

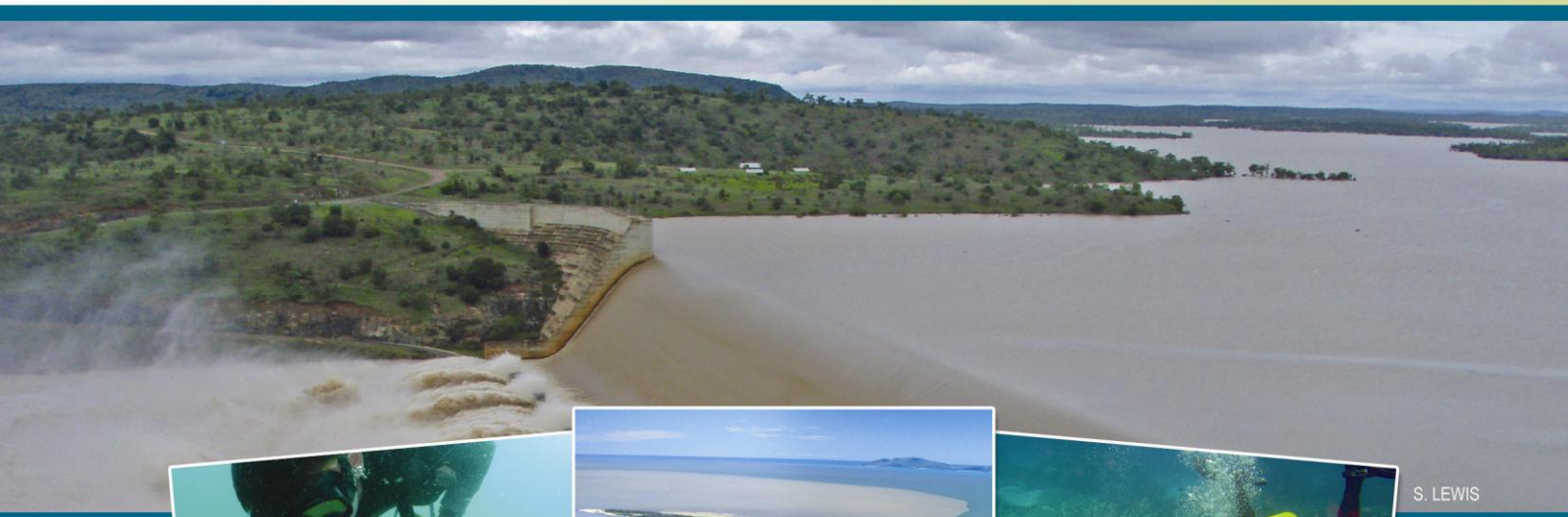


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# Reef Rescue Marine Monitoring Program: Terrestrial Runoff in the Great Barrier Reef (3.7.2b)

## Flood Plume Monitoring for 2009/10 Annual Report



S. LEWIS

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## **1. Executive Summary**

### **1.1. Introduction**

This report details the sampling that has taken place under the Reef Rescue Marine Monitoring Program: Terrestrial discharge into the Great Barrier Reef (project 3.7.2b) for the 2009/10 sampling year. River plume sampling for this period focused on the Tully, Burdekin, Mackay Whitsunday and Fitzroy Rivers.

River plume extents and concentrations were mapped using a combination of data and techniques, including field sampling and remote sensed imagery. True colour imagery has been used to develop a better understanding of the extent of plume waters in relation to weather and flow conditions.

### **1.2. Methods**

Water sampling occurred over four regions in the Great Barrier Reef (GBR), including the Wet Tropics, Mackay Whitsunday, Burdekin and Fitzroy. Plume sampling is carried out on small vessels, taking surface water samples from the mouth of the flooding river along a north east transect away from the mouth. Depth sampling was carried out using a current-temperature-depth (CTD) profiler with additional light attenuation (PAR) measurements.

The extent and concentrations of plume waters, coupled with extensive *in situ* water quality sampling has been used to estimate the frequency of river plume exposure for inshore biological systems within GBR waters for the Tully, Burdekin, Mackay Whitsundays and Fitzroy marine areas in the 2009/10 wet season. This spatial assessment of plume movement has used imagery available from aerial flyovers, true colour MODIS imagery and the application of water quality algorithms.

Classification of water types within the plumes is ongoing, with identification of the water types through a combination of true colour and spectral thresholds. The area and extent of the water types, and characteristics of each water type have been used to develop maps which highlight areas that are most likely to exceed the current Water Quality Guidelines for

the Great Barrier Reef Marine Park (GBRMPA, 2009; hereafter called “the Guidelines”) for TSS and Chl-*a*.

Plume typology was further explored through the analysis of field data and remote sensing imagery. Flood plume categories were defined based upon the concentration of water quality parameters that can be readily derived from ocean colour remote sensing.

Plume types were classified using the following criteria:

- (i) Primary water types were defined as having a high total suspended mineral (TSM) load, minimal chlorophyll (Chl) and high coloured dissolved and organic matter (CDOM).
- (ii) Secondary water types were defined as a region where CDOM is still high however, the TSM has been reduced. In this region, it was deemed that increased light and nutrient availability prompted phytoplankton growth. Thus, the secondary plume exhibits high Chl, high CDOM and low TSM.
- (iii) Tertiary water types are the zone of the plume that exhibit no elevated TSM and reduced amounts of Chl and CDOM when compared with that of the secondary plume. This zone can be described as being the transition between a secondary plume and ambient conditions.

### **1.3. GBR-wide results**

Sampling of flood plumes in 2009/10 was carried out in marine receiving waters of the Tully, Burdekin, Mackay Whitsunday and Fitzroy Rivers at a range of timings following peak flow. The focus within this monitoring is to capture the height of the peak flow within flood plumes, but this is not always possible due to logistics and the increased demand to sample as many catchments as possible in peak flow years. Sampling the peak flow allows better characterization of the primary water types, i.e. the high TSS carrying waters in the lower salinity ranges. However, it is the full extent of both secondary and tertiary water types, with high nutrients, higher capacity for production and high CDOM, which has a much greater influence over time and space. To capture this, the program has shifted focus slightly to try to capture more events, at longer time periods after peak flow. This can be seen in the data presented for 2009/10 sampling for the Tully, Burdekin, Mackay

Whitsunday and Fitzroy Rivers, where sampling took place 1 to 21 days after the peak flow. Note that flow volumes can still be elevated (above the median) for many days after the peak flow was measured and can still deliver significant volume of freshwater to the marine environment. Concentrations of water quality parameters that have been taken at later stages in the hydrograph will be reduced from the initial flush concentrations but still substantially elevated compared to the long term ambient concentrations. These prolonged elevated concentrations of dissolved and particulate nutrients, CDOM, chlorophyll and TSS contribute to higher annual concentrations of TSS and chlorophyll, driving Guideline exceedances of the long term annual mean. Remote sensing images presented in this program for the Burdekin, Fitzroy and Mackay Whitsunday regions show areas of high green colour, due to very high concentrations of Chl-*a* and CDOM over large areas over a period of days to weeks after the largest flow event, supporting that the measurements of water quality parameters stay elevated over a large part of the wet season, particularly for the more episodic rivers such as the Tully River.

## **1.4. Regional results**

### **1.4.1. River flow and event periods**

The results for flood plume sampling in 2009/10 wet season are summarised below. For each sampling location, information is presented on the flow characteristics of the dominant river discharge (compared to long term median discharges) and a description of each of the events sampled including the event period, the peak flow, the number of days where the flow exceeded the 95<sup>th</sup> percentile and the number of sampling days. Note that the event periods are defined by any single day measurements being greater than the 95<sup>th</sup> percentile. The mean concentrations of DIN, chlorophyll and TSS sampled in each event are also presented.

**Table i: Summary of flow characteristics for the four marine areas that were sampled over the 2009/10 sampling year. Colour from green (low) to red (high) denotes the degree of difference between the 2009/10 year to the long term median flow.**

Flow characteristics	Tully	Pioneer	Burdekin	Fitzroy
Long term river discharge median	3128458	731441	5957450	2708440
Total Year discharge (ML)	3175298	1319393	7857344	10683539
Difference between LT median and total yr discharge	0.82	1.8	1.32	3.94
Wet season discharge (ML)	2261121	1282060	7615441	10675175
Wet season flow as % of total year discharge	71%	97%	96%	99%

**Table ii: Tully River 2009/10 flow and sampling measurements.**

Flow characteristics for Tully River 2009/10					
Event	Start date	End date	No of days > 95 <sup>th</sup> %ile (30,000ML)	Peak flow (ML/day)	
1	27/1/09	30/01/10	4	26774	
2	14/3/10	16/3/10	3	27279	
3	28/3/10	31/3/10	4	40698	
4	5/4/10	8/4/10	4	35053	
5	19/4/10	20/4/10	1	25976	
6	25/4/10	26/4/10	1	31043	
Details of sampling in the Tully sub-region for 2009/10					
Sampling event	Date	No of days	Mean DIN (µM)	Mean Chl (µg/L)	Mean TSS (mg/L)
1	29/12/09	1	0.7	0.32	18.6
2	2/2/10	1	1.7	1.1	5.7
3	3/3/10	1	2.1	0.78	2.32
4	1/4/10	1	2.6	0.84	6.2
5	8/4/10	1	2.8	0.94	6.8

- Note that the Tully River plume was also sampled outside of the main flow events, including sampling on 2<sup>nd</sup> February 2010 and 3<sup>rd</sup> March 2010

**Table iii: Mackay Whitsunday region – Pioneer River 2009/10 flow and sampling measurements.**

Flow characteristics for Mackay Whitsunday region 2009/10					
Event	Start date	End date	No of days > 95 <sup>th</sup> %ile (15,000ML)	Peak flow (ML/day)	
1	25/1/10	31/01/10	4	33120	
2	12/2/10	1/3/10	3	40436	
3	21/3/10	24/3/10	4	66002	
Details of sampling in the Mackay Whitsunday region for 2009/10					
Event	Date	No of days	Mean DIN (µM)	Mean Chl (µg/L)	Mean TSS (mg/L)
1	8/2/10	1	2.3	0.93	6.4
2	4/3/10	1	2.1	1.6	16.3
3	5/3/10	1	2.5	1.4	15.0

**Table iv: Burdekin River 2009/10 flow and sampling measurements.**

Flow characteristics for Burdekin River 2009/10					
Event	Start date	End date	No of days > 95 <sup>th</sup> %ile (88,000ML)	Peak flow (ML/day)	
1	31/1/10	1/2/10	1	144874	
2	1/2/10	2/2/10	2	111076	
3	17/2/10	28/2/10	12	281442	
4	1/3/10	10/3/10	9	154547	
5	23/3/10	31/3/10	1	326936	
Details of sampling in the Burdekin region for 2009/10					
Sampling event	Date	No of days	Mean DIN (µM)	Mean Chl (µg/L)	Mean TSS (mg/L)
1	24/2/10	1	4.8	1.9	22.2

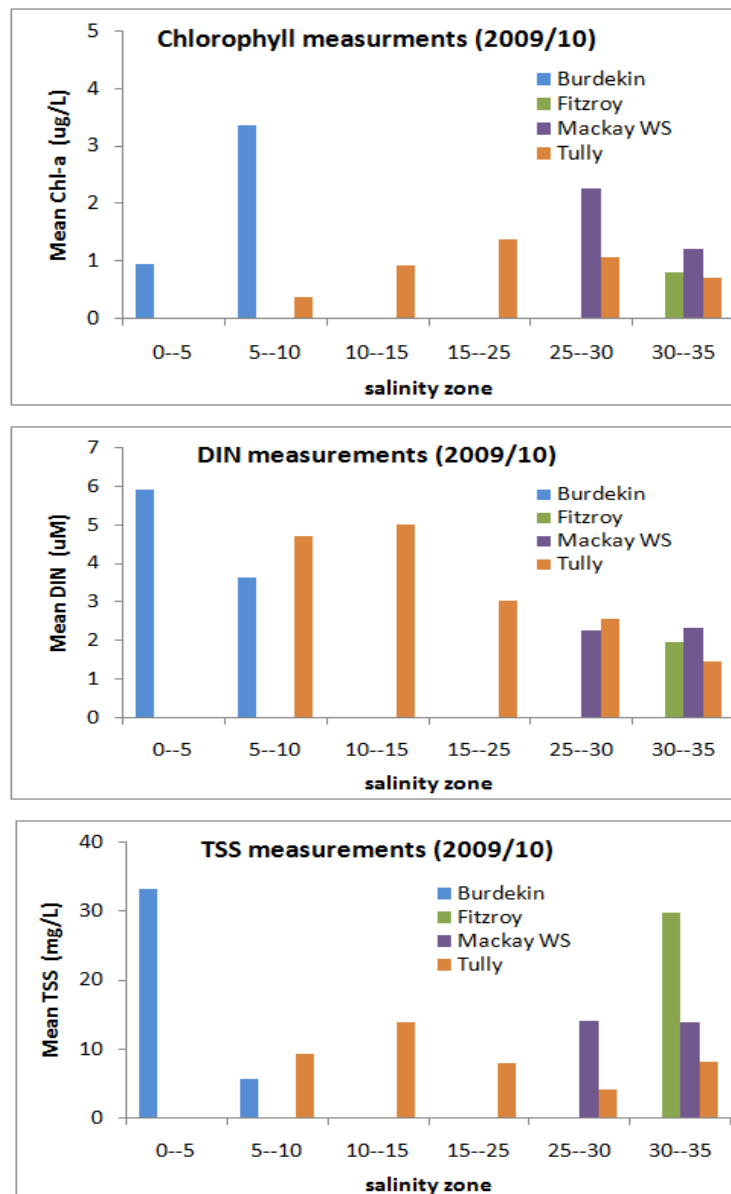
**Table v: Fitzroy River 2009/10 flow and sampling measurements.**

Flow characteristics for Fitzroy River 2009/10					
Event	Start date	End date	No of days > 95 <sup>th</sup> %ile (48,000ML)	Peak flow (ML/day)	
1	1/2/10	31/3/10	59	285066	
Details of sampling in the Fitzroy region for 2009/10					
Sampling event	Date	No of days	Mean DIN (µM)	Mean Chl (µg/L)	Mean TSS (mg/L)
1	8/4/10	1	2.6	1.1	33
1	25/4/10	1	1.9	0.5	26.5

#### **1.4.2. Water quality characteristics**

Water quality measurements in plume waters across the GBR were variable over time and space but did show consistent patterns over the salinity gradient. Dissolved inorganic nitrogen reduced over the salinity gradient; however there was evidence of biological processes in the middle salinity ranges and elevated concentrations at very low salinity values indicating movement of elevated dissolved nutrients into the offshore waters. DIP measurements in the Tully marine area showed increasing inorganic phosphate as salinity decreased, suggesting strong desorption movement of dissolved phosphate from the particulate stage. The assessment of priority pollutants from the Tully catchment may need to be revised in the context of this higher DIP movement. Suspended solid concentrations were higher in the Burdekin catchment, but settled out quickly over short spatial scales. In contrast, suspended solids measured in the Tully marine area showed some reduction in the lower salinities but a contrasting pattern of increasing concentrations at the higher salinities was evident. This may indicate complex transformations with the movement of sediment type. The role and bio-processing of the available dissolved organic nitrogen needs to be further explored. Chlorophyll concentrations were elevated in all plumes and reflect the phytoplankton production which is linked to the availability of light and higher nutrient concentrations. The reduction and mixing processes of the three main pollutants along the salinity gradient (TSS, Chl-*a* and DIN) are compared below (Figure i). Further details on the water quality parameters collected in the plume waters are presented in the regional

summaries within this report. In summary, water quality parameters reduce over the salinity gradient, however there are distinct differences between the source concentrations measured in the low salinity zones (0 -5 ppt) between the marine regions and the mixing processes vary for each water quality parameter dependent on the physical and biological properties for each parameter.



**Figure i: The mean concentrations of Chl-a, TSS and dissolved inorganic nitrogen (DIN) measured across the salinity zones of measured plume water quality in the four regions.**



#### 1.4.1. Spatial delineation of high exposure areas

This report documents a mapping process by which catchment loads and the frequency of plume waters are combined to estimate an area of high exposure to plume waters. This spatial assessment of plume movement has used imagery available from aerial flyovers, true colour MODIS imagery and the application of water quality algorithms, combined with in situ water quality data. The estimated area of high exposure is measured across the GBR, extending into the midshelf region. The numbers of reefs and seagrass beds which are located within the high exposure areas are detailed for each Region in the table below.

**Table vi: Numbers of ecosystems located within the high exposure areas as calculated by spatial mapping of plume extent and catchment loads. Note that only the high exposure category is presented.**

Frequency of exposure to elevated DIN concentrations						
Region	Exposure category	Seagrasses		Reefs		Seabed
		Number	Area (Km <sup>2</sup> )	Number	Area (Km <sup>2</sup> )	Area (Km <sup>2</sup> )
Wet Tropics	High	40	173	33	173	2184
Burdekin	High	66	552	37	20	5025
Mackay Whitsunday	High	90	178	229	145	5052
Fitzroy	High	0	0	0	0	0
Frequency of exposure to elevated TSS concentrations						
Region	Exposure category	Seagrasses		Reefs		Seabed
		Number	Area (Km <sup>2</sup> )	Number	Area (Km <sup>2</sup> )	Area (Km <sup>2</sup> )
Wet Tropics	High	0	0	0	0	0
Burdekin	High	66	552	37	20	5025
Mackay Whitsunday	High	0	0	0	0	0
Fitzroy	High	96	199	106	79	4453
Frequency of exposure to elevated PSII herbicide concentrations						
Region	Exposure category	Seagrasses		Reefs		Seabed
		Number	Area (Km <sup>2</sup> )	Number	Area (Km <sup>2</sup> )	Area (Km <sup>2</sup> )
Wet Tropics	High	40	173	30	25	173
Burdekin	High	0	0	0	0	0
Mackay Whitsunday	High	93	196	264	172	6774
Fitzroy	High	96	199	106	79	4453

Using a combination of exposure mapping and the characterisation of plume water types, we have also been able to extrapolate which areas are most likely to exceed the Guidelines trigger values for TSS and Chl-*a*. The summary table below identifies the number of reefs and seagrass beds which are located in areas most likely to be impacted by anthropogenic water quality, that is, the areas where the Guidelines are most likely to be exceeded. The number of ecosystems in the risk areas are reduced from the numbers within the exposure areas reflecting the much larger area which has been ascribed to exposure but which we have limited data to further define the risk areas.

**Table ii: The number of ecosystems, including reefs, seagrass beds and open coastal waterbody that are found in the different probability classes.**

TSS					
Probability of exceeding WQ guidelines for TSS	Km <sup>2</sup> Marine Park	% of Marine Park	% Open Coastal Waterbody	No. Seagrasses	No. Reefs
High	1,872.4	0.5%	6.6%	53	35
Medium-High	1,746.3	0.5%	4.6%	30	29
Medium	6,218.4	1.8%	11.6%	91	142
Low	108,575.2	31.2%	64.4%	255	1,415
<b>Total</b>	<b>347,861.5</b>	<b>34.0%</b>	<b>100.0%</b>	<b>432</b>	<b>2,983</b>
Chl- <i>a</i>					
Probability of exceeding WQ guidelines for TSS	Km <sup>2</sup> Marine Park	% of Marine Park	% Open Coastal Waterbody	No. Seagrasses	No. Reefs
High	7,890.4	2.3%	26.3%	144	242
Medium-High	10,884.1	3.1%	8.0%	156	254
Medium	24,667.6	7.1%	30.0%	124	410
Low	74,970.1	21.6%	23.0%	63	817
<b>Total</b>	<b>347,861.5</b>	<b>34.0%</b>	<b>87.3%</b>	<b>432</b>	<b>2,983</b>

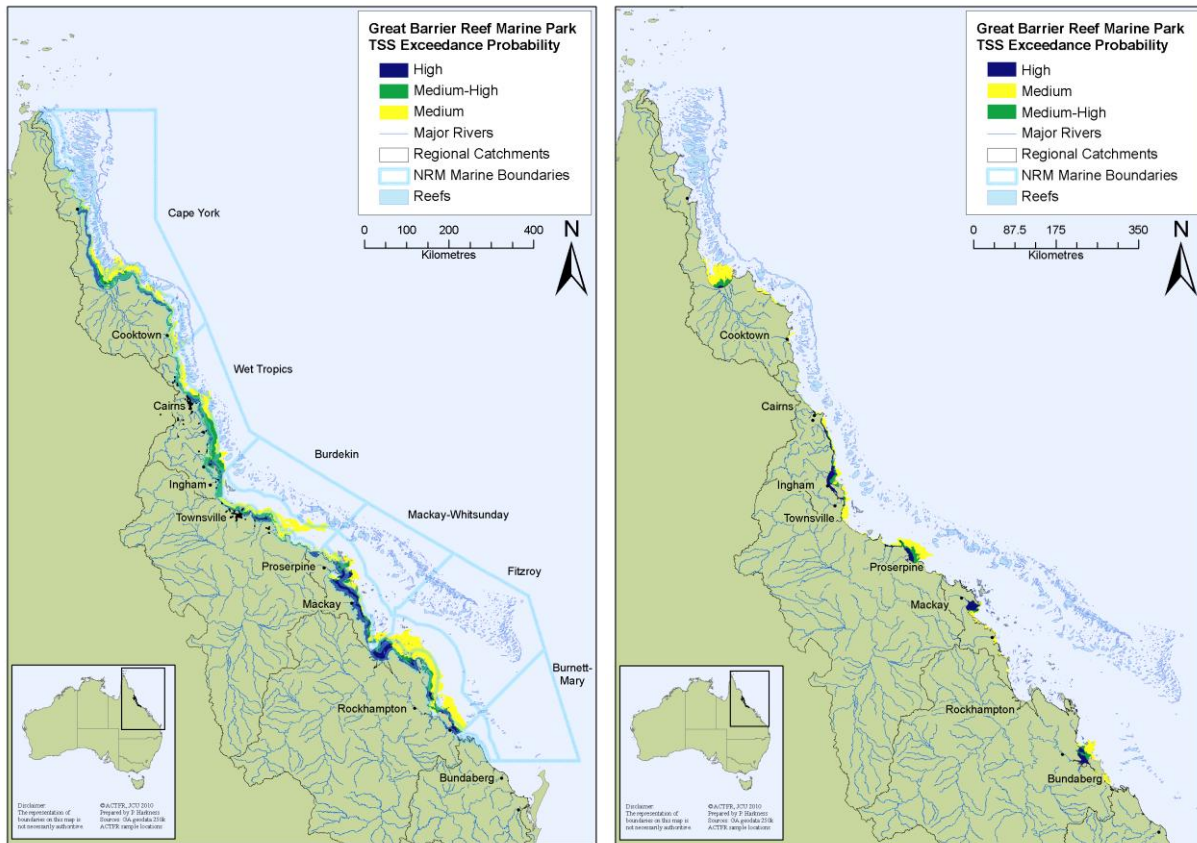
Ongoing integration between *in situ* plume sampling and evolving remote sensing mapping techniques will allow more confidence in our ability to define water types and the maximum concentrations that are likely to be found in these water types. From this information we will continue to refine our understanding of spatial extent of high exposure and high risk areas within GBR waters.

From this work, we have been able to map out areas of high risk as shown below in Figure ii. This is an example of areas at risk of exceeding water quality guidelines for TSS and Chl-a for the whole GBR.

## **1.5. Discussion**

Sampling in the 2009/10 year took place in four regions and showed that the influence and impact of the high flow events is continuous over the whole wet season. Previous work (Devlin et al., 2001) has identified that the concentrations of pollutants measured in plume waters are high and can influence longer term water quality concentrations, however this work did focus more on the transport and transformation on the water quality parameters over a short time scale. Changes in the timing and frequency of the *in situ* plume sampling has now provided a greater source of water quality data over various stages of the flow hydrograph and a better understanding of transport processes over longer time frames. In areas where flow can be continuous, such as the Wet Tropics region, the influence of altered catchment water quality can be seen in higher concentrations of dissolved nutrients, fine suspended sediment and Chl-a. This year was also significant in terms of high flows for the southern catchments, particularly for the Fitzroy River where the daily flow measured above the 95<sup>th</sup> percentile for 59 days. This was seen in the elevated concentrations of dissolve nutrients and Chl-a measured up to three weeks after the peak flow event.

Collection of *in situ* water quality data across different flow scenarios builds into the existing database of plume water quality data and allows for modelling of concentration and flow measurements from different catchments. More *in situ* plume data also allows for validation of the spatial measurements of water types and the identification of high risk areas.



**Figure ii. Final outputs of the spatial mapping of plume frequency and characterisation of water types show areas of high risk for TSS Guideline exceedances are located nearshore between the Mackay Whitsunday and Fitzroy regions, and for Chl-a Guideline exceedances, the area is over a much smaller geographical area along the Mackay Whitsundays and Wet Tropics regions.**

## 2. Introduction

### 2.1. Terrestrial runoff to GBR

The Reef Rescue Marine Monitoring Program (herein referred to as the MMP) undertaken in the Great Barrier Reef (GBR) lagoon assesses the long-term effectiveness of the Australian and Queensland Government's Reef Water Quality Protection Plan and the Australian Government Reef Rescue initiative. The MMP was established in 2005 to help assess the long-term status and health of GBR ecosystems and is a critical component in the assessment of regional water quality as land management practices are improved across GBR catchments. The program forms an integral part of the Reef Plan Paddock to Reef Integrated Monitoring, Modelling and Reporting Program supported through Reef Plan and Reef Rescue initiatives.

Water quality in the GBR is influenced by an array of factors including land-based runoff and river flow, point source pollution, and extreme weather conditions. Monitoring the impacts of terrestrial discharge into the GBR is undertaken within the flood plume monitoring program, which targets the sampling and understanding of the high flow events which input large volumes of terrestrially sourced pollutants through river discharge. Results presented in this report summarise the flood data collected over the 2009/10 wet season. To further the understanding of the extent and frequency of plume waters, remote sensing methods were also incorporated into the flood monitoring and will be reported for the whole of GBR.

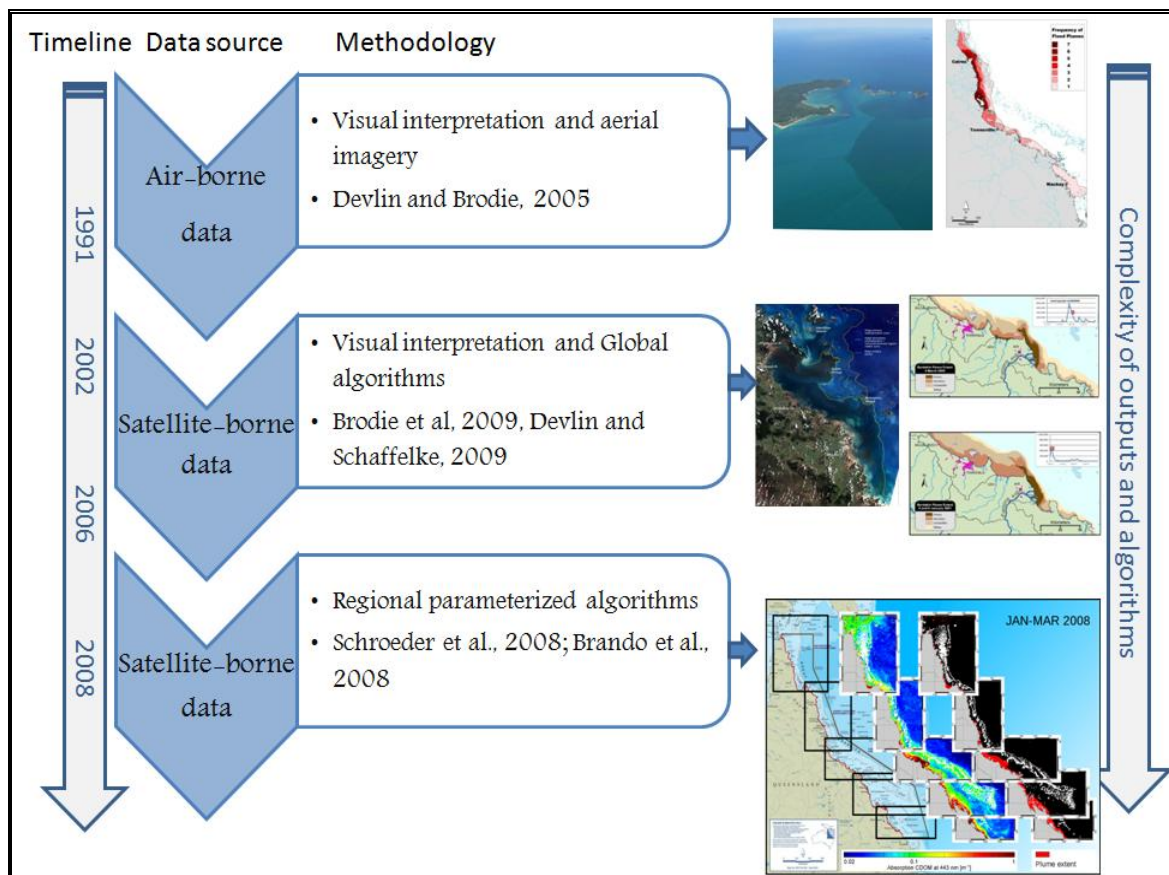
Because of the large size of the GBR Marine Park (350,000 km<sup>2</sup>), the short-term nature and variability (hours to weeks) of runoff events and the often difficult weather conditions associated with floods, it is very difficult and expensive to launch and coordinate comprehensive runoff plume water quality sampling campaigns across a large section of the GBR (Devlin et al., 2001; Furnas, 2005). To counter this variability, this project runs a multi-pronged assessment of the exposure of selected GBR inshore reefs to material transported into the lagoon from GBR Catchment rivers. Plume water quality data is measured through a combination of *in situ* water quality measurements taken at peak and post flow conditions in targeted catchments throughout the wet season. River plume extent, frequency and duration are measured through the use of remote sensing products.

## **2.2. Mapping of plume waters**

Since the commencement of the MMP, significant investment from within the program has supported the development of remote sensing methods as a monitoring tool for water quality (chlorophyll, CDOM, TSS and light attenuation) in the GBR. Field based mapping of flood plume extent and concentrations is relatively accurate, though can be constrained by costs and logistics. It is difficult to employ boats and in situ sampling for the duration of the plumes, specifically the larger dry tropics plumes which may last for several weeks. There are also issues in being able to identify the visible plume extent when the plume water type is related to the nutrient enriched waters driving elevated chlorophyll concentrations. A combination of field and satellite image mapping is suggested as an alternative as flood plumes have been mapped successfully from remote sensed data in number of different coastal environments around the world. Remote sensing is more cost-effective and more informative for a variety of detection, monitoring and processes understanding tasks. These improvements have enhanced the confidence in remote sensing estimates and it is intended that remote sensing may soon be a primary tool for detecting broad scale changes in GBR water quality.

Recent advances in the use of remote sensing algorithms, including the use of regionally parameterised algorithms has allowed a much greater area of the inshore GBR to be monitored by remote sensing and added data value to the program by increasing the frequency of available measurements during periods that can be limiting for vessel sampling due to adverse weather conditions.

The techniques used in remote sensing and their resulting products evolved in complexity with time, from basic aerial photography in combination with in-situ monitoring to the application of advanced regional parameterized ocean colour algorithms (Fig 2.1).



**Figure 2-1: The evolution of remote sensed imagery in the mapping and monitoring of plume waters in the Great Barrier Reef.**

Aerial and remote sensing surveys in other marine waters (Andrefouet et al., 2002, Chérubin et al., 2008; Paris and Chérubin, 2008. Soto et al., 2009) and the GBR (Devlin et al., 2001; Devlin and Brodie, 2005, Brodie et al., 2010) have been useful in the determination of areas of marine coastal ecosystems subject to exposure to river flood plumes. Plumes can be mapped and their intersection with ecosystems visually assessed. Water samples collected from within the plume can be analysed for the contaminants of concern (Devlin et al., 2001) and estimates of the length of exposure and concentrations experienced by biological systems can be assessed

At present there exists uncertainty of the extent of transport and potential influence of catchment-derived contaminants in the GBR system. Previous studies of flood plumes and coastal sediment transport off the Burdekin River (Wolanski and van Senden, 1983;

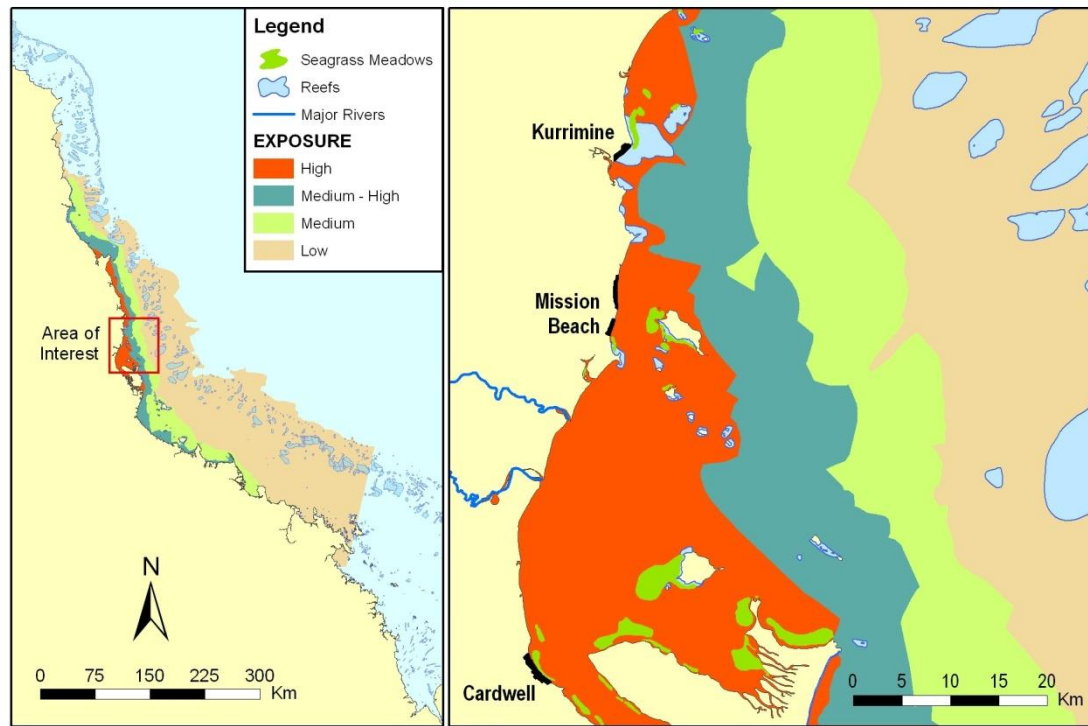


McCulloch et al., 2003; Devlin et al., 2001; Orpin et al., 2004), the Wet Tropics rivers (Devlin et al., 2001; Devlin and Brodie, 2005) and the Fitzroy River (Brodie and Mitchell, 1992; ; Devlin and Brodie, 2005; Devlin and Schaffelke, 2009) have revealed exposure of inshore ecosystems including coral reefs and seagrass to a range of nutrients associated with dissolved and fine particulate fractions of the river load. The use of remote sensed imagery allows us to identify areas of risk in the Great Barrier Reef. Knowledge of high exposure areas will be useful in the links between catchment characteristics and reef health (Brodie et al., 2008a; 2008b), and will link in with the current MMP to provide an invaluable monitoring technique for the assessment of water quality and reef health in GBR waters.

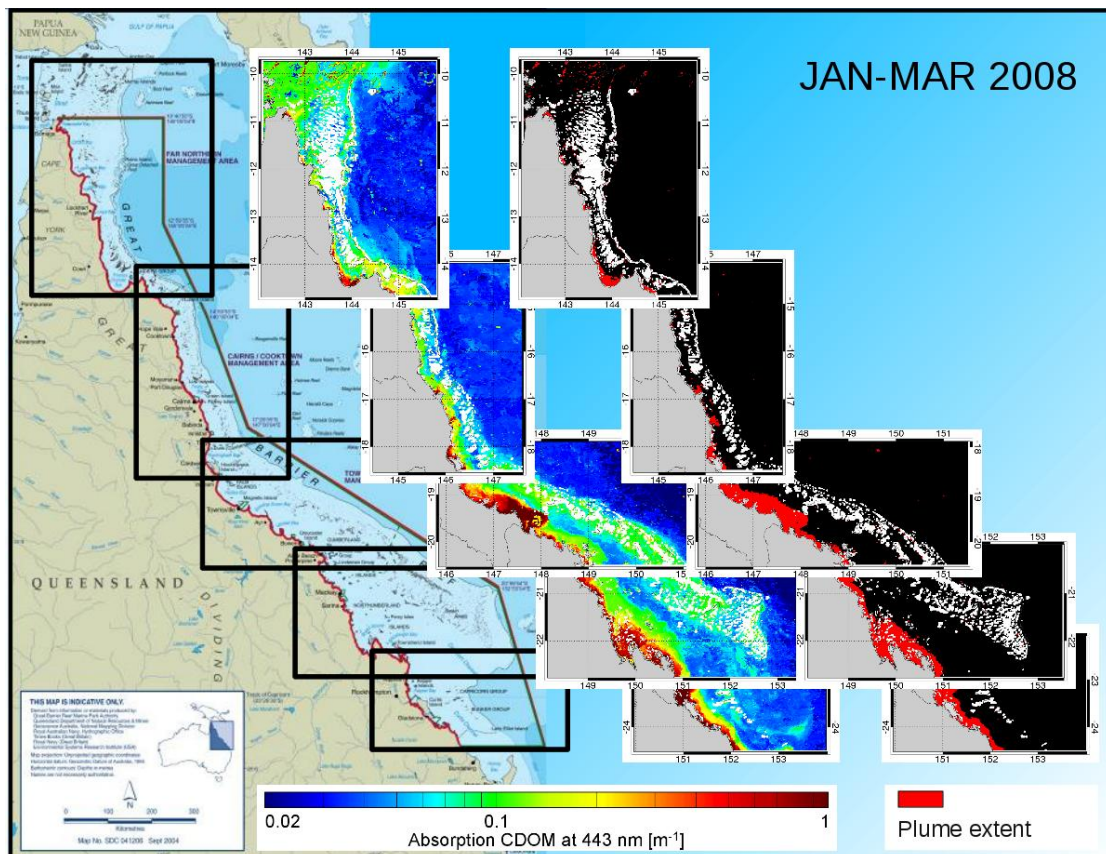
Our understanding of impact relates to our understanding of the links between exposure and impacts. Recent work on the mapping and modelling of plume exposure is a key link to identifying where the terrestrial influence extends to and how frequently an ecosystem may see altered water quality conditions (Devlin and Brodie, 2005, Devlin and Schaffelke, 2009, Maughan and Brodie, 2009). The monitoring and measurement of riverine plumes now uses the combined information from aerial imagery, remote sensing imagery and water quality concentrations during high flow events to identify the areas ‘at high exposure to plumes’ in the GBR marine area. Devlin and Schaffelke, 2009 were able to identify the areas at risk adjacent to the Tully-Murray catchments with a modelled estimate of the frequency at which inshore reefs and seagrass beds would see plume waters (Fig 2.2). Maughan and Brodie, 2009 built on previous work (Maughan et al., 2008 Devlin and Brodie, 2005) and used simple spatial calculations based on plume movement, catchment characteristics, flow intensity and proximity of the inshore ecosystems to model the high risk areas in GBR waters (Maughan et al., 2008; Maughan and Brodie, 2009). This work presented a simple reef exposure model to visualise current contaminant exposure to reefs and future management options (Maughan and Brodie, 2009).

Another new approach to map the extent of freshwater discharge to the GBR is currently under development by using only the regional parameterized CDOM product applied to MODIS data as a surrogate for low salinity waters. A maximum CDOM absorption map is generated from January to March of each year through aggregation of daily CDOM imagery. By applying a CDOM cut-off threshold, previously defined from linear regression of in-situ

CDOM and salinity measurements, freshwater extent can be mapped as illustrated in Figure 2.3. Ongoing work on the relationship between CDOM and salinity will be useful in the further validation of this mapping method.



