Flood plumes in the GBR The Burdekin and Fitzroy flood plumes, 2007/08 Case studies for Marine Monitoring Program



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1. Introduction

1.1. Review of riverine plumes in the Great Barrier Reef

A review of flood plumes in the GBR was published in 2001 (Devlin et al., 2001) and reported on the 8 flood plumes sampled from 1991 to 2001. The main conclusions of this review were

- The main driving influence on plume dispersal is the direction and strength of wind and discharge volume of the river.
- Wind conditions are dominated by south easterly winds which drive the plume north and towards the coast with the majority of plumes being restricted to a shallow nearshore northward band by stronger south-easterly winds following the cyclones or wind events.
- It is possible and probable when light offshore winds are occurring, that the plumes can disperse seaward and north over much of the shelf with (as yet) unknown lengths of direct impingement upon mid and outer-shelf reefs.
- The amount of rainfall that falls over a particular catchment can have a marked effect on the distribution of the plume. Another factor in the distribution of flood plumes is the influence of headlands on the movement of the plumes (steering).
- Modeling of the plumes associated with specific weather conditions has demonstrated that inshore reefal areas adjacent to the Wet Tropics catchment (between Townsville and Cooktown) regularly experience extreme conditions associated with plumes. Inshore areas (north of the Burdekin and Fitzroy Rivers) receive riverine waters on a less frequent basis.
- Data from flood plumes clearly indicate that the composition of plumes is strongly dependent on particular events, between days and through a single event, depths and catchment. Timing of sampling is critical in obtaining reliable estimates of material exported in the flood plumes. There is a hysteresis in the development of a flood plume, which is related to catchment characteristics (size, vegetation cover and gradient) rainfall intensity, duration and distribution and flow volume and duration. The time lag difference is significant in the smaller Wet Tropic rivers (Herbert to Daintree) compared to the larger Dry Tropic rivers of the Burdekin and Fitzroy.

- Mixing profiles demonstrate initial high concentrations of all water quality parameters in low salinity waters, with decreasing concentrations over the mixing zone. Mixing patterns for each water quality parameter are variable over catchment and cyclonic event, though there are similar mixing profiles for specific nutrient species. Processes occurring in addition to mixing can include, the biological uptake by phytoplankton and bacteria, sedimentation of particulate matter and mineralisation or desorption from particulate matter. These processes can occur at the same time and make it difficult to determine which processes dominate. Nutrients carried into coastal waters by river plumes have a marked effect on productivity in coastal waters.
- In the initial mixing zone, water velocity is reduced and changes in salinity, pH and eH promote flocculation of particulate matter. Most of the river derived particulate matter settles from the plume in this zone. This is most clearly shown in the results from the Burdekin for Cyclone Sid where suspended solid and particulate phosphorus concentrations drop to very low levels only a few kilometres from the river mouth at salinity of approximately 10. However benthic sediment distribution information shows that the area off the mouth of the Burdekin River has a low proportion of fine sediments. This apparent inconsistency is best explained by the resuspension and northward transport and deposition in northerly facing bays of fine sediments which occurs throughout the year under the influence of the south-east wind regime on the inner shelf. Reductions in suspended sediment with increasing salinity in the plume are less clear in some of the other plumes but this is complicated by resuspension during the plume event in stronger wind conditions on these occasions.
- Nutrients such as nitrogen associated with the discharge travel much further offshore than sediment. Concentrations of nitrate and orthophosphate measured in flood plumes reached 50 times the concentrations measured in non flood conditions. These elevated concentrations are maintained at inshore sites adjacent to the Wet Tropics catchment for periods of approximately one-week. Plumes associated with the larger Dry Tropics catchments, the Fitzroy and Burdekin Rivers experience elevated concentrations for periods of up to three weeks, but on a less frequent basis.
- Chlorophyll *a* concentrations had an inverse pattern of increasing concentrations at some distance from the river mouth. This was likely to be influenced by the length of time which water column phytoplankton have been exposed to flood generated nutrients and the increasing light as the suspended matter settled out. Chlorophyll *a* concentrations

were higher than phaeophytin concentrations in all samples, confirming that most of the chlorophyll detected was associated with new algal biomass stimulated by flood water discharge.

Concentrations of dissolved nutrients experienced at inshore reefs are considerably above those known to produce adverse affects on coral reef ecosystems, particularly in respect to enhancement of algal growth, reductions in coral reproductive success and increase in mortality.

1.2. Gaps in our knowledge

1.3. Outline of Marie Flood plume monitoring program

The new MTSRF program Marine flood plume monitoring: RWQPP Marine Monitoring Program (3.7.2b) is a long term project to study the exposure of reef ecosystems to land-sourced pollutants. The GBRMPA is responsible for the implementation of the Reef Water Quality Protection Plan (RWQPP) where a key component is the implementation of a long-term water quality and ecosystem-monitoring program in the Great Barrier Reef Lagoon. The RWQPP Marine Monitoring Program is currently managed by the Reef and Rainforest Research Centre. This program will help assess the long-term effectiveness of the RWQPP in reversing the decline in water quality of run-off originating from Queensland catchments.

Because of the large size of the GBR (2000 km), the short-term nature and variability (hours to weeks) of runoff events and the often difficult weather conditions associated with floods, it is very difficult and expensive to launch and coordinate comprehensive runoff plume water quality sampling campaigns across a large section of the GBR. To counter this variability, this project forms a multi-pronged in the assessment of the exposure of the GBR inshore reef to material transported into the lagoon from GBR Catchment Rivers.

The research questions that we intend to investigate over the course of this monitoring program are as follows:

• Extent of exposure of reef ecosystems to terrestrially sourced materials, and further mapping of the extent of risk from these materials;

- The fate of dissolved and particulate materials in flood plumes (sedimentation, desorption, flocculation, biological uptake);
- Processing, dispersal and trapping of materials during flood events;
- Quantify the temporal dynamics of sediment dynamics, light availability and phytoplankton growth during and after plume events;
- Changes in phytoplankton assemblages during the duration of the plume event, and how this influences long term chlorophyll concentrations within the different regions.
- Loads of fine sediments discharging into the GBR lagoon from major GBR catchment rivers.

