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Assessment of the relative risk of degraded water quality to ecosystems of the eastern Cape York NRM Region, Great Barrier Reef

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A Report for South Cape York Catchments as part of the Cape York Water Quality Improvement Plan projects

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Disclaimers

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Executive Summary

A risk assessment method was developed and applied to the eastern catchments of the Cape York Natural Resource Management (NRM) region in the Great Barrier Reef (GBR) to provide robust and scientifically defensible information for catchment managers on the key land-based pollutants of greatest risk to the health of the two main GBR ecosystems (coral reefs and seagrass beds) in the region.

The main water quality pollutants of concern for the whole GBR are enhanced levels of suspended sediments, excess nutrients and pesticides (predominantly photosystem II inhibiting herbicides) added to the GBR lagoon from the adjacent catchments. Until recently, there has been insufficient knowledge about the relative exposure to and effects of these pollutants to guide effective prioritisation of the management of their sources. This assessment has attempted to utilise the best available information to assess the priority pollutants and the differences between the eastern Cape York region in influencing GBR ecosystems.

The relative risk of degraded water quality among the basins in the Cape York region was determined by combining information on the estimated ecological risk of water quality to coral reefs and seagrass meadows in the region with end-of-catchment pollutant loads. The framework was developed from the approach used in the GBR wide relative risk assessment conducted by Brodie et al. (2013a) to inform Reef Plan 2013 priorities, and modified where necessary to reflect issues and data availability in the eastern Cape York region. There are also several improvements to the input data in this assessment including revision of the remote sensing data for water quality parameters, and incorporation of new plume loading and pollutant load data.

Ecological risk is generally defined as the product of the *likelihood* of an effect occurring and the *consequences* if that effect was to occur. However, in this assessment there is some inconsistency in our capacity across the variables to produce a true likelihood or true consequence estimate as mostly we have no or limited ability to produce these estimates right now. Therefore, ecological risk in the GBR is expressed simply as the area of coral reefs and seagrass meadows within a range of assessment classes (very low to very high relative risk) for several water quality variables in river Zone of Influence in the GBR lagoon. Our method for calculating risk essentially assesses the likelihood of exceedance of a selected threshold. This likelihood was set as 1 for a parameter and location if observations or modelled data indicate that the threshold was exceeded. Conversely, the likelihood was set as 0 if observations or modelled data indicate that the threshold was not exceeded. As consequences are mostly unknown at a regional or species level, potential impact was calculated as the area of coral reef, seagrass meadows and area of GBR lagoon waters (in km^2) within the highest assessment classes of the water quality variables (reflecting the highest severity of influence). The effects of multiplying the habitat area by 1 or 0 for the likelihood mean that the final assessment of risk in this assessment is only an indication of potential impact - the area of coral reef and seagrass meadows in which exceedance of an agreed threshold was modeled or observed. Furthermore, the assessment does not take into account the current condition of the systems which would affect the degree of impact on the ecosystem, i.e. the impacts of poor water quality on coral reef or seagrass in good condition is likely to be more significant than the impacts on degraded systems. This becomes an assessment of 'relative risk' by comparing the areas of each habitat affected by the highest assessment classes of the variables among river 'Zones of Influence' in the Cape York region (where available), and was used to generate a 'Marine Risk Index' for coral reefs and seagrass meadows. The Zones of Influence are defined to represent the maximum extent of the wet season river plumes across a number of years.

For assessment of the marine risk, a suite of water quality variables was chosen that represent the pollutants of greatest concern with regards to land-sourced pollutants and potential impacts on coral reef and seagrass ecosystems. These include exceedance of ecologically-relevant thresholds for concentrations of total suspended sediments (TSS) from remote sensing data, chlorophyll *a* (Chl-a) obtained from long term in-situ monitoring data, and the distribution of key pollutants including TSS, dissolved inorganic nitrogen (DIN), particulate nitrogen (PN) and photosystem II-inhibiting herbicides (PSII herbicides) in the marine environment during flood conditions (based on end-of-catchment loads and plume loading estimates). A factor that represents the direct influence of Crown of Thorns Starfish (COTS) on coral reefs in the COTS Initiation Zone was included in previous assessments but has been revised for inclusion in this way and accounted for in the discussion. Modelled end-of-catchment pollutant loads (generated from the Source Catchments model framework for the Paddock to Reef Program) were obtained for each basin for key pollutants (TSS, DIN, PSII herbicides, PN, Dissolved Inorganic Phosphorus and Particulate Phosphorus), and only the anthropogenic portions of regional total pollutant loads were considered in relating the relative risk to the basins. Given the low use of PSII herbicides in the region and limited detection in the marine environment, PSII herbicides were not included in the final assessment. The anthropogenic load is calculated as the difference between the long term average annual load, and the estimated pre-European annual load. A factor representing the differential influence of river discharges on the COTS Initiation Zone was also considered in other assessments and is only included qualitatively as the data is only available for the Normanby River. The influence of McIvor, Endeavour and Annan Rivers on the COTS initiation zone was not assessed but should be part of future risk assessments, because these rivers have the potential to discharge directly into the initiation zone.

It should be noted that the previous GBR risk assessments also incorporated parameters to represent assessment of the exceedance of ecologically-relevant thresholds for concentrations of chlorophyll *a* (Chl-a) and TSS. However, this data was obtained from remote sensing analysis and a recent study undertaken as part of the improvements to the risk assessment method has indicated that there is low confidence in the results in some locations (refer to Maynard et al. 2015 and Petus et al. 2015). More detail analysis of the relationship between Chl-a satellite results and in-situ data in the coastal zone has revealed significant uncertainties in some locations. Until these aspects are resolved further, the Chl-a data has been excluded from this analysis. Instead, results from in-situ chlorophyll monitoring have been included as a measure of long term water quality conditions (sourced from De'ath and Fabricius, 2008). The TSS sourced from remote sensing analysis is still included as we did not have the resources to fully investigate the reliability of this dataset. The information was then combined to make conclusions about the relative risk of degraded water quality to coral reefs and seagrass meadows among the basins in the eastern Cape York region. Final conclusions were also supported by additional information including loads by land use, current condition of the receiving ecosystems and specific research findings related to material transport.

The eastern Cape York marine region has been divided into 3 sub regions to group management priorities in the assessment: *North* which 'links to' the Jacky Jacky, Olive, Pascoe and Lockhart Basins; *Central* which links to the Stewart, Hann and Normanby catchments and *South* which links to the Jeannie and Endeavour Basins.

The key results are summarised below.

Marine risk

In the combined assessment of the relative risk of marine water quality variables, it is notable that there are no areas in the Very High relative risk assessment class in the region (Figure i(a)), in contrast to other NRM regions where large proportions of the inshore areas are in the highest risk classes (Figure i(b)). The condition of the coral reef and seagrass systems also varies with the Cape York systems typically in good or very good condition compared to southern regions, where many are in poor condition (refer Coppo et al. 2015). This is likely to make the Cape York systems more resilient to any increased threats. A majority of the region is within in Very Low assessment class (87% of the area) which extends out to the Marine Park boundary, containing 84% of the coral reefs, 51% of the surveyed seagrass and 70% of the deepwater modelled seagrass in the region. The Low relative risk class extends to the offshore waterbodies in the central part of the region and contains 15% of the coral reefs and ~30% of the surveyed and deepwater modelled seagrass. The greatest area of influence from degraded water quality is in Princess Charlotte Bay where High relative risk assessment classes extend to the midshelf waterbodies of the Bay. The total area of the High relative risk class (717km^2; <1% of the region's area) contains ~6% of the region's surveyed seagrass and <1% of coral reefs and deepwater modelled seagrass. The Moderate relative risk class extends to the outer parts of Princess Charlotte Bay and in some coastal areas northward to the Lockhart River mouth. It contains approximately 14% of the region's surveyed seagrass. The relative risk to the inshore reefs and seagrass meadows in the South sub-region, particularly near the Endeavour and Annan Rivers, may be underestimated due to lack of available data in this region.

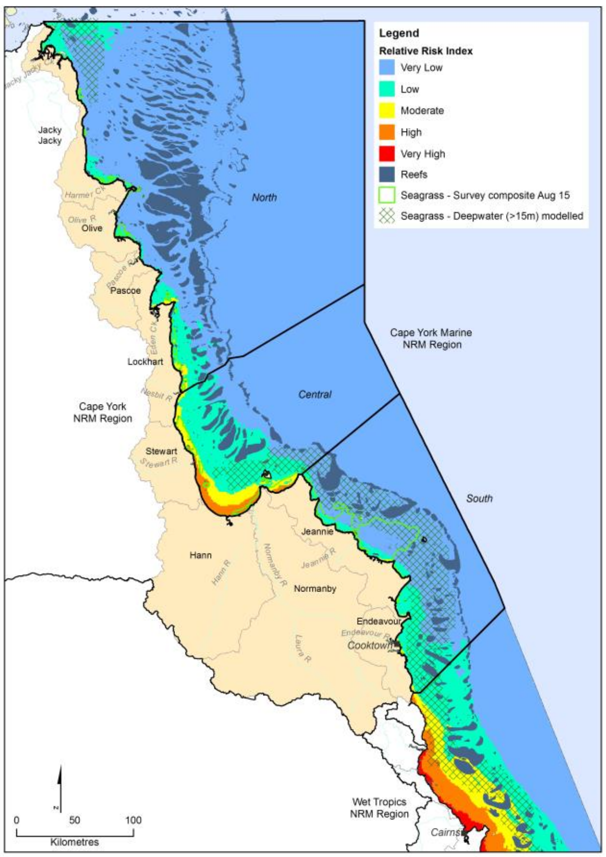

Figure i(a). **Results of the combined assessment of the relative risk of water quality variables in the Cape York region. Much of this influence is driven by total suspended sediment (see text for explanation).**

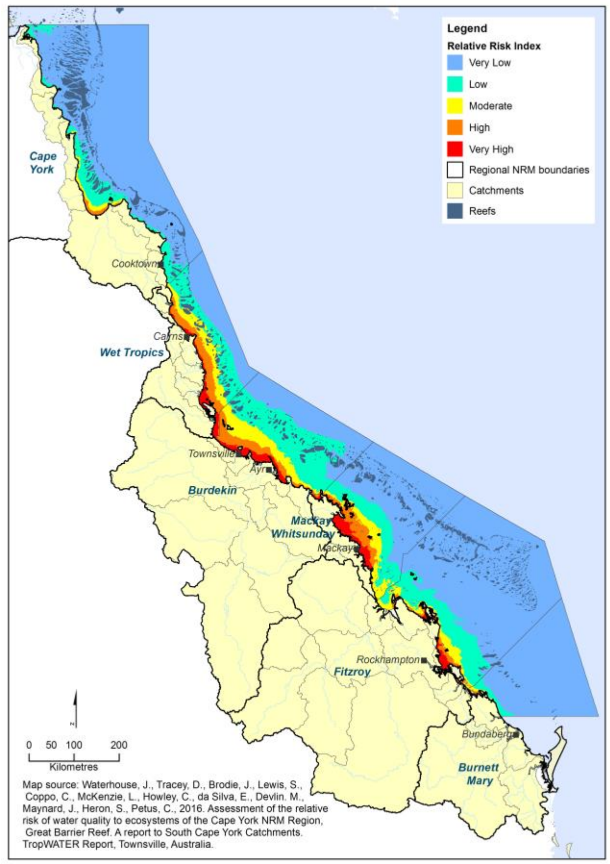

Figure i(b). Results of the combined assessment of the relative risk of water quality variables in the GBR.

Modelling of river plumes in the region between 2009 and 2013, and definition of 'Zones of Influence' for river plume waters in the wet season indicates that the Normanby River dominates the water quality influence in the region. The Zone of Influence extended as far north as Cape Grenville during the 2010-11 wet season, although the southern extent of the estimated Zones of Influence were still within Cape Melville, reflecting the northward movement of the plumes and the role of Cape Melville in steering water inside Princess Charlotte Bay. Additional studies have also shown that while the plumes typically move in a northerly direction driven by south easterly winds, there are conditions when the plumes are deflected outwards in an easterly direction (Petus et al. unpublished). The estimated Zones of Influence from the Stewart, Hann and Normanby River all overlap to some extent in Princess Charlotte Bay which contains notable areas of surveyed potential seagrass habitat and deepwater modelled seagrass. It should be noted that the modelled Zones of Influence for the Endeavour River typically extend north to Cape Flattery and as far south as the southern NRM boundary. This area contains the largest area of surveyed potential seagrass habitat and deepwater modelled seagrass than any other river Zone of Influence. Zones of Influence for rivers in the Jeannie Basin, which discharge onto the largest area of coastal seagrass meadows, were not mapped due to lack of recent discharge data.

Results of the relative risk assessment for important habitat features the eastern Cape York region are summarised in Table (i)Table . This highlights that many of the ecosystems in the region are still considered to be in good condition and are at relatively low risk from water quality influence. Importantly, in the northern rivers where there is limited development in the catchments, the water quality conditions are driven by natural conditions such as ocean upwelling of nutrients in the far northern section, and natural turbidity in shallow coastal waters. As a way of linking these results to catchment water quality influences, modelled end-of-catchment pollutant loads (generated from the Source Catchments model framework for the Paddock to Reef Program) were obtained for each basin for key pollutants (TSS, DIN, PSII herbicides, PN, Dissolved Inorganic Phosphorus and Particulate Phosphorus), and only the anthropogenic portions of regional total pollutant loads were considered in relating the relative risk to the basins. The 'anthropogenic' load is calculated as the difference between the long term average annual load, and the estimated pre-European annual load. In addition, the input variables represent longer term time series, and in most cases, represent average conditions.

Table (i). Results of the relative risk assessment for important habitat features in the East Cape York Region.

Sub-region	Habitat Feature	Description	Relative risk results	Likely rivers of influence
North	*Escape River and Kennedy Inlet River system*	FHA; WNI; the most extensive stand of medium-tall mangroves in Queensland	Very Low / Low	Limited
	Margaret Bay, Lloyd Bay and Cape Grenville area	FHA; WNI; outstanding seagrass beds (size and diversity); important dugong habitat; significant wetlands for wading birds	Very Low / Low	Limited
	Raine Island	Largest known green turtle rookery; most significant seabird rookery in the GBRWHA; National Park	Very Low	Limited
	Temple Bay	FHA; WNI	Very Low / Low	Olive, Pascoe
	Weymouth Bay	High seagrass diversity	Very Low / Low	Olive, Pascoe
	Olive River	WNI	Very Low / Low	Olive
	Cape Direction	High seagrass diversity	Low	Lockhart
Central	*Silver Plains*	FHA; important hawksbill turtle habitat	Low	Stewart
	Princess Charlotte Bay	FHA; WNI; one of largest tidal wetland areas in Australia; high seagrass diversity; important turtle and dugong foraging areas	Moderate / High	Normanby, Hann, Stewart
	Marina Plains – Lakefield Aggregation	WNI; >100 permanent riverine lagoons	Moderate / High	Limited
	Clack Reef Complex	WNI; small continental island with fringing reef and seagrass	Low	Normanby
	Flinders Island	Inner shelf high continental	Low / Moderate	Normanby

Sub-region	Habitat Feature	Description	Relative risk results	Likely rivers of influence
	Group	islands with fringing reef and seagrass		
South	*Bay Creek, Cape Melville – Bathurst Bay*	WNI; Amongst best representative mangroves on Cape York	Very Low / Low	Limited
	Lizard Island	Unique granitic high continental island surrounded by fringing reefs and a lagoonal system	Very Low	Limited
	Starcke River	FHA; one of the most varied Cape York coastlines; extensive coastal seagrass meadows; important indigenous turtle and dugong hunting grounds	Very Low / Low	Limited
	Howick Island Group	Inner shelf high continental islands with fringing reef and seagrass; significant turtle nesting areas	Very Low	Limited
	Cape Flattery Dune Lakes wetland	WNI; in largest dune field (international significance) on the east coast, north of Fraser Island	Very Low / Low	Endeavour
	Barrow Point - Cedar Bay	High seagrass diversity	Low	Endeavour, Annan
	Annan River	FHA	Low	Endeavour, Annan

Note: FHA - Fish Habitat Area; WNI – Wetland of National Importance

End-of-catchment loads

An assessment of end-of-catchment loads provides a link between the marine risk and land based pollutant delivery. The anthropogenic load was incorporated as a proportion of the total regional load, as it is only the anthropogenic portion that is assumed to be the 'manageable' component of pollutant loads. The assessment of end-of-catchment pollutant loads (Section 3.4) showed that the Normanby catchment dominates the contributions to the regional anthropogenic loads for all parameters. The relative contribution from each of the other catchments is 30% (Olive catchment) or less of the loads delivered by the Normanby catchment to the Regions' anthropogenic load. As a result, the Central sub-region dominates the combined anthropogenic load contributions, and there are limited differences between the North and South sub-regions, especially when taking into consideration the areas of the catchments represented in each sub-region (the South sub-region is much smaller than the North sub-region).

The assessment also highlights that the anthropogenic loads of dissolved inorganic nutrients (DIN and DIP) only represent a small proportion of the total loads (3% and 15% respectively), indicating that much of the dissolved nutrients in the marine assessment are not likely to be derived from human-induced sources. However an assessment of the contribution of accelerated gully erosion to dissolved inorganic nutrient loads may increase this proportion of anthropogenic loads. In contrast to nutrients, it is estimated that about half of the regional TSS load, and up to half of the particulate nutrient loads are from human-induced sources (McCloskey et al. in review).

Recent studies that predict the contribution of river discharge to the COTS Initiation Zone have shown that the Normanby River has limited influence on this process (Brinkman et al. 2014). However, specific analysis of satellite imagery (Petus and da Silva unpublished) highlighted that the Normanby, Hann / Kennedy, Marrett and Bizant Rivers produce river plumes which can merge into a significant single plume and that under northwesterly wind conditions, river plumes are deflected toward the east and potentially south. These rivers, and those from the Endeavour and Jeannie Basins, must be taken into account when evaluating contributions to the COTS Initiation Zone from the Cape York rivers in future assessments, and also to secondary outbreaks in the marine areas to the north of Lizard Island.

Combined assessment of the relative risk of degraded water quality in the Cape York region to guide management priorities

Using the information obtained through the above analyses for the marine water quality variables and end of basin pollutant loads, a quantitative combined assessment was completed to inform water quality management priorities among the basins in the eastern Cape York region. This information should be treated as a relative assessment and used to guide management decisions in conjunction with additional qualitative information, some of which is presented in Section 4 of this report, as there is a high degree of uncertainty in some of the modelling data (see section 3.5).

From these findings, it can be concluded that the greatest risk posed to coral reefs and seagrass from degraded water quality in the Cape York region is from the Normanby catchment, followed by the Hann and Stewart catchments, indicating a need to focus catchment management in the Central sub-region. Further analysis of the sediment related parameters shows that almost 15% of the seagrass in the region is in the Moderate relative risk class, with large areas of deepwater modelled seagrass in Princess Charlotte Bay and around the Cooktown coastal areas, although these southern areas are also likely to be influenced by the northern movement of the Wet Tropics River plumes.

It is recognised that there are many uncertainties associated with the input datasets and method for combining these Indexes at a basin scale at this time (see Section 5); further discussion is recommended prior to making any management decisions based on these results.

Other factors

Further analysis of modelled land use and pollutant load data shows that the dominant land uses in the region (by area) are nature conservation (61%) and grazing (37%). Other land uses including urban, horticulture, irrigated cropping and sugarcane are all less than 1% of the regional land use area. The largest total TSS loads are delivered to the end-of-catchment from conservation areas (46% of the regional load) and grazing lands (40% of the regional load). It is noted that cattle grazing is permitted in many conservation areas in the region. Modelling data shows that the dominant erosion sources in the region are gully (44%) and hillslope (42%), with streambank erosion contributing around 13% of the regional TSS load. These proportions vary between catchments, with clear dominance of erosion from gullied areas in the Normanby catchment (71%). Hillslope erosion is the dominant source (>70%) of erosion in the Jacky Jacky, Pascoe, Lockhart, Jeannie and Endeavour catchments. In the Normanby catchment, it is estimated that 60% of the TSS load is from grazing lands with 87% of this from gully erosion, and 30% of the TSS load is from conservation areas with 34% of this from gully erosion and 66% from hillslope erosion. Streambanks contribute approximately 10% of the overall load in the catchment.

It can be concluded that overall, the eastern Cape York catchments currently present a relatively low risk to coral reef and seagrass ecosystems in the GBR, and that the ecosystems in the region are typically in good condition. The catchments in the Central sub-region – the Normanby, Hann and Stewart catchments – are

likely to pose a risk to ecosystems in the Princess Charlotte Bay area from degraded water quality, particularly increased turbidity in wet season conditions. The assessment of pollutant loads and sources indicates that management in these catchments should be focused on management of gully erosion in grazing and conservation areas. This is supported by conclusions from other studies in the region (e.g. Brooks et al. 2013; Howley et al. 2015).

Due to the potential underestimation and lack of validation of models pertaining to risks in the South sub-region, this region also warrants further investigation and management of threats to water quality. In particular, high levels of impacts have been documented from current and historic land-uses in the Annan and Endeavour catchments and increased levels of disturbance from urban and semi-urban development are expected in this area (Howley et al. 2012). Reefs and seagrass meadows in this region are regularly inundated by flood plumes which may contain high levels of suspended sediments (Davies and Hughes, 1983; Davies and Eyre, 2005).

Other threats to water quality in the eastern Cape York region should also be considered and include shipping traffic, particularly on the Inner Route, which may pose an increasing risk to the region with predicted increases in traffic.

The confidence in the results at this time is low to moderate due to limitations in some of the input data related to river flows and pollutant loads for some variables in the model. However, the results do correlate with current status reported in Coppo et al. (2015). This first attempt of assigning relative risk in the marine environment to individual basins by defining modelled Zones of Influence for individual basins in the region (where possible) demonstrates how this method could be applied for future assessments. Further refinement of the definition of these zones is recommended if more definitive results are required to differentiate between the basins with greater confidence.

1 Introduction

Exposure to land-sourced pollution has been identified as an important factor in the world-wide decline in coral reef condition (Pandolfi et al. 2003; Burke et al. 2011). Different parts of the Great Barrier Reef World Heritage Area (GBRWHA) are exposed to different degrees of influence from land-sourced pollutants. The degree of exposure is a function of factors such as distance from the coast and river mouths, the magnitude of river discharges, wind and current directions, the mobility of different pollutant types, and the different land-uses in the Great Barrier Reef (GBR) catchment. This differential exposure to land-sourced pollutants results in varying levels of threats to coastal and marine ecosystems in the GBR including coral reefs and seagrass. Understanding these differences is important for prioritizing investment between management areas.

The Cape York Natural Resource Management (NRM) region is one of 6 NRM regions in the GBR catchment (see inset Figure 1.1). The region is part of the Great Barrier Reef World Heritage Area and Great Barrier Reef Marine Park. The NRM region has an approximate catchment area of 43,000 km^2 and is approximately 10% of the total GBR catchment area (423,122 km^2) (McCloskey et al. 2014). There are seven Australian Water Resources Council Basins that make up the region (ANRA, 2002). From north to south they are the Jacky Jacky, Olive-Pascoe, Lockhart, Stewart, Normanby, Jeannie and Endeavour (Figure 1.1). The Normanby Basin dominates in terms of area (34% of the regional area). Here the Normanby basin is subdivided into the Hann and Normanby catchments (Figure 1.1). The catchments are characterised by savannah dominated landscapes in southern Cape York, and the rainforest type environments of northern Cape York (McCloskey et al. 2014).

The Cape York region is recognised for its diverse and unique marine and coastal environments including coral reefs, seagrass meadows, tidal wetlands, estuaries, continental islands and the species they support. Some of these species are listed as threatened or vulnerable, and have significant cultural values. The region is characterised by a tropical climate with intermittent periods of high river flow driven by the EL Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). Current major land uses are nature conservation (~61%) and grazing (~37%) (derived from QLUMP, 2013). Cooktown is the largest population centre. Several smaller towns are located along the coast and throughout the catchments.

The marine and coastal assets in the Cape York region are considered to be in good or very good condition compared to other parts of the GBR. This is attributed to a combination of factors, including good water quality due to lower levels of development within the catchments, as well as less pressure from recreational and commercial fishers, tourism and other boats (Howley, 2015). However, many of the assumptions in regards to the marine condition are based on short-term studies in isolated areas or modelled water quality parameters. Threats to the marine environment across the whole region are generally poorly quantified in terms of actual impacts on marine receiving waters and ecosystems (Howley, 2015).

The Cape York region has high coral diversity and is generally in good or very good condition. The AIMS Long Term Monitoring Program has conducted coral reef surveys in the region, at 70 sites for broad scale surveys and 8 sites for intensive surveys (AIMS, 2015). At inner, middle and outer shelf reefs in the North sub-region coral cover was very variable between reefs; 20-50%, 10-70% and 20-45% respectively. Hard coral cover in the Central sub-region was 10-50%, 5-30% and 5-50% at inner, middle and outer shelf reefs. All reefs in the South sub-region exhibited variable hard coral cover of between 10-50%. The most significant threats to their viability are reduced water quality and increased storm damage due to climate change (Coppo et al. 2015).

Extensive seagrass meadows are present in the waters surrounding Cape York Peninsula. The Cape York Peninsula's seagrass communities are amongst the richest in the world and are identified as having conservation significance (McKenzie and Yoshida, 2009). Regular seagrass monitoring through the Marine Monitoring Program has reported the status of seagrass condition in the region since 2005, although there is limited spatial coverage across the region. Coastal intertidal seagrass abundance was very good in the Central sub-region, poor in the North sub-region and not monitored in the South sub-region (McKenzie et al. 2015). Intertidal reef seagrass abundance is moderate, very poor and poor in the North, Central and South sub-regions respectively. A higher proportion of colonising species and declining and very poor reproductive effort may suggest weaker ecosystem resistance to perturbations and a more vulnerable state for seagrass meadows in this region. Mapping and monitoring of sub-tidal meadows, indicates that these meadows, which cover extensive areas, particularly in the South sub-region, are in good condition (Howley unpublished data).

Dugong populations in the Eastern Cape York regional coastline, as well as on large reefs in Princess Charlotte Bay, had very high (>0.5 dugongs /km^2) and high relative dugong density and modelling of survey results indicate an almost continuous distribution of dugong along the Eastern Cape York regional coastline (Sobtzick et al., 2014).

A synthesis of marine water quality in the region has been completed by Howley (2015) to support the development of the Eastern Cape York catchments WQIP. Several studies over the past 20 years have shown that water quality and coral reefs in eastern Cape York are generally in better condition than other GBR regions. Fabricius et al (2005) found that water around inshore reefs in northern Princess Charlotte Bay had lower nutrient, sediment and chlorophyll-a concentrations than Wet Tropics reefs, correlating to higher live coral cover, coral species richness and fish abundance in Princess Charlotte Bay. The Long-Term Chlorophyll-a Monitoring Programme (Brodie et al. 2007) found that inner-shelf waters had mean chlorophyll *a* concentrations less than half that of inshore waters of the central and southern GBR. However, flood plume monitoring from the Annan, Endeavour and Normanby Rivers have shown that high concentrations of TSS are discharged to the marine environment, where they regularly inundate inshore reefs and coastal seagrass meadows (Howley, 2015). An analysis of the available eastern Cape York water quality data showed generally low TSS and chlorophyll-a concentrations in the open coastal, mid-shelf and offshore zones, indicating that ambient water quality remains in relatively good condition (insufficient data exists from the enclosed coastal zone to assess the current condition in that zone) (Howley, 2015). Significant variations in water quality were identified between the North, Central and South and sub-regions with typically poorer conditions in the Central sub-region (Princess Charlotte Bay).

Climate change, coastal development and increases in terrestrial pollutants (sediment, nutrients and pesticides) are all considered potential threats to the coastal and marine assets of the Eastern Cape York region, particularly in the Central and South sub-regions where anthropogenic effects are more likely (Coppo et al. 2015).

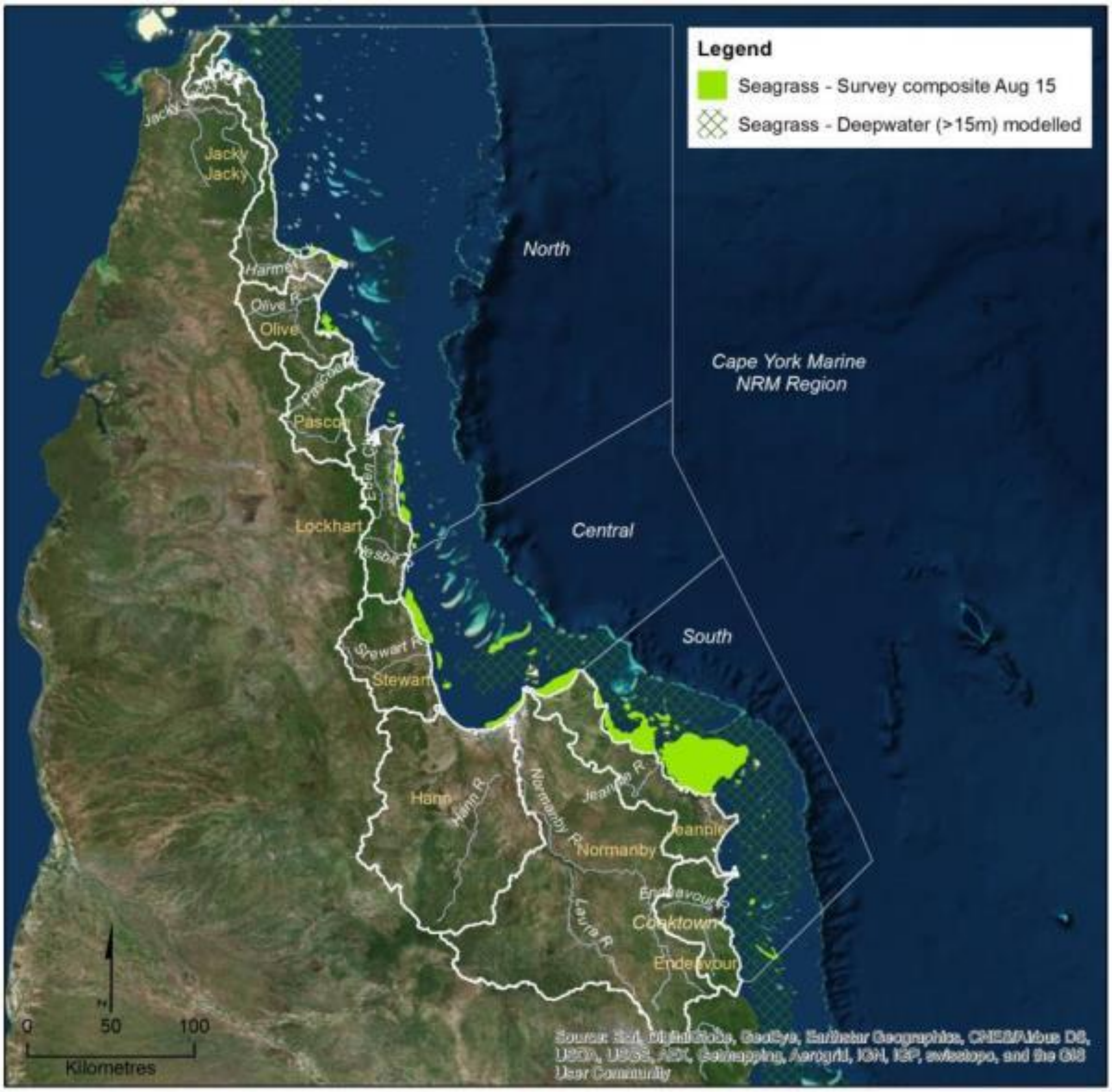

Figure 1.1. Assessment boundaries considered in this risk assessment including the Cape York NRM region catchments, marine NRM region and the marine North, Central and South sub-regions.

The Cape York NRM region has been identified as a low risk region in terms of the influence of degraded water quality on GBR ecosystems (Brodie et al. 2013a; Waterhouse et al. 2012). In the most recent relative risk assessment of degraded water quality on the GBR (Brodie et al. 2013a), the Cape York region was ranked as the lowest risk NRM region compared to other regions for overall water quality risk to coral reefs and seagrass. These rankings were largely associated with the relatively low degree of catchment influence across the region and warrant further consideration for protection.

Previous assessments of the relative risk of degraded water quality on GBR ecosystems have largely been undertaken at a GBR wide scale, with the assessment of relative risk between NRM regions (Brodie et al. 2013a; Waterhouse et al. 2012; Brodie and Waterhouse, 2009; Cotsell et al. 2009; Greiner et al. 2005). The results of these assessments have been used to inform prioritisation across the NRM regions in terms of management effort (such as Reef Plan 2009 and 2013, the *Queensland Great Barrier Reef Protection Amendment Act, 2009*) or investment including the Reef Rescue and Reef Programme initiatives. There has only been one recent regionally-specific assessments of relative risk from degraded water quality in the Cape York region. In 2014 the Australian Government (led by M. Barson)[1] completed an assessment of pollutant loads from catchments flowing to the GBR lagoon and the impact of transported materials (sediments, nutrients and herbicides) on coral reefs and seagrasses, to support and inform discussion and decisions on funding priorities for investment, particularly through Reef Water Quality Grants in 2013 (part of the Australian Government Reef Programme).

Several improvements in catchment modelling (see McCloskey et al. 2014 for most recent published data and Waters et al. in review) and availability of longer time series of monitoring data to support this modelling effort has resulted in greater confidence in the input data required for a regionally based water quality risk assessment. The capability to assess the relative risk of different pollutants and basins to marine ecosystems has also progressed (Brodie et al. 2013b). In the same period, the Australian Government has supported the revision and development of regionally based Water Quality Improvement Plans (WQIPs) in all of the GBR NRM regions. Continued investment towards a water quality grant program for the region has also occurred through the Australian Government Reef Water Quality Programme (formerly Reef Rescue). These initiatives have driven the need to undertake a more comprehensive relative risk assessment of water quality issues in the Cape York region. However, it is acknowledged that due to the relative scarcity of empirical pollutant loads monitoring, ambient and event marine water quality monitoring, and poorly quantified levels of catchment disturbances- particularly in the South and North sub-regions - significant uncertainties remain in the models and assumptions currently used to assess risk in this region.

This report presents the results of an updated assessment, using the best data currently available, of the relative risk of the influence of sediments, nutrients and PSII herbicides on key GBR ecosystems in the eastern Cape York region. The assessment considers the most relevant pollutants for GBR water quality in the GBR, i.e. sediments, nutrients and PSII herbicides - and is based on a methodology developed for the relative risk assessment undertaken for the whole GBR in 2013 (see Brodie et al. 2013a) that has been modified for regional application (Waterhouse et al. 2014a, 2014b). The full report prepared by Brodie and others can be downloaded for a full explanation of the assessment techniques used in that assessment.[2]

As an important note, this report refers to suspended (fine) sediments and nutrients (nitrogen, phosphorus) as 'pollutants'. Within this report we explicitly mean enhanced concentrations of or exposures to these pollutants, which are derived from (directly or indirectly) human activities in the GBR ecosystem or adjoining systems (e.g. river catchments). Suspended sediments and nutrients naturally occur in the environment; indeed, all living things in ecosystems of the GBR require nutrients, and many have evolved to live in or on sediment. The natural concentrations of these materials in GBR waters and inflowing rivers can vary, at least episodically, over considerable ranges. Pesticides do not naturally occur in the environment. Pollution occurs when human activities raise ambient levels of these materials (time averages, or event-related) to concentrations that cause environmental harm and changes to the physical structure, biological communities and biological functions of the ecosystem.

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[1] Australian Government, 2014. *Reef Water Quality Protection Plan 2013 –prioritisation project report*, Canberra. ISBN 978-1-7600307-3-5 (online).

[2] http://research.jcu.edu.au/research/tropwater/publications/copy4_of_1328Assessmentoftherelativeriskofdegradedwaterqualitytoecosystemsofthe GreatBarrierReef.pdf

2 Methods

2.1 The water quality risk assessment framework

Ecological Risk Assessment (ERA) is a term used for a variety of methods to determine the risk posed by a stressor, for example a pollutant, to the health of an ecosystem. "Risk" is usually defined as the probability that an adverse effect will occur as a result of ecosystem exposure to a certain concentration of the stressor. Risk is often quantified as the product of the *likelihood* of an event occurring (exposure) and the *consequences* (also measured as effects) of that event. Risk assessments are used as decision tools that rank risks to human values in order to prioritise management actions and investments (e.g. Burgman, 2005; AS/NZS, 2004). A number of methodologies are available to carry out the analysis with Bayesian techniques now often favoured by decision makers (e.g. Hart et al. 2005; Hart and Pollino, 2008). Due to limitations in data availability and limitations with time and resources, a relatively simple methodology suitable for the existing datasets, resources and timeframes has been developed based on a modification of the typical ERA framework.

Ecological risk is assessed here using a relatively simple approach, following that developed for the GBR wide relative risk assessment in 2013 (Brodie et al. 2013a). The *likelihood of exposure* of a species or habitat to an impact is typically a function of the intensity of the impact (the concentration or load of a pollutant) and the length of time it is exposed to the impact. For example, a seagrass meadow may be exposed to a high intensity impact for a short period of time (acute), or to lower intensities for longer periods (chronic). When quantifying exposure, it is important to determine the threshold concentrations that lead to an effect on species or habitats, that is, the concentration that potentially leads to damage or mortality within hours or days, as well as understanding long-term average concentrations and the duration of exposure. This complicates the description of exposure thresholds given their values may change by one to two orders of magnitude between days, seasons and years. Hence, some key water quality variables such as suspended sediments are divided into different thresholds based on ecological responses and periods of exposure. To reflect this, each threshold is classified into several assessment classes to represent the potential differences between the duration and severity of the influence (from lowest to highest).

The *consequences* are the measured effects of the water quality exposure. Current knowledge of the effects of degraded water quality on the health of the GBR are summarised in the 2013 Scientific Consensus Statement (Brodie et al. 2013b). The GBR Water Quality Guidelines reflect our knowledge of ecological thresholds for water quality variables for coral reefs in the GBR (GBRMPA, 2010). However, only limited information is available to draw conclusions on the effects of the exposure of sediments, nutrients and PSII herbicides on seagrass health. Evidence shows that one of the greatest drivers of seagrass health is the availability of light, which is reduced by increased suspended sediment and the secondary effects of increased nutrients such as increased growth of epiphytes and phytoplankton (Collier et al. 2012). However, in the absence of more regionally- and species-specific knowledge of pollutant impacts on seagrass, the same threshold concentrations have been used for coral reefs and seagrass meadows in this assessment. It is also recognised that the consequence of the exposure of species or habitats to a range of water quality conditions is complicated by the influence of multiple pressures, and many external influences including weather conditions, however it is difficult to factor these into the risk assessment in any quantitative way.

