Assessment of the relative risk of degraded water quality to ecosystems of the Wet Tropics Region, Great Barrier Reef

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Disclaimers

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Executive Summary

A risk assessment method was developed and applied to the Wet Tropics Natural Resource Management 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 differences between the Wet Tropics river catchments in influencing GBR ecosystems.

The relative risk of degraded water quality among the basins in the Wet Tropics 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 based on that developed for the GBR wide relative risk assessment conducted by Brodie et al., (2013a) to inform Reef Plan 3 priorities and modified where necessary to reflect issues and data availability in the Wet Tropics region. There are also several improvements to the input data in this assessment.

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. 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 Wet Tropics region, and was used to generate a 'Marine Risk Index' for coral reefs and seagrass meadows.

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 solids (TSS) and chlorophyll *a* obtained from daily remote sensing observations, and the distribution of key pollutants including TSS, dissolved inorganic nitrogen (DIN) 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 influence of Crown of Thorns Starfish (COTS) on coral reefs, and the differential influence of river discharges on the COTS initiation zone was also included. 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, Particulate Nitrogen, 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.

The information was then combined in a qualitative way to make conclusions about the relative risk of degraded water quality to coral reefs and seagrass meadows among the basins in the Wet Tropics region. The key results are summarised below.

Marine risk

When all water quality variables are combined into the Marine Risk Index (Section 3.3), the risk is greatest for coral reefs in the Tully-Murray basins, and for seagrass in the Tully-Murray and Herbert basins. The areas in the Very High relative risk class were located in the coastal areas around Hinchinbrook Island, extending north to the Tully River mouth and south to the regional boundary at the southern part of the Herbert basin. This area is locally influenced by the Herbert, Murray and Tully Rivers, but also receives water from the Burdekin region. The high relative risk is associated with high exceedance of all water quality parameters in this location, except for the COTS Initiation Zone, and the presence of large areas of inshore coral reefs and seagrass in these high risk areas. While the areas of coral reef and seagrass within the highest assessment classes for individual variables and the Marine Risk Index are relatively small, they often include highly valued tourism and recreation sites of the GBR. Examples include Hinchinbrook Island, Goold Island, the Brooks Islands, and the Family Island group including Bedarra Island and Dunk Island. In the case of seagrass meadows, many of the highest risk areas overlap with dugong protection areas (DPAs) around Hinchinbrook and Taylors Beach, which are assigned because of the large populations of dugongs feeding in the associated seagrass meadows.

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 Wet Tropics basins.

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. In the assessment of end-of-catchment pollutant loads (Section 3.4) the greatest relative contributions of combined end of basin loads to the Wet Tropics region is from the Herbert and Johnstone basins. The anchored score indicates that the contribution from the Tully Murray basin is approximately 60% of that from the Herbert and Johnstone basins, and the contribution from the Russell-Mulgrave basin is approximately 47% of that of the Herbert and Johnstone basins. The Barron and Daintree are relatively low contributors to regional pollutant loads compared to the other basins (approximately 16% of that contributed by the Herbert and Johnstone basins).

COTS Influence

When considering only the Wet Tropics rivers (e.g. Daintree, Barron, Russell-Mulgrave, Johnstone, Tully and Herbert Rivers) the Johnstone is estimated to present the largest risk of contributing to the DIN pool in the COTS Initiation Zone. The high level of DIN risk from the Johnstone River is related to the large volume discharged (mean = 3.2 km^3 over the 4 years of simulation) and but also due to the high estimated concentration of DIN in the discharge (321 $\mu g\ N\ L^{-1}$).

The Russell-Mulgrave and Tully Rivers rank consecutively lower than the Johnstone River for DIN risk, however the mean risk values for these three rivers are similar. When comparing discharges and volumetric contributions to the outbreak region from these three Rivers, the Russell-Mulgrave consistently out ranks the Tully and Johnstone Rivers (in that order), however, when combined with DIN load data, the mean risk values for the Russell-Mulgrave, Tully and Johnstone Rivers are similar. This indicates that for these rivers, it is the DIN load rather than discharge that is the primary determinant of the DIN risk score for these rivers.