1.4. Sampling design

The flood plume monitoring program is set up to run concurrently with ongoing MTSRF program 3.7.2 (Catchment processes?). There are also strong links with other MTSRF programs, such as 3.7.1(?). In all instances, we will try to work closely with other science and government agency to be able to integrate many types of data into the plume monitoring. Finally, this program will be run in partnership with Australian Institute of Marine Science linking to the existing water quality and coral monitoring programs. We will also work closely with AIMS to incorporate the in situ logging data (Schaffelke pers com) into our understanding of the temporal extent of the plumes and what do coral reefs experience during first flush and high flow event situations. Figure 1.1 outlines the various integrative programs linked with the flood monitoring program.



Figure 1-1: Diagrammatic representation of the integrative programs running concurrently with the plume monitoring program.

In summary, the three main drivers of information for the marine flood plume monitoring program are

- > Transport and processing of nutrients and suspended sediment
- Extent and exposure of flood plume related to prevailing weather and catchment conditions
- > Incorporation and synthesis of new data into current receiving water models

2. Methods

2.1. Sampling collection

Sampling collecting methods differed for each agency that participated in the 2008 sampling, thus the sampling collection will be presented for each agency, James Cook University, Australian Institute of Marine Science and CSIRO.

2.1.1. James Cook University

Water was collected using a clean, rinsed bucket in the top meter of water. Surface samples were taken at each site. The samples were filtered for dissolved nutrients, with 100 ml taken for total nutrients. Samples were also collected for chlorophyll, total suspended solids, and colored dissolved organic matter (CDOM), which were all filtered and treated appropriately within 24 hours. Samples were filtered for trace metals. Finally at selected sites, samples were collected for phytoplankton enumeration and pesticides. Depth profiles were taken at each site, collecting a suite of physico-chemical parameters.

Table 3.1 lists all the parameters identified for sampling in this study. However, only those denoted with a cross are presented for this report. Further data on the other parameters will be available over time.

Type of data	Parameter	Comments	Reported
Physico chemical	pH	Taken through the	x
	Salinity	water column.	x
	Dissolved Oxygen	Hydrolab	x
	Turbidity		x
Water quality	Dissolved nutrients	Surface sampling	Х
	Particulate Nutrients only		
	Chlorophyll/Phaeopytin		Х
	SPM (suspended particulate matter)		X
	CDOM		

Table 2-1:	Summary of chemical and biological parameters sampled for the MMP flood plume
monitoring prog	gram.

	Trace Metals	To be reported on in 3.7.2	
Pesticides		Not at all sites	х
Sediment tracing	Clay Minerology	To be reported on in	
	Trace elements	3.7.2	
	Sr/Nd isotopes		
Biological	Phytoplankton counts	Not at all sites	

2.2. Laboratory Analysis

2.3. Data analysis

2.4. Remote sensing methods

One of the newer techniques we will be exploring during this research project is the utilisation of remote sensing to further our understanding of the movement, extent and duration of flood plumes. We have explored two techniques in this reporting year, those being the extraction of true colour images to identify the extent of the riverine plume, and the application of available algorithms satellite images to extrapolate chlorophyll and SPM data for the appropriate images. A brief description of both processes is presented here.

2.4.1. Extent of plumes

Better definitions of the extent of plume boundaries are now available using the information from true colour images. 250 meter resolution true colour images are created. Bands 1, 4 and 3 for red, green and blue are used. Band 1 has originally a 250 meter resolution, however band 3 and 4 have a 500m resolution. Band 3 and 4 are interpolated to a 250 meter resolution.

SeaDAS is used to create those images. To create high resolution true colour images the L0_LAC datasets are needed. The following steps have been carried out in SeaDAS to create true colour images:

- Create a level 1A and geolocation file out of level 0
- Create level 1B by using Level 1A and geolocation file

- Create a ppm image out of the Level 1B and the Geolocation file
- Convert ppm to png
- Created a Geotiff by using the navigation data from level 1B data and the png image.

True color images of before, during and after each plume have been identified where there was low cloud cover and reasonably good visualization of the plume area. Primary and secondary plumes were identified in each image, where the definition of the primary plume is the high turbidity, high sediment plume discharging relatively close to the river mouth. Secondary plumes are defined as the less turbid, higher production plumes where chlorophyll and nutrient levels are elevated. Some increase in turbidity may be present in secondary plumes as a result of the further transport of the finer particulate material and desorption processes occurring later in the salinity mixing curve. We also defined tertiary plumes as the less visible plumes further offshore and north of the river mouth. A confidence factor was applied to the each plume polygon dependent on how visible the plume was, if in-situ data supported the identification of the plume.

Please note that extent of plumes will be mapped with greater accuracy with the application of a CDOM inverse algorithm which will trace the extent of the plume through the identification of CDOM in the plume (need better explanation).



Figure 2-1: The identification of primary and secondary plume in the Fitzroy plume.



Figure 2-2: Application of confidence for extent of plumes

2.4.2. Application of algorithms

MODIS data is used for the mapping of chlorophyll-a. The MODIS (Moderate-resolution Imaging Spectroradiometer) project consists of two sensors; one is attached to the Aqua satellites and the other to the Terra satellite. Each satellite has a revisit time of 1-2 times a day. The sensors have 36 spectral bands and the spatial resolution varies per band. The spatial resolution for the bands which are used to calculate the chlorophyll concentrations in the ocean have a resolution of 1000m. Several MODIS data products are freely available via the internet. We have used a selection of available algorithms to explore which algorithm is the most appropriate in flood plume waters. The first algorithm is the default MODIS algorithm, the OC3. The OC3 is based on empirical relations between remote sensing reflectance and chlorophyll concentrations. The other two are physics based semi-analytical models, the GSM01 (Maritorena et al. 2002) and the Carder (Carder et al. 2003). The algorithms perform well in open ocean but the performance in turbid, coastal waters is often poor due to the variable, conflicting conditions found within inshore waters. According to Qin et al. (2007) does the GSM01 works relatively well over a wide range of turbidity. The Carder algorithm has the highest accuracy in non turbid waters (Qin et al. 2007). (mention of current work from CSIRO?)

The chlorophyll content maps can be downloaded from: http://oceancolor.gsfc.nasa.gov/.