Given the above and recognising the inconsistencies in the spatial and temporal availability of the water quality data in the GBR, our capacity to produce a true likelihood or true consequence estimate for this assessment is limited. It was therefore necessary to develop an effective, simple and standard methodology for the risk assessment that could be implemented with the available data, in a way that could be easily communicated and discussed with decision-makers and stakeholders. For this reason, in this study ecological risk in the GBR is expressed simply as the area of coral reefs and seagrass meadows within a range of assessment classes (very low to very high relative risk) for several water quality variables in each NRM region in the GBR catchment. The method for calculating risk essentially assesses the likelihood of exceedance of a selected threshold. This likelihood was set as 1 for a parameter and location if observations or modelled data indicate that the threshold was exceeded. Conversely, the likelihood was set as 0 if observations or modelled data indicate that the threshold was not exceeded. As consequences are mostly unknown at a regional or species level, potential impact was calculated as the area of coral reef, seagrass meadows and area of GBR lagoon waters (in km^2) within the highest assessment classes of the water quality variables (reflecting the highest severity of influence). The effects of multiplying the habitat area by 1 or 0 for the likelihood mean that the *final assessment of risk in this assessment is only an indication of potential impact* - the area of coral reef and seagrass meadows in which exceedance of an agreed threshold was modelled or observed. This becomes an assessment of 'relative risk' by comparing the areas of each habitat affected by the highest assessment classes of the variables among NRM regions, and was used to generate a 'Marine Risk Index'.

In the GBR-wide study conducted in 2013 (Brodie et al. 2013a; referred to herein as the 2013 risk assessment) the relative risk of degraded water quality to coral reefs and seagrass was assessed by combining information on end-of-catchment pollutant loads of sediments, nutrients and PSII herbicides with the estimated ecological risk of water quality to coral reefs and seagrass meadows for the GBR. Three primary indexes were developed in the original method (see Figure 2.1): 1) a Marine Risk Index that represents an estimate of ecological risk of water quality to coral reefs and seagrass; 2) a Loads Index that represents the contribution of pollutant loads from each basin; and 3) a crown-of-thorns starfish (COTS) Influence Index that represents the regional contribution of observed freshwater discharge to the area where primary outbreaks of COTS are known to occur. The three indexes were combined to generate a Relative Risk Index for coral reefs and seagrass meadows for each NRM region. This index ultimately ranked the relative risk of degraded water quality to coral reefs and seagrass in the GBR among NRM regions. Modelled data (Brinkman et al. 2014) is only available for the Normanby River so formal assessment of the COTS Influence Index is not possible, but the relevance of the regional contributions to the COTS Initiation Zone is discussed.

To conduct a comparable assessment that just focused on the Cape York region of the GBR, separate areas of influence for rivers discharging into the marine environment were estimated where possible. As described in Section 2.3, eReefs hydrodynamic modelling combined with river flow, plume direction and imagery was used to derive the Zone of Influence for the Normanby River. The Pascoe, Stewart, Hann/Kennedy, Endeavour and Annan Rivers are not included in the hydrodynamic model and were estimated using a path-distance modelling approach. This enables the estimated relative risk in the marine environment to be attributed to each basin. Insufficient data is available to estimate Zones of Influence for rivers in the Jacky Jacky, Lockhart, Jeannie Basins using this method.

The combined index ultimately ranks the relative risk of degraded water quality to coral reefs and seagrass among Cape York catchments where possible. The variables selected in the marine assessment represent average conditions over several years (varies between datasets).

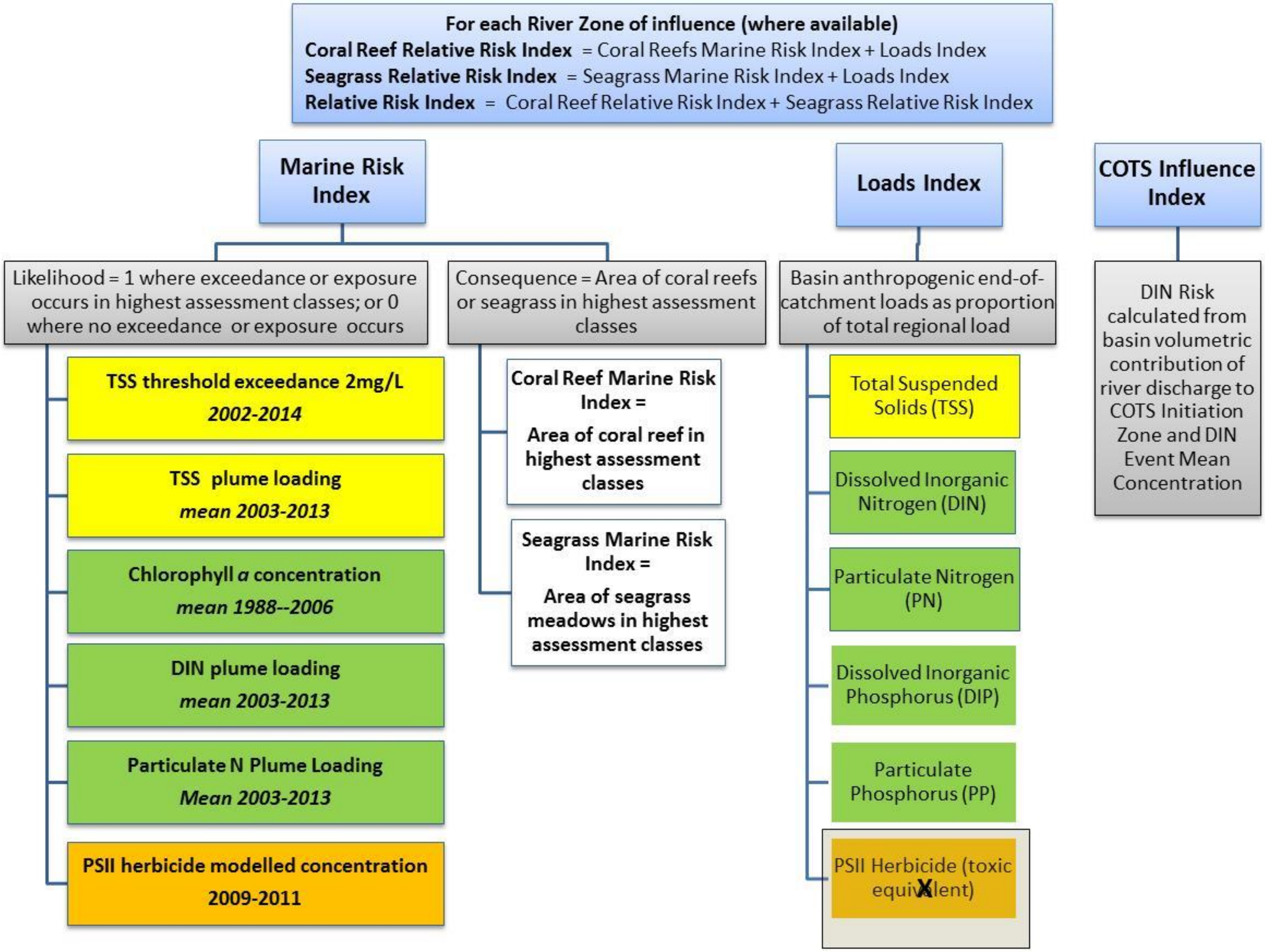


Figure 2.1. The risk assessment framework used in this project showing the components of the Marine Risk Index to represent marine water quality ecological risk to coral reefs and seagrass meadows, and a Loads Index to represent catchment influences on GBR water quality using end-of-catchment anthropogenic pollutant loads. The COTS Influence Index used in previous assessments is only available for the Normanby River and is discussed in this assessment. PSII herbicides were excluded from the final assessment due to limited measurement in the region. The colours represent groups of variables: yellow = sediment related variables, green = nutrient related variables and orange = PSII herbicide related variables.

2.2 Habitats and boundaries

2.2.1 The Cape York marine NRM region

The marine NRM region (as defined by GBRMPA; see Figure 1.1) extends seawards from the northern and southern boundaries of the NRM region, to the outer edge of the Great Barrier Reef Marine Park, and has an approximate area 96,000 km^2. However, this is an administrative boundary and does not necessarily reflect the extent of influence of the catchments on the marine environment in the region. Furthermore, the Wet Tropics rivers to the south catchments outside of the eastern Cape York NRM region may influence the marine ecosystems within the region.

2.2.2 Cape York sub-regions

The Cape York marine region has also been divided into 3 sub-regions to group management priorities (Figure 1.1):

- **North:** Extends from the northern boundary of the GBRWHA south to the Nesbit River mouth, and extending in a north east direction to the outer boundary of the GBRWHA. This marine region 'links to' the Jacky Jacky, Olive, Pascoe and Lockhart catchments.
- **Central:** Extends from the Nesbit River mouth south to Cape Melville, extending in a north east direction to the outer boundary of the GBRWHA. This marine region 'links to' the Stewart, Hann and Normanby catchments.
- **South:** Extends from Cape Melville to the southern boundary of the marine NRM region, and follows that boundary to the outer boundary of the GBRWHA. This marine region 'links to' the Jeannie and Endeavour catchments.

2.2.3 Defining basin 'Zones of Influence'

Normanby River

Zones of Influence for rivers in the eastern Cape York region were defined using a combination of river flow data, in situ salinity data, and output from a highly resolved hydrodynamic model (eReefs) for the 2008-09, 2010-11, 2011-12 and 2012-13 wet seasons (December to April inclusive) (note that the hydrodynamic model is not available for 2009-2010). The Normanby River is the only river in the region that is modelled in eReefs. The area of river plume influence (tracer plume) was mapped using virtual tracers that are released from the river mouth, proportionally to the river discharge. Because tracers present conservative behaviour, a tracer concentration threshold, equivalent to salinity 36 ppt, was used to define the edge of the river plume. The delimitation of the area of river plume influence has been developed by Nicholas Wolff (Wolff et al. 2014). The river basin Zone of Influence was defined as the area where over the wet season (c.a. from December to April, inclusive) tracer concentration was equivalent to salinity 36 ppt at least 5% of the time each year, combined over the four years. Tracer plumes were converted to smoothed shapefiles in a five step process: 1) interpolating into coastal areas, 2) resampling to the same grid used for all Risk Index layers (from 0.036 to 0.01 decimal degrees, using bilinear interpolation), 3) converting from raster to polygon, 4) applying a PAEK smoothing algorithm and 5) erasing mainland and island areas.

Zones of Influence for unmodelled rivers

River plumes for each of the unmodelled rivers can only be generated where flow data is available which includes the Pascoe, Stewart, Hann/Kennedy, Annan and Endeavour Rivers. For these unmodelled rivers, Zones of Influence were derived using the ArcGIS path-distance tool, with plume extent constrained to a maximum distance from the river mouth predicted from river discharge. Zones of Influence for the modelled rivers (tracer plumes) were used to derive this flow-distance relationship (Figure 2.2). Total wet season discharges for all rivers were obtained from the Department of Natural Resources and Mines (Queensland, https://www.dnrm.qld.gov.au/water/water-monitoring-and-data/portal), and they were calculated as the sum of the daily discharges for the period between the 1st of December to the 30th of April for each wet season in the years of interest. These zones cannot be modelled where river discharge data is not available, and have not been estimated for the Jacky Jacky, Olive, Lockhart and Jeannie Rivers. Future work could also use satellite imagery of river plumes to estimate Zones of Influence for these rivers, but this additional analysis was outside the scope of this project.

The path-distance tool determines the minimum accumulative travel cost from a source to each cell location in a raster (ArcMap Spatial Analyst, ESRI, 2010). Path-distance takes into account horizontal and vertical factors that affect this movement, making it useful in dispersion modelling, flow movement, and least-cost path analysis (ESRI, 2010). Three main inputs were used in the path-distance tool to model individual plumes: (i) SOURCE – the point coordinates of the freshwater discharge; (ii) COST RASTER – a surface raster indicating the impedance for the plume movement, and (iii) HORIZONTAL RASTER – a surface raster indicating the main direction of plume propagation. To have a greater control on the modelled plume, the linear type horizontal factor was included to the path-distance function. This horizontal factor was parameterised, and the cost raster selected, based on the best match up (percent overlap) between tracer plumes and path-distance plumes when path-distance plumes were constrained to the same maximum linear extent as the tracer plumes. The cost raster surface used was the reciprocal of the frequency of occurrence of plumes (i.e., 1/frequency) during the wet season (i.e. the accumulative cost of travel was inversely proportional to the frequency of observed river plume). The main direction of plume propagation was set as 315º Azimuth to account for the prevailing wind (i.e. trade winds) and current direction in the wet season (Luick et al. 2007).

River plumes were generated using the path-distance tool for the same four years as the tracer plumes (2008-08, 2010-11, 2011-12, 2012-13). Plume extent was constrained using the predicted maximum distance between river mouth and the outer edge of plume (Figure 2.3). Plume areas for each year were converted to shapefiles and, as with the tracer plumes, Zone of Influence has been defined using the combined area of the four years.

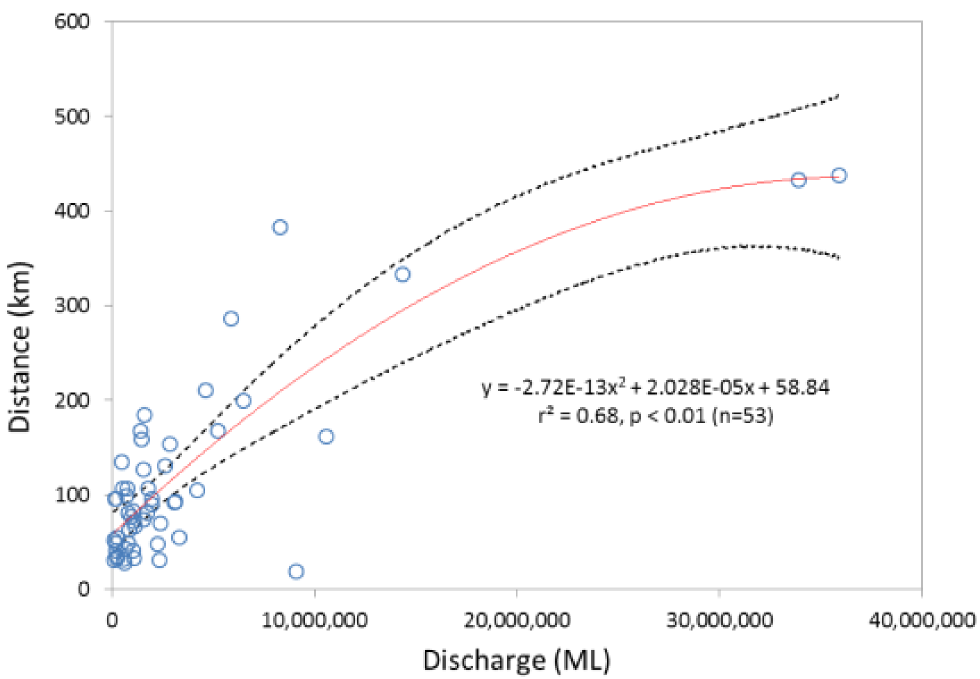


Figure 2.2. Relationship between river discharge and the distance between river mouth and the outer edge of tracer plume.

2.2.4 Habitat mapping

The habitats considered in the assessment were coral reefs and seagrass meadows, based on the best available information (Figure 1.1). For coral reefs, the spatial layer used is the GBRMPA Spatial Data Centre's coral reefs spatial data file (December 2012).

The seagrass habitat map used is a combination of the following datasets:

1. The seagrass monitoring composite survey map up to 2010 (observed habitat) (provided by TropWATER JCU).
2. Seagrass mapping by CYMAG Environmental of 100 km of coastal seagrass meadows from Walsh Bay to Cape Flattery and 4 reef-top meadows, plus additional surveys by C. Howley and Juunjuwarra rangers near the Starcke River mouth.
3. Seagrass assessments undertaken in Princess Charlotte Bay (Carter et al. 2012), South Warden Reef to the Howick Group (Carter and Rasheed, 2014), Bathurst Bay region (Carter and Rasheed, 2013) and Crescent Reef to Cape Flattery (Carter and Rasheed, 2015) (provided by TropWATER JCU).

Deepwater seagrass is also represented using a statistical model of seagrass present in GBRWHA waters >15 metres depth. In this model spatial distribution is a statistically modeled probability of seagrass presence (using generalised additive models with binomial error and smoothed terms in relative distance across and along the GBR), based on ground truthed points (Coles et al. 2009). Locations with seagrass habitat probability >0.5 were included in the assessment.

Calculation of habitat areas is based on a pixel based assessment and therefore, vary slightly from official published figures (which were used in Brodie et al. 2013a). Both datasets should only be presented as **potential** seagrass habitat.

2.3 Selecting and classifying variables for estimating ecological risk

A suite of water quality variables were selected to represent the pollutants of greatest concern with regards to land-sourced pollutants and potential impacts on GBR ecosystems. These are summarised in Table 2.1, and in the marine assessment include ecologically relevant thresholds for concentrations of chlorophyll *a* (Chl-a) from in-situ monitoring data, and the distribution of key pollutants including total suspended sediments (TSS), dissolved inorganic nitrogen (DIN), particulate nitrogen (PN) and photosystem II-inhibiting herbicides (PSII herbicides) in the marine environment during flood conditions (based on end-of-catchment loads and plume loading estimates). For each variable, thresholds above which impacts have been observed or predicted were defined and classified into three to five classes (from lowest to highest). Average conditions over several years (time period varies between datasets) were used for most variables.

More detailed information on pollutant impacts GBR ecosystems is provided in the 2013 Scientific Consensus Statement *Chapter 1 Marine and coastal ecosystem impacts from degraded water quality* (Schaffelke et al. 2013). The selected variables and thresholds represent long-term conditions (chronic exposure) and wet season pollutant loadings in flood plumes (acute exposure).

2.3.1 Annual TSS and Chlorophyll

The 2013 risk assessment used long term remotely sensed data to define the areas where the Chl-a and TSS concentrations exceeded different ecologically-relevant threshold values at different frequency intervals. The frequency of exceedance of the GBR Water Quality Guidelines was used for Chl-a (0.45μg/L) and TSS (2 mg/L) concentrations, and an additional higher threshold was also applied to TSS concentrations (6.6mg/L or 5NTU) to factor in more severe effects on coral reefs, seagrass and fish. However, regionally specific application of this data in the Wet Tropics and Burnett Mary regions (Waterhouse et al. 2014a,b) highlighted a number of limitations with the data relevant to this application, explained below.

The data used in the 2013 water quality risk assessment were provided by CSIRO in November 2012. In the 18 months that followed, the data were re-processed and set to a different, higher-resolution grid. This is the ocean colour data that is now publically available for download through the e-Reefs Water Quality Dashboard (http://www.bom.gov.au/marinewaterquality/), and used for the Burnett Mary WQIP (Waterhouse et al. 2014b). In both cases, the thresholds used for relative risk were based on number of days exceedance (unit=days during ~10-yr time series) of the GBR Water Quality Guidelines (GBRMPA, 2010) for Chl-a (0.45μg/L) and TSS (2 mg/L), plus an additional exceedance for TSS of 6.6mg/L (or 5 NTU) to represent a concentration where greater severity of potential impacts is known to occur. For this assessment, remotely sensed Chl-a and TSS data were acquired from the eReefs Marine Water Quality dashboard for the period 01 November 2002–31 October 2014.

It is possible to record the number of valid observations in each pixel (1km^2 grid) over any time period (see Figure 2.3). The number of valid observations is a result of the strict quality control criteria applied to the imagery: pixels with cloud or cloud shadow, low view and illumination angles (solar zenith and observer zenith higher than 60 degrees) are flagged and dismissed, as are pixels where the atmospheric correction failed. In the 2014 analysis, during the 12 years between 2001 and 2013 the maximum number of valid observations was 1682, which means at best, valid observations are made 38% of the time. For large areas of the GBRWHA, particularly in the wet season, valid observations are made less than 20% of the time. In the Cape York region, there are large areas of low confidence in the northern marine areas, with less than 20% valid observations, and in the wet season, the proportion of valid observations is typically below 20% throughout the region. For this reason, using absolute thresholds for number of days exceedances or even average concentrations can be very misleading as the frequency of valid observations varies greatly in space and time. There are many pixels where there are a low number of valid observations, particularly during the wet season where there is significant cloud cover; some of these pixels may have been given a lower risk classification than would be the case if exceedances were expressed as percentages of valid observations. Therefore for this risk assessment, we have calculated the percentage of the valid observations that exceed the water quality thresholds.

The results for the original and revised methods are available for comparison in Maynard et al. (2015). Importantly, the results vary between the methods, particularly for Chl-a. In summary (across the GBR):

- For **Chl-a** between 40 and 70% of the pixels stayed within the same risk classification/category. However, between 10 and 50% of the pixels increased 1 or 2 classes, which is particularly relevant in the coastal areas. The area of each marine-NRM previously considered to be in the highest risk class for exceedance of Chl-a 0.45 μg/L is roughly half what these current results are suggesting.
- For **TSS 2mg/L** declines in the risk classifications were far more common than increases.
- **TSS 7mg/L** results were largely unchanged using this new method, but this threshold was excluded from the risk analysis.

There are also other, potentially significant factors that influence the confidence of the use of these remotely sensed datasets in the assessment including the reliability of remote sensing data in highly turbid waters. Petus et al. (2015) conducted a preliminary study of the latter aspect which has highlighted that there is limited confidence in the remote sensing data under certain conditions in the GBR – particularly in shallow and turbid waters. The study concluded that:

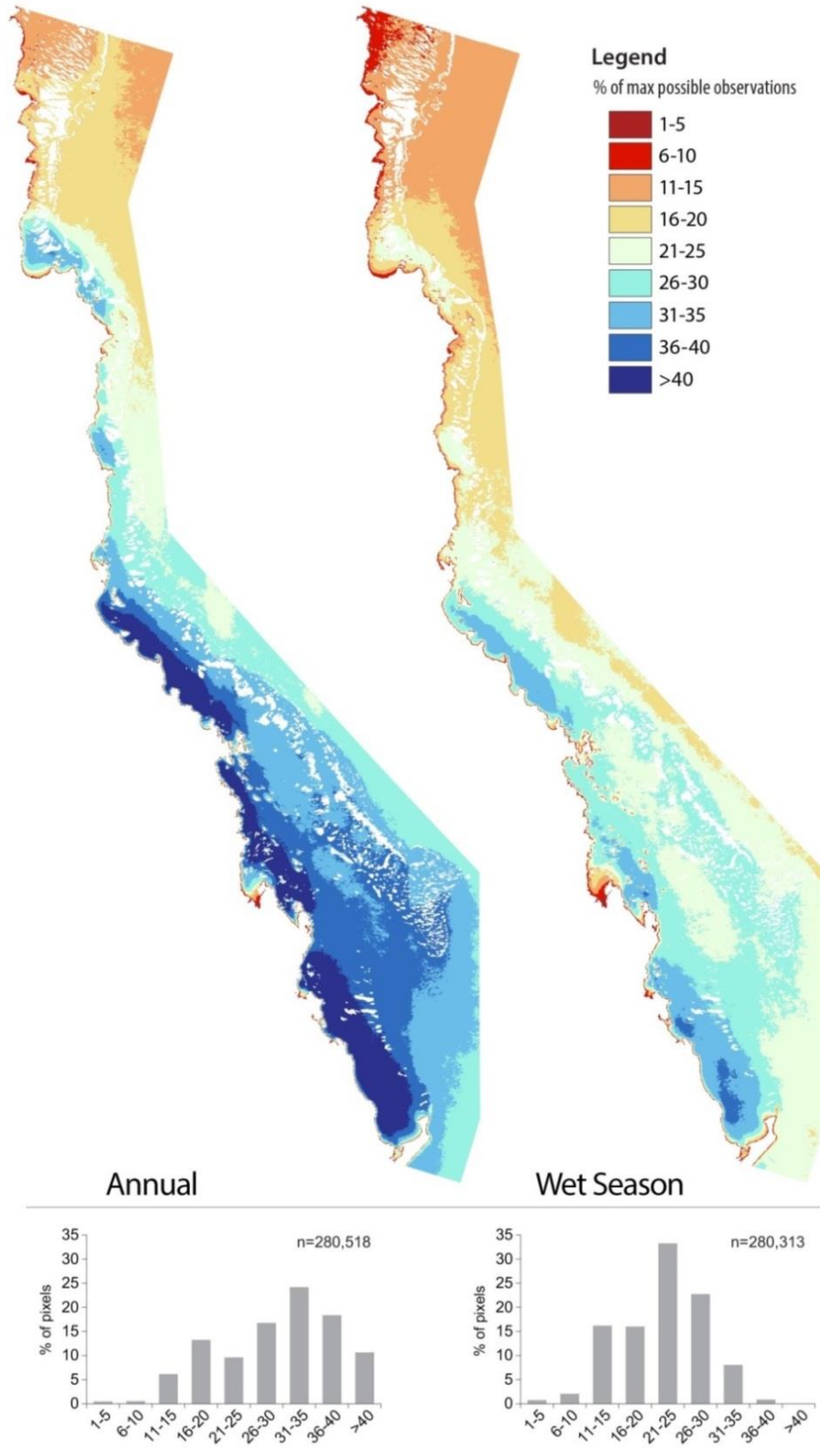


Figure 2.3. Percent of maximum possible observations during annual and wet season periods 2002-2014 that were valid out of a total maximum for Annual of 4383 and for Wet of 2175.

*Note: Max possible observations are calculated as follows: Annual – Nov, 02-Oct, 14 is 12*365+3 leap days = 4383 days; Wet – Nov, 02-Oct, 14 is 12*181+3 leap days = 2175 days.*

- Assessing Chl-a concentrations with remotely sensed data is notoriously challenging in optically complex (case II) coastal waters such as the GBR lagoon and limitations of the remote sensing data must be understood in order to efficiently use these data as a monitoring tool.
- The analyses showed that the satellite Chl-a values were significantly higher than the in-situ MMP measurements (wet season samples collected in plume waters).
- There was a strong variability at the regional NRM scale, and satellite Chl-a values were significantly higher than the in-situ measurements in all regions, except the Mackay Whitsunday region (but results were insignificant in this region).
- **The maximum retrieval errors were calculated in the Cape York region (mean Error 506 ± 651 %)**. The minimum retrieval errors were calculated in Mackay Whitsunday NRM (mean Error 56 ± 61 %) though the results were not significant. Retrieval errors in the Fitzroy were 401 ± 872 % which is also relatively high compared to other regions (Wet Tropics were 128 ± 274 %; Burdekin were 108 ± 148 %; not tested the Burnett Mary region). It must be underlined that the errors and bias reported in this study are performance statistic for the wet seasons and for flood plume waters only. Validation of the remote sensing Chl-a retrievals based on observations performed mainly during the dry season have been presented in King et al. (2014) with stronger validation statistics i.e. Error = 89%.
- There was also a strong variability at the cross-shelf scale and the satellite Chl-a values were significantly higher than the in-situ measurements in all cross-shelf regions, except the offshore region.
- A trend toward an increase of uncertainties in the satellite Chl-a concentration was observed when the TSS concentration increases and the bottom depth decreases; with thresholds values estimated around NAP (proxy for TSS) 2 mg L^{-1} and depth less than 25 metres. Based on this assessment, Figure 2.4 shows a preliminary indication of a Chl-a satellite confidence map based on the 25 metre bathymetry contour. **In the Cape York region, this is almost the entire area defined as the 'inshore' zone (as defined in the GBR Water Quality Guidelines), and also extending into the midshelf areas in the central sections of the marine NRM region including Princess Charlotte Bay.**
- Overall at the GBR scale and at individual regional scales correlation between Chl-a (satellite) and Chl-a (in-situ measurements), using the data analysed here, was poor with $R^2 < 0.23$ in all cases except on Cape York (see above). However for the Cape York results although correlation was good (R^2=0.78) Bias was high giving a constant large overestimation of the Chl-a concentrations.

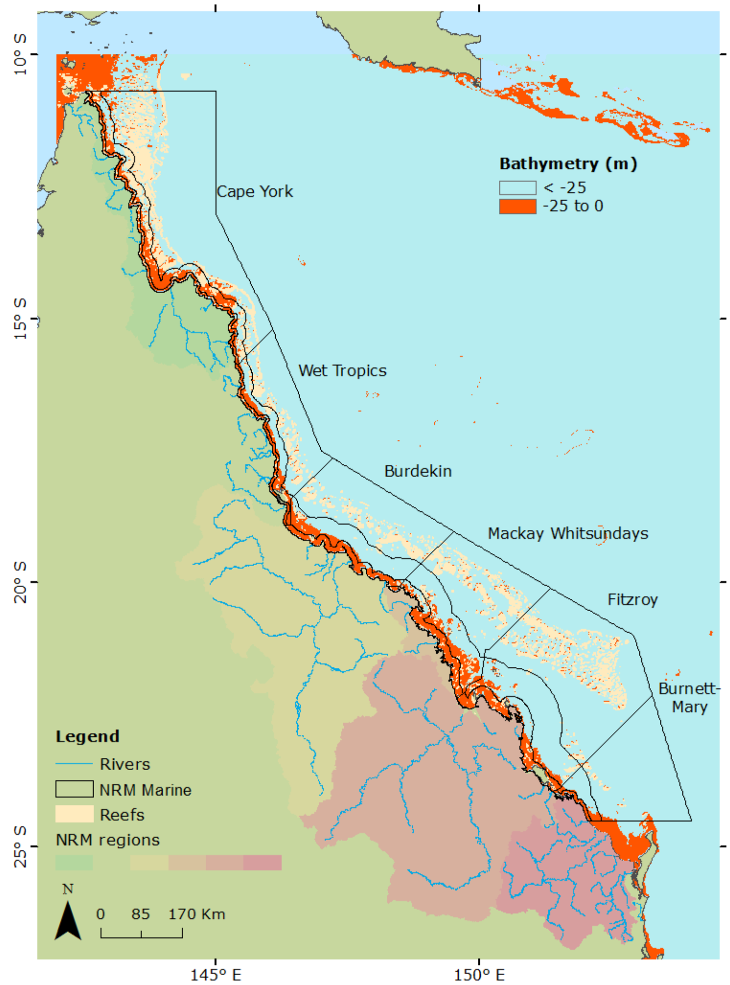


Figure 2.4. Preliminary indication of a Chl-a satellite confidence map based on the 25 metre bathymetry contour, where the areas shown in orange are less than 25m depth and therefore, indicate 'High' uncertainty.

The full results of both of these studies are summarised in a separate report (collated by Waterhouse and others) and fully described in Maynard et al. (2015) and Petus (2015).

As a result of the outcomes of these studies, it was concluded not to use the remote sensing datasets for Chl-a in this assessment, but rather, a long term chlorophyll monitoring dataset (see below). However, based on current information the TSS 2mg/L exceedance assessment was still used as insufficient analysis of the confidence in this dataset has been undertaken to conclude otherwise. Turbidity is highly correlated with depth due to resuspension of fine sediment due to currents and wind events, so the pattern is expected to be influenced by bathymetry anyway. Photic depth was considered as an alternative measure of sediment influence in the marine environment, based on the analysis conducted by Fabricius et al. (2014) and Logan et al. (2014, in review), however, possible limitations of these techniques in shallow waters also require further investigation. In addition, there are potential limits to the application of the GBR Water Quality Guidelines for secchi depth (which can be applied to photic depth in shallow waters).

Chl-a Method and Assessment classes

The dataset used to represent Chl-a is surface water quality data collected by AIMS, GBRMPA and collaborating community organisations between 1988 and 2006. Niskin or bucket surface water samples and laboratory analyses of a suite of physical and chemical water quality data, including Chl-a, were undertaken typically at monthly intervals (Furnas et al. 2005; Furnas, 2003; De'ath, 2007; De'ath and Fabricius, 2008). The values used in this assessment are a representation of the mean concentration, extrapolated in De'ath and Fabricius (2008) to generate a map of long term Chl-a conditions, based on the locations shown in Figure 2.5. The data was then classified against the GBR Water Quality Guidelines to provide a relate risk classification, shown in Table 2.3. There are several limitations in using this dataset including the variability in the collection of data across the region (leading to lower confidence in some locations), the collection period is now dated (1988 and 2006) and it does not provide any indication of the severity of the potential impact, i.e. the frequency of occurrence or exceedance of the thresholds. The data collected under this program also is primarily representative of ambient conditions rather than post flood conditions, when chlorophyll-a concentrations are likely to be elevated. However, given the limitations with the remote sensing data in inshore areas, it is considered to provide the best available indicator of year round nutrient conditions in the GBR for this assessment at this time (noting also time and resource limitations).

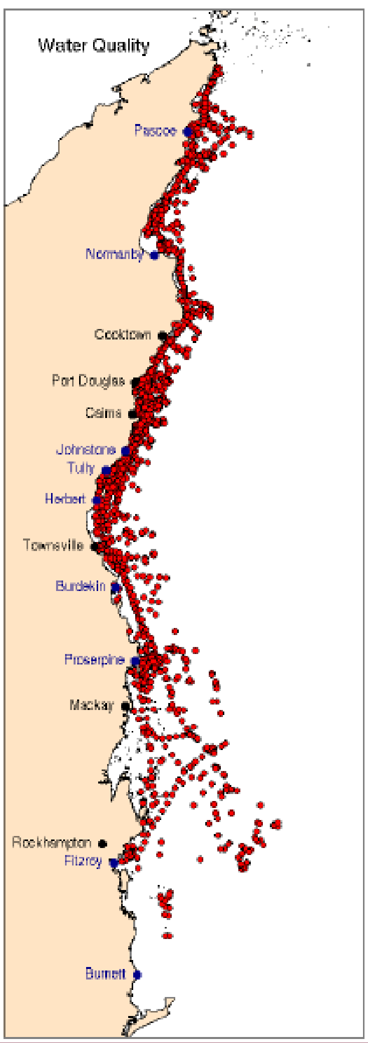


Figure 2.5. Location of the 4067 lagoon water quality stations including in the long term chlorophyll monitoring program between 1988 and 2006.

Table 2.1. Long term Chl-a mean concentration risk classifications.

Mean value µg/L	Score	Reason
<0.18	Very Low: 0	Limit of analysis and considered to be insignificant in terms of potential ecological impacts for coral reefs and seagrass
0.18-0.25	Low: 0.25	Preliminary threshold for seagrass ecological impacts
0.25-0.45	Medium: 0.5	GBR Water Quality Guideline
0.45-0.8	High: 0.75	Increased COTS larval survival
>0.8	Very High: 1	More severe ecosystem impacts and where 100% survival of COTS larvae is likely

TSS Method and Assessment classes

Maynard et al. (2015) calculated the percentage of the valid observations that exceed the water quality thresholds. Remotely sensed TSS data were acquired from the eReefs Marine Water Quality dashboard for the period 01 November 2002–31 October 2014. Exposure thresholds were based on the GBR Water Quality Guidelines for TSS 2 mg/L. Analyses were undertaken for two time periods for each year: the wet season (01 Nov–30 Apr) and annually (01 Nov–31 Oct). Each time period was identified by the year in which it ended (i.e. Apr or Oct). The distribution in the percentage of exceedance data was used to define relative risk classifications from very low to very high, based on the annual aggregated results. These risk classifications were then applied to the percentage of exceedances from each year (as per the 2013 risk assessment), shown in Table 2.2.

Table 2.2. Classifications applied to the remote sensing datasets for the percentage of valid observations exceeding the thresholds.

Classification	Percent of valid observations exceeding the threshold: TSS 2mg/L
Very Low	0
Low	1-10
Medium	11-20
High	21-50
Very High	51-100

2.3.2 TSS, DIN and PN loading

Ecological impacts of terrestrial runoff on coral reefs and seagrass meadows can be experienced as either acute, short term changes associated with formation of high-nutrient, high-sediment, low salinity flood plumes or the more chronic impacts associated with long-term changes in water quality (Devlin et al. 2012). The ecological impact of terrestrial contaminants varies not only with the type of pollutant, the magnitude and extent of the riverine influence but also with the ecosystems being affected and the frequency and duration of plume occurrence (see for example Devlin et al. 2012). River plume models can help to develop risk maps by defining areas which may experience acute or chronic high exposure to pollutants or stressors (Alvarez-Romero et al. 2013). Details of the pollutant movement and frequency of inundation can be key measurements in attributing water quality decline to ecosystem change. These contribute to the 'likelihood' component of the risk equation.

Plume loading maps have been updated since the 2013 risk assessment. These maps are available annually but we have selected a mean assessment across the full period of availability (2003 to 2013) to represent average conditions, however, the influence of large river discharge and flood events are discussed in Section 4.

TSS

The effects of elevated concentrations of suspended solids on GBR ecosystems including coral, seagrass and algal communities were reviewed in Brodie et al. (2013c). The greatest influence of increased turbidity caused by resuspension of sediment in waters of depths less than 12 metres is reduced light for benthic phototropic communities including coral reefs and seagrass (Larcombe et al. 1995; Anthony et al. 2004; Orpin et al. 2004; Alongi and McKinnon, 2005). This resuspension driven turbidity persists for many months of the year in GBR coastal waters. Suspended solids in flood plumes also reduce light for benthic communities but the effects are only present for short periods, typically days to weeks. Hence, a long -term time series is most relevant in the assessment of chronic effects of elevated suspended solids and turbidity on habitats. However, typically the resuspended sediment is that which was delivered as a sediment loading during the previous wet season and potentially earlier wet seasons as well. Hence, there is a strong connection between turbidity and river loadings of sediment (Fabricius et al. 2013). The TSS plume loading modelling (da Silva et al. in review) allows the assessment of pollutant loadings and to predict the likely conditions of suspended sediment in various areas of the GBR lagoon in flood conditions. When fine sediment is delivered to shallow areas less than 12 metres, it is a good indicator for likely resuspension later in the year. Therefore, both the concentration data and the modelled loading distribution is relevant to this assessment. The actual exposure of benthic organisms (for example in Cleveland Bay) to flood plume turbidity is more relevant for the assessment of acute effects (see Petus et al. 2014), however, these specific studies have not been conducted in the Cape York region.

