Australian Government
Department of the Environment, Water, Heritage and the Arts

Terrestrial runoff in the Great Barrier Reef

Marine Monitoring Program (3.7.2b)
Tully and Burdekin case studies

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1. Executive Summary

This report details the sampling that has taken place under the Reef Rescue Marine Monitoring Program project 3.7.2b: Terrestrial Discharge into the Great Barrier Reef for the 2008/2009 sampling year. Flood plume sampling for this period has focused on the Tully and Burdekin marine areas, with additional pesticide sampling reported for the Mackay Whitsunday and Fitzroy regions.

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. Advanced algorithms have been applied to plume imagery to calculate concentrations of total suspended solids, 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 has been used to estimate the risk of plume exposure inshore biological systems within GBR waters for the Tully and the Burdekin marine areas. This risk assessment has used imagery available from aerial flyovers, true colour MODIS imagery and the application of water quality algorithms.

Water quality measurements in plume water are variable over time and space but do show consistent patterns over the salinity gradient. Dissolved inorganic nitrogen reduces over the salinity gradient, however there is evidence of biological processes in the middle salinity ranges and elevated concentrations at very low salinity values indicating movement of elevated DIN and DIP into the offshore waters. DIP measurements in the Tully area show increasing DIP down the salinity gradient, suggesting strong desorption movement of DIP 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 are higher in the Burdekin catchment, but do drop out quickly over short spatial scales. In contrast, suspended solids measured in the Tully marine area do show some reduction in the lower salinities but show a contrasting pattern of increasing concentrations at the higher salinities. This may indicate complex transformations from a inorganic to organic stage. The role and bio-processing of the available DON needs to be further explored. Chlorophyll concentrations reflect the phytoplankton production and is linked to the availability of light and higher nutrient concentrations.

Plume typology was further explored through the analysis of both field data and remote sensing imagery.

Flood plume categories were defined based upon the concentration of water quality parameters which 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 region of the plume that exhibits no elevated TSM and reduced amounts of Chl and CDM when compared with that of the secondary plume. This region can be described as being the transition between a secondary plume and ambient conditions.

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2. Introduction

2.1. Terrestrial runoff to GBR

The marine flood plume monitoring as part of the Reef Rescue Marine Monitoring Program (3.7.2b) is a long term project to study the exposure of Great Barrier Reef (GBR) ecosystems to land-sourced pollutants. The Reef Rescue Marine Monitoring Program is currently managed by the Reef and Rainforest Research Centre. This program will help assess the long-term effectiveness of the Australian and Queensland Governments Reef Plan and Reef Rescue initiatives in reversing the decline in water quality of run-off originating from GBR catchments.

Because of the large size of the GBR (350,000km^2), the short-term nature and variability (hours to weeks) of runoff events and the often difficult weather conditions associated with floods, it is very difficult and expensive to launch and coordinate comprehensive runoff plume water quality sampling campaigns across a large section of the GBR. To counter this variability, this project forms a multi-pronged assessment of the exposure of selected GBR inshore reefs to material transported into the lagoon from GBR catchment rivers.

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

- Extent of exposure of GBR ecosystems to terrestrially sourced materials, and further mapping of the extent of risk from these materials;
- Loads of fine sediments discharging into the GBR lagoon from major GBR catchment rivers.

Further research questions that will be explored under this program include

- The fate of dissolved and particulate materials in flood plumes (sedimentation, desorption, flocculation, biological uptake);
- Processing, dispersal and trapping of materials during flood events;
- Quantify the temporal dynamics of sediment dynamics, light availability and phytoplankton growth during and after plume events;

- Changes in phytoplankton assemblages during the duration of the plume event, and how this influences long term chlorophyll concentrations within the different regions.

2.2. Review of riverine plumes in the Great Barrier Reef

A review of flood plumes in the GBR was published in 2001 (Devlin *et al.* 2001) and a further synthesis of flood plumes sampled from 1991 to 2008 was reported in 2010 (Devlin and Waterhouse 2010). 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 (as yet) unknown lengths of direct impingement upon mid and outer-shelf reefs.
- The amount of rainfall that falls over a particular catchment can have a marked effect on the distribution of the plume. Another factor in the distribution of flood plumes is the influence of headlands on the movement of the plumes (steering).
- Modeling of the plumes associated with specific weather conditions has demonstrated that inshore reefal areas adjacent to the Wet Tropics catchment (between Townsville and Cooktown) regularly experience extreme conditions associated with plumes. Inshore areas (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, which may influence the offshore waters for periods of weeks.

- 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 most clearly shown in the results from the Burdekin for Cyclone Sid (1997) 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.
- 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.

- 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.

2.3. Gaps in knowledge

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 programs.

- 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 modeling scenarios.
- Plume concentrations and extents into a reporting framework for the Reef Rescue Marine Monitoring Program.

3. Methods

3.1. Sampling design

The flood plume monitoring project (3.7.2b) is set up to run concurrently with ongoing MTSRF project 3.7.2 (catchment processes). There are also strong links with other MTSRF projects, such as 3.7.1 and other science and government agencies to integrate all flood plume data. This project is run in partnership with the Australian Institute of Marine Science water quality and coral monitoring programs. Data from this project feeds into the validation of existing models and the development of regionally based remote sensing algorithms (Brando et al. 2009). In situ data collected by fixed loggers will also be incorporated with the fixed water sampling data to increase the temporal extent plume data. This will help measure the conditions during first flush and high flow event situations with respect to inshore biological systems. Data collected under the Marine Monitoring Program (MMP) also feeds into ongoing catchment to reef monitoring programs and the Integrated Paddock to Reef reporting process (Figure 3.1).

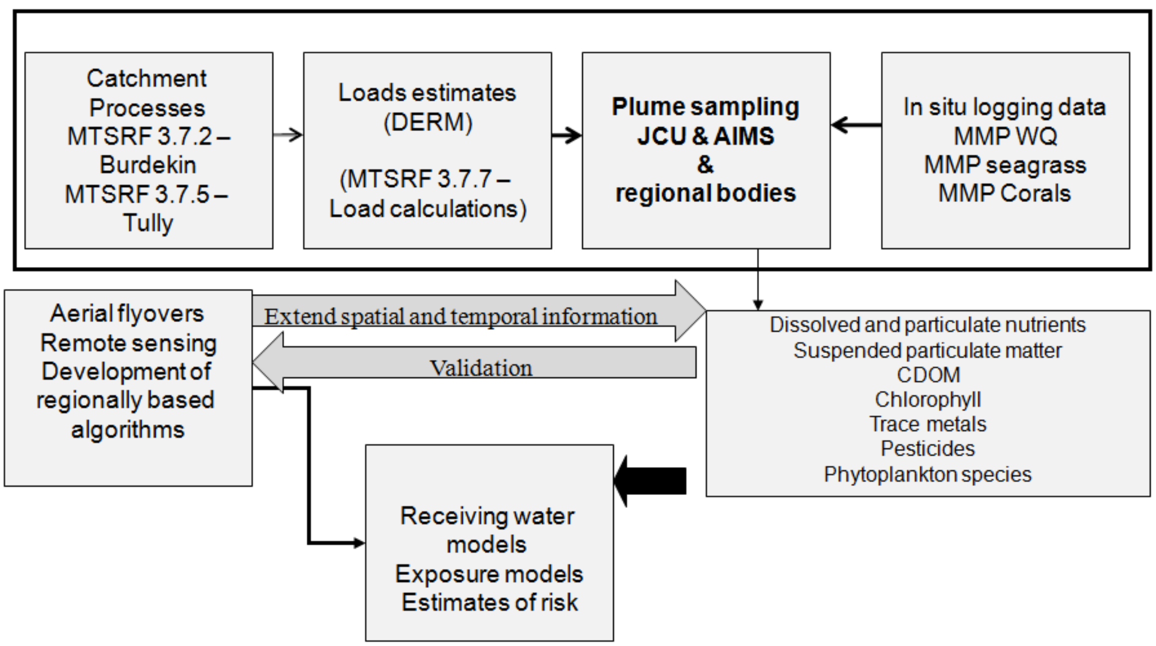


Figure 3-1: Diagrammatic representation of the integrative programs and data availability running concurrently with the plume monitoring project.

In summary, the three main facets of the marine flood plume monitoring project are:

- Transport and processing of nutrients, suspended sediment and pesticides;
- Extent and exposure of flood plumes to reefs related to prevailing weather and catchment conditions; and
- Incorporation and synthesis of monitoring data into current receiving water models, the broader MMP synthesis and Integrated Paddock to Reef reporting.

3.2. Sampling collection

3.3. 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 information on the scope of the laboratory analyses can be found in the MMP QA/QC report (anon 2010).

3.3.1. Dissolved and total nutrients

Total nitrogen and total phosphorus are analysed simultaneously with total filterable nitrogen and phosphorus using an analytical segmented flow analyser. The particulate fraction is calculated by the difference between total and total dissolved nutrient fractions.

3.3.2. Phytoplankton pigments

The concentration of photosynthetic pigments is used extensively to estimate phytoplankton biomass. All green plants contain chlorophyll *a* which constitutes approximately 1-2% of the dry weight of planktonic algae. Other pigments that occur in phytoplankton include chlorophylls *b* and *c*, xanthophylls, phycobilins and carotens. The important chlorophyll degradation products found in the aquatic environment are the chlorophyllides, pheophorbides and pheophytins. The presence or absence of the various photosynthetic pigments is used, among other features, to separate the major algal groups.

Water samples are filtered through a Whatman 47 mm GF/F glass-fiber filter and stored frozen until analysis. Phytoplankton pigments are analysed by the ACTFR using the spectrophotometric method. Conduct work with chlorophyll extracts in subdued light to avoid degradation. Use opaque containers or wrap with aluminum foil. The pigments are extracted from the plankton concentrate with aqueous acetone and the optical density (absorbance) of the extract is determined with a spectrophotometer. The ease with which the chlorophylls are removed from the cells varies considerably with different algae. To achieve consistent complete extraction of the pigments, disrupt the cells mechanically with a tissue grinder. Freeze envelope until grinding is carried out. Samples on filters taken from water having pH 7 or higher may be stored frozen for three weeks. Process samples from acidic water promptly after filtration to prevent possible chlorophyll degradation from residual acidic water on filter.

The pigments are extracted from the plankton concentrate with aqueous acetone and the optical density (absorbance) of the extract is determined with a spectrophotometer. The ease with which the chlorophylls are removed from the cells varies considerably with different algae. To achieve consistent complete extraction of the pigments, disrupt the cells mechanically with a tissue grinder. Glass fibre filters are preferred for removing algae from water. The glass fibres assist in breaking the cells during grinding, larger volumes of water can be filtered, and no precipitate forms after acidification.

- Pour 10 mL of 90% aqueous acetone solution into a measuring cylinder.
- Place sample in tissue grinder, cover with 2-3 mL of the 90% aqueous acetone solution, and macerate at 500 rpm for one minute.
- Transfer sample to a screw cap centrifuge tube and use the remaining 7-8 mL of 90% aqueous acetone solution to wash remaining sample into centrifuge tube.
- Keep samples between two and 24 hours at 4 ºC in the dark.
- Centrifuge samples in closed tubes for approximately ten minutes at 500 g, shake tubes and centrifuge again for another ten minutes.

The absorbance of chlorophyll pigments within the centrifuged samples are read using a dual beam spectrophotometer.

3.3.3. Total suspended solids

Suspended solids refer to any matter suspended in water or wastewater. 'Total suspended solids', or TSS, comprise the portion of total solids retained by a filter. Suspended solids concentrations are determined gravimetrically from the difference in weight between loaded and unloaded 0.4 µm polycarbonate filters after the filters had been dried overnight at 60^{o}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 103-105ºC. The increase in weight of the filter represents the total suspended solids.

3.3.4. 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 µm 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 occurs within 24 hours of collection generally (maximum of 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 (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.

3.4. In situ sampling

Water sampling was carried out by ACTFR staff from the Catchment to Reef research group, James Cook University. Prior to the sampling year, it was decided to identify one catchment for repeated sampling over the wet season, and the Tully catchment was chosen due to its regular flooding cycles. Repeated sampling, if possible was also discussed for the Mackay Whitsunday region, but at this time, only one significant event has been sampled in this area. Due to the magnitude of the flow event for the Burdekin dry tropics region, repeated sampling in the plume and around Magnetic Island was also carried out. All sampling was carried out on marine vessels, with depth profiling for physico-chemical parameters and surface water quality samples. All sites were plotted on maps and overlaid, where possible, on appropriate remote sensing images of the plume extent. Different dates and locations are associated with each individual event (Table 3.1).

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. Samples are also filtered for trace metals. 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. Depth profiles were not collected at all sites due to sampling by volunteers who did not have access to all the sampling equipment (Figure 3.2)

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

Catchment	**date of sampling**	**No of sites**	**description**
Tully-Murray	3/01/2009	12	Full suite of WQ parameters plus Seabird data
Tully-Murray	15/01/09 – 16/01/09	26	Full suite of WQ parameters plus Seabird data
Tully-Murray	17/02/09 – 18/02/09	18	Full suite of WQ parameters plus Seabird data
Tully-Murray	5/3/09 – 6/3/09	21	Full suite of WQ parameters plus Seabird data
Burdekin	9/2/09	10	TSS, some chlorophyll and CDOM
Burdekin (Magnetic island)	11/2/09 – 12/3/09	29	Nutrients, CDOM, salinity and chlorophyll.
Burdekin	21/2/09	8	Full suite of WQ parameters plus Seabird data
Burdekin	24/2/09	12	TSS, some chlorophyll and CDOM
Burdekin - offshore	17/3/09	8	Full suite of WQ parameters, Seabird data
Burdekin - offshore	18/3/09	5	Full suite of WQ parameters plus Seabird data
O'Connell	17/1/09	8	Full suite of WQ parameters plus Seabird data

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

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

3.5. Remote sensing methods

Catchment runoff events involve space scales ranging from hundred of metres to kilometers and time scales from hours to weeks, thus the use of remote sensing in monitoring marine indicators at appropriate time and space scales can be used as key indicators of cause and effect in these systems. Concentrations of suspended sediment and yellow substances can be used to track plume distribution and dilution, and sedimentation. 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. In 2008/09 new analytical tools were investigated for understanding trends and anomalies of GBR waters (specifically wet season to dry season variability, river plume composition and extent of algal blooms) based on the optical characteristics of inshore GBR waters and validation with in situ water quality data where possible.

Remote sensed imagery has become a useful and operational assessment tool in the monitoring of flood plumes in the Great Barrier Reef (GBR), Queensland, Australia. Combined with the more traditional in situ sampling techniques, the use of remote sensing (RS) has become a valid and practical way to estimate both the extent and frequency of plume exposure on GBR ecosystems. The use of RS algorithms has also become invaluable in the estimate of water quality parameters, such as TSS, chlorophyll and absorption of Coloured Dissolved Organic Matter (CDOM).

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.

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 has been used to estimate the risk of plume exposure inshore biological systems within GBR waters.

Notwithstanding substantial advances in remote sensing capability for water quality monitoring in the GBR in recent years, there are still some limitations which require further development before the techniques can be applied as a compliance tool. In particular, the number of available observations is significantly lower in the wet season than the dry season for all the regions, thereby reducing the available dataset for validation and assessment. This is due to the higher cloud cover and aerosol concentration in the monsoonal season. It is possible that the cloud cover introduces a bias in the sampling, which in turn will affect the estimate of the median and mean concentration or any other statistical analysis of the imagery. The effect of cloud cover and of a biased sampling for cloud free data needs further investigation using time series data from a moored sensor or the output from biogeochemical models. In addition, the presence of Trichodesmium leads to a gross underestimation and overestimation of chlorophyll in the water column because of (sub-) surface expression and spatial heterogeneity. To overcome this issue, it is recommended that an operational algorithm to identify Trichodesmium affected pixels for MODIS imagery be implemented followed by development of an inversion algorithm to estimate chlorophyll for pixels with a Trichodesmium expression. Definition of the wet and dry season boundaries on an annual basis also has the potential to substantially influence the rate of exceedance of guideline values on a seasonal basis.

We have explored two techniques in this reporting year, those being the extraction of true colour images to identify the extent of the riverine plume, and the application of available algorithms satellite images to extrapolate chlorophyll and coloured dissolved organic matter (CDOM) data for the appropriate images. A brief description of both processes is presented here.

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.

3.5.1. Application of algorithms

Ocean colour remote sensing provides an "eye-in-the-sky" profile of flood plumes within the Great Barrier Reef. The most common approach for the retrieval of water constituents from ocean colour observations is composed of two main processing or algorithm steps. First, an atmospheric correction procedure is applied to the satellite data to remove the effects of atmospheric absorption and scattering and to obtain the water-leaving radiance or reflectance. In a second step the obtained reflectance spectra is used to retrieve the above water quality parameters.

Remote sensing data has been acquired from the Moderate-resolution Imaging Spectroradiometer (MODIS) onboard NASA's Earth Observing System (EOS) satellites: Terra and Aqua. Data are accessed from the archived on NASA's Ocean Color website (http://oceancolor.gsfc.nasa.gov/). MODIS data is used for the mapping of chlorophyll-a and CDOM. The MODIS (Moderate-resolution Imaging Spectroradiometer) project consists of two sensors; one is attached to the Aqua satellites and the other to the Terra satellite. Each satellite has a revisit time of 1-2 times a day. The sensors have 36 spectral bands and the spatial resolution varies per band. The spatial resolution for the bands which are used to calculate the chlorophyll concentrations in the ocean have a resolution of 1000 m. 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 250m 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.

The large variability of in-water optical properties and concentration ranges, especially during flood events frequently cause empirical ocean colour algorithms to fail. These algorithms, like the default MODIS OC3 or SeaWiFS OC2 (O'Reilley et al. 1998), have been designed for open ocean waters, in which the optical properties are determined solely by phytoplankton their degradation products and the water itself. Simple reflectance ratios of two or more bands in the blue (443-490 nm) and green (550-565 nm) spectral region are used by these algorithms to estimate the concentration of chlorophyll. Coastal waters however, are usually influenced in addition by riverine inputs of terrestrial originated CDOM and inorganic suspended material as well as tidal resuspension. The spectral absorption features of these substances partly overlap with the absorption features of phytoplankton and cause a frequent overestimation of chlorophyll from these ratio algorithms.

In GBR coastal waters the global semi-analytical ocean colour algorithms, such as the GSM01 algorithm for chlorophyll (Maritorena et al. 2002) have been found more accurate than the empirical band ratio approach (Qin et al. 2007).

For this purpose, we worked with daily data of the Moderate Resolution Imaging Spectrometer (MODIS) on-board the NASA Earth Observation System (EOS) Terra and Aqua spacecrafts. The data was acquired in Level-0 quality (geo-referenced raw files) for periods corresponding to high river flow rates and low cloud cover in the Wet Tropics from 2003 to 2008 and subsequently processed to higher level products and true color composites using NASA's freely available processing software SeaDAS v5.40 To overcome limitations in atmospheric correction above turbid waters we applied the combined NIR-SWIR correction scheme of Wang and Shi (2007).

We calculated the chlorophyll concentration on the basis of the GSM01 algorithms which according to Qin et al. (2007) showed best performance for GBR waters over a wide range of turbidity. The total absorption of CDOM at a wavelength of 443 nm was computed within SeaDAS based on a quasi-analytical algorithm by Lee et al. (2002), which uses reflectance spectra for optically deep water as input. In a first stage the algorithm estimates the total spectral absorption and backscattering coefficients, which are then in a second step decomposed into the spectral absorption coefficients of phytoplankton pigments and the total absorption of CDOM and detrital material. The total suspended matter concentration was calculated on the basis of the TSM Clark algorithm, which is a band ratio algorithm using the normalized water leaving radiance of three MODIS bands at 443, 448 and 551 nm. The algorithm was never peer-review published and is a purely empirical algorithm developed through statistical correlation of coincident in-situ radiometric and TSM measurements.

The data then was imported into GIS software in which plume types and boundaries were defined based on visual analysis and a classification scheme as outlined in detail in the case studies for the Tully River.

An example of applying the chlorophyll algorithm is shown in Figure 3.2. This is taken from a 2007 event but the algorithm is successful in delineating the movement of high chlorophyll waters into the Coral Sea. This is an example of where remote sensing techniques can be very useful in mapping extent and duration. This also shows that plumes move further offshore than previously thought.

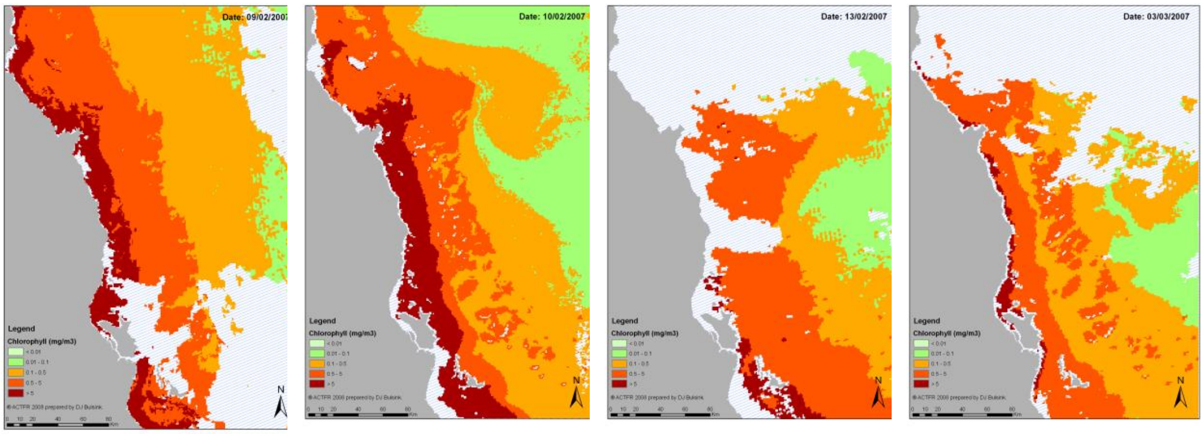


Figure 3-2: The application of the MODIS algorithm to RS images taken in a large flow event (February 2007).

True color images of before, during and after each plume have been identified where there was low cloud cover and reasonably good visualization of the plume area. Primary and secondary plumes were identified in each image, where the definition of the primary plume is the high turbidity, high sediment plume discharging relatively close to the river mouth. Secondary plumes are defined as the less turbid, higher production plumes where chlorophyll and nutrient levels are elevated. Some increase in turbidity may be present in secondary plumes as a result of the further transport of the finer particulate material and desorption processes occurring later in the salinity mixing curve. We also defined tertiary plumes as the less visible plumes further offshore and north of the river mouth. An example of MODIS imagery captures the Fitzroy regions on 14 January 2009 (Figure 3.3). The MMP program is currently implementing a method to classify flood plumes into one of three discrete groups: (i) primary, (ii) secondary and, (iii) tertiary plumes using MODIS imagery as delineated in these images.