**Figure 2-2: Plume exposure map for the Tully-Murray marine area. Exposure is calculated along a high to low gradient, where high exposure relates to a higher frequency of plume intersections.**



**Figure 2-3: Great Barrier Reef subdivided into five management regions (left). Maximum CDOM absorption from regional parameterized ocean colour algorithm mapped for the period January to March 2008 (centre). Freshwater plume extent mapped by applying a CDOM threshold derived from linear regression of in-situ CDOM and salinity measurements.**

An estimate of the exposure of individual reefs to various contaminants can provide the basis of a risk assessment of GBR condition from water quality influences. Mapping of spatial differences in water quality concentrations (De'ath and Fabricius, 2008) demonstrate very clearly a strong gradient of change north to south and inshore to offshore. Linking the movement of flood plumes and impacted water quality to reef exposure has been useful in identifying the reefs at risk from contaminants (Devlin et al., 2005; Maughan et al., 2008). This work led to a Reef Exposure model, where the exposure criterion would factor parameters such as the proximity of the reef to the source of the contaminant, the likelihood and frequency of exposure of the reef to river plumes, and the amount of contaminant within the plumes at a range of distances (Maughan et al., 2008). The model provides a relatively simple way of combining contaminant load estimates, river flow and

variability characteristics with plume and contaminant behavior, and the distance of every reef to each river mouth to give an estimated reef exposure class. Historical flood plume extent data (modelled) was used to quantify the typical spatial extent of the summer runoff–seawater mixing zone of the GBR lagoon. This spatial analysis demonstrated the existence of a discernable north–south gradient along the length of the GBR. The undisturbed catchments of the northern GBR showed much lower levels of nutrient enrichment with a strong correlation between this north–south enrichment gradient and the flood concentration of dissolved inorganic nitrogen (DIN) entrained by the various river systems. Recent work (Deann and De’ath, 2008; Fabricius and De’ath, 2008; De’ath and Fabricius, 2010) identifies strong gradients of water quality with biological measurements, showing very clearly that water quality does and is influencing changes in biological responses. Regionally specific spatial models, created by the combination of remote sensing imagery and in-situ water quality data are now being investigated with exposure models for the Tully and Burdekin (Devlin and Schaffelke, 2009; Devlin et al., 2010) identifying the actual number and location of reefs and seagrass beds at risk from high TSS and/or nutrient waters. Further work on the application of remote sensing algorithms is underway with CDOM measurements being used to define the actual full extent of plume (riverine) waters for each year, and the total area of freshwater influence (Devlin et al., 2010). Finally the use of remote sensing algorithms and high frequency data loggers are being sourced for use in water quality compliance monitoring over the regional areas (Brando et al., 2010; Devlin et al., 2010).

This spatial mapping work has used available spatial information to identify the large scale spatial and temporal changes that occur along and across GBR waters. In all cases, the exposure and risk associated with areas north of Cooktown were different from areas south of Cooktown. This included water quality concentrations, outputs from the long term chlorophyll monitoring and measured impacts on biological systems. We will build on these spatial mapping techniques to further assess the impact of plume (riverine) influence on the GBR, and to identify which areas are more at risk from exposure to altered water quality conditions.

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

- a) Assess the concentrations and transport of major land sourced pollutants to the GBR lagoon,
- b) Assess spatial and temporal variation in near-surface concentrations of suspended solids, turbidity, CDOM and chlorophyll *a* during available 2009/10 river plumes in the GBR catchment using remote sensing,
- c) Assess the concentrations of chemical pollutants in the vicinity of inshore GBR reefs during flood events, and
- d) Quantify the exposure of reef ecosystems to these land based contaminants.

Further research questions that will be explored include:

- The fate of dissolved and particulate materials in flood plumes (sedimentation, desorption, flocculation, biological uptake),
- The 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, and
- Changes in phytoplankton assemblages during the duration of the plume event, and how this influences long term chlorophyll concentrations within the different regions.

### **2.3. Review of riverine plumes in the Great Barrier Reef**

Review of flood plumes in the GBR were published in 2001 and 2010 (Devlin *et al.*, 2001, Devlin and Waterhouse, in press) which reported on flood plumes sampled from 1991 to 2009. The main conclusions from these reviews 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 lengths of direct impingement ranging from days to weeks 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) (Wolanski et al., 1994).
- 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 (south of Townsville) receive riverine waters on a less frequent basis.
- Data from flood plumes clearly indicate that the composition of plumes is strongly event specific, varying over time and water depth. Timing of sampling is critical in obtaining reliable estimates of material exported in the flood plumes. There is a hysteresis (lag effect) 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 less significant in the smaller Wet Tropic rivers (Herbert to Daintree) than in the larger Dry Tropic rivers of the Burdekin and Fitzroy Rivers, which may influence the offshore waters for periods of weeks (Devlin and Brodie, 2005).
- 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 of nutrients, 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 typical for larger rivers such as the Burdekin River, where suspended solid and particulate phosphorus concentrations dropped to very low levels only a few kilometers from the Burdekin River mouth at salinity of approximately 10ppt. 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 predominant south-east trade wind regime on the inner shelf. Reductions in suspended sediment with increasing salinity in the plume have been less clear in some of the other studied plumes, but this is complicated by resuspension during the plume event in stronger wind conditions on these occasions (Devlin et al., 2001).
- 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 during flood events.
- Chlorophyll *a* concentrations have an inverse pattern of increasing concentrations at some distance from the river mouth. This is likely to be influenced by the length of time which water column phytoplankton have been exposed to flood generated



nutrients and increasing light as suspended matter settles 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 (Devlin and Brodie, 2005; Devlin and Schaffelke, 2009).

- 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.

## **2.4. Knowledge gaps**

There are several areas of study which require further work to improve our understanding of flood plume distributions, dynamics and impacts on the GBR. The following areas are currently being investigated under a number of different research and/or monitoring projects:

- Elucidation of load concentrations with actual plume measurements.
- Further integration of remote sensing techniques in the identification of plume extent and plume concentrations.
- Horizontal and vertical definition of plume constituents.
- Plume behavior linked to ongoing climate modelling scenarios.
- Development of a reporting metric for plume concentrations and extents for the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program.

## 3. Methods

### 3.1. Sampling design

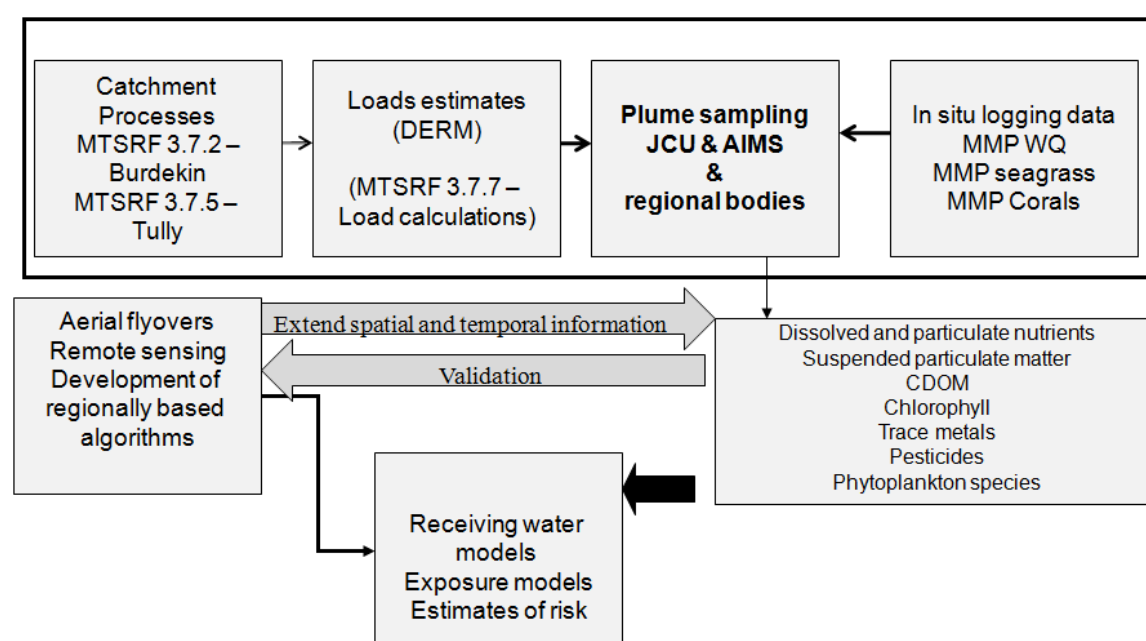
The flood plume monitoring is part of a water quality assessment which includes both baseline and event sampling. This monitoring is run in partnership with the other MMP sub-programs including water quality (3.7.8) and coral monitoring (3.7.1b) (Schaffelke et al., 2010; Thompson et al., 2010).

The three main facets of the marine flood plume monitoring are

1. Transport and processing of nutrients, suspended sediment and pesticides:
  - Delivered through the water quality monitoring. Measurement of water quality parameters presented against salinity gradients for each catchment and each event to describe the movement and transport of water quality parameters.
2. Extent and exposure of flood plumes to reefs related to prevailing weather and catchment conditions:
  - Delivered through spatial mapping of plume extent and frequency. Information acquired from remote sensing products including true colour processing of plume waters and the application of water quality algorithms (Chlorophyll and Coloured dissolved organic matter and Total suspended solids). 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 products at appropriate time and space scales is useful as a key indicators of cause and effect.
3. Incorporation and synthesis of monitoring data into GBR wide understanding of anthropogenic water quality conditions, water models, the MMP and Paddock to Reef reporting:
  - Synthesis and reporting of flood plume water quality data and exposure mapping into the MMP. The 2009/10 reporting will use remote sensing data.

Further work on the integration and reporting of water quality data collected under this sub-program (3.7.2b) and the long-term water quality sub-program (3.7.8) is currently being investigated by JCU, CSIRO and AIMS researchers through Reef Rescue funding. More integrative approach to reporting will be offered in the 2010/11 reporting period.

Data from the flood monitoring feeds into the validation of existing models and the development of regionally based remote sensing algorithms (Brando et al., 2008; 2010). Water quality collected in flood plume waters look to measure the conditions during first flush and high flow event situations to identify the duration and extent of altered water quality conditions. Data collected under the MMP also feeds into the ongoing catchment to reef monitoring programs and the integrated Paddock to Reef reporting process (Fig 3.1).



**Figure 3-1: Diagrammatic representation of the integrative programs and data availability running concurrently with the flood plume monitoring.**

Water quality data collected within this monitoring sub-program are reported against the baseline flow rates over the 2009/10 sampling period. Flow data for this sampling year has

been supplied by the Queensland Department of the Environment Resources Management (DERM) under the GBR catchment monitoring program (DERM , 2010).

### **3.2. Sample collection**

Water sampling was carried out by ACTFR staff from the Catchment to Reef research group, James Cook University. Further sampling was also undertaken by boat operators located in the Tully and Fitzroy areas. Appropriate training was carried out with these individuals prior to the plume sampling. Details of the sampling times and number of sites vary between catchment and marine areas (Table 3.1). Water samples are collected from multiple sites within the flood plume. Location of sites area are always dependent on which rivers were flooding and the areal extent of the plume, but generally samples were taken in a series of transects heading out from the river mouth.

All plume sampling was carried out on marine vessels, with surface water samples collected for a suite of water quality measurements (Table 3.2). Samples in plume waters are collected using a clean, rinsed bucket in the top meter of water, taken at each site. The samples are then filtered for dissolved nutrients and total nutrients. Samples are also collected for chlorophyll, total suspended solids, and colored dissolved organic matter (CDOM), which are place on ice and filtered within 24 hours. At every third to fourth site (dependent on size of sampling area), samples are collected for phytoplankton enumeration and pesticides. Depth profiles are taken at each site with a SeaBird profiler, collecting depth profiles of salinity, temperature, dissolved oxygen and light attenuation (Table 3.2). Depth profiles were not collected at all sites due to sampling by volunteers who did not have access to all the sampling equipment.

Three regions were monitored for pesticide residues in the 2009/10 flood plume monitoring program adjacent to the Wet Tropics (Russell-Mulgrave and Tully Rivers), Burdekin (Burdekin River) and Mackay Whitsunday (Pioneer and O’Connell Rivers) Regions. A total of 34 direct water (‘grab’) samples were collected in 2009/10 for pesticide analysis including 5 samples from the Russell-Mulgrave River flood plume, 9 from the Tully River flood plume, 3 from the Burdekin River flood plume, 12 from the O’Connell River flood plume and 5 from

the Pioneer flood plume. In addition, three passive samplers were deployed and recovered from Bedarra Island (two separate deployments in January and March 2010) and from the Tully River mouth (one deployment in March 2010). Five herbicides (diuron, atrazine, hexazinone, simazine and tebuthiuron) and one insecticide (imidachloprid) were detected in the monitoring program.

Water samples for pesticides were taken from surface waters. These samples were analysed by high performance liquid chromatography mass spectrometry (HPLC-MSMS) at the National Association of Testing Authorities accredited Queensland Health and Forensic Scientific Services Laboratory. The herbicides were extracted with dichloromethane and quantified by HPLC-MSMS adapted to analysis of seawater samples by omitting addition of sodium chloride to extractions). Further analytical details are provided in Lewis et al. (2009) including a summary of analytical preparation procedures, analytical instruments and settings, and reported detection limits.

The passive samplers were collected and refrigerated at 4°C before extracted with acetone, ethyl acetone and trimethylpentane. The extracts were analysed by HPLC-MSMS and herbicide water concentrations were calculated by dividing the mass of the herbicide by the sampling rates (deployment time). Specific details on the extraction procedure, analytical methods and the calculation of herbicide water concentrations from the mass sequestered in the passive samplers are provided in Shaw et al. (2009b; 2010).

**Table 3-1: List of sampling dates and locations for all sampling events in the 2009/10 wet season.**

<b>Trip</b>	<b>Date sampled</b>	<b>Location</b>	<b>No of sites</b>	<b>Description</b>
1	29/12/2009	Tully	13	Full suite of WQ parameters plus Seabird data
2	2/02/2010	Tully	15	Full suite of WQ parameters plus Seabird data
3	3/02/2010	Russell-Mulgrave	11	Full suite of WQ parameters plus Seabird data
4	8/02/2010	Mackay Whitsunday	8	Full suite of WQ parameters plus Seabird data
5	24/02/2010	Burdekin	5	Nutrients, CDOM, salinity and chlorophyll.
6	3/03/2010	Tully	13	Nutrients, CDOM, salinity and chlorophyll.
7	4/03/2010	Mackay Whitsunday	25	Full suite of WQ parameters plus Seabird data
8	8/04/2010	Fitzroy	6	Nutrients, CDOM, salinity and chlorophyll.
9	1/04/2010	Tully	10	Nutrients, CDOM, salinity and chlorophyll.
10	8/04/2010	Tully	11	Nutrients, CDOM, salinity and chlorophyll.
11	25/04/2010	Fitzroy	6	Nutrients, CDOM, salinity and chlorophyll.

**Table 3-2: Summary of chemical and biological parameters sampled for the MMP flood plume monitoring.**

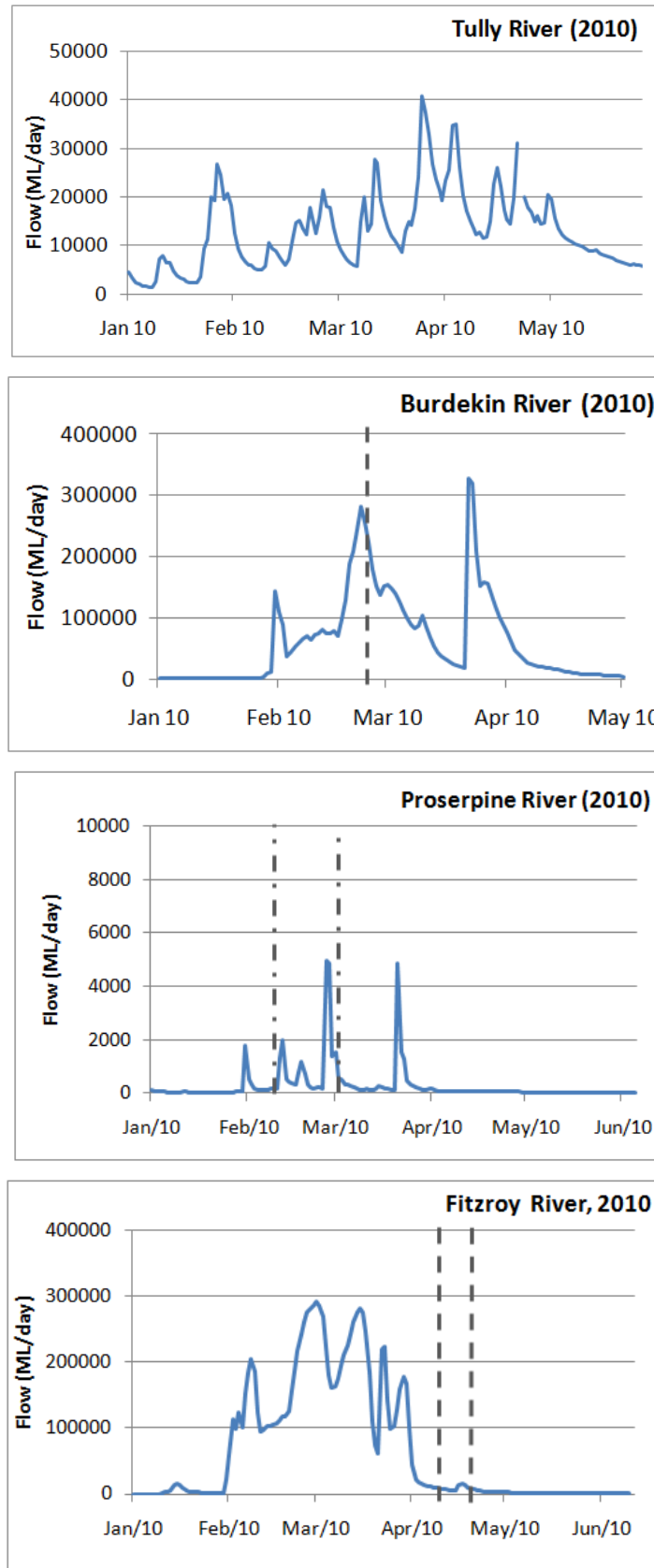
Type of data	Parameter	Comments	Reported
<b>Physico chemical</b>	pH	Taken through the water column. Sampled with Sea Bird profiler	x
	Salinity		x
	Dissolved Oxygen		x
	Turbidity		x
	Light Attenuation (PAR)		x
<b>Water quality</b>	Dissolved nutrients	Surface sampling only	X
	Particulate Nutrients		x
	Chlorophyll		X
	Suspended solids		X
	CDOM		x
	DOC		-
	Trace Metals	Not collected in 2010	-
	Pesticides	Not at all sites	x
<b>Sediment tracing</b>	Clay Minerology	To be reported on in 3.7.2	-
	Trace elements		-
	Sr/Nd isotopes		-
<b>Biological</b>	Phytoplankton counts	Not at all sites	x

### **3.3. Regional sampling**

High flow events occurred in all GBR catchments in the 2009/10 sampling year, with higher than average flows being measured in all catchments south of the Burdekin region (Table 4.1). Water quality sampling took place in plumes associated with the Tully, Burdekin, Mackay Whitsunday and the Fitzroy Rivers. Multiple sampling occasions occurred in the Tully, Mackay Whitsunday and Fitzroy plume waters. Not all sampling was associated with the peak flow, particularly for the Mackay Whitsunday and Fitzroy Rivers, where sampling occurred days to weeks after the highest flow peak occurred. Figure 3.2 identifies the hydrograph associated with these four rivers and the sampling times that occurred along these hydrographs.

Focus was again on the Tully catchment, due to the ongoing monitoring within this area and to the regular flooding cycles. Coordinated sampling was carried out within the Mackay Whitsunday region in conjunction with the Reef Catchments team. Boats were supplied (and funded) by Reef Catchments and sampling and analysis was carried out by ACTFR staff. Inclement weather was a problem with repeated sampling in the Mackay Whitsunday region with only two field trips carried out within this region. The events were not linked to the peak flow events but sampled as closely as possible to the peak date. Assistance from the Reef Catchments group was substantial, with funding for boat hire and help with sampling logistics. The Burdekin River had two significant flow events, but again, due to inclement weather, only the first (24<sup>th</sup> February 2010) was sampled. The Fitzroy River had a very large flow event, with sampling of the plume waters initiated two weeks after peak flow to try to capture the longer term changes in water quality associated with plume waters.





**Figure 3-2: Sampling times identified over the 2010 hydrograph for each river within the 2009/10 sampling period.**

### **3.4. Laboratory analysis**

Laboratory analysis techniques vary slightly between agencies. The methods described in this report are for the ACTFR laboratories at James Cook University. Further detailed information on the scope of the field and laboratory analyses can be found in the MMP QA/QC Report (RRRC 2010; [www.rrrc.org.au](http://www.rrrc.org.au)).

#### **3.4.1. Dissolved and total nutrients**

Samples were analysed for concentrations of dissolved inorganic nutrients ( $\text{NH}_4$ ,  $\text{NO}_2$ ,  $\text{NO}_3$ ,  $\text{NO}_2 + \text{NO}_3$ ,  $\text{PO}_4$  and Si) by standard procedures (Ryle et al., 1982) implemented on a Skalar 20/40 autoanalyser, with baselines run against artificial seawater. Analyses of total dissolved nutrients (TDN and TDP) were carried using persulphate digestion of water samples (Valderrama, 1981), which are then analysed for inorganic nutrients, as above. DON and DOP were calculated by subtracting the separately measured inorganic nutrient concentrations (above) from the TDN and TDP values. Particulate nitrogen concentrations of the particulate matter collected on the GF/F filters were determined by high temperature combustion using an ANTEK Model 707 Nitrogen Analyser. The filters were freeze dried before analysis. Following primary (650 °C) and secondary combustion (1050 °C), the nitrogen oxides produced were quantified by chemiluminescence.

Particulate phosphorus was determined colorimetrically (Parsons et al., 1984) following acid-persulfate digestion of the organic matter retained on the glass fibre filters. Acid-wash glass mini-scintillation vials were used as reaction vessels. Filters were placed in the vials with 5 ml of 5% w/v potassium persulfate and refluxed to dryness on an aluminum block heater using acid-washed marbles as stoppers for the vials. Following digestion, 5 ml of deionized water was added to each vial and the filter and salt residue resuspended and pulverized to dissolve all soluble material. The residue in the vials was compressed by centrifugation and the inorganic P determined colorimetrically in aliquots of supernatant. Inorganic and organic P standards were run with the batch of samples.

#### **3.4.2. Phytoplankton pigments**

Phytoplankton pigments are analysed in the ACTFR laboratories using the spectrophotometric method. Samples are processed promptly after filtration to prevent

possible chlorophyll degradation from residual acidic water on filter Samples on filters taken from water having pH 7 or higher may be stored frozen for three weeks. The pigments are extracted from the plankton concentrate with aqueous acetone and the optical density (absorbance) of the extract is determined with a spectrophotometer. To achieve consistent complete extraction of the pigments, the cells are disrupted the cells mechanically with a tissue grinder. The absorbance of chlorophyll pigments within the centrifuged samples is read using a dual beam spectrophotometer.

#### **3.4.3. Total suspended solids**

Suspended solids refer to any matter suspended in the marine water. Suspended solids concentrations are determined gravimetrically from the difference in weight between loaded and unloaded 0.4  $\mu\text{m}$  polycarbonate filters after the filters had been dried overnight at 60°C. A well-mixed sample is filtered through a weighed standard glass fibre filter and the residue retained on the filter is dried to a constant weight at 103-105 °C. The increase in weight of the filter represents the total suspended solids.

#### **3.4.4. Coloured dissolved organic matter**

Coloured dissolved organic matter (CDOM) is an important optical component of coastal waters defined as the fraction of light absorbing substances that pass through a filter of 0.2  $\mu\text{m}$  pore size. CDOM is typically comprised of humic and fulvic substances which are sourced from degradation of plant matter, phytoplankton cells and other organic matter. Waters dominated by CDOM often appear yellow/orange in color and often black. This is a consequence of strong absorption exhibited by CDOM in the blue and ultra-violet (UV) regions of the electromagnetic spectrum. CDOM has been known to contaminate chlorophyll satellite algorithms and also has been examined as a tracer estuarine/river transport into the marine environment. Thus, knowledge of CDOM variability within the GBR is extremely useful.

Water samples are collected in glass bottles and kept cool and dark until analysis by ACTFR laboratory, which should occur within 24 hours of collection generally (on occasion up to 72 hours). Beyond this period, there might be a slight effect of biological activity on the CDOM concentrations, however provided that the material is cooled this effect will be minimal and

compared to other measurement issues, negligible. Samples are allowed to come to room temperature before placement into a 10 cm pathlength quartz cell. The CDOM absorption coefficient ( $\text{m}^{-1}$ ) of each filtrate is measured from 200-900 nm using a GBC 916 UV/VIS spectrophotometer, and Milli-Q water (Millipore) used as a reference. CDOM absorption spectra are finally normalised to zero at 680 nm and an exponential function fitted over the range 350-680 nm.

### **3.5. Pesticide sampling methods**

The water samples were analysed by liquid chromatography mass spectrometry (LCMS) and gas chromatography mass spectrometry (GCMS) at the National Association of Testing Authorities accredited QHFSS Laboratory. Organochlorine, organophosphorus and synthetic pyrethroid pesticides, urea and triazine herbicides and polychlorinated biphenyls were extracted from the sample with dichloromethane. The dichloromethane extract was concentrated prior to instrumentation quantification by GCMS and LCMS. The only variation to this technique for the seawater samples was that sodium chloride was not added for the extractions.

### **3.6. Remote sensing methods**

Remote sensed imagery has become a useful and operational assessment tool in the monitoring of flood plumes in the GBR. Combined with the more traditional in situ sampling techniques, the use of remote sensing is a valid and practical way to estimate both the extent and frequency of plume exposure on GBR ecosystems. The use of remote sensing algorithms has also become invaluable in the estimate of water quality parameters, such as TSS, chlorophyll and absorption of Coloured Dissolved Organic Matter (CDOM). Concentrations of suspended sediment and yellow substances are used to track plume distribution and dilution, and sedimentation.

Single images of plume extent are selected based on their image quality and transposed from geo-referenced true colour images and/or CDOM measurements into GIS shape files. The MODIS imagery was re-referenced to conform to GDA-94, MGA projection by applying the imagery geographic coordinate values to the MGA-94 projected values (metres) to achieve a simple bilinear solution (i.e. UTM). True colour imagery of before, during and after

each plume have been identified where there was low cloud cover and reasonably good visualization of the plume area

True colour imagery has been used to develop a better understanding of the extent of plume waters in relation to weather and flow conditions. Advanced algorithms have been applied to plume imagery to calculate concentrations of TSS, chlorophyll and CDOM during and after a significant flow event to trace the extent of water quality parameters in at peak concentrations. The extent and concentrations of plume waters, coupled with extensive in situ water quality sampling was used to estimate the risk of plume exposure to inshore biological systems.

### **3.6.1. Application of algorithms**

Remote sensing data has been acquired from the Moderate-resolution Imaging Spectroradiometer (MODIS) onboard NASA's Earth Observing System (EOS) satellites: Terra and Aqua. 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. Data are accessed from the archives on NASA's Ocean Color website (<http://oceancolor.gsfc.nasa.gov/>). MODIS data is used for the mapping of chlorophyll-*a* and colour dissolved organic matter (CDOM). Several MODIS data products are freely available via the internet. At present a library of MODIS data from flood plume events within the Great Barrier Reef 2002-present, are being catalogued at the ACTFR. Data is being sourced both from NASA and CSIRO Land and Water at pixel resolutions of 250 m and 1000 m. Access to data from Medium-spectral Resolution Imaging Spectroradiometer (MERIS) aboard the European Space Agency's (ESA) Environmental Satellite (ENVISAT) has recently been approved.

More detailed methodology on the use of remote sensing in flood plume monitoring was presented in Johnson et al., 2010 and Devlin et al., 2010 and will not be discussed further in this report.

### **3.7. Characteristics of plume water types**

Water characteristics are identified in each remote sensing image, with the primary water type, characterised by high turbidity, high sediment plume discharging relatively close to the river mouth. Plumes characterised by lower turbidity (low values of TSM) and higher production (identified by elevated chlorophyll values) are usually measured in the middle salinity ranges (5 to 25 ppt). Turbidity (measured as TSM) may change through these secondary waters as a result of the offshore transport of the finer particulate material and desorption processes. Plume water types moving further offshore are typically characterised by elevated CDOM values, indicating some influence of freshwater, but TSM and chlorophyll reducing to baseline concentrations. This area can be mapped much further offshore and north of the river mouth than the visually evident primary and secondary waters.

The extent of the enrichment and increased production is hard to define by true colour imagery only, and requires the application of a suite of algorithms, as well as the visual examination of the true colour processing, Total absorption at 443 nm may be used as an indicator of organic material and CDOM absorption at 443 nm as an indicator of riverine freshwater extent. Application of appropriate chlorophyll algorithms can also be helpful in the offshore areas to identify the extent of the higher primary production over the whole plume area.

The derived CDOM and detritus absorption (CDOM+D) at 443 nm combined with careful examination of quasi-true colour and chlorophyll images provided the information used to derive simple qualitative indices for separating the different stages of plume movement, or water “types”, and extent. Flood plume categories were defined based upon parameters which are readily derived from ocean colour remote sensing. Thus the spatial extent of the different water types can be mapped.

Plume types were classified qualitatively using the following criteria:

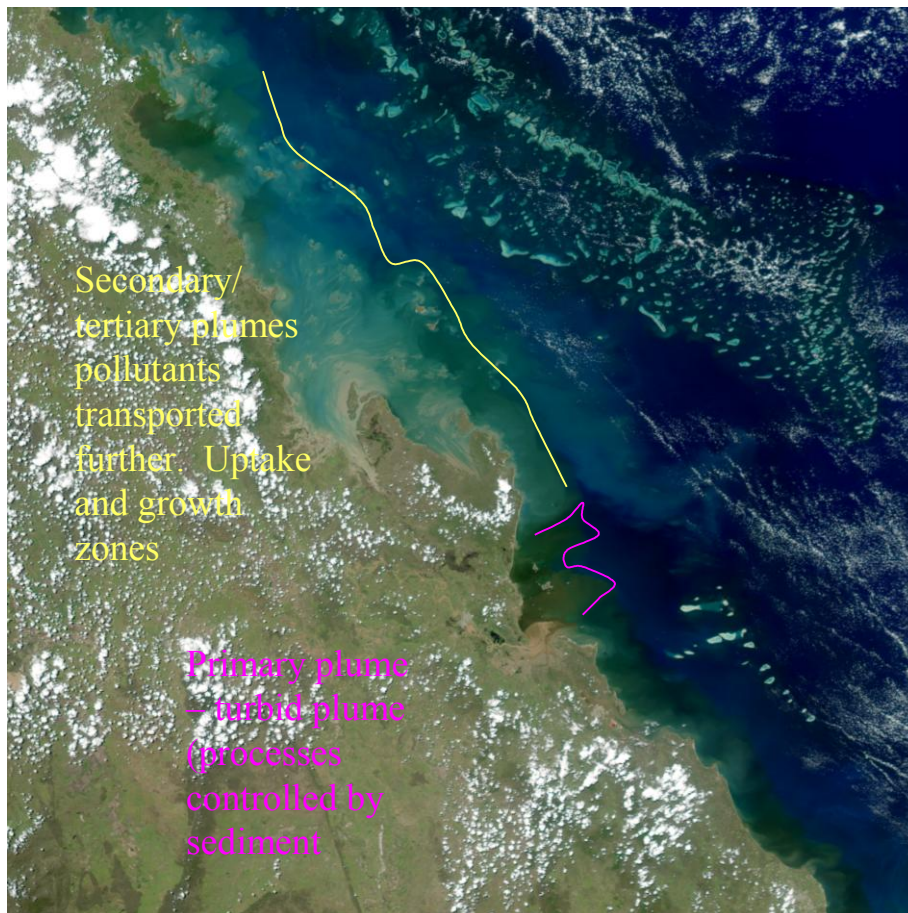
- (i) Primary water type was defined as having a high total suspended solid (TSS) load, minimal chlorophyll and high values of coloured dissolved organic material plus detrital matter (CDOM+D).

(ii) Secondary plume type was defined as a region where CDOM+D are still high however, the TSM has been reduced. In this region, the water is characterised by increased light and nutrient availability, which can prompt phytoplankton growth. Thus, secondary plume waters exhibit high chlorophyll, high CDOM+D and low TSS.

(iii) Tertiary plume type is the region of the plume that exhibits no elevated TSS and reduced amounts of chlorophyll and CDOM+D when compared with that of the secondary plume, but still above ambient conditions. This region can be described as being the transition between a secondary plume and ambient conditions.

Combining true colour information and appropriate algorithm application, identifies the three plume types with a suitable degree of confidence. In the areas where cloud had completely obscured the plume, estimations of the plume extents were achieved by assessing the plume patterns from consecutive imagery epochs in the following days. Figure 3.3 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, moving approximately 60 kilometres north. The secondary plume visible in the left hand side of the picture, moving north past Magnetic Island.

Mapping the water types shows that a combination of total suspended matter (TSM), chlorophyll (Chl) and coloured dissolved and detrital matter (CDOM+D) imagery has been extremely useful in identifying plume boundaries.



**Figure 3-3: The identification of primary and secondary plume in the Burdekin River plume. The pink line denotes the approximate extent of the primary plume water (high TSS) and the yellow line denotes the approximate extent for the secondary plume water (high chlorophyll carrying waters) (Imagery courtesy of CSIRO).**

### **3.8. Mapping water types using spectral thresholds**

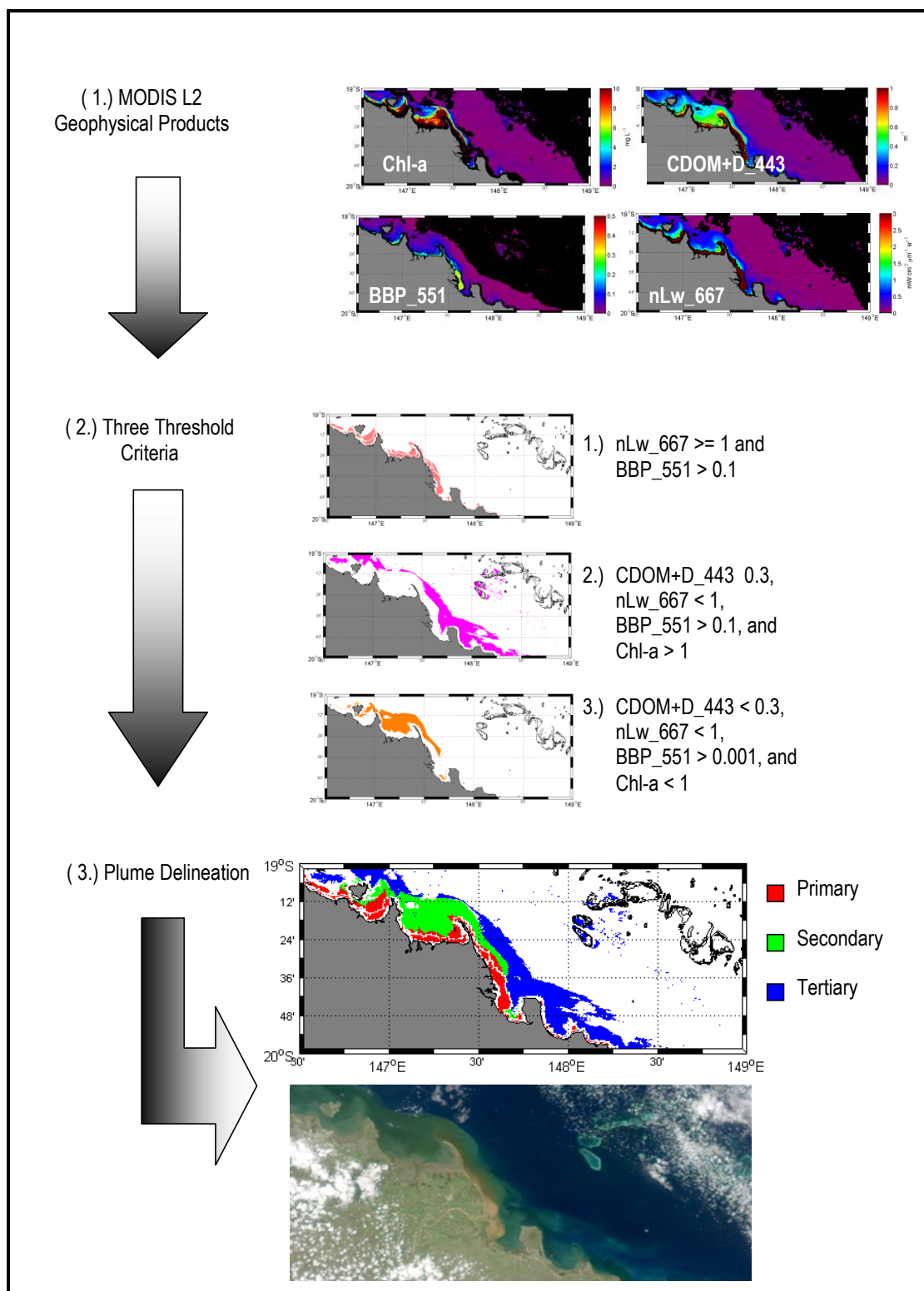
Definition of quantitative thresholds for each water type (primary, secondary and tertiary) will allow us to map the extent and frequency of water types with far greater confidence and identify the full range of spectral properties within each type. Further elucidation of the water types, using thresholds of the water quality concentrations (e.g. CDOM+D and TSM) can be made by defining the range of optical properties within the broad categories of water types.

Further elucidation of the movement of different water types, i.e., the high sediment waters as compared to the secondary clearer productive waters allows better estimate of risk and exposure for biological ecosystems. Figure 3.4 shows an example of mapping plume extents



based on a series of water quality thresholds identified for different water types. More work is required on testing the water quality thresholds related to biological ecosystems and the level of impact, and links with existing Guideline trigger values must be considered.

For comparison and validation, the final imagery classification was compared between the qualitative approach (using true colour) and quantitative (using spectral thresholds). The products were compared and outputs used to redefine the water types. The initial classification method, as described above, allowed us to map the three main plume mapping densities (e.g. primary, secondary and tertiary) based on the true colour images allowed for a visual correlation of the classified values. By using both of these products it was possible to delineate the three recognised plume classifications with a suitable degree of confidence. In the areas where cloud had completely obscured the plume, an estimation of the plume extents were achieved by correlating the plume patterns from any other imagery epochs in the following days.



