported in Section 7 was calculated using the method of Smith and Atkinson (1983) developed originally for hypersaline environments. A key assumption in this approach is that the system is in steady state and consequently (using the nomenclature adopted in the main body of this report):

$$dM_Y/dt = 0$$

where M_Y is the mass of material Y in the coastal creek upstream of the measurement cross-section.

In this appendix we examine the validity of this assumption and estimate the relative size of the error introduced compared to measurement uncertainties. The starting point of the Smith and Atkinson analysis is to relate the rate of change in total amount of dissolved material in the calculation volume to the different contributions due to advection, diffusion, and to the net flux caused by non-conservative processes.

This may be written as:

$$dM_Y/dt = \text{Advection} + \text{Diffusion} + \text{Flux}^* \, A \qquad \text{(Eqn A1)}$$

where A is the surface area. This expression may be re-arranged to give

$$\text{Flux} = (dM_Y/dt - \text{Advection} - \text{Diffusion})/A \qquad \text{(Eqn A2)}$$

The advective and diffusive components are then expressed algebraically using the water and salt balances for the coastal creek, that is, where the non-conservative terms are zero. After substituting into Equation A2 we get the appropriate form of the Smith and Atkinson equation. Thus dM_Y/dt represents the correction for differences between the full equation and the steady state approximation.

Using the EPA data we can estimate dM_Y/dt for NO_x from the monthly observations and compare it with the flux calculated from the Smith and Atkinson formulation. The results are shown in Table 9. If the two terms are markedly different in size with $dM_Y/dt \ll$ (Advection + Diffusion), then the correction is minor and the assumption is valid. This condition is satisfied for four of the five cases examined indicating that the approximation is valid. The exception is for Casuarina creek 26 January 1989 to 16 February 1989. Examination of the salinity profiles for the two dates shows marked changes in salinity indicating a freshwater inflow and is clearly a case where the assumed steady state does not occur.

Table 9. Comparison of advection + diffusion and mass change (dM_Y/dt) terms for Casuarina and Raglan creeks (Units are kg Nd^{-1}; data: EPA)

Dates	Advection + diffusion term	dM_Y/dt	dM_Y/dt as % of advection + diffusion
Casuarina Creek			
21 July 1988 to 25 August 1988	-5.9	-0.07	1.25
9 November 1988 to 6 December 1988	-1.02	-.025	2.5
26 January 1989 to 15 February 1989	-.15	-.104	71
Raglan Creek			
19 October 1988 to 9 November 1988	-43.6	0.1	0.2
6 December 1988 to 26 January 1989	-31.4	0	0

Glossary

ADCP	Acoustic Doppler current profiler
DIN	Dissolved inorganic nitrogen
DO	Dissolved oxygen
DON	Dissolved organic nitrogen
DOP	Dissolved organic phosphorus
DON	Dissolved organic nitrogen
FRP	Filterable reactive phosphorus
MPB	Microphytobenthos
NO	Oxides of nitrogen
TDN	Total dissolved nitrogen
TDP	Total dissolved phosphorus
TKN	Total Kjehldahl nitrogen