An example of applying the chlorophyll algorithm is shown in Figure 3.3. This is taken from a 2007 event but the algorithm is successful in delineating the movement of high chlorophyll waters into the Coral Sea. This is an example of where remote sensing techniques can be very useful in mapping extent and duration. This also shows that plumes move further offshore than previously thought.



Figure 2-3: The application of the MODIS algorithm to RS images taken in a large flow event (February 2007).

For this year, we have been investigating the use of the algorithms to measure chlorophyll, SPM and CDOM in flood plumes. This data would be integrated with our water quality data for to extend our spatial coverage. We are exploring a number of analytical techniques for use with the remote sensing algorithms. However, it is important to note this is preliminary work and further validation is required before we integrate our findings into the flood plume project.

2.5. Application of inverse algorithms

The retrieval of the total absorption, total back-scattering and CDOM absorbance algorithm is based on CSIRO in-house algorithms and has two main steps. First an atmospheric correction algorithm based on inverse modeling of radiative transfer simulations and artificial neural network inversion derives the spectral remote sensing reflectance at mean sea level on a pixel-bypixel basis (Schroeder et al., 2007). Second, the inherent optical properties (IOP) and the concentrations of optically active constituents are retrieved from atmospherically corrected spectra by applying a Linear-Matrix-Inversion algorithm (Brando et al., 2006). The total absorption at 441 nm can be regarded as an indicator for the presence of organic material, while the total back-scattering at 551 nm is mainly an indicator for sediment concentrations. CDOM absorbance at 441nm can be used as an indicator of terrestrial influence for freshwater plumes. Clouds and algorithm failure pixels are generally masked in black, while the reef is masked in white colour.

Catchment runoff events involve space scales ranging from hundred of metres to kilometers and time scales from hours to weeks, thus the use of remote sensing in monitoring marine indicators at appropriate time and space scales can be used as key indicators of cause and effect in these systems. Concentrations of suspended sediment and yellow substances can be used to rack plume distribution and dilution, and sedimentation. We will present some preliminary maps of CDOM absorbance and back-scatter to identify the movement and distribution of the riverine flood waters and sediment. Finally, a demonstrative (summary) map of maximum CDOM absorption for the period JAN-MAR 2008 has been created, which gives you a good indicator of the plume extent for both flood events over the whole wet season.

3. Flood events in 2008

Two events were sampled in 2008, those being major floods which occurred in the Burdekin and Fitzroy catchment. Sites were dependent on the timing and structure of the plume for each day that sampling occurred.

The total discharge of the 13 major rivers discharging into the Great Barrier Reef was approximately 55 million ML, 30% higher than the long term average of 42 million ML. The majority of the water came from the two dry tropic catchments, Burdekin and Fitzroy. This is in contrast to the last three years of below average flow discharge, being 12million ML, 20million ML and 26 million ML for 2004/5, 2005/6 and 2006/7 respectively. For the Northern Great Barrier Reef Rivers there were two distinct flood periods, the first being in January and second in February/March. The Barron River had flood waters associated with the largest flood since 1915/1916. However Normanby, Russell-Mulgrave, South Johnstone and Herbert were all less that the long term average and the Tully was equivalent to the long term average. This emphasizes the variability in each event for each catchment.

For the Southern Rivers, there were two distinct flood peaks measured in January and February. The big dry tropics rivers, Burdekin, Fitzroy and the Pioneer all exceeded the long term average, with the Burdekin experiencing the 3rd largest flood since 1950/1951. The O'Connell and Burnett Rivers had less than the long term average, with both rivers being well below expected flows as can be seen from the Burnett area still being in drought conditions.

Further discussion of the sampling locations and timings will be presented in each case study.





Figure 3-2: Flow rates associated with 5 southern Great Barrier Reef Rivers (July 2007 to Jun 2008).

4. Case study 1 – Burdekin

4.1. Details of event

During the early months of 2008, there was heavy rainfall falling throughout most of North and South East Queensland. Interestingly, the exceeding heavy and prolonged rainfall was not associated with a specific cyclone, but rather a number of low pressure systems moving across the Coral Sea over the Queensland coast throughout January and February.

The 2007/08 wet season produced the 4th largest flow discharge for the Burdekin River in the 87 year end-of-catchment gauged record (Burdekin River @ Clare) with a total discharge of 26.4 million ML (Fig. 1: see Lewis et al., 2006). Broadly, two separate discharge events occurred in the Burdekin River over 2007/08 wet season with the first event peaking on the 18th of January and the second on the 13th February (Fig. 1). Large river flow events occurred in all tributaries of the Burdekin catchment including 6.1 million ML discharged from the upper Burdekin (Burdekin River @ Sellheim), 2.3 million ML from the Cape River (Cape River @ Taemas), 2.0 million ML from the Belyando River (Belyando River @ Gregory Developmental Rd), 7.0 million ML from the Suttor River (Suttor @ St Anns minus Belyando River) and 2.4 million ML from the Bowen River (Bowen River @ Myuna). A total of 16.7 million ML of water spilled over the Burdekin Falls Dam over the 2007/08 wet season beginning on the 29th December 2007.



Figure 4-1: Burdekin River flow rates measured at Clare (120006B).

((http://www.nrw.qld.gov.au/water/monitoring/current_data/map_qld.php).)

4.2. Details of sampling sites and timing

Water sampling was initiated and completed by James Cook University (ACTFR), with some underway sampling by AIMS. , Sampling took place from 22nd January to 7th February. The first trip sailed out of Townsville, south along the coast and into the Burdekin river mouth, Sampling occurred adjacent and within the plume and continued to the second day. Figure 4.2 identifies the sampling times overlaid on the river flow rates. The second sampling trip took place 2 weeks later, primarily sampling around Magnetic Island and the Palms over two days. The second sampling was done in conjunction with QPWS staff from Townsville. Sampling was separated by a two week period, with sufficient time between the sampling events to allow for increased phytoplankton growth. In the second sampling event (Feb 5th and 6th), the water in Cleveland Bay, around Magnetic Island and up to the Palms was very green in colour signifying some elevated growth conditions. Further work on the phytoplankton samples will be useful in identifying species composition and abundance and if there is evidence of correlation to water quality gradients.