**Figure 3-4: Use of spectral thresholds to identify the plume water type (primary, secondary and tertiary). Red denotes the primary, high sediment carrying waters, green, the secondary, high colour and elevated production waters and blue, elevated CDOM waters indicative of the full extent of the freshwater plume.**

## **4. Flood events in 2009/10**

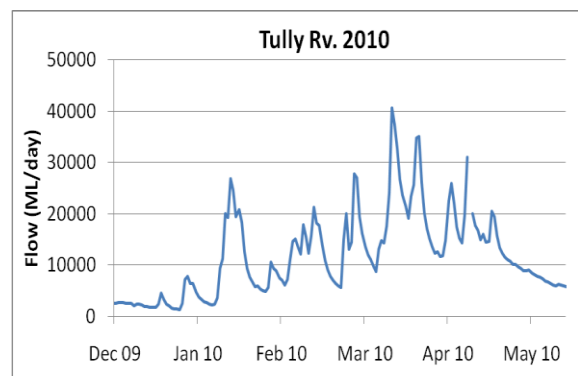
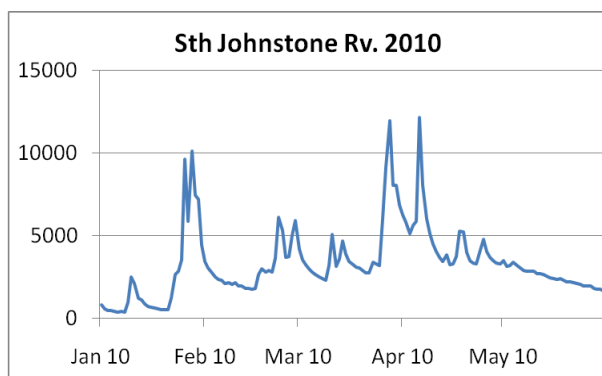
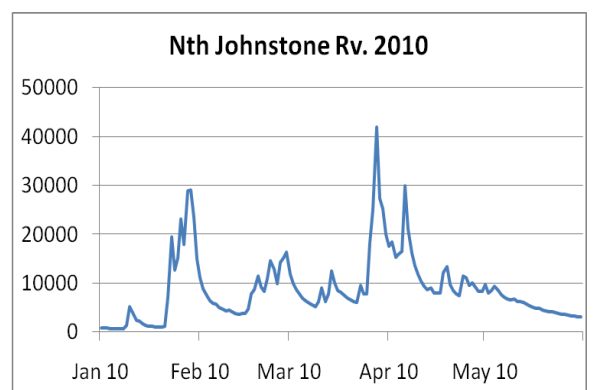
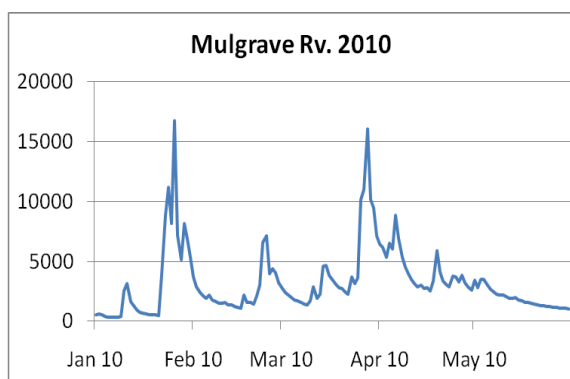
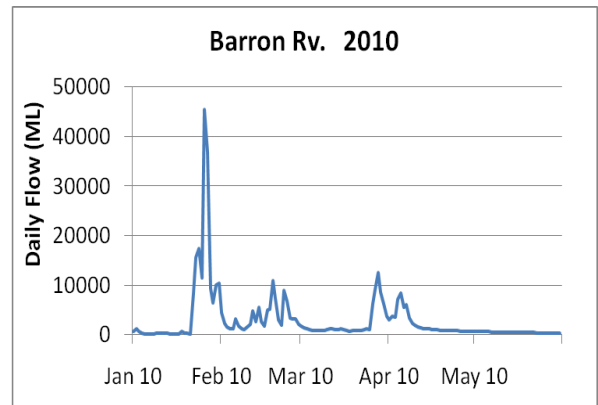
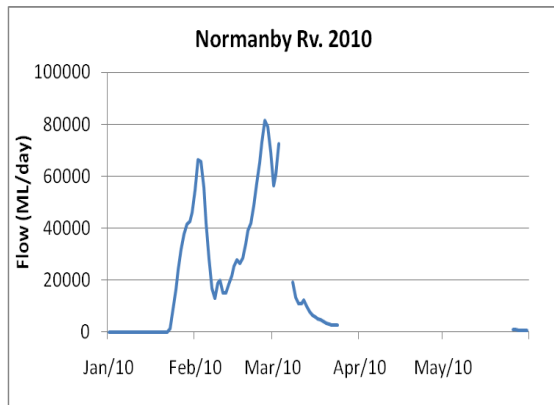
### **4.1. Description of flood events**

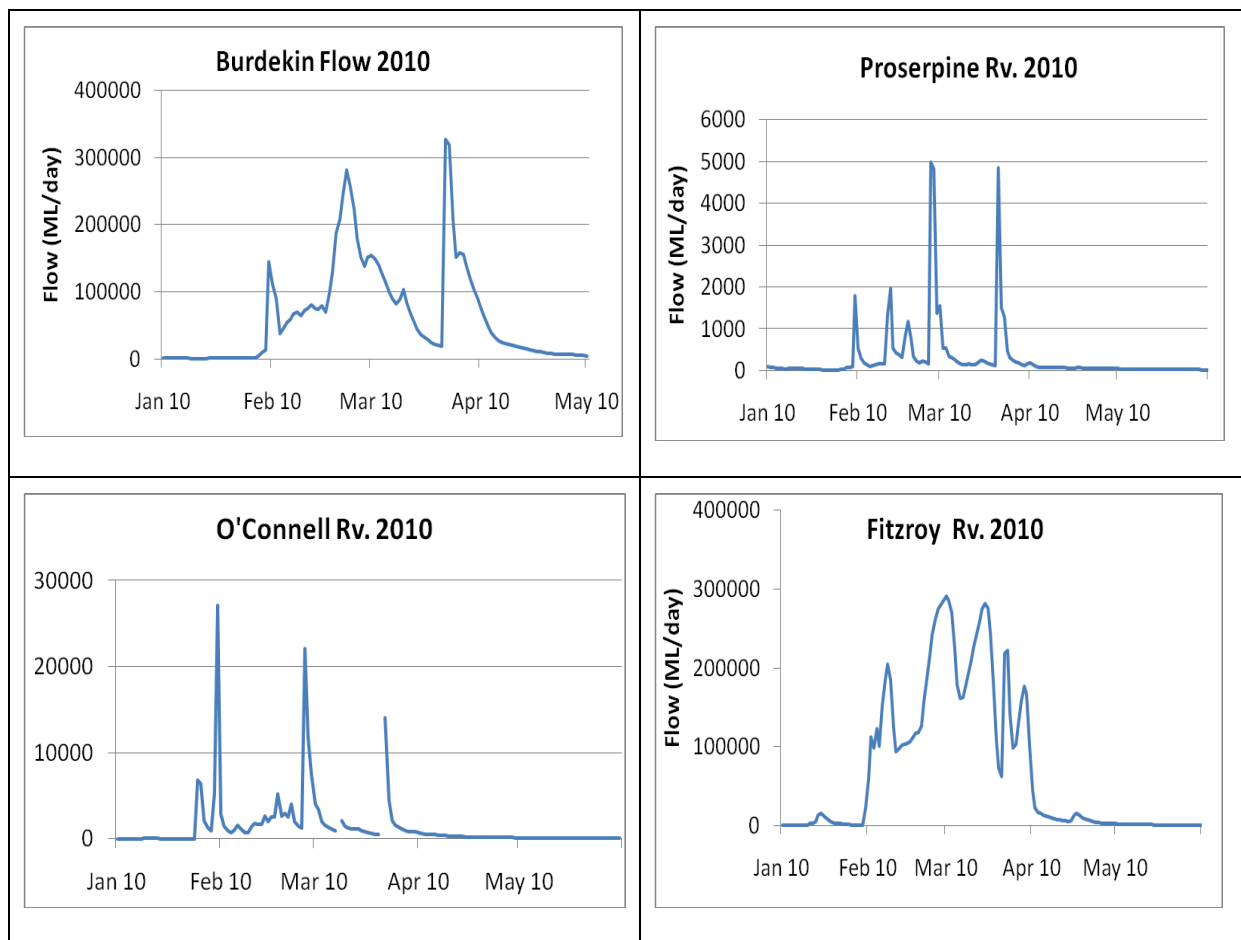
Regional assessments for the Tully, Burdekin, Mackay Whitsunday and Fitzroy River plumes are presented in this report. Reporting is dependent on the timing and structure of the plume for each day that sampling occurred.

There were a number of monsoonal lows associated with the 2009/10 season, with medium flow to high flow measured in the northern catchments. There were some very large events in the southern catchments, with significant flow measured in the Pioneer, Proserpine and Fitzroy Rivers. Flow rates for 2009/10 for the ten wet and dry tropic rivers are presented (Fig 4.1). All rivers north of and including the Herbert has total flows that were less than the long term median flow, with relative differences being from 0.49 (Normanby River) to 0.98 (Russell River) (Table 5.1)

Flow rates for all rivers south of the Herbert River were above the long term median flow (Table 5.1) with the Plane, Fitzroy and Burnett Rivers having total year flow being significantly greater than the long term median flow. Relative differences for the Plane, Fitzroy and Burnett Rivers were 3.27, 3.94 and 5.96 respectively. Whilst the Plane and Burnett Rivers were very large events, their catchment size is quite small, with total discharge volume being 368,619 ML and 881,582 ML for the Plane and Burnett Rivers. In contrast the Fitzroy River has the largest catchment and with significant flooding in 2010, has a total discharge volume of 7,975,099 ML.

The summary of the plume events and the number of days in which flow exceeded a long term 95<sup>th</sup> percentile is shown in Table 5.2.





**Figure 4-1: Flow rates associated with ten Great Barrier Reef rivers (December 2009 to May 2010).**

**Table 4-1: Annual freshwater discharge (ML) for major GBR catchment rivers in 2009/10.** The median and mean annual flow is estimated from available long-term time series for each river. Data supplied by the Queensland Department of the Environment and Resource Management. Long-term medians were estimated from annual total flows (October to October) available on: [www.nrw.qld.gov.au/precomp](http://www.nrw.qld.gov.au/precomp)

Region	River	Long-term river discharge median (ML)	Long-term river discharge mean (ML)	Total year discharge 2009/2010 (ML)	Difference between 2009/2010 flow and long-term median (ML)	Relative difference between 2009/2010 flow and long-term median
Cape York	Normanby	3,550,421	3,707,007	1,723,445	-1,826,976	0.49
Wet Tropics	Barron	692,447	795,275	545,717	-146,730	0.79
	Mulgrave	719,625	743,399	611,602	-131,797	0.85
	Russell	1,049,894	1,051,743	1,026,800	-23,094	0.98
	North Johnstone	1,845,338	1,797,648	1,652,417	-192,921	0.90
	South Johnstone	810,025	801,454	669,178	-140,847	0.83
	Tully	3,128,458	3,175,298	2,557,857	-570,601	0.82
	Herbert	3,122,768	3,492,135	152,352	-2,970,416	0.05
Burdekin	Burdekin	5,957,450	9,575,660	7,857,344	1,899,894	1.32
Mackay Whitsunday	Proserpine	35,736	70,568	49,501	13,765	1.39
	O'Connell	148,376	201,478	214,062	65,686	1.4
	Pioneer	731,441	648,238	1,319,393	587,952	1.8
	Plane	112,790	154,092	368,619	255,829	3.27
Fitzroy	Fitzroy	2,708,440	4,461,132	10,683,539	7,975,099	3.94
Burnett Mary	Burnett	147,814	217,511	881,582	733,768	5.96
Total		24,761,023	30,892,638	30,313,406	5,552,383	1.22

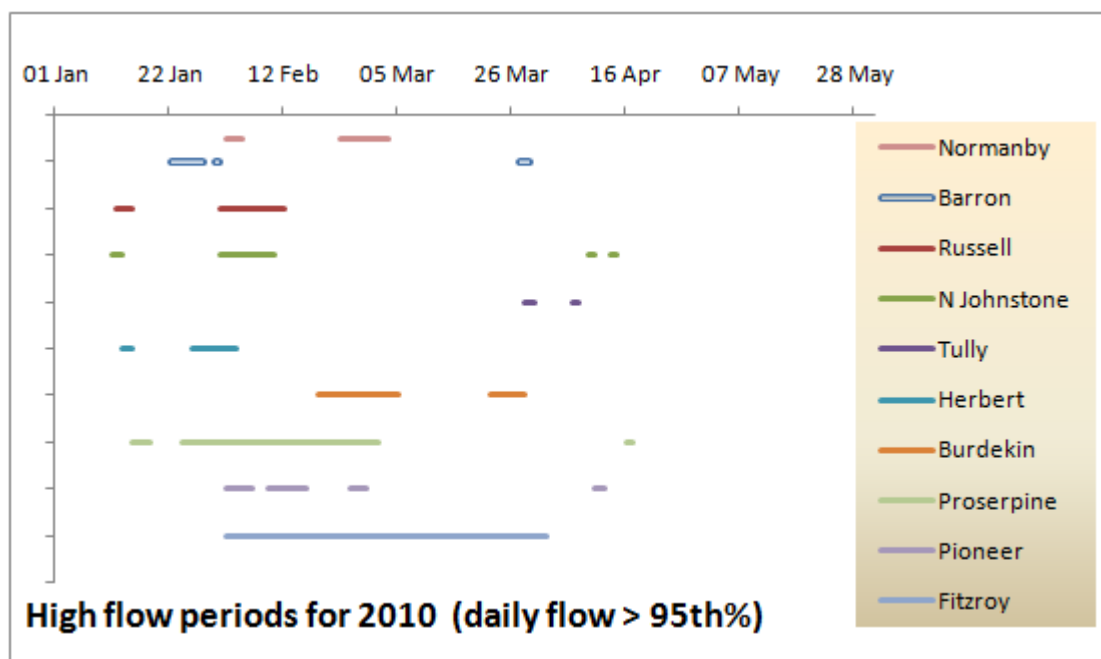


Figure 4-2: High flow periods (daily flow > 95<sup>th</sup> percentile) for 2009/10 in a selection of GBR rivers.

Table 4-2; Summary of plume events in terms of the number of days that flow exceeded 95<sup>th</sup> percentile flow value and the number of “events” (event is described as any period of greater than 2 days where the flow exceeded the 95<sup>th</sup> percentile).

River	Normanby	Barron	Russell	N Johnstone	S Johnstone	Tully	Herbert	Burdekin	Proserpine	Pioneer	Fitzroy
NRM ID	105107	110001D	111101D	112004A	112101B	116001E	116001E	120006B	122005	125007	119003A
75th percentile (daily flow)	4985.4	1156.9	3305.4	5525.5	2253.8	4588.0	5893.6	5816.2	47.8	323.2	2670.0
95th percentile (daily flow)	46105.2	7647.5	12922.8	17756.2	5532.9	31573.0	42382.7	125444.8	218.5	3396.0	35656.0
Exceedance of 95th%ile (no of days)	14	15	18	15	13	5		24	32	64	60
No of "events"	2	2	3	3	2	2		2	5	4	1

## 5. Case study 1 – Burdekin River

### 5.1. Details of sampling sites and timing

In 2010, sampling in the Burdekin plume took place at only one time on the 24<sup>th</sup> February 2010 (Fig 5.2). Due to the low number of samples collected in the Burdekin plume, the data is combined with results from the 2007/08 and 2008/09 sampling period. For the 2009/10 year, samples were taken only at the mouth and slightly north (Fig 5.1). Burdekin River flow was reasonable, with the annual median flow for 2009/10 being greater than the long term median (Table 5.1) with a relative difference of 1.32, however the flow was much lower than the previous events sampled in 2007/08 and 2008/09 (Fig 5.3).

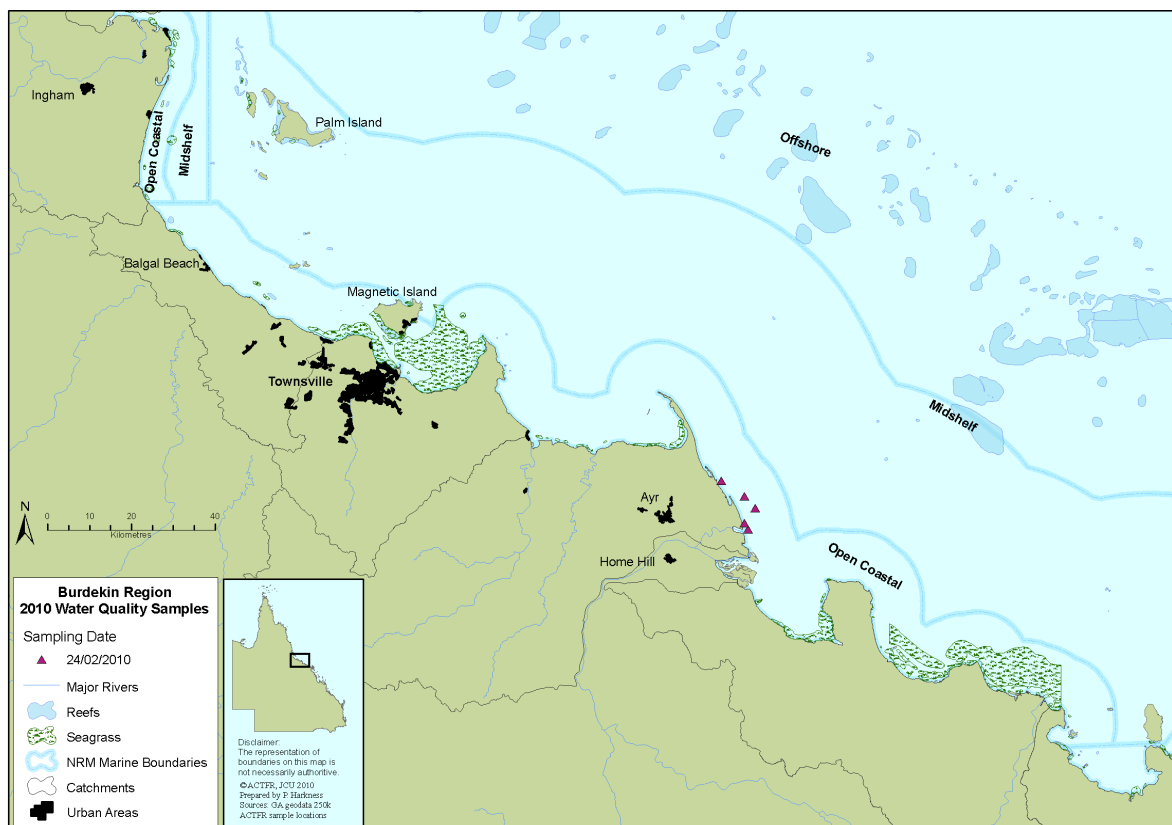


Figure 5-1: Location of all sampling sites delineated by date for the Burdekin region.



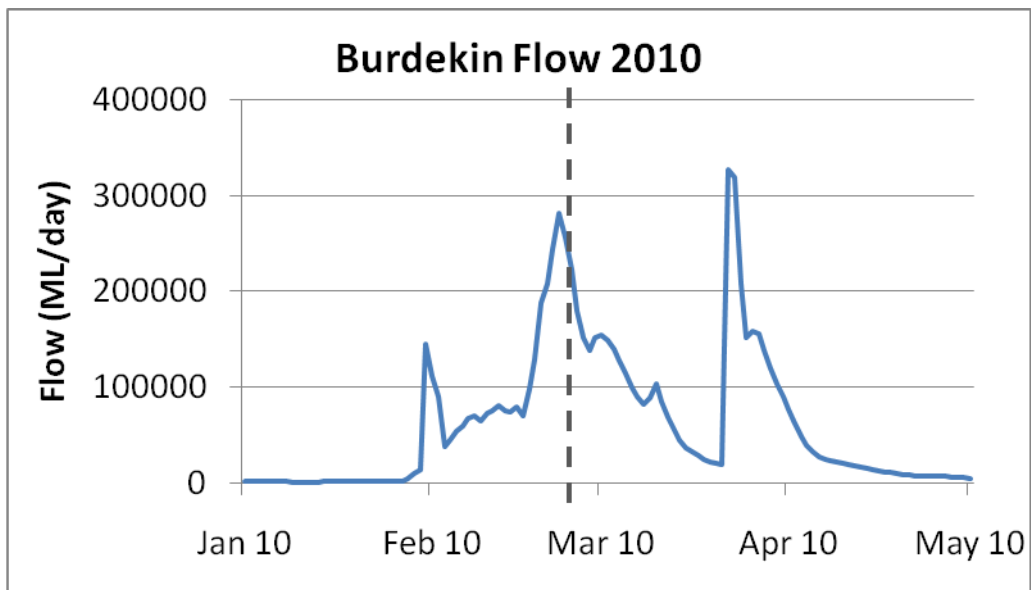


Figure 5-2: Flow hydrograph for the Burdekin River in 2010. Red line denote the periods of time in which sampling took place.

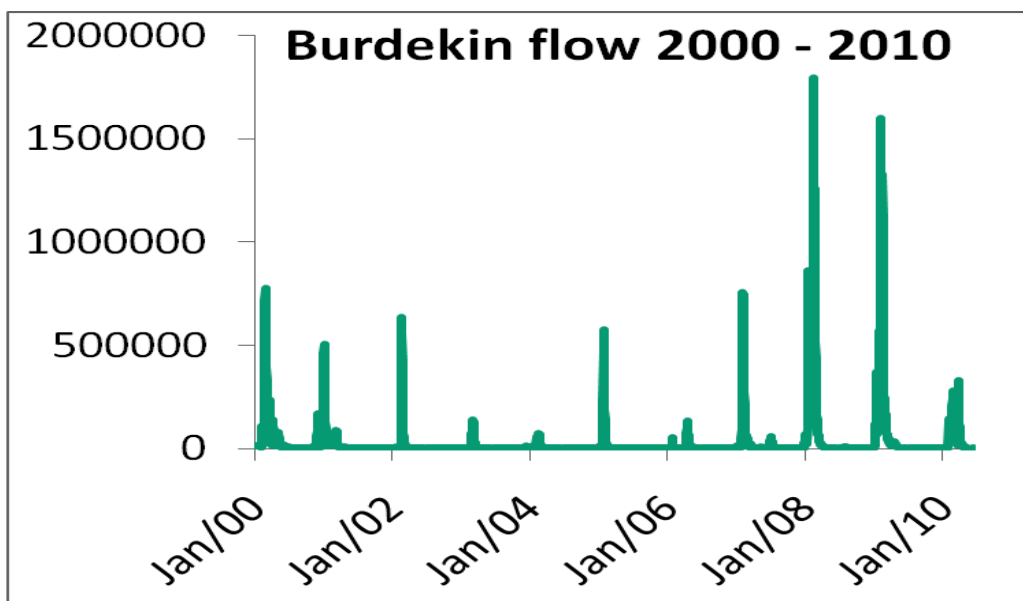


Figure 5-3: Flow hydrograph for the Burdekin River (2000 – 2010).

## 5.2. Water quality results

Water quality data was taken on 24<sup>th</sup> February 2010. The total volume of freshwater moving into the marine environment was significant, with a peak of almost 281,442.7 ML measured on 22<sup>nd</sup> February 2010.

Due to the low number of sites sampled in the Burdekin River for 2009/10, presentation of these values alone would not be instructive or descriptive of the plume components. To counter this, Figure 5.4 shows four mixing plots of the Burdekin River data for total suspended sediment (TSS), dissolved inorganic phosphate (DIP), and dissolved inorganic nitrogen (DIN) and chlorophyll for the last three sampling years, including data from 2009/10.

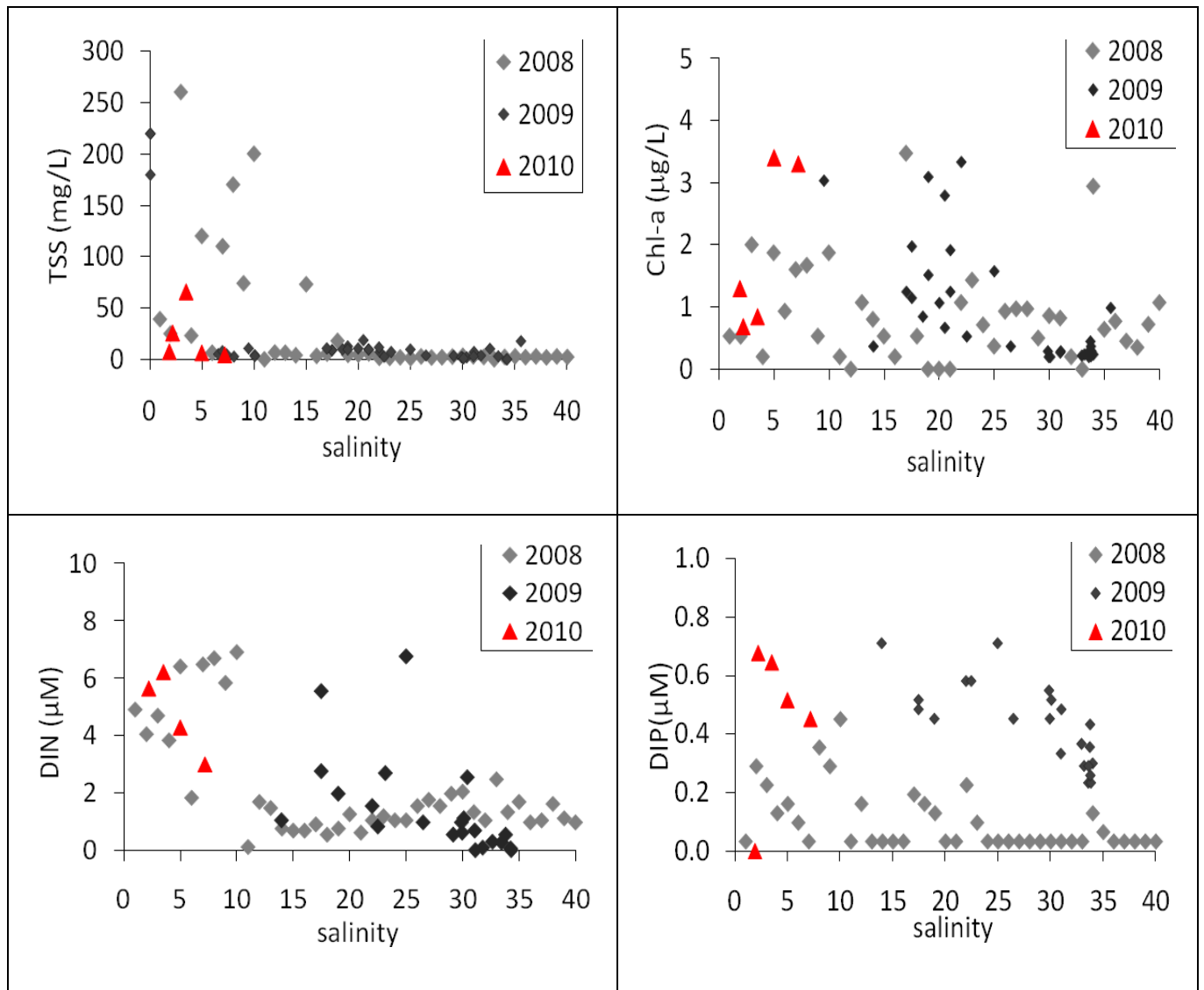
Data analysis illustrates the spatial patterns within the Burdekin River plume waters. Suspended particulate matter (SPM) is substantially elevated in the river mouth as observed in other studies (Devlin *et al.*, 2002; Lewis *et al.*, 2005), and drops off rapidly in the initial mixing zone (0 to 10 ppt). However, there is a marked difference in the SPM concentrations between the three years with the high concentrations measured in 2008/09. This could be indicative of a greater flux of heavier colloidal material in 2008/09 due to the variable flooding of the sub-catchments or the finer particulate matter moving further offshore in 2007/08 and a lack of offshore data in 2009/10. This supports current work by Bainbridge *et al.*, (2009) that describes changes in water quality concentrations within the river and coastal system can be linked back to the sub-catchment source.

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 10 mg/l and the particulate nitrogen and phosphorus measure greater than 20  $\mu$ M and 3  $\mu$ M respectively. High turbidity waters are a characteristic of these low salinity, high sediment concentrations and easily identifiable by aerial and remote sensing imagery.

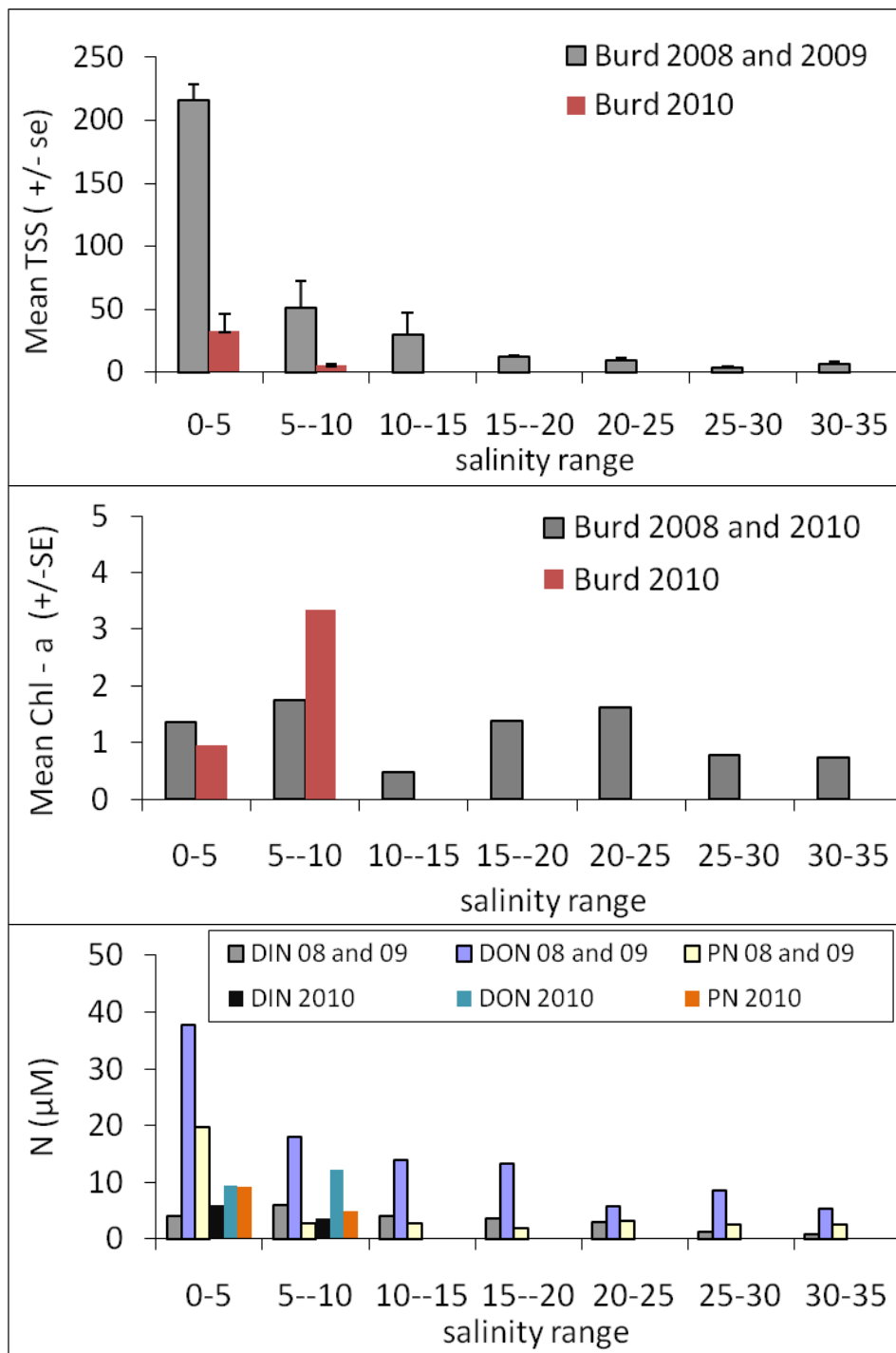
The highest concentrations of DIN measured in 2008/09 (7  $\mu$ M) was taken in salinity waters of approximately 20 ppt, and generally dilutes with distance away from the river mouth, though the peak in the middle salinities does reflect some biological processing through the salinity gradient. The lack of samples in the lower salinities makes it difficult to identify how much of a reduction has occurred from the river mouth. The 2007/08 data demonstrates

non conservative mixing, with high concentrations in the lower salinity end (< 10 ppt) with a subsequent reduction in concentrations after 10 ppt illustrating that the movement of DIN is controlled by both dilution and biological process. Lower DIN concentrations are associated with the drop in SPM and an increase in biological activity. In both years, the DIN concentrations have reduced to approximately 2  $\mu\text{M}$  at the higher salinity end, indicating a long range movement of higher nutrient concentrations throughout the Burdekin plume waters. DIP concentrations in 2007/08 also show non-conservative mixing with the highest concentrations around the 10 ppt mark reducing substantively in the higher salinity waters, Nutrient concentrations for DIN and DIP at 30 ppt are elevated in both sampling events, indicating high inorganic nutrient concentrations have moved north past the 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 (Fig 5.3). 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 their impact on the biological communities is one of the key questions in our marine monitoring programs.

Figure 5.5 presents the plume concentrations over a range of salinity measurements taken over the last three years. The plots show the average concentrations of each parameter (TSS, DIN and chlorophyll) over a set salinity range. In all years, the overall patterns are clear, with TSS falling out rapidly in the lower salinity ranges, with DIN concentrations reducing rapidly in the middle salinity ranges, corresponding to the higher chlorophyll measurements, indicating the zone of higher biological activity.



**Figure 5-4: Mixing curves for total suspended sediment (TSS), dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) and chlorophyll for all sampling events in the Burdekin River plumes during the 2007/08 to 2009/10 wet seasons.**



**Figure 5-5: Salinity profiles for TSS, nitrogen species and chlorophyll. Data is averaged over salinity bands.**

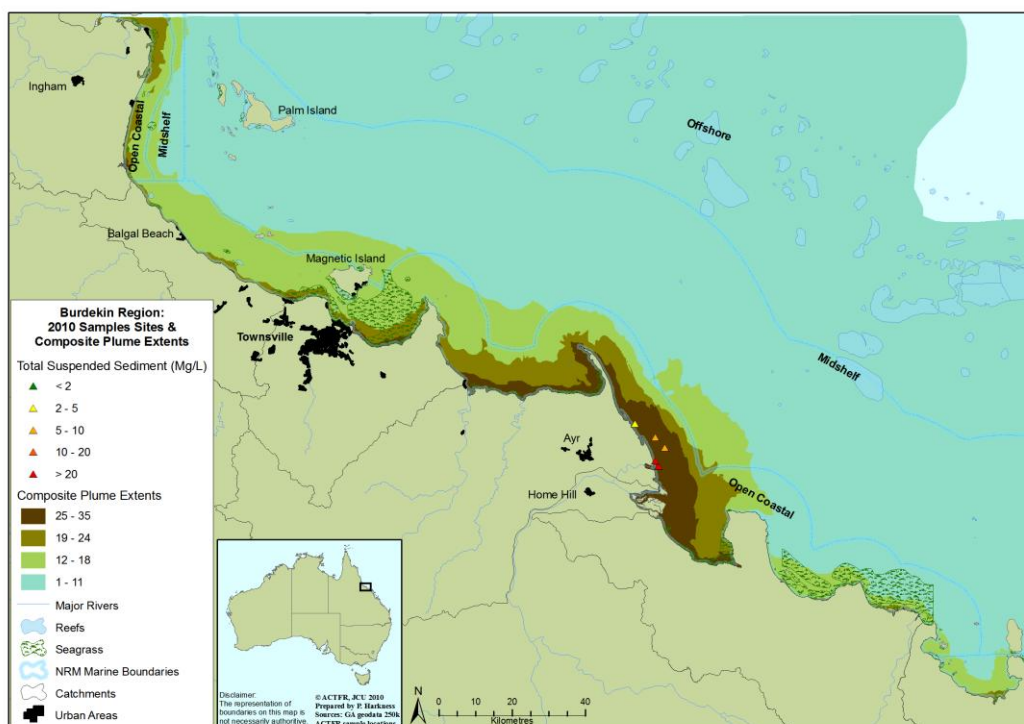
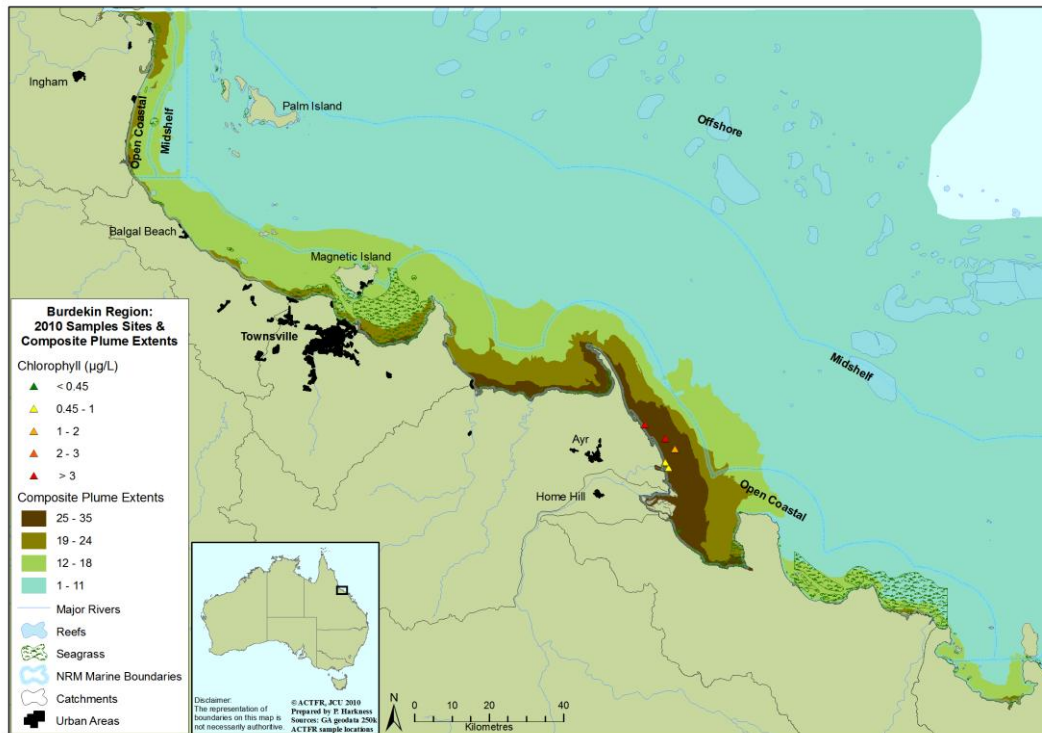
### 5.3. Remote sensing of Burdekin River plumes

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 441 nm as an indicator of organic material and CDOM absorption at 441 nm as an indicator of riverine extent. Application of appropriate chlorophyll algorithms can be used with greater confidence in the offshore areas to identify the extent of the higher primary production in and after the plume intrusion. Plume extents have been identified by true colour and CDOM absorbance at 441 nm (using remote sensing techniques). A true colour image of the Burdekin plume is available from the 6<sup>th</sup> and 7<sup>th</sup> February 2010 tracking the movement of the riverine waters (Fig 5.6). Note that the Burdekin Dam has not overflowed its banks, so the sources of flood waters in these images are from the Lower Burdekin catchment. The TSS concentrations would be relatively low, thus supporting high concentrations of Chl-*a* and CDOM which are evident in the very strong green colours moving away from the Burdekin River mouth.

Figure 5.7 identifies the water types that have been identified for Burdekin River 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. Field sampling was used to validate the water type areas. TSS and Chl-*a* *concentrations* are shown on the water type maps (Fig 6.7). Using a combination of information from catchment loads, the frequency and exposure of plume waters and information on the characteristics of water types most commonly found within the marine regions, we have identified the area most likely to exceed the Guidelines for TSS and Chl-*a* in the Burdekin marine region (Fig 5.8).

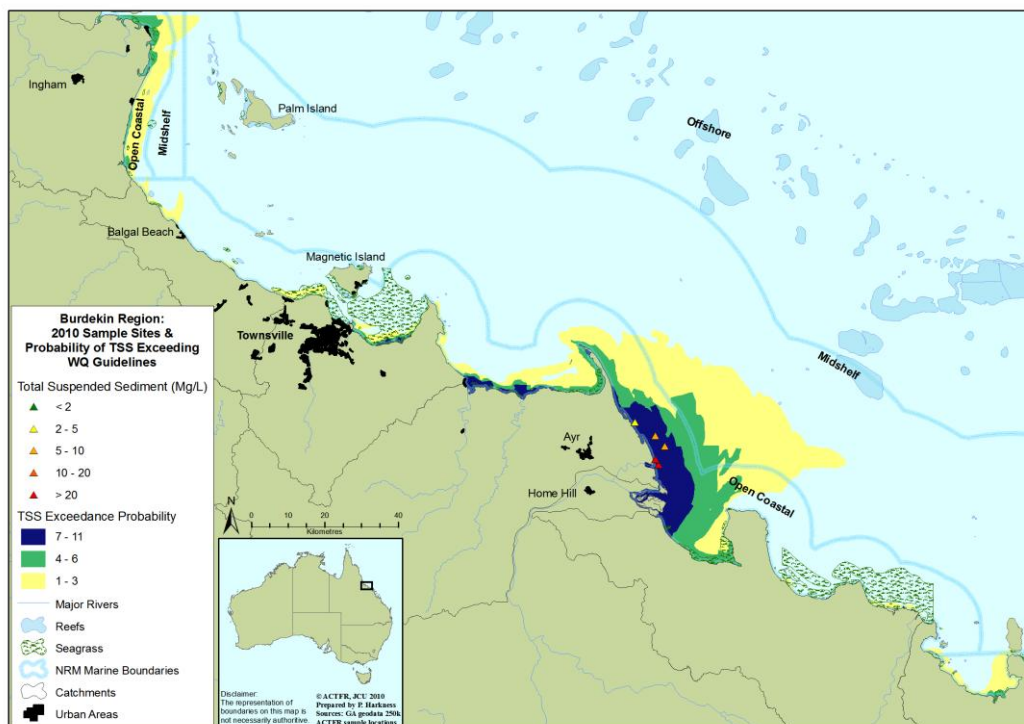
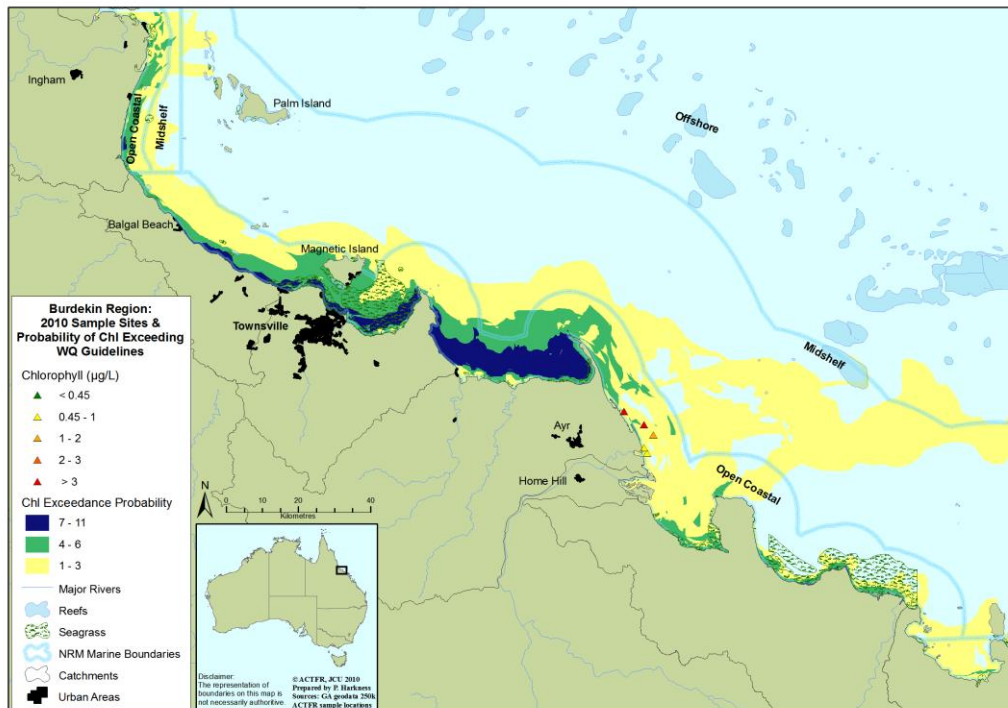


**Figure 5-6: True colour image of the Burdekin River flood taken on the 6<sup>th</sup> and 7<sup>th</sup> February 2010 (courtesy of ACTFR).**



**Figure 5-7: Definition of the water types commonly found within the Burdekin River plume extent and area. (a) TSS and (b) Chl- $\alpha$  concentrations are presented within the water types (sites for 2009/10 are found in the primary water types).**





**Figure 5-8: Definition of the Burdekin areas which are most likely to exceed the Guidelines for (a) chl-a and (b) TSS based on catchment load information, movement and extent of flood plume waters and the characteristics of the common water types.**

## 6. Case study 2 – Tully River

### 6.1. Details of sampling sites and timing

Recent work from Devlin and Schaffelke (2009) shows an area of risk offshore from the Tully-Murray catchment area, identified by water quality exceedances during the wet season and high frequency of plume coverage (Fig 6.1).