The COTS Influence Index reflects the rankings noted above, showing that the DIN risk score for the Russell-Mulgrave and Tully Rivers is 70-75% of that of the Johnstone River, the Herbert River is 42%, Daintree is 34% and the Barron is 10%.

Combined assessment of the relative risk of degraded water quality in the Wet Tropics region to guide management priorities

We used a quantitative technique to combine the results of the marine assessment, end-of-catchment loads and COTS influence to generate a Relative Risk Index for each basin (see Table i). These results show the greatest risk to each habitat in terms of the potential water quality impact from all of the assessment variables in the Wet Tropics region and end -of -catchment anthropogenic loads of TSS, DIN, PSII herbicides, PN, DIP and PP. The rankings are:

- **Coral reefs:** Highest ranking are the Tully Murray and Johnstone basins. The rank of the remaining basins is Herbert (81% of the Tully Murray and Johnstone), Russell-Mulgrave (64%), Daintree-Mossman (42%) and Barron (34%).
- **Seagrass meadows:** Highest ranking is the Herbert basin. The rank of the remaining basins is Tully-Murray (82% of the Herbert), Johnstone (55%), Russell-Mulgrave (30%), Barron (14%) and Daintree-Mossman (10%).

- **Coral reefs and seagrass meadows combined:** Highest ranking are Tully Murray and Herbert basins. The rank of the remaining basins is Johnstone (85% of the Tully Murray and Herbert), Russell-Mulgrave (52%), Daintree-Mossman (29%) and Barron (26%).

From these findings, it can be concluded that ***the greatest risk posed to coral reefs and seagrass from degraded water quality in the Wet Tropics region is from the Tully-Murray, Herbert and Johnstone basins***. The relative risk of the Russell-Mulgrave basin is about half of the score of the highest ranking basins for the combined assessment, but higher when only coral reefs are considered (64%). The Daintree-Mossman and Barron basins are showing to be of lower priority relative to the other basins in the region (around 25-30% of the relative score of the highest ranking basins for the combined reef and seagrass result). However, there are many uncertainties associated with the input datasets and method for combining these Indexes at a basin scale at this time (see Section 6); further discussion is recommended prior to making any management decisions based on these results.

Table i. Summary of the outcomes of the overall assessment of the relative risk of water quality in the Wet Tropics region. Shading represents the following relative classes: Red = Very High (0.8-1.0); Dark orange = High (0.6-0.8); Orange = Moderate (0.4-0.6); Yellow = Low (0.2-0.4); No colour = Very Low (0-0.2)

Region	Basin area (km^2)	Annual Average River Flow (ML)	Zone of influence (km^2)	Marine Risk Index (based on marine assessment only)		COTS Influence Index	Basin Anthropogenic Load as a proportion of the Total Regional Load (%)						Loads Index	Relative Risk Index	Pollutant hotspots	Pollutant sources (anthropogenic loads)	Overall Rating of Relative Risk
				Coral Reef	Seagrass		TSS	DIN	PSII Herb	PN	DIP	PP					
Daintree	2,107	2,639,319	4,913	0.44	0.04	0.34	2	2	5	3	3	2	0.16	0.29		Sugar cane 26% DIN Sugar cane 99% PSII	**LOW**
Mossman	479	507,886														Sugar cane 65% DIN Sugar cane 99% PSII	
Barron	2,189	793,802	860	0.43	0.10	0.10	4	1	4	3	3	3	0.16	0.26		All cropping 9% DIN Cropping (except sugar cane) 66% PSII	**LOW**
Russell-Mulgrave	1,979	3,684,046	3,851	0.45	0.10	0.75	7	5	17	7	7	8	0.47	0.52	PSII 3 DIP 2	Sugar cane 60% DIN Sugar cane >99% PSII	**MOD**
Johnstone	2,326	4,559,029	2,649	0.67	0.12	1.00	13	19	20	19	9	22	0.94	0.85	TSS 2 DIN 1 PSII 3 PN 1 DIP 1 PP 1	Sugar cane 80% DIN Sugar cane 96% PSII	**VERY HIGH**
Tully	1,685	3,448,088	6,998	1.00	1.00	0.70	7	11	25	7	9	7	0.60	1.00	DIN 2 PSII 2 DIP 1	Sugar cane 74% DIN Sugar cane 96% PSII	**VERY HIGH**
Murray	1,115	1,290,985														Sugar cane 81% DIN Sugar cane 99% PSII	
Herbert	9,842	4,273,490	2,707	0.62	0.95	0.42	27	4	29	19	7	23	1.00	0.99	TSS 1 PSII 1 PN 1 DIP 2 PP 1	Sugar cane 88% DIN Sugar cane 97% PSII Grazing TSS	**VERY HIGH**