Timings of sampling for the first trip were approximately two days after the first peak with the second sampling trip occurring before the onset of the second peak. At time of sampling we were not aware of a second peak occurring in such magnitude and had taken equipment down to the Fitzroy catchment. Locations of the sites over the two sampling events is shown in Figure 5.3.



Figure 4-2: List of sampling dates and duration for the three agencies involved in the 2008 sampling of the Fitzroy River plume.



Figure 4-3: Site locations for all ACTFR (JCU) flood plume samples taken in the Burdekin River plume (Jan 22nd to Feb 07th).

4.3. Mapping of plume extents

The flyovers for the Burdekin event was carried out by ACTFR and GBRMPA staff on the 21st January. Due to the inclement weather on day, and the rough sea conditions, it was very difficult to get any aerial shots of the plume edge. Plume extents have been identified by true colour and CDOM absorbance at 441mn (using RS techniques). Figure 5.5 illustrates the primary and secondary plume associated with the Burdekin flood waters. The very turbid inshore plume can be seen moving north and offshore from the Burdekin mouth, almost reaching the offshore reefs. There is also a secondary plume visible in the left hand side of the picture, moving north. We know from other images and in-situ sampling that the plume had moved past the Palms Islands by this date.



Figure 4-4: True colour image of Burdekin flood taken on the 22 February, 2008.

4.4. Mixing profiles for water quality parameters.

Initial data analysis illustrates the spatial patterns within the plume waters. Figure 4.4 shows the mixing profiles for, suspended particulate matter (SPM), dissolved inorganic phosphate (DIP), nitrate + nitrite (NO_X), ammonia (NH₄) and chlorophyll. Suspended particulate matter (SPM) is substantially elevated in the river mouth(Figure 5.7), as observed in other studies (Devlin *et al.*, 2002; Lewis *et al.*, ?), and drops off rapidly in the initial mixing zone (0 to 10 ppt). However, it drops off less rapidly than previous measured sampling events (Devlin *et al.*, 2002), which could be indicative of a greater proportion of finer particulate matter moving out in the initial event. SPM remains elevated through the plume waters; however, there is a substantial drop in concentrations as the water moves into reef waters, signifying that the major proportion of coarse sediment does drop out before the Burdekin plume reaches Magnetic Island. Both particulate nitrogen and particulate phosphorus have elevated concentrations in the initial mixing zone, which drops off rapidly past 5ppt. There is some evidence of scatter for the particulate phosphorus as the higher salinities (5-15ppt) indicating some readsorption of the dissolved

inorganic fraction. However both particulate species are substantially reduced later in the plume (25-35ppt) indicating limited transport of the particulate fraction into reef waters. The higher concentrations of the sediment and particulate nutrients in the initial mixing zone are indicative of the primary plume, where suspended particulate matter measures greater than 10mg/l and the particulate nitrogen and phosphorus measure greater than 20uM and 3um respectively. The properties of the primary plume are reflected in these low salinity, high sediment concentrations and easily identifiable by air and RS images.

There is little indication of conservative mixing for any of the other constituents, including both dissolved and particulate nutrients. The shape of the mixing may be influenced by the presence of headlands and the further distance covered in the sampling locations. The highest concentrations of NO_x occur at 5ppt, and generally dilutes with distance away from the river mouth. However there is high degree of scatter at the higher salinities indicating some desorbtion from particulate matter. In the second sampling event, all NO_x values have decreased substantially at the higher salinities, though still elevated in comparison to baseline values (Furnas, 2005). DIP and NH_4 exhibit non-conservative mixing with the highest NH_4 concentrations around the 10ppt mark signifying some remineralisation about this area and distance away from mouth. NH_4 concentrations at 30ppt are elevated in both the first sampling event and the second sampling event, indicating the plume waters have moved the high nutrients north past Palm Islands. Chlorophyll, as an indicator of phytoplankton growth is elevated in both sampling events, with high concentrations occurring in both low salinities, indicating some intrusion of freshwater phytoplankton, and in higher salinities, indicating favorable growth conditions for the phytoplankton in the non light limiting waters (Figure 5.9). The higher nutrient and higher production in the higher salinity ranges is indicative of what we term secondary plumes, where the movement and transport of dissolved materials can range from 10's to 100's of kilometers away from the river mouth. The properties of the secondary plume can be seen in the higher values of nutrient concentrations, lower sediment concentrations and favorable conditions for the elevated growth of phytoplankton. The extent and duration of secondary plumes and there impact on the biological communities is one of the key questions in our marine monitoring programs. The extent of secondary plumes is harder to define by air surveillance alone, and requires the application of a suite of algorithms, including true colour processing, total absorption at 441nm as an indicator of organic material and CDOM absorption at 441nm as an indicator of riverine extent. Application of appropriate chlorophyll algorithms can also be helpful in the offshore areas to identify the extent of the higher primary production in and after the plume intrusion.



Figure 4-5; Location of sites in the three separate Burdekin sampling periods and mixing curves for SPM and particulate matter.





Figure 4-6: Mixing profiles for all nutrient species for the three different sampling events in the Burdekin Plume taken over three different sampling periods in January $(22^{nd} - 23^{rd})$, February $(5^{th} - 6^{th})$, and February 12^{th} , 2008.

Figure 4-7; Mixing profile of chlorophyll



4.5. Water quality guidelines.

Water quality thresholds for a number of water quality parameters have been published in the "Water quality guideline for the Great Barrier Reef Marine Park Authority by the Great Barrier Reef Marine Park Authority. It is important to note that the levels of contaminants identified in this guideline are not targets. Instead they are guideline trigger values that, if exceeded, identify the need for management responses.

Riverine plumes typically show elevated concentrations of many of the water quality parameters listed in this report, as plume are the main transport and conduit of many of the contaminants that enter the Great Barrier Reef Marine Park. It is not clear at this stage how long or how persistent the elevated concentrations are, but we are able to identify single exceedances of the trigger values from the plume water quality data. Data is presented for each sampling date, thus if three occurrences have occurred, this indicates that the exceedances are occurring over a longer time frame than just the single sample. Table 4.9 and Table 4.10 identify the threshold values for coastal waters which are applied in our assessment.