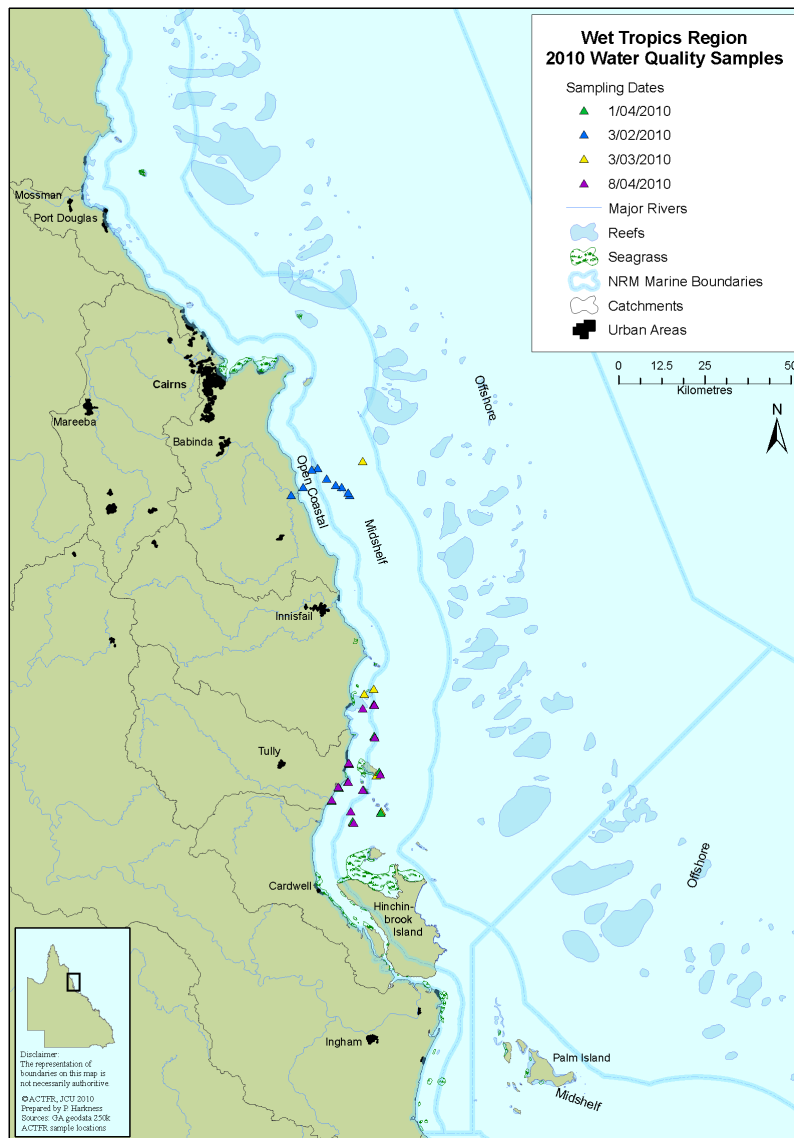
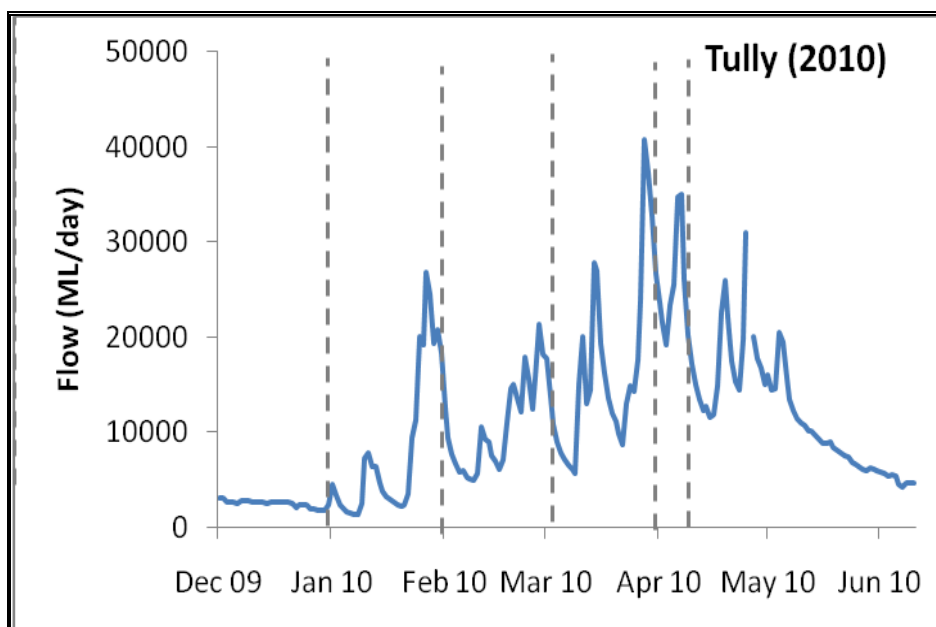


Figure 6-1: Location and dates of sites within the Wet Tropics region.

During the wet season, these coastal and inshore areas adjacent to the Tully catchment are regularly exposed to flood waters from the Tully River, and to a lesser extent from the Herbert River via the Hinchinbrook Channel, carrying high concentrations of suspended solid and nutrients and pesticides into the marine environment. All sampling which occurred in 2008/09 took place in the high to medium risk exposure area. Field data was collected over 5 different sampling events in the Tully marine area. Sampling sites extended from the river mouth offshore to the Sisters group and north to the Barnards (Fig 6.1). Sites were collected over a number of events and locations throughout the wet season (Fig 6.1). Sampling took place after medium to high peak flows were measured in the Tully River (Fig 6.2).



**Figure 6-2: Flow hydrograph for the Tully River in 2009/10. Grey lines denote the periods of time in which sampling took place.**

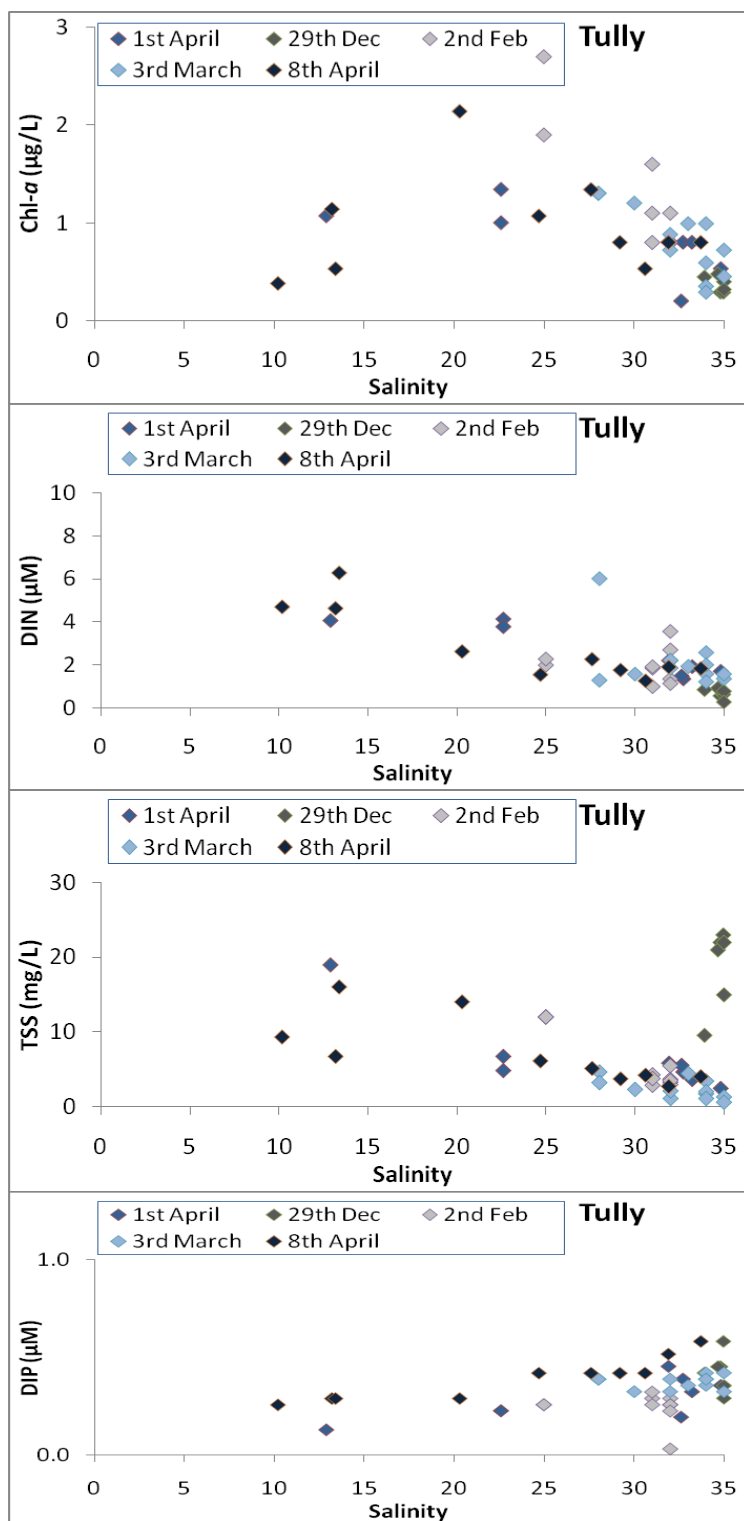
## 6.2. Water quality results

The timing of data collected in the Tully marine area is from the 31<sup>st</sup> December 2009 to the 18<sup>th</sup> March 2010. Figure 6.3 illustrates the spread of data over the salinity range for all sampling events in the Tully-Murray River plumes.

The mixing curves for four water quality parameters (chlorophyll-*a*, TSS, DIN and DIP), show contrasting responses along the salinity gradient. DIN is reasonably conservative in the early stages of the plume, with dilution being the main driver for the decrease in DIN. Non conservative processes act on the DIN in the later plume stages, with a deviation away from the linear dilution curve (Fig 6.3). In contrast, DIP increases in the later stages of the plume, over both space and temporal scales. This is most likely due to the desorption of the particulate phosphorus into a dissolved stage. The impact of the inorganic phosphorus being available over longer time frames and at elevated levels is not clear. The impacts of the fertilized agriculture has typically been seen and measured in elevated concentrations of DIN, and these levels of DIP may require some more thought on the nutrient priorities. Chlorophyll concentrations are non conservative, measuring low in the early stages, increasing in the middle stages, where the combination of excess nutrients and higher light levels promote accelerated phytoplankton growth conditions. The concentrations do fall out in the higher salinities; however, concentrations are still high as compared to the baseline conditions. Chlorophyll measurements show low concentrations in the early stages of the plume, most likely related to growth limitation of light and freshwater, with significant increases in the concentrations in the higher salinity zones, corresponding to secondary plume characteristics. There were very high values of chlorophyll concentrations measured at the reef sites over the separate trips, corresponding to the reports and surveillance of warm, green waters persisting around Dunk Island. Other reports (Schaffelke et al., 2010) report on the extent of coral damage measured in these reefs, but the initial water quality analysis supports a significant, prolonged flood event, with high temperatures and low salinities measured over at least a 6 to 8 week period in the Tully-Murray marine areas.

The SPM measurements along the salinity gradient increase from initially high values of 10mg/L, though they are confounded over time and space for the different sampling days. This increase in the SPM measurements may be due to a movement from inorganic fine

sediment to organic constituents (phytoplankton). Sediment erosion on the Tully-Murray catchment is not seen as one of the main landuse issues and this may be reflected in the lower measurements of SPM in the Tully River samples. However, the suspended sediment does not seem to be falling out in low salinities, implying that it is the finer particulate matter that may be able to travel further offshore and thus further impact on the inshore ecosystems. There is also the combined effect of the Herbert plume, which may be bringing fine suspended particulate matter into the Tully plume, causing the higher SPM measurements in those higher salinity zones.

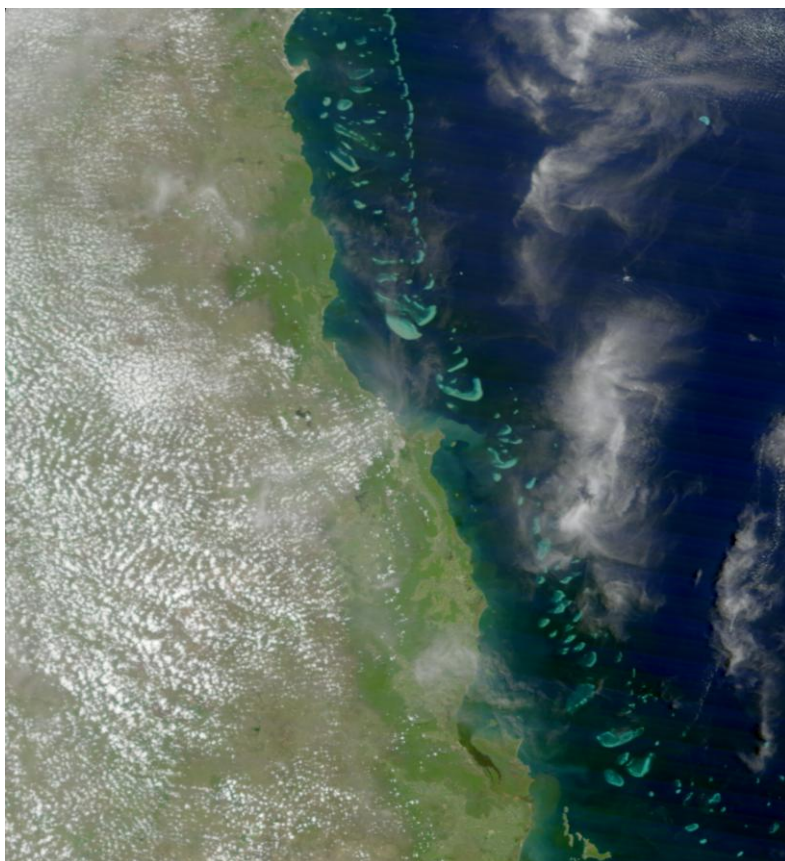


**Figure 6-3: Mixing curves for chlorophyll, suspended solids (SS) dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) for the 5 sampling events in the Tully-Murray plumes during the 2009/10 wet season.**

### **6.3. Remote sensing of the Tully River plumes**

The extent of a visible plume is readily seen in true colour imagery (Fig 6.4). The Tully plume measured on the 7<sup>th</sup> February 2010 moves past Dunk and Bedarra Islands, north to the Barnard Islands. The colour of the primary water is delineated as a brown turbid water mass, contrasting with the secondary water types, characterized by the turbid, “green” coloured waters. It is important to note we are delineating the edge of the ‘plume’ by eye using the ‘true colour’ of water and in addition the use of the total absorption at band 443 nm which, as previously noted, is a proxy for the presence of organic material (phytoplankton, yellow substance and detrital material). Much of the colour, especially the vivid green water colour moving offshore, could be due to phytoplankton (as shown by chlorophyll a concentrations) and hence indicative of the extent of the algal bloom. The co-location of the plume (lowered salinity water) and the bloom (phytoplankton bloom) are not certain but there will be a fair degree of overlap (Devlin and Brodie, 2005) as the dissolved nutrients move with the water and eventually stimulate the algal bloom.

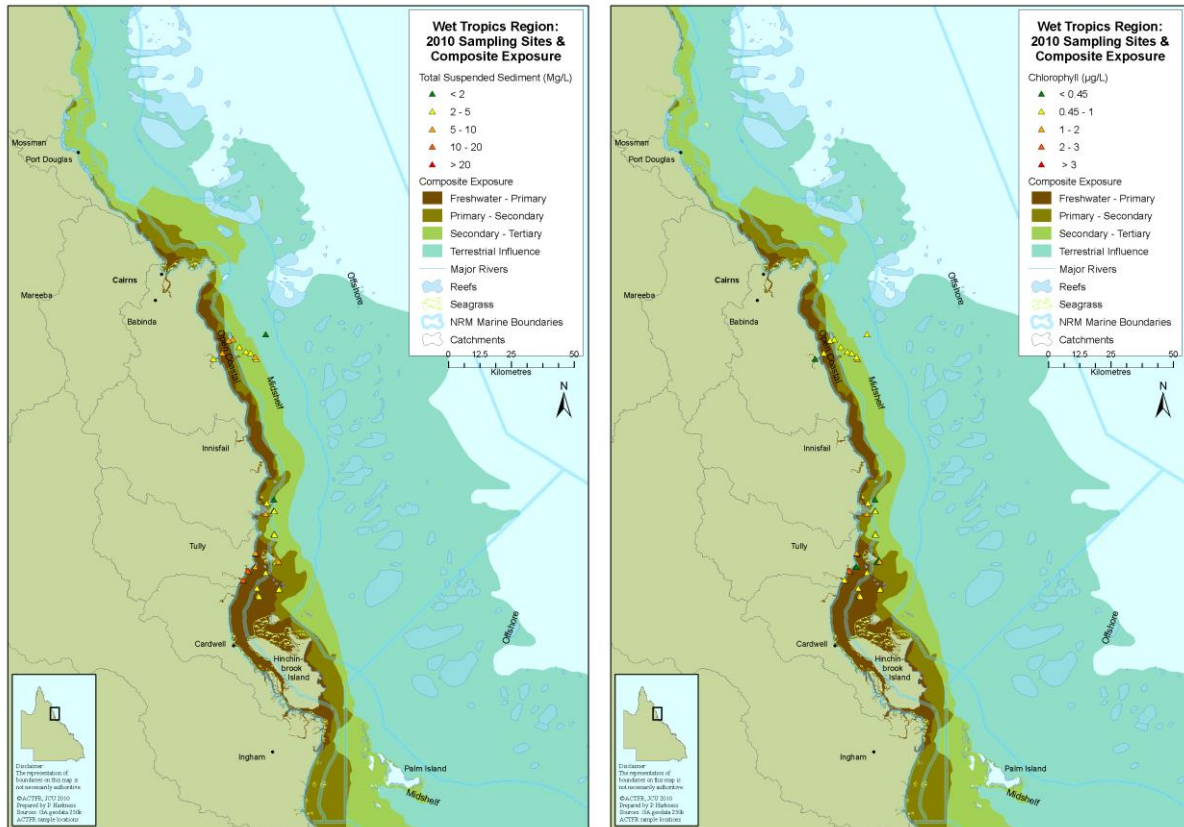
The very turbid inshore plume can be seen moving north and offshore within the Wet Tropics region with secondary waters extending out to the offshore reefs (Fig 6.4). There is also a secondary plume visible in the left hand side of the picture, moving north. Field sampling was used to validate the water type areas. TSS and Chl-*a* concentrations are shown on the water type maps (Fig 7.6). Using a combination of information from catchment loads, the frequency and exposure of plume waters and information on the characteristics of water types most commonly found within the marine regions, we have identified the area most likely to exceed water quality guidelines for TSS (Fig 6.6). and Chl-*a* (Fig 6.7) in the Tully marine area.



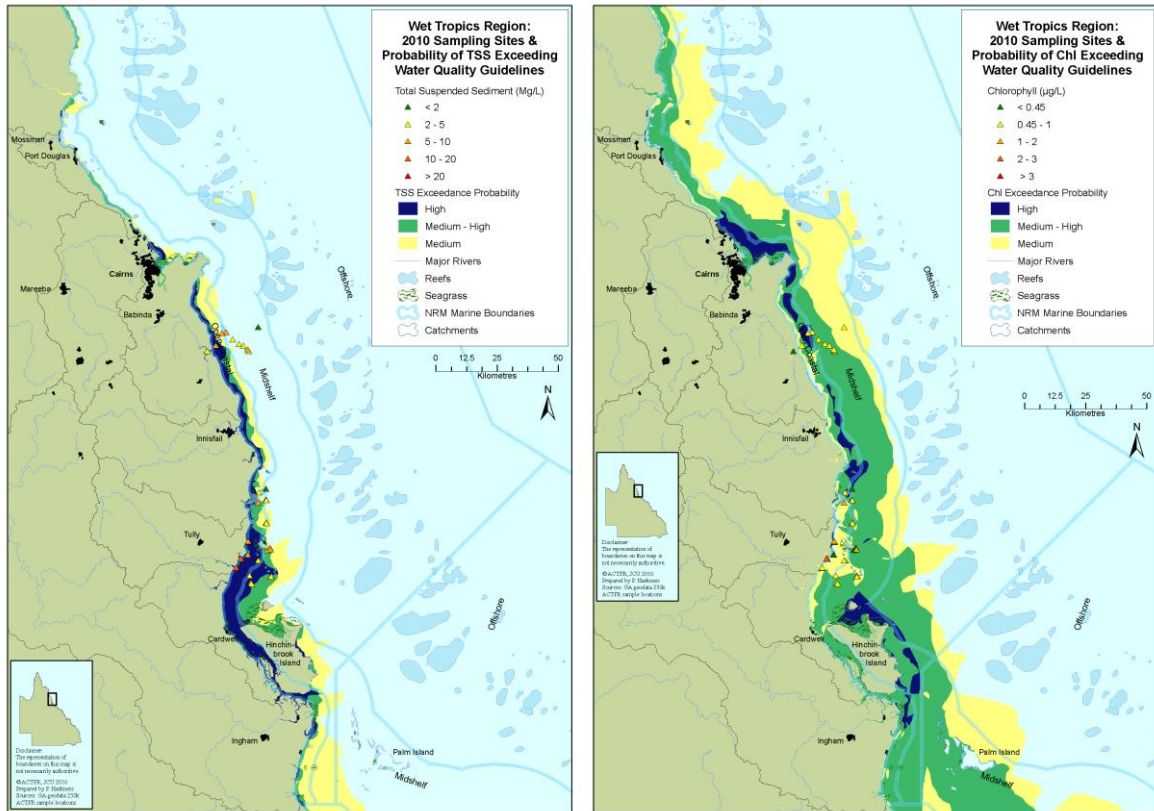
**Figure 6-4: MODIS AQUA image of the Tully River plume at 250 m resolution taken on the 7<sup>th</sup> February 2010. Note the large extent of green water (Image courtesy of ACTFR).**

*a*





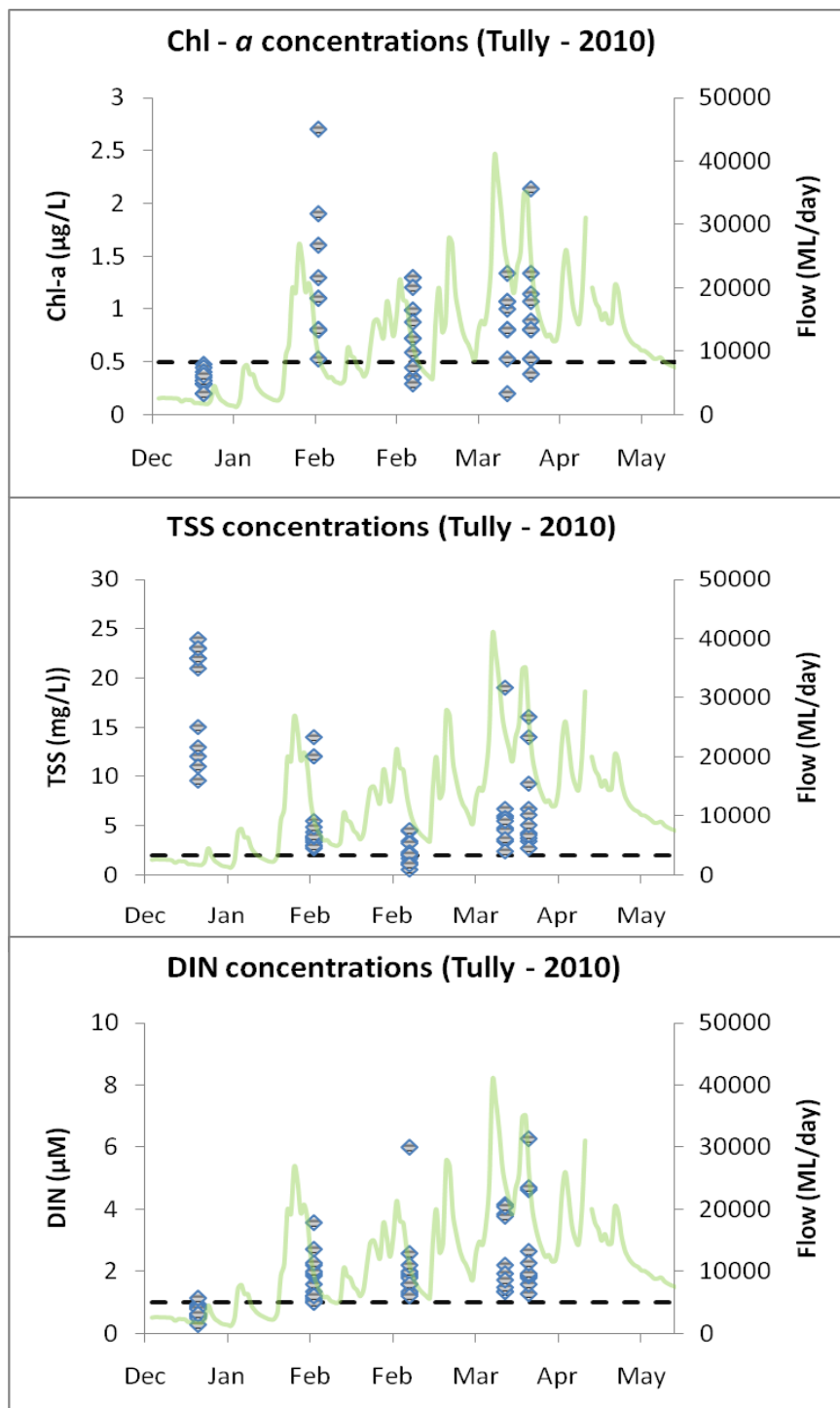
**Figure 6-5: Definition of the water types commonly found within the Wet Tropics region plume extent and area. (a) TSS and (b) Chl-*a* concentrations are presented within the water types (sites for 2009/10 are found in the primary water types).**



**Figure 6-6: Definition of the Wet Tropics areas which are most likely to exceed the Guidelines based on catchment load information, movement and extent of flood plume waters and the characteristics of the common water types.**

#### **6.4. Water quality Guideline exceedances**

The frequency of high water quality values for all Tully River plume sampling sites is presented for the 2009/10 sampling year for chlorophyll (Fig 6.8) and suspended solids (Fig 6.9). In addition, Guideline exceedances at two sites (Dunk Island and Tam O Shanter point) are shown over five sampling times (Jan to April 2010). Over 90% of all samples taken exceeded the Guideline trigger values for chlorophyll and TSS. For the two sites with repeated sampling, the chlorophyll value was exceeded for the first three sampling times and TSS was exceeded for all four of the sampling times. The Guideline exceedances for samples taken across the 2009/10 wet season imply that there were long periods of time in which the chlorophyll *a* and TSS concentrations were elevated above the recommended Guidelines.



**Figure 6-7: Water quality concentrations by date and presented against Tully River flow. Data presented for (a) Chl-*a*, (b) TSS and (c) DIN. Lines denote the value of the Guideline trigger value for Chl-*a* and TSS presented for comparison against the measured concentrations. DIN values presented against wet season average (Furnas, 2003).**

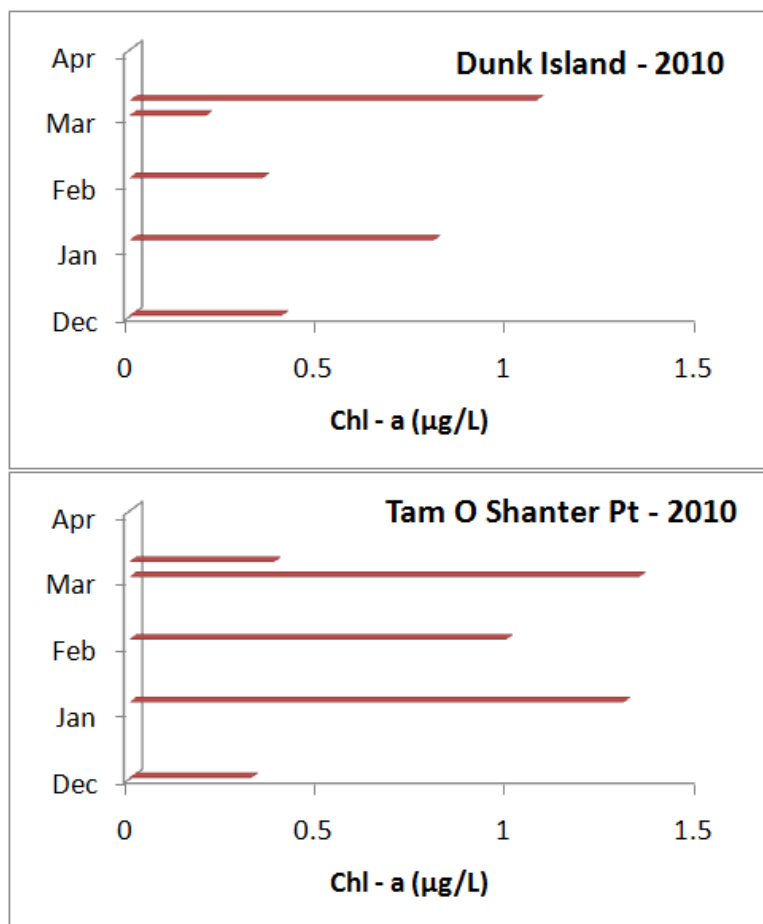
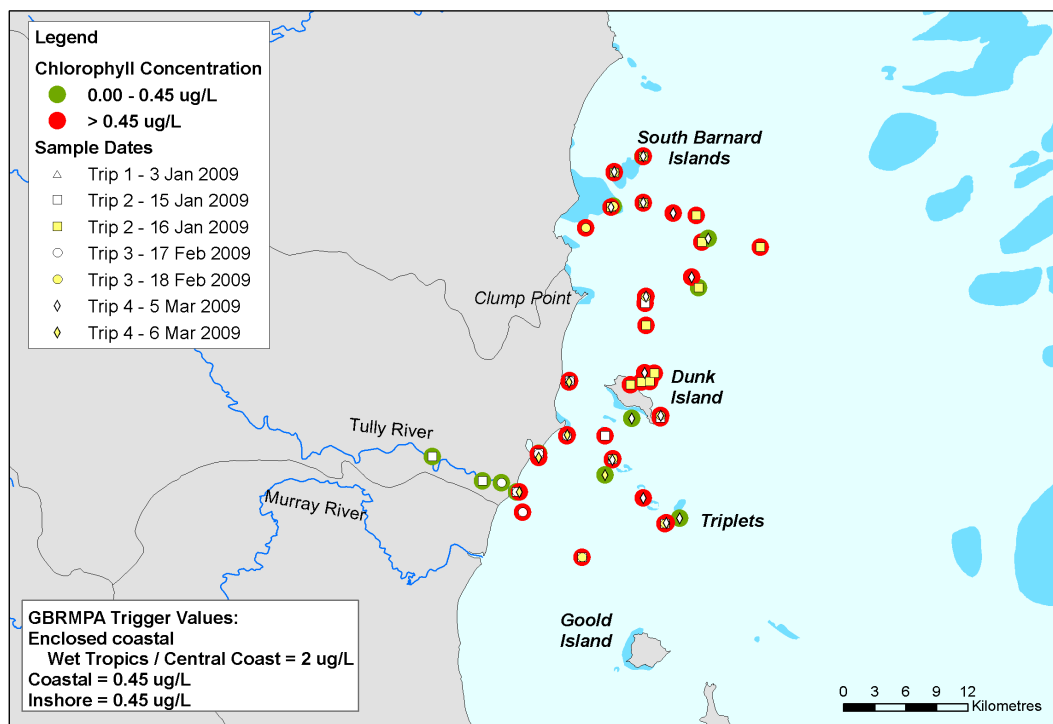
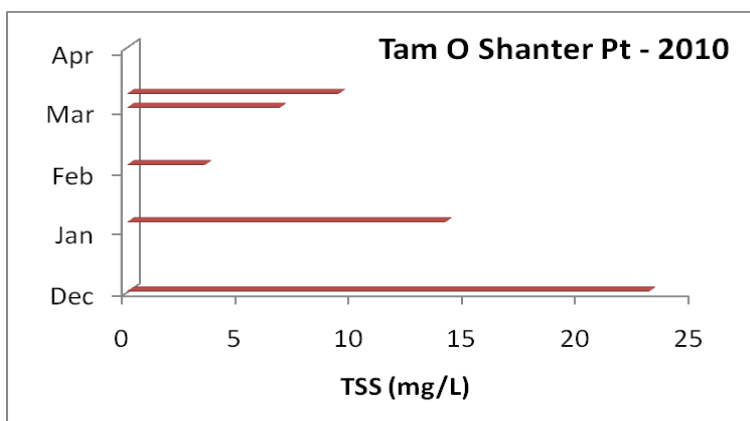
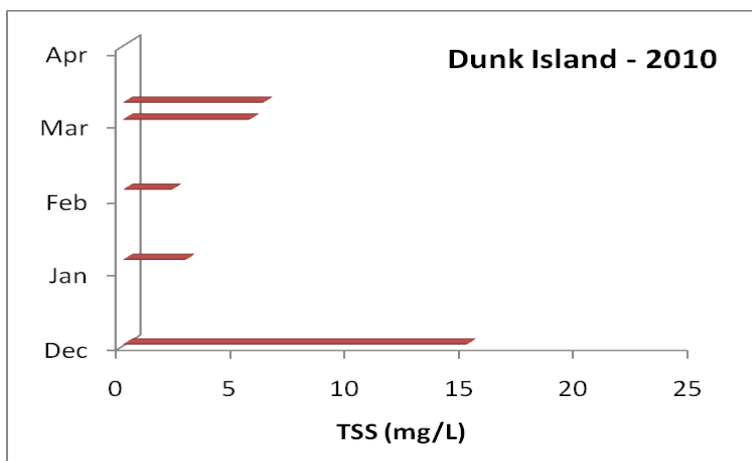
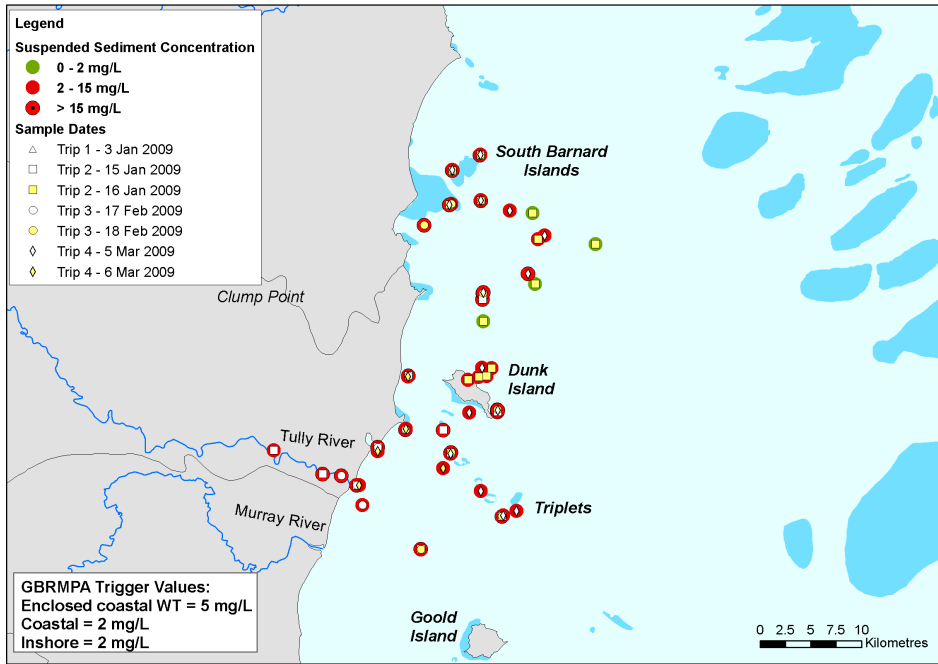


Figure 6-8: (a) Guideline exceedances for Chl-*a* in the Tully River plume sampling site (b). Concentrations of Chl-*a* measured at two sites over the sampling period (Dec 2009 – May 2010).

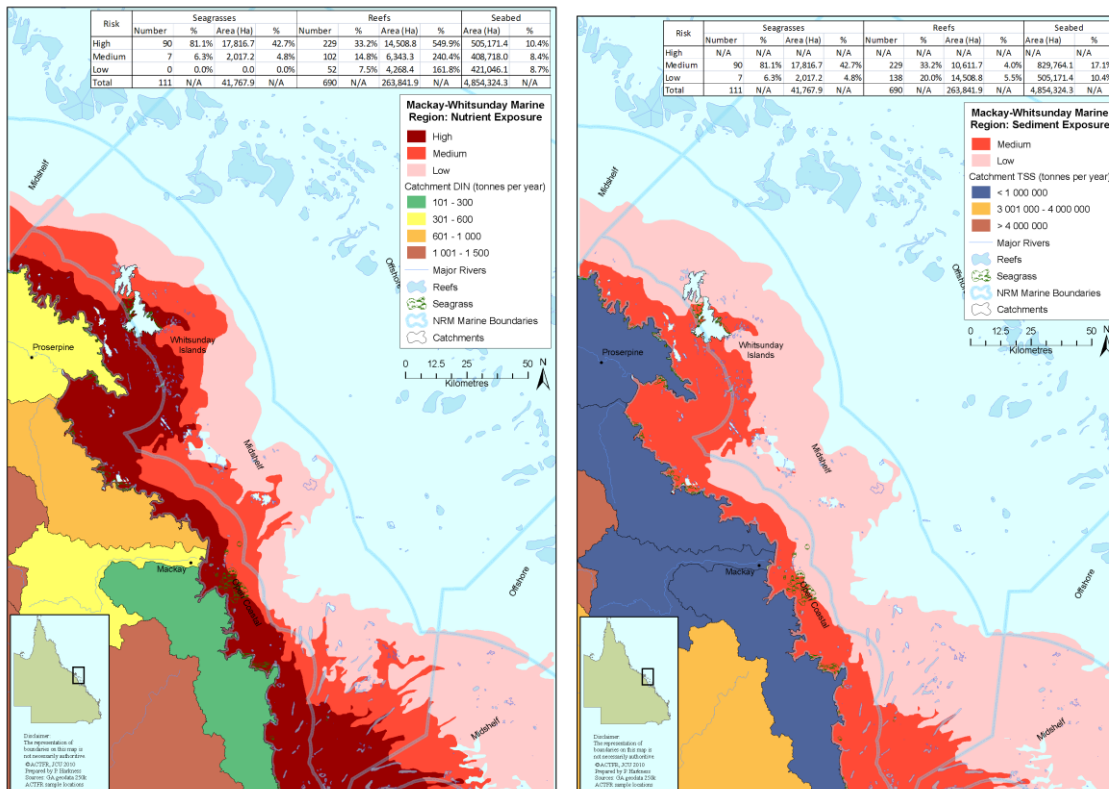


**Figure 6-9: Guideline exceedances for TSS in the Tully River plume sampling site (b). Concentrations of TSS measured at two sites over the sampling period (Dec 2009 – May 2010).**

## 7. Case study 3 – Mackay Whitsunday region

### 7.1. Details of sampling sites and timing

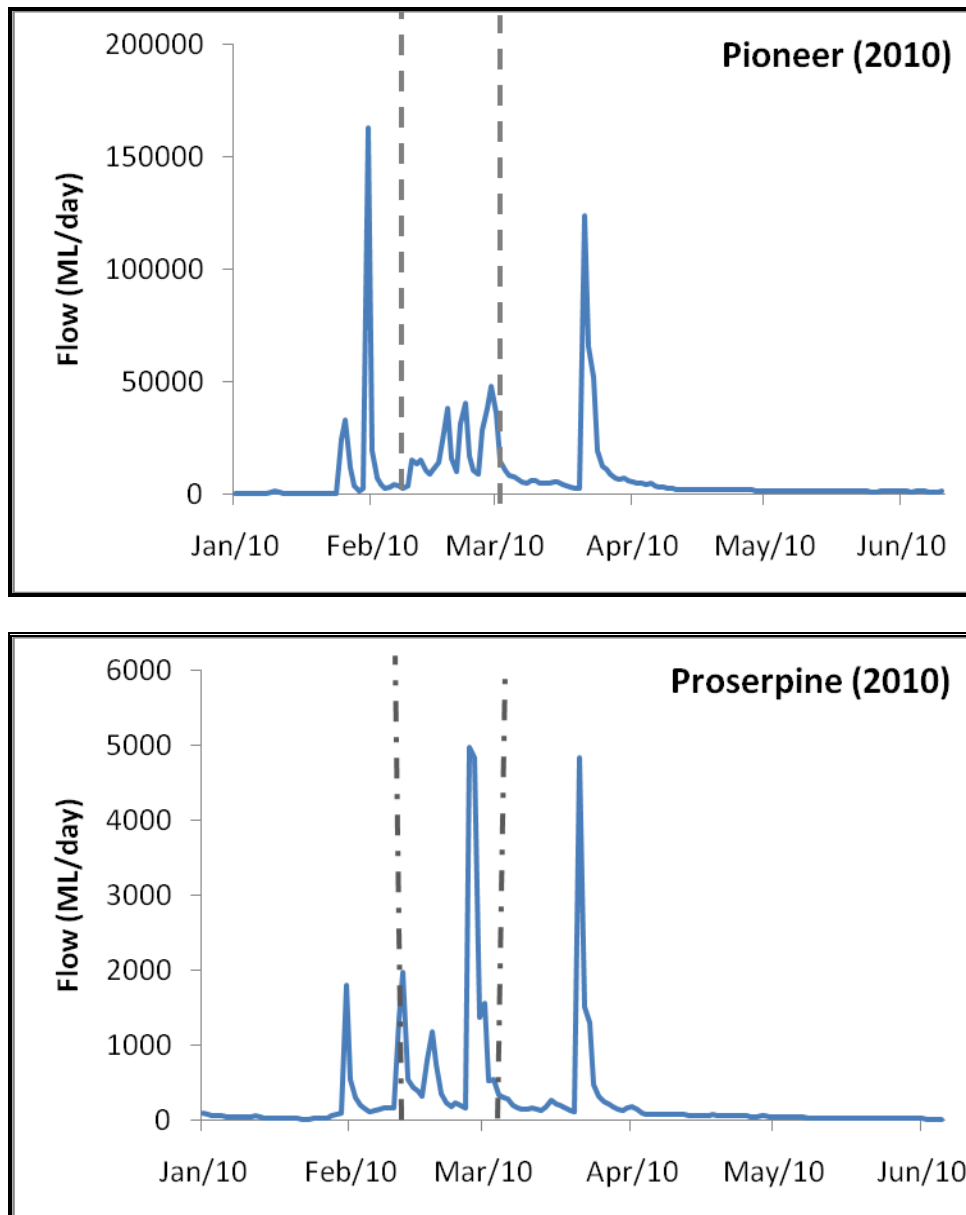
Recent work from Devlin et al. (2010) shows an area of risk offshore from the Mackay Whitsunday catchment, identified by Guideline trigger value exceedances during the wet season and high frequency of plume coverage (Fig 7.1).