Nutrients

Land sourced runoff containing elevated nutrient concentrations results in flood plumes in the GBR lagoon which may result in a range of impacts on coral communities (Fabricius et al. 2005; Fabricius, 2011; Brodie et al. 2011). Dissolved inorganic and particulate forms of nutrients discharged into the GBR are both important in driving ecological effects but it is currently thought that increased nitrogen inputs are more important than phosphorus inputs (Furnas et al. 2013a), although this is still uncertain. Dissolved inorganic forms of nitrogen and phosphorus are considered to be of greatest concern compared to dissolved organic and particulate forms of nutrients, as they are immediately and completely bioavailable for algal growth. Particulate forms mostly become bioavailable over longer time frames, and dissolved organic forms typically have limited and delayed bioavailability (Furnas et al. 2013).

Most studies in GBR waters show that high levels of dissolved inorganic nitrogen and phosphorus can cause significant physiological changes in corals, but do not kill or greatly harm individual coral colonies (reviewed in Fabricius, 2005). However, exposure to dissolved inorganic nitrogen can lead to declining calcification, higher concentrations of photo-pigments (affecting the energy and nutrient transfer between zooxanthellae and host; Marubini and Davies, 1996), and potentially higher rates of coral diseases (Bruno et al. 2003). Macroalgae and heterotrophic filter-feeders benefit more from dissolved inorganic and particulate organic nutrients than do corals. As a result, corals that can grow at extremely low food concentrations may be out-competed by macroalgae and/or more heterotrophic communities that grow best in high nutrient environments (Fabricius, 2011). Densities of benthic filter feeders – such as sponges, bryozoans, bivalves, barnacles and ascidians – increase in response to nutrient enrichment (Costa Jr et al. 2000). In high densities some filter feeders, such as internal macro-bioeroders, can substantially weaken the structure of coral reefs and increase their susceptibility to storm damage. Critically, more recent research shows that direct interactions between nutrients species such as nitrate and enhanced coral bleaching susceptibility will be important as a clear example of direct synergy between climate change stress and nutrient enrichment stress (Wooldridge, 2009a; Wooldridge and Done, 2009).

The impacts of nutrients on seagrass are less well known and there has been limited, detailed exploration of nutrient dynamics and nutrient limitation in the GBR, with notable exceptions (Udy et al. 1999; Mellors, 2003). Therefore, nutrients as an environmental driver has so far been difficult to elucidate because of other overriding factors such as light limitation, which tends to be a primary driver (Collier and Waycott, 2009). Nutrient enrichment can stimulate seagrass growth (Udy and Dennison, 1997; Udy et al. 1999) if other factors, such as light availability, are not limiting (Collier, 2013). Although a theoretical nutrient toxicity level does exist, nutrient over-enrichment tends to impact at ecosystem scales and follow a path of eutrophication with excessive production of organic matter. In addition, nutrients favour the growth of plankton, macroalgae and epiphytic algae, all of which attenuate light to seagrass leaves (Collier, 2013). In the GBR some very high epiphyte loads occur on seagrass meadows of the GBR (McKenzie et al. 2012) and are likely to reduce light reaching seagrass leaves. However, to date, these have largely been seasonal blooms, and epiphyte cover has not correlated well with seagrass abundance (McKenzie et al. 2012). Although nutrient enrichment has been linked to high algal cover (Campbell et al. 2002), seagrass loss has rarely been attributed to nutrient over-enrichment. Further discussion of the impact of flood plumes and degraded water quality on seagrass ecosystems in the GBR is included in Petus et al. (2014).

It is important to note that particulate matter in plumes typically changes from 'clay' (or mineral)-based material in inshore regions, to organic matter (algal material) in offshore regions, although clay particles can stay in suspension for long distances (Bainbridge et al. 2012). These different types of particulate matter can have different effects on coral reefs and seagrass meadows as described in Brodie et al. (2013c).

Further discussion of the impacts of TSS and DIN on GBR ecosystems is provided in Schaffelke et al. (2013). Given the importance of flood plumes in delivering TSS, DIN and PN to the GBR, plume loadings have been included in the assessment. While it is assumed that there is limited anthropogenic nutrient supply to the Cape York NRM region due to the low levels of horticultural land use, relatively high concentrations of DIN have been detected in Normanby flood plumes (Howley et al in prep). While the flood plume DIN is not likely to be from the use of fertilisers in the upper Normanby catchment, accelerated sediment erosion in the upper catchment is a significant source of dissolved nutrients and may be responsible for the high concentrations in Normanby flood plumes.

Method

The frequency and extent of the influence of flood plumes containing differing concentrations of TSS, DIN and PN is used to provide an estimation of the extent of surface exposure of coral reefs and seagrass during wet season conditions. TSS, DIN and PN plume load maps were produced combining in-situ data collected under the Marine Monitoring Program (GBRMPA), plume maps derived from MODIS imagery and monitored end-of-catchment load for each parameter in each wet season (c.a. Dec to Apr, inclusive) from 2003 to 2013 (da Silva et al. in review). Monitored end-of-catchment loads were only available for the Normanby River and data was extrapolated for other rivers.

The river loads provide the amount of each constituent (TSS, DIN or PN) that has been delivered along the GBR. The in-situ data provides the constituent mass variation as a function of the river plume movement away from the river mouth. The satellite imagery provides the direction and intensity that each constituent mass is transported over the GBR lagoon. As a result, this method produces maps of dispersion of each constituent in the GBR waters expressed in mass per area. Annual maps of each constituent were produced to describe differences in GBR exposure to these pollutants. Mass/area maps were converted to concentration maps by dividing it by the bathymetry of the GBR lagoon. Annual maps were averaged to represent the mean distribution of each constituent concentration over the GBR lagoon.

Assessment classes

Parameter	Classification: Score				
	Very Low: 0	Low: 0.25	Medium: 0.5	High: 0.75	Very High: 1
TSS loading (mg/L)	<1	1-2	2-6.6	6.6-15	>15
PN loading (µg/L)	<10		10-20	>20	
DIN loading (µg/L)	<1	1-2	2-7	7-25	>25

2.3.3 Pesticide concentration mapping

Waters of the GBR lagoon are contaminated with a range of pesticides including herbicides, insecticides and fungicides. Pesticides, unlike nutrients, sediments and metals, have no natural sources and their concentrations have been positively correlated with low salinity associated with river runoff (Lewis et al. 2009; Kennedy et al. 2012a). Therefore, the occurrence of pesticides in the GBR can be attributed with great confidence to agriculture in the catchments that result in river discharge into the GBR lagoon. Of the 34 pesticides that have been detected in catchments draining to the GBR, several persistent and mobile PSII herbicides dominate the pesticides identified in water samples and passive samplers in both near-shore and offshore sites on the GBR. However, monitoring in the Cape York region has not detected pesticides beyond detection limits with a few exceptions, including very low levels of diuron, atrazine and simazine at the mouth of the Endeavour River (Gallen et al. 2014; Howley et al. 2010; Howley et al. 2012).

Multiple PSII herbicides are usually detected in water samples from the GBR (Lewis et al. 2012) and their combined effects on microalgae are additive (Shaw et al. 2009; Magnusson et al. 2010). This additive toxicity is not currently addressed in regulatory guidelines (King et al. 2013; Lewis et al. 2012) and is considered to be important in this assessment. The reduced photosynthesis in algae due to herbicide exposure causes reductions in the growth of these algae (Magnusson et al. 2008) and changes in species composition (Magnusson et al. 2012) but the effects of chronic exposures in near-shore environments remain largely unknown. This assessment incorporates an assessment of the acute exposure of PSII herbicides in the 2009-11 wet seasons.

Method:

The Cape York region was excluded from this process due to the limited use of pesticides in this region and low concentrations detected by monitoring projects (Howley, 2010; Howley, 2012), however the method is included for comparison of the results in this region compared to other GBR regions. The area is all assumed to be No Risk.

A full description of this method is provided in Lewis et al. (2013). A modelling approach based on the relationship between CDOM and sea surface salinity (Schroeder et al. 2012), was used with the results of in situ end of catchment and GBR lagoon pesticide concentration results for the 2009-2010 and 2010-2011 wet seasons.

Pesticide concentrations were assessed at the end-of-catchment monitoring sites in the 2009-2010 and 2010-2011 water years (Smith et al. 2012; Turner et al. 2012, 2013) to identify the periods where the higher concentrations coincided with elevated stream flows (based on the gauges of the Queensland Department of Natural Resources and Mines; QDNRM, 2012). Moderate Resolution Imaging Spectroradiometer (MODIS) Level-0 data with 1 km^2 resolution were acquired from the NASA Ocean Colour website (http://oceancolor.gsfc.nasa.gov). The most appropriate satellite image (i.e. the most free of cloud cover and sun glint) was selected for each NRM region within one week following the highest PS-II concentration. MODIS images were processed with the SeaWiFS Data Analysis System (SeaDAS). The semi-analytical model developed by Garvel-Siegel-Maritorena (GSM, Maritorena et al. 2002) implemented in SeaDAS was used to retrieve the absorption coefficient for dissolved and detrital material (CDOM+D). Bio-optical algorithms often fail to retrieve correct information over reef bottom type. Pixels values corresponding to reef locations were thus masked out from the CDOM regional maps.

CDOM was extracted from the satellite images and the relationship established by Schroeder et al. (2012) between measured salinity and CDOM was used to estimate sea surface salinity in the flood plumes. All of the regional pesticide maps were imported in ArcGIS for post-processing. Missing information (related to atmospheric perturbations, cloud cover or reefs that were masked out) was interpolated in ArcGIS. Pesticide levels were classified into different level of risk and the areas of reef and seagrass meadows at risk for each NRM region were quantified.

Two different but complimentary methods were used to determine the risk posed by mixtures of PSII herbicides. These were the Toxic Equivalence Quotient (TEQ) method (eg. Kennedy et al. 2012; Smith et al. 2012) and the multiple substances potentially affected fraction (ms-PAF) method (Traas et al, 2002). Importantly both methods use the concentration addition model to determine the toxicity of mixtures of PSII herbicides. The maps shown in this assessment are from the TEQ method.

Assessment classes

The key PSII herbicides of concern (diuron, hexazinone, atrazine, tebuthiuron, ametryn and simazine) were normalised to an herbicide-equivalent concentration which is based on the relative toxicity of diuron; the risk posed by PSII herbicides collectively could then be examined using the concentration addition model for joint toxicity (see Kennedy et al. 2012). The relative toxicities (EC50s and EC25s) of marine organisms including coral species (*Seriatopora hystrix* and *Acropora formosa*), diatoms (*Phaeodactylum tricornutum*) and green algae (*Chlorella vulgaris*) (Jones and Kerswell, 2003; Bengtson Nash et al. 2005; Muller et al. 2008) to each PSII herbicide compared to diuron was determined and then averaged to produce the relative toxicity factors (RTFs) (Kennedy et al. 2012). The TEQ method was applied to the measured EC50s and EC25s of PSII herbicides that inhibit the effective quantum yield (YII) in plants. Inhibition in YII by PSII herbicides is proportional to inhibition of photosynthesis and growth in tropical microalgae (Magnusson et al. 2008) as well at reduced energy acquisition by the host coral from its photosynthetic symbionts (Cantin et al. 2009).

Based on the toxicity of diuron calculated in several studies on coral and seagrass species we devised a set of threshold values that were considered to match the following risk classifications:

- **Very High**: >10 µg/L causes reduced growth and mortality in seagrass (Gao et al. 2011) and loss of symbionts (bleaching) in corals (Jones et al. 2003; Negri et al. 2005). The effect on health and survival of foundation species of the GBR can be catastrophic.
- **High:** 2.3 – 10 µg/L Photosynthesis is reduced by between 50% and 90% in corals (Jones and Kerswell, 2003; Negri et al. 2011); seagrass (Chesworth et al. 2004; Gao et al. 2011; Flores et al. 2013) and microalgae (Magnusson et al. 2008, 2010). A 50% reduction of growth and biomass of tropical microalgae was also reported in this concentration range (Magnusson et al. 2008). The community structure of tropical microalgae is significantly affected and this causes significant changes in the tolerance of microbial communities to herbicides (Magnusson et al. 2012). The effect on primary production is major.
- **Medium:** 0.5-2.3 µg/L Photosynthesis is reduced by between 10% and 50% in corals (Negri et al. 2011); seagrass (Haynes et al. 2000; Chesworth et al. 2004; Gao et al. 2011; Flores et al. 2013) and microalgae (Magnusson et al. 2008, 2010). The community structure of tropical microalgae can be affected by concentrations of diuron as low as 1.6 µg/L (Magnusson et al. 2012). The effect on primary production is moderate.

- **Low:** 0.1-0.5 µg/L Photosynthesis is reduced by up to 10% in corals (Negri et al. 2011); seagrass (Haynes et al. 2000; Chesworth et al. 2004; Gao et al. 2011; Flores et al. 2013) and microalgae (Magnusson et al. 2008, 2010). The effect on primary production is minor.
- **Very Low:** 0.025-0.1 µg/L No observed effect on photosynthesis in corals (Negri et al. 2011); seagrass (Haynes et al. 2000; Flores et al. 2013) and microalgae (Magnusson et al. 2008, 2010).
- **No Risk:** < 0.025 µg/L

The highest risk classification determined for any point in a flood plume from a catchment was adopted as the risk posed by that catchment.

Further explanations of the methods are provided in Lewis et al. (2013).

2.3.4 Other variables

Additional variables were considered that have not been included here due to the current lack of data showing their temporal and spatial patterns and ecological impacts. These include: phosphorus exposure, chronic exposure to PSII herbicides and non-PSII herbicides, and time series of PSII herbicide concentration data; although the PSII herbicide indicators are probably less relevant to the Cape York region at this time.

However, it is possible to include more pollutants in the loads assessment. For the loads assessment, while we consider nitrogen to be a more important nutrient than phosphorus with respect to effects in the marine environment (Furnas et al. 2013), we have limited certainty around this assumption. In our assessment in the ranking of end-of-catchment pollutant loads, we have considered PP and DIP to be equally relevant to PN and DIN given our current limitations in understanding.

Table 2.3. Summary of water quality variables, assessment classes and data sources included in the marine risk assessment.

Variables	Assessment Class					Data source/methodology
	Very Low 1	**Low 2**	**Medium 3**	**High 4**	**Very High 5**	
Sediments						
Total Suspended Solids (TSS) concentration (mg/L)						Based on daily satellite observations of TSS in the period 1 Nov 2002 to 30 April 2014. Data has been interpolated across reefs (which are masked during image processing) using Euclidean Allocation in ArcGIS. Classification of frequency of exceedance is based on the number of valid observations in the full observation period. Method for extraction described in Maynard et al. (2015).
Frequency of exceedance % 2 mg/L threshold	<1	1-10	10-20	20-50	50-100	Threshold correlates strongly with declines in ecosystem condition such as increased macroalgal growth and declining diversity. Average annual threshold for TSS in the Great Barrier Reef Water Quality Guidelines.
TSS Plume Loading (mg/L) (mean 2003-2013)	<1	1-2	2-6.6	6.6-15	>15	The frequency and extent of the influence of flood plumes containing differing concentrations of TSS is used to provide an estimation of the extent of surface exposure of coral reefs and seagrass during wet season conditions. TSS plume load maps were produced combining in-situ data collected under the Marine Monitoring Program, plume maps derived from MODIS imagery and monitored end-of catchment TSS load in each wet season (c.a. Dec to Apr, inclusive) from 2003 to 2013 (Brodie et al. 2015; da Silva et al. in prep.). The river loads provide the amount of TSS that has been delivered along the GBR. The in-situ data provides the TSS mass variation as a function of the river plume movement away from the river mouth. The satellite imagery provides the direction and intensity the TSS mass is transported over the GBR lagoon. This method produces maps of the TSS dispersion in the GBR waters expressed in mass per area. Annual maps of TSS were produced to describe differences in GBR exposure to this pollutant. Mass/area maps were converted to concentration maps by dividing it by the bathymetry of the GBR lagoon. Annual maps were averaged to represent the mean distribution of the TSS concentration over the GBR lagoon. The same method is applied to calculate DIN and PN loading.
Nutrients						
Chlorophyll *a* concentration (µg/L)						Assessment classes were based on long term Chl-a mean concentration derived from in-situ monitoring data (1988-2006) (De'ath and Fabricius 2008).
Mean concentration (µg/L)	<0.18	0.18-0.25	0.25-0.45	0.45-0.8	>0.8	Chlorophyll *a* is an indicator of nutrient enrichment in marine waters. De'ath and Fabricius (2008) identified 0.45 µg/L as an important ecological threshold for macroalgal cover, hard coral species richness, octocoral species richness. Annual average threshold for chlorophyll in the Great Barrier Reef Water Quality Guidelines. Significant benefits for the ecological status of reefs in the region are likely if mean

Variables	Assessment Class					Data source/methodology
	Very Low 1	Low 2	Medium 3	High 4	Very High 5	
						annual chlorophyll concentrations remain below this concentration. Other classes are described in Section 1.1.1.
Dissolved Inorganic Nitrogen (DIN) Plume Loading (µg/L) (mean 2003-2013)	<1	1-2	2-7	7-25	>25	Elevated dissolved inorganic nitrogen (DIN) is an indicator of nutrient enrichment. High concentrations of DIN can reduce coral recruitment (Babcock and Davies, 1991; Loya et al. 2004), enhance coral bleaching susceptibility (Wooldridge and Done, 2009) and change the relationship between coral and macroalgal abundance (De'ath and Fabricius, 2010). Elevated concentrations can also be deleterious to seagrass by lowering ambient light levels via the proliferation of local light absorbing algae thereby reducing the amount of photosynthesis in seagrass, particularly in deeper water (Collier, 2013). Particulate nutrients are also important in driving ecological effects. Particulate forms mostly become bioavailable over longer time frames than dissolved inorganic nutrients (Furnas et al. 2013). The same method is applied to calculate TSS, DIN and PN loading. Refer above.
Particulate Nitrogen (PN) Plume Loading (µg/L) (mean 2003-2013)	<10		10-20		>20	The same method is applied to calculate TSS, DIN and PN loading. Refer above.
PSII Herbicide modelled concentration (µg/L)	0.025-0.1	0.1-0.5	0.5-2.3	2.3-10	>10	Based on an estimate of the relationship between Colour Dissolved Organic Matter (CDOM) and salinity, and then a modelled salinity to PSII herbicide concentration relationship in a flood plume event in one river in each NRM region in 2009-2011. Data has been interpolated across reefs (which are masked during image processing) using Euclidean Allocation in ArcGIS. Risk posed was determined using a number of methods - some only assessed acute toxic effects, others both acute and chronic. Described in Lewis et al. (2013). **No Risk: <0.025 µg/L**; **Very Low: >0.025-0.1 µg/L**: No observable effect; **Low: 0.1-0.5 µg/L**: Photosynthesis is reduced by up to 10% in corals (Negri et al. 2011); seagrass (Haynes et al. 2000; Chesworth et al. 2004; Gao et al. 2011; Flores et al. 2013) and microalgae (Magnusson et al. 2008, 2010). The effect on primary production is minor. **Medium: 0.5-2.3 µg/L**: Photosynthesis is reduced by between 10% and 50% in corals (Negri et al. 2011); seagrass (Haynes et al. 2000; Chesworth et al. 2004; Gao et al. 2011; Flores et al. 2013) and microalgae (Magnusson et al. 2008, 2010). The community structure of tropical microalgae can be affected by concentrations of diuron as low as 1.6 µg/L (Magnusson et al. 2012). The effect on primary production is moderate. **High: 2.3-10 µg/L** Photosynthesis is reduced by between 50% and 90% in corals (Jones and Kerswell, 2003; Negri et al. 2011); seagrass (Chesworth et al. 2004;

Variables	Assessment Class					Data source/methodology
	Very Low 1	**Low 2**	**Medium 3**	**High 4**	**Very High 5**	
						Gao et al. 2011; Flores et al. 2013) and microalgae (Magnusson et al. 2008, 2010). A 50% reduction of growth and biomass of tropical microalgae was also reported in this concentration range (Magnusson et al. 2008). The community structure of tropical microalgae is significantly affected and this causes significant changes in the tolerance of microbial communities to herbicides (Magnusson et al. 2012). The effect on primary production is major. **Very High: > 10 µg/L**: reduced growth and mortality in seagrass (Gao et al. 2011) and loss of symbionts (bleaching) in corals (Jones et al. 2003; Negri et al. 2005).

2.4 Assessment Indexes

The variables described above and shown in Figure 2.1 have been combined into a number of indexes related to marine ecological risk and end-of-catchment pollutant loads. A COTS influence factor is also discussed for the Normanby River.

2.4.1 Marine Risk Index

To estimate ecological risk in this assessment, the six water quality variables (described above) that represent key runoff-transported pollutants of greatest concern to two GBR ecosystems in the region: seagrass meadows and coral reefs. To account for limitations in the available datasets (see Brodie et al. 2013a for further explanation), ecological risk was expressed as the area of these ecosystems within a range of spatially defined assessment classes (very low to very high relative risk) for several water quality variables for the marine NRM region, and then in each river's Zone of Influence where available (see explanation below). The variables included ecologically relevant thresholds for concentrations of Chl-a obtained from long term in-situ monitoring data and TSS from remote sensing observations, and the distribution of key pollutants including TSS, DIN, PN and PSII herbicides (No Risk) in the marine environment during flood conditions (based on end-of-catchment loads and plume loading estimates). A factor that represents the influence of Crown of Thorns Starfish (COTS) on coral reefs, and the differential influence of river discharges on the COTS initiation zone was included in previous assessments and is relevant here. However, the modelled influence is only available for the Normanby River, and therefore, can only be included as an additional explanatory variable.

For each of the variables shown in Figure 2.1 and Table 2.1 a classified spatial data layer was prepared in ArcGIS. The classifications, scores and overall weightings for this assessment were customised using the expert opinions of the project team and are shown in Table 2.5. The assessment classes for each variable were allocated a score between 0 (lowest severity) and 1 (highest severity) at the 1 km^2 pixel scale. Pixels in the highest assessment class all received the maximum value of 1. For example, for the TSS threshold of 2 mg/L the scores for the frequency of exceedance classes would be Very Low (<1% exceedance) = 0; Low (1-10% exceedance) = 0.25; Medium (10-20% exceedance) = 0.5; High (20-50% exceedance) = 0.75; and Very High (50-100% exceedance) = 1.0. The areas of coral reefs and seagrass meadows were reported for each assessment class in for the marine NRM region and each available river Zone of Influence in ArcGIS.

Table 2.4. Summary of the classes for each variable and the weightings given to each assessment class for the combined relative risk assessment. The variables are described in Table 2.3.

Variables	Overall weighting	Assessment Class				
		Very Low 1	Low 2	Medium 3	High 4	Very High 5
TSS threshold exceedance 2mg/L Frequency of exceedance (%)	1/6	<1	1-10	10-20	20-50	50-100
Score		0	0.25	0.5	0.75	1.0
TSS Plume Loading (mg/L) (mean 2003-2013)	1/6	<1	1-2	2-6.6	6.6-15	>15
Score		0	0.25	0.5	0.75	1.0
Chl long term concentration (µg/L) (mean 1988-2006)	1/6	<0.18	0.18-0.25	0.25-0.45	0.45-0.8	>0.8
Score		0	0.25	0.5	0.75	1.0
DIN Plume Loading (µg/L) (mean 2003-2013)	1/6	<1	1-2	2-7	7-25	>25
Score		0	0.25	0.5	0.75	1.0
PN Plume Loading (µg/L) ((mean 2003-2013)	1/6	<10		10-20	>20	
Score		0		0.5	1	
PSII Herbicide modelled concentration (µg/L) (2009-2011)	1/6	0.025-0.1	0.1-0.5	0.5-2.3	2.3-10	>10
Score		0.25	0.5	0.75	1.0	No occurrence

Ideally the classes for each variable would be scaled so that they are equivalent in terms of potential ecological impacts to provide comparable weightings between variables. However, our knowledge of ecosystem impacts is not sufficiently advanced to allow comparable scaling of variables. As temporal and spatial resolution of the input data increases and the knowledge of the impacts of sediments, nutrients and PSII herbicides on GBR ecosystems is advanced, this capability can be improved in future assessments. After testing several approaches to weighting the variables, it was agreed to weight each spatial layer equally and as additive factors. The data layers were then combined using the Union tool in ArcGIS and the values of each coincident pixel were summed, normalised and classified into five even break classes ranging from Very Low to Very High. An example of the process applied ArcGIS is shown in Figure 2.6.

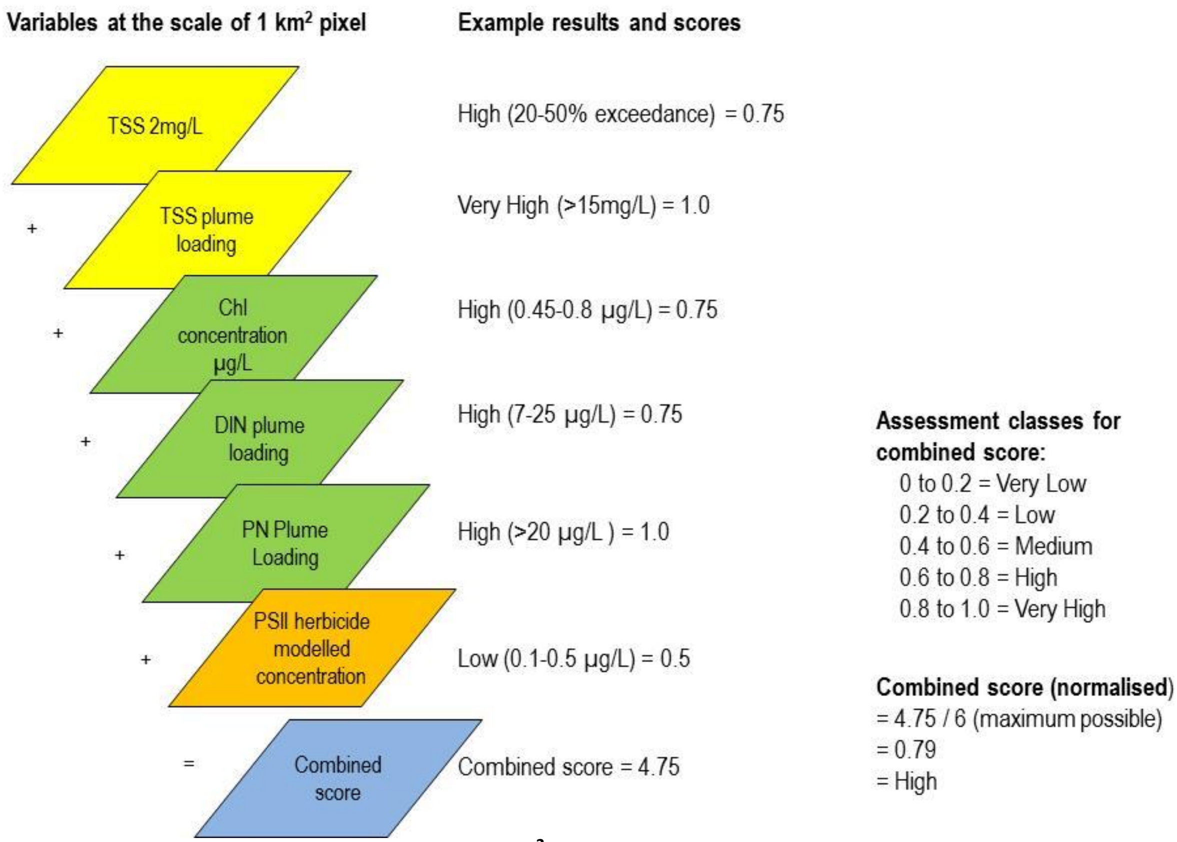


Figure 2.6. Example of the results in one pixel (1km^2) in ArcGIS. The result for coincident cells from each layer is summed to give a combined score, normalised and classified into five assessment classes (Very Low to Very High). In this example the combined score gives the cell a score within the High assessment class in terms of relative risk of degraded water quality. The colours represent groups of variables: yellow = sediment related variables, green = nutrient related variables and orange = PSII herbicide related variables.

The area of coral reefs and seagrass meadows in each of the five assessment classes of the combined layer in the marine NRM region was calculated. Where the river Zones of Influence area available, areas were calculated to allow comparison between basins. The Marine Risk Index for each basin was calculated by summing the areas of coral reefs and seagrass meadows only in the highest assessment classes of the combined layer. To allow relative comparison between the basins in the region, each result was anchored to the basin with the maximum area which was given a score of 1.0. This enabled an assessment of the relative differences between basins in terms of combined water quality risk for coral reefs and seagrass meadows. The final output is a Coral Reef Marine Risk Index and a Seagrass Marine Risk Index.

As a final step, these Indexes were summed with the Loads Index for each basin to determine the overall relative risk of degraded water quality to coral reef and seagrass ecosystems for each basin in the Cape York region.

2.4.2 Loads Index

To inform management priorities that aim to address the risks identified in the Marine Risk Index, it is necessary to understand the influence of river discharge from each of the basins, as these discharges carry the majority of the pollutants into the GBR lagoon. Modelled end-of-catchment pollutant loads, generated from the Source Catchments model framework for the Paddock to Reef Program (McCloskey et al. in review) were obtained for each basin for key pollutants: TSS, DIN, PN, DIP, PP and PSII herbicides. Load estimates have also been generated by Howley et al. (2015) for the Normanby, Annan and Pascoe Rivers to support the WQIP but the Source Catchments model results are used here for consistency of methods across all catchments.

First, the Source Catchments modelling framework was used as a synthesis tool that incorporates new information on paddock modelling of TSS, speciated N and P, and PSII herbicides, plus spatially and temporally remote sensed inputs (McCloskey et al. in review). This resulted in a consistent set of end-of-catchment pollutant loads for each of the catchments in the eastern Cape York region (McCloskey et al. in review), which is part of a larger project that models all of the 35 GBR basins (Waters et al. 2014). Anthropogenic load is calculated as the difference between the long term average annual load and the estimated pre-European annual loads. A fixed climate period was used (1986 to 2014) for all model runs to normalise for climate variability and provide a consistent representation of pre-development and anthropogenic generated catchment loads. This therefore represents an 'average' year rather than the extremes such as those recorded in the period 2008 to 2013. In addition, functionality from the previous iteration of catchment modelling, SedNet/ANNEX (for example see Cogle et al. 2006), has been incorporated into Source Catchments to represent hillslope, gully and streambank erosion and floodplain deposition processes. This has also improved in the most recent update of the Source Catchments modelling platform (2015) with improved gully mapping. Other improvements include extension of the model run period (was 1986 to 2009 in previous reporting), improved hydrological calibration and additional load validation (Gillian McCloskey, pers. comm.). However, according to the empirical loads estimates from Howley et al. (2015), the Source Catchments results have significantly underestimated sediment loads discharged to the GBR lagoon from the Annan and Pascoe Rivers.

For this assessment the anthropogenic load was incorporated as a proportion of the total load, as it is only the anthropogenic portion that is assumed to be the 'manageable' component of pollutant loads. The anthropogenic load is calculated as the difference between the long term average annual load (when 2008-2009 management inputs and distributions are assumed), and the estimated pre-European load. The proportional basin contributions were then normalised to a standard scale and summed to generate a combined **Loads Index** for TSS and speciated N and P for each catchment. This assumes that the relative importance of each load is equal which may not be the case, although there is currently insufficient knowledge to weight the importance of the pollutants relative to each other. PSII herbicides were not included in the assessment as there is limited measured data in the region and concentrations in the coastal and marine ecosystems are expected to be low due to limited use in the catchments.

2.4.3 COTS Influence Index

In recognition of the importance of the influence of catchment discharges (mainly due to DIN) in driving COTS outbreaks (see Fabricius et al. 2010; Furnas et al. 2013a; Brinkman et al. 2014; Wooldridge and Brodie, 2015), an index of regional contributions of river discharges to the COTS Initiation Zone is considered for coral reefs; the 'COTS Influence Index'. This index is considered the Marine Risk Index (see Section 2.3.1) because approximately 40% of the loss of coral cover in the GBR since 1987 has been attributed to COTS predation (De'ath et al. 2012). The COTS Initiation Zone shown in Figure 2.7 has been identified as the area of highest risk with respect to initiating COTS primary outbreaks. **However, in this assessment, the Index is calculated but not formally incorporated into the final Relative Risk Index as the supporting analysis (Brinkman et al. 2014) is constrained to the Normanby River only.**

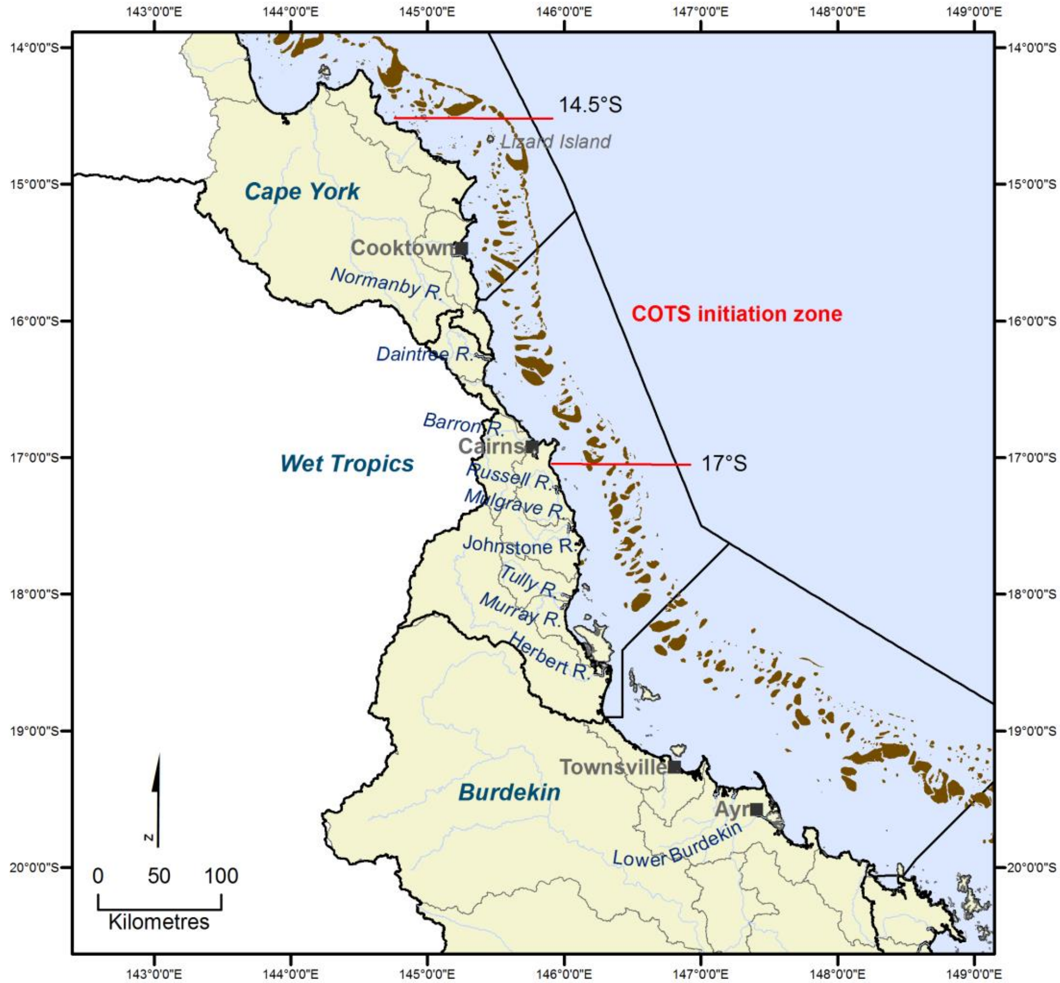


Figure 2.7. Location of the COTS Outbreak Initiation Zone, defined as a high risk area for COTS primary outbreaks based on current understanding of the outbreak initiation zone between 14.5 ° S and 17 ° S. Refer to Furnas et al. (2013a) for further explanation.

On total volumetric basis, most of the estimated freshwater input (direct and indirect) to the COTS Initiation Zone comes from Wet Tropics Rivers, with the remaining from the Burdekin River (Furnas et al., 2013a). The influence of the Burdekin River is particularly significant in large flow years, which on average (over a long term record) occurs every 6 years (Fabricius et al., 2010). Using this information across 4 years (2008-09, 2010-11, 2011-12, 2012-13) and Event Mean Concentrations of DIN for each basin, of river-sourced DIN inputs into the COTS Initiation Zone were calculated to generate a DIN Risk Score for each basin. These estimates were used to create a **COTS Influence Index**. The southern Cape York rivers (Annan, Endeavour, Jeannie, etc) are also likely to influence the COTS Initiation Zone to some extent in most years, but these rivers were not able to be included in the analysis as they are not included in the hydrodynamic model.

The following method description is extracted from Brinkman et al. (2014).

River Discharge

For estimates of river flows and runoff volumes likely to affect the risk area for COTS outbreaks, runoff from the Normanby (mean annual discharge ~ 7.5 Km^3), Daintree (~ 1.3 Km^3), Barron (~0.8 Km^3), Russell-Mulgrave (~3.6 Km^3), Johnstone (~4.7 Km^3), Tully (~3.3 Km^3), Herbert (~4.0 Km^3) and Burdekin Rivers (~10.3 Km^3) were considered. This assessment did not include the Annan, Endeavour, McIvor, Starcke and Jeannie rivers from south Cape York which discharge directly into the COTS Initiation Zone as they are not gauged, and therefore, not included in the hydrodynamic model. Daily river discharges (ML day^{-1}) for the rivers that were assessed were obtained from the Queensland Department of Natural Resources and Mines (DNRM) for the 2008-09, 2010-11, 2011-12, 2012-13 wet seasons. Estimates of annual discharge from individual rivers over this period were made from integrations of daily flows from 1 October to 30 September (water year). Because COTS spawn in the early summer, integrations of discharge likely to affect pelagic COTS larvae were also done from 1 November to 28 February. For the purpose of integrating discharges, gaps in flow records for individual rivers were filled. Short gaps were filled by linear interpolation of daily flows across gaps. Longer gaps were filled using regressions derived between daily flows in a particular river and flows in adjacent rivers with nominally similar rainfall and catchment runoff characteristics (e.g. Tully and Johnstone Rivers) on the premise that integrating reasonable, if imprecise estimates of flows across a gap is better than integrating "0's". Annual fresh water discharges were normalised by the Daintree River discharge, the largest river discharging directly into the outbreak initiation region.