Water quality trigger values were applied to the water quality data collected in the Burdekin plume. We looked at the percentage of failures per sampling day to identify the potential duration of water quality exceedances. The number of exceedances (presented as a % of total count for each individual day) is shown in Figure 4.9. During the early days of the plume formation, there are almost 100% exceedances of all values excepting chlorophyll. During the evolution of the plume over the following weeks, the exceedances are still high, measuring between 55 to 100% in

the latter days. Note that the latter measurements are also taken further offshore and representative of changes in time and space for the plume waters.

Figure 5.10 shows the % exceedances against the day after the first high flow event (measured on the 20th January). % exceedances go down over time for the suspended particulate matter and increase for the chlorophyll guidelines. Figure 5.11 shows this change in the exceedances over time with the % exceedances presented against the Burdekin flow. Water quality guidelines are exceeded during the first flow event, and for a period of weeks after the initial first flush. Note that the final sampling occurred just prior to the second major flow event and would indicate that these water quality exceedances will have continue to occur for a period of weeks after the final sampling date. This identifies that plume waters can have far reaching impacts on the biological ecosystems for a period far longer that a short plume intrusion. Further work on the correlation with the long term changes in concentrations and impacts on biology is required.

Table 4-1: Guideline trigger values for water clarity and chlorophyll a.

Parameter\Water Body	Coastal	Inshore	Offshore
Secchi (m)			
(minimum mean annual water clarity) ¹	10	11	17
Chl a (µg/L) ²	0.45	0.4	0.4

¹At shallower depths Secchi will be visible on the seafloor. Guideline trigger values for water clarity need to be decreased by 20% for areas with greater than 5 m tidal ranges. Seasonal adjustments for Secchi depths are presently not possible due to the lack of seasonal data.

²Chlorophyll values are ~40% higher in summer and ~30% lower in winter than mean annual values.

Table 4-2: Guideline trigger values for SS, PN, and PP

Parameter ¹ \Water Body	Coastal	Inshore	Offshore
SS (mg/L)	2.0	1.7	0.7
PN (µg/L)	20	20	17
PP (µg/L)	2.8	2.5	1.9

¹ Seasonal adjustments for SS, PN and PP are approximately 20 per cent of mean annual values.

 $[\]mathbf{a}$

	No and % of exceedances per sampling occasion									
Date	22/1/08		23/1/08		5/2/08		6/2/08		12/2/08	
Total No. samples	Total No. samples 12		9		10		9		10	
	No	%	No	%	No	%	No	%	No	%
Chl a (0.45ug/L)	9	75	6	66.7	9	90	7	77.8	10	100
SS (2.0mg/L)	12	100	9	100	5	50	8	88.9	7	70
PN (1.4uM)	12	100	7	77.8	8	80	5	55.9	8	80
PP (0.09uM)	12	100	7	77.8	9	90	9	100	8	80

Figure 4-8: Number and percentage of exceedances for the 5 different sampling events. Guidelines are taken from trigger values set for coastal water bodies.







Figure 4-10: % exceedances for each day during the high flow event in the Burdekin River (15th January – 11th March)

4.6. **Pesticides**

Pesticide residues were detected in the flood plumes sampled from the Burdekin River and from the Fitzroy River. Tebuthiuron residues were detected in the Burdekin River plume up to 50 km from the river mouth. A sample collected near the mouth of the Burdekin River had the highest tebuthiuron concentration of 0.03 μ g/L. This concentration exceeded the locally derived ecological trigger value for the Great Barrier Reef (0.02 μ g/L: GBRMPA, 2008).

4.7. Remote sensing

The extent of the primary plume during the Burdekin flood event was identified by the use of total backscattering at 551nm. The extent of both primary and secondary plumes were identified by the application of the CDOM algorithm at 441nm

Figure 4.11 shows the evolution of the Burdekin plume before, during and after the high flow events. The first image is taken on the 1st January, 2008 and shows that the high concentrations of CDOM are constrained closely to the shore, and represents first flush of the river waters and tidal movement. The next set of three images is taken from 24th January to the 28th January, 2008, which corresponds to the period just after the first flood peak (see figure 4.1). Plume waters are constrained to the coast, as would be expected from the prevailing south easterly winds, however, the plume waters move north past the Palm Islands by the 26th January. Note that the high CDOM readings inshore may also be influenced by localised flooding from the smaller rivers and creeks. The next sets of images are later in February, taken between 20th and 23rd February, aligning with the second peak of the Burdekin flood waters. Plume waters are still moving a large distance north, however a significant movement offshore seems to have occurred, with high CDOM measurements extending out into the reef and approaching the Coral Sea. This identifies the movement of the secondary plume offshore, affecting a far larger area than originally identified in previous Burdekin floods (link to biological sites?). There are also high concentration of CDOM south of the Burdekin, which may be a combination of the localised flooding and influences from further south flooding rivers such as the Pioneer and perhaps even the Fitzroy. The final set of images are taken on the 7th and 25th March, just on the end of the flow event, and three weeks after the end of significant flow. There is still a easily identifiable northward movement of CDOM past the Palm Islands, though constrained to the coast, however there still seem to be some indication of higher CDOM concentrations in the reef on the 7th March. By the 25th. CDOM extent is mainly observed in a northwards gradient. The images suggest that riverine influence is

measurable for over 2 months during the two flow events, with a considerable north ward movement, extending well past the Palm Islands and possible much further than this (Pesticide data suggests that the plume influenced Normandy Islands?). There was also movement offshore of the plume waters suggesting that thresholds for water quality guidelines would have been exceeded at many reef and seagrass sites.

The second set of images show the evolution of the suspended sediment using total backscatter absorption at 551nm. The first image from 1st January shows the most of the higher particulate matter is constrained to the coast, in a small area north of the Burdekin River mouth. As the flow event evolves, the higher concentrations of suspended particulate matter are found north along the coast line. After the second event, there are very high concentrations of suspended solids moving out of the mouth and being pushed offshore due to the high volume of flow. There is movement of higher suspended load offshore, though this may be related to the high wind conditions and resuspension that existed during this time. By early March, most of the higher concentrations of suspended sediment had constrained to the shore in a northwards movement, but with quite high values measured past Palm Islands which could be indicative of a lateral movement of the finer suspended load during the second flood event. The latter image on the 25th March suggests that most of the heavier sediment had been deposited and was back to pre flood conditions by 25th March. The evolution and extent of the back scattering signal suggests that the primary plume is constrained to a nearshore area around the Burdekin mouth, though some evidence does suggest a further movement of the finer particulate matter.