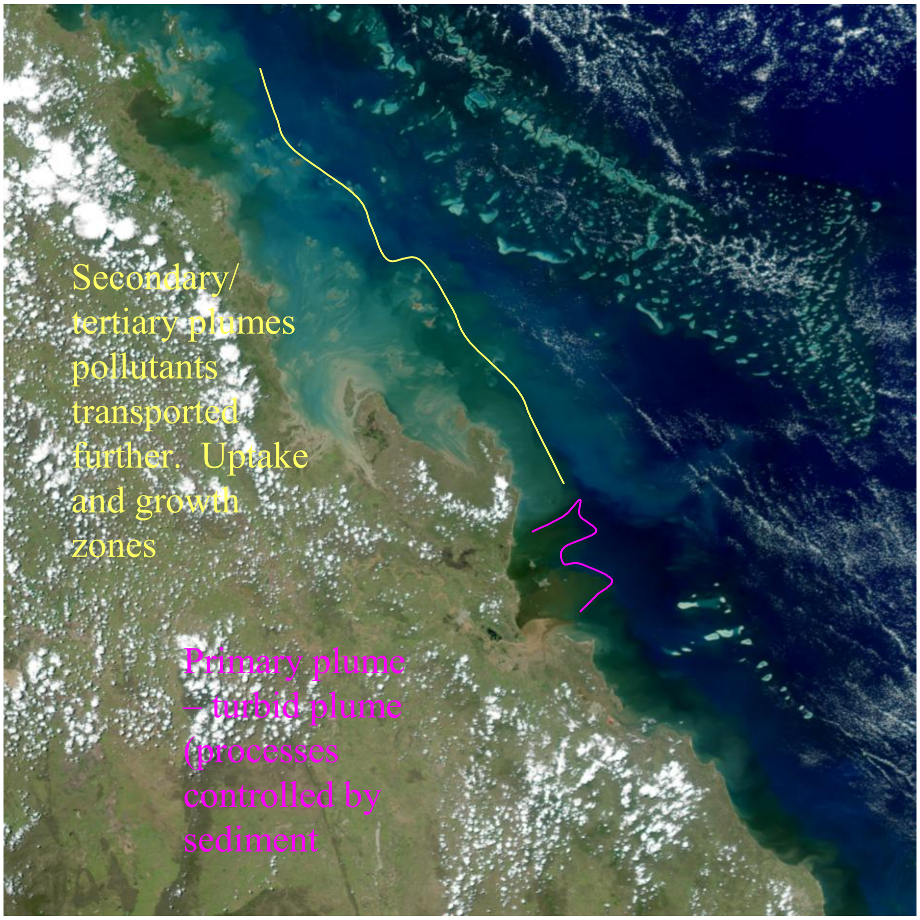


Figure 3-3: The identification of primary and secondary plume in the Fitzroy plumeThe pink line denotes the approximate extent of the primary plume water (high TSS) and the yellow line denotes the approximate extent for the secondary plume water (high chlorophyll carrying waters). (Imagery courtesy of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

In summary, the derived CDOM absorption at 412 nm combined with careful examination of quasi-true colour and chlorophyll-a 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 readily derived from ocean colour remote sensing. Thus the spatial extent of the different water types can be mapped.

Plume types were classified using the following criteria:

(i) A primary plume was defined as having a high total suspended mineral (TSM) load, minimal chlorophyll (Chl) and high coloured dissolved and organic matter (CDOM).

(ii) A secondary plume was 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) A tertiary plume is the region of the plume that exhibits no elevated TSM and reduced amounts of Chl and CDM when compared with that of the secondary plume. This region can be described as being the transition between a secondary plume and ambient conditions.

Because flood plumes can be complex in composition, if a region did not fall into one of the three discrete categories it was labelled as “unclassified”. Unclassified regions of the plume were typically located between secondary and tertiary regions where the water mass did not completely fall into either category.

CDOM imagery was cross-validated with the true-colour images for a visual check of the extent of the primary high sediment plume. By using both of these approaches it was possible to delineate the three recognised plume types with a suitable degree of confidence. In the areas where cloud had completely obscured the plume, estimations of plume extent were achieved by assessing the plume patterns from consecutive imagery epochs in the following days.

Figure 3.4 presents two images of the same the flood plume scene using: a) a quasi-true colour image and b) a CDOM absorption (443 nm) map. The extremely high CDOM absorption during such an event is a consequence of elevated dissolved pigments introduced into marine waters from estuarine and terrigenous sources via flood plumes.

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 well offshore, will 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.

Regional parameterized ocean colour algorithms

To overcome the limitations of global ocean colour algorithms in GBR optically complex coastal waters, CSIRO researchers have developed a model based inversion scheme by coupling an artificial neural atmospheric correction (Schroeder et al. 2006, 2008) with an in-water algorithm based on a variable parameterization of in-situ measured inherent optical properties (Brando et al. 2008). Work is underway for us to link with CSIRO on the implementation of the regional algorithms into the JCU computing process. In the interim, CSIRO have provided the MMP program with updated maps for the use of compliance monitoring and the frequency of exceedances through wet and dry seasons (refer to CSIRO report for 3.7.2b). Chlorophyll and CDOM concentrations, as reported for 2008 case studies have been mapped with the GSM01 algorithm. This was thought to be appropriate for the mapping of extent and water type with the use of true colour imagery as well. As we move into the rigorous reporting as required by GBRMPA paddock to reef reporting process, the regionally based algorithms will be applied.

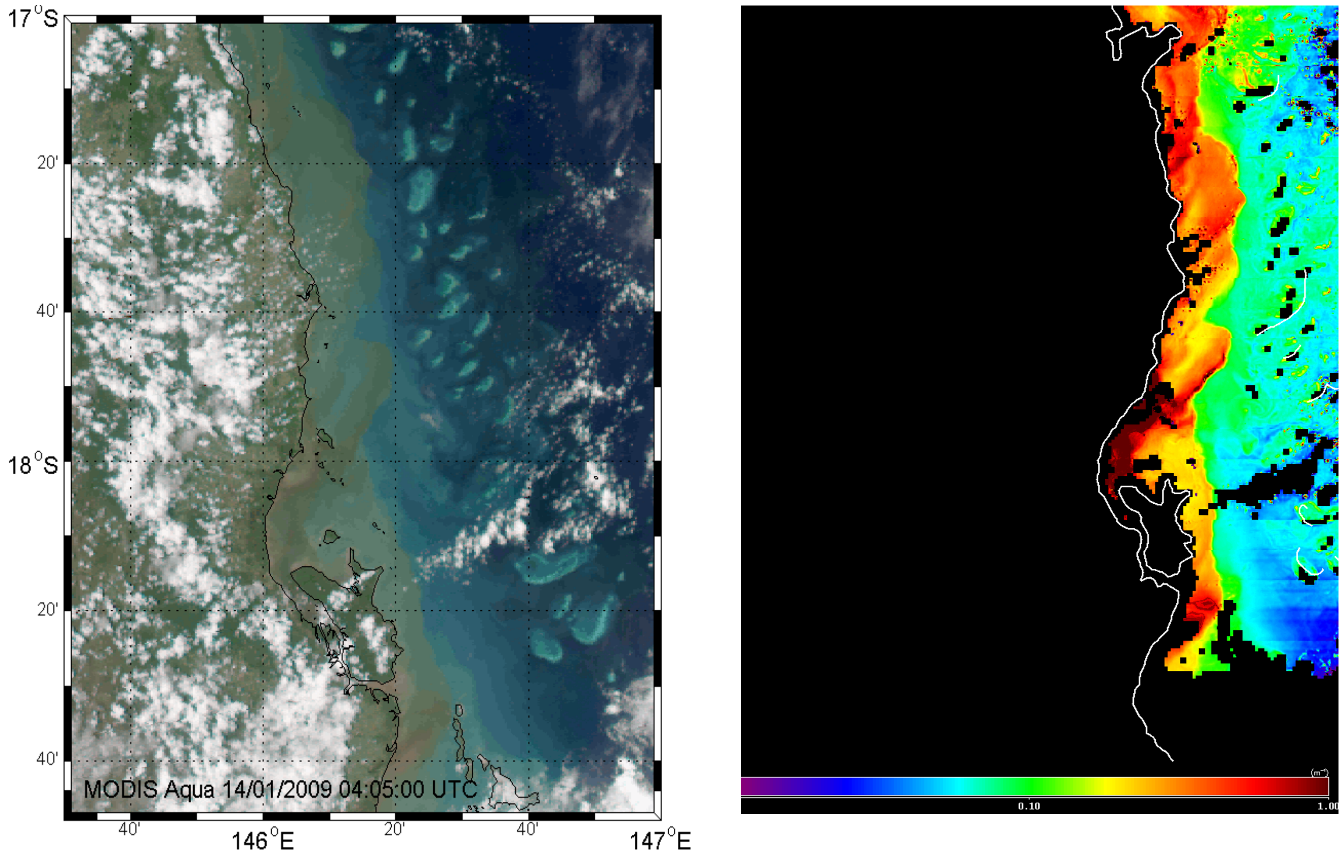


Figure 3-4: MODIS Aqua 250m resolution images of the Herbert and Tully River flood plumes on 14 Jan 2009 following a high rainfall event (a) Quasi-true colour image of the flood event (notice the high suspended sediment near the mouth of the Tully and Herbert Rivers and the extremely high chlorophyll biomass along the coast which appears very green). (b) Shows absorption by coloured dissolved matter (CDM) using the QAA algorithm at 443nm (a clear plume boundary is evident parallel to the coast).

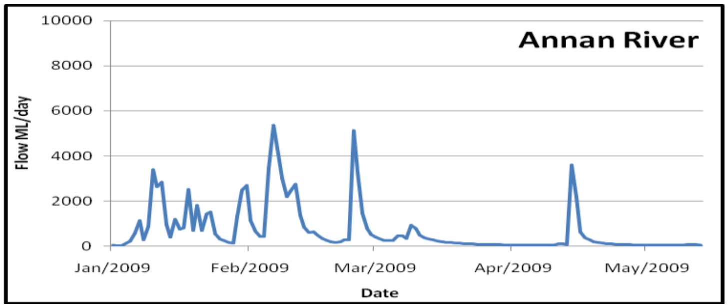
For the final imagery classification and interpretation, two products were provided. The initial classification method (described above) allowed mapping of the three main plume densities (e.g. primary, secondary and tertiary) based on CDOM absorption and secondly, the true colour images allowed for a 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 other imagery epochs in the following days.

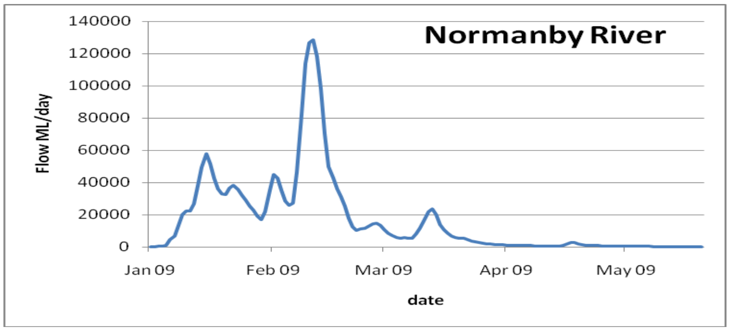
4. Flood events in 2009

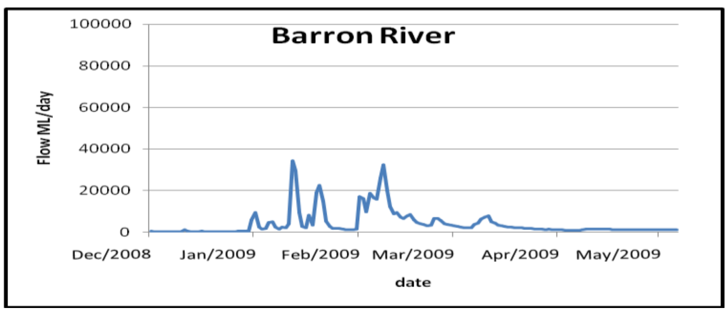
4.1. Description of flood events

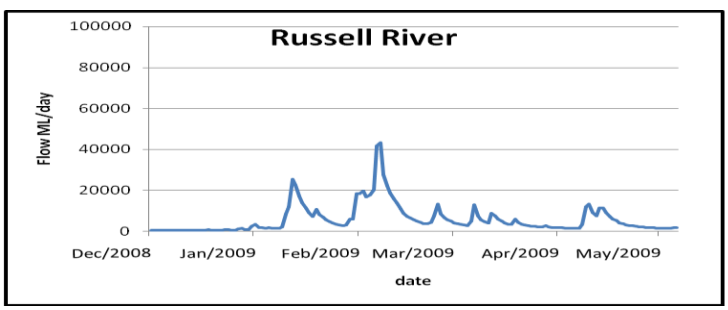
Regional assessments for the Tully and Burdekin plumes are presented in this report. Reporting is dependent on the timing and structure of the plume for each day that sampling occurred.

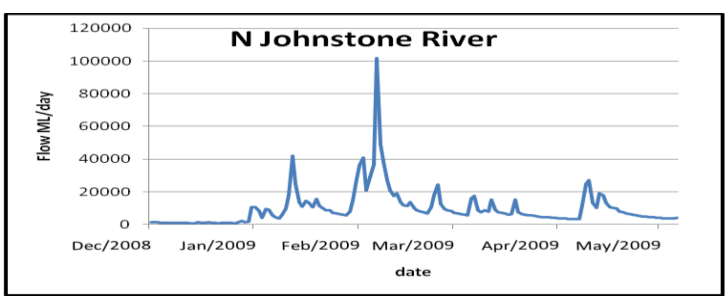
During the early months of 2009, there was heavy and persistent flooding throughout most of north and southeast Queensland from a combination of an early January cyclone and low pressure rain systems. The combination of consecutive low pressure systems caused prolonged flood events in catchments from the Burdekin to the Normanby and Wet Tropics rivers, (including the Herbert and Tully Rivers). Flow rates for 2009 for the 10 wet and dry tropical rivers are presented (Figure 4.1). Flow rates for a number of rivers was above the long term average annual flow (Table 4.1) with the North and South Johnstone, Tully, Herbert and Burdekin Rivers all having a higher flow than the long term median annual flow. In particular, the event in the Burdekin River was significantly higher than the average flow, being a 5.1 factor higher than the long term median flow.


Annan River
Flow ML/day
10000
8000
6000
4000
2000
0
Jan/2009
Feb/2009
Mar/2009
Apr/2009
May/2009
Date


Normanby River
Flow ML/day
140000
120000
100000
80000
60000
40000
20000
0
Jan 09
Feb 09
Mar 09
Apr 09
May 09
date


Barron River
Flow ML/day
100000
80000
60000
40000
20000
0
Dec/2008
Jan/2009
Feb/2009
Mar/2009
Apr/2009
May/2009
date


Russell River
Flow ML/day
100000
80000
60000
40000
20000
0
Dec/2008
Jan/2009
Feb/2009
Mar/2009
Apr/2009
May/2009
date


N Johnstone River
Flow ML/day
120000
100000
80000
60000
40000
20000
0
Dec/2008
Jan/2009
Feb/2009
Mar/2009
Apr/2009
May/2009
date

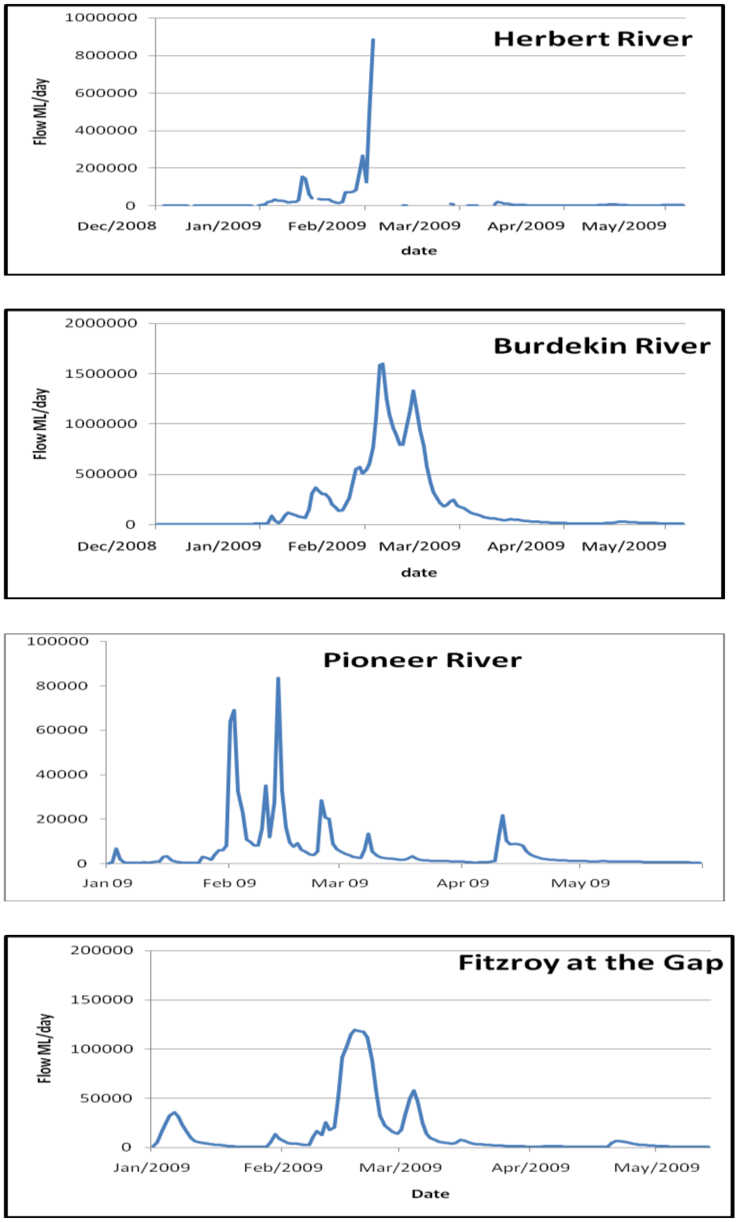


Figure 4-1: Flow rates associated with 10 Great Barrier Reef Rivers (Dec 2008 to May 2009).

Table 4-1: Annual freshwater discharge (ML) for major GBR catchment rivers in 2008/09. 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

Region	River	Long-term river discharge median (ML)	Long-term river discharge mean (ML)	Total year discharge 2008/09 (ML)	Difference between 2008/09 flow & long-term median (ML)	Relative difference between 2008/09 flow & long-term median
Cape York	Normanby	3,550,421	3,707,007	2,338,784	-1,211,637	0.66
Wet Tropics	Barron	692,447	795,275	779,456	87,009	1.13
	Mulgrave	719,625	743,399	688,515	-31,110	0.96
	Russell	1,049,894	1,051,743	1,212,230	162,337	1.16
	North Johnstone	1,845,338	1,797,648	1,986,776	141,438	1.08
	South Johnstone	810,025	801,454	1,043,893	233,868	1.29
	Tully	3,128,458	3,175,298	3,759,051	630,593	1.20
	Herbert	3,122,768	3,492,135	9,606,409	6,483,641	3.08
Burdekin	Burdekin	5,957,450	9,575,660	30,110,062	24,152,612	5.05
Mackay Whitsunday	Proserpine	35,736	70,568	63,263	27,527	1.77
	O'Connell	148,376	201,478	167,586	19,211	1.13
	Pioneer	731,441	648,238	931,808	200,367	1.27
	Plane	112,790	154,092	188,195	75,405	1.67
Fitzroy	Fitzroy	2,708,440	4,461,132	2,193,040	-515,400	0.81
Burnett	Burnett	147,814	217,511	12,079	-135,735	0.08
Total		**24,761,023**	**30,892,638**	**55,081,147**	**30,320,124**	**2.22**

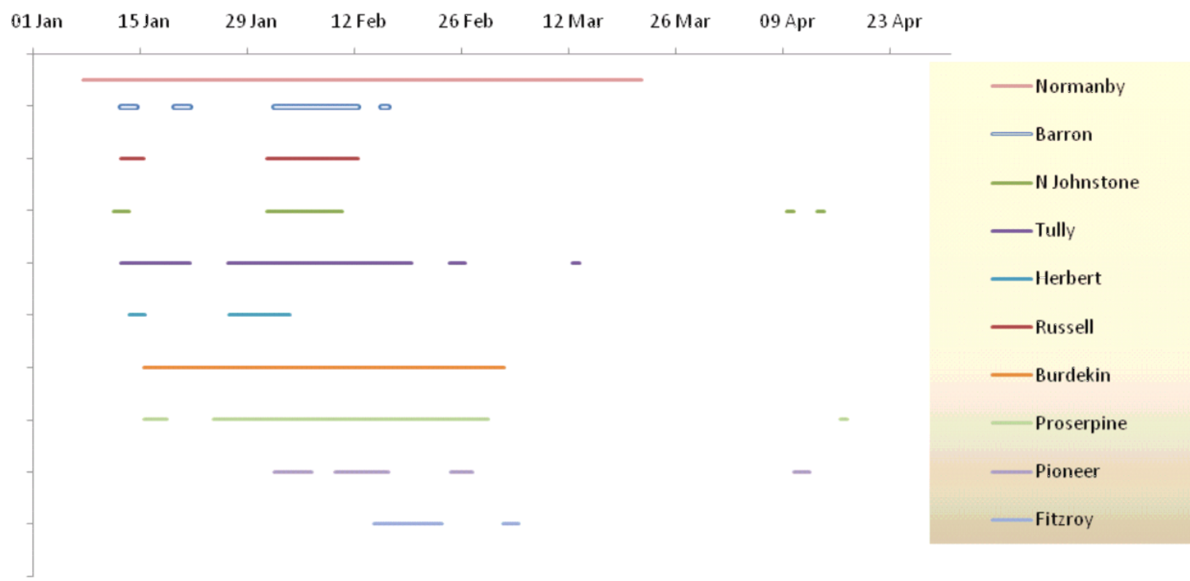


Figure 4-2: High flow periods (daily flow > 95th percentile) for 2009 in a selection of GBR rivers.

5. Case study 1 – Burdekin River

5.1. Details of sampling sites and timing

In 2009, sampling in the Burdekin River plume took place over a number of weeks at different locations within the Burdekin plume. Initial sampling in February was taken at the mouth of the Burdekin plume and linked to the MTSRF project 3.7.2 (sampling of riverine sediments). Sampling was carried out over 6 sampling dates over various stages of the hydrograph (Figure 5.1). Location of the sites were dependent on the sampling trip, with inshore sampling being taken by the plume program and offshore sampling taken in conjunction with GBRMPA sampling surveys. Further sampling was undertaken over a period of weeks off Magnetic Island. Offshore sampling was also undertaken in two transects out to the midshelf reefs in late March (Figure 5.2).

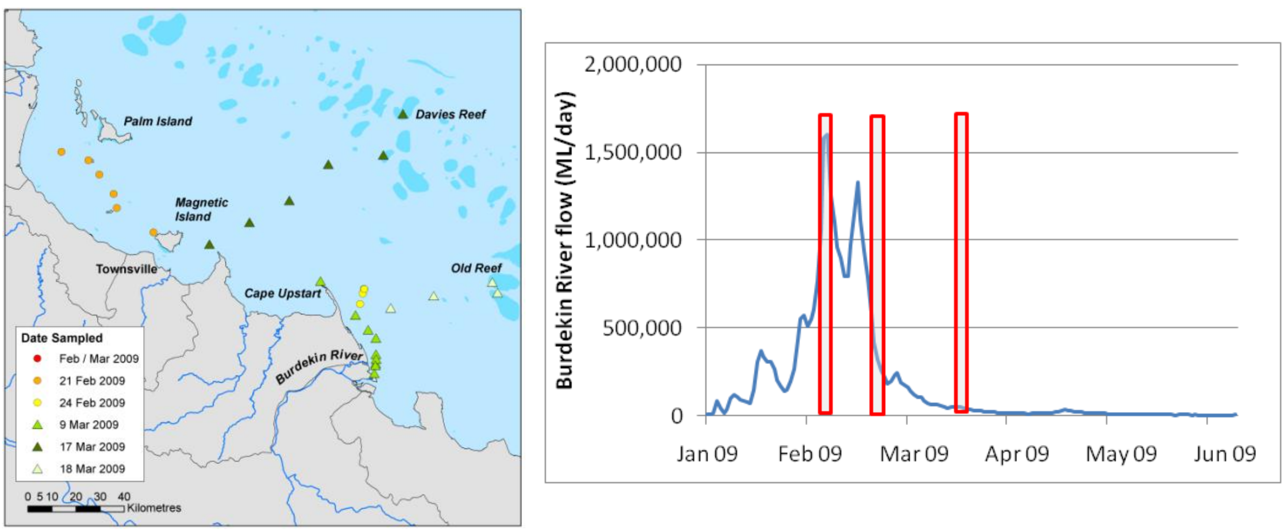


Figure 5-1: Sampling sites offshore from the Burdekin River, January to March 2009; (b) Flow hydrograph for the Burdekin River in early 2009. The red boxes denote the periods of time in which sampling took place.