DIN Loading

Estimates of annual DIN loads from regional rivers for the period 1999-2013 were obtained from TropWATER (Lewis et al. 2014). DIN loads based on event mean concentrations (EMCs inμg/L) were calculated for each water year (Oct 1 to Sept 30). Mean EMCs for the period 1999-2013 were calculated for each river and used in conjunction with the yearly volumetric contributions to assess DIN contributions to the outbreak region.

Risk scores

DIN exposure risk scores were calculated for each river, for each modelled year by multiplying the event mean concentration (μg/L) by the annual freshwater volume (normalised against the Daintree), multiplied by the % volumetric contribution to the outbreak initiation region, i.e. Risk Score = DIN Conc * FW volume * % contribution to source region. Using flows normalised to against the Daintree does not alter the risk rankings for each year, but allows comparison between years (and therefor the mean risk) as flows have been referenced to a consistent baseline. Mean risk scores were calculated for each river for the 4 modelled wet seasons. Rivers were then ranked based on their risk for individual years, and also based on the mean risk.

2.4.4 Relative Risk Index

To provide an overall relative ecological risk ranking between the eastern Cape York catchments (where possible), the Marine Risk Indexes for coral reefs and seagrass meadows were summed with the Loads Index, to generate a Coral Reef Relative Risk Index and a Seagrass Relative Risk Index. These final indexes for coral reefs and seagrass were then summed and normalised (0 to 1) to give an overall assessment of the relative risk of degraded water quality to coral reefs and seagrass meadows to generate a Relative Risk Index for each basin. Since the COTS Influence Index is only available for the Normanby River, it is not included as a formal index in the assessment.

2.5 Recognising and assessing uncertainties in the data

Given the limited time and resources available for this study, differences in uncertainty and hence confidence in the data can only be assessed subjectively and no specific quantitative estimates were considered. If such qualitative assessments of uncertainty in the methodologies and data were undertaken, uncertainty would be assessed as varying as much within as among catchments with the exception of Normanby Basin where more monitored data is available. However, in an attempt to provide relative differences between datasets, a qualitative statement of data confidence is included (low, moderate or high) below and noted in the Results for each variable.

The zones of influence defined for the modelled rivers in the eastern Cape York region are an estimate only and the method requires refinement and validation by actual monitoring of flood plumes and detailed analysis of MODIS imagery from Cape York flood plumes. There are a number of limitations to the existing approach:

- For the hydrodynamic model, each river is modelled individually ('turned on' in the model one at a time) so there is no assessment of the combined forcing of multiple river discharges. The general movement of river discharges in a northern direction will influence water movement and hence spatial extent in reality.
- The selection of the threshold requires further testing to optimise the representation of average wet season conditions. The tracer thresholds also need to be correlated with in situ and / or remote sensing data to show that the threshold level is physically, chemically and biologically relevant.
- The zones were defined using four years of data and should be extended to account for greater inter-annual variability.
- For the unmodelled rivers, the path-distance approach enabled the assessment to extend beyond the rivers that are covered by the hydrodynamic model (just the Normanby River in this region). However, the sources of error in the path-distance approach are twofold: 1) the ability to predict plume maximum extent (i.e. the river mouth to plume edge distance) is only as good as the relationship between extent and flow; and 2) even if the mouth-to-edge distance could be accurately predicted, the plume shape cannot be accurately replicated. The path-distance function was parameterised based on the best overlap with tracer plumes, but with the current technique, overlap is in the order of 50-70(+) %. Further work is underway to test this, for example, working on shorter timescales (e.g. weekly) may be beneficial.

The relative ranking of uncertainty in the input data for this study has been estimated from the literature and expert opinion. The results for this ranking are included in the description of each variable, and can be summarised as follows:

- Remote sensing TSS – low certainty
- Long term chlorophyll – low certainty (limited samples)
- TSS plume loading –moderate certainty
- DIN Plume loading –low certainty
- PN Plume loading - low certainty
- PSII concentration model – moderate certainty
- River loads – moderate certainty
- Coral reef areas – high certainty
- Seagrass areas – monitored: moderate certainty; modelled: low/moderate certainty - applied 50% probability map
- River zones of influence – low certainty

Further discussion of the uncertainties and limitations of the assessment, in addition to improvements to the previous risk assessments, are presented in Section 5.

3 Results

3.1 River Zones of Influence

Flow and runoff characteristics are important in providing context to this assessment. The Normanby Basin has the highest modelled average annual flow (estimated to be 4,700,000 ML/yr in the Source Catchments model), followed by the Olive-Pascoe (3,600,000 ML/yr) and Jacky Jacky (2,800,000 ML/yr) basins. The annual flow from 2008 to 2014 for the rivers included in the assessment are shown in Table 3.1, showing that 2010-2011 was a large flow event for all of the modelled rivers.

Table 3.1. Total annual freshwater discharge (in ML per water year, c.a. 1 October to 30 September) and the long-term (LT) median (c.a. from 1970-1971 to 1999-2000) for major gauged rivers in the Cape York NRM region. Colour code stands for: yellow, 1.5 to 2 folds LT median; orange, 2 to 3 folds LT median, and red, >3 folds LT median. Data supplied by the Department of Natural Resources and Mines (Queensland Government, https://www.dnrm.qld.gov.au/water/water-monitoring-and-data/portal). Source: Devlin et al. (in press).

River	Annual long term freshwater discharge						
	Annual long term median	2008 - 2009	2009 - 2010	2010 - 2011	2011 - 2012	2012 - 2013	2013 - 2014
Pascoe	1,252,975	636,350	1,534,694	1,972,999	758,509	827,844	1,577,527
Stewart	217,473	113,018	188,528	376,009	106,219	90,233	226,187
Normanby	4,700,000[1]	2,346,173	2,945,850	5,964,886	1,148,416	1,822,230	2,663,005
Annan	276,538	175,800	407,257	550,403	331,370	196,441	302,309

Notes: The full dataset does not exist for the Normanby gauging station, so this is the long term modelled flow in Source Catchments (McCloskey et al. 2014).

Generally, the Normanby, Endeavour, Stewart and Jeannie basins have a similar pattern of flow with little dry season flow between July and November, while the Olive-Pascoe, Jacky Jacky and Lockhart are similar with more continuous annual flows.

The main characteristics of the estimated Zones of Influence (ZoI) are summarised below. All of the ZoI extend beyond the inshore areas to the midshelf areas, noting though that the 'midshelf areas' in the Cape York region (as defined by GBRMPA, 2010) are within approximately 6 kilometres of the coast in most locations, and the outer reef boundary is approximately 24 kilometres offshore. The outer boundary of the ZoI are typically within 20 kilometres of the coast (Figure 3.1) except in the receiving area of Princess Charlotte Bay where the outer edge is approximately 40 kilometres from the river mouth at the furthest point and therefore technically within offshore areas.

There is high variability between years for the estimated ZoIs for each river in the assessment years – 2008-09, 2010-11, 2011-12 and 2012-13 (as noted above, 2009-10 is not included in the model but this was also a relatively large discharge event for some rivers (see Table 3.2).

- As expected, the area of coral reefs and seagrass in the zones varies considerably between rivers and is not directly proportional to the area of the zone, due to spatial variability in habitat distribution in the region.
- The largest river ZoI in the region is by far from the Normanby River, with an estimated maximum extent area of 7,180km^2 (Figure 3.1). This extent was associated with the 2010-2011 flood events, when the river discharge was almost 5,965,000 ML, compared to 2,346,000 ML in 2008-2009, 1,148,000 ML in 2011-2012 and 1,822,000 ML in 2012-2013. The Zone of Influence extended as far north as Cape Grenville during the 2010-11 wet season, although the southern extent of the estimated zones of influence were still within Cape Melville, reflecting the northward movement of the plumes and the role of Cape Melville in steering water inside Princess Charlotte Bay. The plume extends to the offshore area in Princess Charlotte Bay and encompasses the Flinders Island group in

2011 and 2013. The maximum extent (2010-2011) ZoI includes approximately 700km^2 of surveyed potential seagrass habitat, 830km^2 of deepwater modelled seagrass and 450km^2 coral reef.

- Additional information is also available for assessing the influence of the Normanby River in the region. CYMAG Environmental mapped the visual extent of a 2009 flood plume by aerial survey (Howley unpublished). Howley et al. (in prep) mapped the extent of Princess Charlotte Bay flood plumes during three flood events in 2012, 2013 and 2014 using MODIS imagery, aerial surveys and monitoring of salinity along transects across the plumes. Petus et al. (unpublished) tested the use of MODIS true color images and plume water type maps produced using the method of Álvarez-Romero et al. (2013) to study the spatial and temporal variability of Princess Charlotte Bay river plumes formed by Cape York flood events over the last 7 years, with specific attention to potential intrusions to the COTS Initiation Zone. This is discussed in Section 3.6. While the plumes typically move in a northerly direction, driven by south easterly winds, there are conditions when the plumes are deflected outwards in an easterly direction, as shown in Figure 3.2. In addition, Furnas et al. (2013) used an analysis of passive tracers from the Normanby River in 2010-11 using the eReefs hydrodynamic model to estimate freshwater exposure from the plume. This assessment showed that the area of influence was within Princess Charlotte Bay and northwards to the Lockhart River mouth (Figure 3.3).
- The maximum extent of the Pascoe River ZoI is estimated to be 2,740km^2 extending in a northerly direction to Cape Grenville and the Home Island group (Figure 3.4a). In terms of southern extent, the plume did not extend beyond Cape Weymouth, except in 2012 where it extended to Cape Griffith. The maximum extent ZoI includes approximately 120km^2 of surveyed potential seagrass habitat, 48km^2 of deepwater modelled seagrass and 620km^2 coral reef.
- The maximum extent of the Stewart River ZoI (Figure 3.4b) is estimated to be 2,720km^2 extending into the northern areas of Princess Charlotte Bay, up to the Nesbit River mouth in the Lockhart Basin. The ZoI extended into offshore areas in 2011, 2012 and 2013. The maximum extent ZoI (2010-2011) includes approximately 2308km^2 of surveyed potential seagrass habitat, 218km^2 of deepwater modelled seagrass and 290km^2 coral reef.
- The maximum extent of the Hann River ZoI is estimated to be 1,494km^2 extending into Princess Charlotte Bay (Figure 3.4c). The maximum extent ZoI (2010-2011) includes approximately 100km^2 of surveyed potential seagrass habitat, 180km^2 of deepwater modelled seagrass and 20km^2 coral reef.
- The maximum extent of the Endeavour River ZoI is estimated to be 1,445km^2 extending north to Cape Flattery in all modelled years (Figure 3.4e). The southern extent is located south of the Annan River mouth, but within the Cape York marine NRM region boundary. The maximum extent ZoI includes approximately 30km^2 of surveyed potential seagrass habitat, 940km^2 of deepwater modelled seagrass and 50km^2 coral reef. The area of deepwater modelled seagrass in the ZoI is the largest of all of the modelled rivers.
- The ZoIs from the Stewart, Hann and Normanby River all overlap to some extent in Princess Charlotte Bay which contains notable areas of surveyed potential seagrass habitat and deepwater modelled seagrass. The largest area of coral reefs is in the Pascoe River ZoI, the largest area of surveyed potential seagrass habitat is in the Normanby River ZoI (700km^2) and the largest area of deepwater modelled seagrass is in the Endeavour River ZoI (940km^2).
- ZOI have not been mapped for a number of rivers including the Jacky-Jacky, Olive, Lockhart, Jeannie, Starcke and McIvor Rivers.

Data confidence: Low due to limitations associated with river flow (see Section 2.4), definition of the threshold, coverage of the spatial layer in coastal areas and limited consideration of the combined effect of river discharges. In addition, not all rivers in the region are modelled so it is difficult to use as a region-wide assessment.

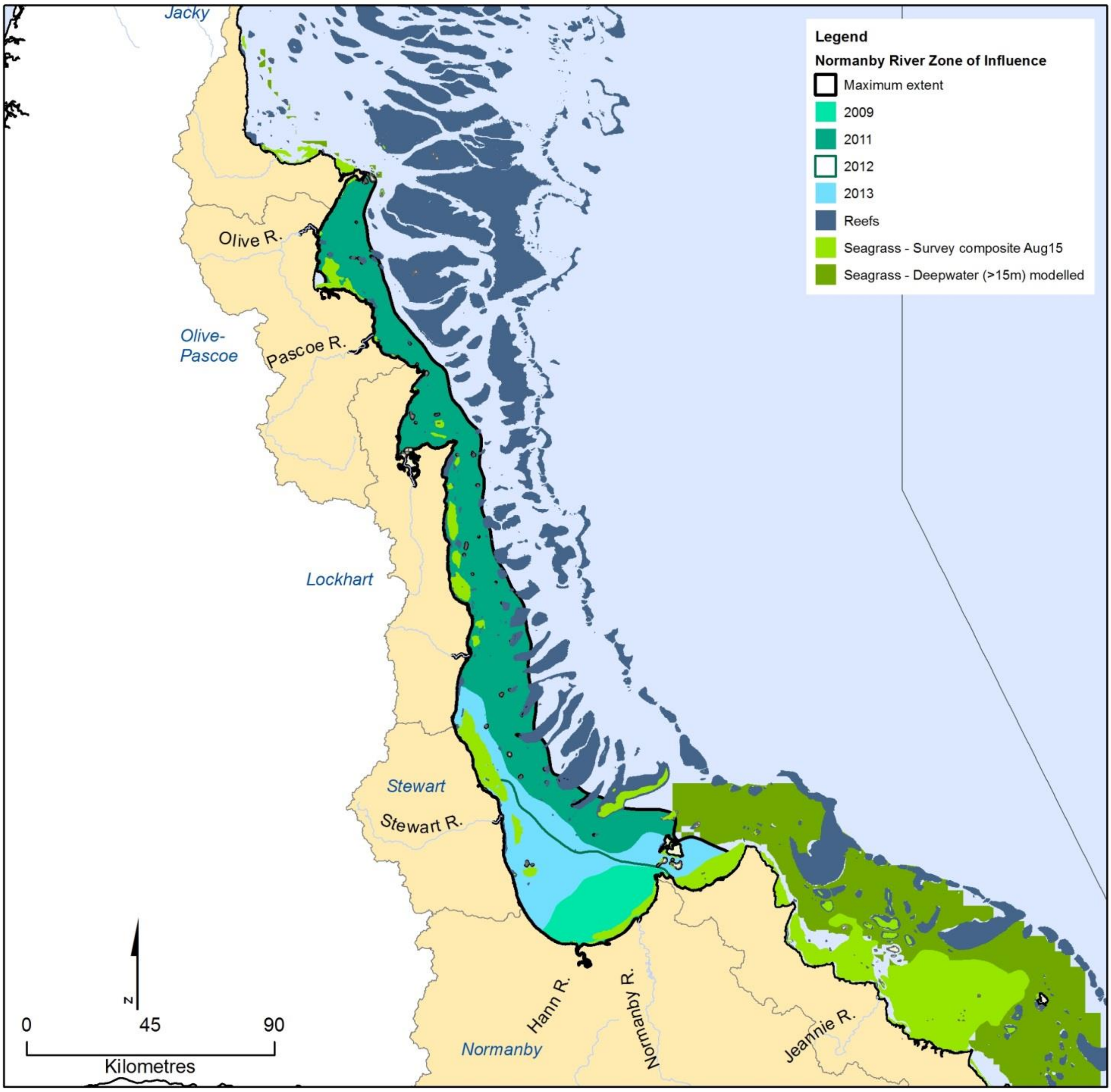


Figure 3.1. Modelled Zone of Influence for the Normanby River. The method for deriving these zones is described in Section 2.2.2.

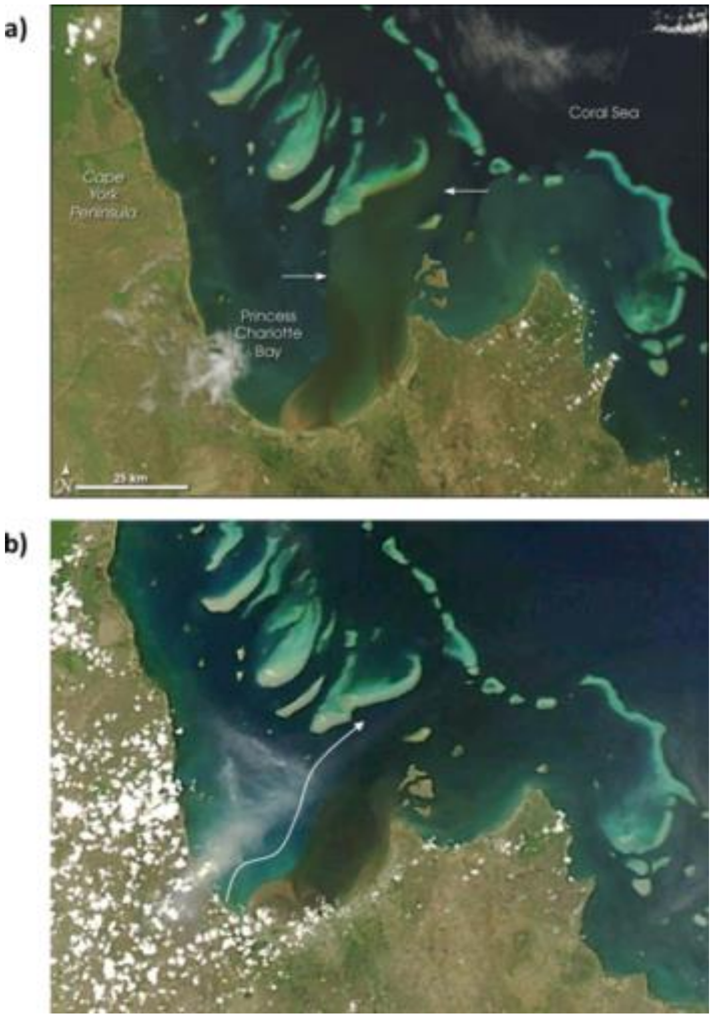


Figure 3.2. MODIS true colour images of the 9th of February 2007 and 31th of January 2013 showing Princess Charlotte Bay river plumes deflected to the right and reaching coral reefs. Source: Petus et al. (unpublished).

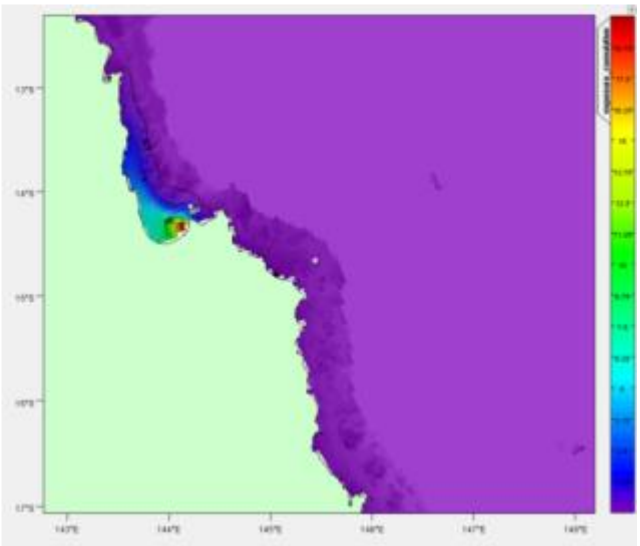


Figure 3.3. Cumulative exposure index for the Normanby River in the 2010-2011 wet season showing influence of the Normanby river plume in Cape York; from Furnas et al. (2013).

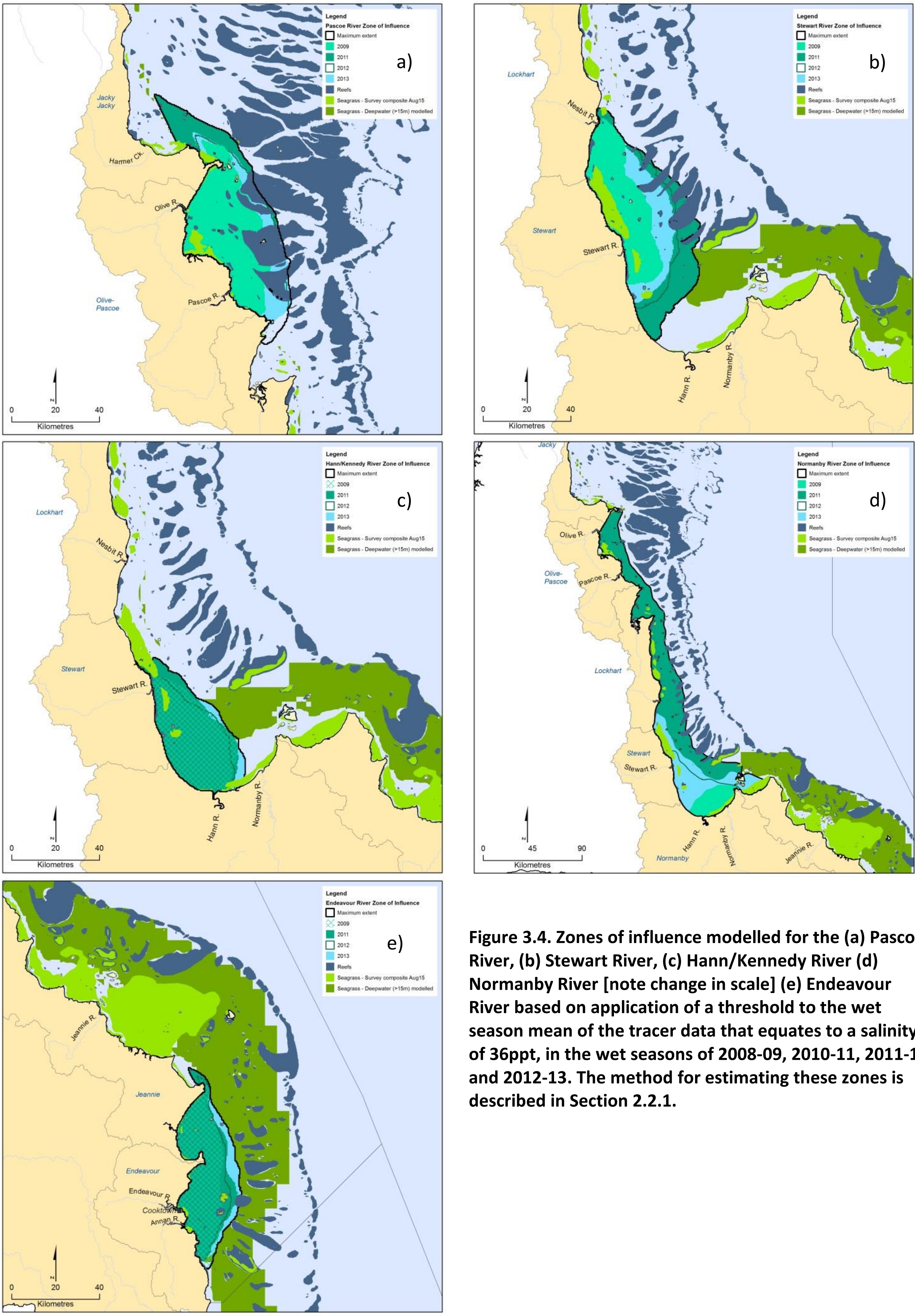


Figure 3.4. Zones of influence modelled for the (a) Pascoe River, (b) Stewart River, (c) Hann/Kennedy River (d) Normanby River [note change in scale] (e) Endeavour River based on application of a threshold to the wet season mean of the tracer data that equates to a salinity of 36ppt, in the wet seasons of 2008-09, 2010-11, 2011-12 and 2012-13. The method for estimating these zones is described in Section 2.2.1.

A number of additional boundaries and features are also used to describe the results, including Dugong Protection Areas, coastal bays and cross shelf waterbodies. These are shown in Figure 3.5. The cross shelf waterbodies are defined by GBRMPA (C. Honchin, 2015) and are the current boundaries for establishing Environmental Values under the *Environment Protection (Water) Policy 2009*. For the purposes of this report, the Enclosed Coastal and Open Coastal waterbodies are described as a combined 'Inshore' area.

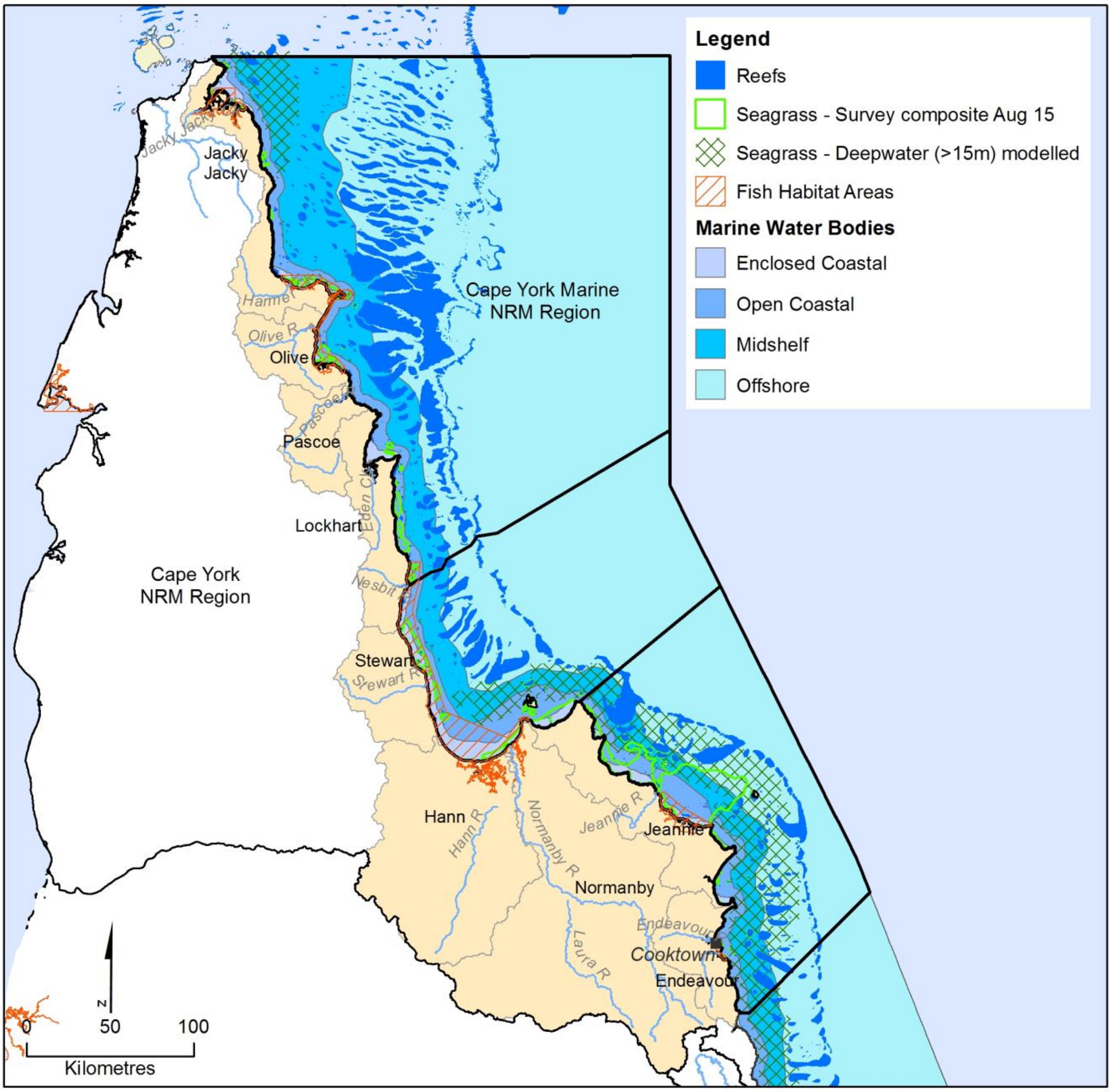


Figure 3.5. Boundaries and features in the Cape York Region used to describe the results for this relative risk assessment. Note: Marine waterbodies and reefs courtesy of GBRMPA; seagrass supplied by JCU; DPAs and FHA supplied by the Queensland Government.

3.2 Habitat areas

Table 3.2 shows the area of coral reef, seagrass, sub-regions, and Zone of Influence for the rivers modelled in the Cape York region. The total area of coral reef in the GBR is estimated around 24,000 km^2. The total area of coral reefs calculated in the Cape York marine NRM region for this assessment is 10,408km^2. This varies slightly (<1%) from the standard reported area of 10,354 km^2 (Coppo et al. 2015) due to the pixel based analysis used in this assessment. A large proportion of reefs are located in the North sub-region.

Approximately 35,000 km^2 of potential seagrass habitat has been mapped in the coastal waters around Queensland and Torres Strait since the mid-1980s. Surveys and statistical modelling of seagrass in offshore waters deeper than 15 metres (using the 50% probability assessment) shows that 37,454 km^2 of the sea floor within the Great Barrier Reef World Heritage Area and Torres Strait has some seagrass present making Queensland's seagrass resources globally significant. From the mapping data used in this assessment, the total area of potential seagrass habitat (surveyed) in the marine NRM region for Cape York is 2,668km^2 and the modelled deepwater (>15m) seagrass estimate is 5,668km^2. The combined total of 12,218km^2 accounts for ~35% of the total area reported for the GBR. A large proportion of surveyed seagrass and deepwater modelled seagrass are in the South sub-region.

Data confidence: High for coral reefs, and low/moderate for seagrass given spatial and temporal coverage of the monitoring and lack of ZoI data for the rivers in the Jeannie catchment, which discharge onto the most extensive coastal seagrass meadows in Cape York. The potential extent of deepwater seagrass is modelled and we have used the 50% probability assessment.

Table 3.2. The calculated total area (km^2) of the Zone of Influence (maximum extent: 2009, 2011, 2012, 2013), mapped coral reef, and mapped and modelled seagrass for the modelled river basins in the Cape York region used for this assessment. Note that river Zones of Influence are not available for the Jacky Jacky, Olive, Lockhart, Jeannie, Starcke or McIvor Rivers .

River	Mean Annual Discharge (ML)	Zone of Influence (km^2)	Reef (km^2)	Seagrass (km^2)		
				Survey composite	Deepwater (>15m) modelled	Total
Pascoe		2,736	620	118	46	164
Stewart		2,716	294	228	218	445
Hann		1,494	22	102	184	287
Normanby		7,182	450	704	833	1,537
Endeavour		1,445	53	30	938	968
TOTAL Cape York marine NRM region		**96,316**	**10,408**	**2,668**	**9,550**	**12,218**
Sub-regions						
North			7,189	315	1,502	58,107
Central			1,284	561	1,587	19,623
South			1,943	1,774	6,397	18,586

3.3 Relative differences between marine water quality variables and basin influences

The following section presents the results of the individual variables considered in this assessment. This part of the risk assessment identifies the areas where each water quality variable is considered to pose the greatest relative risk to coral reefs and seagrass in the Cape York region. The output can be used to guide priorities for management of individual pollutants, but is not definitive and should only be used in conjunction with expert opinion.

We also applied this approach at a basin scale using the zones of influence for each basin as the assessment unit, however, it has been agreed by the project team that the data is not sufficiently reliable at this stage to take the assessment to this level of detail to draw specific conclusions to differentiate relative importance between pollutants. These results are available from the project team as a demonstration of the potential application of this approach but not presented in this report. The areas reported here are relevant to the entire Cape York marine NRM region.

The maps for each classified variable are presented below to give an indication of the spatial patterns of pollutant influence in the Cape York region. Area calculations are rounded to the nearest whole km^2 for ease of reporting but does include summed portions of some $1km^2$ pixels.

a) Sediments

Total suspended solids threshold exceedance, 2 mg/L

Five assessment classes were used for TSS 2 mg/L based on the percentage of valid observations that exceed the threshold in the period 2002 to 2014, ranging from Very Low to Very High. The results of the assessment are shown in Table 3.3 and Figure 3.6.

The areas of greatest exceedance are located along the coastal areas in Princess Charlotte Bay. There are $12km^2$ of coral reefs in the Very High assessment class (which is <1% of reefs in the region), and approximately $195km^2$ of surveyed seagrass in this area which is ~7% of the surveyed seagrass in the region. There is no deepwater modelled seagrass within the Very High assessment class. Approximately 28% of the surveyed seagrass is in the High assessment class which extends in a coastal band northward to the Nesbit River mouth and south to Cape Flattery. A large proportion (>90%) of the coral reefs and deepwater modelled seagrass are in the Very Low or Low assessment classes.

This is consistent with the analysis of available water quality data by Howley (2015) that showed that during the dry season, mean TSS was almost twice as high in the Central sub-region (Princess Charlotte Bay) than in the North or South sub-regions. Median TSS concentrations in the Princess Charlotte Bay open coastal (dry season) and offshore (dry and wet season) zones and the northern open coastal zone exceeded the GBR Water Quality Guidelines (GBRMPA, 2010).

Data confidence: Low due to limited validation of remote sensing data in nearshore coastal areas, particularly in the shallow and naturally turbid areas such as Princess Charlotte Bay. There is reasonable alignment with monitoring results, however monitoring data for nearshore coastal areas across all of Cape York is very limited (Howley, 2015).

Table 3.3. Area of coral reefs and seagrass meadows within the Very Low to Very High assessment classes for TSS 2 mg/L and the percent of the total habitat area in the region in each class. Results for the assessment are based on frequency of exceedance of TSS 2 mg/L using remote sensing data 2002-2014 (see methods in Section 2.3.1).

TSS 2mg/L Exceedance	Very Low		Low		Moderate		High		Very High		Total
	<1%		1-10%		10-20%		20-50%		50-100%		
Proportion of valid observations	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)
Total Area	66759	69	24266	25	2170	2	2353	2	766	1	96316
Coral Reefs	5437	52	4738	45	111	1	110	1	12	<1	10408
Seagrass											
Composite survey	10	0	1388	52	327	12	752	28	192	7	2668
Deepwater	2902	30	6125	64	513	5	10	<1	0	0	9550
Total Seagrass	2911	24	7514	61	840	7	762	6	192	2	12218

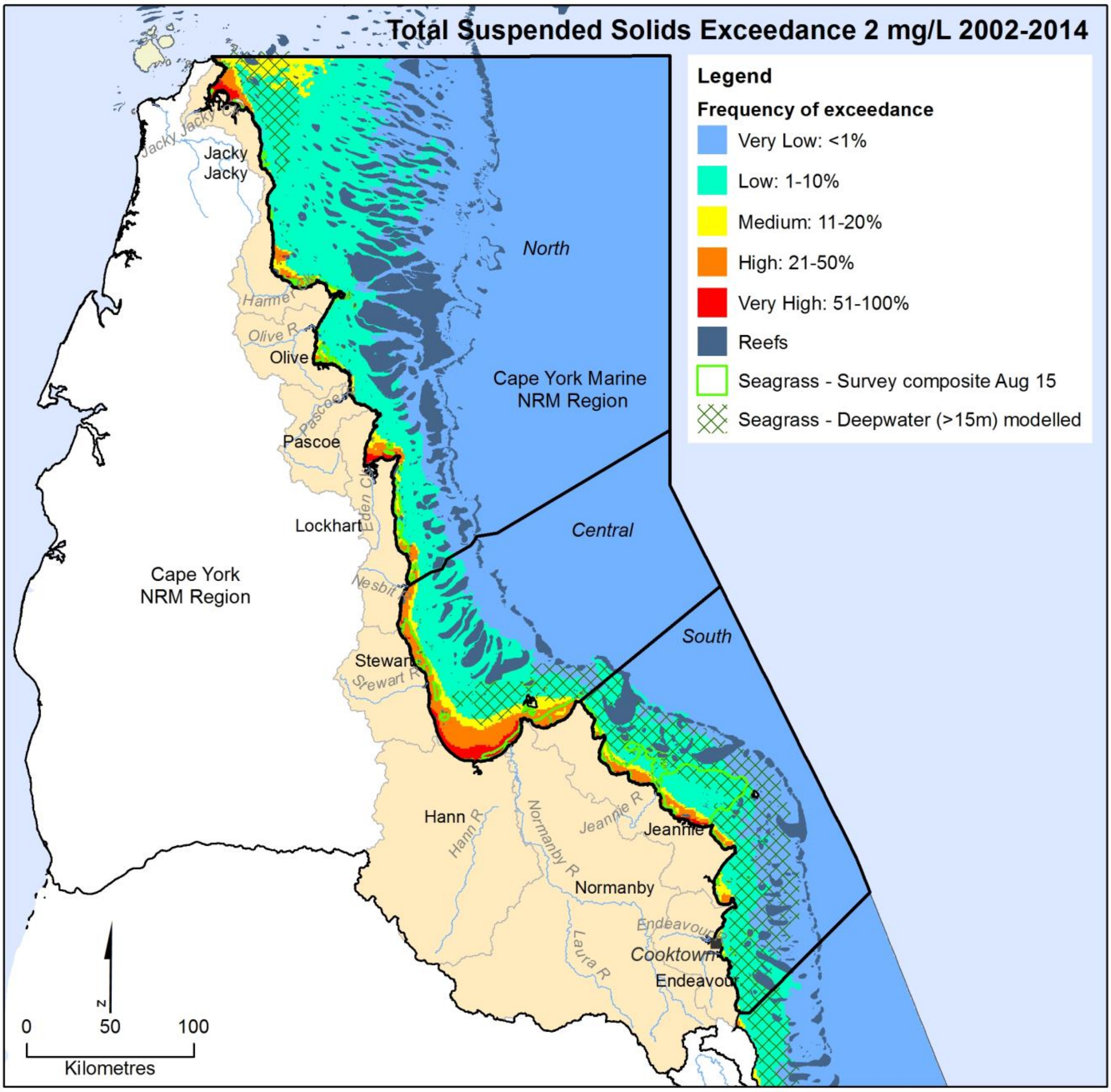


Figure 3.6. Results for the assessment of frequency of exceedance of TSS 2 mg/L using daily remote sensing data 2002-2014. Results for the assessment are based on frequency of exceedance of TSS 2 mg/L (see methods in Table 2.1).

TSS plume loading (mean 2003-2013)

As shown in Table 2.1, five assessment classes (Very Low to Very High) were used for TSS plume loading based on an interpolated map derived from plume frequency information from remote sensing and scaled river load data. The results of the assessment are shown in Table 3.4 and Figure 3.7.