These results can also be considered in the context of the dominant land uses and typical water quality runoff characteristics to further guide management priorities. The overall management priorities for addressing degraded water quality in the Wet Tropics region are summarised below in Table (ii).

Table ii. Summary of management priorities for reducing the relative risk of degraded water quality to the Wet Tropics region.

Relative Priority	Priority management areas for GBR outcomes		
	Basin	**Pollutant management**	**Key land uses**
Very High	1. Johnstone	Nitrogen	Sugar cane, bananas
	2. Tully Murray	Nitrogen	Sugar cane, bananas
	3. Herbert	Nitrogen	Sugar cane
	4. Russell Mulgrave	Nitrogen	Sugar cane
	5. Herbert	PSII herbicides	Sugar cane
	6. Tully Murray	PSII herbicides	Sugar cane
High	1. Johnstone	PSII herbicides	Sugar cane
	2. Herbert	Sediment / Phosphorus	Grazing Disused mining sites in the Upper Herbert
Moderate	1. Johnstone	Sediment / Phosphorus	Sugar cane
	2. Barron	Sediment	Tableland mixed cropping; urban (broader Cairns area)
	3. Russell Mulgrave	Sediment	Urban (broader Cairns area)
	4. Barron	Nutrients	Sugar cane, urban
	5. Daintree-Mossman	Nutrients	Sugar cane
	6. All basins	Phosphorus	Sugar cane, bananas, cropping, grazing, coastal urban
Lower	Barron, Daintree	PSII herbicides	Sugar cane

It should be noted that 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, particularly for the Johnstone and Russell Mulgrave basins. Accordingly, it is suggested that the results for these basins are likely to be an underestimate of the relative risk of degraded water quality in the region. This first attempt of assigning relative risk in the marine environment to individual basins by defining zones of influence for each basin demonstrates how this method could be applied for future assessments, however, 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 Wet Tropics Natural Resource Management (NRM) region is one of 6 NRM regions in the GBR catchment (Figure 1.1). The region includes 91% of the Wet Tropics of Queensland World Heritage Area and 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 22,000 km^2 and is approximately 5% of the total GBR catchment area (423,122 km^2) (Hateley et al., 2014). There are eight Australian Water Resources Council Basins that make up the region (ANRA, 2002). From north to south they are Daintree, Mossman, Barron, Russell-Mulgrave, Johnstone, Tully, Murray and Herbert (Figure 1.1). 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 area of approximately 32,000km^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, catchments south of the Wet Tropics NRM region such as the large Burdekin River influence the marine ecosystems adjacent to the NRM region, as illustrated in Figure 1.2.