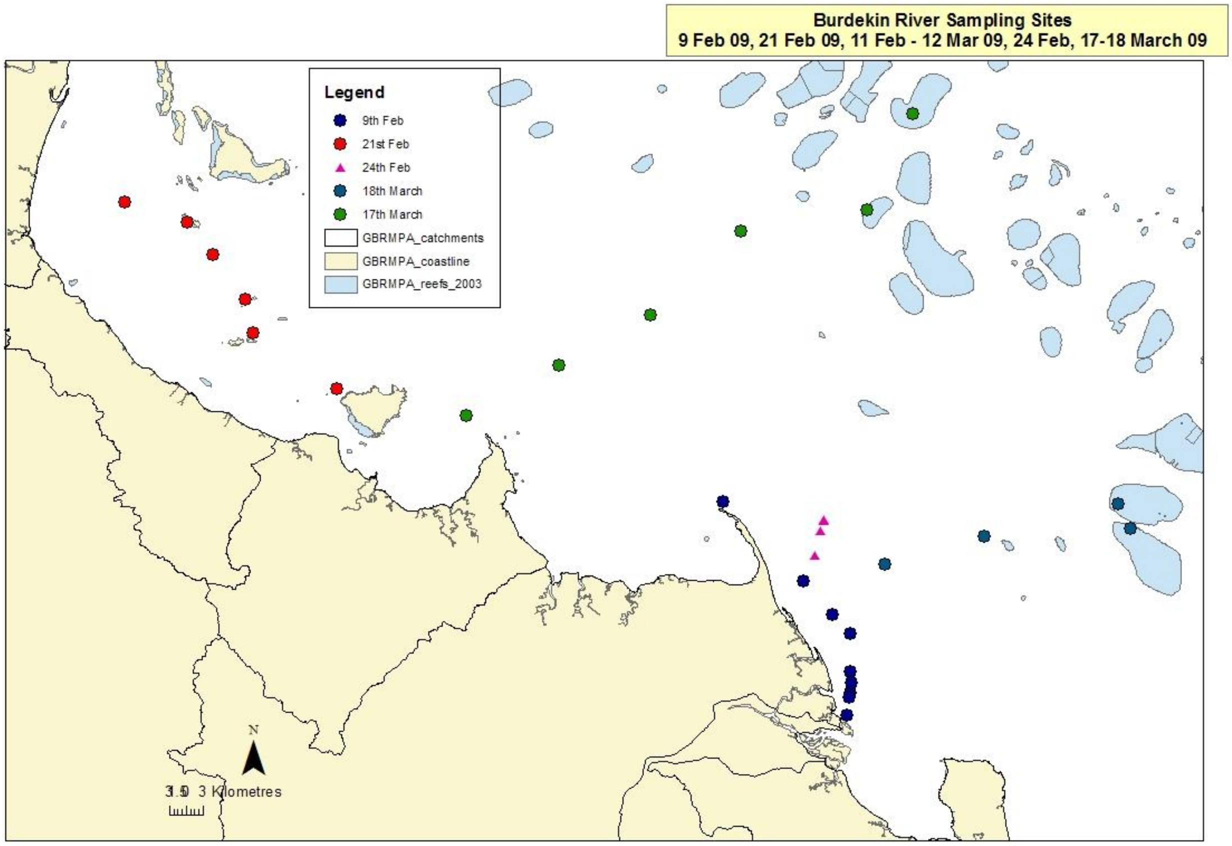


Figure 5-2: Location of all sampling sites delineated by date for the Burdekin catchment

5.2. Water quality sampling

Water quality data was measured during two month period over the 2008/09 wet season. The total volume of freshwater moving into the marine environment was significant, with over 30,110,062 ML of water discharging from the Burdekin catchment over the 2008/09 wet season, an increase of 24,152,612 ML from the long term annual median. Flow was elevated from baseline for over 10 weeks (Figure 5.2). Sites were dependent on the location of the plume waters as identified by true colour imagery and/or by the extent of the visible plume. The sites extended from the Burdekin mouth past Palm Islands as well as a series of offshore samples taken by John Brewer reef (Figure 5.1) Water quality samples were taken for the suite of nutrient parameters, chlorophyll, DOC and physico-chemical parameters.

The variation in the sampling ensured that there was a gradient of data from low to high salinity but care must be taken in the analysis to appreciate the time and distance lag when comparing differences in concentrations. 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 5.3 shows four mixing plots of the Burdekin River data for total suspended sediment (TSS), dissolved inorganic phosphate (DIP), dissolved inorganic nitrogen (DIN) and chlorophyll. For compatibility Burdekin plume data from the previous year sampling (2008) has been overlaid on the plots.

Data analysis illustrates the spatial patterns within the Burdekin plume waters. Suspended particulate matter (SPM) is substantially elevated in the river mouth (Figure 5.3), 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 two years (2008 and 2009), with the high concentrations dropping out quicker in 2009.. This could be indicative of a greater flux of heavier colloidal material in 2009 or the finer particulate matter moving further offshore in 2008. There were two events associated with the 2008 data, and the higher SPM concentrations could reflect the characteristics of a secondary flow event. SPM remains elevated through the plume waters; however, there is a substantial drop in concentrations as the water moves into Reef waters, signifying that a major proportion of coarse sediment drops out before reaching Magnetic Island. This is supported by the gradient in particulate nitrogen and particulate phosphorus concentrations, which are high in the initial mixing zone, dropping out past salinity measurements greater than 5ppt. The higher concentrations of the sediment and particulate nutrients in the initial mixing zone are indicative of the primary plume, where suspended particulate matter measures greater than 10mg/l and the particulate nitrogen and phosphorus measure greater than 20μM and 3μm respectively. High turbidity waters are a characteristic of these low salinity, high sediment concentrations and easily identifiable by aerial and RS imagery.

The highest concentrations of DIN measured in 2009 (7 μM) was taken in salinity waters of approximately 20ppt, 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 2008 data demonstrates non conservative mixing, with high concentrations in the lower salinity end (<10 ppt) with a subsequent reduction in concentrations after 10ppt 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 μM at the higher salinity end, indicating a long range movement of higher nutrient concentrations throughout the Burdekin plume waters. DIP concentrations in 2008 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 Palm Islands.

Chlorophyll, as an indicator of phytoplankton growth is elevated in both sampling events, with high concentrations occurring in both low salinities, indicating some intrusion of freshwater phytoplankton, and in higher salinities, indicating favorable growth conditions for the phytoplankton in the non light limiting waters (Figure 5.3). 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 5.4 presents the plume concentrations over a range of salinity measurements. The plots show the average concentrations of each parameter (TSS, DIN and chlorophyll) over a set salinity range. Similar patterns to the 2008 and 2009 mixing plots are shown; however the overall patterns are clearer, 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.

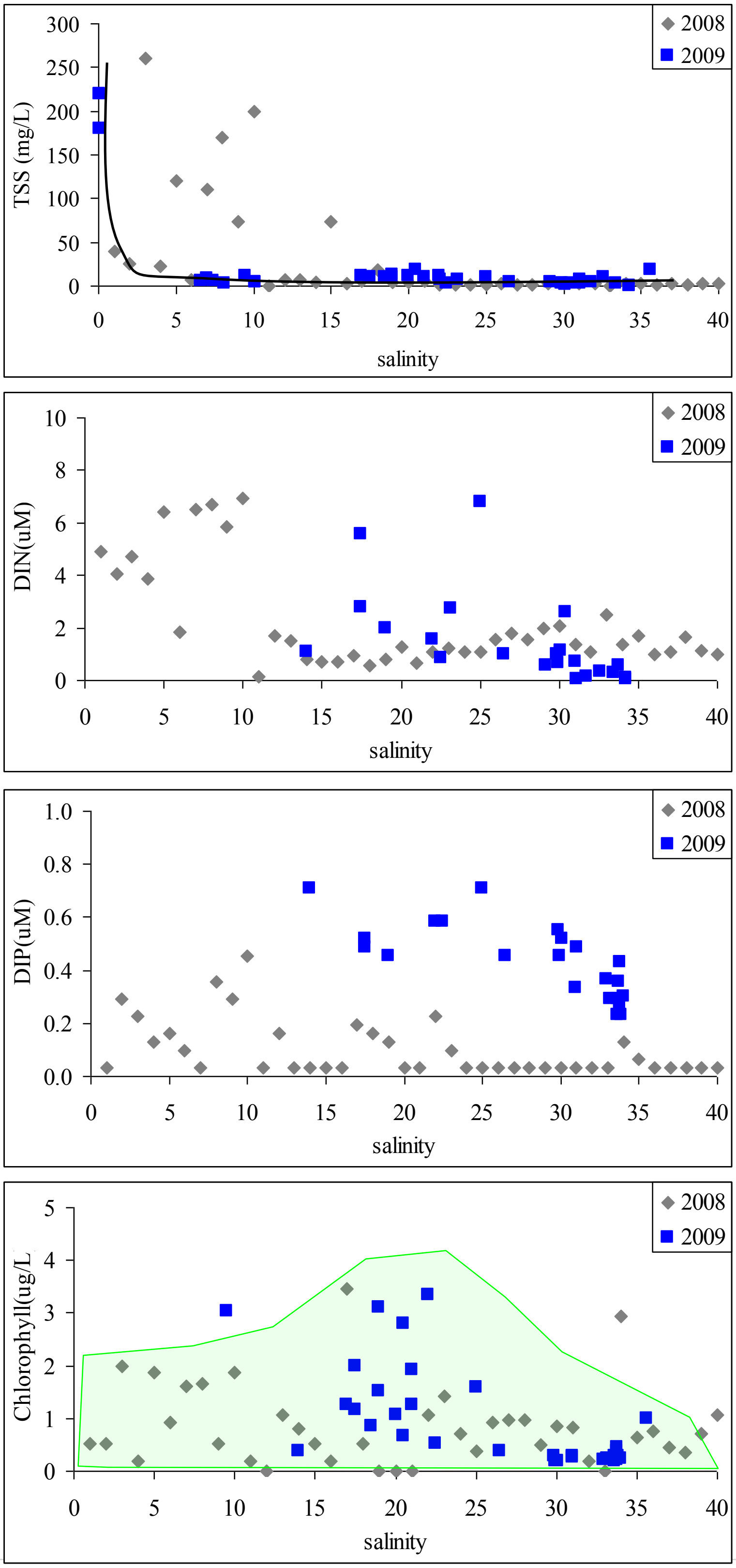


Figure 5-3: Mixing curves for total suspended sediment (TSS), dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) and chlorophyll for all sampling events in the Burdekin River plumes during the 2008/09 wet season.

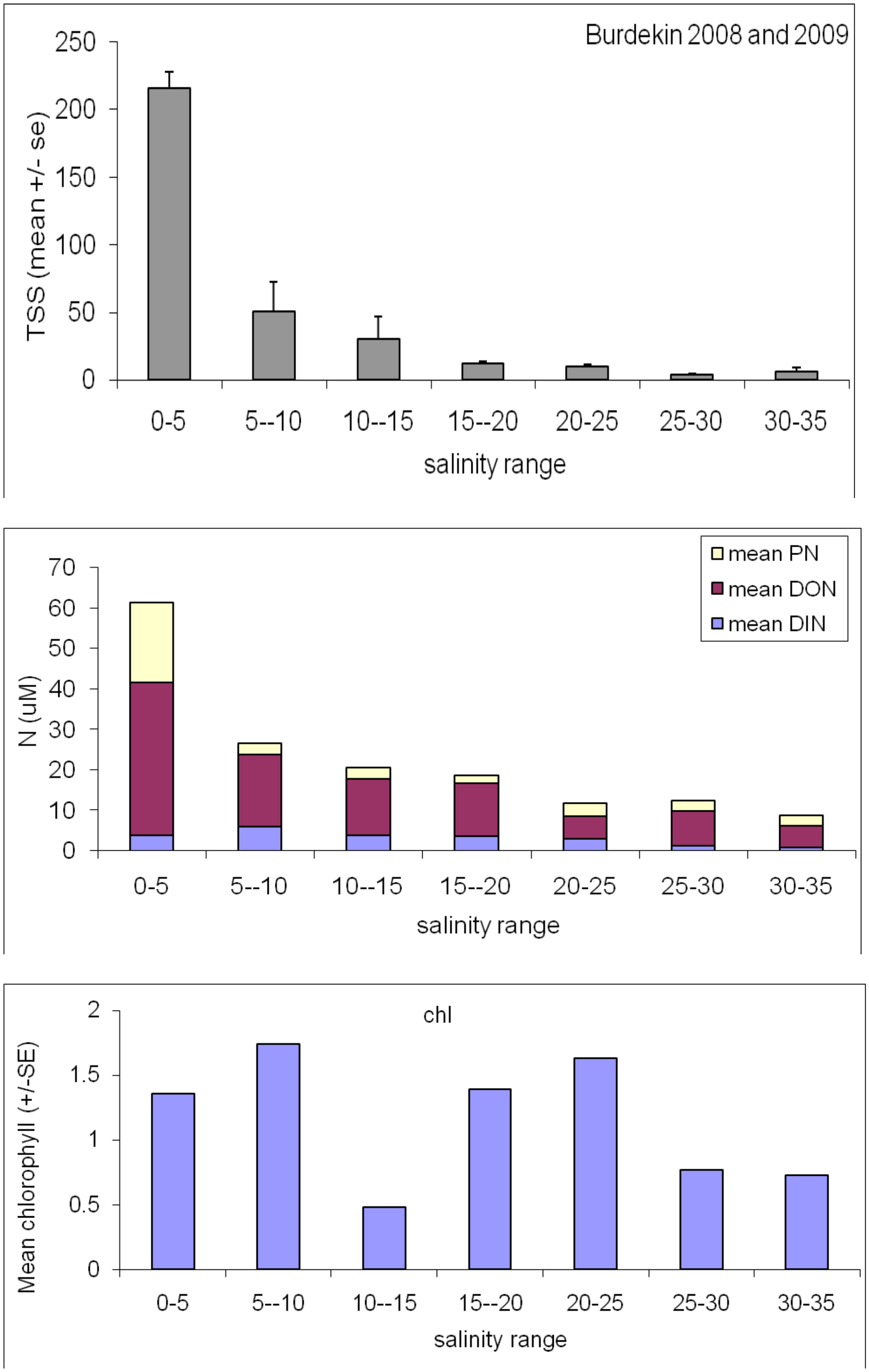


Figure 5-4: Salinity profiles for TSS, nitrogen species and chlorophyll. Data is averaged over salinity bands

5.3. Remote sensing of Burdekin River plume

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 mn (using RS techniques). A true colour image of the Burdekin plume is available from 14 January 2009 tracking the movement of the riverine waters (Figure 5.5). The two consecutive images are of the calculated CDOM (Figure 5.6) and chlorophyll (Figure 5.7) concentrations as calculated by the application of the CSIRO regional algorithms. Figure 5.5 identifies the primary and secondary plume associated with the Burdekin flood waters. The very turbid inshore plume can be seen moving north and offshore from the Burdekin mouth, almost reaching the offshore reefs. There is also a secondary plume visible in the left hand side of the picture, moving north. Field sampling was used to validate the movement of plume waters past the Palms Islands by this date.

Large volumes of high sediment water discharging from the Burdekin River is clearly seen on 14 January 2009 image (Figure 5.5) showing clearly the movement of the riverine waters into the GBR. Primary, high SPM waters have moved offshore and north to Magnetic Island. Secondary waters, with high measurements of chlorophyll and CDOM have reached past the midshelf reefs and extend north past the Palm Island group.

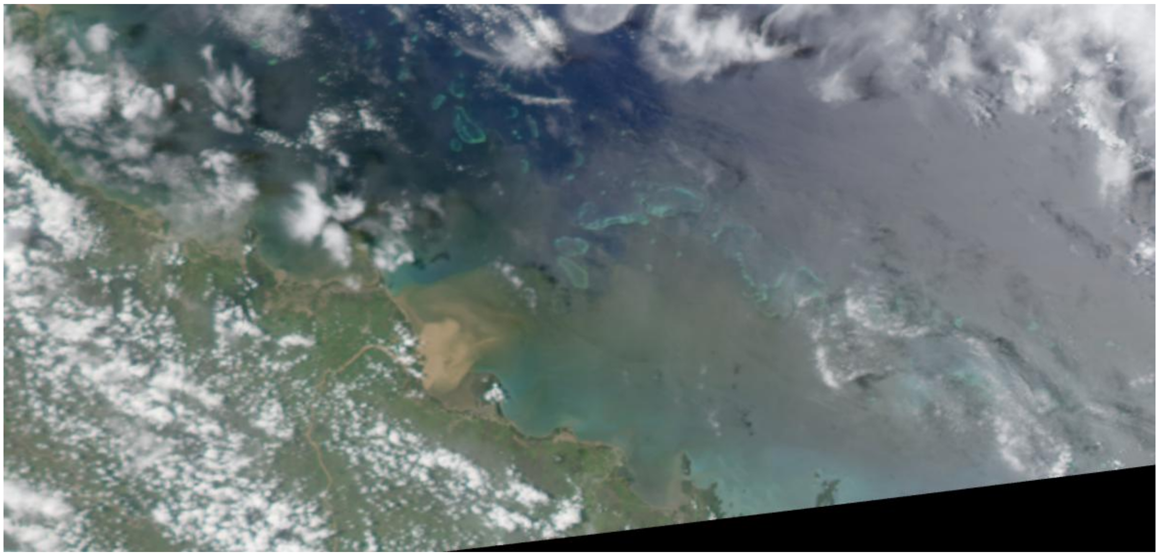


Figure 5-5: True colour image of Burdekin flood taken on 14 January 2009 (courtesy of CSIRO)

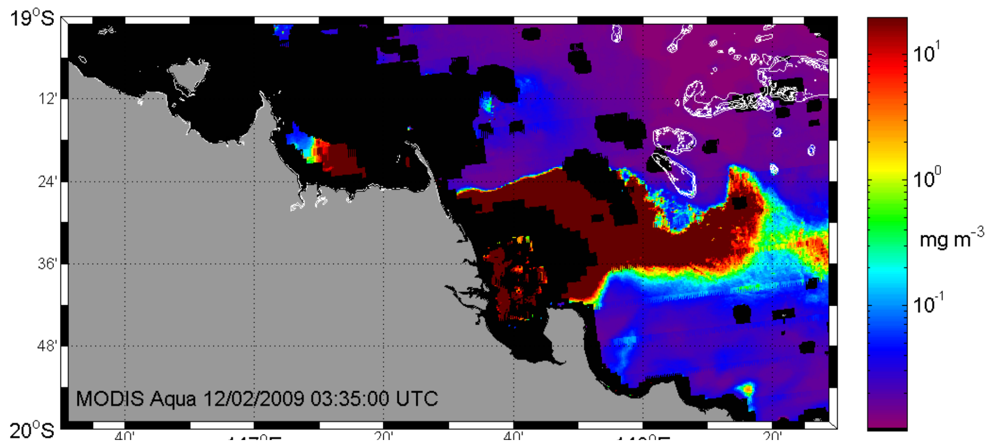


Figure 5-7: Chlorophyll values measured within the Burdekin flood on 14 January, 2009 (coutesy of CSIRO) Concentrations calculated by the application of regionally specific algorithms (Schroder et al. 2009).

5.4. Water quality exceedances – Burdekin region

Water quality thresholds for a number of water quality parameters have been published in the "Water quality guideline for the Great Barrier Reef Marine Park Authority (Table 5.1 and Table 5.2). It is important to note that the levels of contaminants identified in this guideline are not targets but should be taken as guideline trigger values that, if exceeded, identify the need for management responses.

Riverine plumes typically show elevated concentrations of many of the water quality parameters listed in this report, as plume movement is the main transport and conduit of many of the contaminants that enter the Great Barrier Reef Marine Park. The length and breadth and persistence of these the elevated concentrations are being identified but difficult to compare against one trigger value. However single measurement values are compared against the trigger values and the percentage (%) of exceedances can be calculated from the plume data. Note that this is useful as a guide to the plume concentrations and not indicative of the wet season values.

Further integration with the logger and RS data will show the full range of exceedances over the entirety of the wet season. Data is presented for each sampling date, thus if three occurrences have occurred, this indicates that the exceedances are occurring over a longer time frame than just the single sample. Table 4.1 and Table 4.2 identify the threshold values for coastal waters which are applied in our assessment.

Table 5-1: Guideline trigger values for water clarity and chlorophyll a.

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

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

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

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

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

Burdekin data from the 2009 sampling season was compared against the guideline trigger values. The percentage of failures per sampling day was calculated to identify the potential duration of water quality exceedances. The number of exceedances (presented as a % of total count for each sampling event) is shown in Table 5.3. During the first flush period for both years, there are almost 100% exceedances of all values with the exception of chlorophyll. During the evolution of the plume in the 2009 event, the exceedances are still high in samples measured around Magnetic Island measuring between 55 to 100%. However, the later measurements in the 2009 sampling period were taken further offshore and exceedances fall to less than 35% for all parameters.

Table 5.3 illustrates the scale of exceedances over the sampling area for both SPM and chlorophyll. Water quality guidelines are exceeded for nearly all SPM samples with the exception of the later offshore samples. Note that the final sampling occurred just prior to the second major flow event and would indicate that these water quality exceedances will have continued to occur for a period of weeks after the final sampling date. Plume waters can have far reaching impacts on the biological ecosystems for a period far longer that a short plume intrusion of days to a week.

Table 5-3: Number and percentage of exceedances for all Burdekin plume sampling events (defined by date or location) for 2008 and 2009.

	No and % of exceedances per sampling occasion 2008									
Date	22/1/08		23/1/08		2/05/2008		2/06/2008		2/12/2008	
Total No. samples	12		9		10		9		10	
	No	%	No	%	No	%	No	%	No	%
Chl a (0.45ug/L)	9	75	6	66.7	9	90	7	77.8	10	100
SS (2.0mg/L)	12	100	9	100	5	50	8	88.9	7	70
PN (1.4uM)	12	100	7	77.8	8	80	5	55.9	8	80
PP (0.09uM)	12	100	7	77.8	9	90	9	100	8	80

	No and % of exceedances per sampling occasion 2009									
Date	9th Jan 09		11th- 20th Feb 09		21st Feb 09		17th- 18th Mar 09			
Tot.No. samples	9		15		7		12			
	No	%	No	%	No	%	No	%		
Chl a (0.45ug/L)			14	93	2	29	2	17		
SS (2.0mg/L)	9	100	15	100	1	14	4	33		
PN (1.4uM)		100	12	100	2	29	4	33		
PP (0.09uM)		100	12	100	7	100	0	0		

The frequency of exceedances for all Burdekin sampling sites for the 2008 and 2009 events are shown for SPM (Figure 5.8) and chlorophyll (Figure 5.9). Spatial representation of the exceedances identifies the areas which are most prone to high concentrations, including the zone between Magnetic Island and Palms Island. There were overall less exceedances in Burdekin plume waters as compared to the sites measured at the Tully plume waters (see section 5), however a substantial number was exceeded, particularly for TSS. Sampling of the

Burdekin plume water was over much larger temporal and spatial scales, with 8 of the samples taken offshore quite late in the plume with only slightly elevated nutrient levels, representing tertiary type waters. The 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 AIMS logger data will be useful in identifying the period of time in which concentrations were exceeded over the extent of the flooding event. Integration of high frequency logger data and in situ plume data has been reported in Devlin and Schaffelke (2009) and in the plume synthesis report (Devlin and Waterhouse 2010).