The TSS plume loading area of influence is relatively constrained and only the Low and Very Low assessment classes extend beyond the Inshore area. The areas of greatest exceedance are located in Princess Charlotte Bay. There are only 4km^2 of coral reefs in the Very High assessment class (which is <1% of reefs in the region) with a majority of reef area in the Very Low assessment class (87%). Approximately 94km^2 (~4%) of surveyed seagrass (and no deepwater modelled seagrass) are in the Very High assessment class. The largest proportion of surveyed seagrass is in the Very Low assessment class (65%) and a majority of the deepwater modelled seagrass is in the Very Low or Low assessment class.

Data confidence: Moderate, supported by the analysis of water quality data from Princess Charlotte Bay, however there has been no plume monitoring from other regions (Howley, 2015). Based on Davies and Eyre (2005), higher concentrations have been detected in very small discharge (below average) plumes from the Annan River (20-100mg/L in Walker Bay) and Davies and Hughes (1983) detected >18mg/L approximately 15 km offshore in a 1 in 5 year Endeavour River discharge plume. This implies that a small area of Very High or High loading may occur at the mouths of the rivers and in coastal area.

Table 3.4. Area of coral reefs and seagrass meadows within the Very Low to Very High assessment classes for TSS Plume loading and the percent of the total habitat area in the region in each class. The assessment classes are based on mean wet season TSS loading concentrations 2003 to 2013 (see methods in Section 2.3.2).

TSS loading	Very Low		Low		Moderate		High		Very High		Total
mg/L	<1		1 to 2		2 to 6.6		6.6 to 15		>15		
	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)
Total Area	85457	89	5501	6	4358	5	633	<1	368	<1	96316
Coral Reefs	9051	87	1000	10	331	3	22	<1	4	<1	10408
Seagrass											
Composite survey	1726	65	240	9	488	18	121	5	94	4	2668
Deepwater	6253	66	2049	21	1248	13	0	0	0	0	9550
Total Seagrass	7979	65	2288	19	1736	14	121	1	94	1	12218

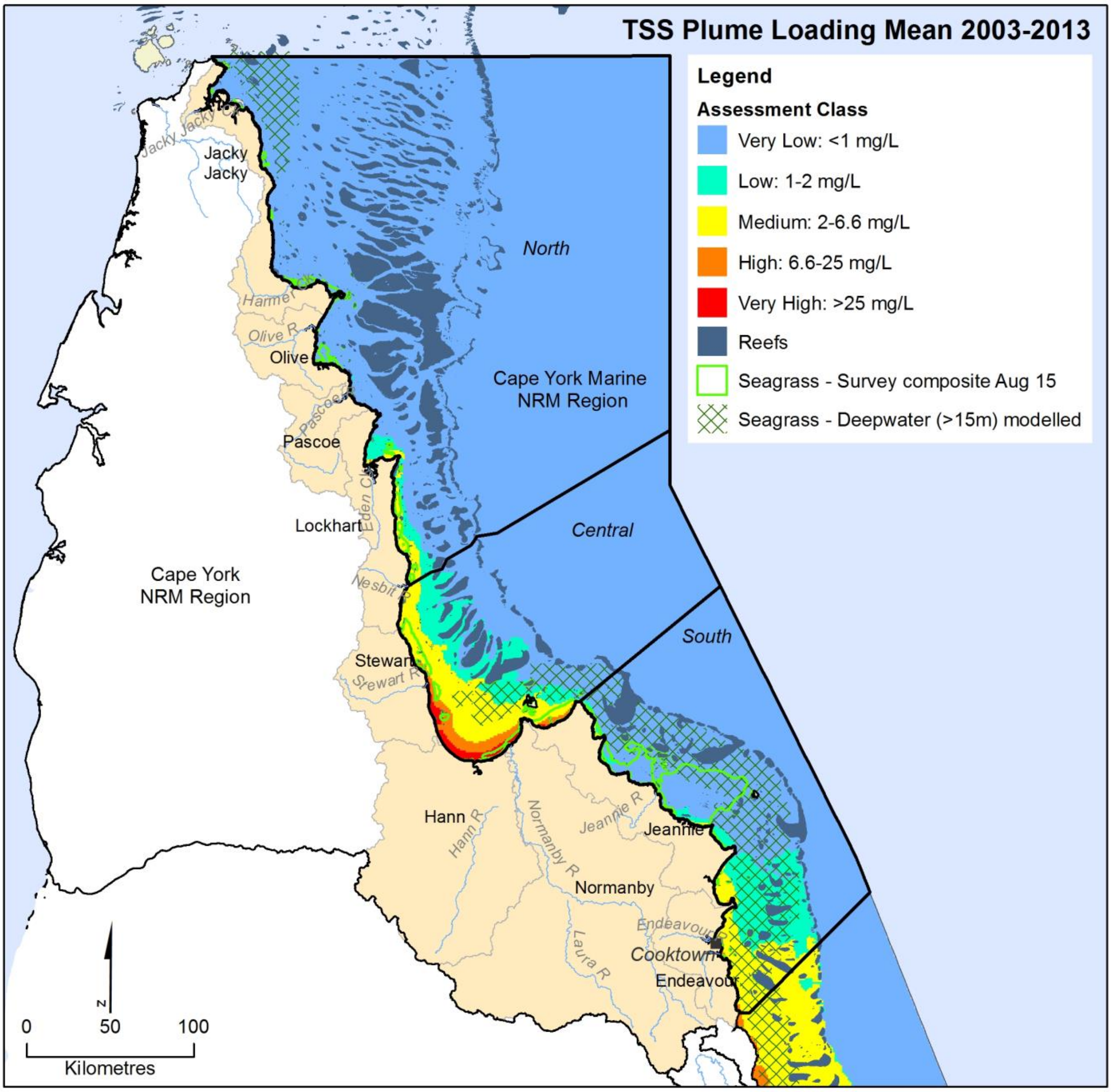


Figure 3.7. Results for the assessment of TSS plume loading (mean of annual assessments 2003 to 2013). The assessment classes are based on concentration estimates derived from an interpolation of a multi-year analysis that combines scaled river loads data and flood plume frequency analysis from satellite imagery (see methods Table 2.1).

b) Nutrients

Chlorophyll-a long term monitored concentration

Chl-a concentrations are relevant year round as an indication of nutrient enrichment in marine waters. As shown in Table 2.1, five assessment classes were used for long term mean Chl-a concentrations based on in situ monitoring in the period 1988 to 2006, classified according to relative potential impact ranging from Very Low to Very High. In the analysis of this dataset for the development of the GBR Water Quality Guidelines by De'ath and Fabricius (2008), the exceedance of the Chl-a guideline of 0.45μg/L was assessed including a level of confidence in the estimates; see Figure 3.9. The confidence map shows relatively low confidence in the areas north of Princess Charlotte Bay, and particularly in the northern part of the region extending to the NRM boundaries. This is due to relatively low frequency of sampling in these locations (Figure 3.9).

The results of the assessment are shown in Table 3.5 and Figure 3.8. **While these indicate that the areas of greatest exceedance are in the northern part of the region, there is very limited data in these areas and these results are highly uncertain (see Figure 3.9 for representation of data confidence)**. The remaining area is shown to be within the mean annual GBR Water Quality Guideline value of 0.45ug/L, containing 42% of the coral reefs, 96% of the surveyed seagrass and 83% of the deepwater modelled seagrass. The classes for this assessment could be revised in the future to reduce the relative risk of the areas that meet the value to Low Risk. There is a coastal band south of Cooktown into the Wet Tropics region which appears to be influenced by the Wet Tropics Rivers, Annan or Endeavour Rivers. Analysis of available water quality data by Howley (2015) that showed that dry season chlorophyll-a concentrations were highest in the South sub-region enclosed coastal zone and mean concentrations in this zone exceeded the GBR Water Quality Guidelines. Maximum wet season chlorophyll-a concentrations were also detected in the South region enclosed coastal zone. However, limited chlorophyll-a data was available from the North or Central enclosed coastal zones for comparison.

In the context of the relatively low anthropogenic nutrient loads delivered to the region (see Section 3.5), it is concluded that much of nutrient influence in the region is not caused by human influences.

Data confidence: Low due to limited spatial coverage of monitored data (see Figure 3.9).

Table 3.5. Area of coral reefs and seagrass meadows within the Very Low to Very High assessment classes for mean long term chlorophyll concentration and the percent of the total habitat area in the region in each class. The assessment classes are based on mean concentrations 1988 to 2006 (see methods in Section 2.3.1).

Chl-a long term mon concentration	Very Low		Low		Moderate		High		Very High		Total
µg/L	<0.18		0.18 to 0.25		0.25 to 0.45		0.45 to 0.8		>0.8		
	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)
Total Area	44633	46	1762	2	25935	27	23986	25	0	0	96316
Coral Reefs	69	<1	347	3	4309	41	5683	55	0	0	10408
Seagrass											
Composite survey	0	0	0	0	2556	96	112	4	0	0	2668
Deepwater	0	0	84	<1	7878	82	1588	17	0	0	9550
Total Seagrass	0	0	84	1	10433	85	1700	14	0	0	12218

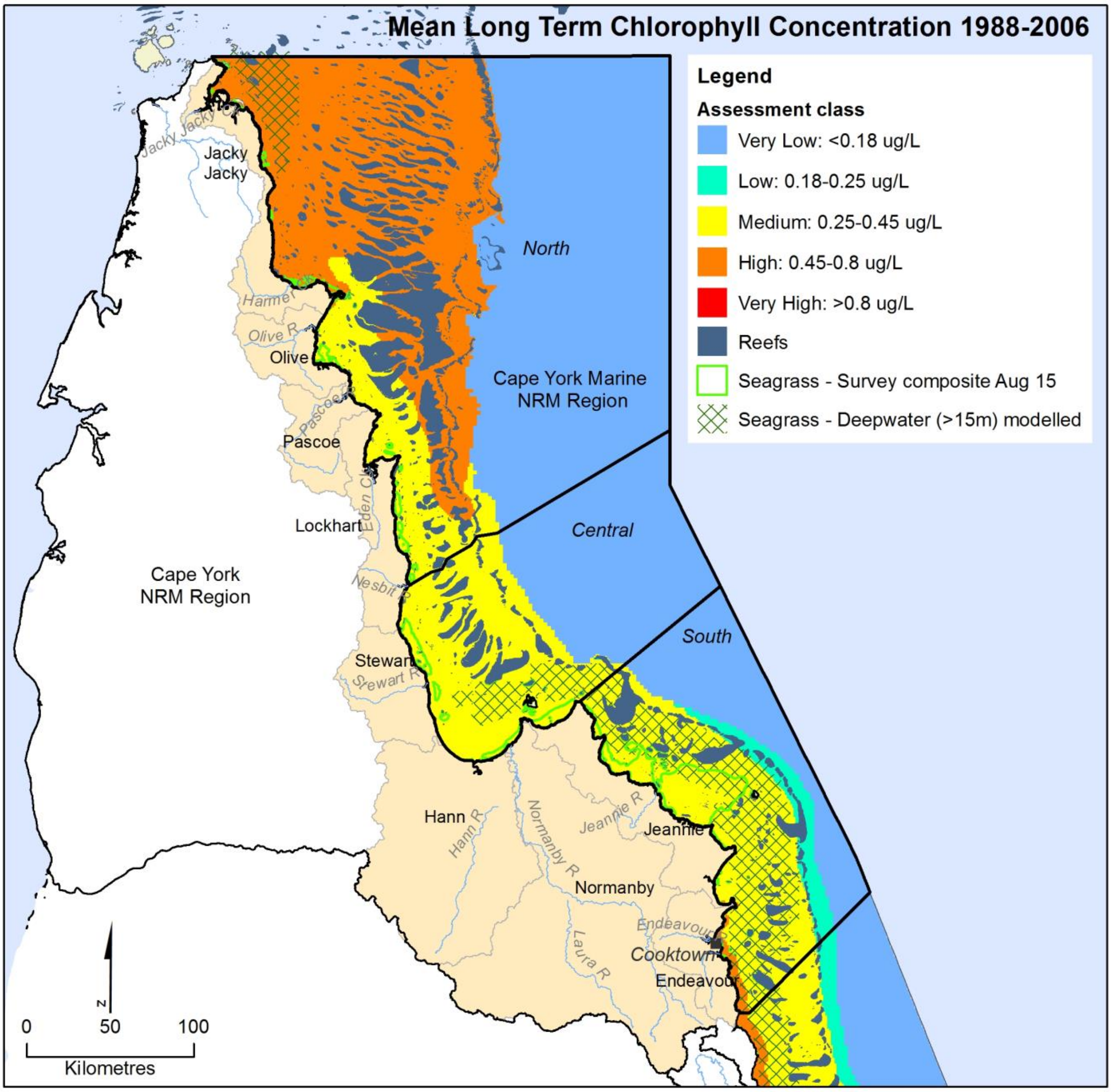


Figure 3.8. Results for the assessment of frequency of exceedance of Chl a 0.45 µg/L using monitored data between 1998 and 2008. Results for the assessment are based on mean long term chlorophyll monitoring data (see methods in Table 2.1). ***Note: Refer to Figure 3.9 for a map showing variability in data confidence, highlighting very low confidence, particularly in the North sub-region.***

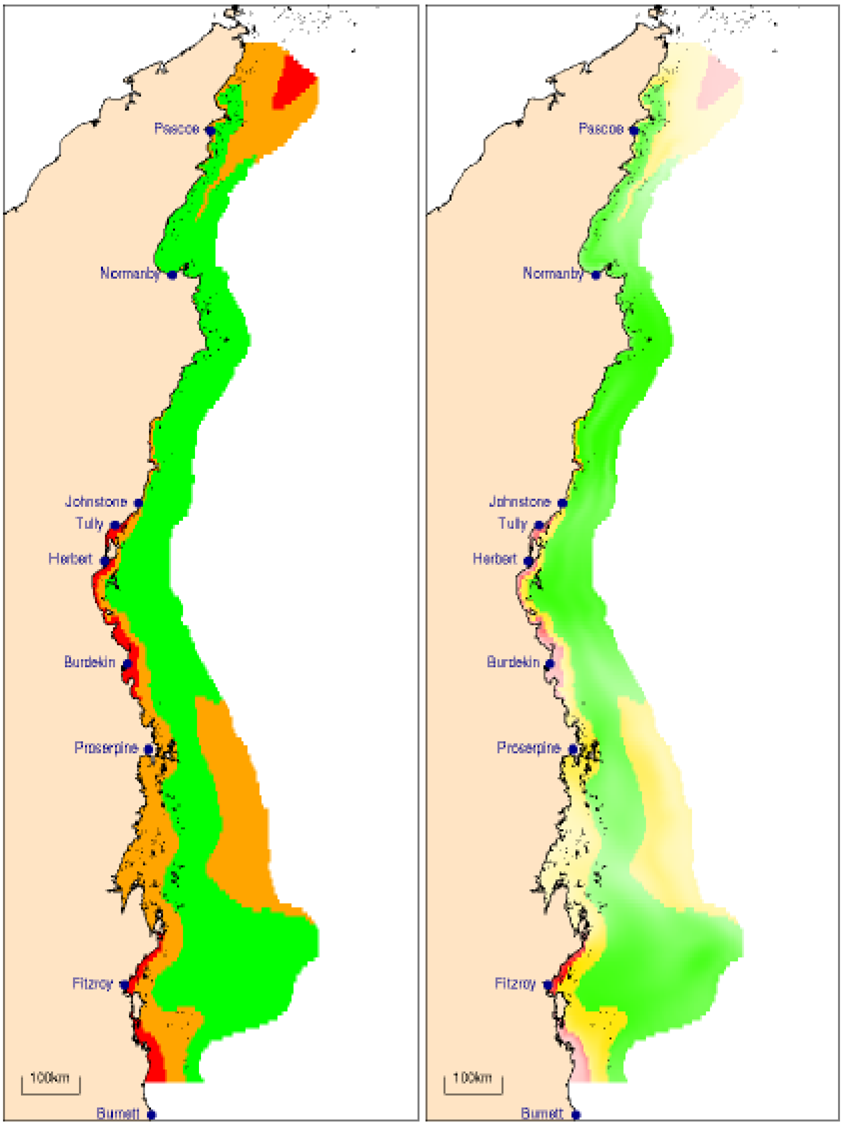


Figure 3.9. Locations that are presently at less than (green) or exceed (orange and red) the water quality guideline trigger value of a maximum annual mean of 0.45 µg/L chlorophyll. Orange zones show areas that exceed the guideline trigger values, having chlorophyll values of 0.45 – 0.8 µg/L. Red zones show areas of greatest concern with >0.8 µg/L chlorophyll. The level of fading (right panel) indicates the level of confidence in the estimates with faded areas being more uncertain. Source: De'ath and Fabricius (2008).

DIN plume loading (mean 2003-2013)

As shown in Table 2.1, five assessment classes (Very Low to Very High) were used for DIN plume loading based on an interpolated map derived from plume frequency information from remote sensing and scaled river load data (Brodie et al. 2015; da Silva et al. in prep). The results of the assessment are shown in Table 3.6 and Figure 3.10.

The DIN plume loading area of influence is relatively constrained to the area between Cape Direction (near Lockhart River mouth) and south to Cape Melville incorporating Princess Charlotte Bay. The majority of Princess Charlotte Bay is in the in Very High or High assessment class however these results are uncertain due to the influence of bottom reflectance in bay (E. da Silva, pers. comm.). Approximately 22% of the surveyed seagrass is in the Very High or High assessment class and there is very limited (<1%) coral reef and deepwater modelled seagrass in these areas. A large proportion (>70%) of coral reefs, surveyed seagrass and deepwater modelled seagrass are located in the Very Low or Low assessment classes. However, as noted above for Chl-a, in the context of the relatively low anthropogenic nutrient loads delivered to the region (see Section 3.5), it is possible that much of nutrient influence in the region is not caused by human influences and there is a high level of modelling uncertainty due to limited validation data in the South and North sub-regions. Therefore, DIN loading is currently considered to pose Low risk in the region, but this assumption needs further review. There is emerging evidence that accelerated gully erosion in the Normanby and other Cape York catchments is a significant source of dissolved nutrients, which may contribute to the high levels of DIN measured in Normanby River flood plumes (Howley et al. unpublished; A. Brooks pers. comm April 2016). This anthropogenic source of DIN should be considered in future assessments.

Data confidence: Low due to limited validation data in the region, particularly in the South and North sub-regions. Plume monitoring in Princess Charlotte Bay confirms that very high (>25ug/L) TSS concentrations are detected across Normanby and Kennedy River flood plumes (Howley et al. in prep).

Table 3.6. Area of coral reefs and seagrass meadows within the Very Low to Very High assessment classes for DIN Plume loading and the percent of the total habitat area in the region in each class. The assessment classes are based on mean wet season DIN loading concentrations 2003 to 2013 (see methods in Section 2.3.2).

DIN loading	Very Low		Low		Moderate		High		Very High		Total
µg/L	<1		1-2		2-7		7-25		>25		
	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)
Total Area	79827	83	6505	7	7359	8	1971	2	653	<1	96316
Coral Reefs	7692	74	1264	12	1368	13	63	<1	22	<1	10408
Seagrass											
Composite survey	1686	63	137	5	251	9	435	16	159	6	2668
Deepwater	6063	64	1791	19	1615	17	82	<1	0	0	9550
Total Seagrass	7749	63	1928	16	1865	15	517	4	159	1	12218

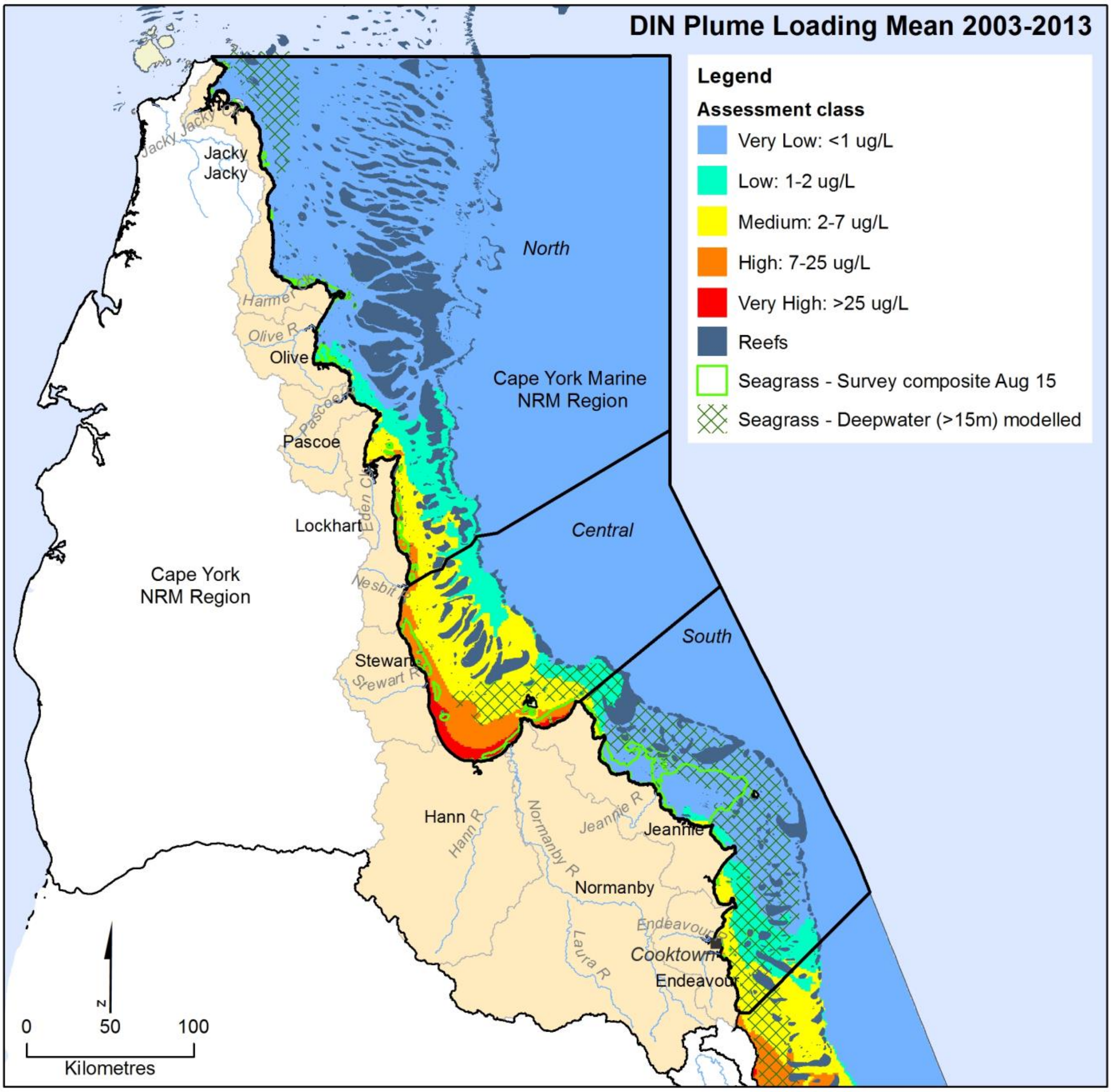


Figure 3.10. Results for the assessment of DIN plume loading (mean of annual assessments 2003 to 2013). The assessment classes are concentration estimates derived from an interpolation of a multi-year analysis that combines scaled river loads data and flood plume frequency analysis from satellite imagery (see methods in Section 2.3.2).

PN plume loading (mean 2003-2013)

As shown in Table 2.1, three assessment classes (Low, Moderate, High) were used for PN plume loading based on an interpolated map derived from plume frequency information from remote sensing and scaled river load data (Brodie et al. 2015; da Silva et al. in prep). The results of the assessment are shown in Table 3.6 and Figure 3.11.

The PN plume loading area of influence is relatively constrained to the coast and only occurs in Princess Charlotte Bay, where the majority of the Inshore areas are in the High assessment class. This area only contains 22km^2 coral reefs (22%) and 148km^2 surveyed seagrass (6%). Nearly all of the coral reefs (99%), surveyed seagrass (89% and deepwater modelled seagrass (100%) are located in the Low assessment class. However, analysis of available water quality data by Howley (2015) showed that during the wet season, mean PN concentrations were highest in the North sub-region for all zones but exceeded the GBR Water Quality guidelines in a range of regions and zones.

Data confidence: Low due to limited validation data in the region.

Table 3.7. Area of coral reefs and seagrass meadows within the Low to High assessment classes for PN Plume loading and the percent of the total habitat area in the region in each class. The assessment classes are based on mean wet season PN loading concentrations 2003 to 2013 (see methods in Section 2.3.2).

PN Plume Loading	Low		Moderate		High		Total
µg/L	<10		10-20		>20		
	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)
Total Area	94988	99	660	<1	668	<1	96316
Coral Reefs	10373	99	13	<1	22	<1	10408
Seagrass							
Composite survey	2386	89	134	5	148	6	2668
Deepwater	9550	100	0	0	0	0	9550
Total Seagrass	11936	98	134	1	148	1	12218

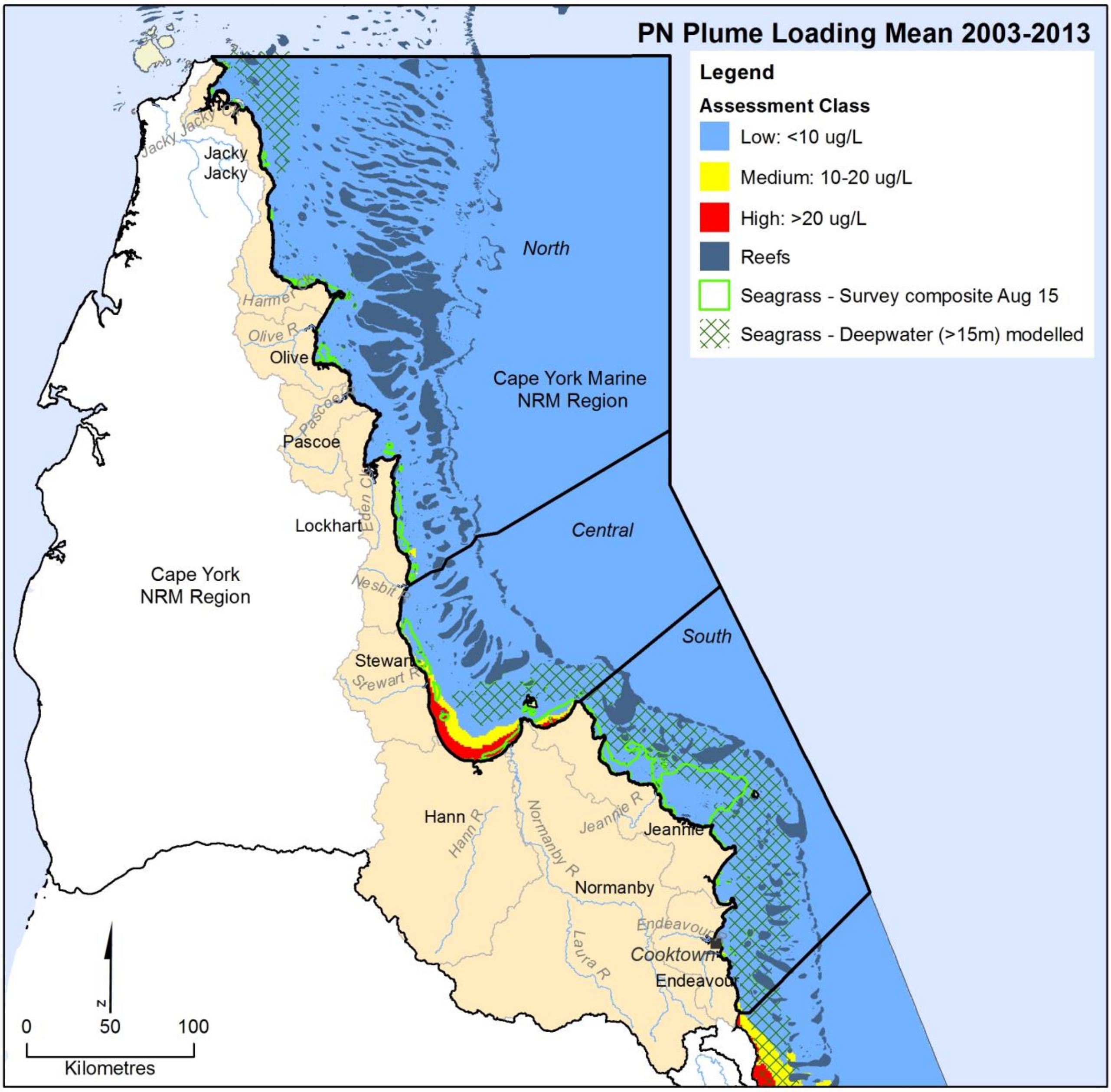


Figure 3.11. Results for the assessment of PN plume loading (mean of annual assessments 2003 to 2013). The assessment classes concentration estimates derived from an interpolation of a multi-year analysis that combines scaled river loads data and flood plume frequency analysis from satellite imagery (see methods in Section 2.3.2).

c) PSII Herbicides

PSII Herbicide modelled concentration, 2009-2011

There was insufficient data to complete the modelling assessment for the region. However, based on the previous limited monitoring data available (e.g. Gallen et al. 2014; Howley et al. 2010; Howley et al. 2012), all of the marine areas in the Cape York region were assumed to be in the No Risk assessment class.

Data confidence: Low-Moderate due to availability of PSII herbicide concentration data in only a few rivers (Normanby and Endeavour) during flood events, however, pesticides would not be expected to be detected in the region due to the limited extent of intensive land uses that rely on pesticide applications, and very low concentrations have been detected in the marine environment (where monitored).

d) *Relative differences between pollutants*

The assessment of individual variables presented above can be used to guide priorities for management of individual pollutants in the Cape York region to some extent, but should be used in conjunction with further expert opinion and local technical expertise due to the data limitations noted above for each variable.

Table 3.8 shows the area of coral reefs and seagrass in the Very High and High assessment classes for each variable and each map is shown in a panel in Figure 3.12 for comparison. In summary:

- The inshore areas of Princess Charlotte Bay is within the Very High or High assessment classes for TSS exceedance, TSS plume loading, DIN plume loading and PN plume loading.
- The greatest proportion of coral reefs in the Very High and High assessment classes occurs in the Chl-a assessment (55%) however given the low confidence in this data, this result is highly uncertain. There is also expect to be limited anthropogenic influence on nutrient concentrations in the marine environment in the region when considering nutrient load data, although the contribution of accelerated gully erosion to anthropogenic nutrient loads has not been considered. For the remaining variables less than 1% of the regional area of coral reefs is in these classes.
- The proportion of surveyed seagrass area in the Very High and High assessment classes is greatest for TSS exceedance (35%) and DIN loading (22%). A large proportion of this seagrass is located in the coastal areas between the Nesbit River mouth and Cape Melville.
- There is limited deepwater modelled seagrass in the Very High and High assessment classes.
- There is very limited risk from pesticides to coral reefs and seagrass in the region.

This highlights that the water quality influence in the region is generally constrained to the inshore areas, with hotspot areas in the inshore waterbody areas of Princess Charlotte Bay. It also highlights the importance of TSS in driving water quality conditions in the region when natural nutrient influences are also taken into account.

Table 3.8. Area of coral reefs and seagrass within the Very High and High assessment classes for each variable and the percent of the Cape York NRM region that the area represents. Note that there is low confidence in the results of the nutrient variables (see Section 3.3a (nutrients)).

Habitat	Sediment				Nutrients						Pesticides	
	TSS 2mg/L exceedance		TSS loading		Chl-a mean concentration		DIN loading		PN loading		PSII herb modelled concentration	
	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region
Total Area	3120	3%	1000	1%	23986	25%	2625	3%	668	1%	0	0%
Coral Reefs	122	1%	25	0%	5683	55%	84	1%	22	0%	0	0%
Seagrass												
Composite survey	944	35%	215	8%	112	4%	594	22%	148	6%	0	0%
Deepwater	10	0%	0	0%	1588	17%	82	1%	0	0%	0	0%
Total Seagrass	953	8%	215	2%	1700	14%	676	6%	148	1%	0	0%

Sediment **Nutrient** **Particulate N (top) and PSII herbicides (bottom)**

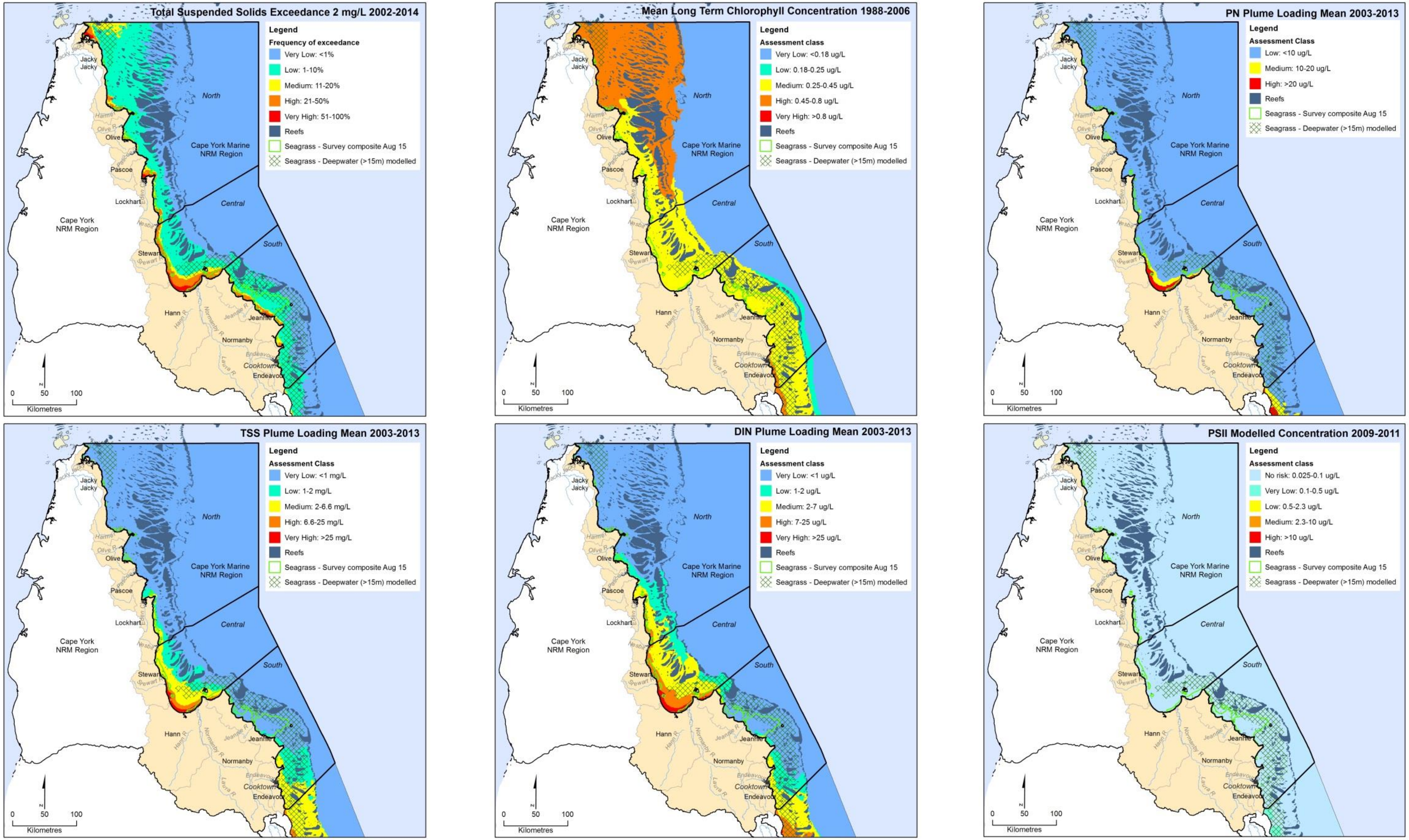


Figure 3.12. Results of all variables presented for comparison and identification of the areas of highest relative risk from individual variables in the Cape York NRM region.

3.4 Marine Risk Index: Combined risk of degraded water quality to coral reefs and seagrass

The combined assessment takes into account all assessment classes for each variable to identify the areas of highest relative risk to degraded water quality in the Cape York region, and hence where coral reefs and seagrass are most likely to be under pressure from degraded water quality.

As described in Section 3, five assessment classes were used for the combined assessment of relative risk ranging from Very Low to Very High. The results of the assessment are shown in Table 3.9 and Figure 3.13. The key findings are:

- There are no areas in the Very High relative risk assessment class in the region.
- The greatest area of influence from degraded water quality is in Princess Charlotte Bay. The High relative risk assessment classes extend to the midshelf waterbodies of the Bay.
- The total area of the High relative risk class (717km^2; <1% of the region's area) contains ~6% of the region's surveyed seagrass and <1% of coral reefs and deepwater modelled seagrass.
- The Moderate relative risk class extends to the outer parts of Princess Charlotte Bay and in some coastal areas northward to the Lockhart River mouth. It contains approximately 14% of the region's surveyed seagrass.
- The Low relative risk class extends to the offshore waterbodies in the central part of the region and contains 15% of the coral reefs and ~30% of the surveyed and deepwater modelled seagrass.
- A majority of the region is within in Very Low assessment class (87% of the area) which extends out to the Marine Park boundary, containing 84% of the coral reefs, 51% of the surveyed seagrass and 70% of the deepwater modelled seagrass.
- Risk posed to some areas, including the extensive coastal seagrass meadows off the Jeannie Basin from the adjacent McIvor, Starcke and Jeannie Rivers has not been assessed.

Table 3.9. Estimated area of coral reefs and seagrass meadows within the five relative risk classes in the Cape York NRM region. The % region is the proportion of the habitat in the region for each assessment class.