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Figure 4-11: the evolution of the CDOM plume from the 1/1/2008 to the 25th March, 2008. Note the true colour images are on left, and CDOM extent (calculated from CDOM absorbance at 441nm) are right hand side images.







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Figure 4-12: the evolution of the total back-scatter signal from 1st January to the 25th March, 2008. Note the true colour images are on left, and backscatter extent (calculated from total backscatter absorbance at 551nm) are right hand side images.

5. Case study 2 – Fitzroy catchment

5.1. Details of event

During the early months of 2008, there was heavy rainfall falling throughout most of North and South East Queensland. The heavy and prolonged rainfall was not associated with a specific cyclone, but rather a number of low pressure systems moving across the Coral Sea over the Queensland coast throughout January and February.

Flow rates for the last 40 years are illustrated in Figure 5.1. Comparatively the event in 2008 was significantly higher than the last decade. However the 1991 peak is approximately double that of the 2008 event. Note however that the 2008 event has a double peak in a short period of time (3 weeks) and the volume discharged is comparable to the 1991 event. Long term analysis identifies this event as a one in 25 year event (pers comm.).

This heavy rainfall created heavy flooding in all the Fitzroy catchments, though there was a distinct difference in when the sub-catchments flooded due to the rainfall signal. Flooding in the Fitzroy River peaked at two different times in February with the resultant plumes moving north for a number of weeks (Figure 5.6). Prevailing weather conditions were south easterlies forcing a generally northern movement. However, aerial images do show some movement offshore with variable wind direction and speed.



Figure 5-1: Flow rate for the Fitzroy River from 1991 to present date. Data collected from site 13005A (http://www.nrw.qld.gov.au/water/monitoring/current_data/map_qld.php). Data courtesy of NRW.

Flow data for the 2008 event is illustrated in Figure 6.2. The event initiated on the 18th January until leveling off about the 2nd March, approximately 42 days of high flow. There were two distinct peaks, measuring greater than 500000 ML per day, on the 29th January and 25th February respectively.



Figure 5-2: Fitzroy River flow rates measured at site 130005a

((http://www.nrw.qld.gov.au/water/monitoring/current_data/map_qld.php).)

5.2. Details of sampling sites and timing

Water sampling was carried out by 3 agencies, including JCU (ACTFR), CSIRO and AIMS. Sampling took place from 31st January to 6th February. Unfortunately extreme wind warning persisted during late February and early March making a return trip for any of the organizations impossible.

Figure 6.3 identified the sampling times overlaid on the river flow rates. Timings of sampling were concurrent with the first peak (one day after) and with the onset of the second peak.



Organisation	catchment	Timings			
JCU	Fitzroy	31/1 – 1/2			
AIMS	Fitzroy	23/2 – 26/2			
00100		= 10 0.10			
CSIRO	Fitzroy	5/2 – 6/2			

Figure 5-3: List of sampling dates and duration for the three agencies involved in the 2008 sampling of the Fitzroy River plume.

In situ water quality data was measured in 3 different sampling events. Figure 5.4 identifies all the sampling sites from the respective agencies. AIMS completed a long survey from Townsville to Fitzroy mouth with underway samples taken between Cape Upstart and the Fitzroy plume waters. Plume sampling by AIMS focused on and around coral reef monitoring sites in the Keppels. Further sampling was carried out by CSIRO, with additional sampling for optical measurements and remote sensing validation. Both agencies also collected surface and depth water samples for the suite of nutrient parameters, chlorophyll, DOC and physico-chemical parameters. Sampling by ACTFR (JCU) was focused on obtaining the full range of salinities within the plume. Sampling was initiated out of Rosslyn Bay, working with QPWS staff and vessel. Low salinity sampling in the primary plume was targeted on the first day, with additional samples taken for geochemical analysis. Higher salinity waters (plume influenced) around Keppels and northward were targeted to obtain information on the secondary plumes, with a number of additional samples taken for phytoplankton analysis. Sample points and extent of sampling are shown on Figure 6.4. Sampling was completed over a two day period, with the first day of sampling moving as close to the river mouth as possible (Figure 6.5). Second day sampling moved eastwards to the Keppel's and north to Corio Bay.



Figure 5-4: Location of all sampling sites delineated by agency (JCU, AIMS and CSIRO).



5.3. Mapping of plume extents

5.3.1. Aerial flyover

The flyovers for the Fitzroy flood event was carried out by the Queensland, Parks and Wildlife Service based in Rockhampton and Emu Park. The following descriptions are taken are pers comm from John Olds (QPWS) and crew on the 8th February.

The edge of the fresh plume (ie seaward of which is clear blue water, so this is effectively the 'front') is well on its way out towards North West Island. There is a very distinct line east of the Keppels, however north of Corio Bay and south of Cape Capricorn the line of the 'front' is less distinct (Figure 6.6). There are some heavy sediment plumes inside of a curved line from Cape Capricorn to Hummocky, Peak, Divided, Wedge and Pelican Islands. There are also some finer sediment plumes around most of the western sides of the Keppels, all of which are now surrounded by green fresh surface water. This includes Barren Is and Egg Rock, as the fresh now extends several Ks east of the outer Keppels. This is a significant movement of the plume from the flight on Tuesday, at which time the front was halfway between the inner (Great Keppel Island and North Keppel Island) and outer Keppels (Outer Rock, Barren Is & Egg Rk). Thus is it clear that the plume moved a significant distance offshore into the Keppels Reef area and further offshore into the Cape Bunkers.