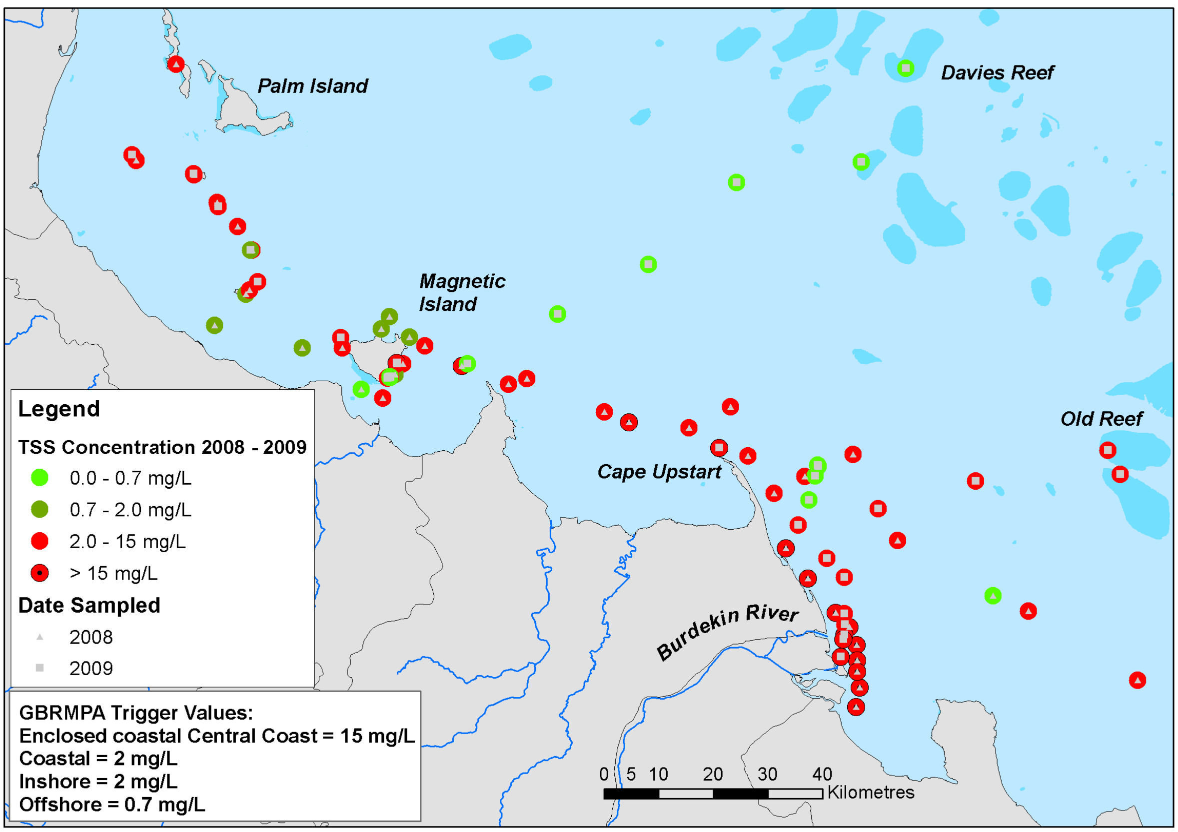


Figure 5-8: TSS exceedances of the GBRMPA water quality guidelines for the 2008/09 sampling period of the Burdekin plume waters.

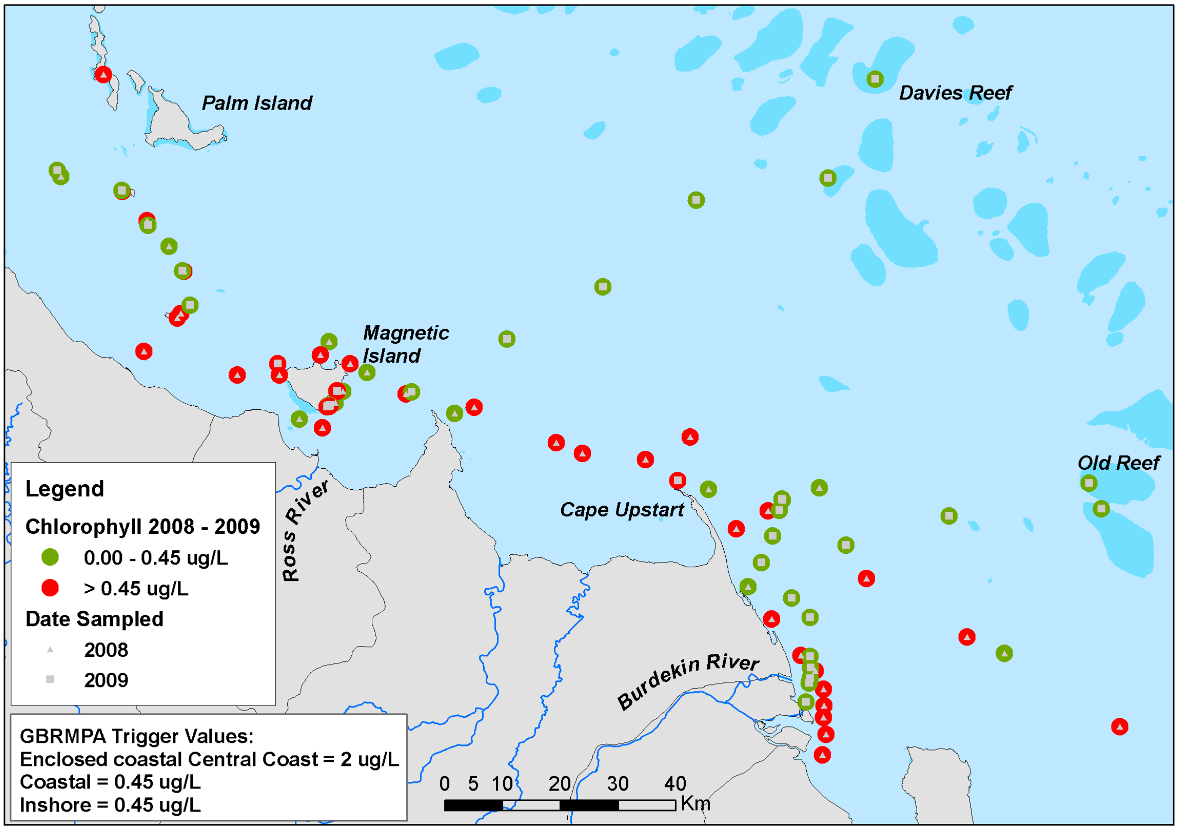
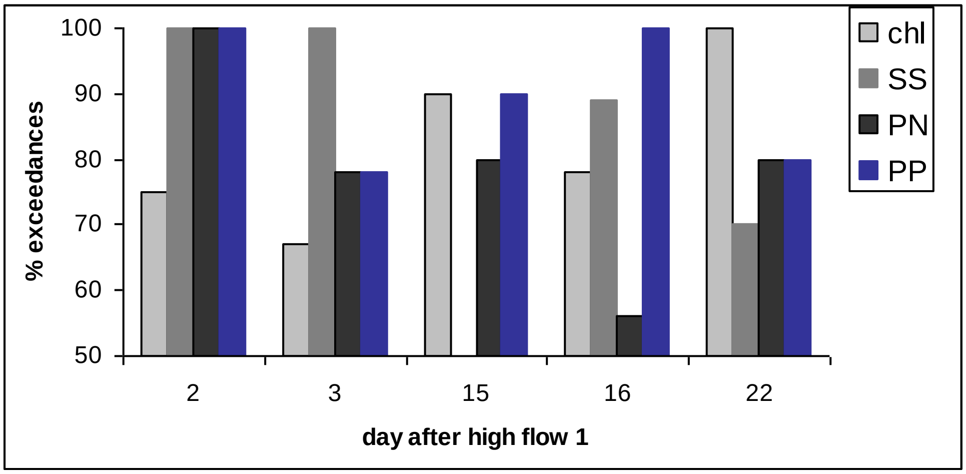


Figure 5-9: Chlorophyll exceedances of the GBRMPA water quality guidelines for the 2008/09 sampling period of the Burdekin plume waters.

Figure 5-10: Number of exceedances for each day after the first high flow in the Burdekin (18 – 20 January 2009).



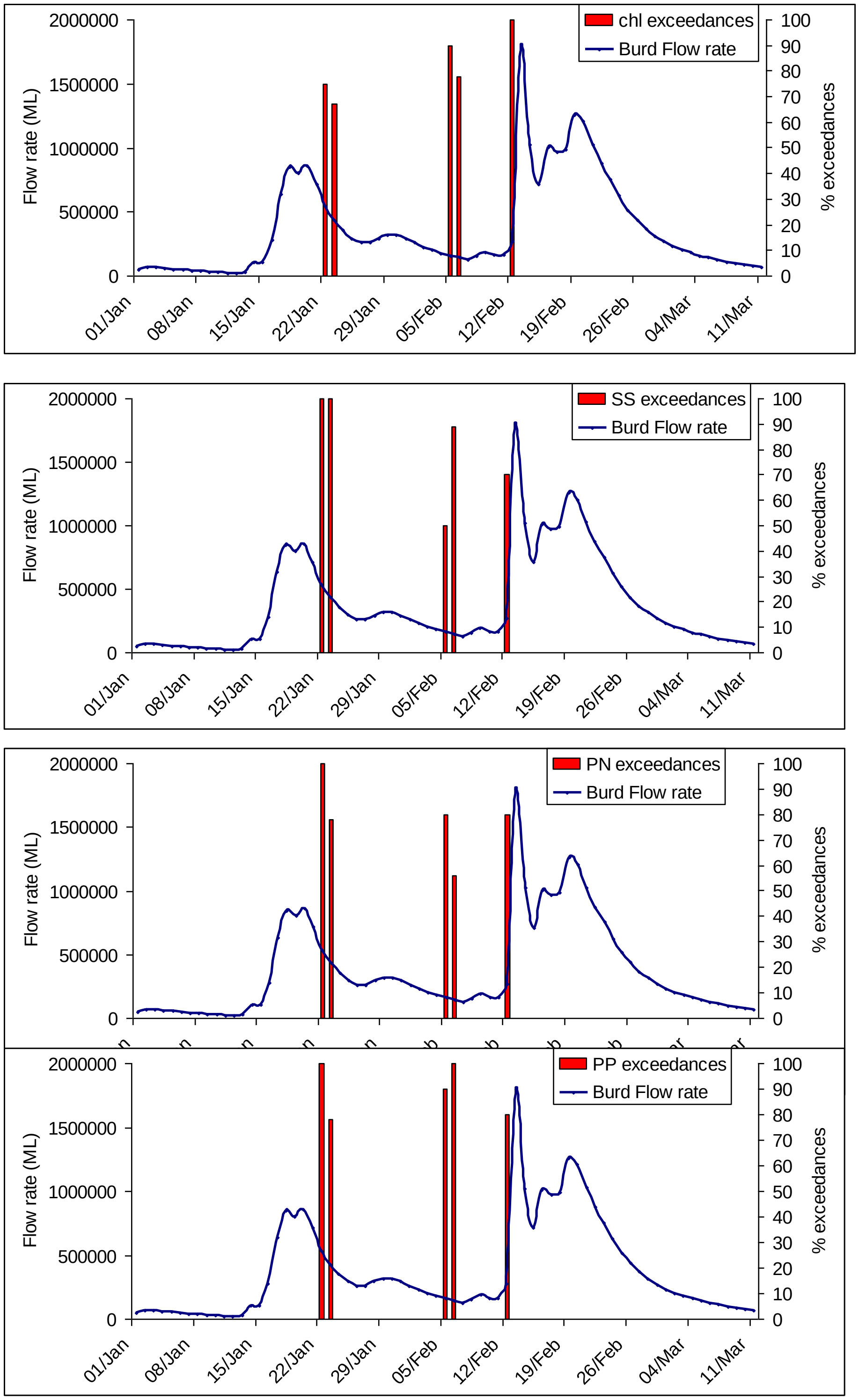


Figure 5-11: % exceedances for each day during the late 2008 high flow event in the Burdekin River (15 January – 11 March 2009).

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 (Figure 6.1).

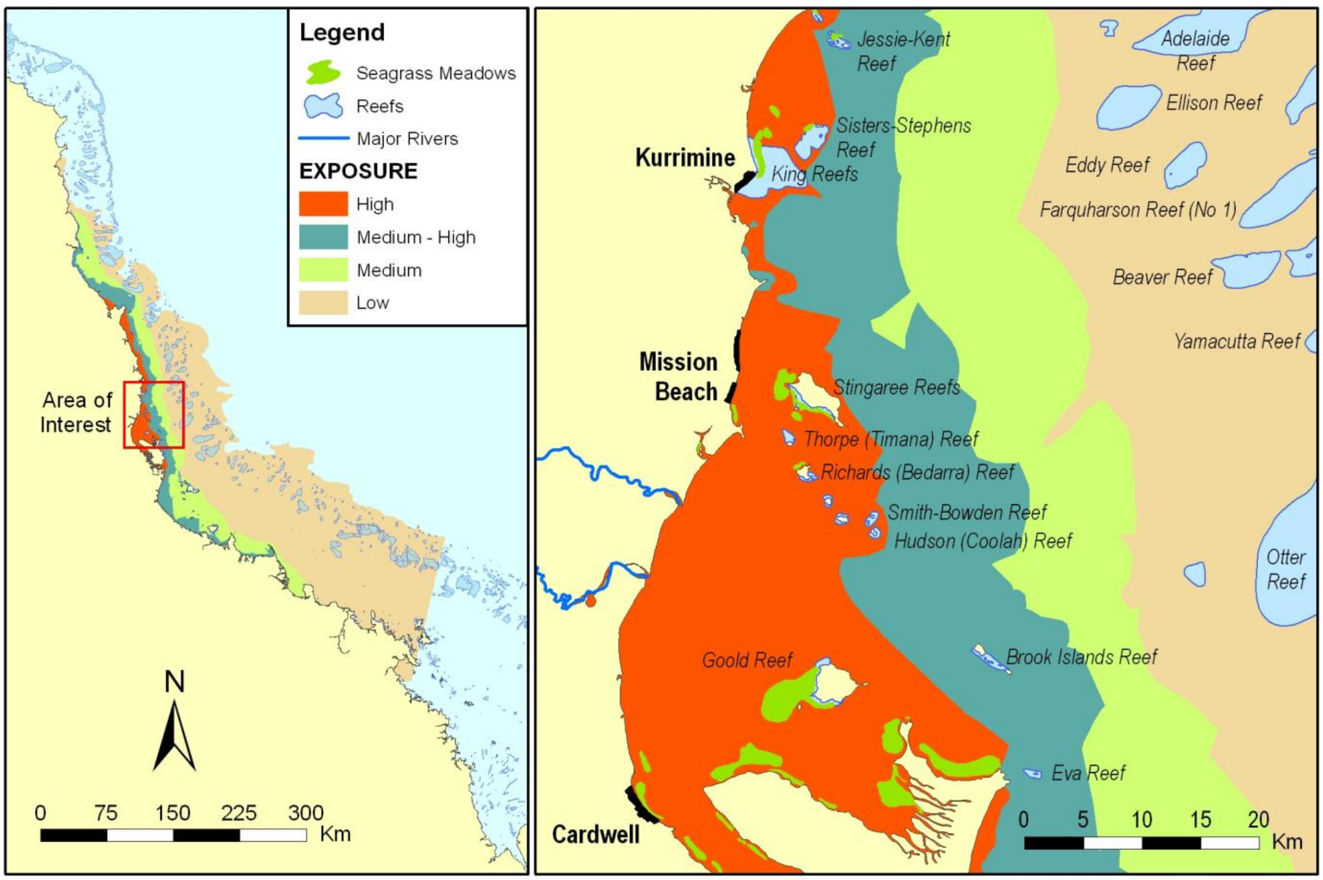


Figure 6-1: The exposure of biological communities within the plume exposure area. Colours denote level of plume exposure (high, medium-high, medium and low).

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 2009 took place in the high to medium risk exposure area. Field data was collected over five different sampling events in the Tully marine area. Sampling took place after medium to high peak flows were measured in the Tully River (Figure 5.2). Sampling sites extended from the river mouth offshore to the Sisters group and north to the Barnards (Figure 5.2). Sites were collected over a number of events and locations throughout the wet season (Figure 5.3).

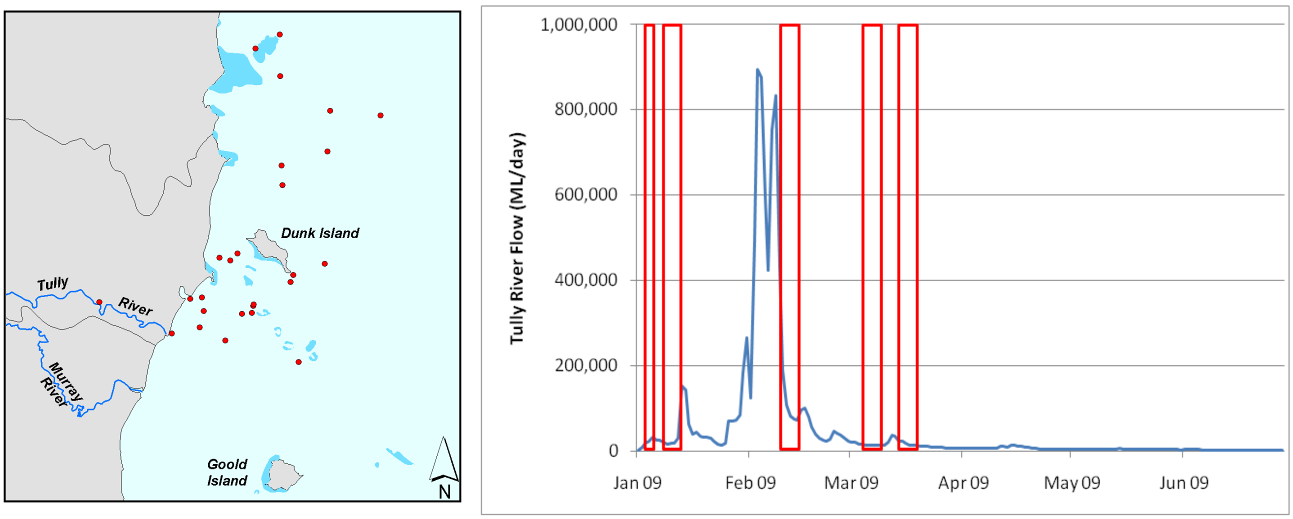


Figure 6-2: Sampling sites offshore from the Tully River sampled January to March 2009; (b) Flow hydrograph for the Tully River in early 2009. Red boxes denote the periods of time in which sampling took place.

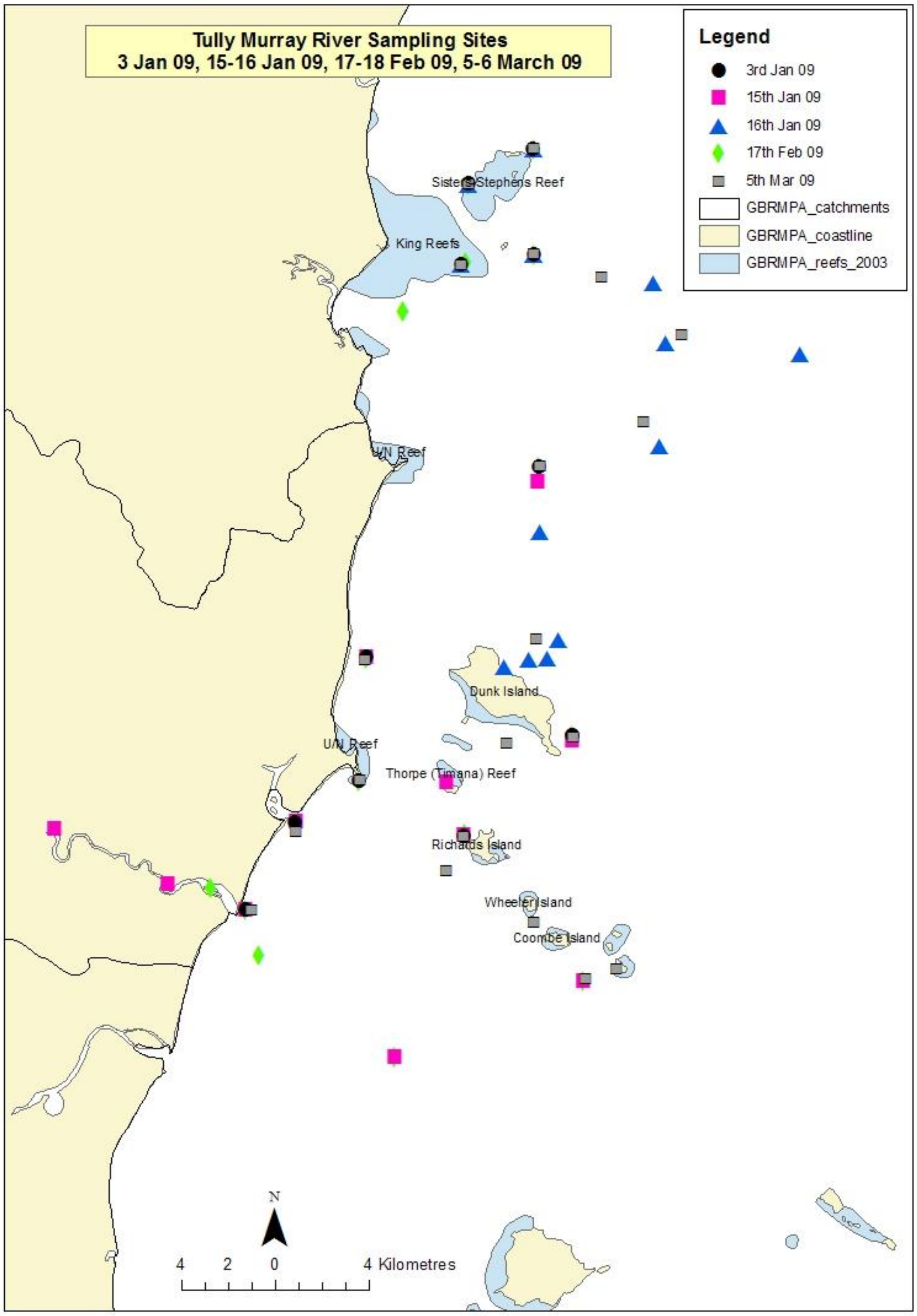


Figure 6-3: Location of all sampling sites delineated by date for sampling sites offshore from the Tully River. Sampling took place between January and March 2009.

6.2. Water quality sampling

Figure 5.4 illustrates the spread of data over the salinity range for all sampling events in the Tully-Murray plumes.

The timing of data is from 3 January to 18 March 2009. 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 (Figure 5.4). 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.