Habitat	Very Low		Low		Moderate		High		Very High		High + Very High	
	Area (km^2)	% region	Area (km^2)	% region	Area (km^2)	% region	Area (km^2)	% region	Area (km^2)	% region	Area (km^2)	% region
Total Area	83718	87	10602	11	1279	1	717	<1	0	0	83718	87
Coral Reefs	8750	84	1596	15	41	<1	22	<1	0	0	8750	84
Seagrass												
Composite survey	1362	51	770	29	368	14	169	6	0	0	1362	51
Deepwater	6722	70	2828	30	0	0	0	0	0	0	6722	70
Total Seagrass	8084	66	3598	29	368	3	169	1%	0	0	8084	66

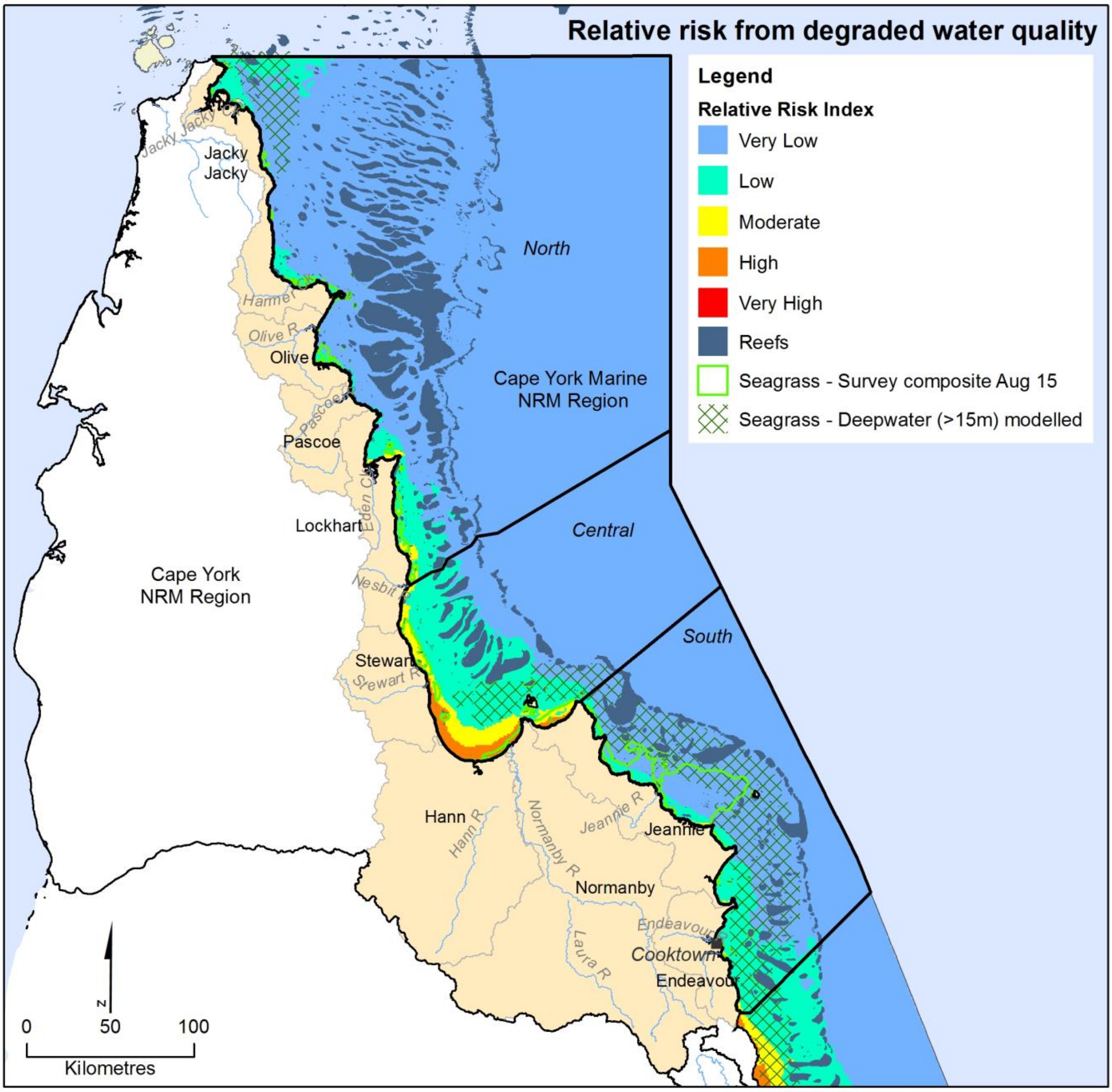


Figure 3.13. Combined assessment (1 km^2 resolution) of the relative risk of water quality variables. The areas (in km^2) of habitat types within each class are shown in Table 3.7.

The assessment can also be conducted for each river Zone of Influence (Table 3.11). However, there is low confidence in these results given the uncertainty in defining the Zones of Influence at this stage, and the limitations of the input data for the Marine Risk Index. These findings should only be used with the support of regional expert opinion. The analysis shows that:

- Due to its larger discharge volumes, the Normanby River dominates the water quality influence in the region. The Zone of Influence extended as far north as Cape Grenville during the 2010-11 wet season, although the southern extent of the estimated Zones of Influence were still within Cape Melville, reflecting the northward movement of the plumes and the role of Cape Melville in steering water inside Princess Charlotte Bay. The maximum extent (2010-2011) ZoI includes approximately 700km^2 of surveyed potential seagrass habitat, 830km^2 of deepwater modelled seagrass and 450km^2 coral reef. It is estimated that 23% of the seagrass areas and 5% of the coral reefs in the ZoI are within the High and Very High relative risk classes.

- The Normanby River has a dominant influence on seagrass in the region, with the results indicating that the influence of the other rivers is less than 30% of the Normanby. The Hann-Kennedy Rivers appear to have a greater water quality influence on seagrass than the Pascoe, Stewart and Endeavour Rivers. However the combined influence of the McIvor, Starcke and Jeannie Rivers, which discharge directly onto the largest coastal seagrass meadows in Cape York, have not been quantified.
- There is limited difference between the Normanby, Stewart and Hann-Kennedy Rivers in terms of relative influence on coral reefs in the region. However, this is difficult to distinguish due to the modelling of separate plumes for these rivers, when in reality they are combined in high discharge conditions (see Petus and da Silva, unpublished).

Table 3.10. Area of coral reefs and seagrass meadows within the 5 relative risk classes in each river Zone of Influence. The sum of the area within the High and Very High classes form the Risk Index, which compares all summed areas to the maximum area, which is given a score of 1. The highest scores are shaded in red, the second highest are shaded in orange.

Basins and habitat	Area (km^2)							Based on area VH+H
Coral Reefs	**V Low**	**Low**	**Moderate**	**High**	**V High**	**Total**	**High & V High**	**Marine Risk Index**
Pascoe	603	17	0	0	0	620	0	0.00
Stewart	0	247	28	19	0	294	19	0.88
Hann-Kennedy	0	0	2	19	0	22	19	0.89
Normanby	42	346	40	22	0	450	22	1.00
Endeavour	7	44	1	0	0	53	0	0.00
Total	**652**	**654**	**71**	**60**	**0**	**1438**	**60**	
						Max	*22*	
Seagrass (surveyed)	**V Low**	**Low**	**Moderate**	**High**	**V High**	**Total**	**High & V High**	**Marine Risk Index**
Pascoe	43	76	0	0	0	118	0	0.00
Stewart	0	7	190	30	0	228	30	0.18
Hann-Kennedy	0	0	54	48	0	102	48	0.29
Normanby	31	185	323	164	0	704	164	1.00
Endeavour	0	20	5	5	0	30	5	0.03
Total	**74**	**288**	**572**	**248**	**0**	**1182**	**248**	
						Max	*164*	
Seagrass (deepwater modelled)	**V Low**	**Low**	**Moderate**	**High**	**V High**	***Total***	**High & V High**	**Marine Risk Index**
Pascoe	46	0	0	0	0	46	0	0
Stewart	0	218	0	0	0	218	0	0
Hann-Kennedy	0	184	0	0	0	184	0	0
Normanby	29	804	0	0	0	833	0	0
Endeavour	156	783	0	0	0	938	0	0
Total	**231**	**1989**	**0**	**0**	**0**	**2220**	**0**	**0**
						Max	*0*	

The assessment can also be repeated for the 3 sub-regions (Table 3.11) with the same caution as noted above, particularly noting that some potentially significant areas have not been assessed due to insufficient data, such as the rivers of the Jeannie and Jacky-Jacky Basins. The analysis shows that the Central sub-region dominates the assessment for coral reefs and surveyed seagrass, with limited or no relative risk from the North and South sub-regions.

Table 3.11. Area of coral reefs and seagrass meadows within the 5 relative risk classes in the 3 sub-regions. The sum of the area within the High and Very High classes form the Risk Index, which compares all summed areas to the maximum area, which is given a score of 1. The highest scores are shaded in red. The highest scores are shaded in red.

Basins and habitat	Area (km^2)							Based on area VH+H
Coral Reefs	**V Low**	**Low**	**Moderate**	**High**	**V High**	**Total**	**High & V High**	**Marine Risk Index**
North	6824	353	11	0	0	7189	0	0.00
Central	311	922	29	22	0	1284	22	1.00
South	1627	315	1	0	0	1943	0	0.00
Total	**8750**	**1596**	**41**	**22**	**0**	**10408**	**22**	
						Max	*22*	
Seagrass (surveyed)	**V Low**	**Low**	**Moderate**	**High**	**V High**	**Total**	**High & V High**	**Marine Risk Index**
North	56	206	53	0	0	315	0	0.00
Central	0	110	287	163	0	561	163	1.00
South	1293	450	26	5	0	1774	5	0.03
Total	**1362**	**770**	**368**	**169**	**0**	**2668**	**169**	
						Max	*163*	
Seagrass (deepwater modelled)	**V Low**	**Low**	**Moderate**	**High**	**V High**	***Total***	**High & V High**	**Marine Risk Index**
North	1109	393	0	0	0	1502	0	0.0
Central	462	1124	0	0	0	1587	0	0.0
South	5102	1295	0	0	0	6397	0	0.0
Total	**6722**	**2828**	**0**	**0**	**0**	**9550**	**0**	
						Max	*0*	

Results for important habitat features in the Cape York region are summarised in Table 3.12.

Table 3.12. Results of the relative risk assessment for important habitat features in the Very High to Low areas of the Cape York region.

Sub-region	Habitat Feature	Description	Relative risk results	Likely rivers of influence
North	*Escape River and Kennedy Inlet River system*	FHA; WNI; the most extensive stand of medium-tall mangroves in Queensland	Very Low / Low	Limited
	Margaret Bay, Lloyd Bay and Cape Grenville area	FHA; WNI; outstanding seagrass beds (size and diversity); important dugong habitat; significant wetlands for wading birds	Very Low / Low	Limited
	Raine Island	Largest known green turtle rookery; most significant seabird rookery in the GBRWHA; National Park	Very Low	Limited
	Temple Bay	FHA; WNI	Very Low / Low	Olive, Pascoe
	Weymouth Bay	High seagrass diversity	Very Low / Low	Olive, Pascoe
	Olive River	WNI	Very Low / Low	Olive
	Cape Direction	High seagrass diversity	Low	Lockhart
Central	*Silver Plains*	FHA; important hawksbill	Low	Stewart

Sub-region	Habitat Feature	Description	Relative risk results	Likely rivers of influence
		turtle habitat		
	Princess Charlotte Bay	FHA; WNI; one of largest tidal wetland areas in Australia; high seagrass diversity; important turtle and dugong foraging areas	Moderate / High	Normanby, Hann, Stewart
	Marina Plains – Lakefield Aggregation	WNI; >100 permanent riverine lagoons	Moderate / High	Limited
	Clack Reef Complex	WNI; small continental island with fringing reef and seagrass	Low	Normanby
	Flinders Island Group	Inner shelf high continental islands with fringing reef and seagrass	Low / Moderate	Normanby
South	*Bay Creek, Cape Melville – Bathurst Bay*	WNI; Amongst best representative mangroves on Cape York	Very Low / Low	Limited
	Lizard Island	Unique granitic high continental island surrounded by fringing reefs and a lagoonal system	Very Low	Limited
	Starcke River	FHA; one of the most varied Cape York coastlines; extensive coastal seagrass meadows; important indigenous turtle and dugong hunting grounds	Very Low / Low	Limited
	Howick Island Group	Inner shelf high continental islands with fringing reef and seagrass; significant turtle nesting areas	Very Low	Limited
	Cape Flattery Dune Lakes wetland	WNI; in largest dune field (international significance) on the east coast, north of Fraser Island	Very Low / Low	Endeavour
	Barrow Point - Cedar Bay	High seagrass diversity	Low	Endeavour, Annan
	Annan River	FHA	Low	Endeavour, Annan

Note: FHA - Fish Habitat Area; WNI – Wetland of National Importance

Note: FHA - Fish Habitat Area; WNI – Wetland of National Importance

This combined assessment of water quality variables can be used to guide overall management priorities for addressing the risks from degraded water quality to coral reefs and seagrass between Cape York basins in conjunction with information about catchment pollutant load delivery. This information is presented in the following section. However, it is important to recognise that the input variables represent longer term time series, and in most cases, represent average conditions. The response of coral reef and seagrass ecosystems to conditions in individual flood events, and the influence of repeated years of flood conditions are also important. These aspects are discussed further in Section 4.

3.5 Loads Index: Assessment of end-of-catchment pollutant loads

The pollutant load information allows managers to relate the Marine Risk results to management priorities among basins and land uses. Further analysis of basin pollutant loads can be undertaken for TSS, DIN, PN, DIP, PP and PSII herbicides including comparisons of the total and anthropogenic annual average load contributions from each basin to the total regional loads. The data is derived from the Source Catchments modelling for the Cape York region, led by Gillian McCloskey from DNRM (McCloskey et al. in review), using the baseline (2013) annual average loads.

There is limited data on PSII herbicide concentrations in the region, and therefore, low confidence in the results presented here. The available data indicates that some atrazine, hexazinone and tebuthiuron is measured in the Normanby catchment, with small amounts of atrazine also measured in the Endeavour and Annan Rivers, however, there is limited data to validate this information and therefore, it is not included in this assessment.

The estimated annual average pollutant loads for the basins in the Cape York region are shown in Table 3.13 and Table 3.14, and graphed in Figures 3.14 to 3.18.

Data confidence: Low / Moderate due to limited monitoring data for model validation in many of the catchments. The available monitoring data in the Cape York region shows relatively good correlation with the end-of-catchment monitoring data from the Normanby River and poor correlation (underestimation) of loads from the Pascoe and Annan Rivers, but it is difficult to compare annual average data with limited monitored results. Confidence in anthropogenic loads is low due to lack of model validation.

Table 3.13. Total and anthropogenic modelled annual average loads for TSS, and DIN load estimates from Cape York basins, and as percentages of the total regional load (Source Catchments 2013 baseline).

TSS loads ($kt.y^{-1}$)					
Basin Name	**Pre-Development Load**	**Total Load (2013)**	**Anthropogenic load (2013)**	**Anthropogenic load % of Regional Total Load**	**Ranking**
Jacky Jacky	13	16	3	0.7	7
Olive	10	16	6	1.7	4
Pascoe	16	19	2	0.7	8
Lockhart	17	18	0	0.1	9
Sub total North	56	68	11	3.1	
Stewart	20	25	5	1.5	5
Hann	16	45	29	7.9	2
Normanby	50	181	131	35.8	1
Sub total Central	86	251	165	45.2	
Jeannie	22	25	3	0.9	6
Endeavour	14	21	7	1.9	3
Sub total South	36	46	10	2.8	
Regional total	178	365	186	51.1	

DIN loads ($t.y^{-1}$)					
Basin Name	**Pre-Development**	**Total Load (2013)**	**Anthropogenic load (2013)**	**Anthropogenic load % of Regional Total Load**	**Ranking**
Jacky Jacky	71	71	0	0.0	7
Olive	49	50	1	0.1	4
Pascoe	55	55	0	0.0	8
Lockhart	48	48	0	0.0	9
North sub total	224	224	1	0.2	
Stewart	30	30	0	0.0	6
Hann	38	42	3	0.8	2
Normanby	48	52	4	1.0	1
Central sub total	116	124	8	1.9	
Jeannie	31	31	0	0.0	5
Endeavour	40	41	1	0.3	3
South sub total	70	72	1	0.3	
Regional total	410	420	10	2.4	

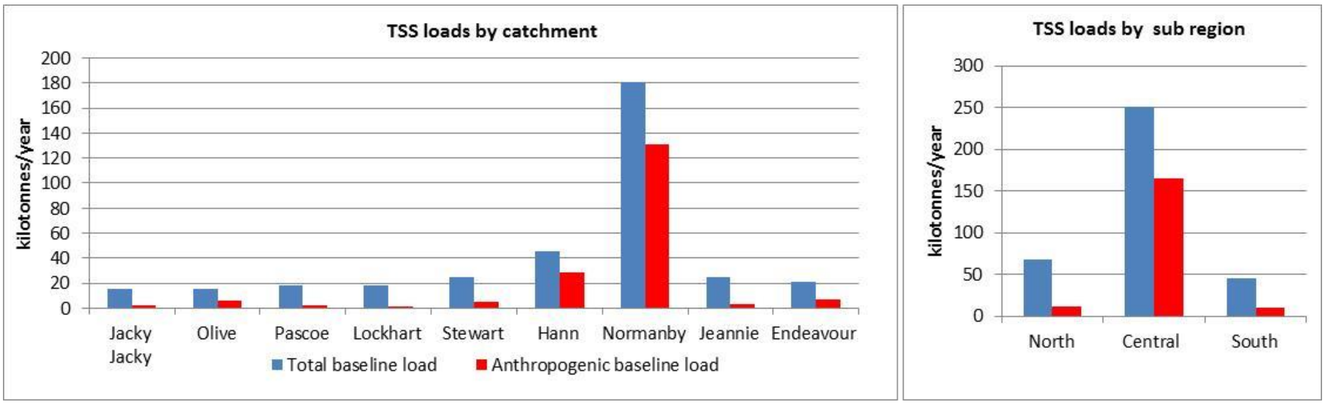


Figure 3.14. Annual load estimates for TSS from the basins in the Cape York region. The graphs show (a) Total (2013) and anthropogenic loads (2013) (kilotonnes), and (b) the proportion that the anthropogenic TSS from each basin contributes to the regional Total TSS Load.

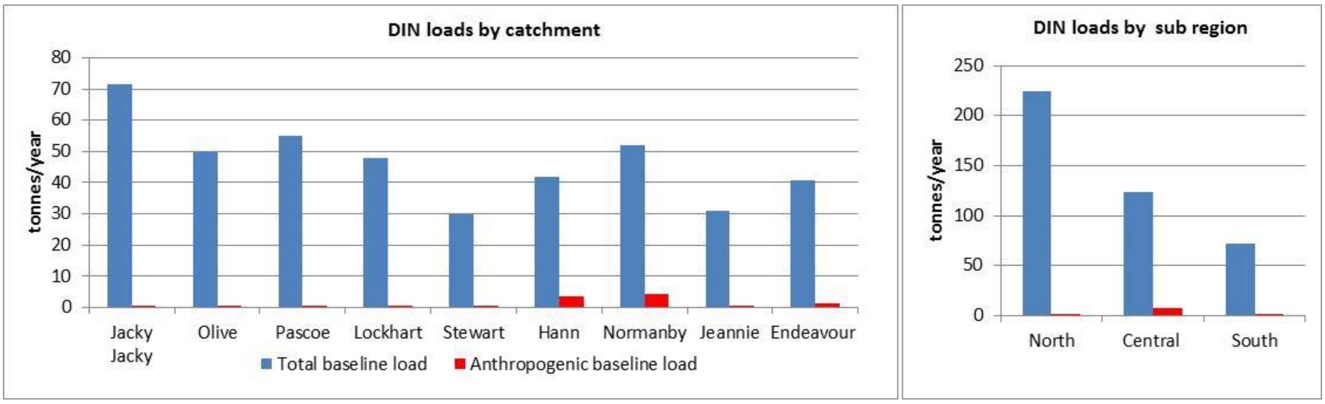


Figure 3.15. Annual load estimates for DIN from the basins in the Cape York region. The graphs show (a) Total (2013) and anthropogenic loads (2013) (tonnes), and (b) the proportion that the anthropogenic DIN from each basin contributes to the regional Total DIN Load.

Table 3.14. Total and anthropogenic modelled annual average loads for PN, DIP and PP loads from Cape York basins, and as percentages of the total regional load (Source Catchments 2013 baseline).

PN loads ($t.y^{-1}$)

Basin Name	Pre-Development	Total Load (2013)	Anthropogenic load (2013)	Anthropogenic load % of Regional Total Load	Ranking
Jacky Jacky	57	124	67	3.0	5
Olive	38	159	121	5.4	3
Pascoe	44	64	20	0.9	7
Lockhart	156	169	12	0.5	9
North sub total	294	515	221	9.9	
Stewart	32	48	16	0.7	8
Hann	851	1045	195	8.7	1
Normanby	191	326	135	6.0	2
Central sub total	1074	1419	346	15.5	
Jeannie	77	139	63	2.8	6
Endeavour	37	157	120	5.4	4
South sub total	113	296	183	8.2	
Total	1481	2231	750	33.6	

DIP loads ($t.y^{-1}$)

Basin Name	Pre-Development	Total Load (2013)	Anthropogenic load (2013)	Anthropogenic load % of Regional Total Load	Ranking
Jacky Jacky	11	12	1	0.8	6
Olive	8	9	1	1.7	4
Pascoe	9	9	1	1.0	5
Lockhart	7	8	0	0.1	8
North sub total	35	38	3	3.6	
Stewart	5	5	0	0.1	9
Hann	6	9	3	3.4	2
Normanby	7	11	3	4.4	1
Central sub total	18	24	6	7.9	
Jeannie	5	5	0	0.6	7
Endeavour	6	8	2	2.4	3
South sub total	11	13	2	3.0	
Total	64	75	11	14.6	

PP loads ($t.y^{-1}$)					
Basin Name	**Pre-Development**	**Total Load (2013)**	**Anthropogenic load (2013)**	**Anthropogenic load % of Regional Total Load**	**Ranking**
Jacky Jacky	10	31	22	4.2	4
Olive	7	41	35	6.7	3
Pascoe	11	20	10	1.9	7
Lockhart	27	30	2	0.5	9
North sub total	54	123	68	13.3	
Stewart	11	15	4	0.8	8
Hann	110	218	108	21.0	1
Normanby	38	96	58	11.2	2
Central sub total	159	329	170	33.0	
Jeannie	15	33	18	3.4	6
Endeavour	10	32	21	4.2	5
South sub total	26	65	39	7.6	
Total	238	516	278	53.8	

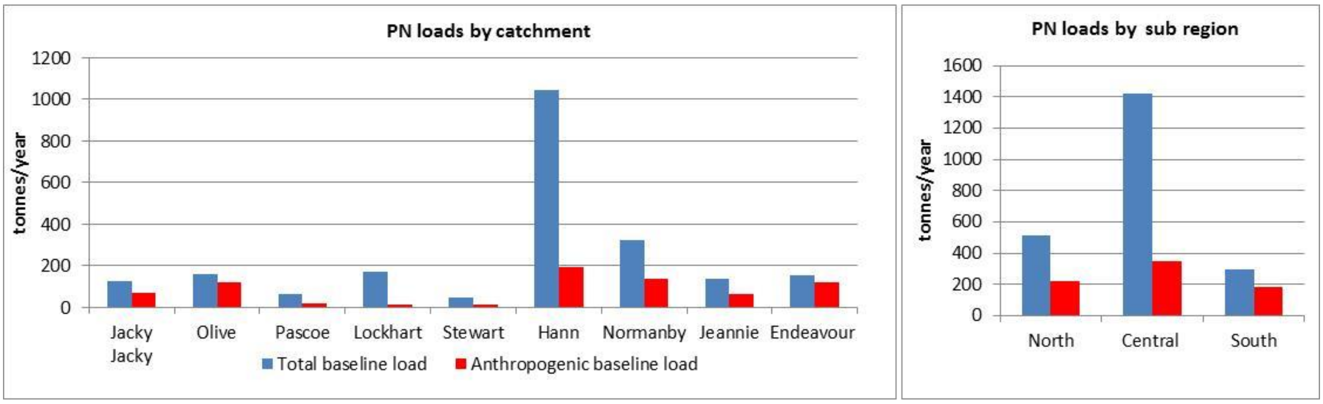


Figure 3.16. Annual load estimates for Particulate Nitrogen (PN) from basins in the Cape York region. The graphs show (a) Total (2013) and anthropogenic loads (2013) (tonnes), and (b) the proportion that the anthropogenic PN from each basin contributes to the regional Total PN Load.

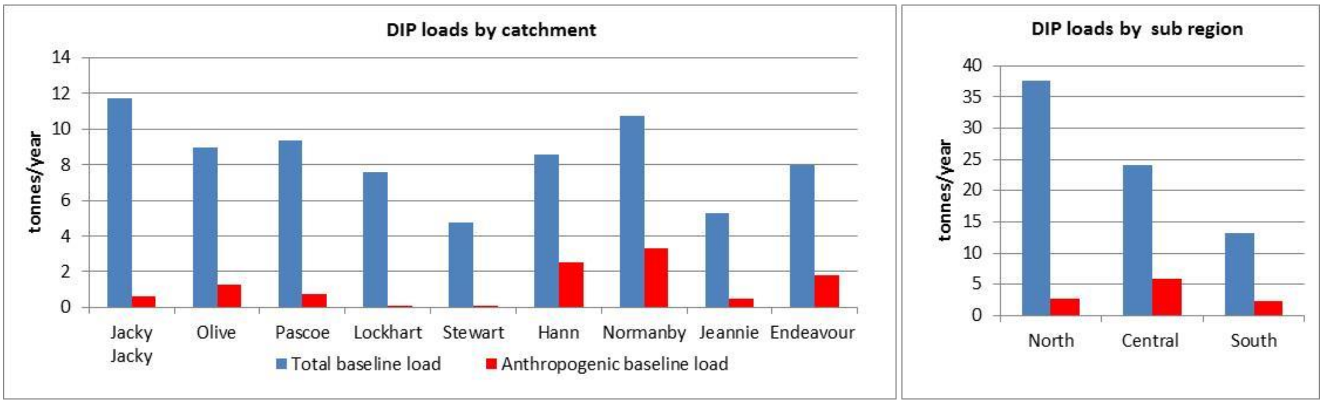


Figure 3.17. Annual load estimates for Dissolved Inorganic Phosphorus (DIP) from the basins in the Cape York region. The graphs show (a) Total (2013) and anthropogenic loads (2013) (tonnes), and (b) the proportion that the anthropogenic DIP from each basin contributes to the regional Total DIP Load.

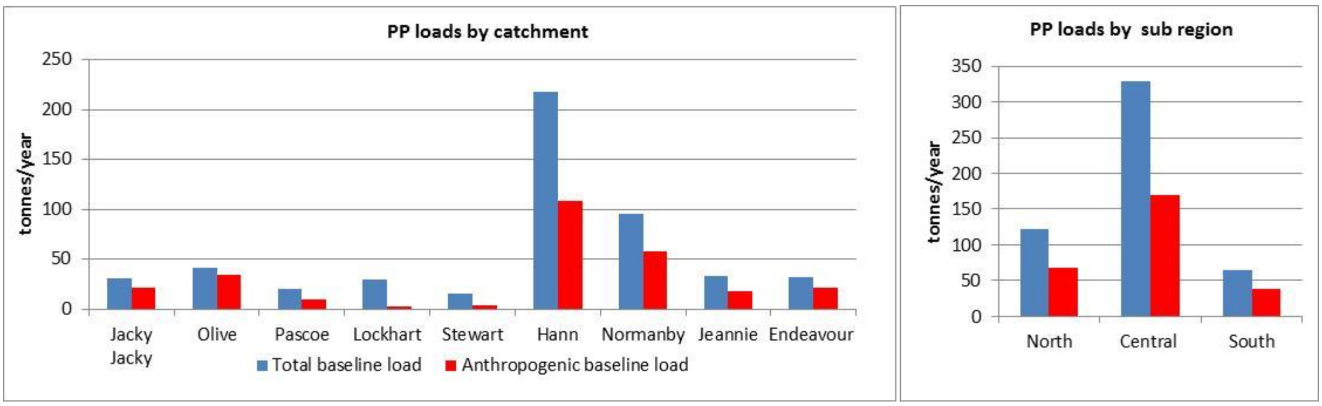


Figure 3.18. Annual load estimates for Particulate Phosphorus (PP) from the basins in the Cape York region. The graphs show (a) Total (2013) and anthropogenic loads (2013) (tonnes), and (b) the proportion that the anthropogenic PP from each basin contributes to the regional Total PP Load.

The 2014 Source Catchments modelling (2013 baseline) end-of-catchment pollutant load estimates for the eastern Cape York region indicate that the dominant contributions for each constituent vary between the catchments, but that the largest loads are consistently contributed by the Central sub-region. The key findings for the total end of catchment loads (modelled annual average estimates) for each constituent are summarised below.

- **TSS:** The estimated regional total TSS load for the Cape York catchments is 365kt/yr, with an anthropogenic estimate of 187kt/yr (51% of the regional total load). The greatest TSS contributions are from the Normanby catchment, which contributes almost 50% of the regional total TSS load (180kt/yr). The next largest contributor is the Hann catchment (12%; 45kt/yr). All other catchments contribute less than 7% of the total regional load. As a result, the Central sub-region dominates the TSS load, accounting for almost 70% of the regional total load. The pattern is similar when considering the anthropogenic loads except that the dominance of the Normanby catchment is more significant (70% of the anthropogenic load).
- **DIN:** The estimated regional total DIN load for the Cape York catchments is 420t/yr, with an anthropogenic estimate of 10t/yr (3% of the regional total load). The catchment contributions to the total regional DIN load do not vary substantially between catchments and range between 7% and 17%. The greatest contribution is from the Jacky Jacky River (17% or 72t/yr). The Olive, Pascoe, Lockhart, Hann and Normanby catchments are all estimated to contribute 10-12% each to the regional total DIN load. The Northn sub-region contributes 54% of the total regional DIN load, compared to the Central (30%) and South (17%). When considering anthropogenic loads, the Hann and Normanby catchments are estimated to contribute almost 80% of the regional anthropogenic load (34% and 44% respectively), the Endeavour 12% and all other catchments contribute less than 6% each; the Central sub-region dominates.
- **PN:** The estimated regional total PN load for the Cape York catchments is 2,231t/yr, with an anthropogenic estimate of 750t/yr (34% of the regional total load).The greatest contributions to the regional total PN load is from the Hann catchment (47% or 1045t/yr), followed by the Normanby (15% or 326t/yr). All other catchments contribute less than 8% each to the regional load. As a result, the Central sub-region dominates the PN load, accounting for almost 65% of the regional total load. The pattern is similar for anthropogenic PN loads.
- **DIP:** The estimated regional total DIP load for the Cape York catchments is 75t/yr, with an anthropogenic estimate of 11t/yr (15% of the regional total load).The catchment contributions to the total regional DIP load do not vary substantially between catchments and range between 6% and 16%. The greatest contribution is from the Jacky Jacky River (16% or 12t/yr). The Olive, Pascoe, Lockhart, Hann, Normanby and Endeavour catchments are all estimated to contribute 10-14% each to the regional total DIP load. The Northn sub-region contributes 50% of the total regional DIP load, compared to the Central (32%) and South (18%). When considering anthropogenic loads, the Normanby and Hann catchments are estimated to contribute 53% of the regional anthropogenic load (30% and 23% respectively), the Endeavour 16% and all other catchments contribute less than 10% each; the Central sub-region dominates.
- **PP:** The estimated regional total PP load for the Cape York catchments is 516t/yr, with an anthropogenic estimate of 278t/yr (54% of the regional total load).The greatest contributions to the regional total PP load is from the Hann catchment (42% or 218t/yr), followed by the Normanby (19% or 96t/yr). All other catchments contribute less than 8% each to the regional load. As a result, the Central sub-region dominates the PP load, accounting for almost 65% of the regional total load. The pattern is similar for anthropogenic PN loads.

These pollutant load estimates were combined into a Loads Index which is based on the anthropogenic proportion of the regional load for each basin and pollutant (described further in Section 2.3.2), shown in Table 3.15. This recognises that while the total load is important in affecting marine ecosystems, it is only the anthropogenic portion that is assumed to be the ‘manageable’ component. The proportional contributions for TSS, DIN, PN, DIP and PP were summed for each basin, and then normalised to the maximum to give a relative assessment. PSII herbicides were excluded from this assessment as the contributions are minimal and are currently not detected in the marine environment.

The assessment shows the greatest relative contribution of combined end of catchment loads to the eastern Cape York region is from the Normanby catchment, followed by the Hann catchment. The relative contribution from each of the other catchments is 30% (Olive catchment) or less of the loads delivered by the Normanby catchment to the Regions' anthropogenic load. As a result, the Central sub-region dominates the combined anthropogenic load contributions (see Table 3.16), and there are limited differences between the North and South sub-regions, especially when taking into consideration the areas of the catchments represented in each sub-region (the South sub-region is much smaller than the North sub-region).

Table 3.15. Loads Index for TSS, DIN, PN, DIP and PP derived from the sum of the proportion of the basin anthropogenic load contributions to the total regional load. The basin that had the largest summed contribution was given a score of 1; all other basins are expressed as a proportion. Loads data derived from McCloskey et al. (in prep).

	Basin anthropogenic load as % of Cape York regional total load							
Catchment	TSS	DIN	PN	DIP	PP	Sum	Loads Index	Loads Index Rank
Jacky Jacky	0.7	0.0	3.0	0.8	4.2	8.7	0.1	5
Olive	1.7	0.1	5.4	1.7	6.7	15.7	0.3	3
Pascoe	0.7	0.0	0.9	1.0	1.9	4.5	0.1	7
Lockhart	0.1	0.0	0.5	0.1	0.5	1.3	0.0	9
Stewart	1.5	0.0	0.7	0.1	0.8	3.2	0.1	8
Hann	7.9	0.8	8.7	3.4	21.0	41.8	0.7	2
Normanby	35.8	1.0	6.0	4.4	11.2	58.5	1.0	1
Jeannie	0.9	0.0	2.8	0.6	3.4	7.8	0.1	6
Endeavour	1.9	0.3	5.4	2.4	4.2	14.1	0.2	4
					MAX	*58.5*		

Table 3.16. Loads Index for TSS, DIN, PN, DIP and PP derived from the sum of the proportion of the sub-regional anthropogenic load contributions to the total regional load. The sub-region that had the largest summed contribution was given a score of 1; the other sub-regions are expressed as a proportion. Loads data derived from McCloskey et al. (in prep).

Loads Index	TSS	DIN	PN	DIP	PP	Sum	Loads Index	Loads Index Rank
North	3.1	0.2	9.9	3.6	13.3	30.1	0.3	2.0
Central	45.2	1.9	15.5	7.9	33.0	103.5	1.0	1.0
South	2.8	0.3	8.2	3.0	7.6	21.9	0.2	3.0
Total						**103.5**		

3.6 COTS Influence Index

As described in Section 2.3.4, an important factor in attributing the Marine Risk Index to the influence of individual rivers is that rivers outside of the Cape York NRM region may influence the marine ecosystems. For example, satellite imagery during periods of high flow and recent modelling of hydrodynamics has shown that the Wet Tropics Rivers influence the marine areas located offshore from the southern Cape York basins. While it is outside the scope of this study to fully assess the impacts of the river plumes on ecosystems in other marine NRM regions or other rivers influencing the region, the cross regional influence of a selection of GBR rivers has been considered in the assessment of the influence of river discharge on the COTS

Initiation Zone (Brinkman et al., 2014; Furnas et al., 2013). This influence is considered to be an important factor in assessing relative risk in the context that over 40% of the loss of coral cover in the GBR since 1987 is attributed to COTS (De'ath et al., 2012) and river discharges are known to play an important role in driving primary outbreaks (Furnas et al., 2013a).

On total volumetric basis, hydrodynamic modelling estimates that approximately 85% of the estimated freshwater input (direct and indirect) to the COTS Initiation Zone comes from Wet Tropics rivers, with the remaining inputs from the Burdekin River (Furnas et al., 2013a). Using this information across 4 years (2008-09, 2010-11, 2011-12, 2012-13) and Event Mean Concentrations of DIN for each basin, a Risk Score was calculated for each basin to create a **COTS Influence Index**. The results are derived from the supporting study prepared for the Wet Tropics WQIP by Brinkman et al. (2014).

Hydrodynamic modelling and analysis of passive tracer movements were applied to assess the relative freshwater volumetric contributions of the major rivers impacting the Cairns – Lizard Island section of the GBR lagoon (Table 3.16). Rivers were ranked based on their freshwater volumetric contribution to the entire Cairn-Lizard Island COTS Initiation Zone (14.5° – 17°S).

Because of its central location (ca. 16°S) and significant runoff volume (annual mean ~ 1.3 Km^3), the Daintree River has the largest direct influence (discharge volume x duration [days] = Conc.Days) on the Cairns – Lizard Island region, followed in most cases in decreasing order by the Russell-Mulgrave, Barron and Tully Rivers. Within the Cape York region, the Annan, Endeavour, McIvor, Starcke and Jeannie rivers are also likely discharge directly into the COTS Initiation Zone. As identified above, the Normanby River generally flows north of Cape Melville and is believed to have little impact. The influence of the Burdekin is variable. The 2008-2009 and 2010-2011 wet season flows from the Burdekin were of similar magnitude (~29,000 GL and ~35,000 GL, respectively), however, during 2008-2009 the Burdekin plume had a significant southerly trajectory, before mixing across the shelf, limiting its northward propagation. During 2010-2011, the Burdekin plume remained close to the coast and travelled several hundred kilometres north, beyond Cape Grafton.

Table 3.17. Relative freshwater volumetric contributions of individual rivers to the COTS Initiation Zone between Cairns (17°S) and Lizard Island (14.5°S). The relative contributions of individual rivers where hydrodynamic modelling data is available were normalised against the Daintree River, the largest river discharging directly into the outbreak initiation region. Ranking is based on magnitude of contribution, from 1 (highest – shaded red) to 8 (lowest).

	Volumetric contribution normalised to Daintree				**Ranking** (1 highest contribution, 8 lowest)			
River	**2008/09**	**2010/11**	**2011/12**	**2012/13**	**2008/09**	**2010/11**	**2011/12**	**2012/13**
Normanby	0	0	0	0	6	8	8	8
Daintree	100	100	100	100	1	1	1	1
Barron	39	52	40	37	2	4	3	3
Russell-Mulgrave	20	59	55	44	3	2	2	2
Johnstone	7	29	24	20	5	6	5	5
Tully	13	57	25	27	4	3	4	4
Herbert	0	7	0	0	6	7	6	7
Burdekin	0	47	0	0	6	5	7	6

Estimated volumetric contributions (Table 3.16) were combined with estimated DIN concentrations to assess and rank the DIN exposure contributions from the major rivers (Table 3.17). A risk score was calculated for each river, for each year, and rivers were ranked according to their DIN risk score (Table 3.18).