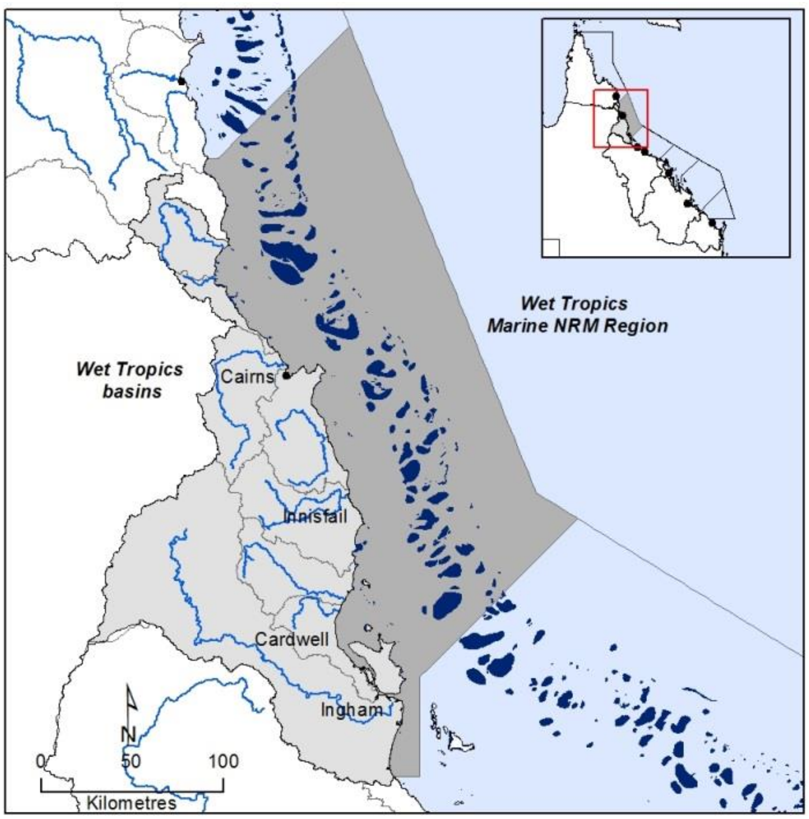


Figure 1.1. Map showing the assessment boundaries considered in this risk assessment. The light shaded grey areas in the catchment show the main river basins, and the dark shaded area in the GBR represents the Wet Tropics Marine NRM region. The inset shows the region in the context of the whole GBR and its catchments.

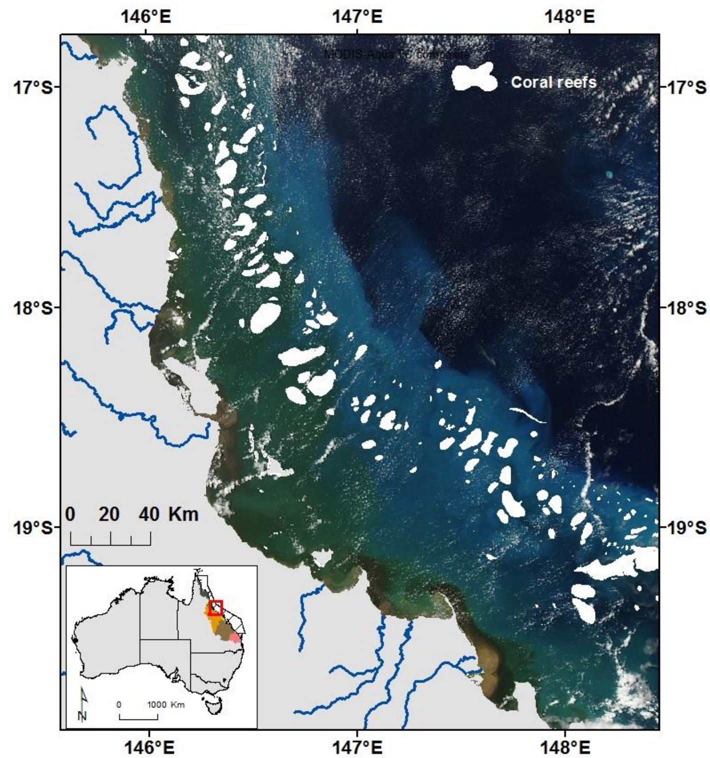


Figure 1.2. MODIS-Aqua image from 5 February 2011 showing the extent of river plume influences from rivers along the central GBR coast (provided by TropWATER).