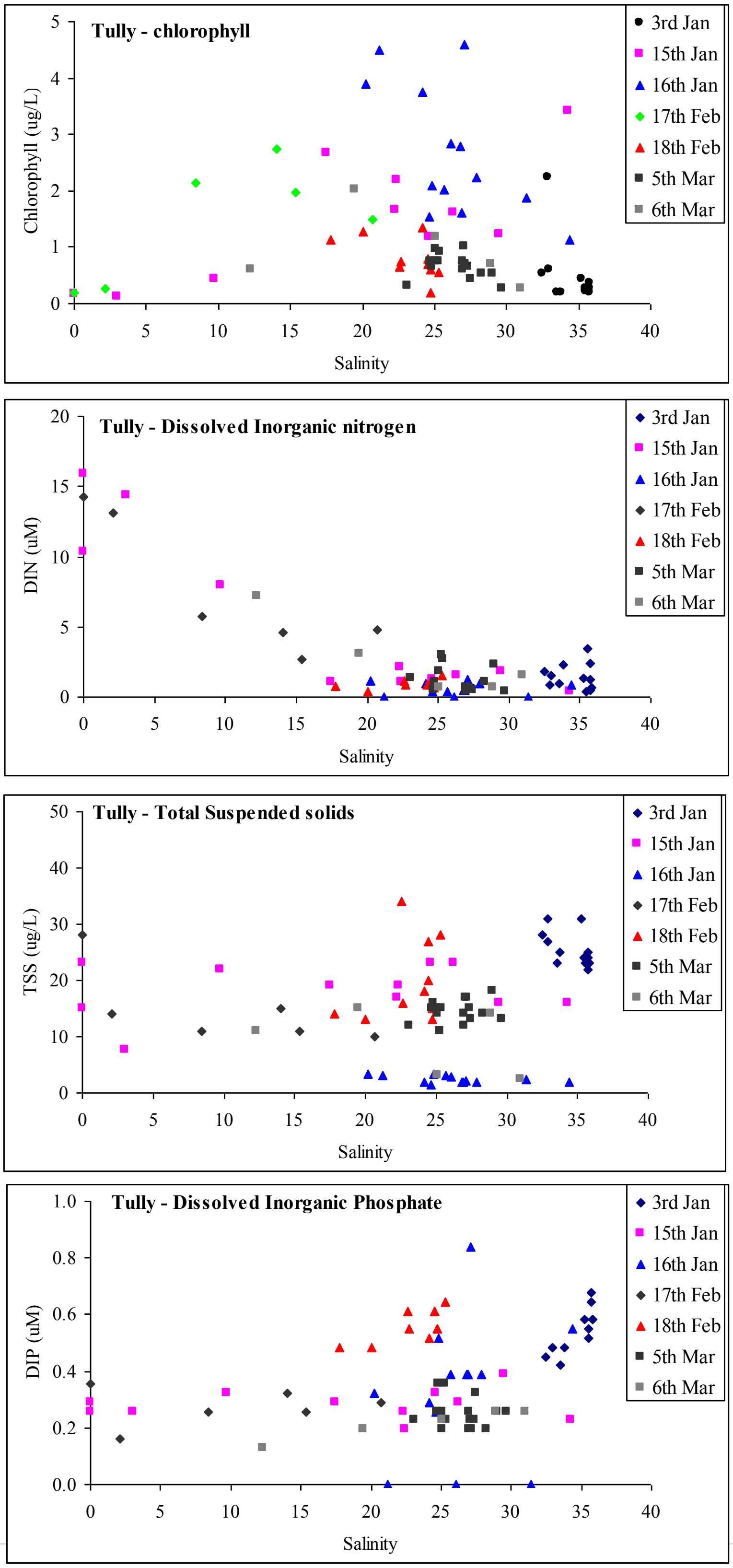


Figure 6-4: Mixing curves for chlorophyll, suspended solids (SS) dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) for the 7 sampling events in the Tully-Murray plumes during the 2008/09 wet season.

6.1. Remote sensing of the Tully plumes

The extent of a visible plume is ready seen in true colour imagery (Figure 6.5). The Tully plume measured on 14 January, 2009 moves past Dunk and Bedarra Island, north to the Barnards. 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 well offshore, will 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.

Application of the CDOM and chlorophyll-*a* algorithms were used to validate the true colour extents, with CDOM measuring elevated concentrations (from baseline measurements) well past the mid shelf reefs. Chlorophyll concentrations are elevated over large temporal scales, however the increase in the offshore waters is only slightly above baseline levels. These three figures show that the Tully plume extent was more than likely influenced by the ongoing flooding from the Southern Rivers (Herbert and Burdekin Rivers) and that the amalgamated plume water was a significant and large moving mass, extending over large areas of GBR waters.

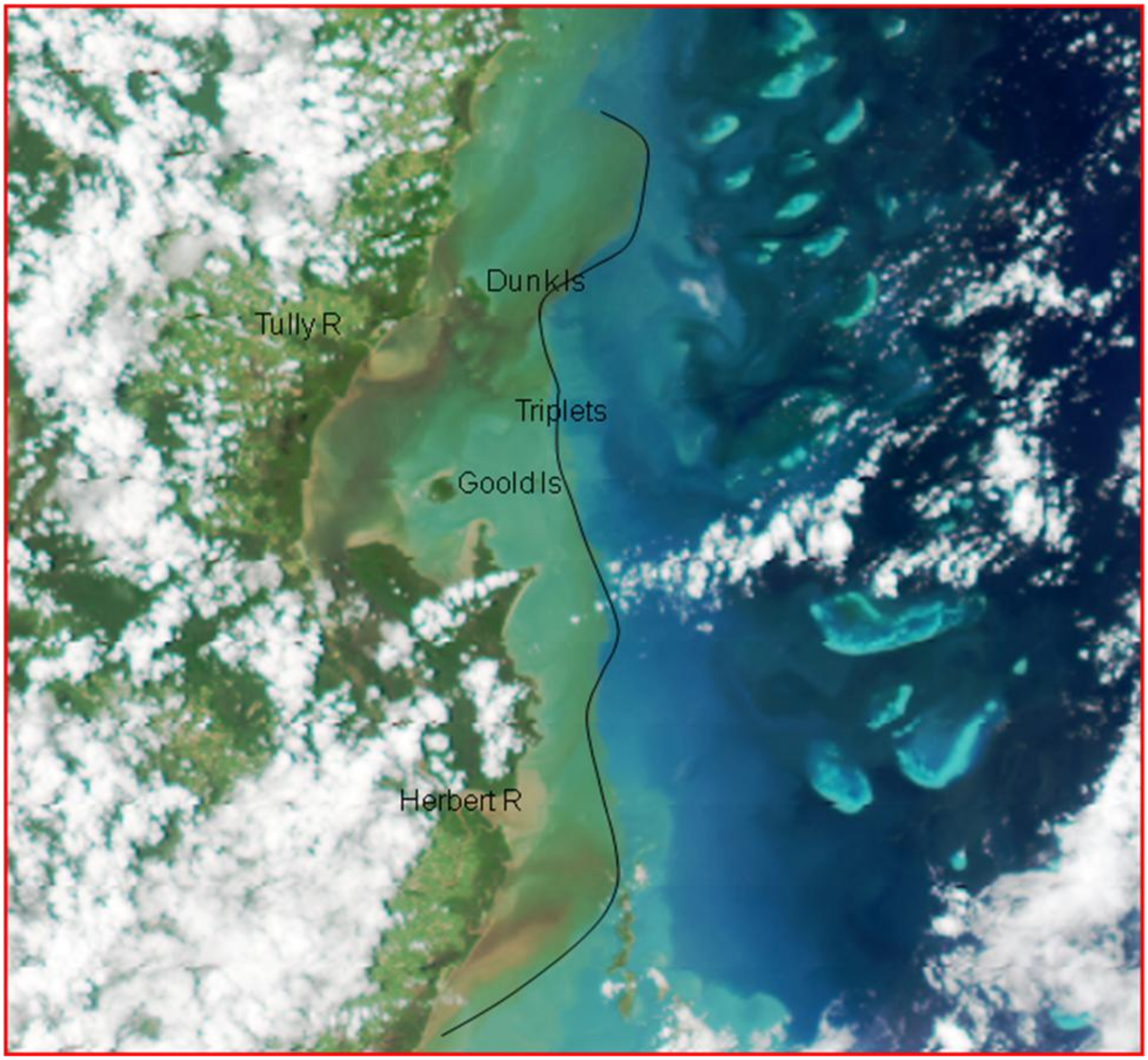


Figure 6-5: Modis AQUA image at 250 m resolution taken on 14 January 2009. The bold line denotes the edge of the visible (secondary) plume. Image courtesy of CSIRO.

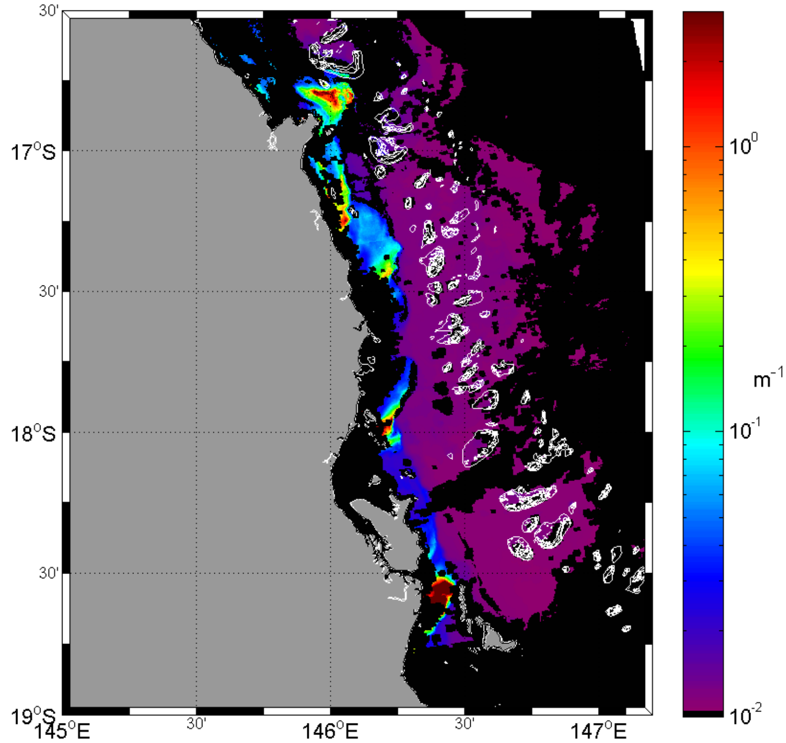


Figure 6-6: CDOM image of the Wet Tropics plume on 14 January 2009. Atmospheric corrected spectra were used to derive the inherent optical properties and the absorption of CDOM at 440 nm, by applying a Linear-Matrix-Inversion (LMI) algorithm. Image courtesy of CSIRO.

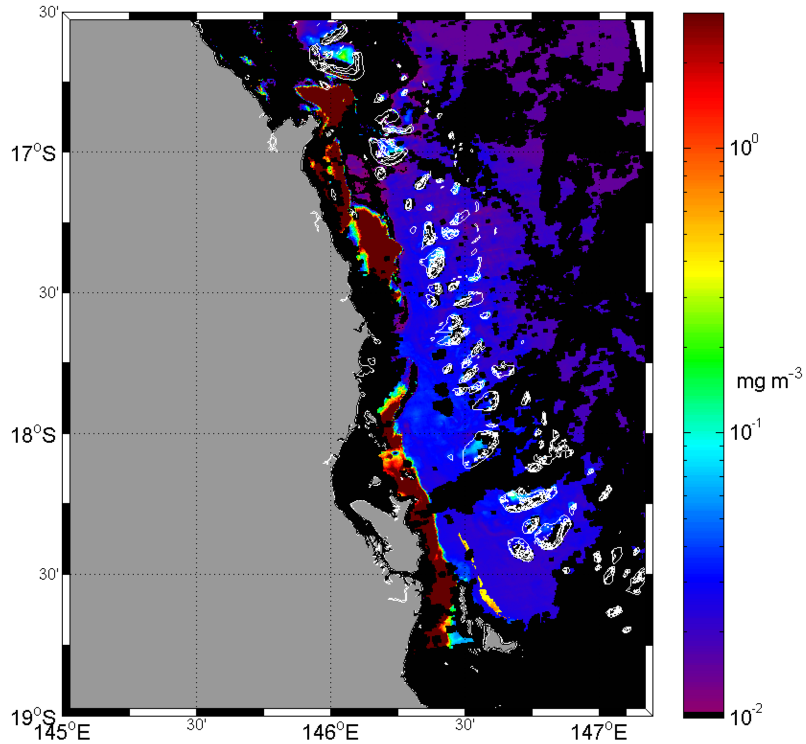
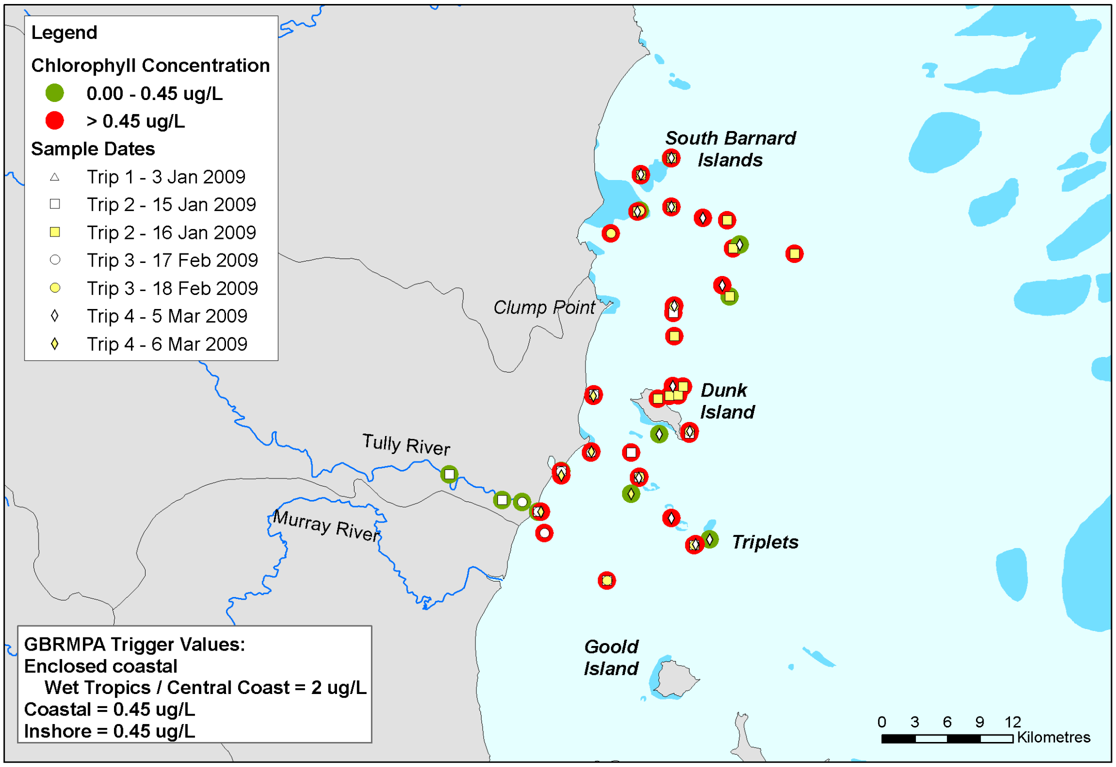
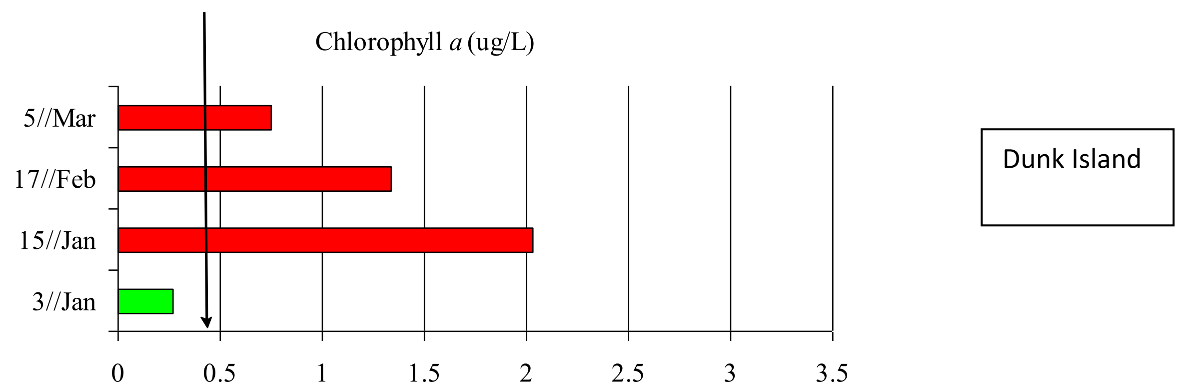


Figure 6-7: Chlorophyll image of the Wet Tropics plume on 14 January 2009. Atmospheric corrected spectra are then used to derive the inherent optical properties and the concentrations of optically active constituent, chlorophyll-a by applying a Linear-Matrix-Inversion (LMI) algorithm. Image courtesy of CSIRO.

6.2. Water quality exceedances.

The frequency of water quality exceedances for all Tully sampling sites is presented for the 2009 sampling year for chlorophyll (Figure 6.9) and suspended solids (Figure 6.10). In addition, exceedances at two sites (Dunk Island and Triplets) are shown over four sampling times (January to April 2009). Over 90% of all samples taken exceeded the water quality guidelines for chlorophyll and TSS. For the two sites with repeated sampling, chlorophyll was exceeded for the first three sampling times and TSS was exceeded for all four of the sampling times. The 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 AIMS logger data will be useful in identifying the period of time in which concentrations were exceeded.





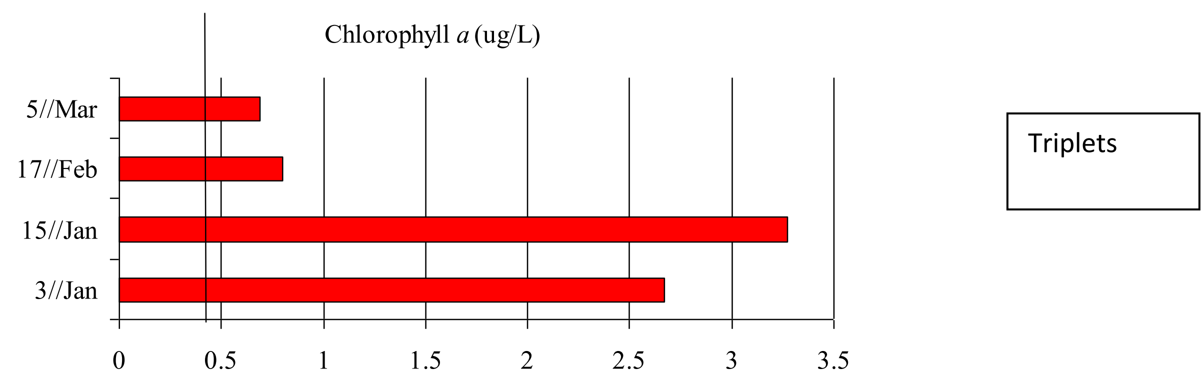


Figure 6-8: Water quality exceedances for chlorophyll *a* in the Tully River plume sampling sites.

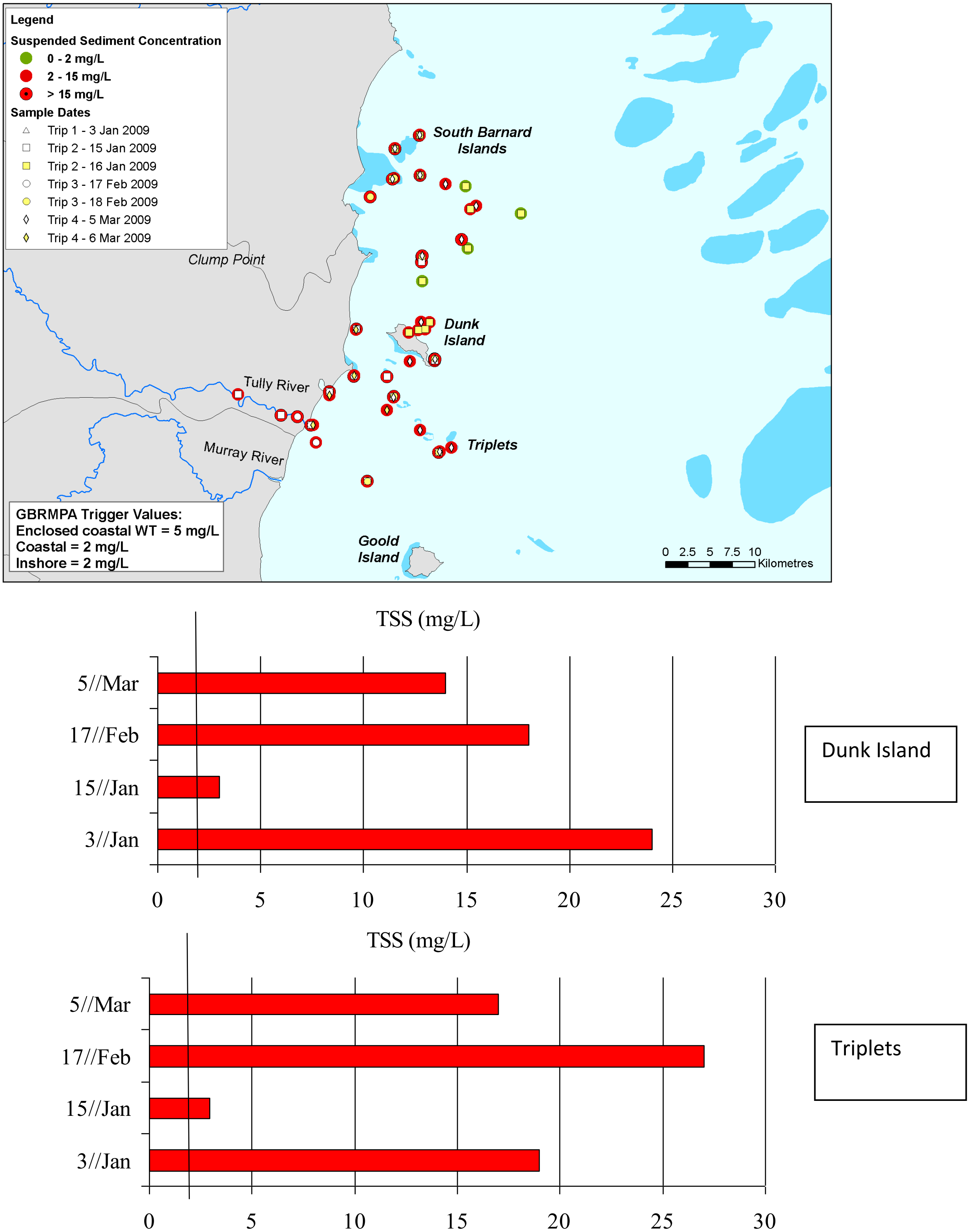


Figure 6-9: Water quality exceedances for TSS in the Tully River plume sampling sites.

7. Pesticides

7.1. Whitsunday Islands

A total of 11 samples were collected for pesticide analysis from the Whitsunday Islands over the 2008/09 wet season. A small 'first flush' flow event was sampled offshore from the mouth of the O'Connell River (six samples) through to the Whitsunday Islands on 17 January 2009. Diuron, atrazine and hexazinone were detected in the plume waters with the highest concentrations near the mouth of the O'Connell River (Figure 7.1). Detectable levels of herbicides reached as far as Cape Conway in this event. The herbicides appear to display a conservative mixing trend as the river waters become mixed with seawater. Concentrations of these herbicides off the O'Connell River mouth were consistent with previous years.

An additional 5 samples were collected through the Whitsunday Islands on the 19-20 February 2009. Interestingly, herbicides were detected at the more offshore sites with diuron (0.01 µg/L) detected offshore from Edward Island and bromacil (0.02 µg/L) detected off Deloraine Island. No pesticide residues were detected at the inshore sites which included Daydream, Pine and Double Cone Islands. These herbicides detected at the more offshore sites are probably sourced to local runoff or diuron could be potentially sourced to anti-fouling paints on boats.