Data confidence: Low to moderate confidence due to the issues identified above with the flow data that has been utilised (see Section 2.4). This includes a lack of discharge data from some of the Cape York rivers that discharge into the initiation zone.

Table 3.18. Relative contributions of freshwater and DIN Risk score and ranking for individual rivers influencing the COTS outbreak initiation region between Cairns (17°S) and Lizard Island (14.5°S). DIN risk is based on event mean concentrations of river DIN for the rivers included in the hydrodynamic model.

2008-2009	**FW Contribution (%)** normalised to Daintree	**Volumetric Ranking**	**FW Volume** from DERM (GL)	**FW Volume** normalised to Daintree	**EMC DIN Conc** (ug/L)	**Risk Score** (DIN x FW volume % contribution)	**DIN Risk Score Ranking**
Normanby	0	8	2,346	4.48	80	0.000	8
Daintree	100	1	524	1.00	84	0.084	6
Barron	52	2	773	1.48	51	0.039	7
Russell-Mulgrave	25	3	1,801	3.44	172	0.149	4
Johnstone	15	5	2,945	5.62	321	0.270	3
Tully	16	4	3,597	6.86	126	0.136	5
Herbert	6	7	9,505	18.14	253	0.291	2
Burdekin	12	6	29,352	56.02	201	1.365	1
2010-2011							
Normanby	0	8	5,965	3.59	80	0.000	8
Daintree	100	1	1,662	1.00	84	0.084	6
Barron	52	4	1,929	1.16	51	0.031	7
Russell-Mulgrave	59	2	3,243	1.95	172	0.200	4
Johnstone	29	6	5,269	3.17	321	0.293	3
Tully	57	3	7,060	4.25	126	0.307	2
Herbert	7	7	11,447	6.89	253	0.121	5
Burdekin	47	5	34,839	20.97	201	1.994	1
2011-2012							
Normanby	0	8	1,148	1.25	80	0.000	8
Daintree	100	1	918	1.00	84	0.084	4
Barron	40	3	775	0.84	51	0.017	5
Russell-Mulgrave	55	2	2,330	2.54	172	0.242	2
Johnstone	24	5	2,949	3.21	321	0.252	1
Tully	25	4	3,618	3.94	126	0.123	3
Herbert	0	6	4,360	4.75	253	0.000	6
Burdekin	0	7	15,529	16.91	201	0.000	7
2012-2013							
Normanby	0	8	1822	2.69	80	0.000	8
Daintree	100	1	677	1.00	84	0.084	4
Barron	37	3	282	0.42	51	0.008	5
Russell-Mulgrave	44	2	1371	2.03	172	0.153	2
Johnstone	20	5	1904	2.81	321	0.177	1
Tully	27	4	2586	3.82	126	0.131	3
Herbert	0	7	2819	4.17	253	0.000	7
Burdekin	0	6	3355	4.96	201	0.001	6

Table 3.19. Summary of DIN Risk scores, mean DIN Risk score and ranking based on the mean DIN Risk score for all rivers. The results are then normalised to the maximum mean DIN Risk Score to generate the COTS Influence Index.

River	DIN Risk Score						
	2008/09	2010/11	2011/12	2012/13	Mean	Normalised to max value	Ranking
Normanby	0.00	0.00	0.00	0.00	**0.00**	0.00	8
Daintree	0.08	0.10	0.10	0.08	**0.08**	0.10	6
Barron	0.04	0.03	0.03	0.01	**0.02**	0.03	7
Russell- Mulgrave	0.15	0.22	0.22	0.15	**0.19**	0.22	3
Johnstone	0.27	0.30	0.30	0.18	**0.25**	0.30	2
Tully	0.14	0.21	0.21	0.13	**0.17**	0.21	4
Herbert	0.29	0.12	0.12	0.00	**0.10**	0.12	5
Burdekin	1.37	1.00	1.00	0.00	**0.84**	1.00	1
				Max	*0.84*		

The following conclusions are drawn:

- Rankings based on volumetric contributions were generally consistent between years, with the Daintree dominating freshwater delivery into the COTS Initiation Zone, typically followed in ranking by the Russell-Mulgrave, Tully and Barron Rivers. The Normanby River was consistently the lowest contributor. Rivers from the Annan-Endeavour and Jeannie Basins were not considered as they are not included in the hydrodynamic model, but are likely to be important; this requires further investigation.
- Overall, the Burdekin, Johnstone, Russell-Mulgrave and Tully Rivers are the dominant rivers contributing to the DIN pool in the outbreak region. Together these rivers contributed >75% of the total DIN input to the region, based on mean DIN contributions over the 4 years modelled. The Normanby River was consistently the lowest contributor.
- Rankings based on DIN Risk scores showed that the greatest risk to the COTS Initiation Zone was estimated to come from the Burdekin River during high flow years (2008-2009, 2010-2011), and the Johnstone River during lower flow conditions.
- While the Burdekin River has a significant influence periodically (approximately every 5 to 6 years), the Wet Tropics Rivers typically have high river flows annually. In addition, the annual flows of the Wet Tropics Rivers are often also significant when the Burdekin River discharge is high – thereby complicating the current knowledge of the specific influence of the Burdekin River on the COTS Initiation Zone. There is further discussion of this issue in Fabricius et al. (2010).

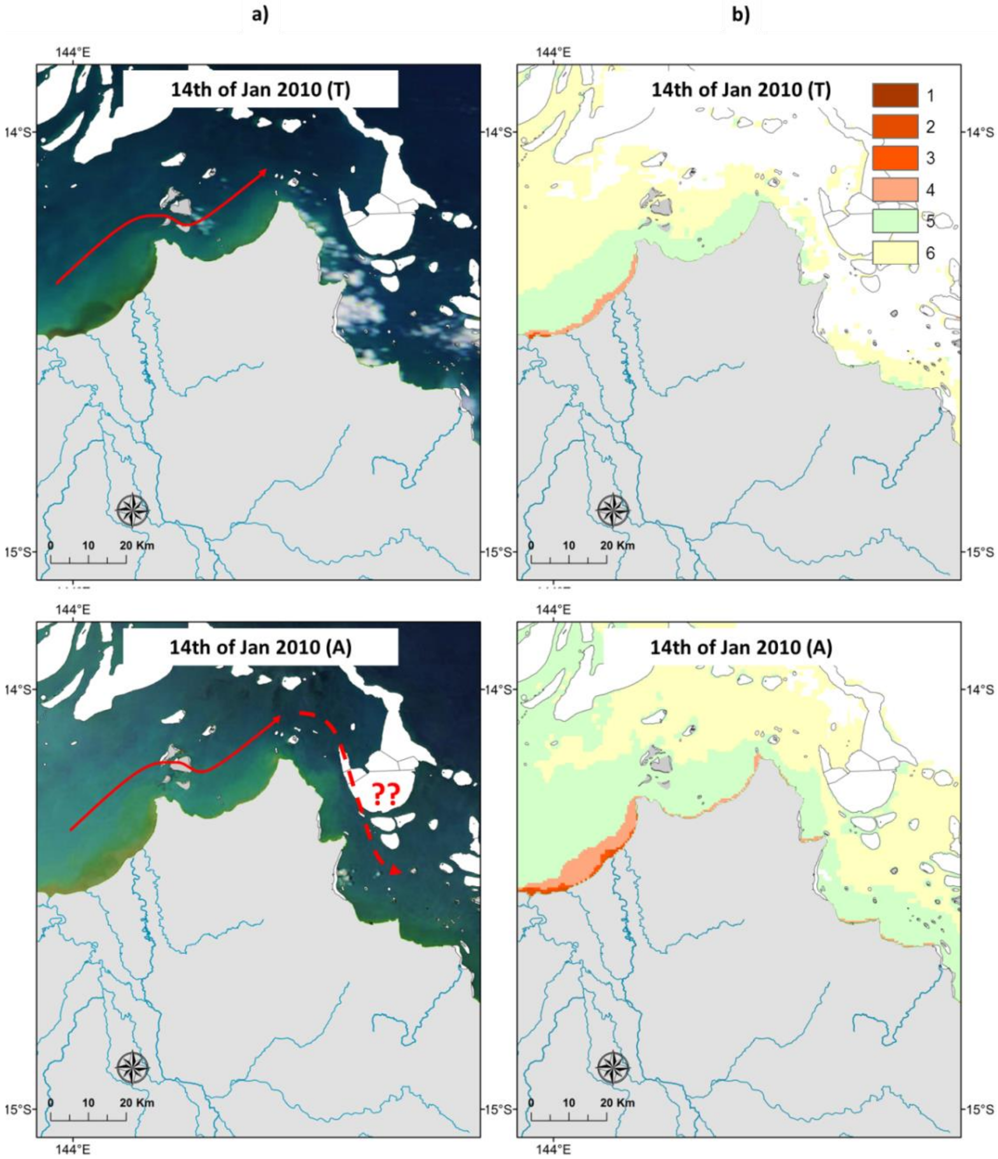
From this study, it was concluded that the Normanby River has limited influence on the COTS Initiation Zone. However, given the limited period of modelling used and recognition of the influence of wind conditions on plume dynamics, Petus et al. (unpublished) tested the use of MODIS true colour images and plume water type maps to assess the spatial and temporal variability of Princess Charlotte Bay river plumes over the last 7 years, with specific attention to potential intrusions to the COTS Initiation Zone. It was highlighted that:

- The Normanby, Marrett, Bizant and North Kennedy Rivers produce river plumes which can merge into a significant single plume;
- Plume events have a return period of maximum 1 year and are observed during the wet season and more particularly from January to March;
- Under northwesterly wind conditions, river plumes are deflected toward the east and, under continuous (i.e., several days) north to west winds periods, narrow turbid coastal plumes are observed inundating Bathurst Bay and reaching Cape Melville;
- On the MODIS-Aqua image of the 14th of January 2010 turbid coastal waters are observed in the coastal waters of Cape Melville as well as in southern coastal waters between Cape Melville, the Howick Group and potentially Lizard Island (i.e., in the COTS high risk area; Figure 3.20). Whether

these turbid waters are Normanby plume waters deflected toward the south or resulted from local sediment resuspension is not possible to determine from the satellite images; and

- Small rivers located between Cape Melville and Lizard Island, like the Starcke and Jeannie Rivers, can produce plumes located in proximity to Lizard Island. Those rivers must be taken into account when evaluating contributions to the COTS Initiation Zone from the Cape York rivers in future assessments.

Figure 3.19. a) True colour and b) plume waters mapped on the 14th of March, 2010 during the late morning (Top:



MODIS-Terra image) and early afternoon (Bottom: MODIS-Aqua image) in Princess Charlotte Bay using the method of Álvarez-Romero et al. (2013). Images show Princess Charlotte Bay plume waters reaching Cape Melville. On the MODIS-Aqua image, turbid coastal waters are also observed in the coastal waters between Cape Melville, the Howick Group and Lizard Island (i.e. the COTS high risk area). For a better observation of Princess Charlotte Bay plumes saturation of the true colour image has been enhanced to 200%).

3.7 Combined assessment: Relative Risk Index

Using the information obtained through the above analyses for the marine water quality variables and end of catchment pollutant loads, it is possible to make an assessment of the management priorities for minimising the risk of water quality impacts in the eastern Cape York marine region. This section presents an option for a quantitative combined assessment to inform water quality management priorities among the catchments in the eastern Cape York region. This information should only be used to guide management decisions in conjunction with additional qualitative information, some of which is presented in Section 4 of this report.

As described in the methods (Section 2), to provide an overall ranking of relative risk between the basins the Loads Index and the Marine Risk Index for coral reefs and potential seagrass habitat were combined to generate a Coral Reef Relative Risk Index and Seagrass Relative Risk Index (Table 3.19). The final indexes for coral reefs and seagrass were then summed and normalised to provide an overall assessment of the relative risk of water quality to coral reefs and potential seagrass habitat – the Relative Risk Index (Table 3.20). This was also conducted for the sub-regions (Table 3.21 and 3.22).

Table 3.20. Results of the overall risk assessment from summing the Loads and Marine Risk Index for coral reefs and seagrass. The catchment that had the maximum value was given a score of 1; all other catchments are expressed as a percentage based on the value in each catchment relative to the area in the catchment with the maximum value.

Coral Reefs Risk Index	**Risk Index for Reefs**	**Loads Index**	**Sum of Indexes**	**Final Index Reefs (Anchored)**	**Rank**
Jacky Jacky	-	0.15	-	-	
Olive	-	0.27	-	-	
Pascoe	0.00	0.08	0.08	0.04	5
Lockhart	-	0.02	-	-	
Stewart	0.88	0.05	0.94	0.47	3
Hann	0.89	0.71	1.60	0.80	2
Normanby	1.00	1.00	2.00	1.00	1
Jeannie	-	0.13	-	-	
Endeavour	0.00	0.24	0.24	0.12	4
		Max	*2.00*		
Seagrass Risk Index (surveyed only)	Risk Index for Seagrass	Loads Index	Sum of Indexes	Final Index Seagrass (Anchored)	Rank
Jacky Jacky	-	0.15	-	-	
Olive	-	0.27	-	-	
Pascoe	0.00	0.08	0.08	0.04	5
Lockhart	-	0.02	-	-	
Stewart	0.18	0.05	0.24	0.12	4
Hann	0.29	0.71	1.01	0.50	2
Normanby	1.00	1.00	2.00	1.00	1
Jeannie	-	0.13	-	-	
Endeavour	0.03	0.24	0.27	0.14	3
		Max	*2.00*		

Table 3.21. Results of the overall risk assessment using a sum of the normalised Indexes for coral reefs and seagrass. The catchment that had the largest sum of indexes was given a score of 1; all other catchments are expressed as a percentage based on sum of indexes in each catchment relative to the sum in the catchment with the maximum sum of indexes.

Coral Reefs and Seagrass - FINAL INDEX	Final Index Reefs	Final Index Seagrass	Sum of Final Indexes	Final Score (Anchored)	Rank
Jacky Jacky					
Olive					
Pascoe	0.04	0.04	0.08	0.04	5
Lockhart					
Stewart	0.47	0.12	0.59	0.29	3
Hann	0.80	0.50	1.30	0.65	2
Normanby	1.00	1.00	2.00	1.00	1
Jeannie					
Endeavour	0.12	0.14	0.26	0.13	4
		Max	*2.00*		

These results show that the Normanby River dominates the relative water quality risk to each habitat in the eastern Cape York region when linked to end -of -catchment anthropogenic loads of TSS, DIN, PN, DIP and PP. The Hann River poses two thirds of the relative risk posed by the Normanby River and the Stewart River one third. The Central sub-region also dominates for relative water quality risk to coral reefs and seagrass, with the North and South posing 15% and 11% respectively of that of the Central sub-region.

Table 3.22. Results of the overall risk assessment from summing the Loads and Marine Risk Index for coral reefs and seagrass. The sub-region that had the maximum value was given a score of 1; other sub-regions are expressed as a percentage based on the value in each sub-region relative to the area in the sub-region with the maximum value.

Coral Reefs Risk Index	Risk Index for Reefs	Loads Index	Sum of Indexes	Final Index Reefs (Anchored)	Rank
North	0.00	0.30	0.30	0.15	2
Central	1.00	1.00	2.00	1.00	1
South	0.00	0.20	0.20	0.10	3
		Max	*2.00*		
Seagrass Risk Index (surveyed only)	Risk Index for Seagrass	Loads Index	Sum of Indexes	Final Index Seagrass (Anchored)	Rank
North	0.00	0.30	0.30	0.15	2
Central	1.00	1.00	2.00	1.00	1
South	0.03	0.20	0.23	0.11	3
		Max	*2.00*		

Table 3.23. Results of the overall risk assessment using a sum of the normalised Indexes for coral reefs and seagrass. The sub-region that had the largest sum of indexes was given a score of 1; other sub-regions are expressed as a percentage based on sum of indexes in each basin relative to the sum in the sub-region with the maximum sum of indexes.

Coral Reefs and Seagrass - FINAL INDEX	Final Index Reefs	Final Index Seagrass	Sum of Final Indexes	Final Score (Anchored)	Rank
North	0.15	0.15	0.30	0.15	2
Central	1.00	1.00	2.00	1.00	1
South	0.10	0.11	0.21	0.11	3
		Max	*2.00*		

There are many uncertainties associated with the input datasets and method for combining these Indexes at a catchment and even sub-region scale at this time (see Section 6); further discussion is recommended prior to making any management decisions based on these results particulary for the northern catchments where there is limited monitored data.

It is also noted that the value of using this type of final assessment where all values are combined into a single score can reduce the intrinsic value of each of the multiple datasets and stages of assessment used in this study and without sufficient explanation, may leave the final results subject to misinterpretation. However, it does provide an overall assessment of the relative risk of all water quality in the marine environment in the context of the end-of-catchment anthropogenic loads which may be useful for managers in prioritising catchment based investments in the eastern Cape York region.

4 Linking Marine Risk to land based pollutant loads

This section summarises the outcomes of the risk assessment using additional evidence from the supporting studies to draw conclusions about the relative risk of water quality to GBR ecosystems from the 9 river catchments in the region. Further work by Higham et al. (2015) identifies spatial prioritisation methodology within grazing and agricultural industries and wetlands part of the implementation strategy for the WQIP.

Several limitations to the quantitative assessment are identified in Section 5; however, a number of these can be overcome by incorporation of new knowledge in a qualitative way to make conclusions about the relative risk of degraded water quality to the GBR.

Supplementary evidence that is important the conclusions of our assessment are also included below.

4.1 Catchment land use

Land use characteristics of the Cape York region are shown in Table 4.1, and mapped in Figure 4.1. This information is all derived from QLUMP 2013 data. The dominant land uses by area are nature conservation (61%) and grazing (37%). Cattle were introduced to Cape York around 1865, and stocking rates are low compared to other savannah regions. The area is considered only marginally productive, due to limited infrastructure, poor soil fertility and the remoteness of the region (Tropical Savannas CRC, 2011). Despite low stocking rates, research has shown that grazing has had a significant impact on erosion rates and anthropogenic sediment and associated nutrient loads in the Central sub-region (Brooks et al. 2013; Shellberg and Brooks, 2013; Shellberg et al. 2013). This also applies but has not been well quantified in the South and North regions.

Other land uses including urban, horticulture, irrigated cropping and sugarcane are all less than 1% of the regional land use area.

Clearing for agricultural production is relatively new to Cape York and exists in small pockets particularly around the Lakeland area, in the southern part of the region, and around Cooktown. Cropping in this region includes maize, sorghum and coffee. In the past, peanuts have also been produced, and there may be small areas of grass seed crops in existence. Bananas, mangoes and passionfruit are also in production in this region. These crops occupy a very small but rapidly expanding area, and are represented as irrigated or dryland cropping, and horticulture crops in Figure 4.1 and the catchment modelling (McCloskey et al. 2014).

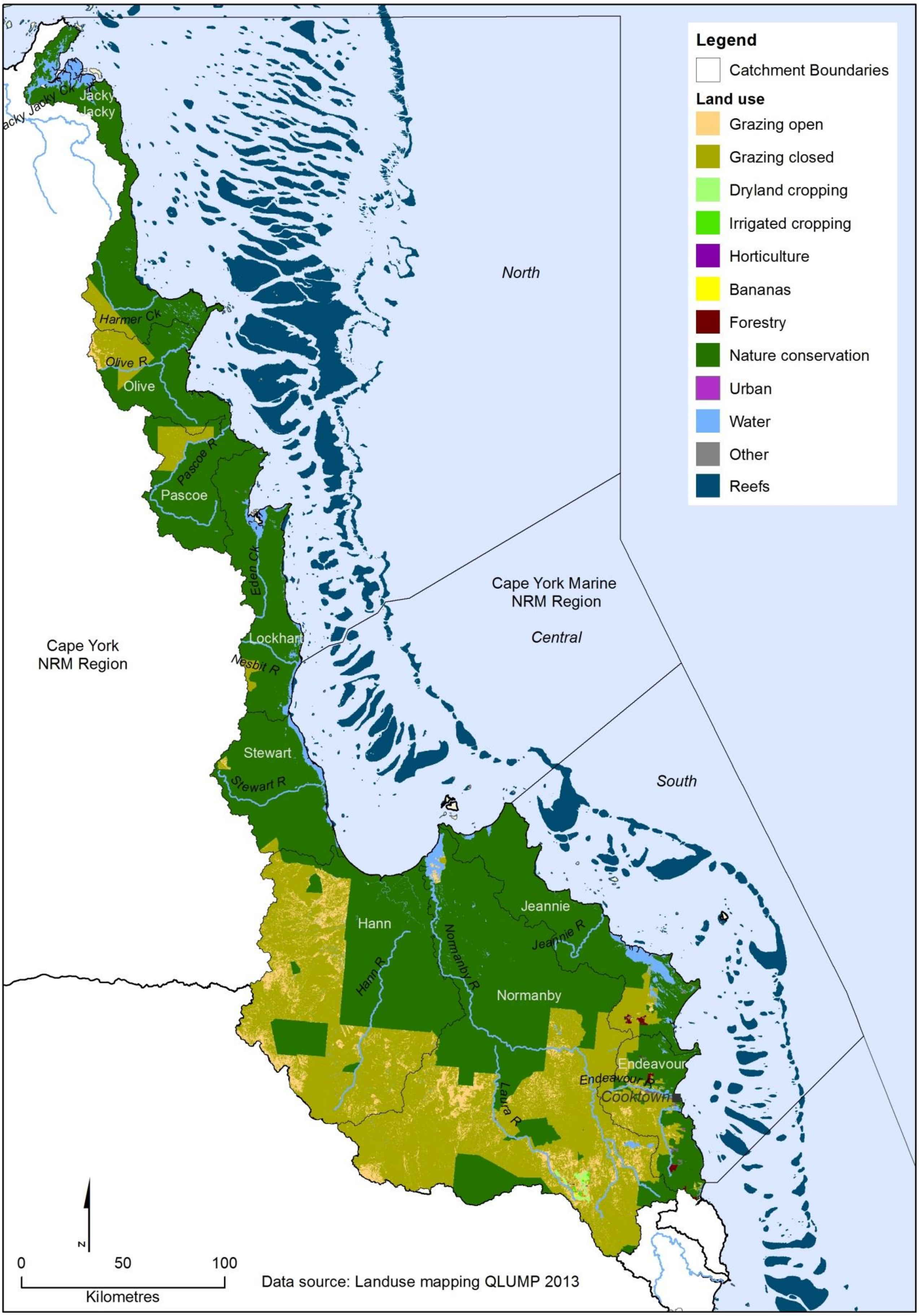


Figure 4.1. Land use map of the Cape York region. Prepared using QLUMP 2013 data.

Table 4.1. Estimated land use by area (ha) in the Cape York region (based on QLUMP 2013 data used in Source Catchments).

Catchment	Grazing	Dryland & Irrigated Cropping	Forestry	Horticulture	Urban	Conservation	Water	Other	Total
Jacky Jacky	26,065				9	243,725	29,180	56	**299,036**
Olive Pascoe	54,511					152,755	1,142		**208,408**
Pascoe	32,463					176,035	327	12	**208,837**
Lockhart	7,434				60	262,996	16,659	114	**287,263**
Stewart	6.469		3			260,500	10,011		**276,983**
Hann	547,100				22	422,671	5644	170	**975,607**
Normanby	762,713	5,718	186	461	144	675,849	16,848	528	**1,462,447**
Jeannie	39,013	52	2,050	44	15	296,575	25,492	480	**363,721**
Endeavour	95,579	267	2,529	173	2,617	113,814	2,927	709	**218,616**
Total Area	**1,564,884**	**6,037**	**4,768**	**678**	**2,867**	**2,604,920**	**108,230**	**2,069**	**4,300,918**
Regional Proportion	36.4%	0.14%	0.11%	0.02%	0.07%	60.6%	2.5%	0.05%	

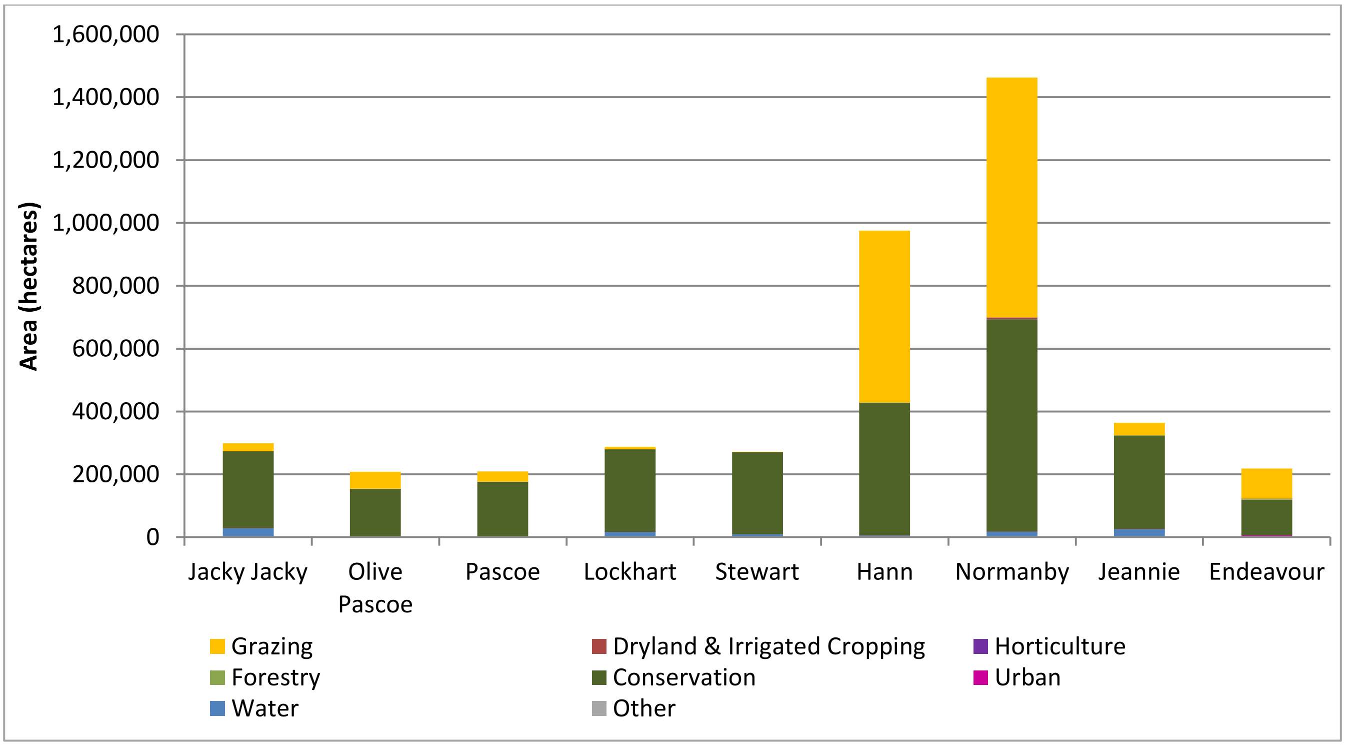


Figure 4.2. Land use characteristics in each Basin, showing the proportion of the area of each Basin in each land use. Derived from QLUMP 2013 data.

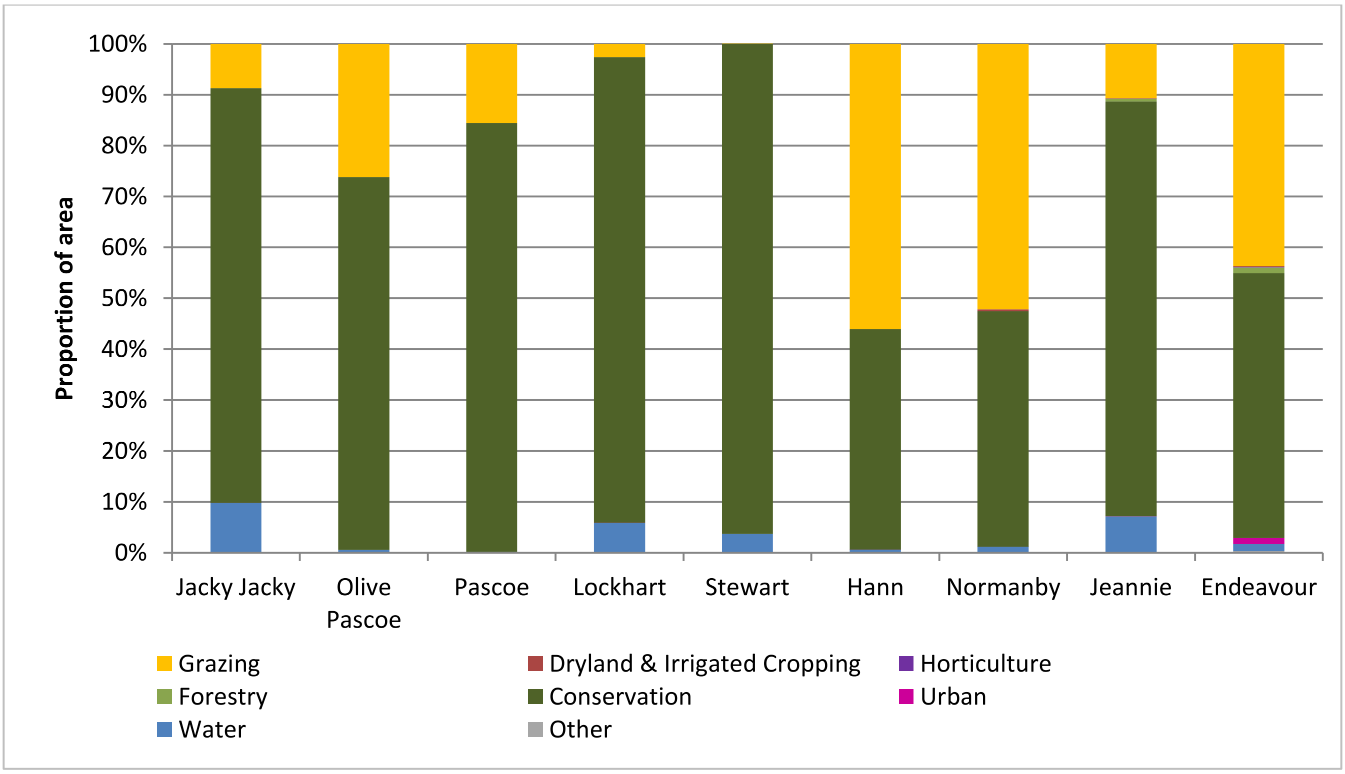


Figure 4.3. Land use areas in each Basin in the Cape York NRM region. Derived from QLUMP 2013 data.

The area and land use characteristics of the basins are varied. A common feature of land use across the whole region is the relatively high proportion of nature conservation land which includes National Parks and Traditional Owner land tenures. In the last 20 years there has been a significant shift in land tenure from Pastoral Lease to National Park and Traditional Owner land tenures which has implications for grazing management. So while the current area of grazing land use is relatively low in many of the catchments, cattle remain in the landscape within a large proportion of the area designated as nature conservation land use.

Urban (including peri urban) and other intensive landuses represent less than 1% of the total planning area, but have important local water quality implications:

- Lockhart township in the Claudie River catchment,
- Laura and Lakeland townships within the Laura River catchment,
- Cooktown, Hopevale townships and several peri urban precincts within the Endeavour River catchment, and
- Rossville township and several peri urban precincts within the Annan River catchment.

The landuse characteristics for each catchment are summarised below.

- Jacky Jacky: Nature conservation (82%) and grazing (9%) are the dominant land uses. Urban and other intensive land uses represent less than 1% (65ha) and water represents 9% of the basin area.
- Olive: Nature conservation (73%) and grazing (26%) are the dominant land uses.
- Pascoe: Nature conservation (84%) and grazing (16%) are the dominant land uses.
- Lockhart: Nature conservation (92%) is the dominant land uses. Grazing represents 3%, Urban and other intensive land uses represent less than 1% (174ha) and water represents 5% of the basin area.
- Stewart: Nature conservation (92%) is the dominant land uses. Grazing represents 2% and water represents 4% of the basin area.
- Hann: Grazing (56%) and nature conservation (43%) are the dominant land uses. Urban and other intensive land uses represent less than 1% (192ha) of the basin area.
- Normanby: Grazing (52%) and nature conservation (46%) are the dominant land uses. Cropping (5,718 ha), horticulture (461 ha) and urban and other intensive land uses (672ha) represent less than 1% of the basin area.
- Jeannie: Nature conservation (81%) and grazing (11%) are the dominant land uses. Forestry (2,050 ha), horticulture (44 ha), cropping (52ha), and urban and other intensive land uses (495ha) represent less than 1% and water represents 7% of the basin area.
- Endeavour: Nature conservation (52%) and grazing (44%) are the dominant land uses. Urban and other intensive land uses (3326 ha) represent 2% and forestry represents 1 %. While horticulture (173 ha) and cropping (267ha) represent less than 1% and water represents 1% of the basin area.

The relative contribution of different land uses in the Cape York region to TSS loads from hillslope, gully and streambank erosion is summarised in Table 4.2 (derived from Source Catchments modelling data; McCloskey et al. in review). These estimates indicate that the dominant erosion sources in the region are gully (44%) and hillslope (42%), with streambank erosion contributing around 13% of the regional TSS loads. These proportions vary between catchments, with clear dominance of erosion from gullied areas in the Normanby catchment (71%). Hillslope erosion is the dominant source (>70%) of erosion in the Jacky Jacky, Pascoe, Lockhart, Jeannie and Endeavour catchments.

This can be assessed further within different land uses for each catchment (Table 4.3 and Figure 4.4 and 4.5), however, it is recognised that uncertainty in the results increases at smaller scales and these results are likely to require further validation to inform decision making. The results shown that the largest total TSS loads are delivered to the end of catchment by areas designated as conservation areas (46% of the regional load) and grazing lands (40% of the regional load). Conservation land, as designated in Source Catchments functional unit, includes a range of traditional owner land tenures, some of which do not exclude grazing, however regardless of the conservation land tenure, cattle are at high numbers throughout the landscape and are considered a pest of national park and nature refuge land tenures. A majority of the streambank sources are also likely to be within these areas.

In the Normanby catchment, it is estimated that 60% of the TSS load is from grazing lands with 87% of this from gully erosion, and 30% of the TSS load is from conservation areas with 34% of this from gully erosion and 66% from hillslope erosion. Streams contribute approximately 10% of the overall load in the catchment.

Table 4.2. Total TSS loads by process for each Basin in the Cape York NRM region. Source: Derived from McCloskey et al. (in review).

Sediment Fine Exported	Streambank		Gully		Hillslope		All Sources
Catchment	tonnes	%	tonnes	%	tonnes	%	tonnes
Jacky Jacky	558	4%	2,336	15%	12,943	82%	15,837
Olive	1,599	10%	3,834	25%	10,212	65%	15,646
Pascoe	4,629	25%	745	4%	13,146	71%	18,520
Lockhart	2,406	14%	97	1%	15,268	86%	17,771
Stewart	4,915	20%	4,579	18%	15,396	62%	24,890
Hann	8,778	19%	19,377	43%	17,073	38%	45,228
Normanby	19,009	11%	127,753	71%	33,961	19%	180,723
Jeannie	1,251	5%	2,257	9%	21,687	86%	25,195
Endeavour	4,961	24%	814	4%	15,163	72%	20,938
Grand Total	**48,106**	**13%**	**161,793**	**44%**	**154,849**	**42%**	**364,748**

Table 4.3. Land use contribution to total TSS load exported (tonnes) to GBR for the eastern Cape York catchments.

Catchment/ TSS exported (tonnes)	Erosion source	Grazing open and closed	Nature Conservation	Dryland and irrigated cropping	Forestry	Horticulture	Urban	Other	Streambank
Jacky Jacky / 15,837	Hillslope (%)	68%	87%				94%	100%	
	Gully (%)	32%	13%				6%		
	Total tonnes (%)	**1,935 (12%)**	**13,318 (84%)**				**4 (0.03%)**	**22 (0.1%)**	**558 (4%)**
Olive / 15,646	Hillslope (%)	71%	73%						
	Gully (%)	29%	27%						
	Total tonnes (%)	**3,776 (24%)**	**10,270 (66%)**						**1,599 (10%)**
Pascoe / 18,520	Hillslope (%)	85%	96%					99%	
	Gully (%)	15%	4%					1%	
	Total tonnes (%)	**2,127 (11%)**	**11,759 (63%)**					**4 (0.02%)**	**4,629 (25%)**
Lockhart / 17,770	Hillslope (%)	100%	99%				100%	100%	
	Gully (%)		1%						
	Total tonnes (%)	**325 (2%)**	**14,982 (84%)**				**20 (0.1%)**	**37 (0.2%)**	**2,406 (14%)**
Stewart / 24,890	Hillslope (%)	60%	78%						
	Gully (%)	40%	22%						
	Total tonnes (%)	**497 (2%)**	**19,478 (78%)**						**4,915 (20%)**
Hann / 45,218	Hillslope (%)	33%	66%					57%	
	Gully (%)	67%	34%					43%	
	Total tonnes (%)	**21,175 (47%)**	**15,264 (34%)**					**11 (0.02)**	**8,778 (19%)**
Normanby / 180,723	Hillslope (%)	13%	35%	100%	34%	100%	16%	15%	
	Gully (%)	87%	65%		66%		84%	85%	
	Total tonnes (%)	**105,946 (59%)**	**54,023 (30%)**	**1,538 (0.85%)**	**18 (0.01%)**	**17 (0.01%)**	**35 (0.02%)**	**137 (0.08%)**	**19,009 (11%)**
Jeannie / 25,195	Hillslope (%)	93%	90%	100%	97%	99%	100%	100%	
	Gully (%)	7%	10%		3%	1%			
	Total tonnes (%)	**3,318 (13%)**	**20,247 (80%)**	**50 (0.2%)**	**214 (0.85%)**	**11 (0.04%)**	**3 (0.01%)**	**100 (0.4%)**	**1,251 (5%)**
Endeavour / 20,938	Hillslope (%)	91%	99	100%	100%	99%	98%	98%	
	Gully (%)	9%	1			1%	2%	2%	
	Total tonnes (%)	**7,583 (36%)**	**7,034 (33%)**	**421 (2%)**	**168 (0.8%)**	**47 (0.22%)**	**576 (3%)**	**148 (0.7)**	**4,961 (24%)**

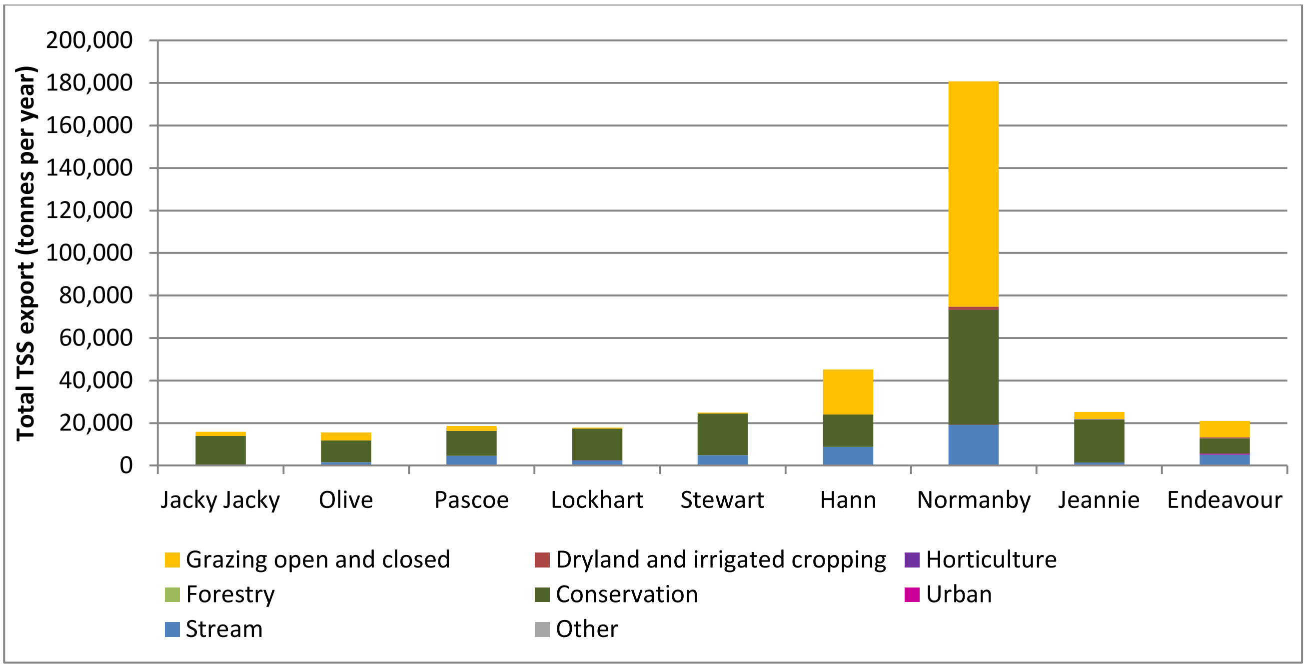


Figure 4.4. Modelled annual average TSS export loads by catchment and landuse. Derived from Source Catchments modelling (2013 baseline), DNRM 2015.