Figure 5-6: Aerial shots of the Fitzroy river plume (a), (b) and (c) (photos curtesy of John Olds, QPWS)

5.4. Mixing profiles for water quality parameters.

Initial data analysis illustrates the spatial patterns within the plume waters. Figure 5.7 shows the location of the sampling sites in the Fitzroy plume waters. Sites are defined by the agency responsible for collection of the samples. All data was integrated into the dilution curves. Figure 5.8 shows the mixing profiles for suspended particulate matter (SPM) and particulate nitrogen and phosphorus. Figure 5.9 shows the mixing profiles for, dissolved inorganic phosphate (DIP), dissolved inorganic nitrogen (DIN - nitrate + nitrite (NO_X) and ammonia (NH₄)), dissolved organic nitrogen (DON) and dissolved organic phosphorus (DOP). Figure 5.10 shows the mixing profile for the chlorophyll along the salinity gradient.

SPM is substantially elevated in the river mouth and drops off rapidly in the initial mixing zone (0 to 10 ppt). SPM remains elevated through the plume waters; with values of grater than 10mg/L measured in reef waters further north and offshore of the Fitzroy mouth. The mixing profiles of the particulate nutrients also show elevated concentrations in the low salinity samples; however concentrations do drop rapidly from the initial mixing zone. There is a substantial amount of scatter for both particulate nitrogen and phosphorus, once again indicating adsorption and desorption processes occurring as the plume waters move north. The high concentrations of the particulate matter in the low salinity plumes is typical of primary plume characteristics, identified by the high turbidity and rapid drop out of the particulate matter as the plume waters move north.

DIP and DIN mix predominately conservatively, diluting with distance away from the river mouth. However both nutrient elements have peaks outside of the conservative mixing curve signifying some uptake or desorption processes occurring through the plume waters.

Chlorophyll concentrations are very high in the river mouth sample, but this most likely represents freshwater phytoplankton movement into the riverine plume. As the freshwater phytoplankton dies out, and the increased turbidity limits phytoplankton growth, there is a fall in chlorophyll concentrations in the lower salinities. However, there are two distinct peaks of chlorophyll from 10 to 20ppt, from sites some distance away from the river mouth (Figure 5.1), related to the corresponding higher nutrient secondary plume waters and higher light levels.

The secondary plume can be identified in the salinity range of 5-20ppt, where there is high nutrient availability and peaks of growth identifiable by the high chlorophyll concentrations. Advantageous growing conditions in the secondary plume can be identified around the Keppel reefs and slightly north of Great Keppel Island.



Figure 5-7 Timing of sampling for the Fitzroy flood event. Colours on the map denote the agency responsible for sampling at that time, including AIMS (red), CSIRO (yellow) and JCU (green)



Figure 5-8: Mixing profiles of SPM and particulate nitrogen and phosphorus for Fitzroy plume sampling. Colors denote the timings of sampling.



Figure 5-9: Mixing profiles of dissolved nutrients and chlorophyll a for Fitzroy plume sampling. Colors denote the timings of sampling.

5.4.1. Distance from river mouth

Figure 5.11 places the concentrations of the four of the water quality constituents (DIP, DIN, SPM and chlorophyll) along a distance gradient from the Fitzroy mouth (as the crow flies). As expected, the distance gradient correlates with the salinity gradient identified in Figure 5.8. What we can furthert identify from the distance graphs is the area most likely to support increased production from a combination of high nutrients and adequate light availability. This area would be identified as the secondary plume. This area would be approximately 15 to 20 kilometers from the mouth of the river, where the nutrient concentrations are still elevated with DIN and DIP measuring greater than 4μ M and 0.6μ M respectively and SPM levels are elevated (>10mg/L) but greatly reduced from the initial mixing zone. A draft outline of the plume areas is identified in Figure



Figure 5-10: Water quality gradients along distance from shore.

5.5. Water quality guidelines

Water quality trigger values were applied to the water quality data collected in the Fitzroy plume. We looked at the percentage of failures per sampling day to identify the potential duration of water quality exceedances. Table 5-3 and Table 5-4 identify the threshold values for coastal waters which are applied in our assessment. The number of exceedances (presented as a % of total count for each individual day) is shown in Figure 5.5. During the early days of the plume formation, there are almost 100% exceedances of all values. During the evolution of the plume over the following weeks, the exceedances are still high, measuring between 25 to 100% in the latter days. Note that the latter measurements are also taken further offshore and representative of changes in time and space for the plume waters.

Figure 5.11 shows this change in the exceedances over time with the % exceedances presented against the Fitzroy flow. Water quality guidelines are exceeded during both flow events, and for a period of weeks after the initial first flush. This identifies that plume waters can have far reaching impacts on the biological ecosystems for a period far longer that a short plume intrusion. Further work on the correlation with the long term changes in concentrations and impacts on biology is required.

Finally maps of the water quality exceedances are shown in Figure 5.13. Chlorophyll, total nitrogen and SPM are presented for each site within the Fitzroy plume.

Parameter\Water Body	Coastal	Inshore	Offshore
Secchi (m)	10		15
(minimum mean annual water clarity) ¹	10	11	17
Chl a (µg/L) ²	0.45	0.4	0.4

¹At shallower depths Secchi will be visible on the seafloor. Guideline trigger values for water clarity need to be decreased by 20% for areas with greater than 5 m tidal ranges. Seasonal adjustments for Secchi depths are presently not possible due to the lack of seasonal data. ² Chlorophyll values are ~40% higher in summer and ~30% lower in winter than mean annual values.

Table 5-2: Guideline trigger values for SS, PN, and PP

Parameter ¹ \Water Body	Coastal	Inshore	Offshore
SS (mg/L)	2.0	1.7	0.7
PN (µg/L)	20	20	17
PP (µg/L)	2.8	2.5	1.9

¹ Seasonal adjustments for SS, PN and PP are approximately 20 per cent of mean annual values.

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 Table 5-3: Number and percentage of exceedances for the 5 different sampling events in FITZROY

 flood plumes. Guidelines are taken from trigger values set for coastal water bodies.