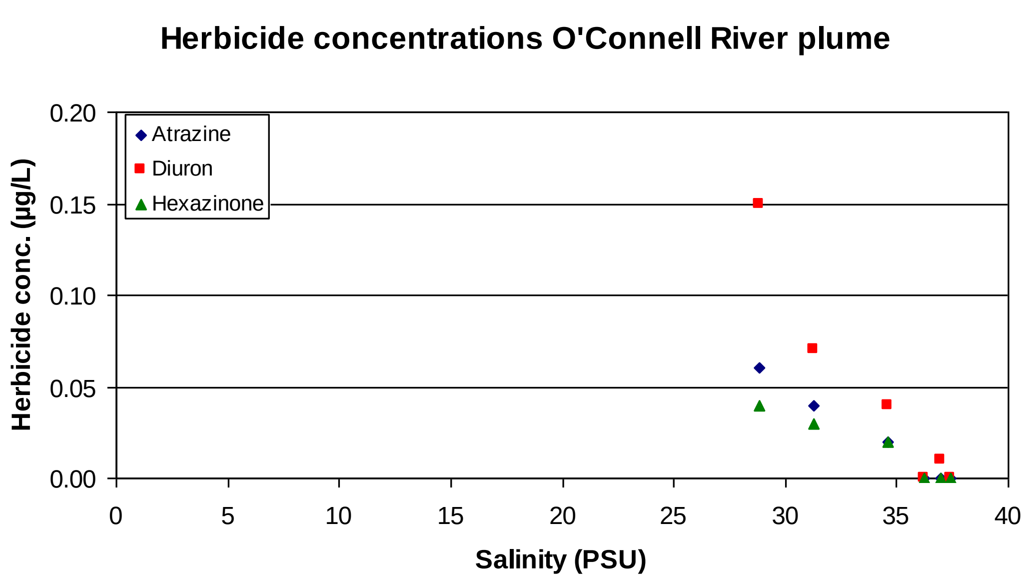


Figure 7-1: Herbicides in the O'Connell River flood plume on 17 January 2009.

7.2. Burdekin region

A total of 16 samples were collected for pesticide analysis offshore from the Burdekin River extending up to Hinchinbrook Island in the 2008/09 wet season. The Burdekin River had a very large event in 2008/09 with a total discharge of 29.5 million ML of water, most of which occurred in January to February 2009. The samples were collected over three trips including the 9th February (4 samples), 21 February (2 samples), 23 February (3 samples), 24 February (2 samples) and 16-17 March (5 samples) 2009. The results from the March 2009 samples have not yet been received, although no pesticide residues were detected in any samples from the earlier trips. However, residues of atrazine and tebuthiuron were detected in the Burdekin River earlier in the wet season at the 'Rocks' (near the end-of-catchment) site (13 January 2009) and at the Burdekin Falls Dam (29 January 2009) and so residues of atrazine and tebuthiuron were probably in the plume waters during the January event flows before becoming diluted below detectable limits.

7.3. Wet Tropics (Tully) region

A total of 31 samples were collected for pesticide analysis from the Tully/Wet Tropics Region in the 2008/09 wet season with a particular focus offshore from the Tully River (Figure 7.2). Five separate field campaigns occurred in the region including 3 January (2 samples), 15-16 January (13 samples), 17-18 February (8 samples), 24-28 February (4 samples – Wet Tropics) and 5-6 March (4 samples) 2009. We note that no results have yet been received for the sampling in March. Herbicide residues were detectable offshore from the Tully River and included sites off Dunk Island, the Triplets, Bedarra Island and King Reef. Diuron, atrazine, hexazinone and simazine residues were all detected in the January plume and diuron and hexazinone residues were still detectable in the samples collected in February. While the concentrations in February were considerably lower (e.g. see Figure 7.2 for diuron), the fact the residues were still detectable following high river flows in both January and February suggests longer term persistence. In addition, imidacloprid residues (an insecticide) were below detection in the January sampling but were detected in four of eight samples collected in February (concentrations range from below detection to 0.03 µg/L). This result suggests that this insecticide was applied to paddocks following the January rains.

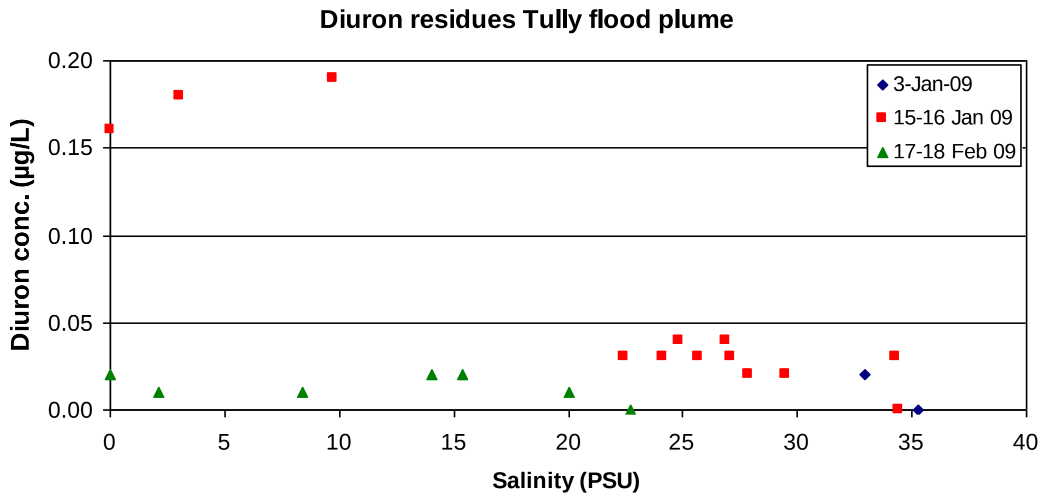


Figure 7-2: Diuron residues detected offshore from the Tully River in January and February 2009 over the salinity gradient.

Three additional samples were collected from islands further north of the Tully sub-region in February 2009 including Green, Russell and High Islands. No pesticide residues were detected off Green or Russell Islands although atrazine (0.01 µg/L) and diuron (0.03 µg/L) residues were detected off High Island. The residues detected at High Island are probably sourced to the nearby Russell River which had a flow at the time of sampling (L. McKinna pers comm. 2009).

7.4. Fitzroy region (2008)

Five herbicide residues were detected in the 2008 Fitzroy River plume including atrazine, desethyl atrazine, desisopropyl atrazine, tebuthiuron and metolachlor (Figure 7.3). In particular, atrazine and tebuthiuron show strong conservative mixing patterns (r^2 >0.99) suggesting that concentrations were the highest near the river mouth and that these herbicides were associated with the dissolved fraction (Figure 7.3). Atrazine and tebuthiuron residues were detected ~50 km from the river mouth in close vicinity to the Keppel Islands. While the GBRMPA marine trigger value (0.4 µg/L) for atrazine was not exceeded, the tebuthiuron guideline (0.02 µg/L) was exceeded in every sample collected. In addition, the combination of atrazine, its decay products and tebuthiuron are likely to induce additive effects on marine plants as these herbicides are all designed to inhibit photosystem II. Metolachlor, on the other hand is a product designed as a growth inhibitor of seedlings. The runoff of atrazine and metolachlor in the Fitzroy River is likely to be sourced to grain crops within the catchment while tebuthiuron is used in grazing lands (Lewis et al. 2009, Packett et al. 2009).

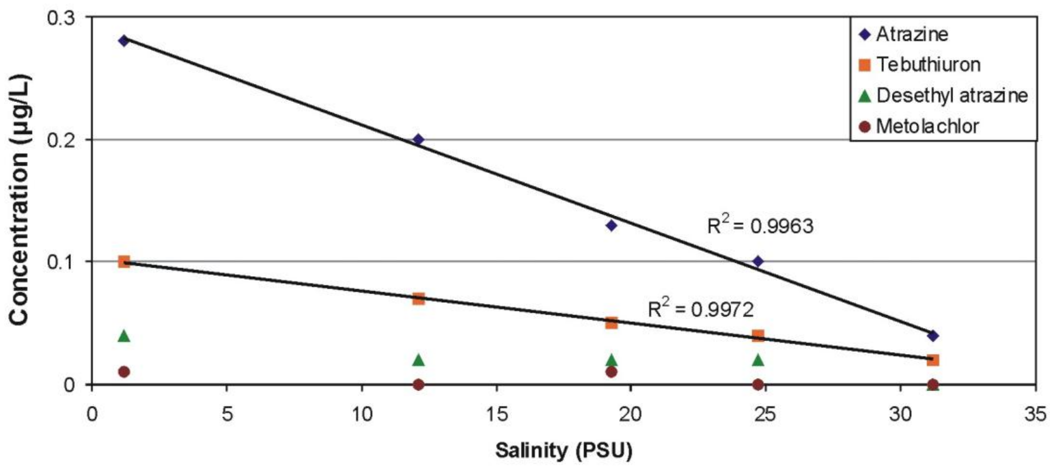


Figure 7-3: Concentrations of atrazine, tebuthiuron, desethyl atrazine and metolachlor in the 2008 Fitzroy River plume over the salinity gradient.

8. Comparison between the Tully and Burdekin River plumes

Water quality data in the Burdekin and Tully River plumes have been collected over a long period of time, with seven events sampled in the Burdekin region between 1994 and 2009 and nine events in the Tully sub-region between 1994 and 2009. All data was averaged over set salinity ranges for SS, DIN, DIP and chlorophyll for each catchment (Figure 8.1).

The data suggests that the behavior of the water quality constituents varies between catchments, with higher suspended solid concentrations being measured in the Burdekin catchment at low salinities, falling quickly over the salinity gradient as compared to the Tully catchment with elevated suspended sediments being measured in the lower salinities at much lower values than the Burdekin. There is also little difference between in first two salinity zones, implying that there is a movement of finer particulate sediment from the Tully River which moves further offshore. Also suspended solids measured in the Tully River plumes may increase in the later salinity zones, indicating some transformation to a higher concentration of organic materials.

DIN measurements are similar in the fact that there is a gradual reduction of DIN concentration over the salinity zones. However, similar to higher concentrations are being measured in the Burdekin, indicating that there is a large movement of inorganic nitrogen from a catchment which has suspended solid loss as a priority management action. Thus the increase in fertilized agriculture coupled with the sheer size of the 2009 Burdekin event has potentially moved high concentrations over the considerable distance of the offshore Burdekin plume. Both catchments show elevated DIN concentrations at lower salinity levels, with high inorganic nutrient levels potentially available for days to weeks in both areas.

DIP shows a contrasting pattern with DIP concentrations in the Burdekin plume diluting conservatively over the salinity zones, with some desorption potentially happening in the lower salinity zones. DIP measurements in the Tully plume show that distinctive increase of DIP in the middle salinity ranges indicating complex interactions between the different stages of phosphorus and desorption processes. The impact of this phosphate delivery is unclear at this stage.

Chlorophyll concentrations for both areas are influenced by the patterns of DIN and suspended solids, with low values measured at the lower salinities, and increasing in the middle salinities where suspended solids and associated turbidity decreases and the inorganic nutrient availability is still high. There is some reduction in the higher salinities, though the Tully plume waters show an increase in the higher salinities, showing persistence of elevated phytoplankton concentrations in the Tully region.

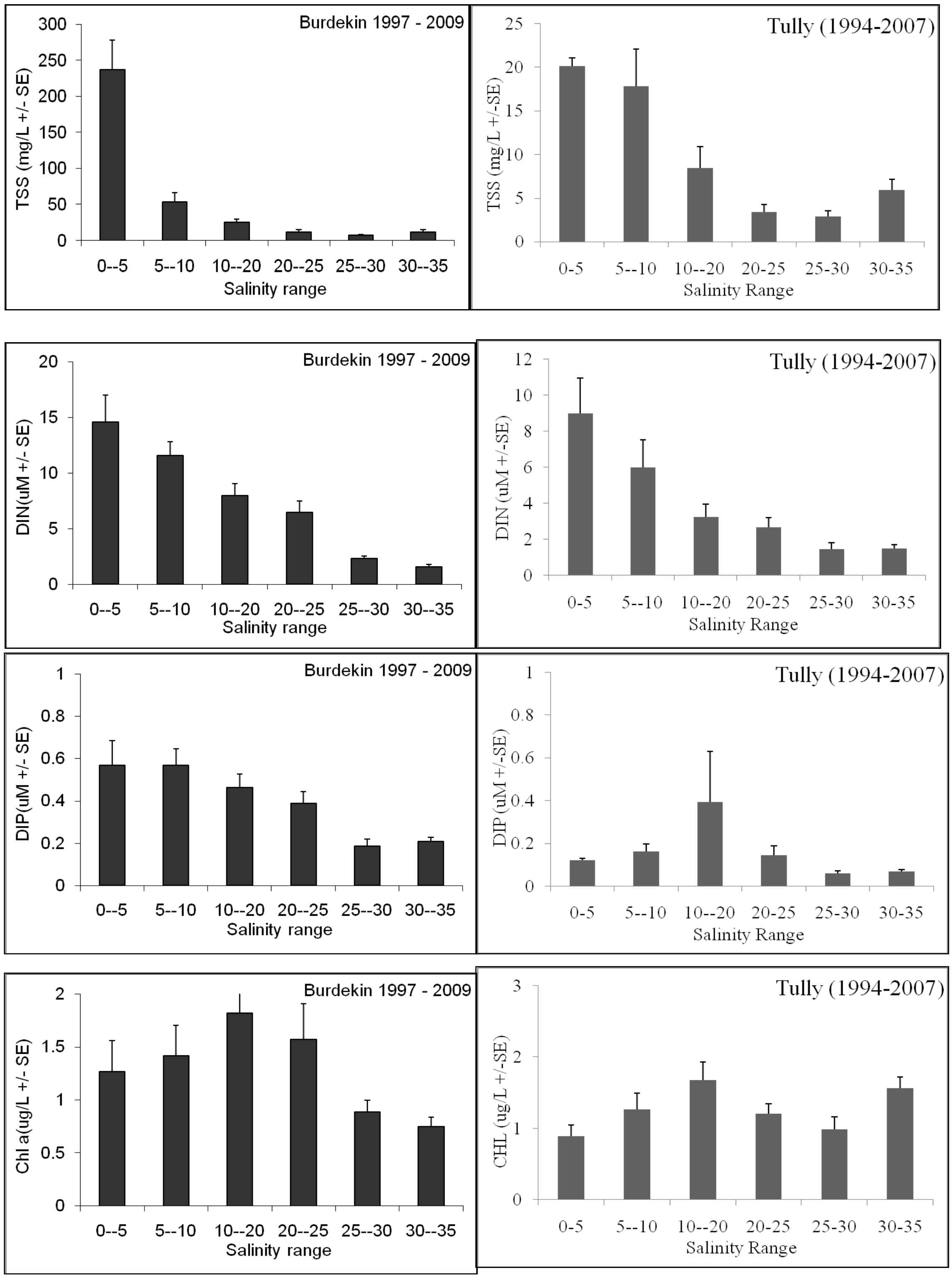


Figure 8-1: Comparison of water quality concentrations between Burdekin and Tully plume sampling for events measured between 1994 and 2009. .

9. Extent of exposure from plume waters

9.1. Background

There is evidence that land run-off can negatively affect growth and abundance of coastal and inshore seagrasses by increasing turbidity and levels of herbicides (Schaffelke et al. 2005, Waycott et al. 2005). In addition to physical disturbance, water quality is an important driver of coral reef health at local (reviewed in Fabricius 2005), regional (van Woesik et al. 1999, Fabricius et al. 2005), and a GBR-wide scales (De'ath and Fabricius 2008). The effects of various water quality constituents are manifold, ranging from disturbance by sedimentation, light reduction by increased turbidity, reduced calcification rates by excess inorganic nutrients, inhibition of photosynthesis by herbicide exposure and generally affect early life history stages more than adult corals (e.g. Fabricius 2005, Negri et al. 2005, Cantin et al. 2007). Thus the impacts of plume can be many fold in the high risk exposure area.

9.2. Tully River plume exposure (risk) area

Aerial images from 1994 – 2000 were combined with remote sensing images from 2002-2009 to describe the full extent of riverine plumes from the Tully River during eleven events and the Burdekin River during seven events.

River plumes monitored from 1994 to 2009 were mapped using aerial survey techniques. Over the monsoonal season, weather reports were monitored closely and when plumes formed, aerial surveys were conducted once or twice during the event. Plumes were readily observable as brown turbid water masses contrasting with clearer seawater. The visible edge of the plume was followed at an altitude of 1000 – 2000 metres in a light aircraft and mapped using GPS. Where individual rivers flooded simultaneously, as often happens in the Wet Tropics, adjacent plumes merge into a continuous area. In these cases efforts were made to distinguish the edge of the individual river plumes through colour differences (only during 1998 and 2000). In all other years, the extents of the combined plumes were mapped. The aerial survey results were transferred to ArcMap for subsequent spatial analysis. Flood plumes associated with Cyclone

Sadie (1994), Cyclone Violet (1995), Cyclone Ethel (1996), Cyclone Justin (1997), Cyclone Sid (1998) and Cyclone Rona (1999) were plotted.

Aerial images from 1994 – 1999 were combined with remote sensing images from 2002-2008 to describe the full extent of riverine plumes from the Tully River during eleven events over that period.

River plumes monitored from 1994 to 1999 were mapped using aerial survey techniques. Over the monsoonal season, weather reports were monitored closely and when plumes formed, aerial surveys were conducted once or twice during the event. Plumes were readily observable as brown turbid water masses contrasting with clearer seawater. The visible edge of the plume was followed at an altitude of 1000 – 2000 metres in a light aircraft and mapped using GPS. Where individual rivers flooded simultaneously, as often happens in the Wet Tropics, adjacent plumes merge into a continuous area. In these cases efforts were made to distinguish the edge of the individual river plumes through colour differences. In all other years, the extents of the combined plumes were mapped. The aerial survey results were transferred to ArcMap for subsequent spatial analysis.

Imagery was taken from available remote sensing products for the period between 2001 and 2009. Single images were selected based on their image quality and transposed from georeferenced 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 images of before, during and after each plume have been identified where there was low cloud cover and reasonably good visualization of the plume area. Water characteristics were identified in each image, with the high turbidity, high sediment plume discharging relatively close to the river mouth. Secondary plumes identified as the less turbid, higher production plumes where chlorophyll and nutrient levels are elevated. Some increase in turbidity may be present in secondary plumes as a result of the further transport of the finer particulate material and desorption processes occurring later in the salinity mixing curve. We also defined a tertiary water type as the less visible plume further offshore and north of the river mouth.

The extent of the enriched plume water is hard to define by true colour imagery, and requires the application of a suite of algorithms, including true colour processing, total absorption at 441nm as an indicator of organic material and CDOM absorption at 441 nm as an indicator of riverine extent. Application of appropriate chlorophyll algorithms can also be helpful in the offshore areas to identify the extent of the higher primary production in and after the plume intrusion.

The plume exposure map for Tully (Figure 9.1) was calculated from the intersection of the plume image and type from both the aerial surveys (1995–2000) and remote sensing images (2003-2009) for the Tully and Burdekin marine area. Thirty seven reefs and 14 seagrass beds in the Tully marine area were exposed to some degree to riverine plume waters during eleven flood events from the period from 1994 to 2007. The number of reefs and seagrasses exposed to the plume waters varies from year to year, and is dependent on the type of plume. Over the 11 years, a minimum of 11 reefs (30%) and a maximum of 37 reefs (100%) were inundated by either a primary or secondary plume indicating that it is likely that at least a third of the reefs are exposed to plume waters every year. In years with data to validate plume type (1998, 2003-2008), we estimated that 6 to 15 reefs were inundated by primary plumes carrying high sediment loads, which is up to 41% of the inshore reefs in the Tully marine area and 5 to 16 reefs (43%) were inundated by secondary plumes with elevated nutrient and chlorophyll concentrations. A smaller number of inshore reefs were inundated by a tertiary flood plume in three flood events. Note that tertiary plume extents and associated exposure of reefs may have been underestimated in the years where plume extent was estimated from aerial images only (1995-2000), based on a colour change between the fresh and marine waters. Out of the 14 seagrass beds within the Tully marine area, at least 13 were inundated by either a primary or secondary plume in 10 of the events with the exception of 2000 where only seven seagrass bed were impacted,

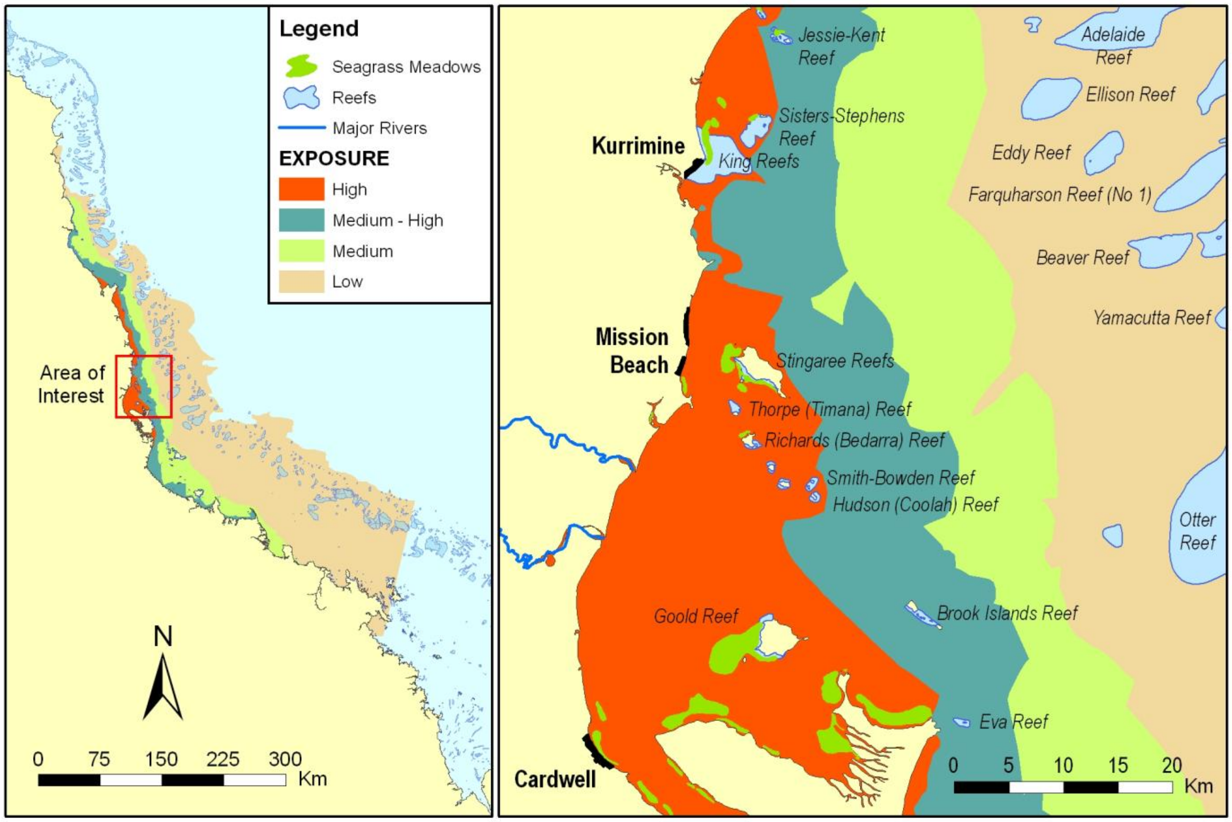


Figure 9-1: Exposure map for the Tully marine area. Image was constructed from GIS imagery of plume extents from 1994 to 2008.