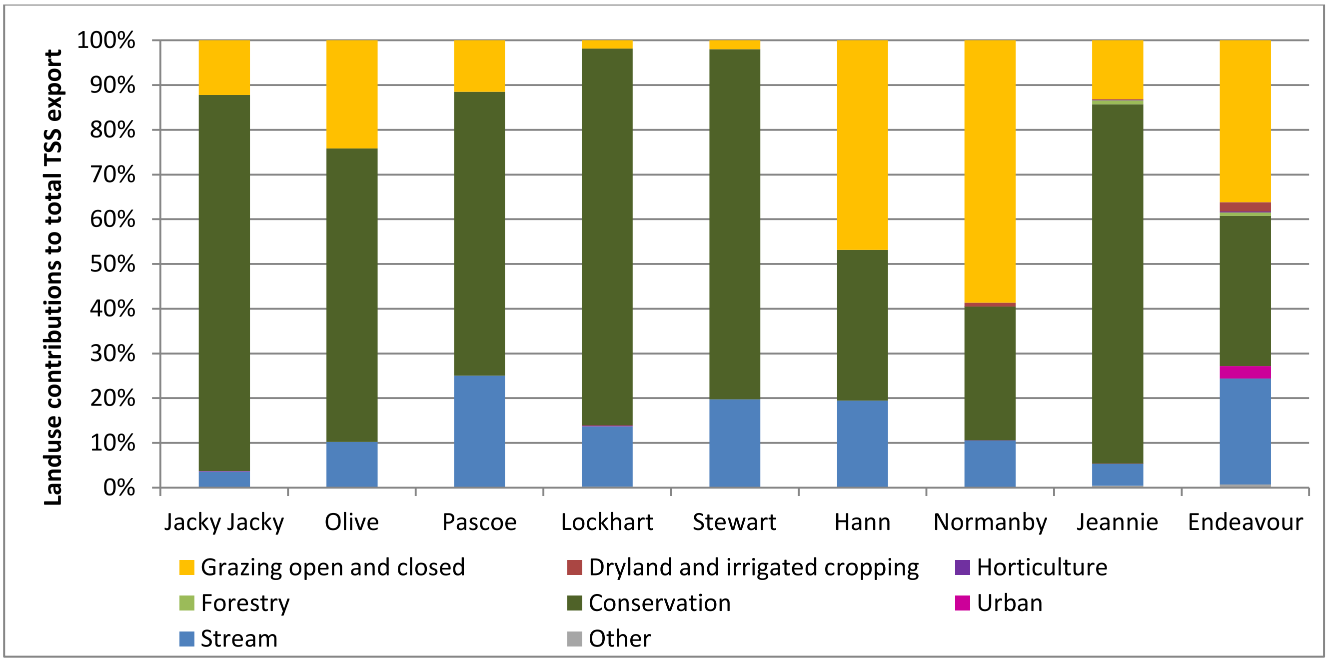


Figure 4.5. Modelled annual average TSS export loads showing proportional contributions by landuse and catchment. Derived from Source Catchments modelling (2013 baseline), DNRM 2015.

4.2 Ports and Shipping

The eastern Cape York region includes the Port of Cape Flattery which is used for the export of silica sand from Cape Flattery mine. There are onshore silica sand handling and stockpiling facilities and a 500 metre, single trestle jetty and conveyor running from the mine to an offshore berth and ship loader[3]. There is also a general purpose wharf for the import of fuel and other supplies for the mine.

[3] http://www.portsnorth.com.au/our-ports/capeflattery.php

The Port of Cooktown is also a declared port, however no commercial trade takes place. Port of Quintell Beach is a community port with a barge facility that services the needs of the Lockhart River community and remote grazing properties.

The water quality risk associated with these facilities is considered to be relatively minor. In contrast In contrast, the risk from spills, groundings and the re-suspension of sediments by large ships is considered to be high.

A number of major international shipping channels transverse Cape York and this region of Australia forms an important passage for international shipping servicing eastern Australian ports. The Inner Route (from Cairns to Cape York) passes between the mainland and the GBR. In some sections it is extremely narrow, with reefs edges only 3 cables from the ship's track. In other sections the nearest reef will be at a distance of several miles. Vessels with an overall length of 70 metres or more, and all loaded oil tankers, chemical carriers and liquefied gas carriers irrespective of length are required to use the services of a licensed coastal pilot in the following compulsory coastal pilotage areas on this route.

To date, the documented impacts of shipping have mainly related to: physical damage and pollution from toxic antifoulant paint as a result of ship groundings; small chemical spills; large and small oil spills; increased noise; vessel strikes on wildlife; vessel-based waste discharge; the introduction of exotic marine species; and marine debris (GBRMPA 2012a). There have been many shipping incidents reported in the Cape York region. Particular examples include Piper Reef where the Peacock ran aground in 1996 (Australian Transport Safety Bureau 1997) and the Doric Chariot in 2002 (Marshall, 2002).

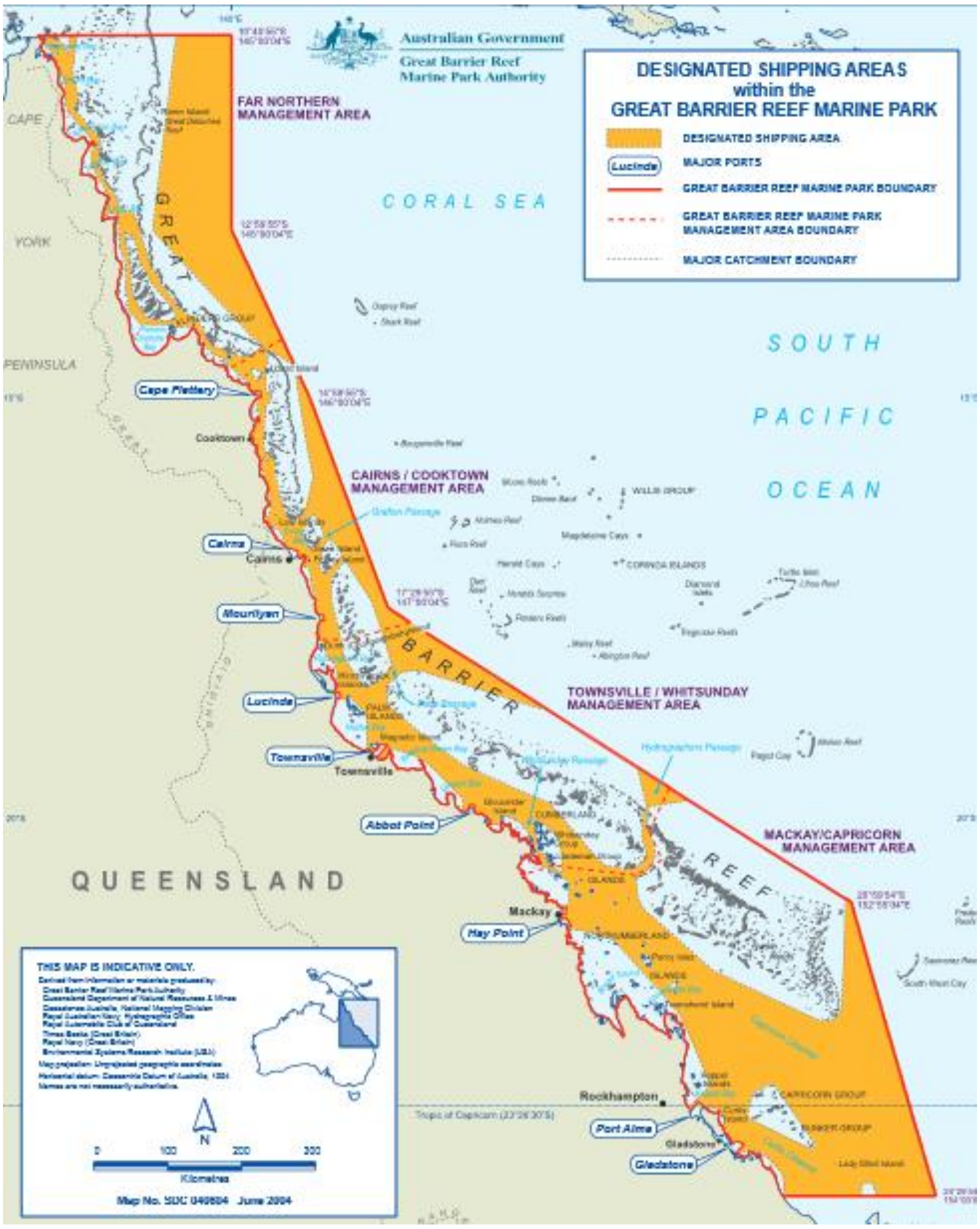


Figure 4.6. Designated shipping areas in the Great Barrier Reef Marine Park. Source: GBRMPA http://www.gbrmpa.gov.au/managing-the-reef/how-the-reefs-managed/Managing-multiple-uses/shipping/designated-shipping-areas.

Figure 4.7 shows an example of shipping reporting data for the Australian coast (sourced from GBRMPA July 2012). It highlights the density of traffic in the coastal areas of the region. In addition to the potential for shipping incidents such as collisions or groundings, the types of substances carried on the ships transiting these areas is important. In the absence of any limitations on the movement of particular types of cargo, the full range of materials listed in the International Maritime Dangerous Goods Code (IMDG Code, 2002) are carried through these waters, either as containerised deck cargo or in bulk. This includes hazardous wastes, chemical products and raw materials (including pesticides), bulk fertilisers, bulk cereals, crude oils, fuel oils and petroleum products, bulk coal, mineral concentrates, etc. Very few cargoes, if released in the event of a maritime incident, would not have an environmental impact. Even a completely inert cargo, such as fine silica sand, could smother seagrass beds with a significant impact on dugong feeding and prawn and lobster breeding (IMO MEC, 2003).

Therefore, it is concluded that larger trading ships could sustain significant damage during a grounding or collision event in the Cape York region. For example, a grounding event could result in the release of up to

700 tonnes of heavy fuel oil whilst a collision involving an oil tanker could result in a spill in excess of 20,000 tonnes of crude oil. The stranding of a fishing vessel on an isolated reef, possibly away from recognised shipping routes could also result in a spill of up to 5,000 litres of diesel fuel and other oil products (AMSA, 2012).

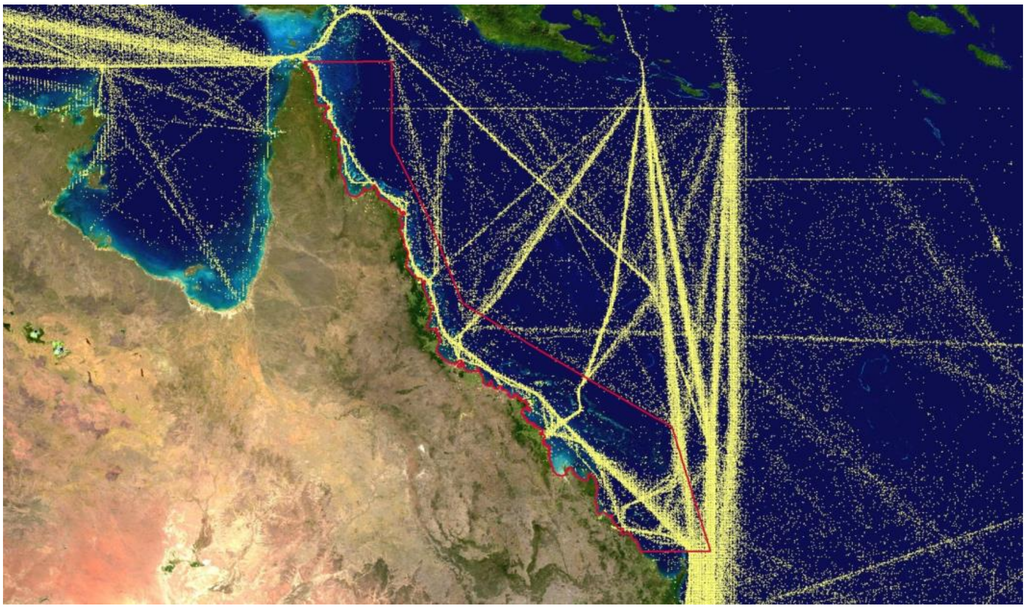
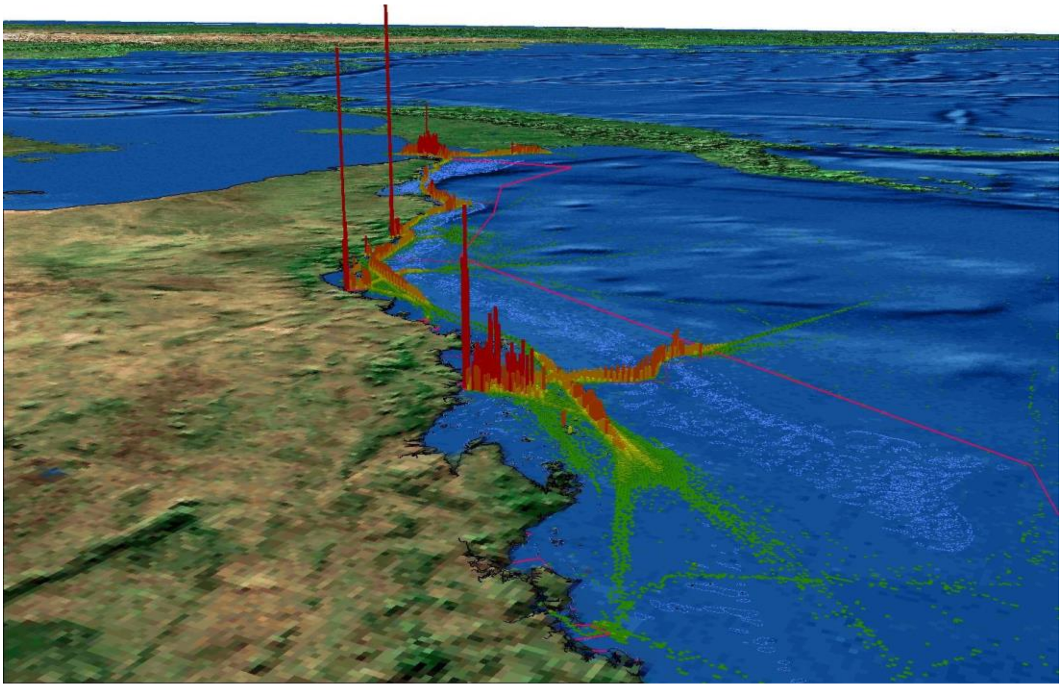
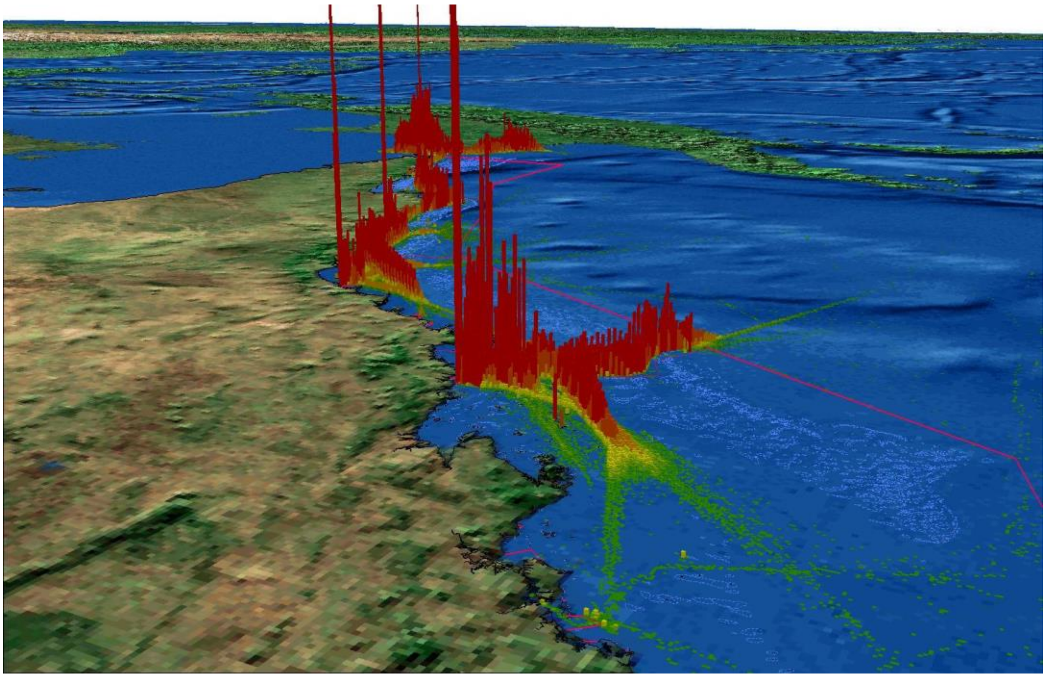


Figure 4.7. Shipping traffic in north east Australia. Source: GBRMPA, supplied July 2012.

With the expansion of ports, especially coal loading ports, on the Australian east coast in response to proposed large increases in coal export (GBRMPA, 2012b) large increases in shipping traffic along the Queensland coast are predicted as shown in Figure 4.8. Under these scenarios a large increase in shipping traffic through the Cape York and Torres Strait is predicted over the next decade. These increases will result in greatly increased risk of accidents and sediment re-suspension. Currently there is very limited capacity to respond in any meaningful way to a large oil spill in the more remote parts of the region. Any large oil spill would have severe environmental consequences. Therefore shipping traffic is considered to be a major potential and existing water quality and environmental threat to the eastern Cape York region.



a.



b.

Figure 4.8. Estimated shipping traffic with a modeled threefold increase in shipping from 2010. (a) AIS Reports 2010 in GBR on a 2 x 2 kilometre grid to (b) expected trend using a trebling of reports for future shipping volumes. Shipping traffic is represented by the height of the line and colour with red having highest frequencies and green showing lowest frequencies. Source: GBRMPA (2012).

The influence of shipping on sediment re-suspension has not been quantitatively documented in any of the existing datasets but it is likely to have significant localised impact on water quality in the shipping channels (Howley, 2015) where highly turbid plumes are generated by prop wash from ship transit in relatively shallow areas. Sediment plumes greater than 20km long behind ships in the Cape York shipping channels are regularly observed from the air. Anecdotal reports from fishermen in Cape York and Traditional

Owners in the Torres Straits indicate that reefs adjacent to the shipping zones have been significantly impacted.

In 2011 an assessment was undertaken of the risk of pollution from marine oils spills in Australian ports and waters (DNV, 2011). The report contains comprehensive information on factors that determine potential risk to the environment, including those of the Cape York region. For example, Figure 4.9 shows the overall frequencies of spills exceeding 1,100 and 10,000 for each sub-region. The South and Central sub-regions are in the High and Moderate respectively. An Environmental Risk Index (Figure 4.10) shows the Cape York region to be High, and is allocated the 'Very High' Environmental Sensitivity Index (not shown).

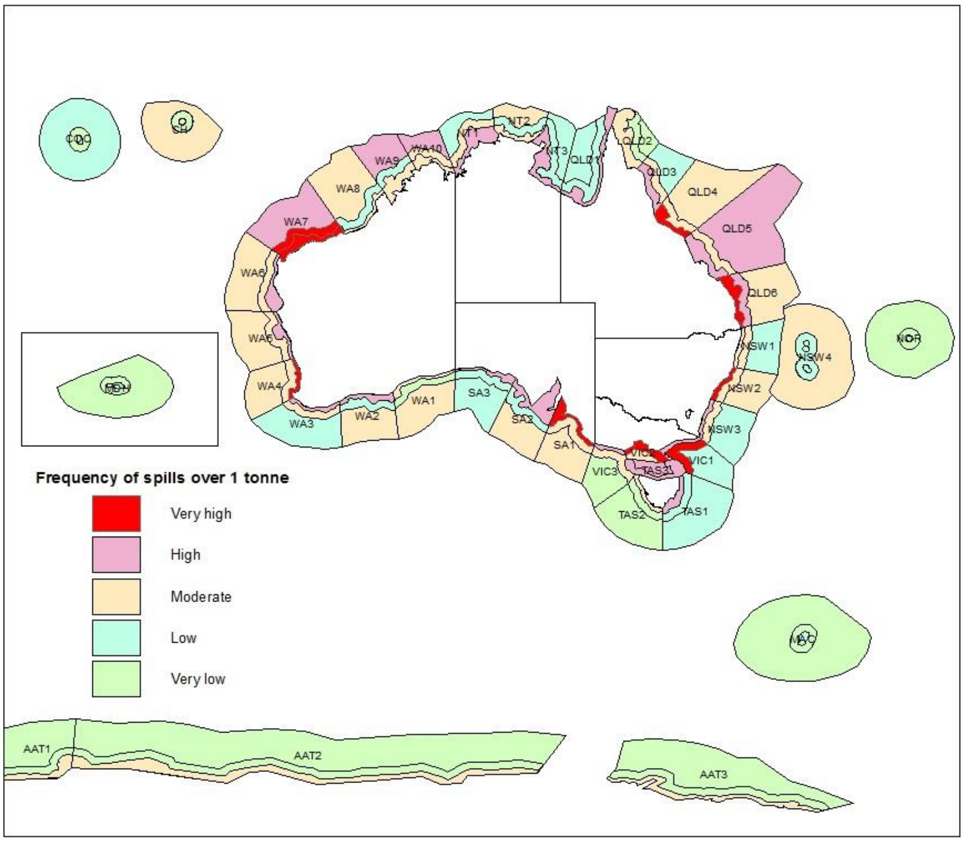


Figure 4.9. Frequencies of spills greater than 1 tonne. Source: DNV, 2011.

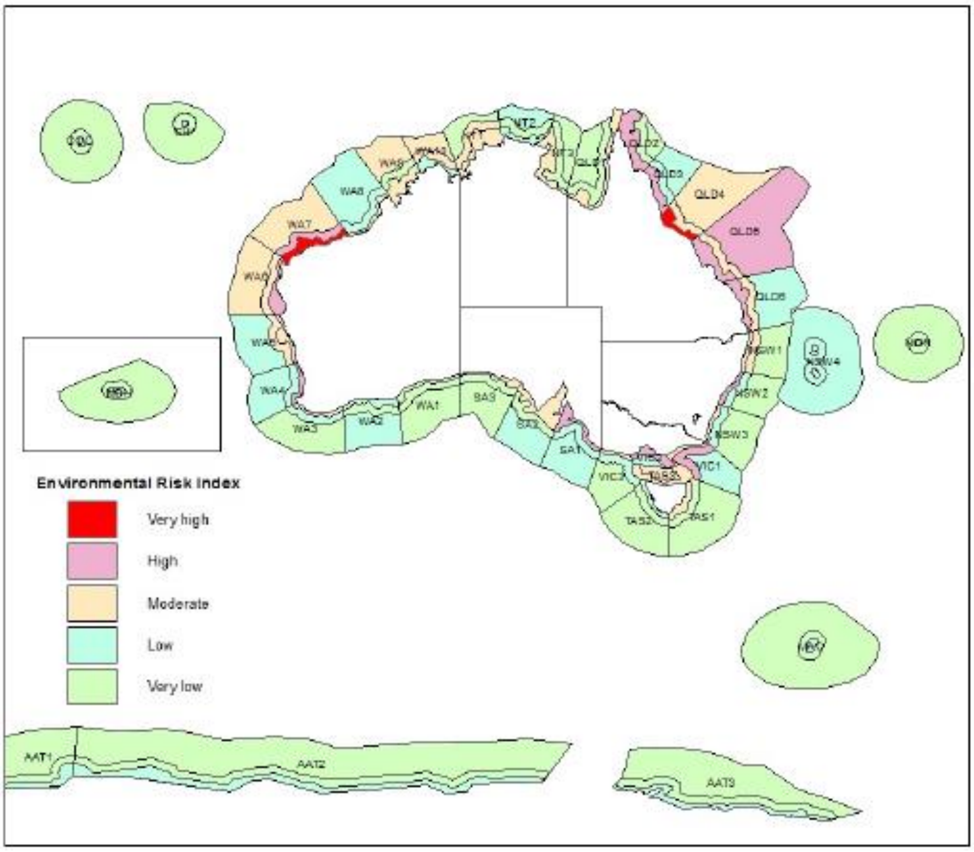


Figure 4.10. Environmental Risk Index developed as part of the National Oil Spill Risk Assessment. Source: DNV, 2011.

4.3 Future scenarios

It is important to consider the future threats to the GBR ecosystems in the Cape York region, and how this might change the extent and severity of the relative risk from water quality factors in the future.

4.4 Conclusions and potential management priorities

Based on consideration of the Load Index and the areas of greatest relative risk identified in this assessment, we can draw the following conclusions regarding potential priorities for managing degraded water quality in the eastern Cape York region:

1. The water quality influence in the region is generally constrained to the inshore areas, with hotspot areas in Princess Charlotte Bay for sediments and nutrients. The percentage of anthropogenic impact on nutrient loads is unclear but emerging research indicates that anthropogenic sediment erosion is also a source of nutrients. Further validation of the data is required. There is most likely no influence of PSII herbicides in the region.
2. Relative risk to the inshore reefs and seagrass meadows in the South sub-section has been poorly quantified due to a lack of monitoring of discharge, pollutant loads and Zones of Influence in this region. Existing data indicates that the risk posed to these habitats may be greater than the models have indicated. Further evaluation of this region is warranted.
3. In the combined assessment of the relative risk of marine water quality variables, it is notable that there are no areas in the Very High relative risk assessment class in the region, in contrast to other NRM regions where large proportions of the inshore areas are in the highest risk classes. A majority of the region is within in Very Low assessment class (87% of the area) which extends out to the Marine Park boundary, containing 84% of the coral reefs, 51% of the surveyed seagrass and 70% of the deepwater modelled seagrass in the region. The Low relative risk class extends to the offshore waterbodies in the central part of the region and contains 15% of the coral reefs and ~30% of the surveyed and deepwater modelled seagrass. The greatest area of influence from degraded water quality is in Princess Charlotte Bay where High relative risk assessment classes extend to the midshelf waterbodies of the Bay. The total area of the High relative risk class (717km^2; <1% of the region's area) contains ~6% of the region's surveyed seagrass and <1% of coral reefs and deepwater modelled seagrass. The Moderate relative risk class extends to the outer parts of Princess Charlotte Bay and in some coastal areas northward to the Lockhart River mouth. It contains approximately 14% of the region's surveyed seagrass.
4. Results of the relative risk assessment for important habitat features the eastern Cape York Region highlight that many of the ecosystems in the region are still considered to be in good condition and are at relatively low risk from current water quality influences. Importantly, in the northern rivers where there is limited development in the catchments, the water quality conditions are driven by natural conditions such as ocean upwelling of nutrients in the far northern section, and natural turbidity in shallow coastal waters.
5. In the assessment of end-of-catchment pollutant loads (Section 3.4) the Normanby catchment dominates the contributions to the regional anthropogenic loads for all parameters. The assessment also highlights that the anthropogenic loads of dissolved inorganic nutrients (DIN and DIP) represent a small proportion of the total loads (3 percent and 15 percent respectively), further supporting the conclusion that much of the dissolved nutrients in the marine assessment are not likely to be derived from human-induced sources. In contrast, it is estimated that about half of the regional TSS load, and up to half of the particulate nutrient loads are from human-induced sources.
6. Further analysis of modelled land use and pollutant load data shows that the dominant land uses in the region (by area) are nature conservation (61%) and grazing (37%). Other land uses including urban, horticulture, irrigated cropping and sugarcane are all less than 1% of the regional land use area. The largest total TSS loads are delivered to the end of catchment from conservation areas (46% of the regional load) and grazing lands (40% of the regional load). It is noted that cattle grazing is

permitted in many conservation areas in the region. Modelling data shows that the dominant erosion sources in the region are gully (44%) and hillslope (42%), with streambank erosion contributing around 13% of the regional TSS load. These proportions vary between catchments, with clear dominance of erosion from gullied areas in the Normanby catchment (71%). Hillslope erosion is the dominant source (>70%) of erosion in the Jacky Jacky, Pascoe, Lockhart, Jeannie and Endeavour catchments. In the Normanby catchment, it is estimated that 60% of the TSS load is from grazing lands with 87% of this from gully erosion, and 30% of the TSS load is from conservation areas with 34% of this from gully erosion and 66% from hillslope erosion. Streams contribute approximately 10% of the overall load in the catchment.

It can be concluded that overall, the water quality from eastern Cape York catchments present a relatively low risk to coral reef and seagrass ecosystems in the GBR, and that the ecosystems in the region are typically in good condition. The catchments in the Central sub-region – the Normanby, Hann and Stewart catchments – are likely to pose a risk to ecosystems in the Princess Charlotte Bay area from degraded water quality, particularly increased turbidity in wet season conditions. The assessment of pollutant loads and sources indicates that management in these catchments should be focused on management of gully erosion in grazing and conservation areas. This is supported by conclusions from other studies in the region (e.g. Brooks et al. 2013; Howley et al. 2015). However, the risks in the Central sub-region are quanitified with more certainty due to the much higher level of detailed monitoring and quantification of land degradation in this region. The risks to marine ecosystems in the other regions, particularly in the South sub-region where significant water quality impacts have been documented (Howley et al. 2012; Shellberg et al. 2016) and inshore reefs and seagrass meadows are frequently exposed to flood plumes, warrant further monitoring and assessment. Other threats to water quality in the eastern Cape York region include shipping traffic, particularly on the Inner Route, which may pose an increasing risk to the region with predicted increases in traffic.

5 Limitations to the risk assessment and future needs

The risk assessment described in this report provides the best available assessment of the relative risk of water quality pollutants to the GBR and the information outlined above can be used as the first step in prioritising management based on regional 'hot spots' for pollutant sources, contributing industries and resulting impacts in the marine environment.

A number of improvements from the 2013 risk assessment (Brodie et al. 2013a) have been incorporated. These include:

1. Analysis of the reliability of Chl-a data obtained using remote sensing and replacement of this parameter with results from long term Chl-a monitoring data.
2. Applied a revised method to assess the frequency of exceedance of TSS concentration data obtained using remote sensing data, factoring in the proportion of valid observations.
3. Definition of Zones of Influence for each basin in an attempt to attribute marine risk back to individual basins.
4. Incorporation of additional pollutants in the assessment of end-of-catchment loads; this assessment includes TSS, DIN, PSII herbicides as well as PN, DIP and PP.

However, there are several limitations to the assessment that are important to identify, and are summarised below.

Limitations to the input datasets in terms data collection, temporal and spatial resolution, influence the certainty of the outcomes. Several examples can be presented here:

- The input for Chlorophyll *a* is based on a long term mean of in-situ data collected between 1988 and 2006, TSS 2mg/L exceedance is based on daily remote sensing observations over a 10 year monitoring period (with a range of uncertainties described in Petus et al. 2015), while TSS, DIN and PN plume loading is based on a mean of 2003 to 2013 (which were in fact relatively wet years in the long term record), and PSII herbicide concentration modelling is based on single flood events in 2009 to 2011. In addition, the temporal resolution of the remote sensing data (which is used for daily observations, the plume loading and PSII herbicide modelling) is only 1 or 2 valid observations every 5 days. This presents difficulties in getting good temporal representation of the water quality parameter (eg. TSS, chlorophyll a or DIN). For these reasons the final conclusions of the assessment are supported by additional evidence of known water quality conditions, spatial and temporal patterns and ecological impacts. Additional variables that were considered but not included due to the current lack of temporal and spatial data, and / or knowledge of ecological impacts include chronic exposure to PSII herbicides and non-PSII herbicides, particulate nutrients and phosphorus exposure, and micro-pollutants presence and distribution in the GBR.
- The modelled estimates of anthropogenic end-of-catchment loads are long term averages and do not capture the influence of large floods. Empirical datasets included in the assessment (eg. TSS, DIN and PN plume loading) do factor in these events. In comparing the modelled results against empirical data, the relative contributions of individual basins are in general agreement with monitoring data (where available) except during extreme wet seasons.
- Modelled loads data from Source Catchments is moderately well correlated with empirical (monitored) loads estimates from the Normanby River, but poorly correlated with loads from the Pascoe and Annan Rivers.
- The marine hydrological modelling is only available for the Normanby River to estimate the Zones of Influence, and the path-distance approach applied for the other rivers was not applied to the Jacky Jacky, Olive, Lockhart, Jeannie, Starcke and McIvor Rivers as there is no gauging station in these catchments. Therefore the full analysis cannot be extended to all rivers in the region.

- The relative abundance of monitoring data and land disturbance analyses which show a high level of disturbance in the Central sub-region may bias the risk assessment in this region compared to regions where there has been little quantification of impacts.

The risk classes for individual water quality variables are not equivalent in terms of ecological impact, and are therefore not directly comparable without recognition of these differences. Further studies should adequately address this limitation to provide a better representation of the severity of potential ecological impacts between assessment classes for each water quality variable. Community characteristics such as the sensitivity and resilience of particular seagrass or coral communities (e.g. associated with their natural levels of exposure to pollutants) are additional parameters that must be considered when defining the ecological consequences of the risk. Indeed, different species assemblages will respond differently to the same exposure (i.e. same likelihood magnitude of risk) to river plumes. The consequence of the exposure of species to a range of water quality conditions is complicated by the influence of multiple stressors and additional external influences including weather and climate conditions, and consequences are mostly unknown at a regional or species level.

The approach to classification used is also a potential weakness of multi criteria analysis, which is an interval scale approach, while risk consequence is inherently oriented to a need for quantification of magnitudes. In addition, the assessment does not account for the potential synergistic or antagonistic effects that these multiple stressors when acting together may have on ecosystems.

Only a limited sensitivity analysis that tested weighting of variables has been conducted. More scenarios that scale or 'weight' individual factors or pollutants as being more or less important and the effect of only selecting the highest assessment classes in the final analysis should be tested. For example, a more detailed assessment of the patterns in the lower assessment classes should be considered in future work, particularly given the potential influence of chronic exposure to pollutants, or the effects of periodic exposure to high concentrations of pollutants.

Further validation of remote sensing-based results is required for locations where high turbidity that confounds existing algorithms may naturally occur. These areas include the shallow areas of the coast which can be naturally turbid, but there is evidence of increased turbidity in some areas. Uncertainties in products derived from remote sensing of these areas have not been resolved (see results and discussion in Petus et al. 2015). In addition, the number of valid observations for the remote sensing assessment varies between seasons and locations and over the year equates to an average of less than 2 valid observations every 5 days (refer to Maynard et al. 2015).

The scope of the assessment is limited in terms of the coverage of social and economic issues. It should be recognised and highlighted that the results presented in this study only represent the biophysical perspective of relative risk to guide management priorities to reduce pollutant impacts on the GBR.

These limitations have been translated into priority information needs for future risk assessments of water quality in the GBR:

1. Scoping of the availability of, and acquisition of, more consistent temporal and spatial data for all water quality variables (including those not included in the most recent assessment such as phosphorus and particulate nutrients) and their ecological impacts to enable improved classification in terms of ecological risk and application of a formal risk assessment framework (which includes assessments of likelihood and consequence).
2. Refinement of the approach to estimate 'Zones of Influence' for each River.
3. Better understanding of the responses of key GBR ecosystem components to cumulative impacts of repeated exposure to poor water quality, and the cumulative impacts of multiple water quality pressures.
4. Validation of the remote sensing data for turbidity throughout the region.

5. Better understanding of the prevalence and associated effects of other pollutants (e.g. microplastics, endocrine disrupting substances, oil and PAHs, pharmaceuticals and heavy metals) on GBR ecosystems.
6. Extending the habitat assessments beyond coral reefs and seagrass to include coastal ecosystems such as freshwater and coastal wetlands, mangroves and estuarine environments, and non-reef bioregions.
7. Incorporation of the principles of conservation management and the increasing need to protect areas in the GBR that are in good condition as many parts of the GBR become more degraded.

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