The Wet Tropics 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. Marine and coastal ecosystems also support important tourism and fisheries industries that depend on the healthy natural resources of the region. The region is characterised by heavy rainfall and frequent periods of high river flow. The dominant land use in the coastal areas is sugarcane, and to a lesser extent, bananas. The Tablelands support diverse horticultural crops and dairy farms, and the large drier areas of the upper Herbert catchment support grazing land uses. Cairns is the largest population centre (~157,000 resident people), with other larger centres in Innisfail, Cardwell and Ingham. Many smaller towns are located along the coast and throughout the catchments.

Three Water Quality Improvement Plans in the Wet Tropics region (Douglas, Barron and Tully WQIPs) have identified water quality issues in the region. These include: dissolved nutrient runoff from sugarcane, horticulture (predominantly bananas), cropping and urban land uses, herbicide runoff from sugarcane, horticulture and cropping land uses, and to a lesser extent, sediment runoff from grazing and streambank erosion. Nutrient rich drainage to shallow groundwater in cropping areas affects water quality through lateral sub-surface water movement into the waterways (Hateley et al., 2014; Rasiah et al., 2010).

The Wet Tropics NRM region has been identified as a high risk region in terms of the influence of degraded water quality on GBR ecosystems (Brodie et al., 2009, 2013a). In the most recent relative risk assessment of degraded water quality on the GBR (Brodie et al., 2013a), the Wet Tropics region was ranked as the highest risk NRM region compared to other regions. This ranking was largely associated with loads of nutrients and PSII herbicides that are delivered to the GBR from the catchments in the region, and the influence of the region's river flow and nutrient load on the initiation of the outbreak of Crown of Thorns Starfish populations. In addition, the midshelf and offshore reef complex is located relatively close to the coast in the Wet Tropics region in comparison to southern areas of the GBR (Figure 1.1), which results in regular exposure of these ecosystems to river plumes during the wet season (typically November to May) (see Figure 1.2).

Previous assessments of the relative risk of degraded water quality on GBR ecosystems have largely been undertaken at a GBR wide scale, with relative assessments 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 initiatives. The primary, and most recent, regionally based assessment was conducted to help direct management activities to basins and pollutants of most concern under the Queensland Government Reef Protection Package in 2009 (Brodie et al., 2009; see also Waterhouse et al., 2012).

The assessment focused on pollutant loads at a basin scale, and identified the highest total loads and generation rates of anthropogenic suspended sediment, dissolved inorganic and PSII herbicide loads in the Wet Tropics, Burdekin, Mackay Whitsunday and Fitzroy NRM regions. Waterhouse et al. (2012) summarises a case study of the Wet Tropics results, including the following key findings based on best available data at the time (2009):