9.3. Burdekin River plume exposure (risk) area

The plume exposure map for Burdekin (Figure 9.2) was calculated from the intersection of the plume image and type from both the aerial surveys (1996 - 1999) and remote sensing images (2002-2009) for the Burdekin marine area. The number of reefs and seagrasses exposed to the plume waters varies from year to year, and is dependent on the type of plume. The primary extent of the Burdekin plume, defined by higher sediment carrying waters, is shown to regularly move past Cape Upstart. High exposure areas are identified between Cape Upstart and moving beyond Townsville is most likely to be influenced by the smaller rivers between the Burdekin and Cleveland Bay. Medium to high exposure areas are identified offshore of the Burdekin

Rivers moving past Magnetic Island. Medium to low exposure areas are identified all the way past the Palms Island group and moving towards the offshore reefs.

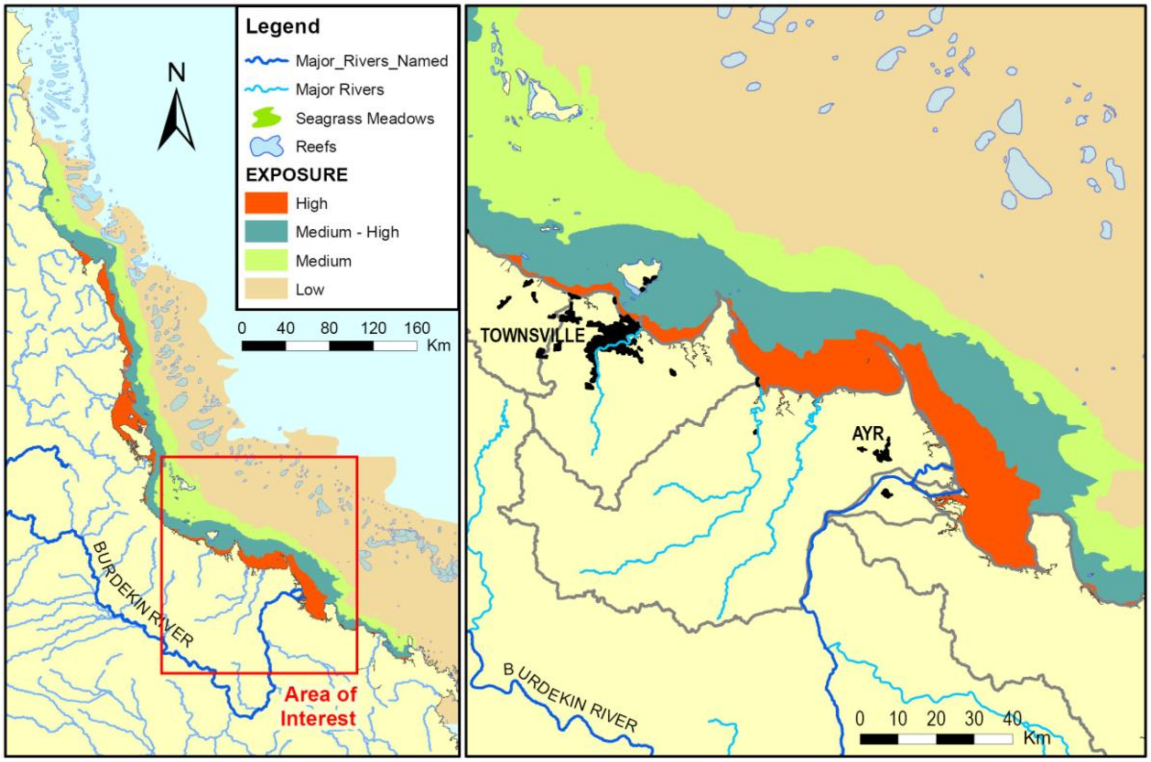


Figure 9-2: Exposure map for the Burdekin marine area. Image was constructed from aerial survey techniques (1991 – 2001) and remote sensing techniques (2002 to 2009).

10. Conclusions

Heavy and persistent flooding occurred in many rivers draining into the Great Barrier Reef over January to March 2009. This report presents the outcomes of water quality measurements and mapping of the riverine plumes from the Burdekin and Tully 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 Burdekin and Tully 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.

Work over the last two years in the MMP plume program 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 characterized 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).

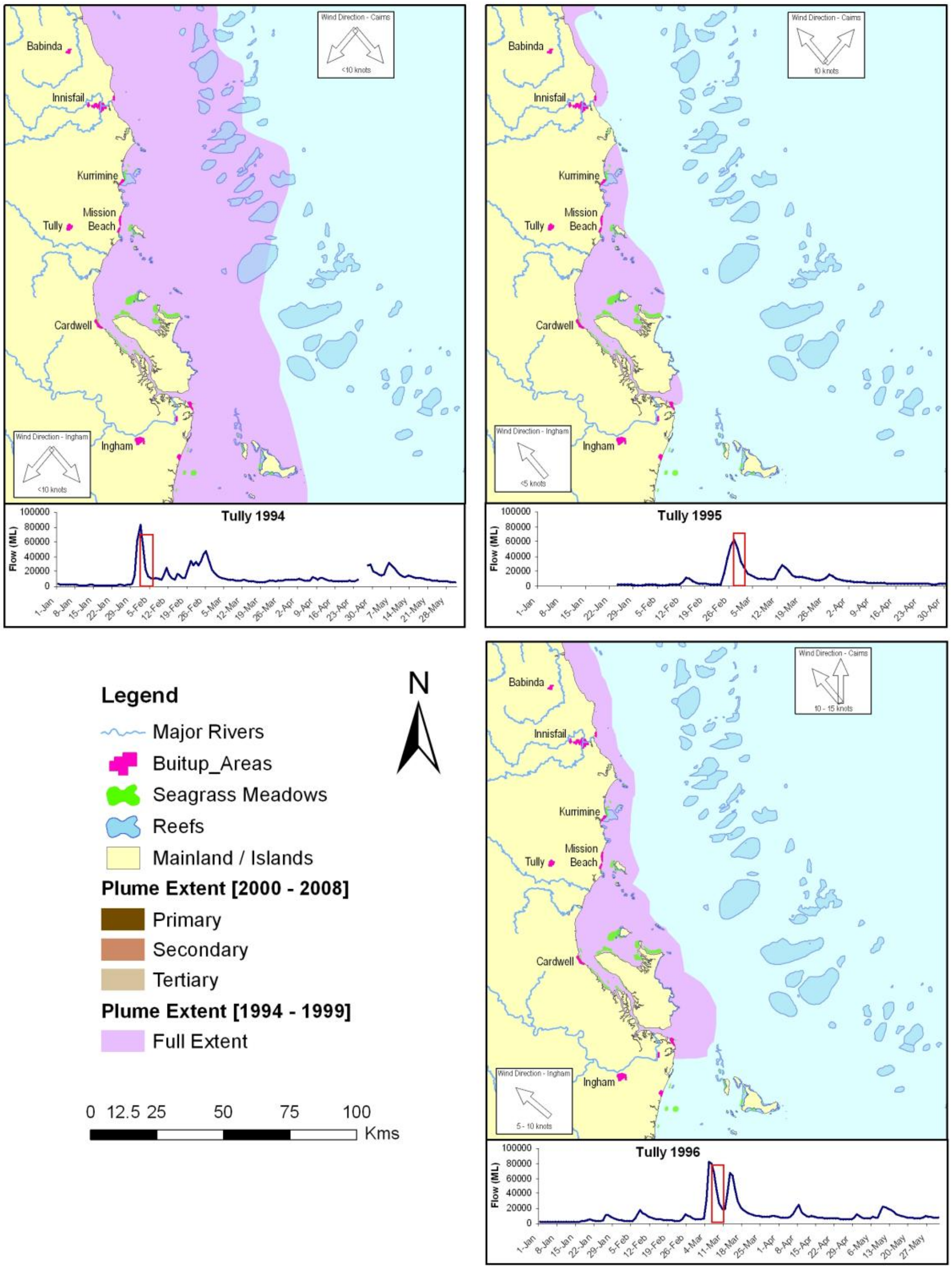
As the river waters move beyond the river mouth, the heavier clay material drops out, but the finer particulate matter can still move kilometers offshore, as can be seen in the elevated concentrations of suspended solids in the later stages of Tully plume waters. Generally there is enough reduction in 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 characterized 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.

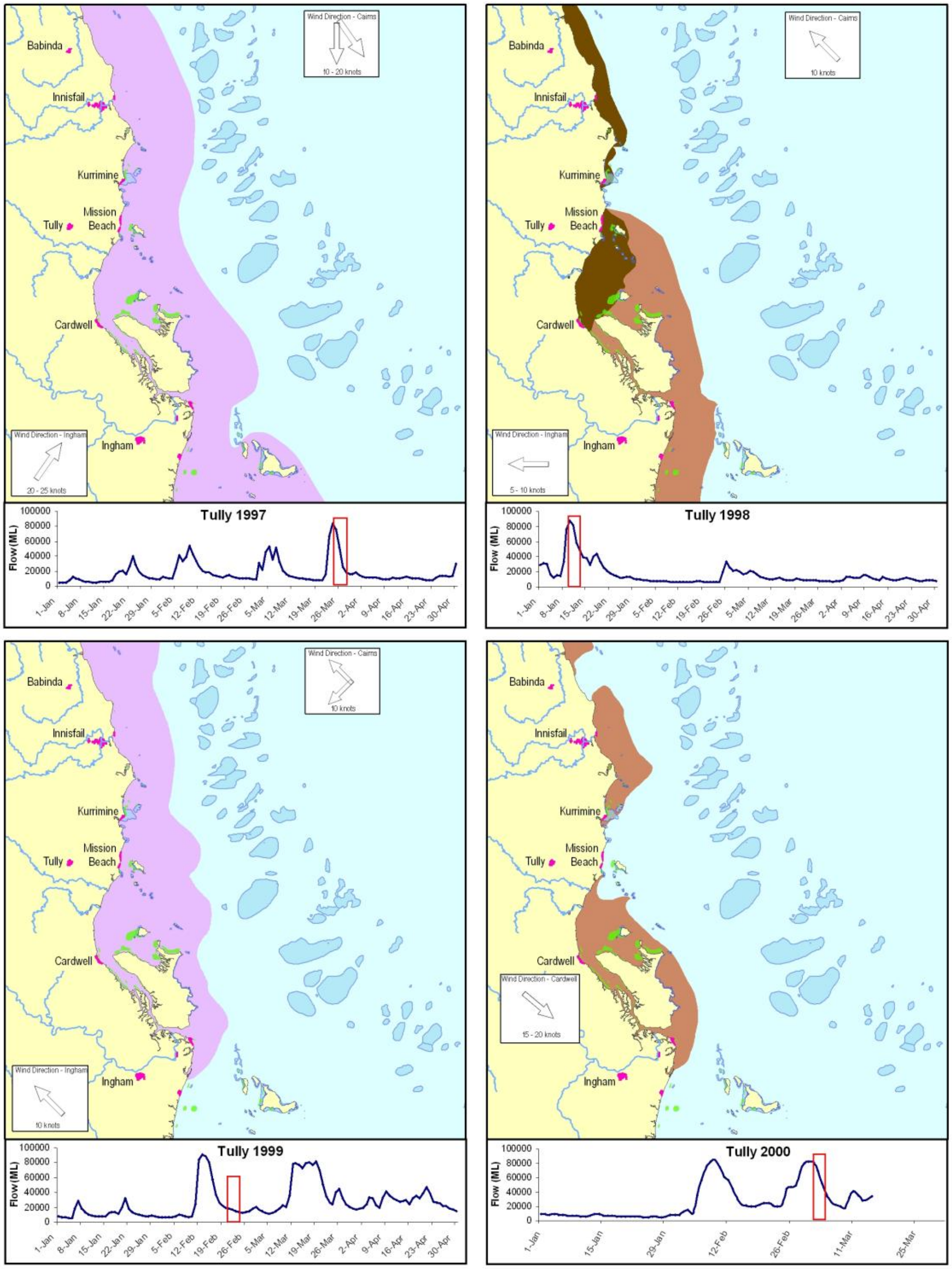
This type of work illustrates how remote sensing products can be utilised to describe and define areas of risk in the Great Barrier Reef. The effects of excess nutrients and sediments in the marine environment are being increasingly understood (e.g. De'ath and Fabricius 2008). However, less well known 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 e.g., 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.

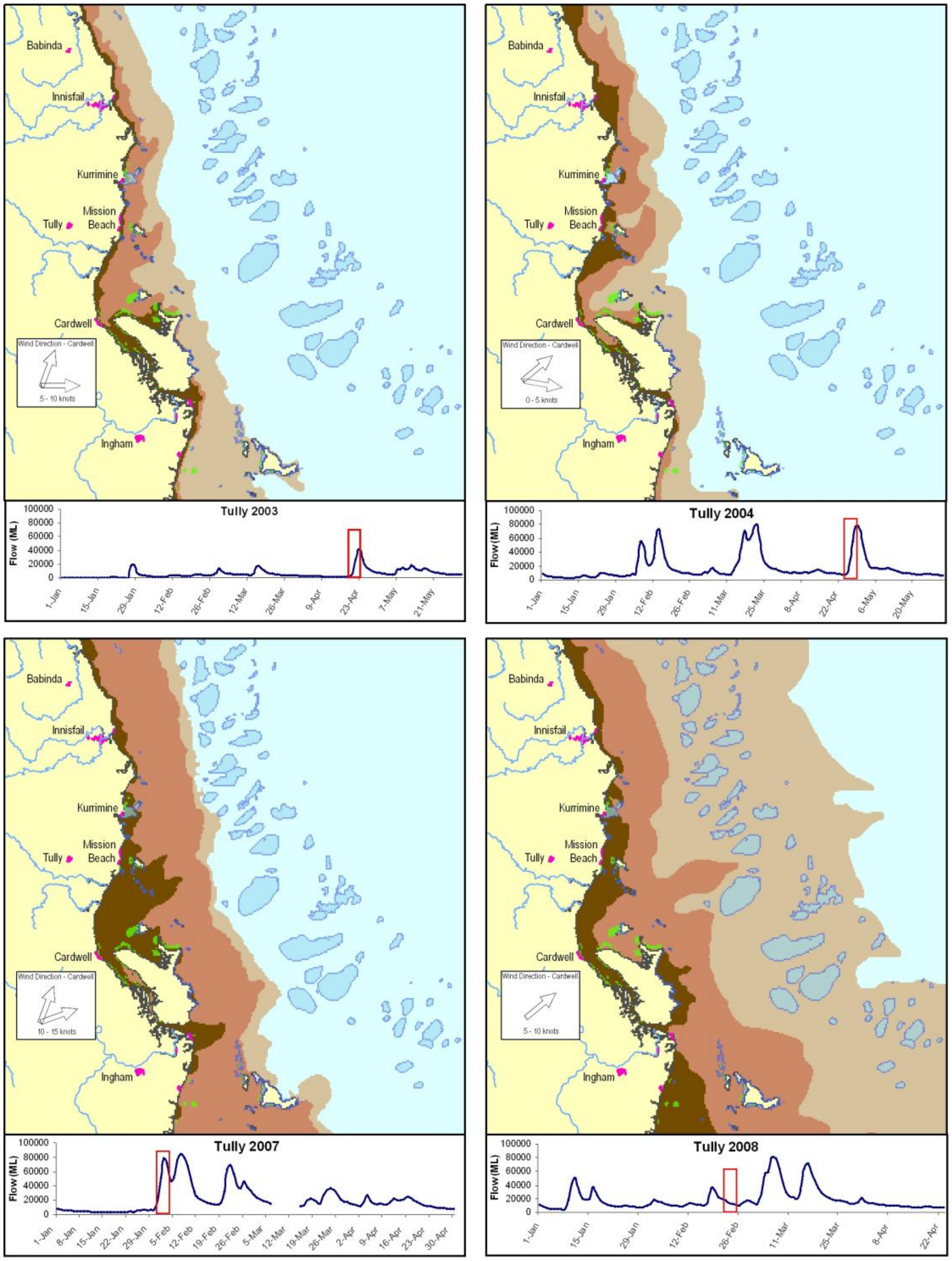
11. Appendices

Tully plume extents for 1994 to 2009



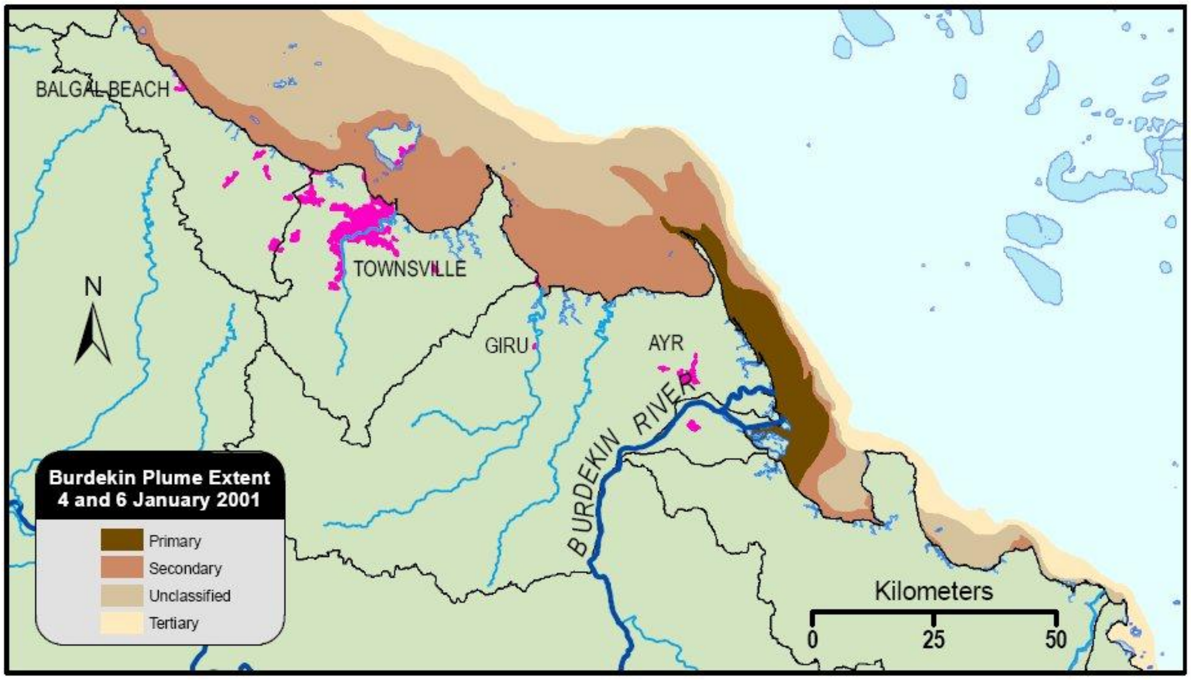


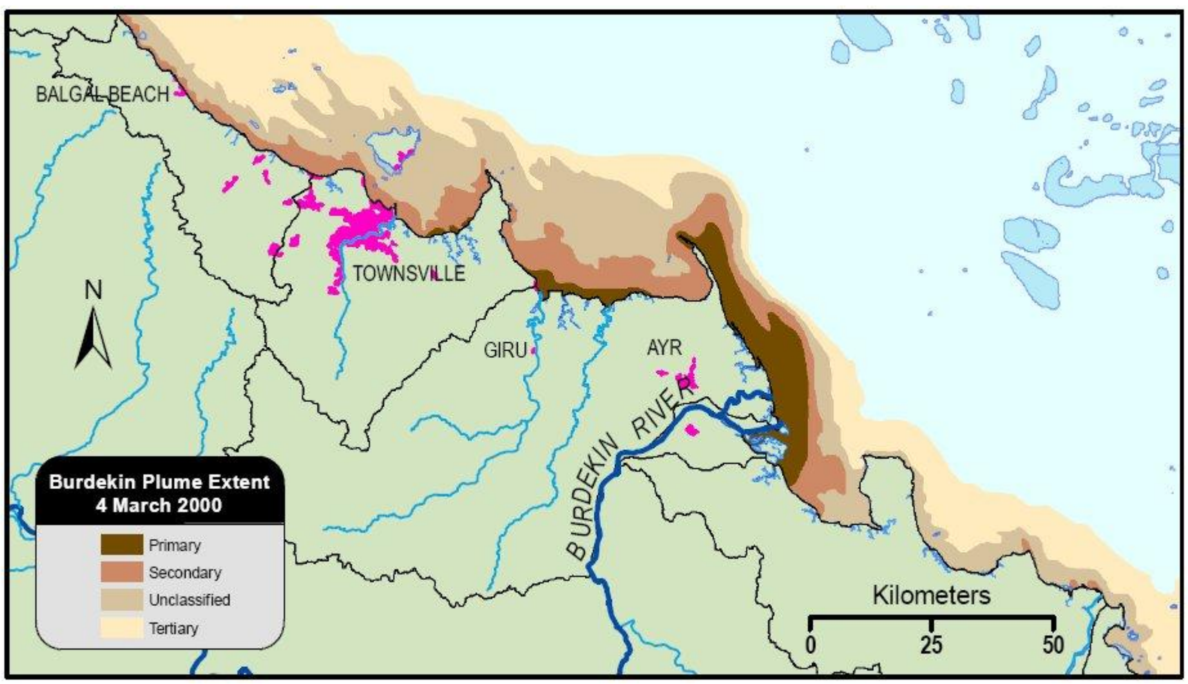
Babinda
Innisfail
Kurrimine
Mission Beach
Tully
Cardwell
Ingham
Wind Direction - Cairns
10 - 20 knots
Wind Direction - Ingham
20 - 25 knots
Tully 1997
Wind Direction - Cairns
10 knots
Wind Direction - Ingham
5 - 10 knots
Tully 1998
Wind Direction - Cairns
10 knots
Wind Direction - Ingham
10 knots
Tully 1999
Wind Direction - Cardwell
15 - 20 knots
Tully 2000
Flow (ML)