**Figure 7-1:** TSS and Chl-a exposure areas for the Mackay Whitsunday marine area.

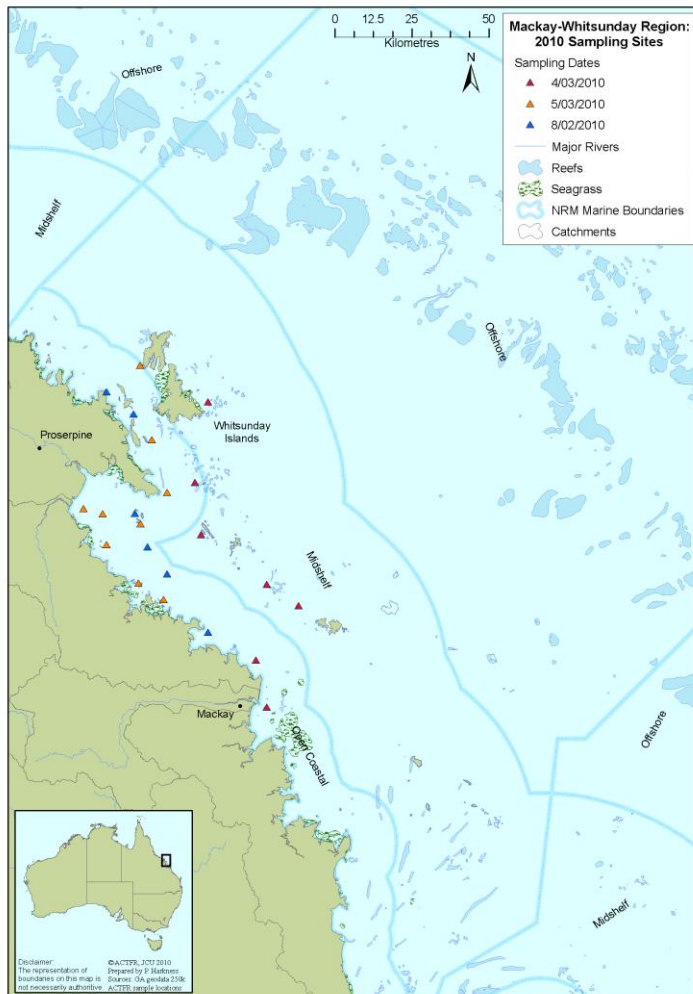
During the wet season, these coastal and inshore areas adjacent to the Mackay Whitsunday catchments are regularly exposed to flood waters from the Pioneer, Proserpine and Plane Rivers, carrying high concentrations of suspended solid and nutrients and pesticides into the marine environment. All sampling which occurred in 2009/10 took place in the high to medium exposure area. Field data was collected over two different sampling events in the Mackay Whitsunday region. Sampling took place after medium to high peak flows were measured in the Proserpine and Pioneer Rivers (Fig 7.2). Sampling sites extended from the

Proserpine River mouth offshore to the inshore coral reefs and islands of the Whitsunday sub-region (Fig 7.3).



**Figure 7-2: Flow hydrograph for the Pioneer and Proserpine Rivers from January to June 2010. Grey lines denote the periods of time in which sampling took place.**





**Figure 7-3: Location of all sampling sites delineated by date for sampling sites offshore from the Proserpine, Pioneer and Plane Rivers. Sampling took place between February and March 2010.**

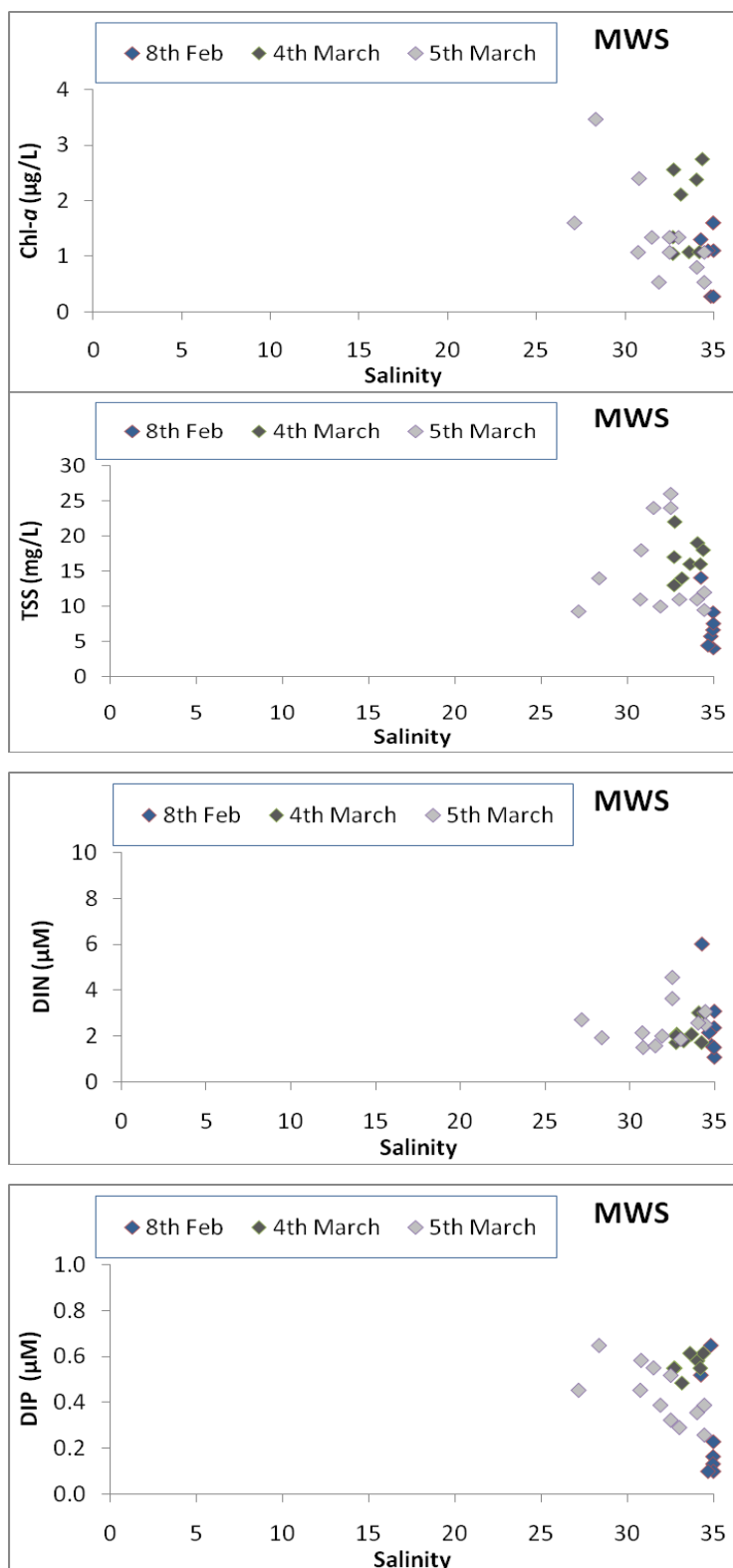
## 7.2. Water quality results

Figure 7.4 illustrates the spread of data over the salinity range for all sampling events in the Mackay Whitsunday river plumes.

The timing of data is from the 8<sup>th</sup> February to 5<sup>th</sup> March 2010. The mixing curves for four water quality parameters (chlorophyll-*a*, TSS, DIN and DIP), are all grouped around the higher salinity end. At the time of sampling, flow rates had reduced slightly and thus the peak of the event was not measured. As mention previously, the focus is now on understanding the extent, both temporally and spatially, of plume waters and their longer

term impact on the water quality in GBR waters. All samples were taken in the later stages of the plume in higher salinity waters. In all samples, the nutrient concentrations were elevated 2 to 10 times past baseline levels (Furnas, 2003). TSS and Chl-*a* were all elevated with TSS concentrations ranging from 4 to 26 mg/L, and Chl-*a* concentrations ranging from 0.2 to 3.5 µg/L. All other water quality parameters were elevated (see Appendices)

These elevated concentrations, in particular the high measurements of Chl-*a* and CDOM indicate the spatial and temporal extent of the secondary water characteristics, with eutrophic conditions of high nutrient, high biomass and other potential secondary effects persisting over days to weeks. Considering that we measured the events 14 days after the peak flow measured on the 31<sup>st</sup> January 2010 in the Pioneer River, and at the same time as the small peak in the Proserpine River, the full extent of the plume would have been potentially over a greater area and over a longer period of time. The second event sampled was 4 days after peak flow in the Proserpine River, but still before the much larger event in both the Pioneer, Proserpine and O'Connell Rivers (21<sup>st</sup> March 2010). Thus the Mackay Whitsunday marine region, in a year with exceptional flows in all four rivers, would have experienced the high concentrations in water quality parameters for up to 7 to 10 weeks over the multiple flow peaks. This is an area of high ecological significance and the number of reefs and seagrass beds impacted by these multiple plume events ranged from 1 to 16% (Table 7.1).

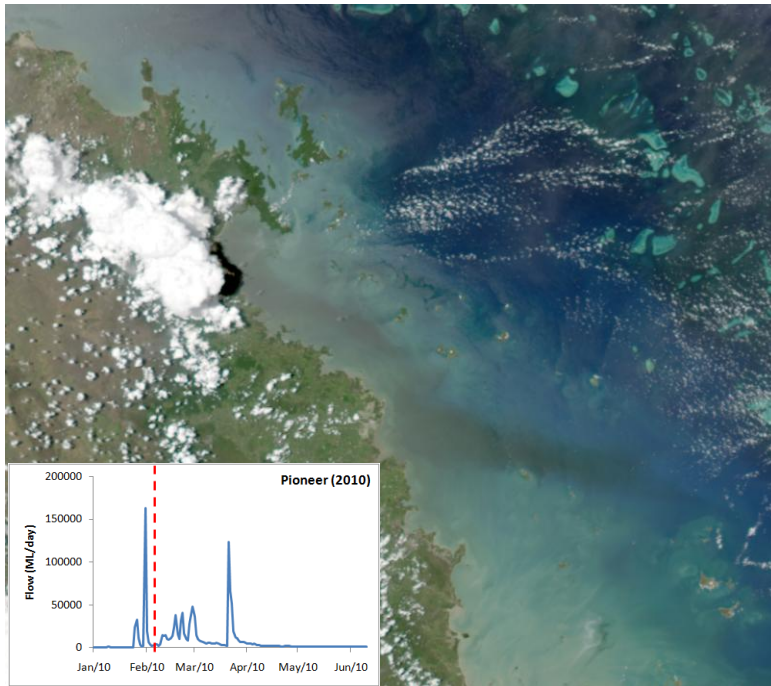


**Figure 7-4: Mixing curves for chlorophyll, suspended solids (SS) dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) for the 2 sampling events in the Mackay Whitsunday (MWS) plumes during the 2009/10 wet season.**

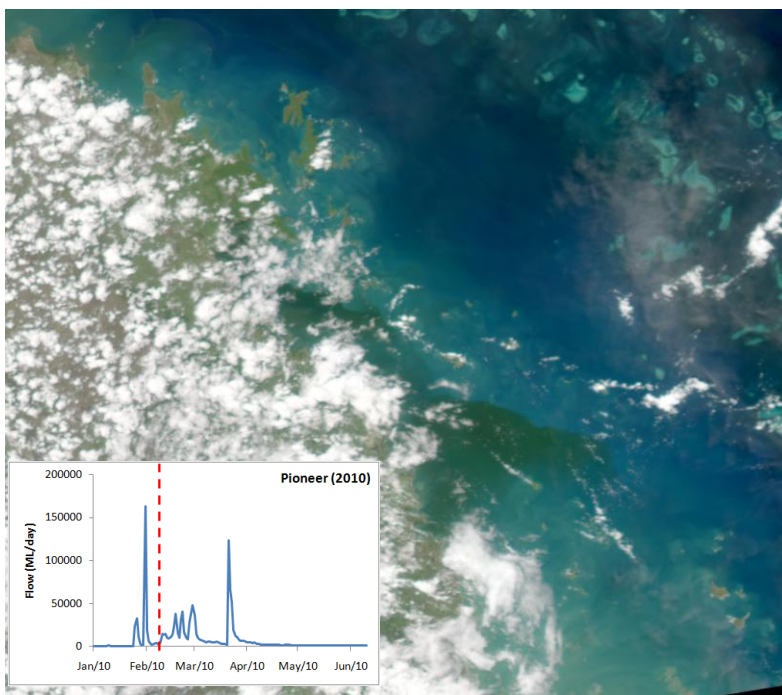
### **7.3. Remote sensing of the Mackay Whitsunday river plumes**

The extent of a visible plume is readily seen in true colour imagery (Fig 8.5 – 8.7). Flow rates and timing of the image are presented within the pictures, for Pioneer River only. All the Mackay Whitsunday rivers had large flow events, with total year discharge measuring 49,501 ML for Proserpine River, 214,062 ML for O’Connell River, 1,319,393 ML for the Pioneer River and 368,619 ML the Plane River. These annual discharge values were all greater than the long term river discharge median with relative differences of 1.4, 1.4, 1.8 and 3.3 respectively for Proserpine, O’Connell, Pioneer and Plane Rivers. Three consecutive images are presented for the Mackay Whitsunday region, taken from the 2<sup>nd</sup> to the 4<sup>th</sup> February 2010 (Fig 7.5 to Fig 7.7). The movement of the plume offshore, north and also slightly to the south can be seen on the 2<sup>nd</sup> February 2010. Much of the colour, especially the vivid green water colour moving offshore, could be due to phytoplankton (as shown by chlorophyll *a* concentrations) and hence indicative of the extent of the algal bloom. Over the next two days, the spatial extent of the secondary waters does not move too much further, however the colour of the water changes into a more vivid green, possibly representative of the increase in phytoplankton and Chl-*a* concentrations.

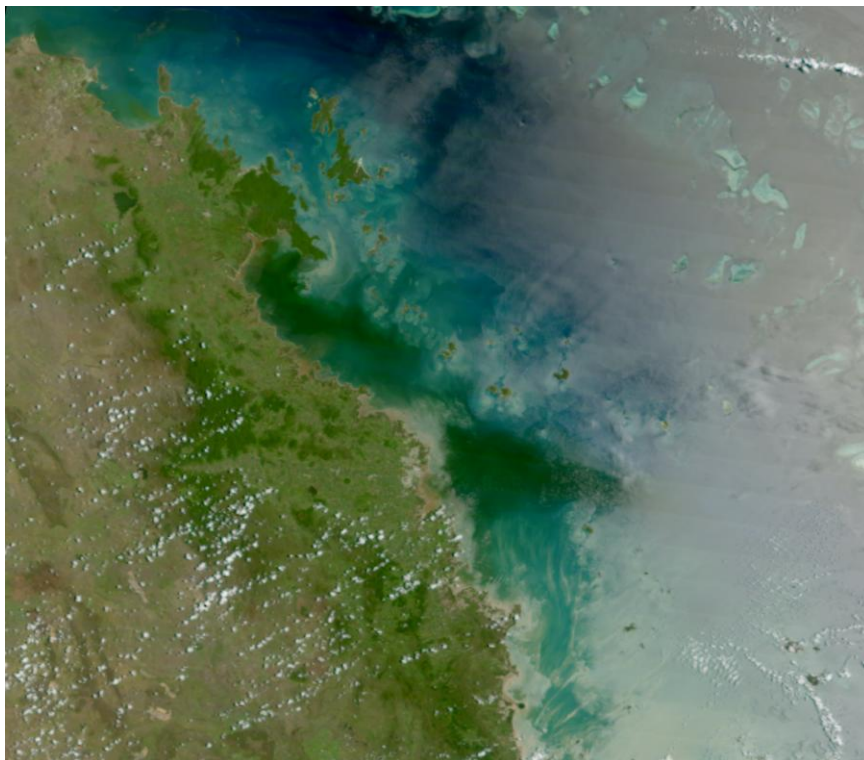
Using a combination of information from catchment loads, the frequency and exposure of plume waters and information on the characteristics of water types most commonly found within the marine regions, we have also identified the area most likely to exceed the Guideline trigger values for TSS and Chl-*a* in the Mackay Whitsunday region (Fig 7.9). The number of reefs and seagrass beds which are located in these risk areas vary between TSS risk (28 reefs and 44 seagrass beds) and chl-*a* risk (93 reefs and 306 seagrass beds). The large number of reefs and seagrass beds at risk from chl-*a* exceedance reflects the high DIN concentrations sourced from Mackay Whitsunday catchments and the close proximity of the inshore reefal system (Table 7.1).



**Figure 7-5: MODIS AQUA image of Mackay Whitsunday river plume, at 250 m resolution taken on the 2<sup>nd</sup> February 2010. Note the vivid green colour of the secondary plume waters (Image courtesy of ACTFR).**

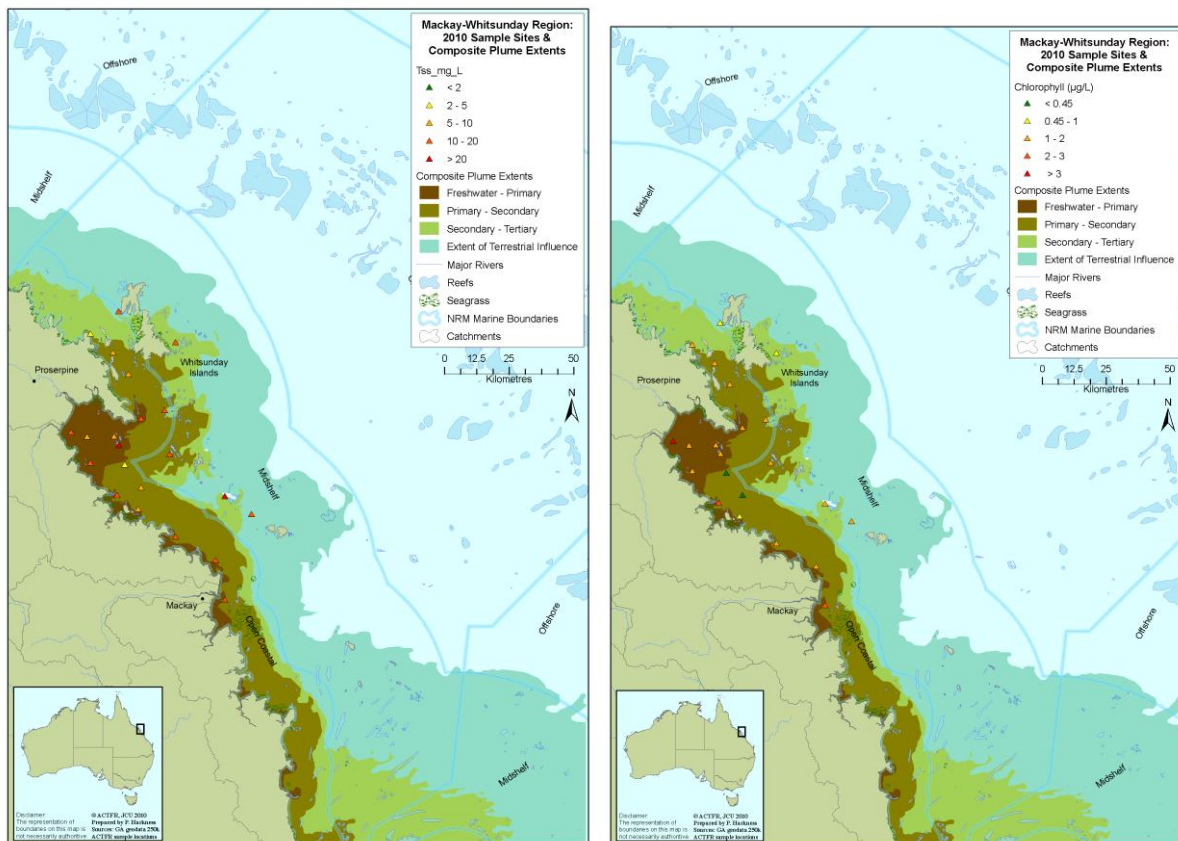


**Figure 7-6: MODIS AQUA image of Mackay Whitsunday river plume, at 250 m resolution taken on the 3<sup>rd</sup> February 2010. Note the vivid green colour of the secondary plume waters (Image courtesy of ACTFR).**

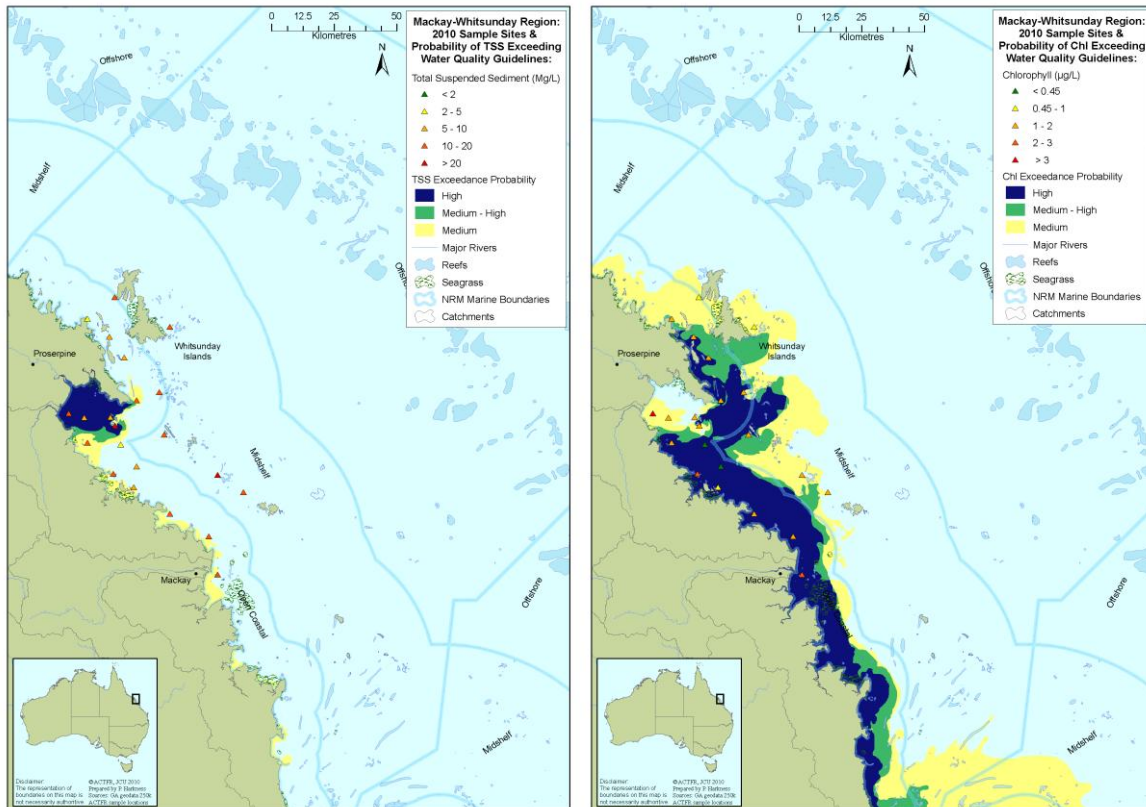


**Figure 7-7: MODIS AQUA image of Mackay Whitsunday river plume, at 250 m resolution taken on the 4<sup>th</sup> February 2010. Note the vivid green colour of the secondary plume waters (Image courtesy of ACTFR).**





**Figure 7-8: Definition of the water types commonly found within the Mackay Whitsunday plume extent and area. (a) TSS and (b) Chl-*a* concentrations are presented within the water types (sites for 2009/10 are found in the primary water types).**



**Figure 7-9: Definition of the Mackay Whitsunday areas which are most likely to exceed Guideline trigger values based on catchment load information, movement and extent of flood plume waters and the characteristics of the common water types.**

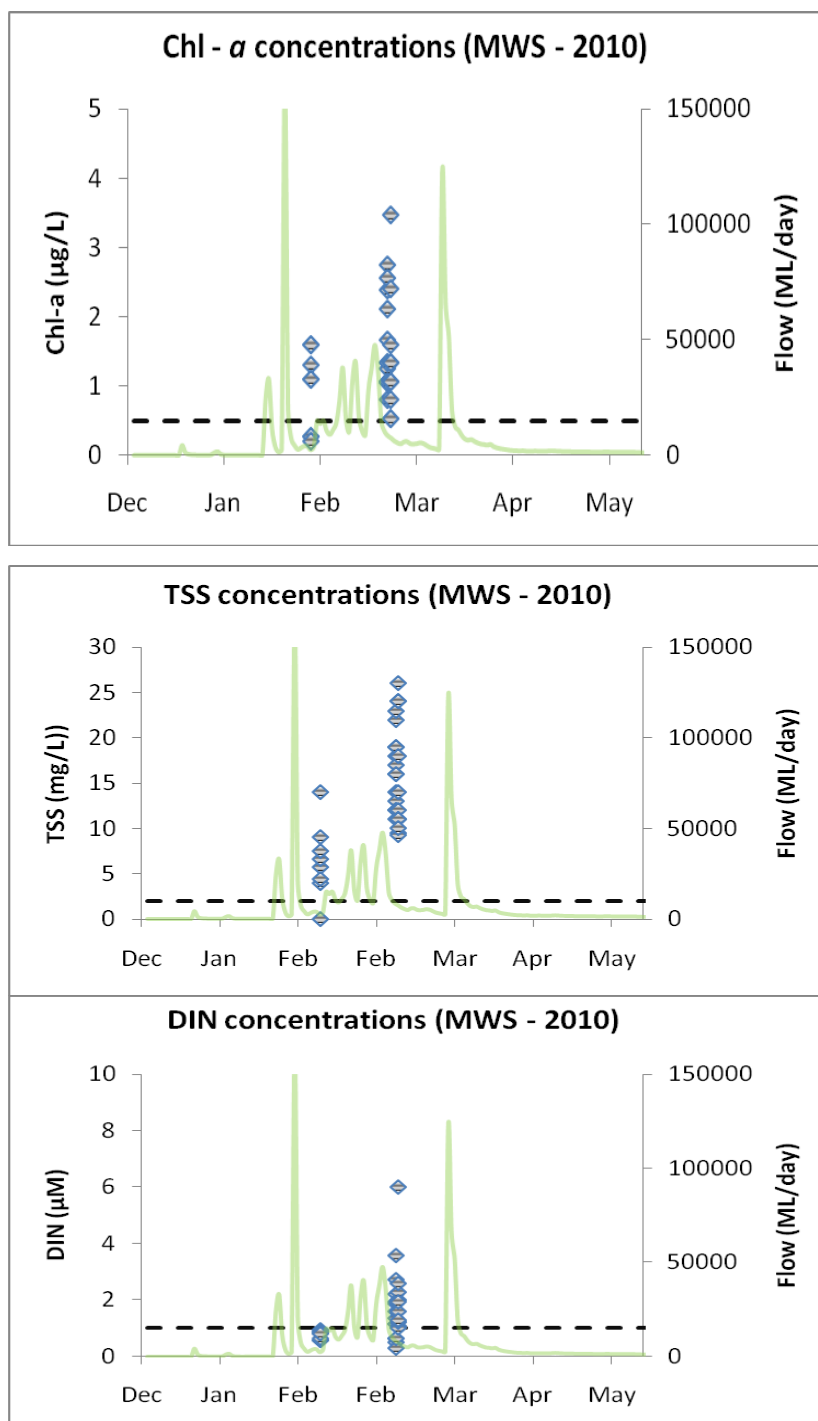
**Table 7-1: The number of reefs and seagrass beds that are located in the high to medium Guideline exceedance areas. The categories (high, medium- high and medium) refer to the probability of that area exceeding the Guidelines for either TSS or Chl-*a***

Region	Water quality parameter	Probability of exceedance (WQ)	Number	%	Area	%	Number	%	Area	%
Mackay-WS	TSS	High	6	5.4%	14.1	4.4%	6	0.9%	1.4	0.1%
		Medium-High	4	3.6%	1.1	0.4%	5	0.7%	0.6	0.0%
		Medium	16	14.4%	34.9	10.9%	33	4.8%	14.1	0.6%
		None	82	73.9%	271.3	84.4%	338	49.0%	2,526.1	99.4%
	Chl	High	51	45.9%	140.1	43.6%	110	15.9%	54.0	2.1%
		Medium-High	14	12.6%	5.1	1.6%	72	10.4%	36.1	1.4%
		Medium	38	34.2%	50.7	15.8%	124	18.0%	76.7	3.0%
		None	14	12.6%	125.5	39.1%	124	18.0%	2,375.3	93.4%
	Total		111	100.0%	321.5	100.0%	690	100.0%	2,542.2	100.0%



#### **7.4. Water quality Guideline exceedances**

The frequency of high water quality values for all Mackay Whitsunday region sampling sites is presented for the 2009/10 sampling year for chlorophyll (Fig 7.10) and suspended solids (Fig 8.10). For the two sites with repeated sampling, the Guideline chlorophyll trigger value was exceeded for the first three sampling times and TSS was exceeded for all four of the sampling times. The Guideline exceedances for samples taken across the wet season imply that there were long periods of time in which the chlorophyll *a* and TSS concentrations were elevated above recommended guidelines. Further integration of this data with the *in situ* logger data (Schaffelke et al., 2010) will be useful in identifying the period of time in which concentrations were exceeded.



**Figure 7-10: Water quality concentrations by date and presented against Tully River flow. Data presented for (a) Chl- $\alpha$ , (b) TSS and (c) DIN. Lines denote the value of the Guideline trigger value for Chl- $\alpha$  and TSS presented for comparison against the measured concentrations. DIN values presented against wet season average (Furnas, 2003).**

## 8. Case study 4 – Fitzroy River

### 8.1. Details of sampling sites and timing

In 2009/10, sampling in the Fitzroy River plume took place over two occasions on the 24<sup>th</sup> February 2010. Samples were taken along a transect from the Fitzroy River mouth, north along the Keppel Islands. Location of the sites and dates are shown in Figure 8.1. Fitzroy River flow was substantial, with the median flow measuring 10,683,538 ML, which is greater than the long term median (2,708,440 ML), with a relative difference of 3.94 (Table 5.1). The total flow for the year was the third largest in the last ten years.

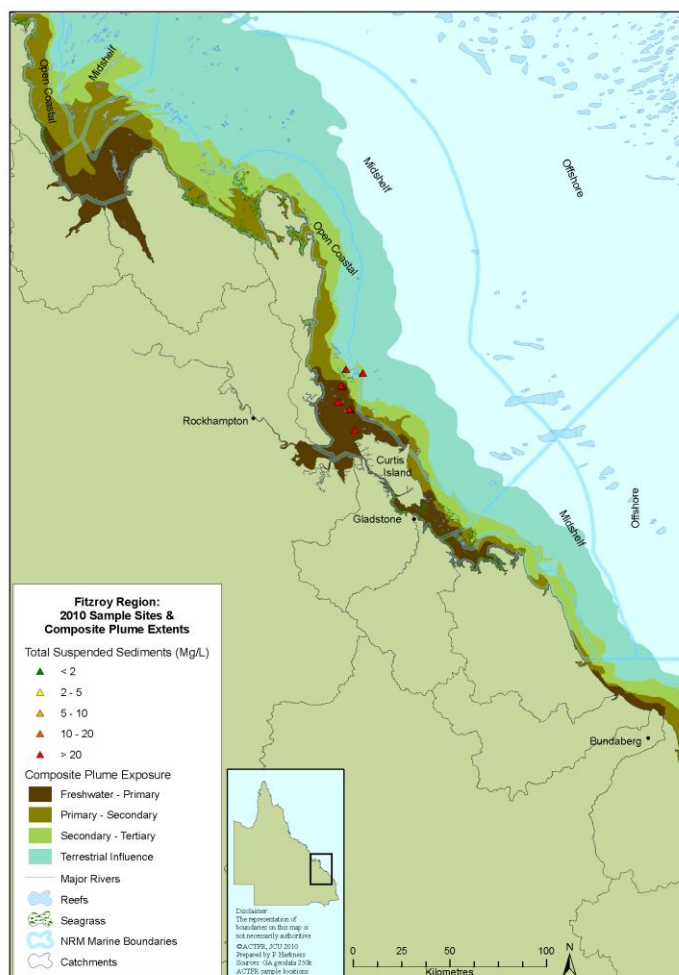
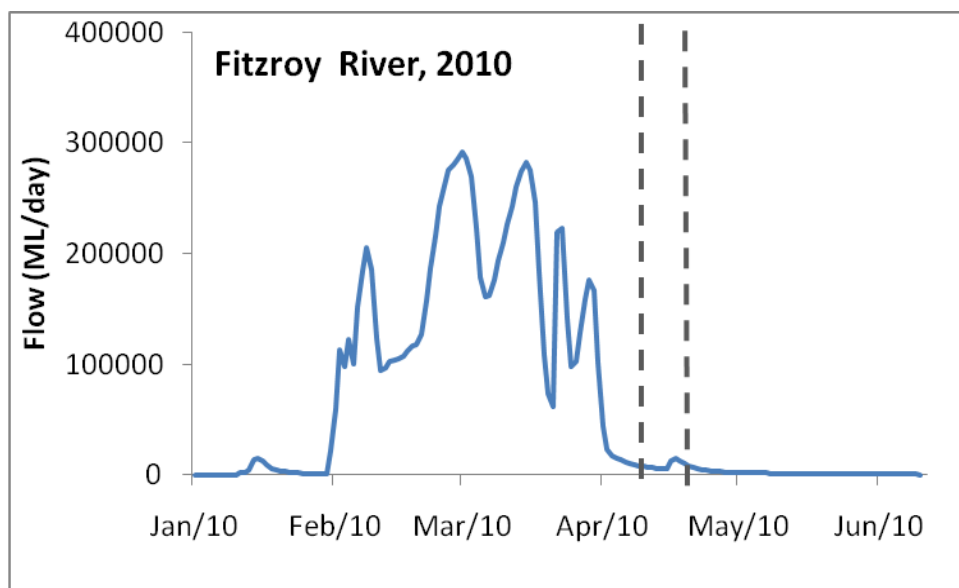
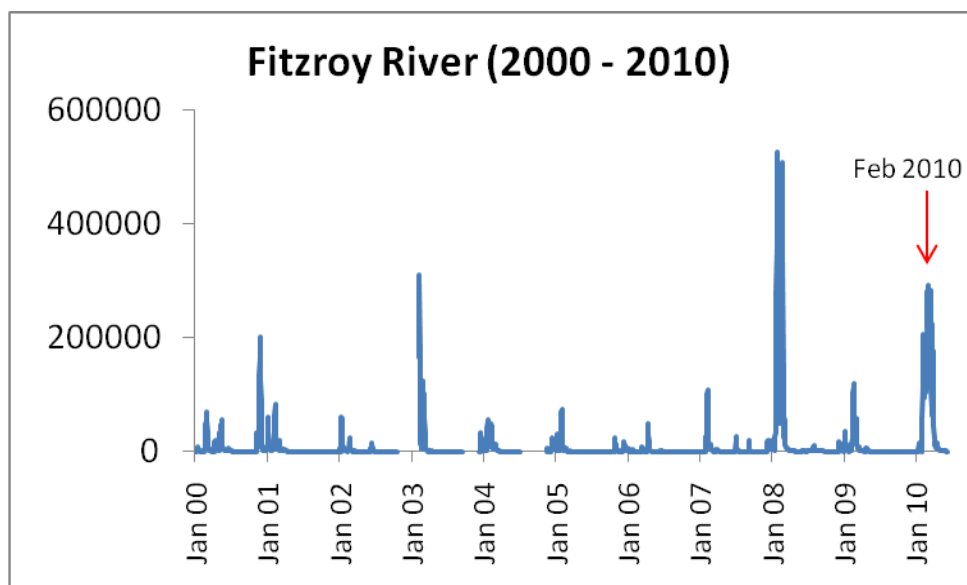


Figure 8-1: Location of all sampling sites delineated by date for the Fitzroy region.



**Figure 8-2: Flow hydrograph for the Fitzroy River in 2010. Dotted line denote the periods of time in which sampling took place.**



**Figure 8-3: Flow hydrograph for the Fitzroy River (2000 – 2010).**

## **8.2. Water quality results**

Water quality data was collected during two field trips at 15 to 25 days past the peak flow period (Fig 8.2). The total volume of freshwater moving into the marine environment was significant, with over 2,193,040 ML of water discharging from the Fitzroy catchment over the 2009/10 wet season. Note that the sampling periods are, at least, 15 days after the highest peak measured in the hydrograph. This reflects both the inclement weather that was experienced during the latter part of March and early April 2010. It also reflects the shift in focus of the flood plume monitoring program to extend the sampling for days to weeks following peak flow to capture the full extent of both the secondary and tertiary water types and to identify the longer term impact of the less visible plume constituents.

There were a limited number of samples taken at the lower salinities which are reflected in the low number of samples at the freshwater end of the mixing curves. Figure 10.4 shows four mixing plots of the Fitzroy water quality data for total suspended sediment (TSS), dissolved inorganic phosphate (DIP), dissolved inorganic nitrogen (DIN) and chlorophyll. Due to the limited number of samples taken in the 2009/10 sampling year, concentrations have been overlaid on the salinity scatter plots with 2008 and 2010 data.