Parameter and WQ guidelines		Chlorophyll (0.45ug/L)	SS (2.0mg/L)	PN (1.4uM)	PP (0.09uM)	
Date	Total number of samples	No of exceedances (% of total count)				
31/1/2008	11	8 (73%)	11 (100%)	11 (100%)	11 (100%)	
1/2/2008	9	4 (44.4%)	9 (100%)	7 77.8%	4 (36.4%)	
6/2/2008	3	3 (100%)	3 (100%)	3 (100%)	3 (100%)	
7/2/2008	4	4 (100%)	4 (100%)	1 (25%)	4 (100%)	
8/2/2008	4	3 (75%)	4 (100%)	3 (75%)	4 (100%)	
9/2/2008	4	2 (50%)	4 (100%)	3 (75%)	4 (100%)	
25/2/2008	7	7 (100%)	4 (57%)	3 (43%)	5 (71%)	
26/2/2008	2	2 (100%)	2 (100%)	2 (100%)	2 (100%)	



Figure 5-11: % exceedances for each day during the high flow event in the Fitzroy River (15th January – 4th March)



Figure 5-12: Areas of water quality guideline exceedances. Green denotes concentrations below the current coastal water quality guidelines. Yellow, orange and red colours (denoted in red box) indicate all sites that had exceedances for (a) chlorophyll, (b) Total nitrogen and (c) SPM



5.6. Pesticides

Higher tebuthiuron concentrations (range from 0.02 to 0.1 μ g/L) were detected offshore from the Fitzroy River plume with a peak concentration of 0.1 μ g/L detected near the mouth of the river. Tebuthiuron residues were detected up to 60 km from the mouth of the Fitzroy River. Atrazine residues (and associated degradation products desethyl and desisopropyl atrazine) were also detected in the Fitzroy River plume (range from 0.04 to 0.28 μ g/L) with a peak concentration of 0.28 μ g/L near the mouth of the river. However, no samples exceeded the ecological trigger value for the Great Barrier Reef (0.7 μ g/L: GBRMPA, 2008). Both atrazine and tebuthiuron residues were detected in all pesticide samples collected in the Fitzroy River plume. The other herbicide detected in the Fitzroy River flood plume was metolachlor which was only detected in two samples collected near the mouth of the river in low concentrations (0.01 μ g/L).

5.7. Remote sensing

True colour images were created from 250 meter resolution true colour images is created. Bands 1, 4 and 3 for red, green and blue are used. Band 1 has originally a 250 meter resolution, however band 3 and 4 have a 500m resolution. Band 3 and 4 are interpolated to a 250 meter resolution. The extents of both primary and secondary plumes were visualized and mapped from these true colour images into a GIS processing package. The series of maps that identify the evolution of both plumes

Figure 5.7 shows the evolution of the Fitzroy plume from the mapping of the true colour images. Each image is identified by a sampling data associated with the flow measurements. The first two images, taken on the 26th and 28th January, show the primary plume constrained to the coast and within a small salinity zone. The secondary plume moves northwards, still relatively close to the coast. By the second flood event, the primary plume was extending offshore past the Keppel islands, with the secondary plume having a substantial movement northwards and offshore. By the final image, both primary and secondary plumes had moved offshore, possibly due to the very high volumes of flow from the second event.

The CDOM images taken before, during and after the Fitzroy flood events are shown in Figure 5.8. Images taken from the 21st January to 28th January also demonstrate that the initial plume from the first flow event did move north but constrained to coast line. Images from the 20th to 22nd February, which align to the second flow event show a significant movement offshore of the higher CDOM signal, moving into the Swains and Capricorn Bunker reef systems. This high CDOM concentrations support the true colour images, also taken around that time, and show that the offshore influence of the Fitzroy flood was significant in the second flow event. By the 8th March, the CDOM signal was once again constrained to the shore and measured only north of the river mouth.



Figure 5-13: Plume extents calculated from true colour images for the Fitzroy Plume from the 25th January to the 23rd February.



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Figure 5-14: the evolution of the CDOM plume from the 21st February to the 9th March, 2008. Note the true colour images are on left, and CDOM extent (calculated from CDOM absorbance at 441nm) are right hand side images.

6 Conclusions

Heavy and persistent flooding occurred in many rivers draining into the Great Barrier Reef over January and February 2008. This report presents the preliminary findings of water quality measurements taken in the riverine plumes from the Burdekin and Fitzroy plumes. Sampling was mixtures of traditional water quality grab sampling and investigation of new mapping techniques using currently available remote sensing algorithms.

Water quality sampling in the Burdekin and Fitzroy plumes show high concentrations of all water quality parameters moving off the catchments. Concentrations of the various parameters are intrinsically linked to both time and space related to the riverine flow. Flow volumes and water quality concentrations are also linked to location of the flooding on the sub-catchments.

Particulate nutrients and suspended particulate matter are both elevated in the initial plume at the lower salinity end. However the particulate matter drops out rapidly in this lower salinity zone, creating what is now termed a primary plume. The definition of the primary plume is an area of plume waters with high turbidity and high concentrations of particulate matter. Concentrations of suspended mater and particulate nutrients are elevated in this area. Dissolved nutrient concentrations are also very high in the primary plume but not advantageous to primary production due to the light limiting conditions. However, fluxes of high chlorophyll were measured in this area which are most likely the intrusion of freshwater phytoplankton. The extent of the primary plume is easily defined by aerial photography and remote sensed images as the edge of the high sediment bearing plume is well defined. (Note that bad weather and cloudy days can interfere with this mapping).

As the particulate matter falls out of the plume waters, there is a greater movement of finer particulate matter, as can be seen in the elevated concentrations of SPM and particulate nutrients. However, light availability does increase as the waters move away from the river mouth and a combination of light and increased dissolved nutrients leads to higher concentrations of chlorophyll a being measured further out in the plume, with salinity ranges from about 5 to 25ppt. This area is known as the secondary plume; it has a far greater extent, both in space and over time, than the primary plume, and as such may have longer term impacts on the biological ecosystems that are inundated. The secondary plumes are typically defined as high nutrients, lower SPM (though still elevated in respect to baseline conditions) and higher peaks of chlorophyll signifying higher primary production.

Remote sensing techniques were used to identify the extent of these primary and secondary plumes (through the investigation of true color images). Further information on the extent and duration of the riverine plumes was available through the application of the CDOM and total backscatter inverse algorithms created by CSIRO remote sensing group. This report presented some outputs from the remote sensing and showed the evolution of both the Burdekin and Fitzroy plume extended 100's of kilometers north as well as a significant movement offshore after both flow events. Further work is required on mapping of the CDOM concentrations and the potential impacts of these extended plume waters on the biological communities.

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