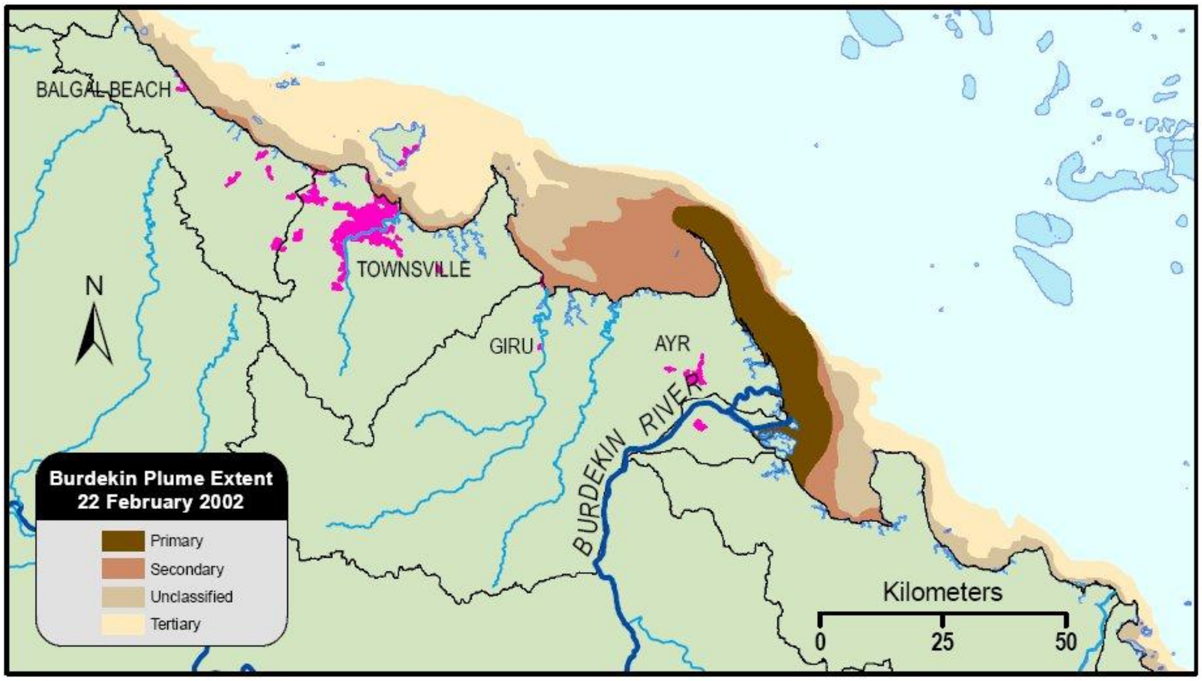


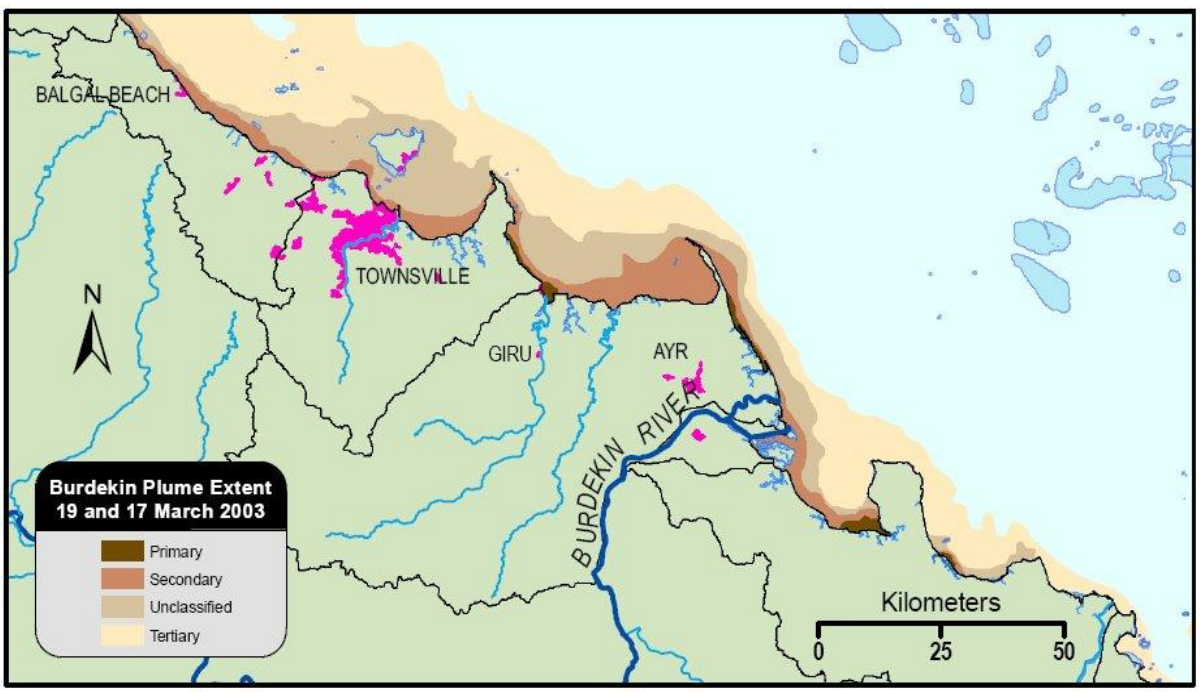
Babinda
Innisfail
Kurrimine
Mission Beach
Tully
Cardwell
Ingham
Wind Direction - Cardwell
5 - 10 knots
Tully 2003
Flow (ML)
100000
80000
60000
40000
20000
0
1-Jan 15-Jan 29-Jan 12-Feb 26-Feb 12-Mar 26-Mar 9-Apr 23-Apr 7-May 21-May
Wind Direction - Cardwell
0 - 5 knots
Tully 2004
1-Jan 15-Jan 29-Jan 12-Feb 26-Feb 11-Mar 25-Mar 8-Apr 22-Apr 6-May 20-May
Wind Direction - Cardwell
10 - 15 knots
Tully 2007
1-Jan 8-Jan 15-Jan 22-Jan 29-Jan 5-Feb 12-Feb 19-Feb 26-Feb 5-Mar 12-Mar 19-Mar 26-Mar 2-Apr 9-Apr 16-Apr 23-Apr 30-Apr
Wind Direction - Cardwell
5 - 10 knots
Tully 2008
1-Jan 15-Jan 29-Jan 12-Feb 26-Feb 11-Mar 25-Mar 8-Apr 22-Apr

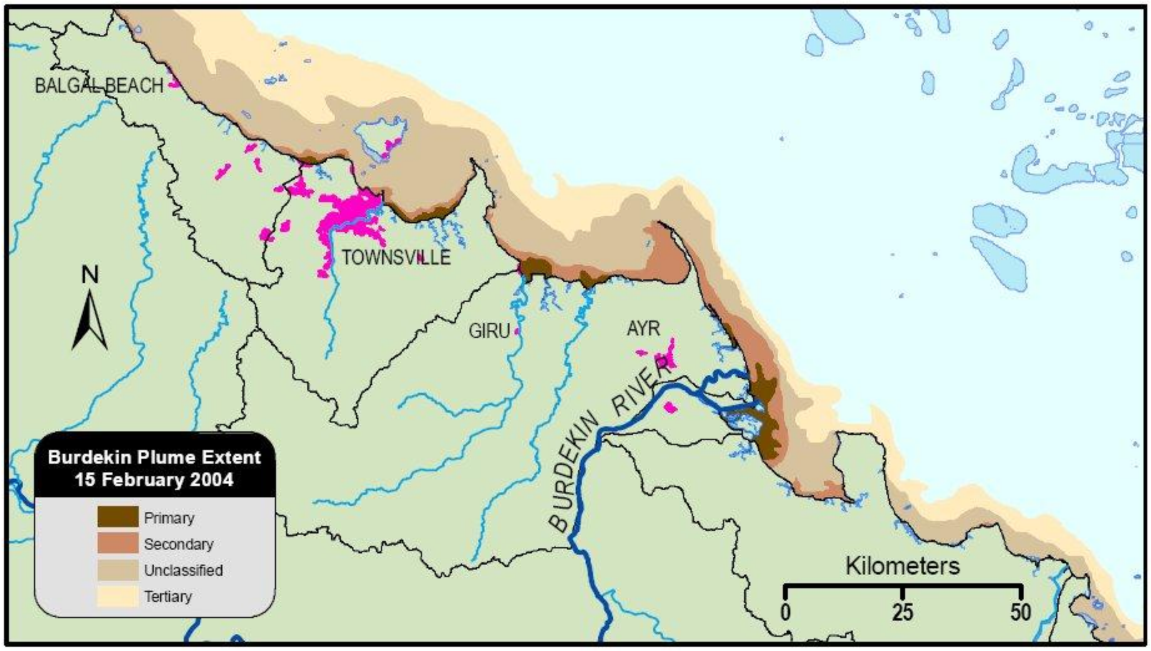
Burdekin plume extents for 1994 to 2008

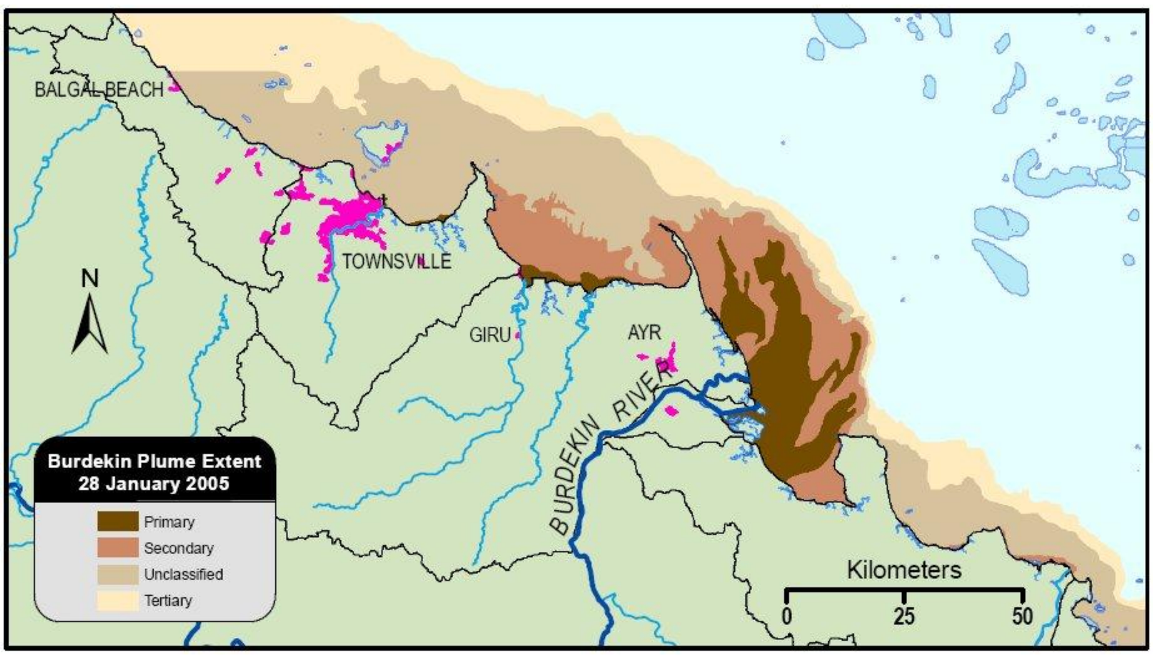


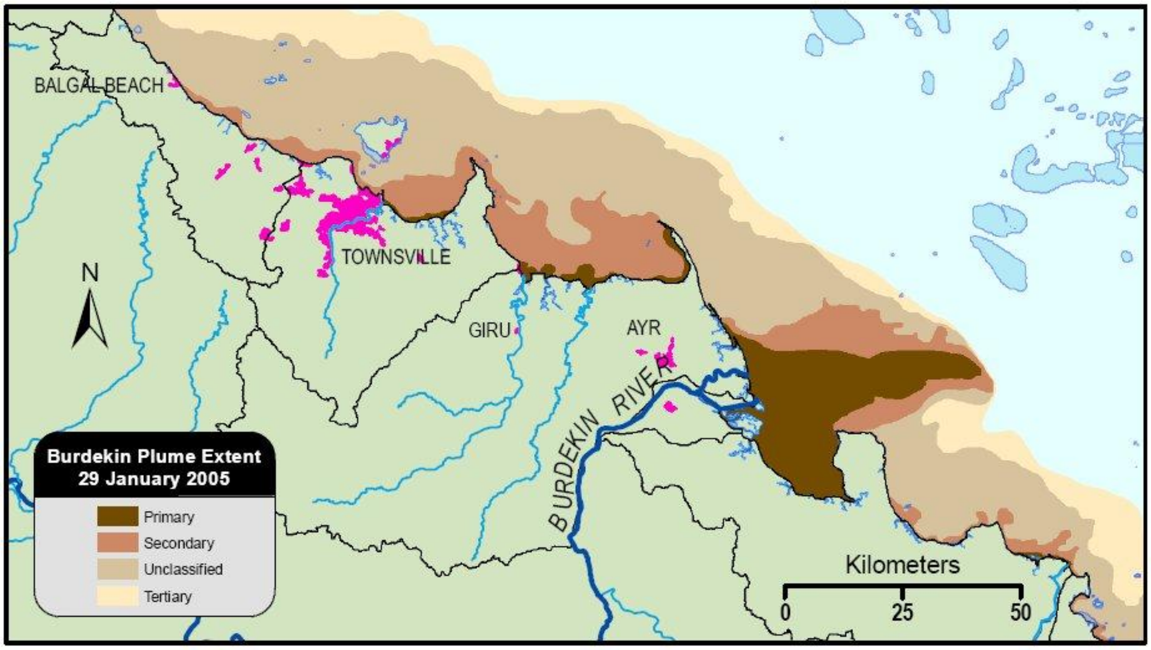


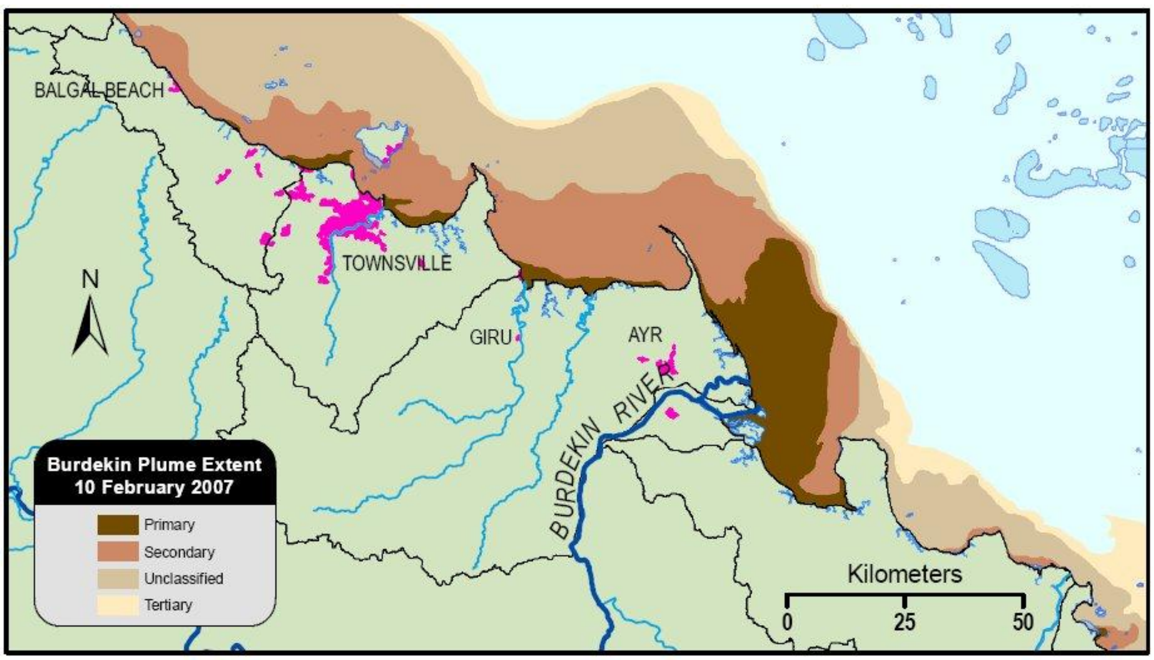

BALGAL BEACH
TOWNSVILLE
GIRU
AYR
BURDEKIN RIVER
N
Burdekin Plume Extent
22 February 2002
Primary
Secondary
Unclassified
Tertiary
Kilometers
0
25
50

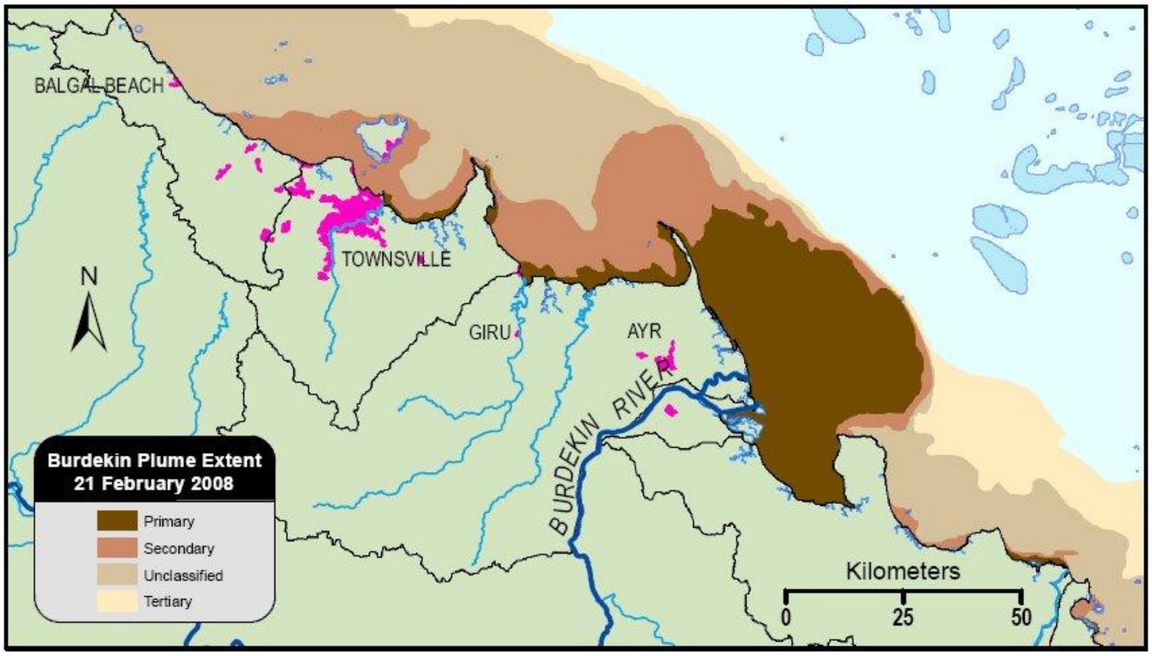

BALGAL BEACH
TOWNSVILLE
GIRU
AYR
BURDEKIN RIVER
N
Burdekin Plume Extent
19 and 17 March 2003
Primary
Secondary
Unclassified
Tertiary
Kilometers
0
25
50

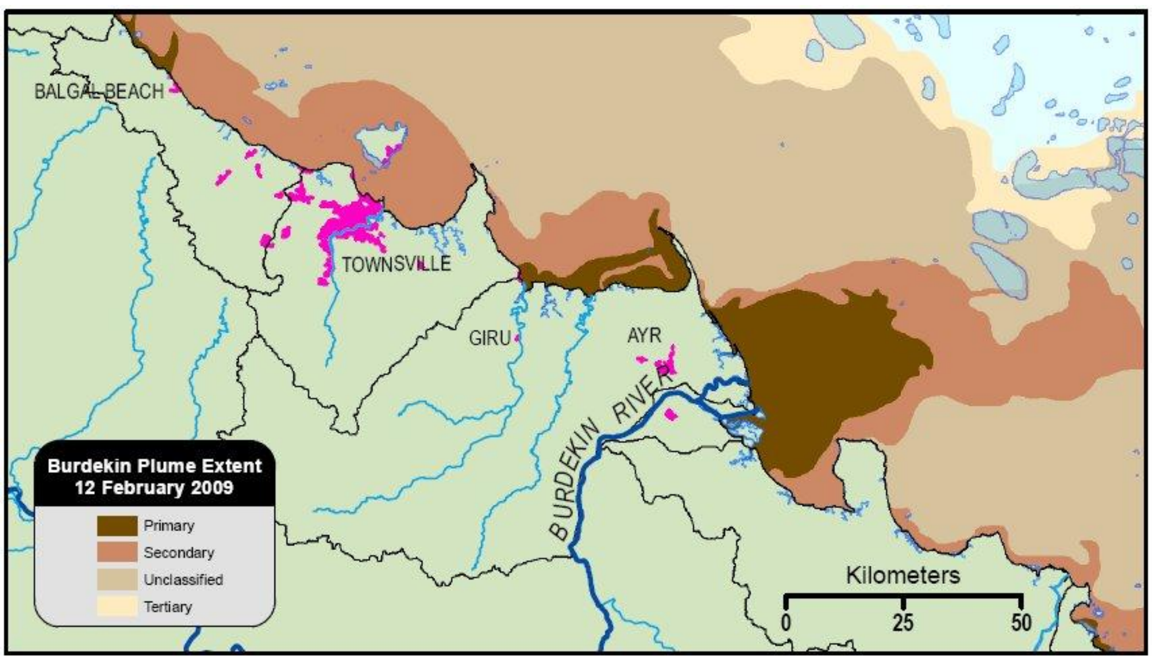

BALGAL BEACH
TOWNSVILLE
GIRU
AYR
BURDEKIN RIVER
N
Burdekin Plume Extent
15 February 2004
Primary
Secondary
Unclassified
Tertiary
Kilometers
0
25
50

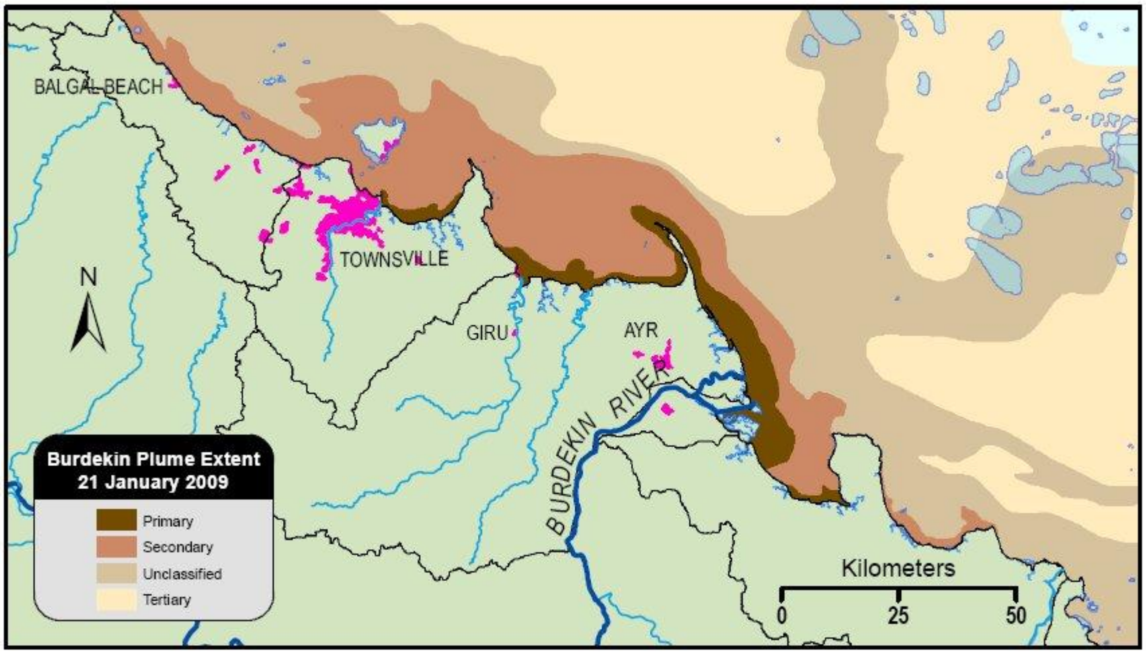

BALGAL BEACH
TOWNSVILLE
GIRU
AYR
BURDEKIN RIVER
N
Burdekin Plume Extent
28 January 2005
Primary
Secondary
Unclassified
Tertiary
Kilometers
0
25
50


BALGAL BEACH
TOWNSVILLE
GIRU
AYR
BURDEKIN RIVER
N
Burdekin Plume Extent
29 January 2005
Primary
Secondary
Unclassified
Tertiary
Kilometers
0
25
50


BALGAL BEACH
TOWNSVILLE
GIRU
AYR
BURDEKIN RIVER
N
Burdekin Plume Extent
10 February 2007
Primary
Secondary
Unclassified
Tertiary
Kilometers
0
25
50


BALGAL BEACH
TOWNSVILLE
N
GIRU
AYR
BURDEKIN RIVER
Burdekin Plume Extent
21 February 2008
Primary
Secondary
Unclassified
Tertiary
Kilometers
0
25
50


BALGAL BEACH
TOWNSVILLE
GIRU
AYR
BURDEKIN RIVER
Burdekin Plume Extent
12 February 2009
Primary
Secondary
Unclassified
Tertiary
Kilometers
0
25
50


BALGAL BEACH
TOWNSVILLE
GIRU
AYR
BURDEKIN RIVER
N
Burdekin Plume Extent
21 January 2009
Primary
Secondary
Unclassified
Tertiary
Kilometers
0
25
50

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