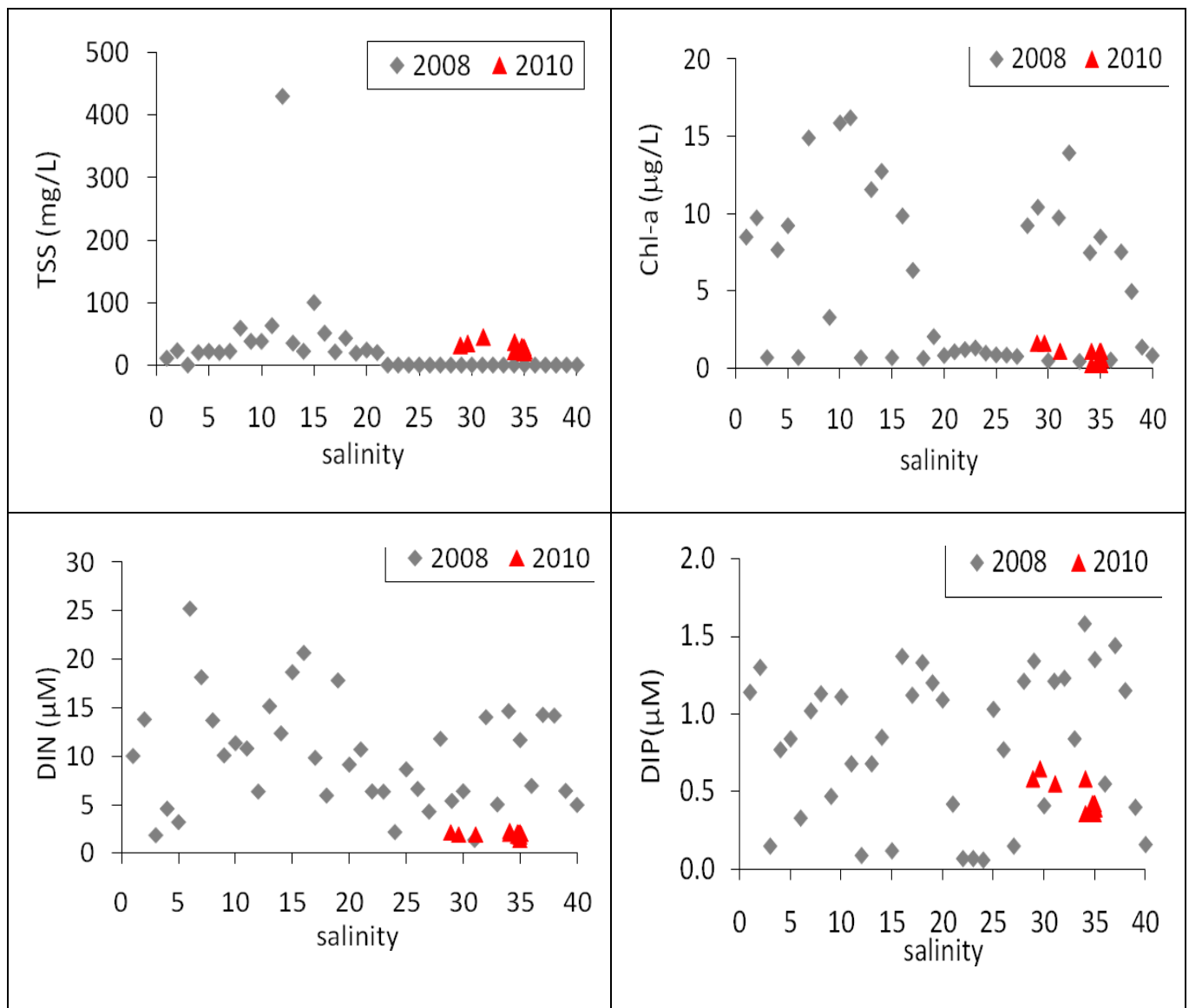
Data analysis illustrates the spatial patterns within the Fitzroy River plume waters. Suspended particulate matter (SPM) is low compared to the Burdekin River data. There are elevated concentrations, but not the high values that would be expected in the very low salinity waters. Landuse activities and time and location of sampling related to the river mouth will affect the TSS measurements. In both these events, particularly 2010, sampling occurred a number of days to weeks after the peak flow, which is reflected in the TSS concentrations. However, all values are higher than 2.0 mg/L, thus still indicating a ongoing source for particulate matter. At later stages in plume, it is also possible that the TSS is incorporating a significant proportion of phytoplankton cells and by-products. Further work on sediment particle size and composition is ongoing in Burdekin and Tully Rivers and may help define the sources of TSS in plume waters.

DIN concentrations were elevated in the 2009/10 samples but still reduced considerably from concentrations measured in the 2008/09 event. This variation in concentrations is due a combination of the differences in time lag between the peak flow and the sampling time

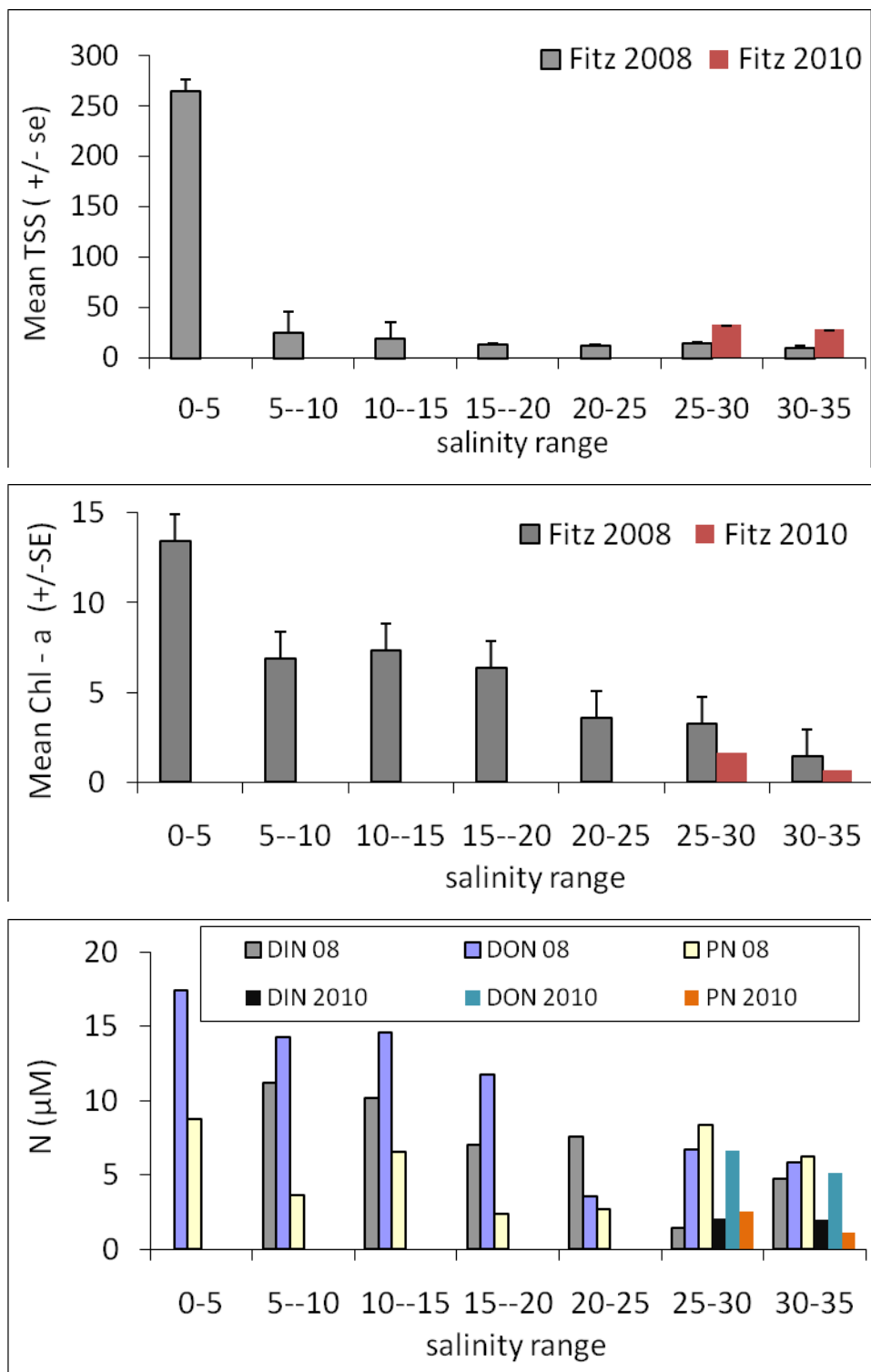
and the riverine flow being sourced from different sub-catchments. DIN is significantly correlated with the salinity and thus high flow periods do correspond to high concentrations. In the later stages of the plume, as measured in 2009/10 sampling period, the majority of the DIN would have been taken up and assimilated by the standing crop of phytoplankton. However, there is still elevated concentrations within the plume waters (1.4 to 2.3  $\mu\text{M}$ ) illustrating the length of influence these large dry tropics flood events can have, with elevated concentrations of nutrients discharging for weeks and extending hundreds of kilometers into the marine park.

Chlorophyll, as an indicator of phytoplankton growth is elevated in both sampling events, though very much reduced in the 2009/10 samples. As with the Burdekin and Tully River samples, there are high concentrations occurring in lower salinities, indicating some intrusion of freshwater phytoplankton, and in higher salinities, indicating favorable growth conditions for the phytoplankton in the non light limiting waters (Fig 9.5). 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 pattern of chlorophyll concentrations is difficult to identify and is possibly related to shifting water masses along the inshore coral reefs. Further analysis of location and flow is required to identify the shifts in production along the salinity gradient

Figure 9.5 presents the plume concentrations over a range of salinity measurements taken over the two events. The plots show the average concentrations of each parameter (TSS, DIN and chlorophyll) over a set salinity range. In all years, the overall patterns are clear, with TSS falling out rapidly in the lower salinity ranges, with DIN concentrations reducing rapidly in the middle salinity ranges, corresponding to the higher chlorophyll measurements, indicating the zone of higher biological activity. The other nitrogen species, particularly DON, do not reduce linearly along the salinity gradient. DON is the largest contribution to the N pool, and stays elevated, with reduction in the higher salinities. PN is variable, and potentially reflects transformation between the inorganic particulate matter to phytoplankton.



**Figure 8-4: Mixing curves for total suspended sediment (TSS), dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) and chlorophyll for all sampling events in the Fitzroy River plumes during the 2008/09 and 2009/10 wet seasons.**



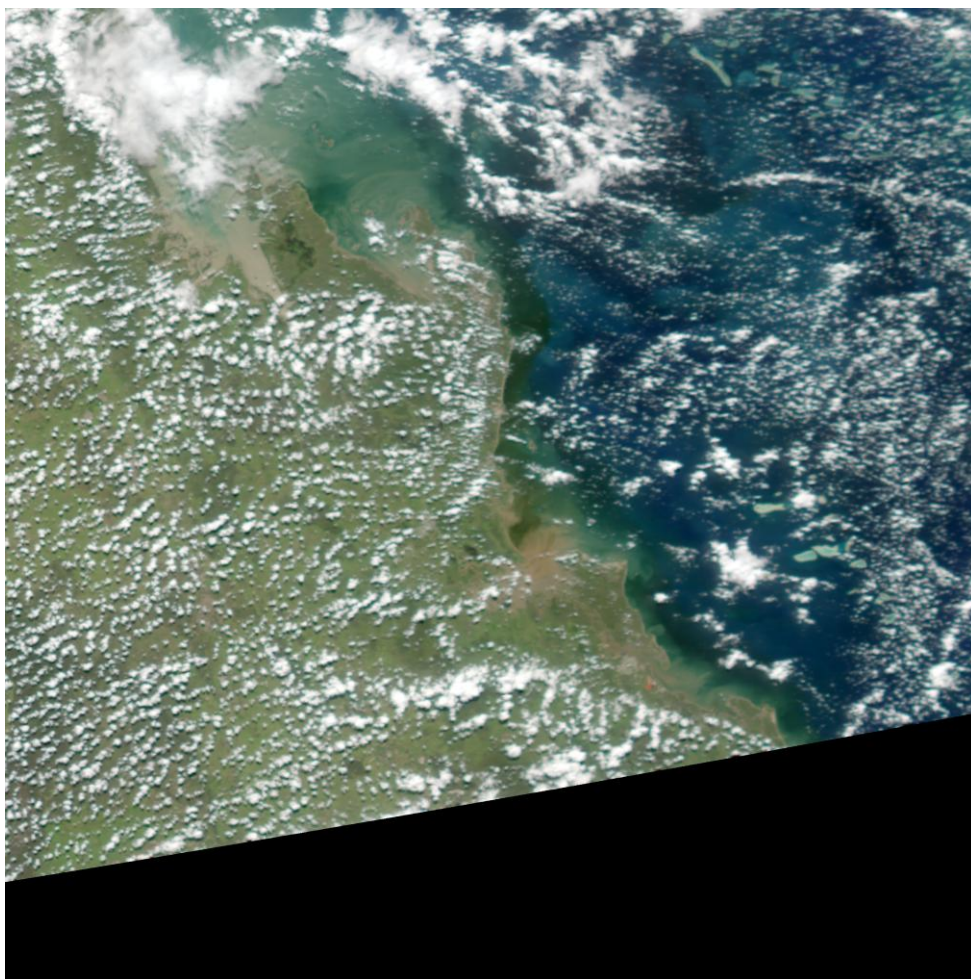
**Figure 8-5: Salinity profiles for TSS, nitrogen species and chlorophyll collected in the Fitzroy River plumes (2008/09 – 2009/10). Data is averaged over salinity bands.**



### **8.3. Remote sensing of Fitzroy River plume**

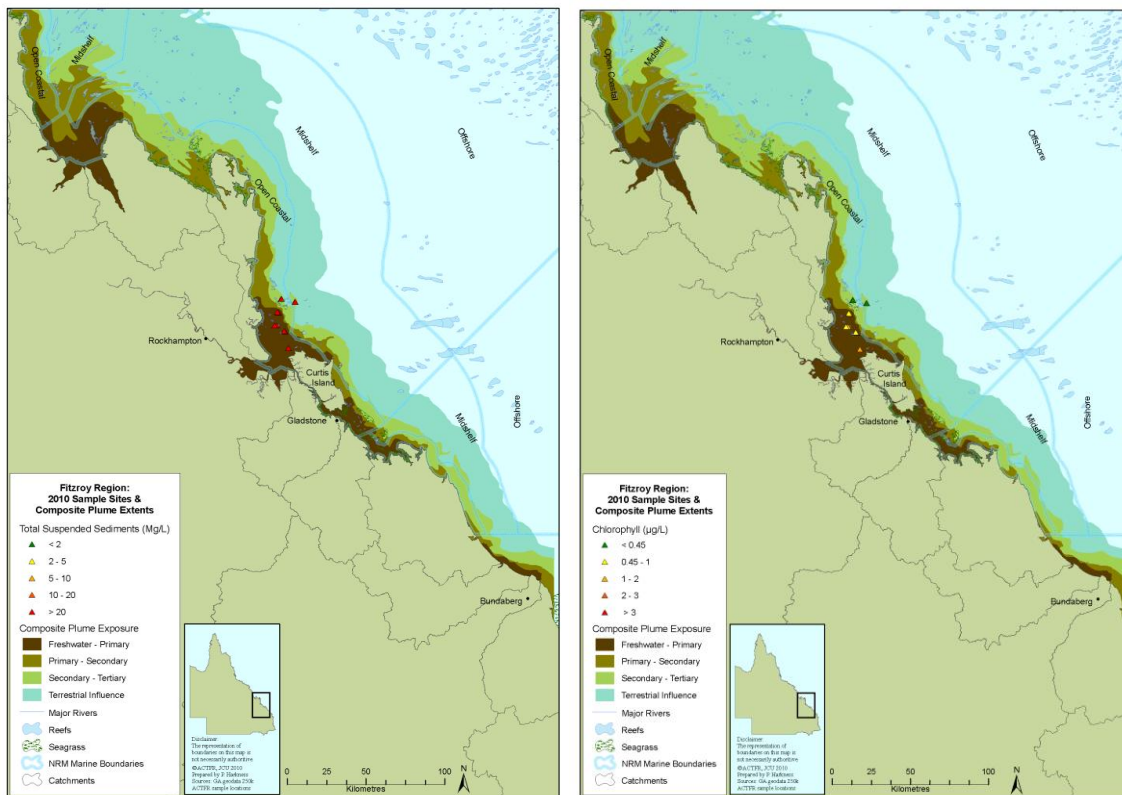
The extent of a visible plume out of the Fitzroy River is seen in true colour imagery (Fig 8.6). The Fitzroy River plume measured on the 29<sup>th</sup> February 2010 is visible as long streaks of high sediment carrying waters discharging from the Fitzroy River. The colour of the primary water is delineated as a brown turbid water mass, contrasting with the secondary water types, characterized by the turbid, “green” coloured waters. The turbid water mass can be seen along the coastline extending past Rosslyn Bay to the North. The water mass is constrained to the coast at this point, reflecting the very strong south easterlies which dominate this systems for weeks from February to March, making the sampling of the plume waters very difficult.

Figure 8.7 identifies the water types that have been identified for Fitzroy River flood waters. These maps identify a small area out of the Fitzroy and local rivers that would be dominated by primary water characteristics during the wet seasons. There is a much larger area characterise by the occurrence of secondary waters, extending north for at least 100 km, and offshore past and around the Keppel Island reefs. Using a combination of information from catchment loads, the frequency and exposure of plume waters and information on the characteristics of water types most commonly found within the marine regions, we have identified the area most likely to exceed water quality guidelines for TSS and Chl-*a* in the Burdekin region (Fig 8.8).

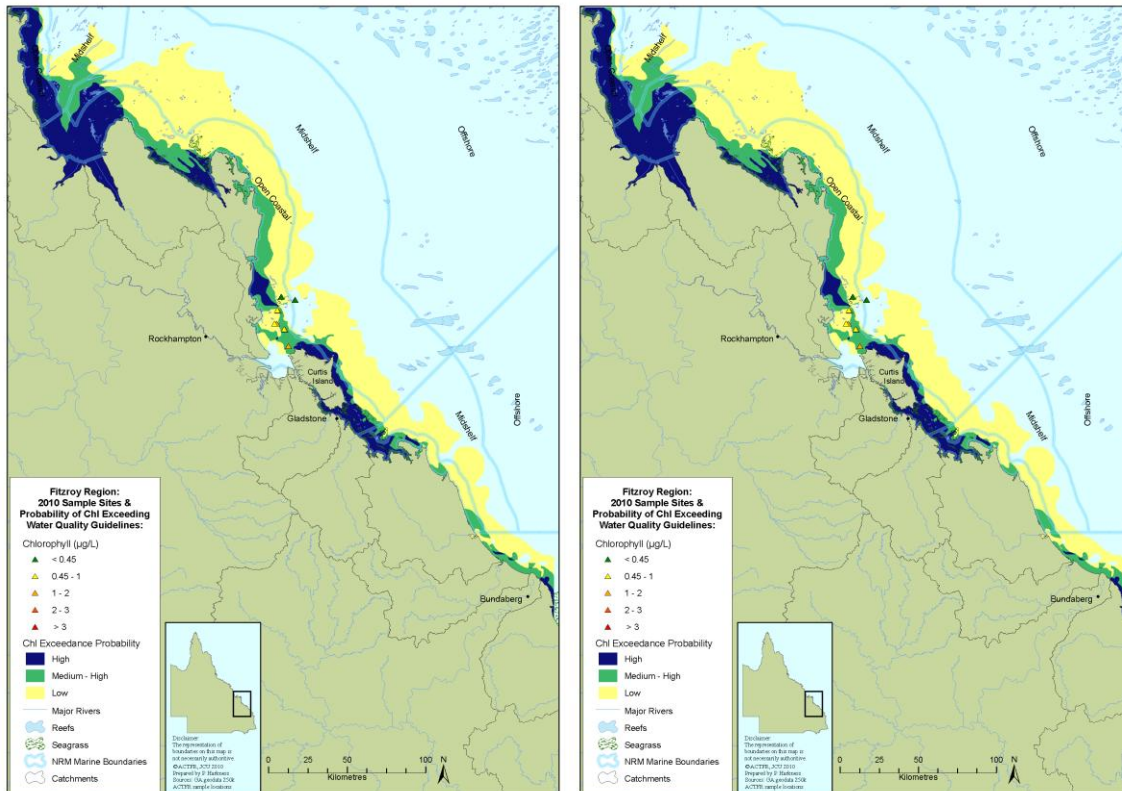


**Figure 8-6: MODIS AQUA image of the Fitzroy River plume at 250 m resolution taken on the 29<sup>th</sup> February 2010. Note the large discharges of riverine waters along coast (Image courtesy of ACTFR).**

*a*



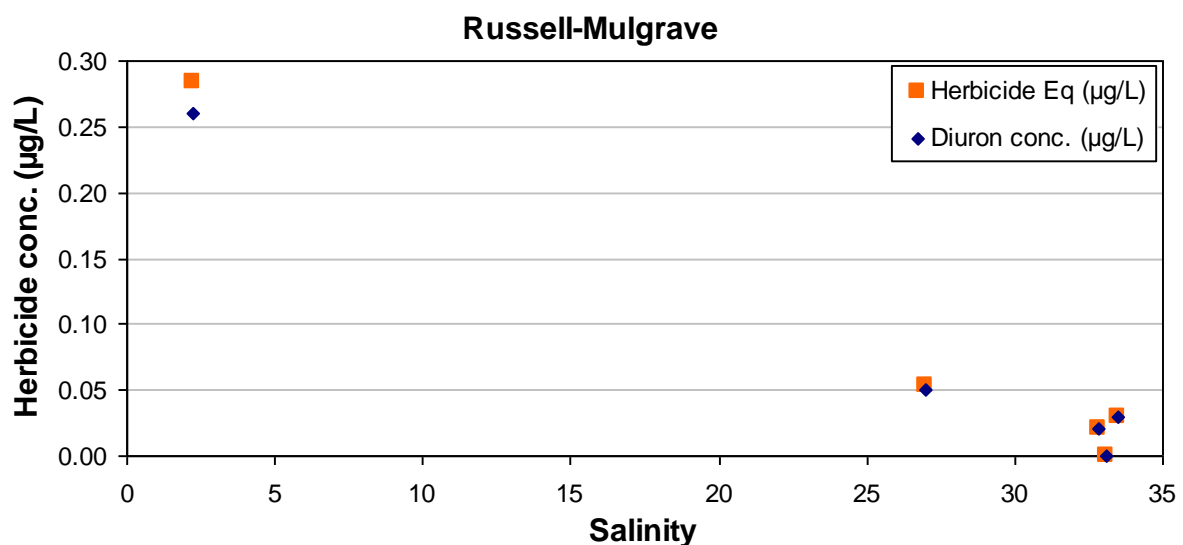
**Figure 8-7: Definition of the water types commonly found within the Fitzroy River plume extent and area. (a) TSS and (b) Chl-*a* concentrations collected in 2010 are marked on the map (sites in 2009/10 are located only in the primary water types).**



**Figure 8-8: Definition of the Wet Tropics areas which are most likely to exceed the Guidelines based on catchment load information, movement and extent of flood plume waters and the characteristics of the common water types.**

## 9. Pesticides

Sampling adjacent to the Russell-Mulgrave Rivers (Wet Tropics region) showed that the highest diuron (0.26 µg/L) and herbicide equivalent (0.284 µg/L, sample contained diuron, atrazine, hexazinone and also the insecticide imidachloprid) concentration was at the river's mouth before being diluted at the offshore sites (including out to the Frankland Island Group) (Fig 9.1). These samples were all below guidelines (0.9 µg/L) but samples from the mouth and near High Island were above seagrass and diatom effect levels (>0.05 µg/L). We note that these samples were collected at the tail end of a moderate flow event and that the concentrations during the initial rise and peak of this event were probably much higher. As has been observed in monitoring from other rivers (Lewis et al., 2009), the herbicides display conservative mixing behavior becoming progressively diluted as the river water is mixed with seawater.



**Figure 9-1; Samples collected adjacent to the Russell-Mulgrave Rivers on the 3<sup>rd</sup> February 2010.**

Pesticide sampling adjacent to the Tully River (Wet Tropics region) occurred on 29<sup>th</sup> December 2009 (2 samples) and on the 2<sup>nd</sup> February 2010 (7 samples). The December 2009 samples were collected from the mouths of the Tully and Hull Rivers prior to any large event flows and as such pesticide residues were not detected at this time. The early February 2010

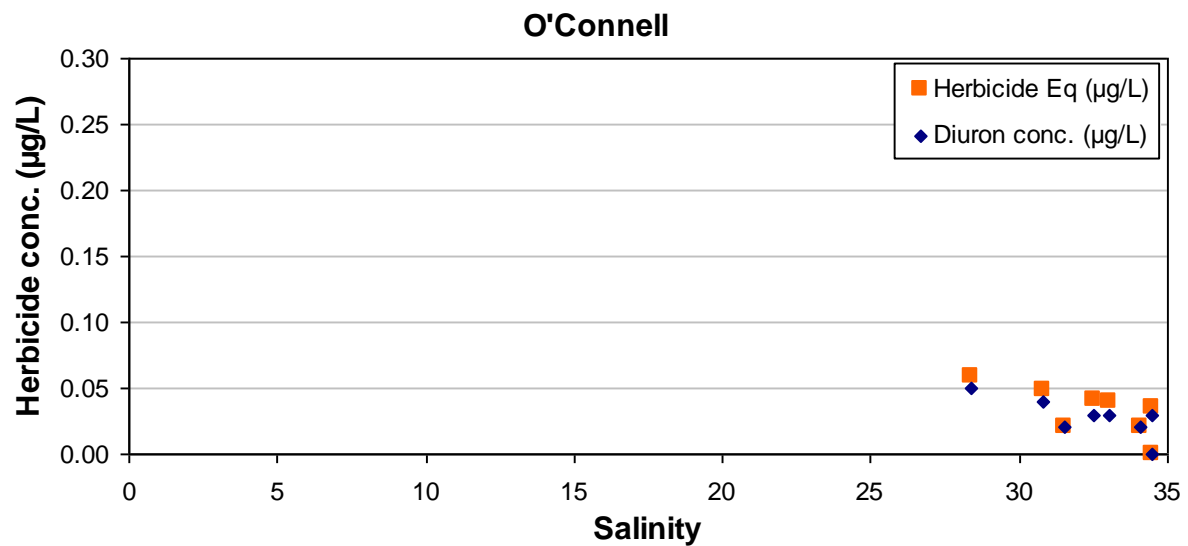
sampling was conducted towards the end of a moderate flow event in the Tully River. Diuron was the only herbicide detected in three of the seven samples from this event and concentrations were below guidelines and effect levels ( $\leq 0.02 \mu\text{g/L}$ ). Similarly to samples collected off the Russell-Mulgrave River, the concentrations during the early-peak stages of the flow were probably much higher. The passive samplers recorded flow-averaged herbicide equivalent concentrations of  $0.01 \mu\text{g/L}$  at the mouth of the Tully River during a 38 day deployment (3<sup>rd</sup> March – 1<sup>st</sup> April 2010) while the site at Bedarra Island recorded average concentrations of  $0.03 \mu\text{g/L}$  over the first 29 day deployment (1<sup>st</sup> January – 8<sup>th</sup> February 2010) and  $0.004 \mu\text{g/L}$  over the second 38 day deployment (3<sup>rd</sup> March – 1<sup>st</sup> April 2010). Herbicide residues detected by the passive samplers at these sites included diuron, atrazine, hexazinone, simazine and tebuthiuron.

Three samples were collected off the Burdekin River mouth (Burdekin region) during the peak of a moderate flow event on the 24<sup>th</sup> February 2010. Tebuthiuron was the only herbicide detected in all three samples at  $0.01 \mu\text{g/L}$ .

Pesticide sampling off the mouth of the O'Connell River (Mackay Whitsunday region) was conducted following two separate flow events on the 8<sup>th</sup> February 2010 and 5<sup>th</sup> March 2010. The samples from February 2010 were collected at the very end of a small-moderate flow event and as such only diuron residues were detected at very low concentrations (range below detection –  $0.02 \mu\text{g/L}$ ) in two of the five samples collected. Diuron was detected near South Repulse Island ( $0.01 \mu\text{g/L}$ ) and from Rabbit Island – Newry Group ( $0.02 \mu\text{g/L}$ ). The samples collected in March 2010 followed moderate flows in the O'Connell River but also occurred after peak flow. Diuron was detected in seven of the eight collected samples (range between  $0.01$  and  $0.05 \mu\text{g/L}$ ) and atrazine (5 of 8 samples) and hexazinone (5 of 8 samples) were also detected. The herbicide equivalent concentrations did not exceed guidelines although the sample collected near the mouth of the O'Connell River exceeded effect concentrations for seagrass and diatoms (Fig 9.2).

The samples off the mouth of the Pioneer River on the 4<sup>th</sup> March 2010 also were collected following moderate flows, although the samples were collected ~5 days after the event peak. Diuron was detected in all four samples which were collected along a transect from the mouths of the Pioneer River and Sandy Creek out to Keswick Island, but the concentrations

were below both guidelines and known effect concentrations (range 0.01 – 0.02 µg/L). No other herbicides were detected in these samples.



**Figure 9-2; Samples collected adjacent to the O'Connell River on the 4<sup>th</sup> – 5<sup>th</sup> March 2010.**

## 10. Plume exposure mapping

To identify those areas of risk which are most likely to receive high concentrations of pollutants, the catchments which transported the greatest amounts of pollutant loading were identified and ranked. Regional areas were ranked according to the volume of pollutant loading for dissolved nutrients (DIN), total suspended sediments and PSII herbicides (Table 10.1). Ranking of the pollutant load was combined with the relative risk assessment for broad scale agriculture on the GBR presented in Brodie and Waterhouse, 2009. This report highlights the main catchments of risk include the Wet Tropics (sugar cane) and Burdekin (grazing) regions. The combined rankings of the catchment loads and risk assessments were then combined with the overall areal coverage and frequency of plume extents to identify the regional areas most at risk from specific pollutants, including TSS (Fig 10.2), Chl-*a* (Fig 10.3) and PSII herbicides (Fig 10.4).

The greatest risk from elevated pollutants in GBR loads is where the pollutants can reach ecosystems upon which they can cause an impact. For example, it is the inshore area of the Mackay Whitsunday region where elevated pollutants in flood plumes can impact a significant number of reefs and seagrasses due to the high number of ecosystems and their close proximity to the frequent exposure from flood plumes (see Section 5).

GBR seagrass meadows are dynamic and vary considerably in space and time, which is due to various environmental drivers such light and nutrient availability as well as disturbance such as floods, cyclones and other severe storms and high temperature events (Schaffelke et al., 2005, Waycott et al., 2005). Flood events, with excess sediment and nutrient loads can cause local declines of GBR seagrasses (Schaffelke et al., 2005, Waycott et al., 2005). Seagrasses can be impacted by flood plumes if inundated every year by primary plumes, and thus were exposed to intermittently high sediment and high nutrient concentrations during flood plumes, and potentially high loads of sedimenting particles.

The major adverse effect on corals from flood plumes is decreased light availability due to high water turbidity and short-term or intermediate smothering by high sedimentation during flood events or due to resuspension of terrigenous fine sediments by wind and waves. Corals are phototrophic organisms and reduced light availability due to high turbidity or

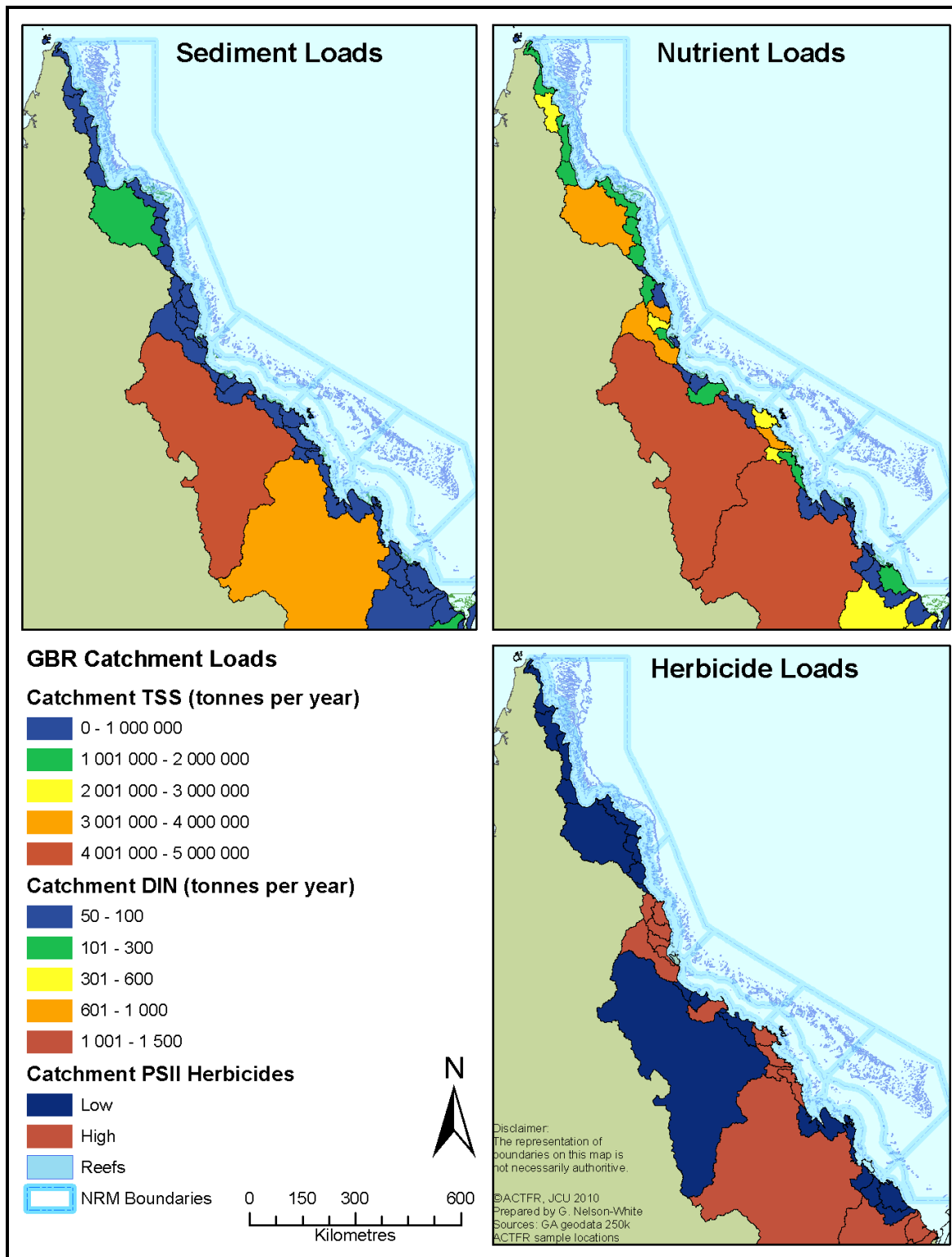


sedimentation leads to resource limitation (Fabricius 2005, Cooper *et al.* 2008). In addition, exposure of corals to elevated levels of nutrients, sedimentation and turbidity may affect certain species that are sensitive or vulnerable to these environmental conditions. This may lead, in the medium to long-term, to reduced densities of juvenile corals, subsequent changes in the community composition, decreased species richness and shifts to communities that are dominated by more resilient coral species and macroalgae (van Woesik *et al.* 1999; Fabricius *et al.* 2005; DeVantier *et al.* 2006).

**Table 10-1: NRM region (catchment) ranked by pollutant load for Dissolved inorganic nutrients (DIN), TSS and PSII herbicides.**

Ranking	DIN	TSS	Pesticides
1	Wet Tropics	Burdekin	Mackay Whitsunday
2	Mackay Whitsunday	Fitzroy	Wet Tropics
3	Burdekin	Wet Tropics	Burdekin
4	Fitzroy	Mackay Whitsunday	Fitzroy
5	Cape York	Cape York	Cape York

Flood plume data, both in situ water quality and the ongoing spatial assessments using remote sensing methods will be incorporated into the exposure mapping. Further validation, both through the continual measurement of the water quality concentrations and through the integration of spatial extent models will continually test and refine these areas of high exposure, giving a greater confidence in our ability to predict if and where the ecosystems are exposed to altered water quality conditions.



**Figure 10-1: Spatial representation of catchment loads based on load estimates for TSS, DIN and PSII herbicides as reported in Brodie et al., 2009.**

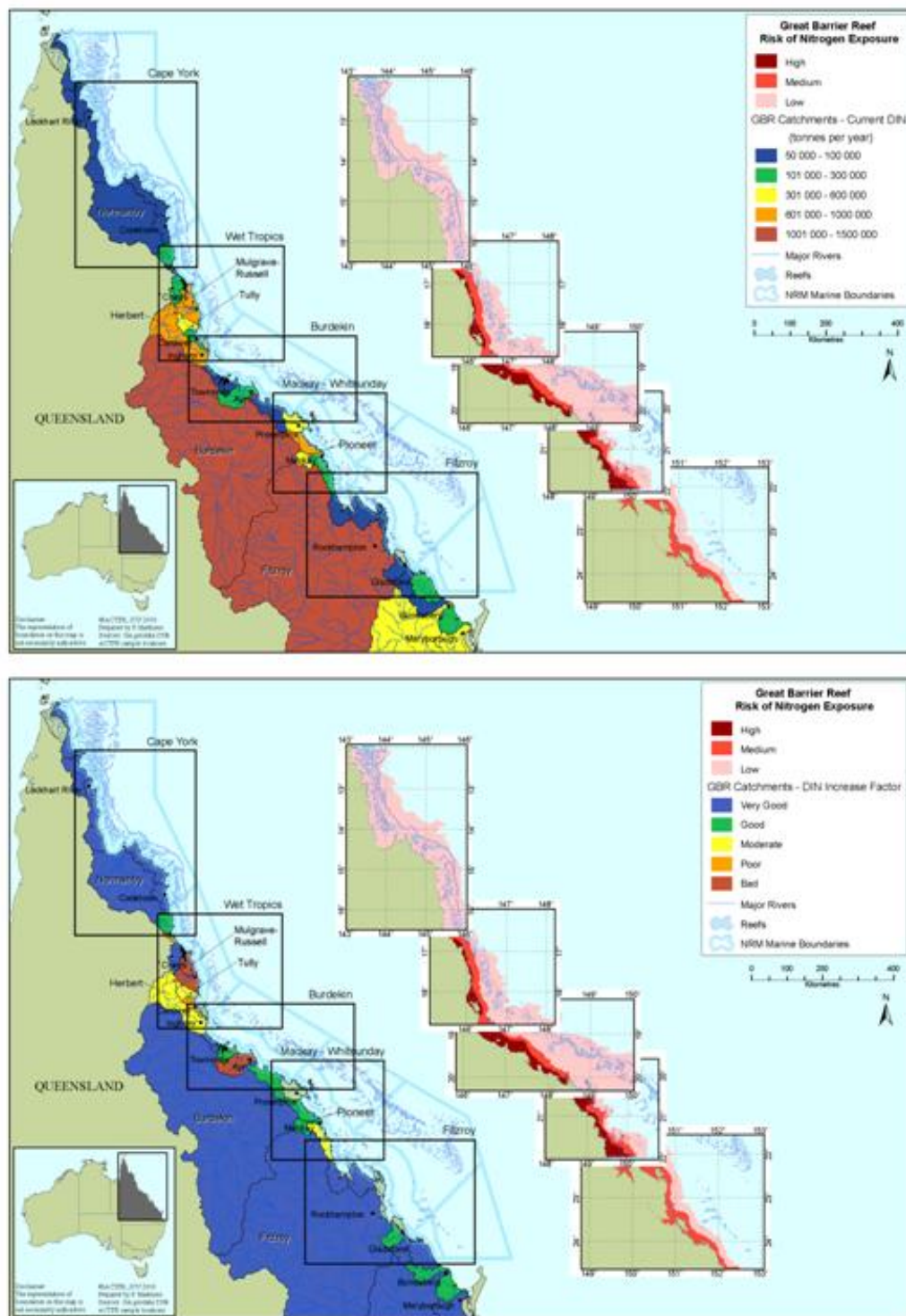


Figure 10-2: Mapping of the areas identified as high exposure areas to the influence of altered plume water quality from increased Chl- $\alpha$ . Ranking of catchment risk is based on (a) total DIN loads and (b) the increase of DIN from reference to current loads.

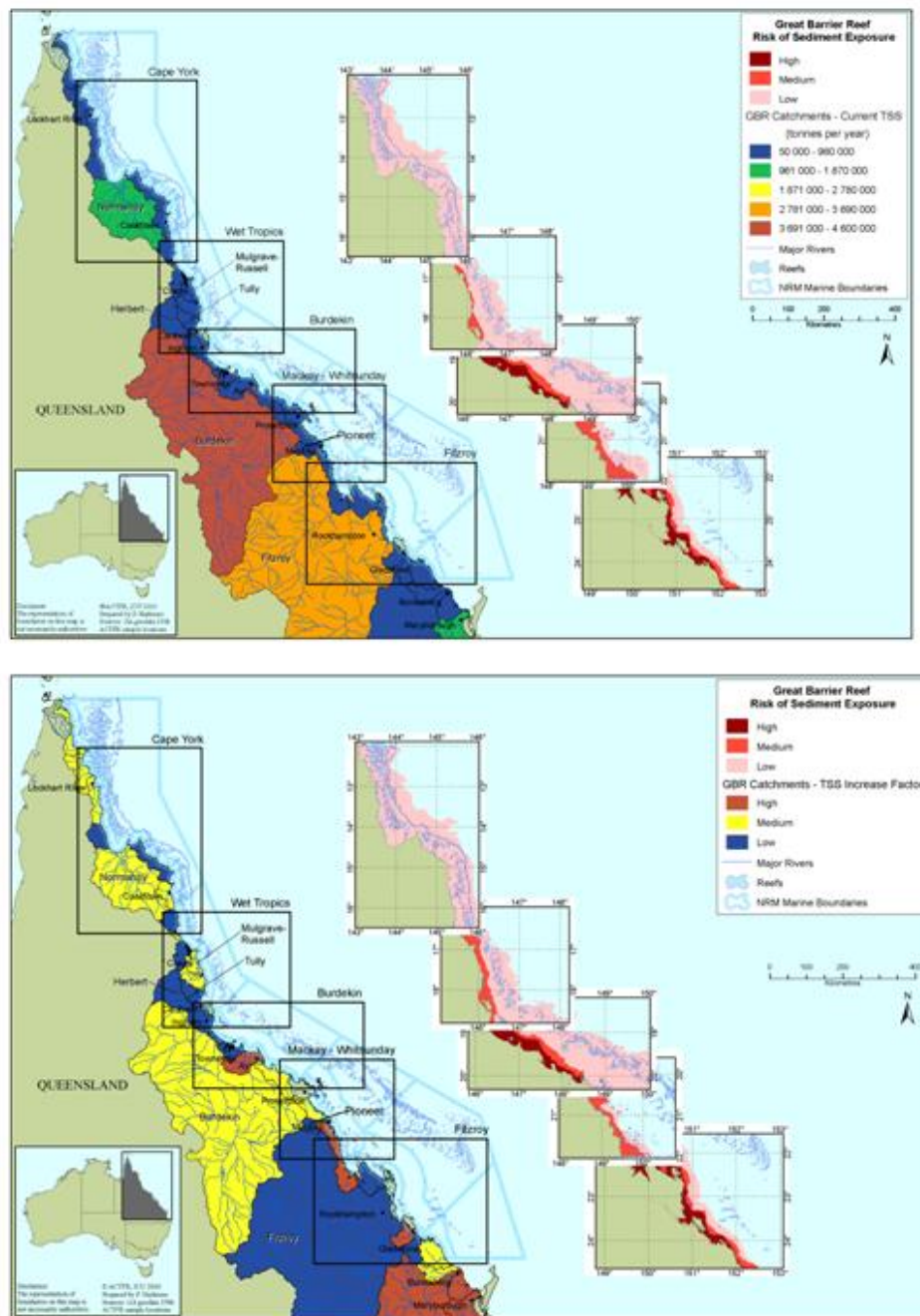
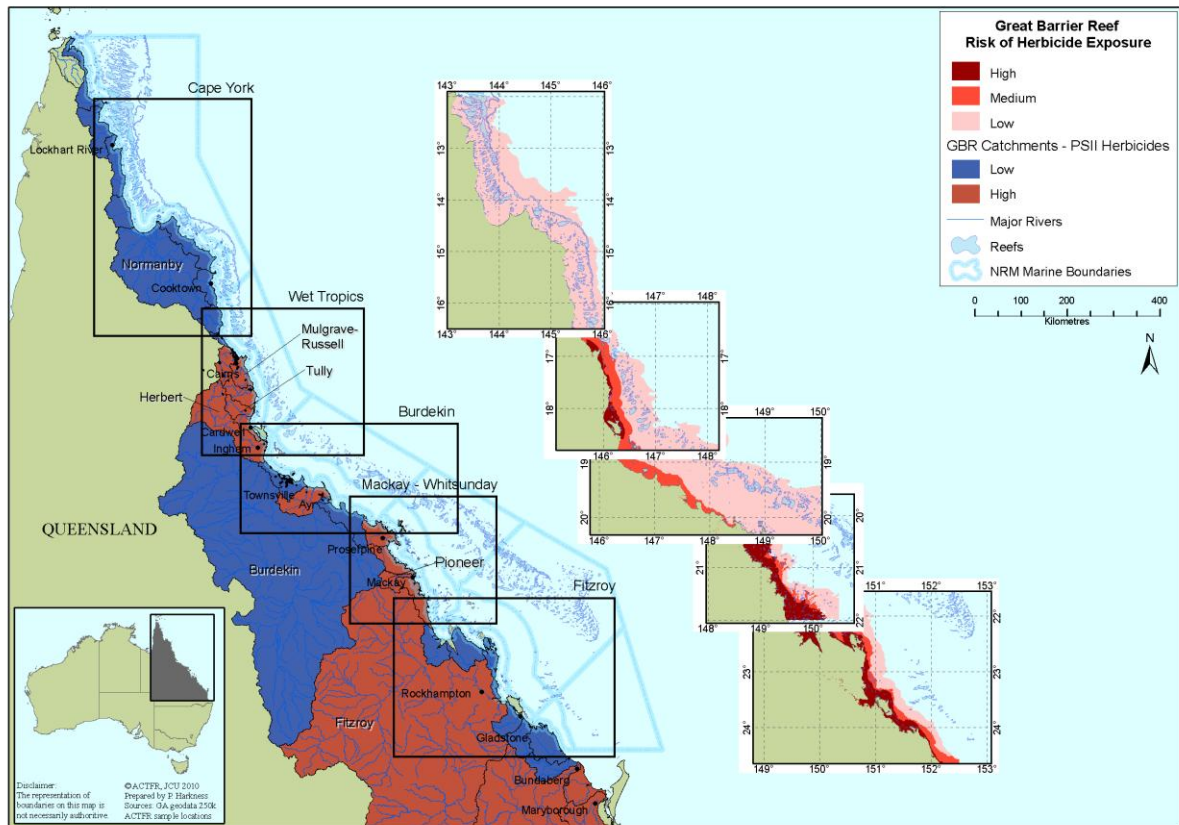


Figure 10-3: Mapping of the areas identified as high exposure areas to the influence of altered plume water quality from increased TSS. Ranking of catchment risk is based on (a) current annual TSS loads and (b) the increase of TSS from reference to current loads.



**Figure 10-4: Mapping of the areas identified as high exposure areas to the influence of altered plume water quality from increased PSII herbicides. Ranking of catchment risk is bases on (a) current annual TSS loads.**

## 10.1. Water types

Plume types were classified using the following criteria:

- (i) Primary water type was defined as having a high total suspended solid (TSS) load, minimal chlorophyll and high values of coloured dissolved organic material plus detrital matter (CDOM+D). For the quantitative analysis, we used a threshold on back scatter information derived from remote sensing imagery.
- (ii) Secondary plume type was defined as a region where CDOM+D are still high however, the TSM has been reduced. In this region, the water is characterised by increased light and nutrient availability, which can prompt phytoplankton growth. Thus, secondary plume waters exhibit high chlorophyll, high CDOM+D and low TSS.
- (iii) Tertiary plume type is the region of the plume that exhibits no elevated TSS and reduced amounts of chlorophyll and CDOM+D when compared with that of the secondary plume, but still above ambient conditions. This region can be described as being the transition between a secondary plume and ambient conditions.

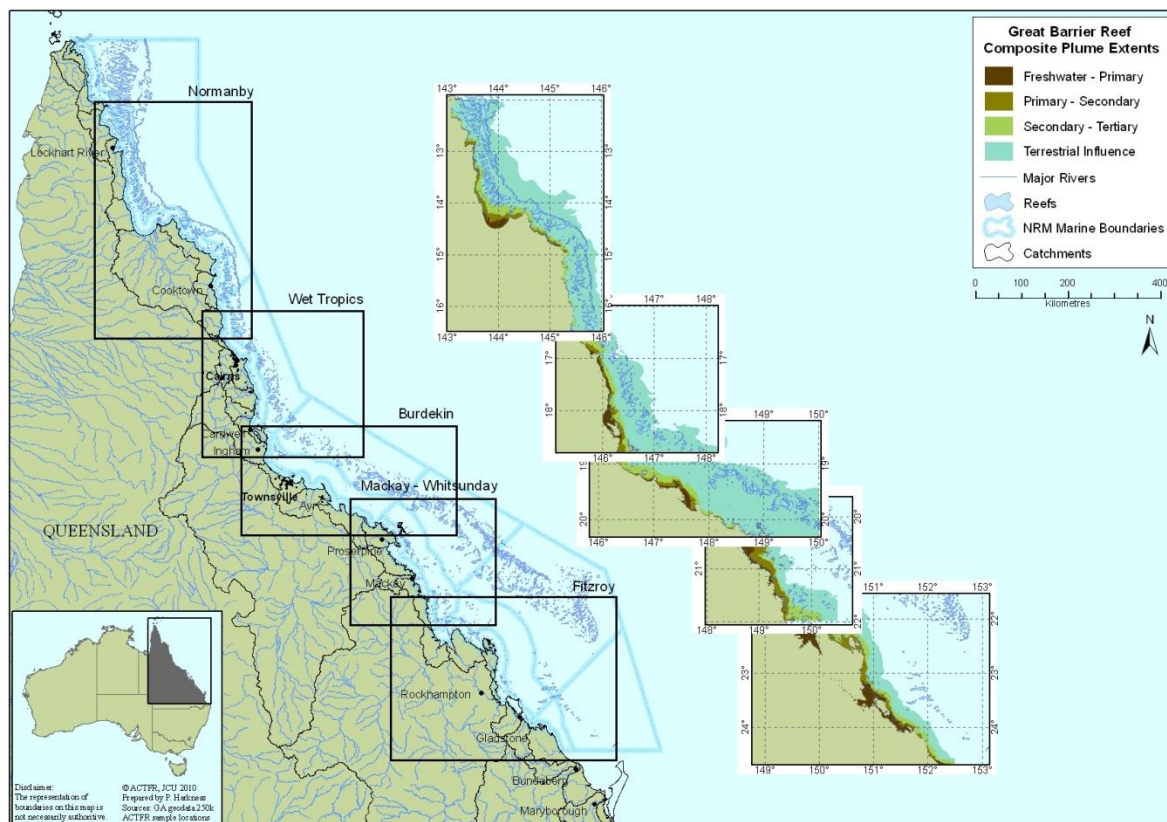
The boundary between the different water types can be difficult to assess with complete accuracy so we define the water types in a continuum of change, with four steps in the plume water gradient including freshwater – primary, primary – secondary, secondary – tertiary and terrestrial influence. The extent of these water types over the GBR is mapped in Figure 10.5.

Knowledge of the water types and their movement can help us to define the area most likely to be exceeded during flood plume conditions. Note that high values would have typically occurred in flood plumes, but concern now is for the elevated concentrations of TSS and chlorophyll (as proxy for DIN) exceeding, or causing the exceedance of the Guideline annual average by the high proportion of high values measured during high flow periods. Recent reporting of flood plume measurements (Devlin et al., 2009) have discussed the impact of flood plumes now being seen as a high seasonal shift, not just a limited number of elevated measurements seen in the high flow event. Regular sampling in the Tully River plume over the whole of wet season points to a system which has persistently higher values for TSS and chlorophyll over 3 to 4 months of the wet season. Thus the impact of the high risk exposure area in the inshore Wet Tropics would be a shift in flood plume

measurements, thus higher maximum values being measured, a shift in seasonal mean concentrations, indicating a persistent, productive water type carrying higher concentrations of finer particulate matter and finally a shift in the long term annual mean, driven by these seasonally high values. This shift in the annual mean has consequences for the long term turbidity of the region and thus impacting on the coral and seagrass community through the changes in light conditions. Coupled with these high measurements are the extreme conditions which can be measured in flood plumes, including higher temperatures, lower salinity and higher concentrations of pesticides, thus creating a physical environment with multiple stressors on the reef and seagrass community.

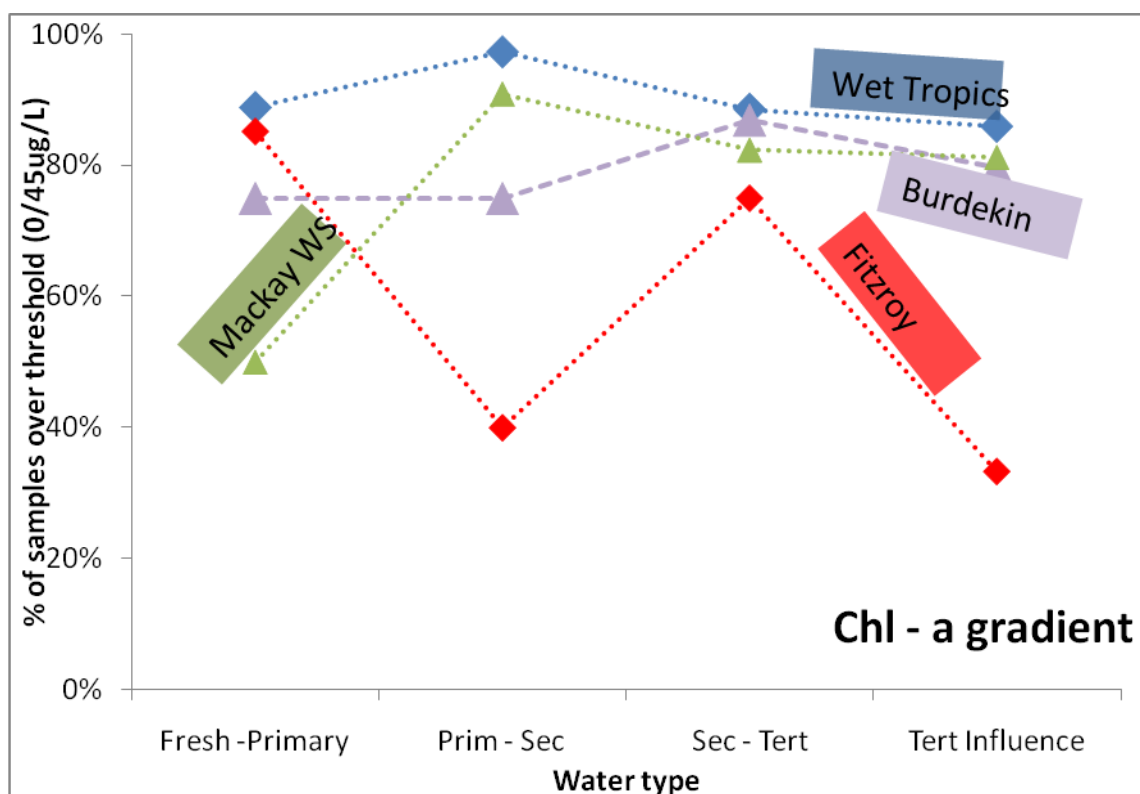
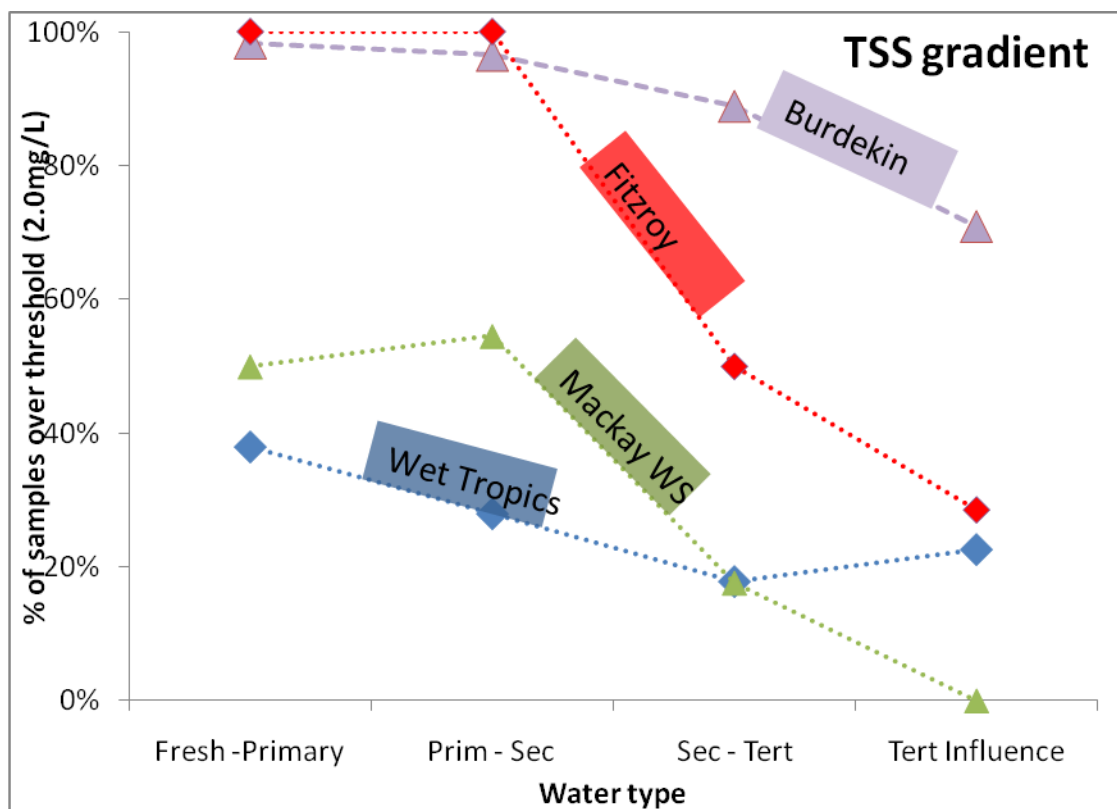
Classification of the riverine plumes into distinct types (primary, secondary and tertiary plumes) helps elucidate more clearly the transport of different water quality constituents of riverine plumes by defining the spatial movement of the suspended sediments, dissolved nutrients and chlorophyll by the extent of the specific plume type (Fig 10.6). Strong gradients exist in the transition between the freshwater to primary water, which is characterised by high TSS concentrations, to secondary waters, characterised by high dissolved inorganic nutrients, non light limiting conditions and high phytoplankton biomass to tertiary plume waters, which are indicative of waters with some degree of freshwater influence, typically measured by Coloured Dissolved organic matter (CDOM) being greater than  $0.15\text{m}^{-1}$ . This CDOM value correlates to salinities greater than 30 ppt and thus still indicative of riverine influence. The gradient between the water types can be identified by the number of Guideline exceedances or high concentrations of TSS and chlorophyll (Fig 4.8). Knowledge of these water types can be used to identify the area most likely to exceed the Guidelines and also identify the reefs and seagrass beds which are most likely to be or are currently being impacted.





**Figure 10-5: Mapping of water types in GBR flood plumes (water types include the transition from freshwater to primary marine waters, primary-secondary, secondary - tertiary and the full terrestrial extent).**





**Figure 10-6: The number of samples which have exceeded a threshold (based on Guideline trigger values for annual means) along the water type transition gradient.**

## **10.2. Mapping the probability of Guideline exceedances**

Thresholds for water quality parameters were developed by GBMRPA to identify boundaries at which known biological impacts could occur. This information is summarised in the Water Quality Guidelines for the Great Barrier Reef Marine Park (GBRMPA, 2009). Information on the composition of water and where it occurs can be invaluable in mapping out areas which have a high probability of exceeding the Guidelines. We have taken the occurrence and frequency of water types, and combined with the catchment risk characteristics to identify areas which are most likely to exceed the Guidelines for both TSS and chlorophyll (Fig 10.7 – Fig 10.11). Areas identified in these maps are ranked from high to medium probability of Guideline exceedance (Table 10.2). There are a number of assumptions in this prediction and that use of these areas is a guide only. Further mapping from additional images would be required. More discussion on the actual Guidelines trigger values for plume waters is also required, for example, the Guidelines are set for wet season averages and not for plume water specifically. Areas most likely to exceed needed to have at least one coverage per year and the probability of exceedance increased in proportion to the number of coverages that had been mapped in that area. Further research into the integration of this large scale risk mapping and the identification of biological response is ongoing and seeking further funding with an ARC linkage research funding proposal.

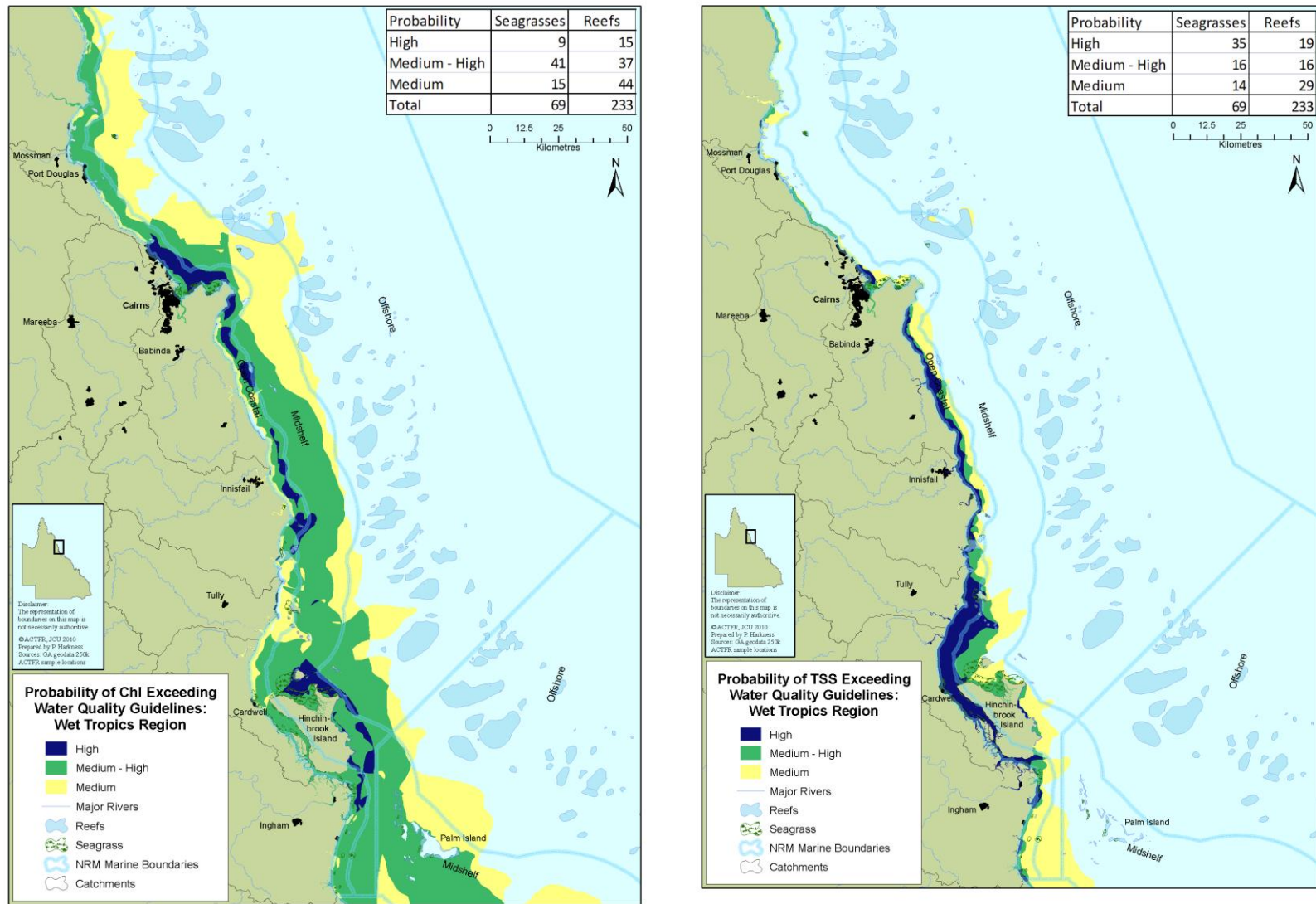
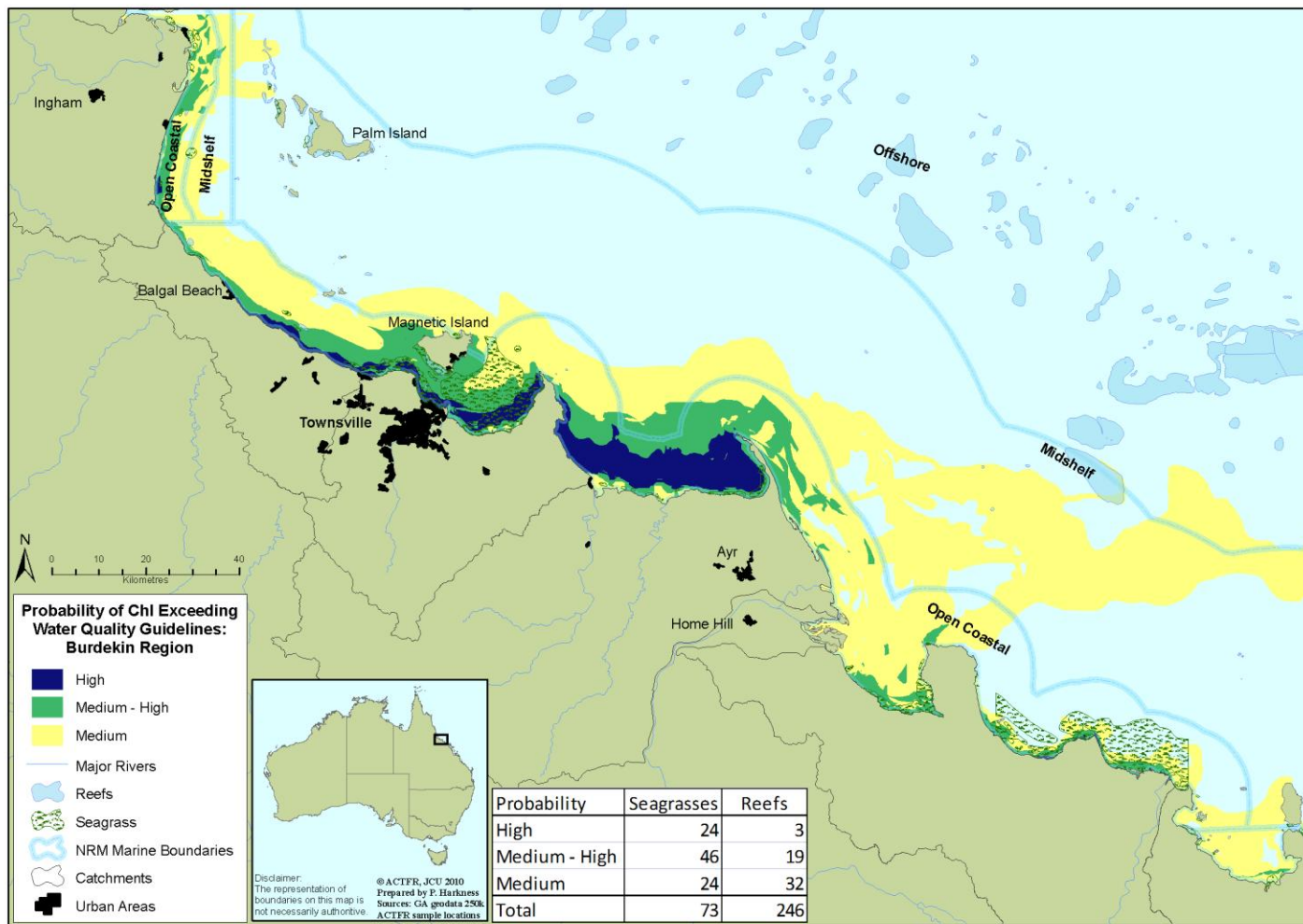


Figure 10-7: Identification of high exposure areas that are most likely to exceed the Guideline trigger values for TSS and chlorophyll in the Wet Tropics region.



**Figure 10-8: Identification of high exposure areas that are most likely to exceed the Guideline trigger values for chlorophyll in the Burdekin region.**

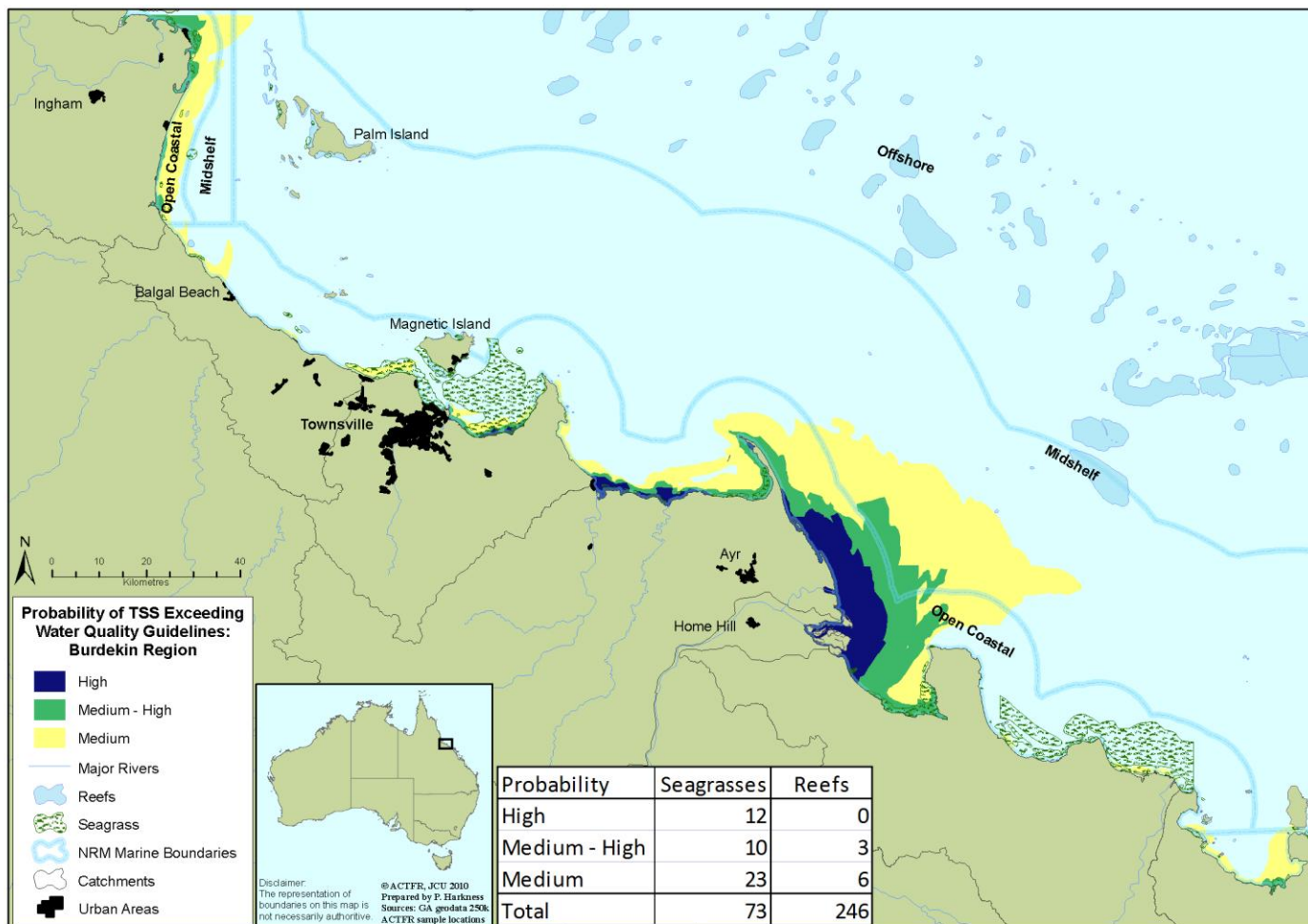
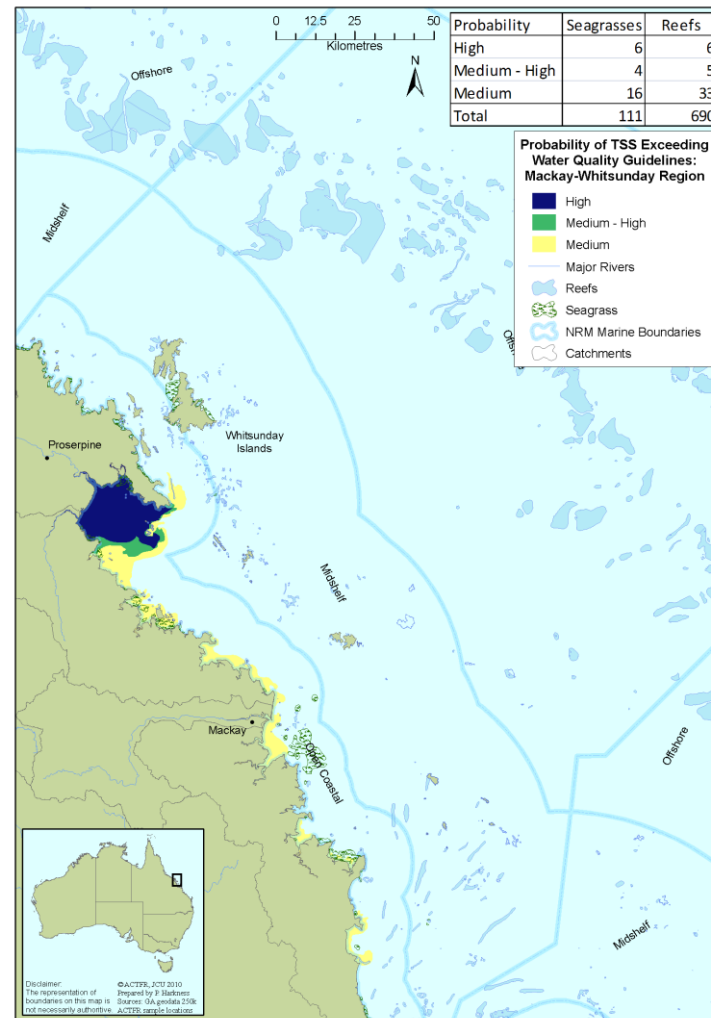
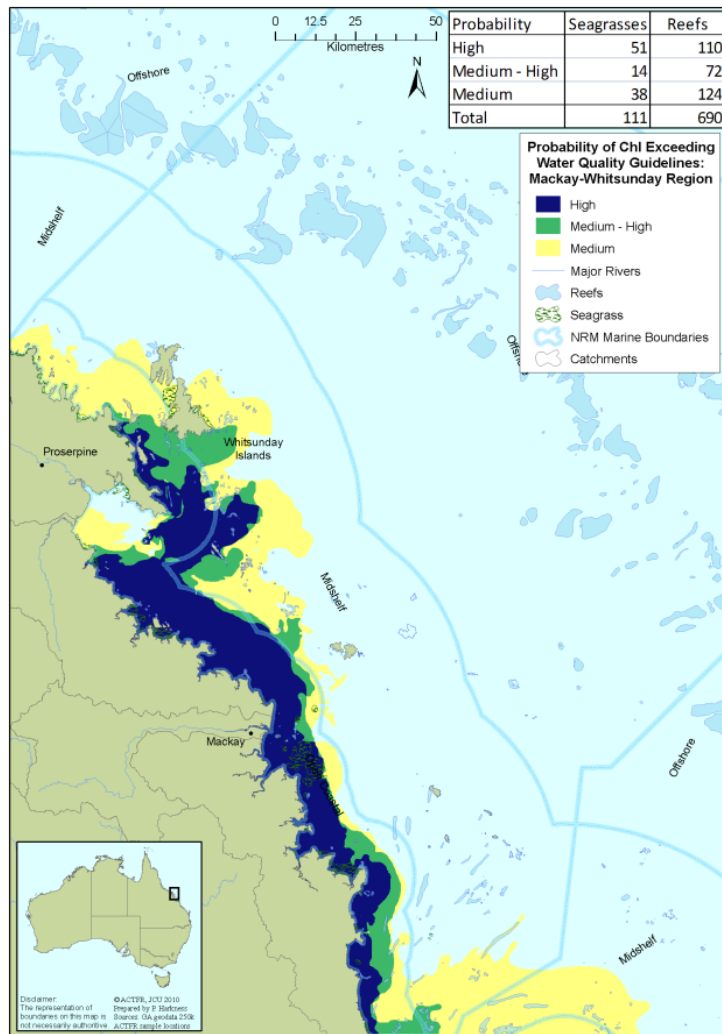
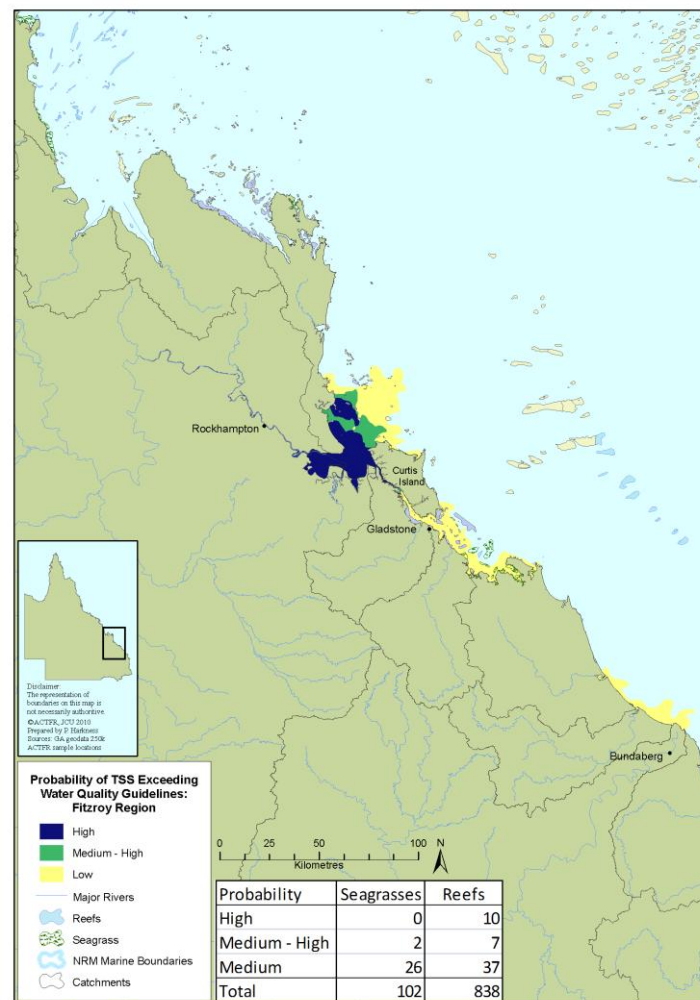
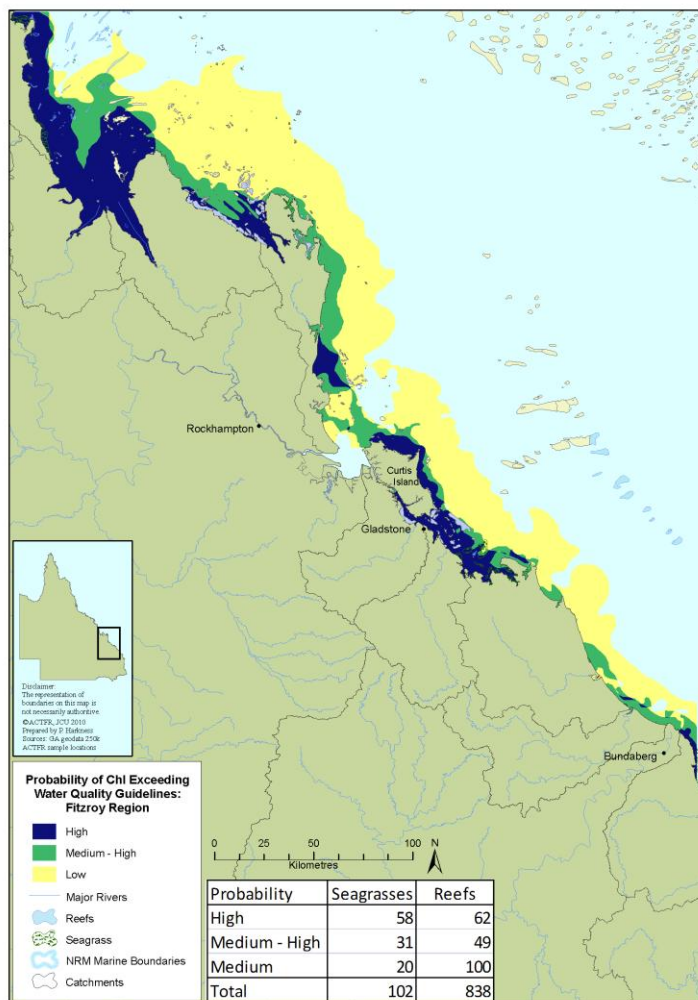


Figure 10-9: Identification of high exposure areas that are most likely to exceed the Guideline trigger values for TSS in the Burdekin region.





**Figure 10-10: Identification of high exposure areas that are most likely to exceed the Guideline trigger values for chlorophyll and TSS in the Mackay Whitsunday region.**



**Figure 10-11; Identification of high exposure areas that are most likely to exceed the Guideline trigger values for TSS and Chl –  $a$  in the Fitzroy region.**

**Table 10-2: Summary of the number of reefs and seagrass beds that are located within each risk category (Risk defined as a probability (high, med- high, medium) of exceeding the Guidelines) for the particular pollutant (TSS or Chl-a).**

Number of Seagrasses within each category			
Chl-a	Probability class		
Region	High	Med-high	Medium
Wet Tropics	9	41	15
Burdekin	24	46	24
Mackay Whitsunday	51	14	38
Fitzroy	58	31	20
Number of Seagrasses within each category			
TSS	Probability class		
Region	High	Med-high	Medium
Wet Tropics	35	16	14
Burdekin	12	10	23
Mackay Whitsunday	6	4	16
Fitzroy	0	2	26
Number of coral reefs within each category			
Chl-a	Probability class		
Region	High	Med-high	Medium
Wet Tropics	9	41	15
Burdekin	24	46	24
Mackay Whitsunday	51	14	38
Fitzroy	58	31	20
Number of coral reefs within each category			
TSS	Probability class		
Region	High	Med-high	Medium
Wet Tropics	9	16	29
Burdekin	0	3	6
MWS	6	5	33
Fitzroy	10	7	37



## 11. Conclusions

Heavy and persistent flooding occurred in many rivers draining into the Great Barrier Reef from January to April 2010. The largest flows were seen in the southern catchments, particularly in the Mackay Whitsunday region and the Fitzroy River. This report presents the outcomes of water quality measurements and mapping of the riverine plumes from the Burdekin, Tully, Mackay Whitsunday and Fitzroy river plumes. Analysis of plume concentrations and extent was taken from a combination of field sampling and mapping techniques using currently available remote sensing algorithms and true colour imagery.

Water quality concentrations in the flood plumes show high concentrations of all water quality parameters moving off both catchments. Concentrations of the various parameters are intrinsically linked to both time and space related to the riverine flow. Sampling in the Mackay Whitsunday and Fitzroy river plumes were taken several days to week after peak flow conditions, however values of water quality constituents is still high (in respect to baseline values) and indicative of the long term influence of the plume conditions.

Work over the last two years in the MMP plume monitoring has been to define the types of water found in plume waters and how these water types can influence and impact on the biological systems that are inundated by the waters. Primary waters are areas characterised by high turbidity and high concentrations of particulate matter. Concentrations of suspended solid 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 have been measured in this area, most likely the intrusion of freshwater phytoplankton. The extent of the primary water can be defined by field sampling, aerial photography and true colour imagery as the edge of the high sediment plume can be identified. (Note that bad weather and cloudy days can interfere with this mapping). The application of remote sensing data has changed the perception that plumes are nearly always constrained to the coast, with recognition that plume waters with high concentrations of chlorophyll and CDOM can be mapped at large distances offshore. Remote sensing imagery has been used to further our understanding of the movement, extent and duration of flood plumes.

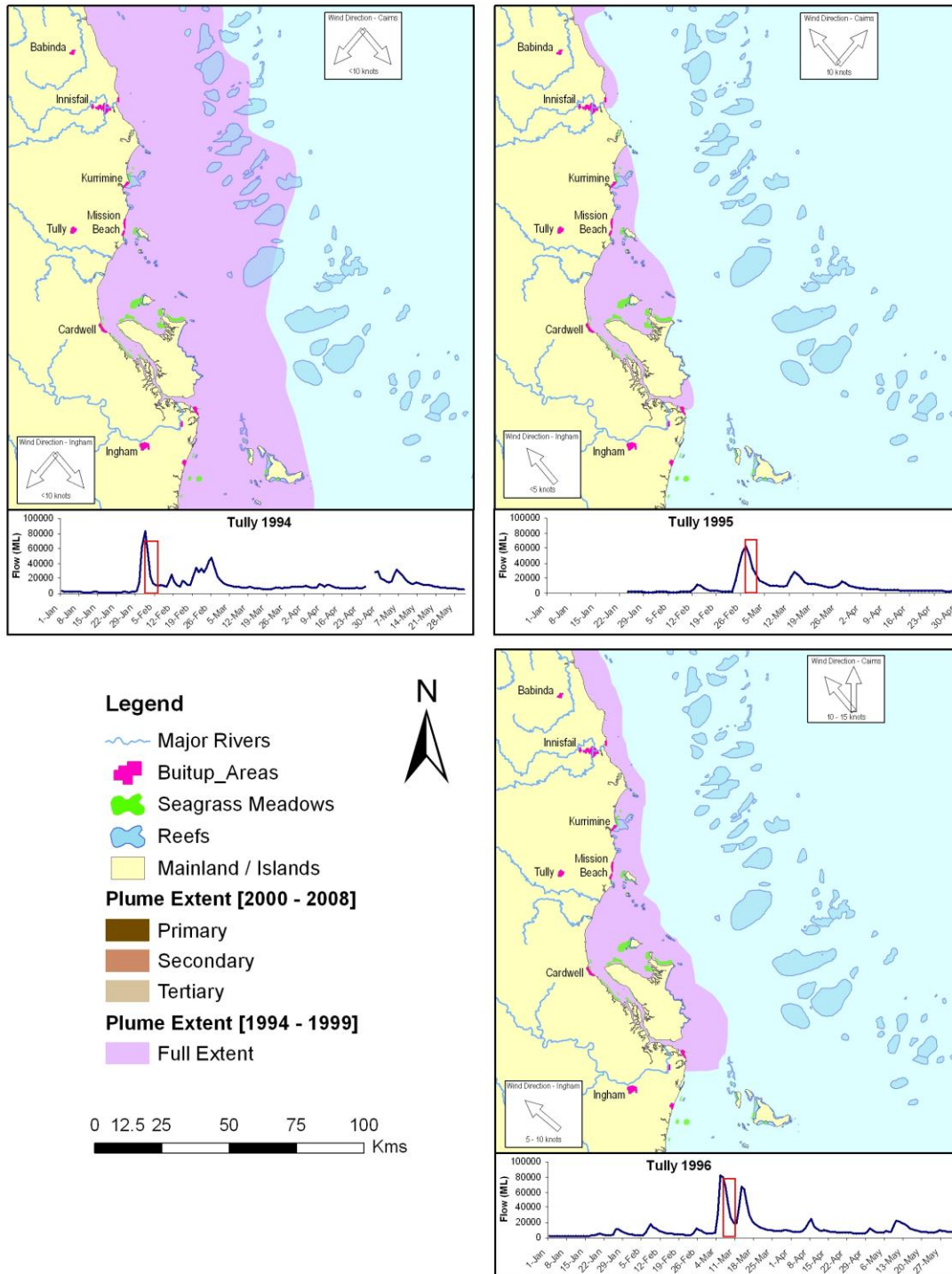
As the river waters move beyond the river mouth, the heavier clay material drops out, but the finer particulate matter can still move kilometers offshore, as can be seen in the elevated concentrations of suspended solids in the later stages of Tully River plume waters. Generally there is enough reduction in the sediment loads to promote an increase in the light availability and this combination of light and increased dissolved nutrients promotes elevated production of phytoplankton. Secondary water types are characterised by high nutrients, elevated chlorophyll and CDOM measurements, and has a far greater extent than the primary water type, both in space and over time and as such may have longer term impacts on the biological ecosystems that are inundated.

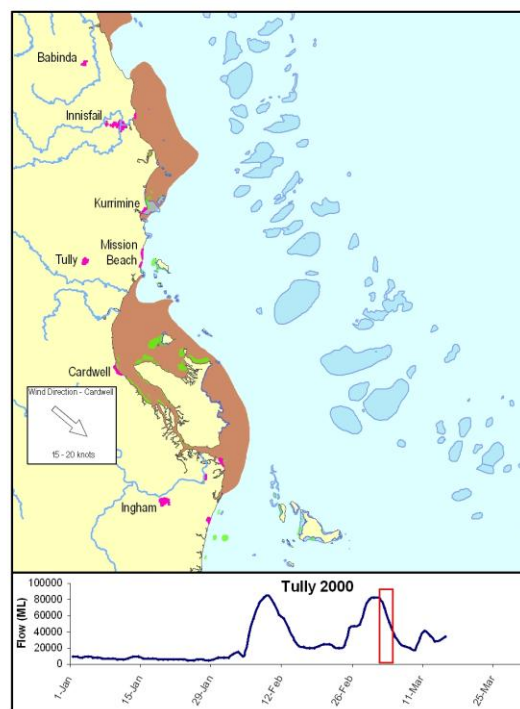
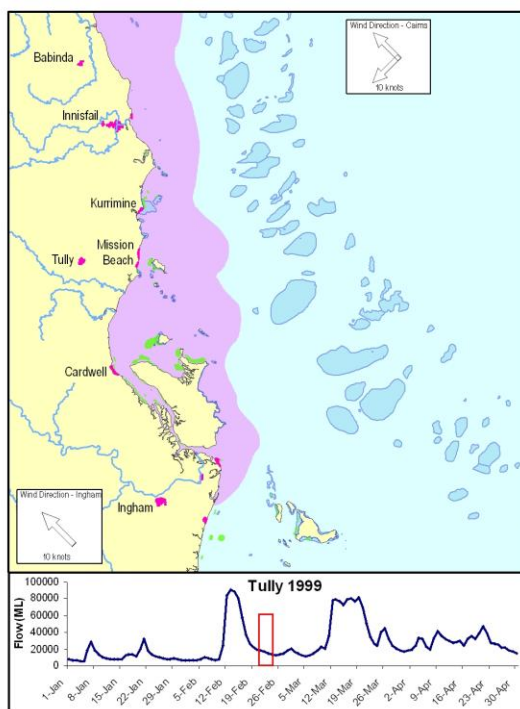
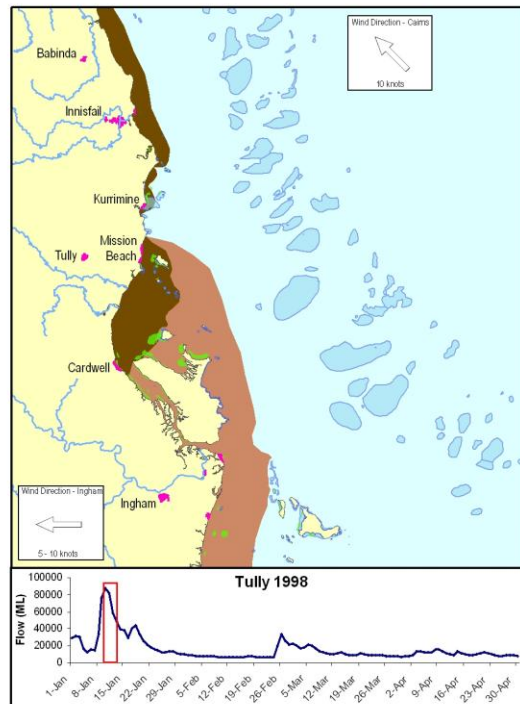
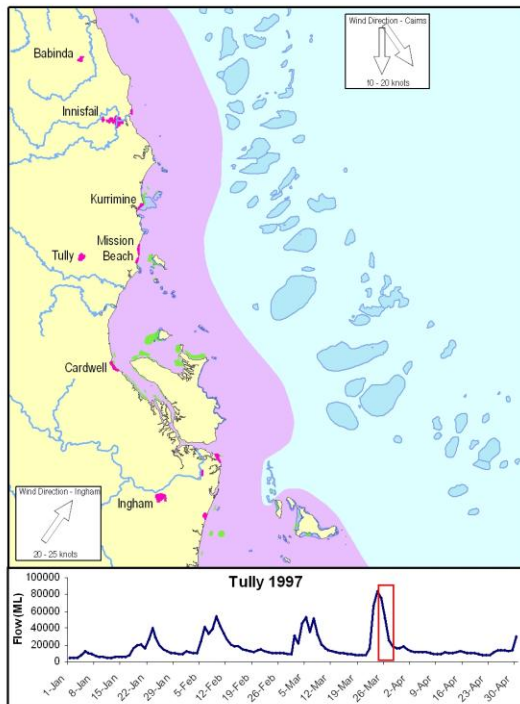
This type of work illustrates how remote sensing products can be utilised to describe and define areas of risk in the Great Barrier Reef. The effects of excess nutrients and sediments in the marine environment are being increasingly understood (e.g. De'ath and Fabricius, 2008). However, less well known are physical and biogeochemical processes transporting and transforming land-derived materials in the marine environment, as well as the hydrodynamics of the GBR inshore area which controls for example, residence times. The missing links between catchment and marine processes hampers the implementation of management options for specific water quality constituents. A primary use of results from this type of study will be to set targets connecting end-of-river loads of particular materials to an intermediate end point target such as chlorophyll (Brodie et al., 2009) or, in the future, to an ecological end point target such as a composite indicator for coral reef health (Fabricius et al., 2007).

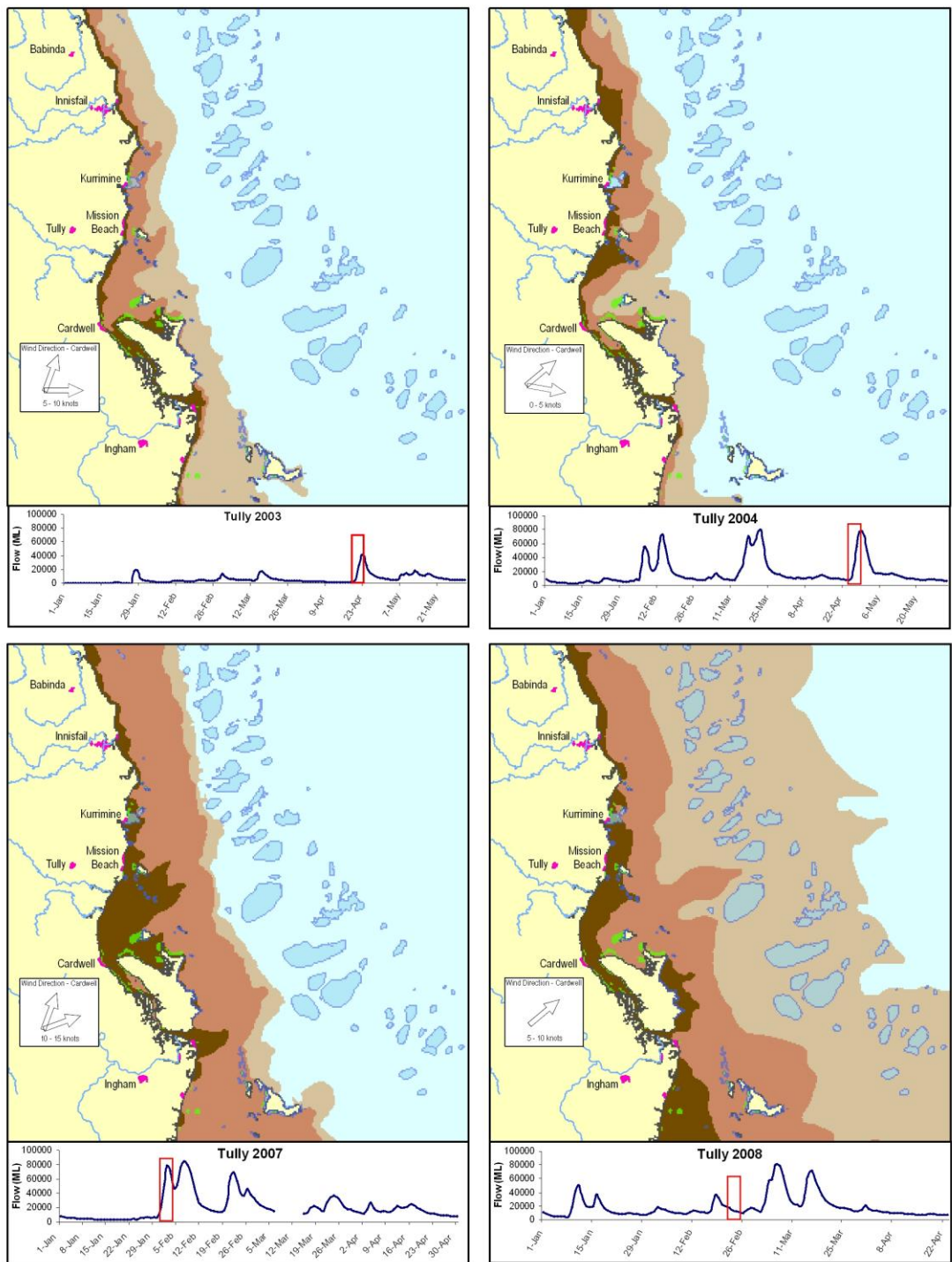
The ecological consequences associated with exposure of coral reefs and seagrasses to flood plumes is dependent upon a number of parameters including the time and severity of exposure, the status of the ecosystem prior to exposure and other concurrent disturbance events (Fabricius, 2005). The need to develop a metric for the MMP that integrates these drivers is recognised as an important need for future reporting.

## 12. Appendices

Tully plume extents for 1994 to 2009

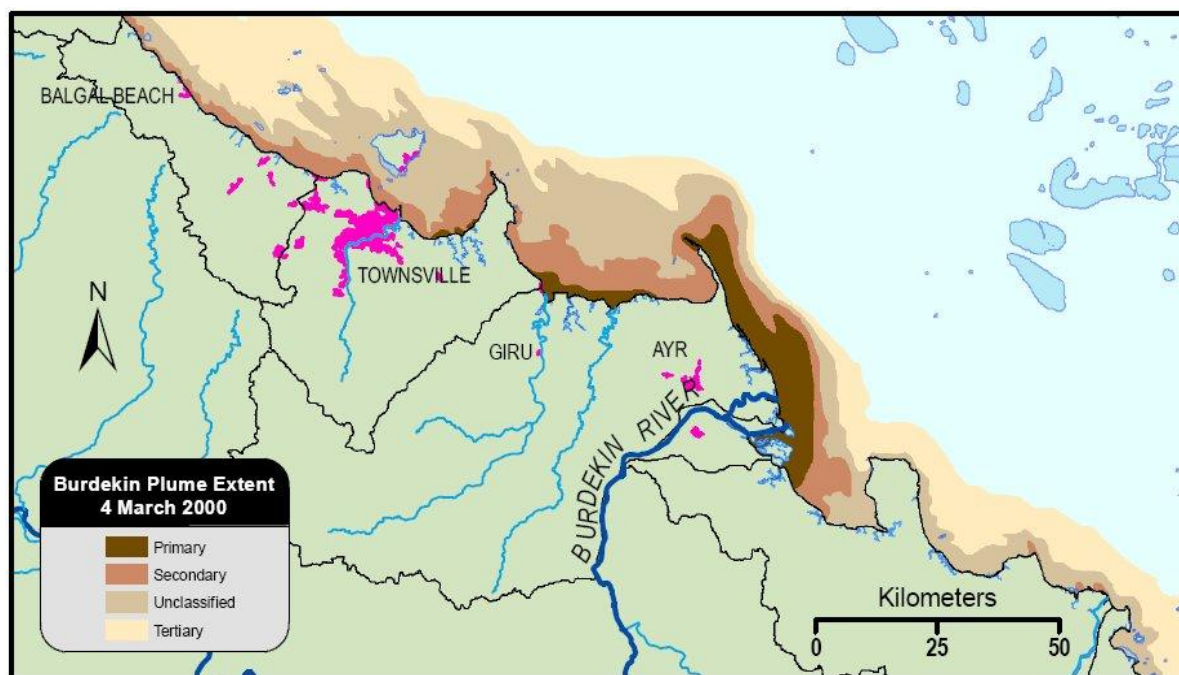
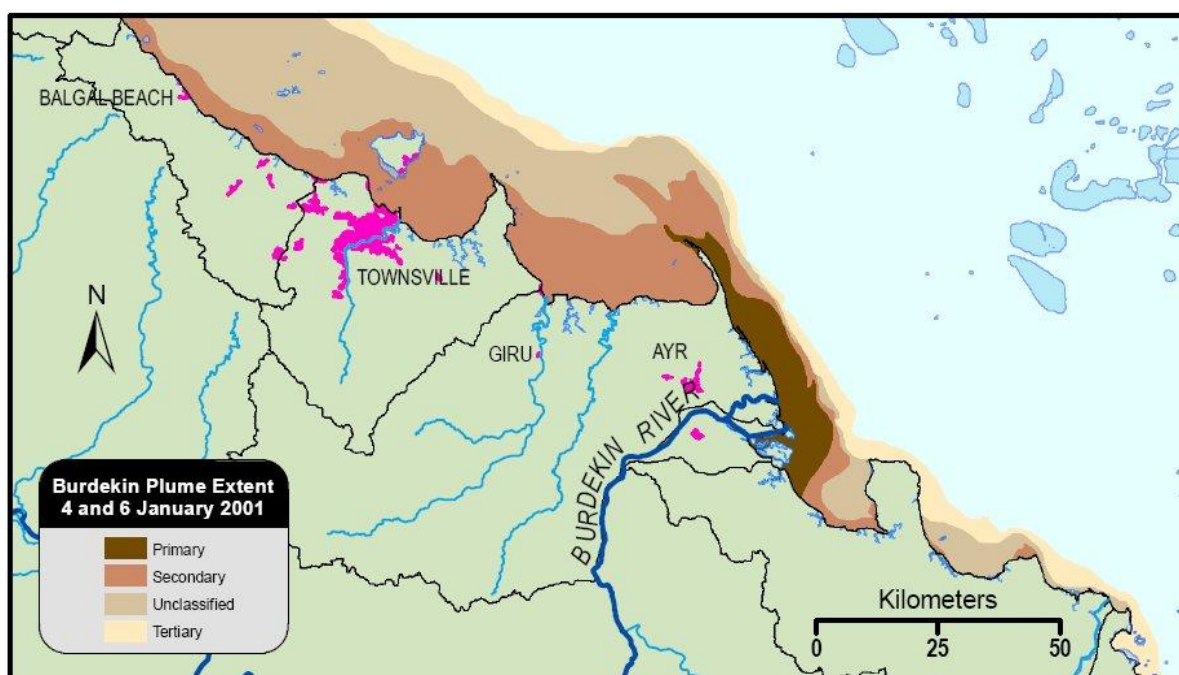


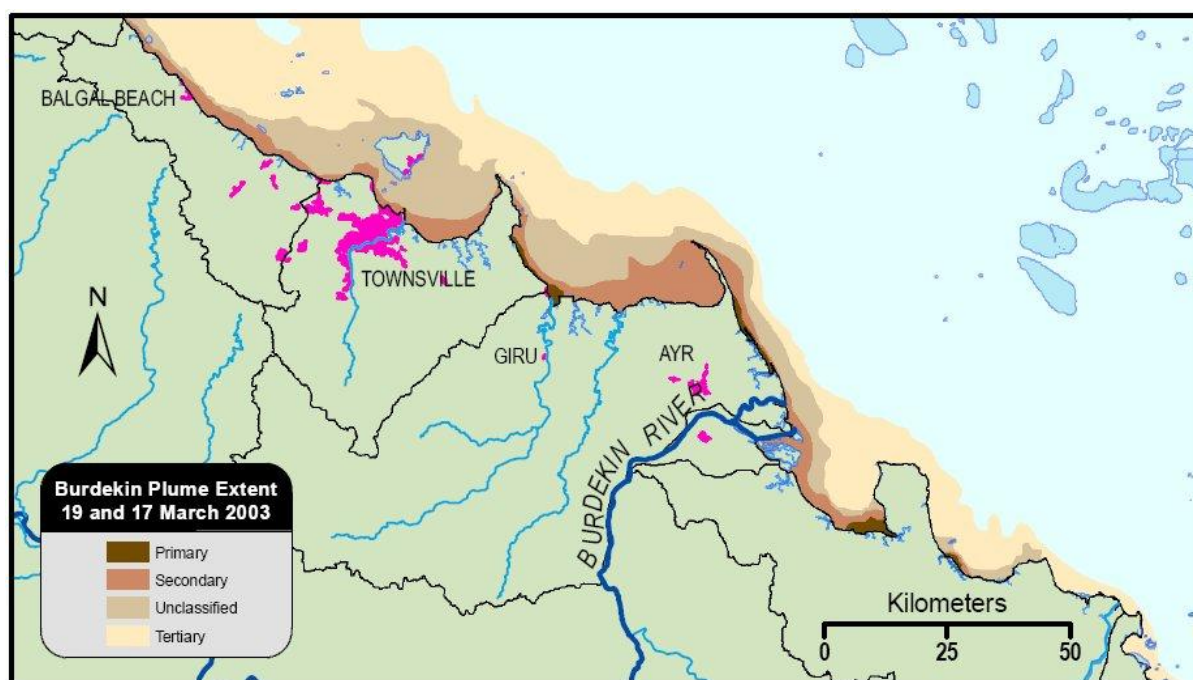
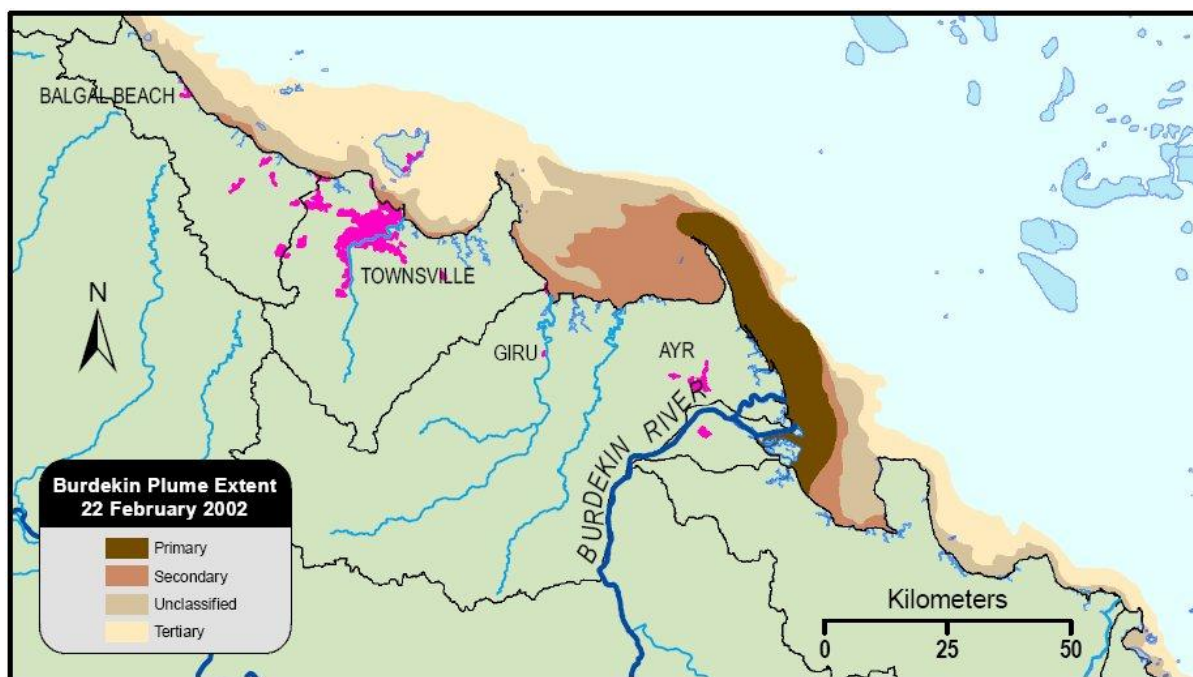


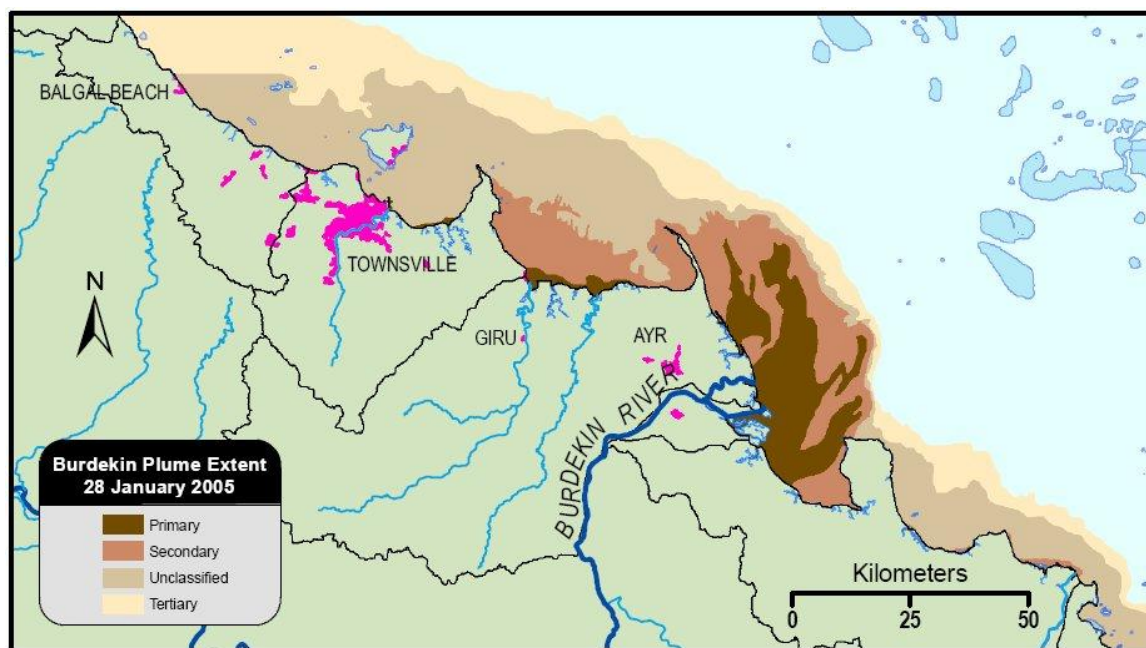
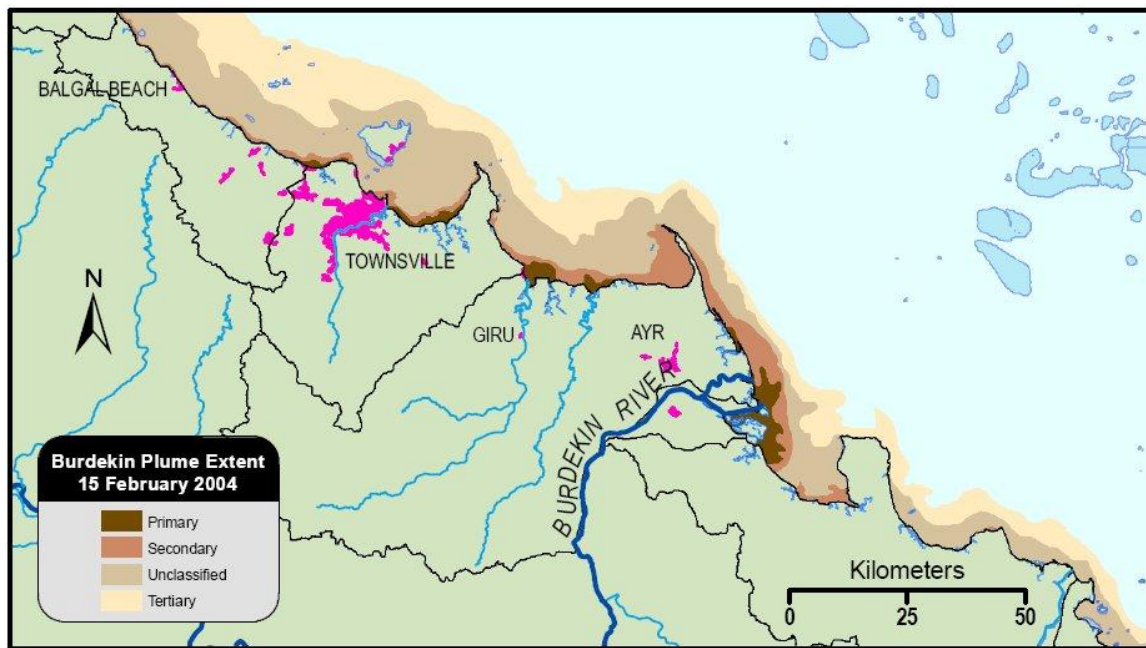


Burdekin plume extents for 1994 to 2008

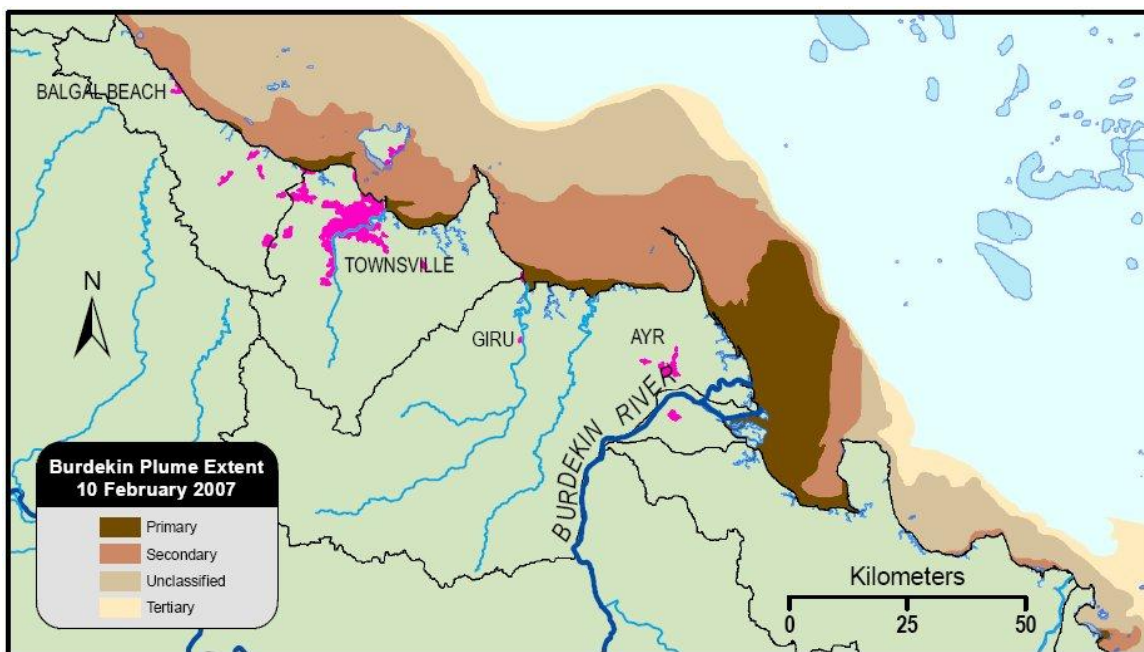
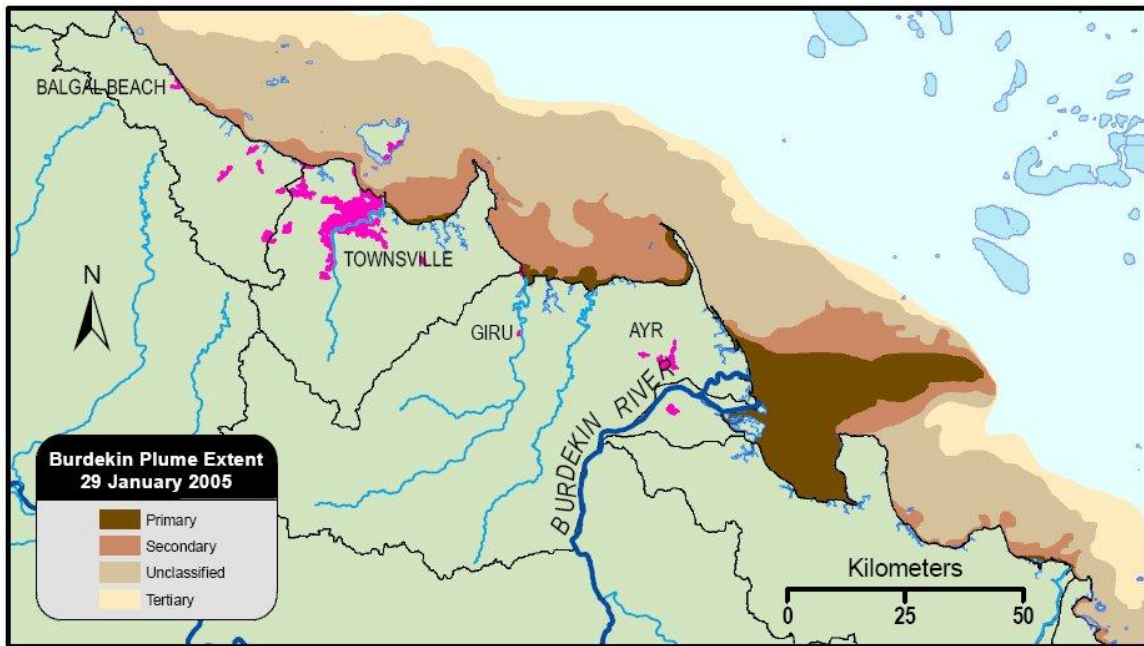


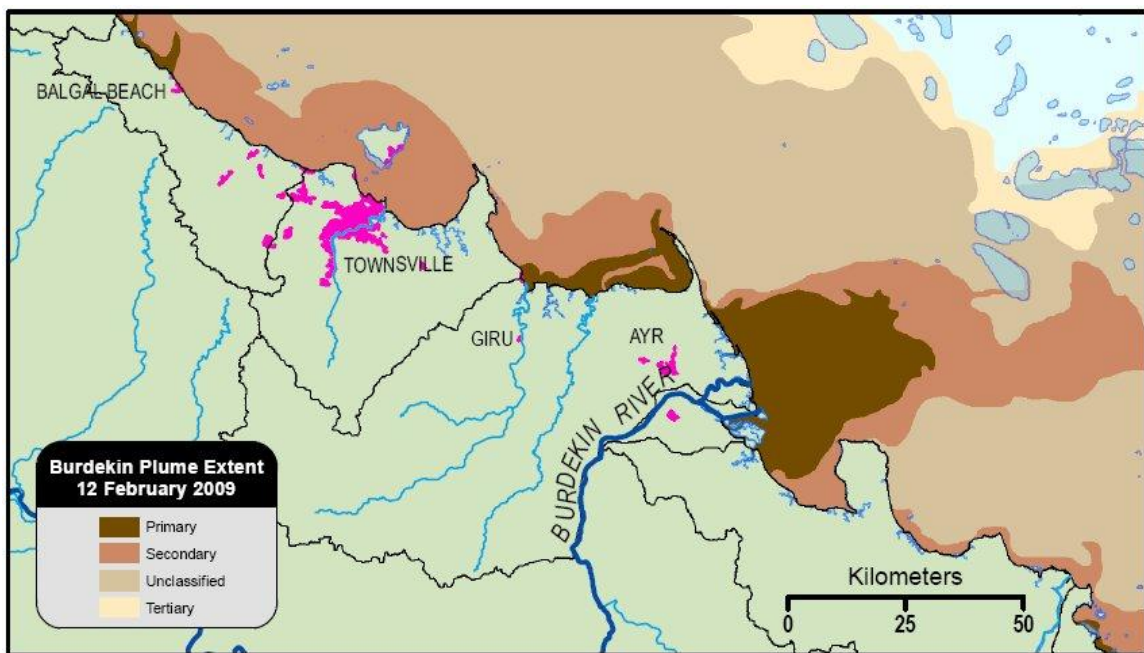
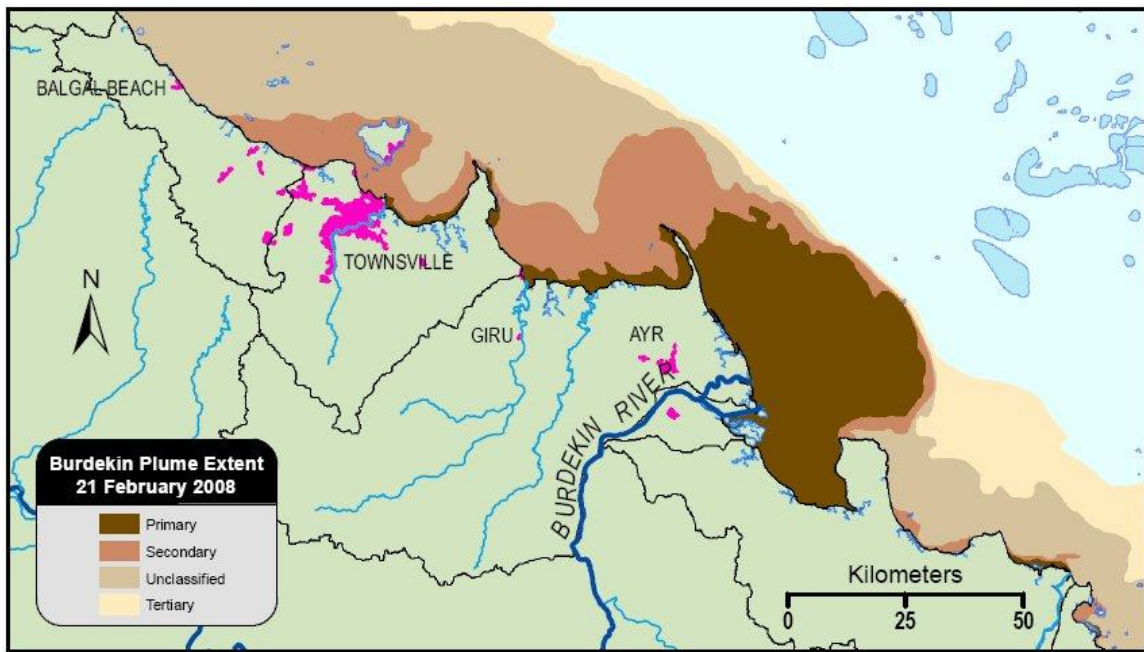


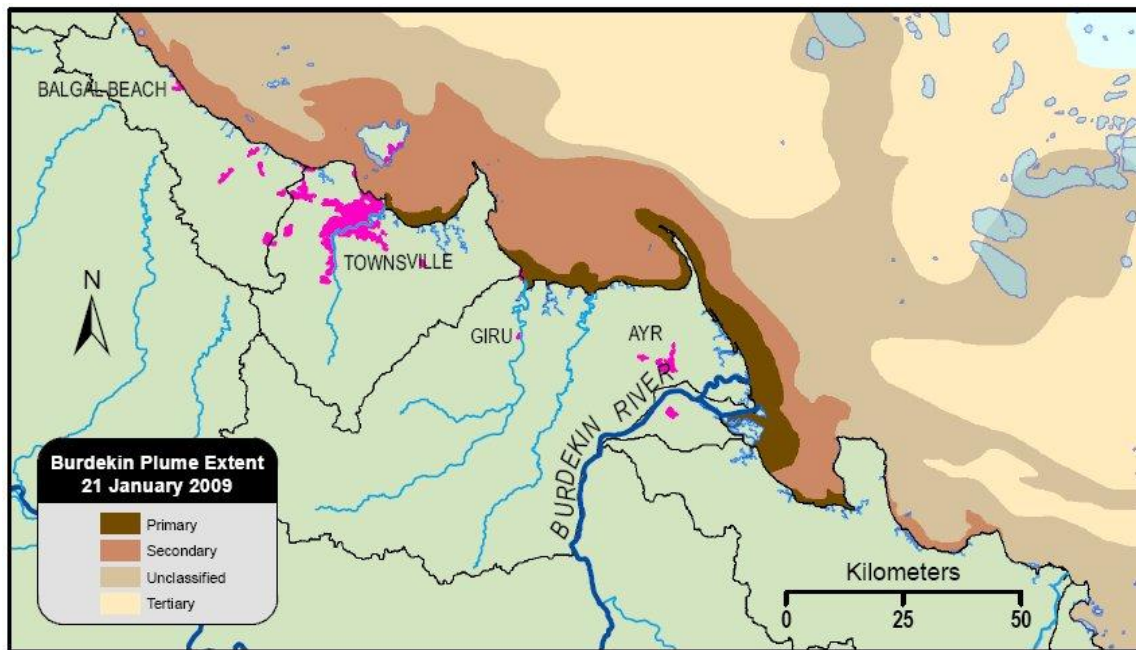












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