- The Russell Mulgrave basin generates the highest total DIN load on an annual basis, followed by the Johnstone, Herbert and Tully basins.
- The key contributing land use to DIN loads is sugarcane and associated fertiliser application.
- The largest proportion of total anthropogenic DIN load from sugarcane is from the Johnstone basin, with high contributions also from the Russell Mulgrave, Herbert, Tully and Murray basins.
- In terms of DIN load from sugarcane per unit area of sugarcane cultivation, the highest loads per unit area are from the Russell Mulgrave, Tully, Murray and Johnstone basins.
- In the Wet Tropics Region, it is estimated that the source of DIN loads is approximately 75% sugarcane and 5% bananas, 12% grazing and forest, and 8% other crops/dairy and urban.
- The Herbert basin delivers the greatest load of PS-II herbicide followed by the Johnstone, Russell Mulgrave and Tully basins. The loads from remaining basins are comparatively lower.
- The greatest proportion of PS-II herbicides is generated from sugarcane areas in all Wet Tropics basins.
- Diuron is the PS-II herbicide discharged in the highest amounts from the region, followed by atrazine and hexazinone. The Herbert, Russell Mulgrave, Johnstone and Tully basins deliver substantial exports of diuron.
- Generally suspended sediment loading from Wet Tropics catchments is believed to have stabilized or declined over the last 10 years, although river monitoring data to support this is problematic as yet due to natural variability in flow and time lags (Bainbridge et al., 2009). This is the expected trend associated with improved management practices in sugarcane (e.g. minimum tillage and green cane harvesting) and, to some extent, grazing in the region over the last 20 years (Rayment, 2003).
- The Herbert basin generates the most current total and anthropogenic suspended sediment load on an annual basis, followed by the Johnstone, Daintree and Russell Mulgrave basins. However, the Mossman basin generates the most suspended sediment per basin area on an annual basis, followed by the Russell Mulgrave, Daintree and Johnstone basins.
- The greatest anthropogenic load of suspended sediment to the GBR per unit area of land use is from sugarcane in most Wet Tropics basins (except Murray where 'Other crops' are higher). Grazing is also an important bulk source in the Herbert, Daintree and Mossman basins.

Since 2009, several improvements in catchment modelling (see Hateley et al., 2014) 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 some of the GBR NRM regions, including the Wet Tropics. 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 an updated relative risk assessment of water quality issues in the Wet Tropics region.

This report presents the results of an updated assessment of the relative risk of the influence of sediments, nutrients and PSII herbicides on key GBR ecosystems in the Wet Tropics region which attempts to identify relative differences at a basin scale. 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 the methodology developed in the relative risk assessment undertaken for the whole GBR in 2013 (see Brodie et al., 2013a). The full report prepared by Brodie and others can be downloaded for a full explanation of the assessment techniques used in that assessment.[1]

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.

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, 2009). 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

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

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, 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, 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. 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 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.

To conduct a comparable assessment that just focused on the Wet Tropics region, separate areas of influence for each river discharging into the marine environment were estimated using hydrodynamic modelling. This enables relative risk in marine environment to be attributed to each basin. The marine boundaries used for each river to create 'zones of influence' were defined using the eReefs model as described in Section 2.3. The basic elements of the framework shown in Figure 2.1 remain the same. The combined index ultimately ranks the relative risk of degraded water quality to coral reefs and seagrass among Wet Tropics basins.

2.2 Selecting and classifying variables

The same suite of water quality variables were selected as for the 2013 risk assessment 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 total suspended solids (TSS) and chlorophyll *a* from daily remote sensing observations, and the distribution of key pollutants including TSS, dissolved inorganic nitrogen (DIN) and photosystem II-inhibiting herbicides (PSII herbicides) in the marine environment during flood conditions (based on end-of-catchment loads and surface water exposure estimates). A spatial variable is included that represents an area of the GBR lagoon where primary crown-of-thorns starfish (COTS) outbreaks have most frequently been observed (see Furnas et al., 2013a). COTS outbreaks are an important cause of coral loss on the midshelf and outer reefs of the GBR (De'ath et al. 2012) and based on current understanding, a response to excess nutrient runoff from certain catchments that reaches this 'COTS initiation zone' (Fabricius et al. 2010). The COTS Initiation Zone has been identified as the area of highest risk with respect to initiating COTS primary outbreaks, described in further detail in Furnas et al. (2013a). This area is assessed here as the coral reefs between 14.5°S and 17°S inside the GBR Marine Park boundary

(Figure 2.2) The areas affected by this zone are within the Cape York and Wet Tropics regions (see Figure 2.3). Evidence for the degree to which each river in these regions (and in the Burdekin region) influences nutrient conditions in the Initiation Zone is included in the assessment in the COTS Influence Index (see Section 2.3.3).

More detailed information on pollutant impacts GBR ecosystems is provided in the recently completed 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).

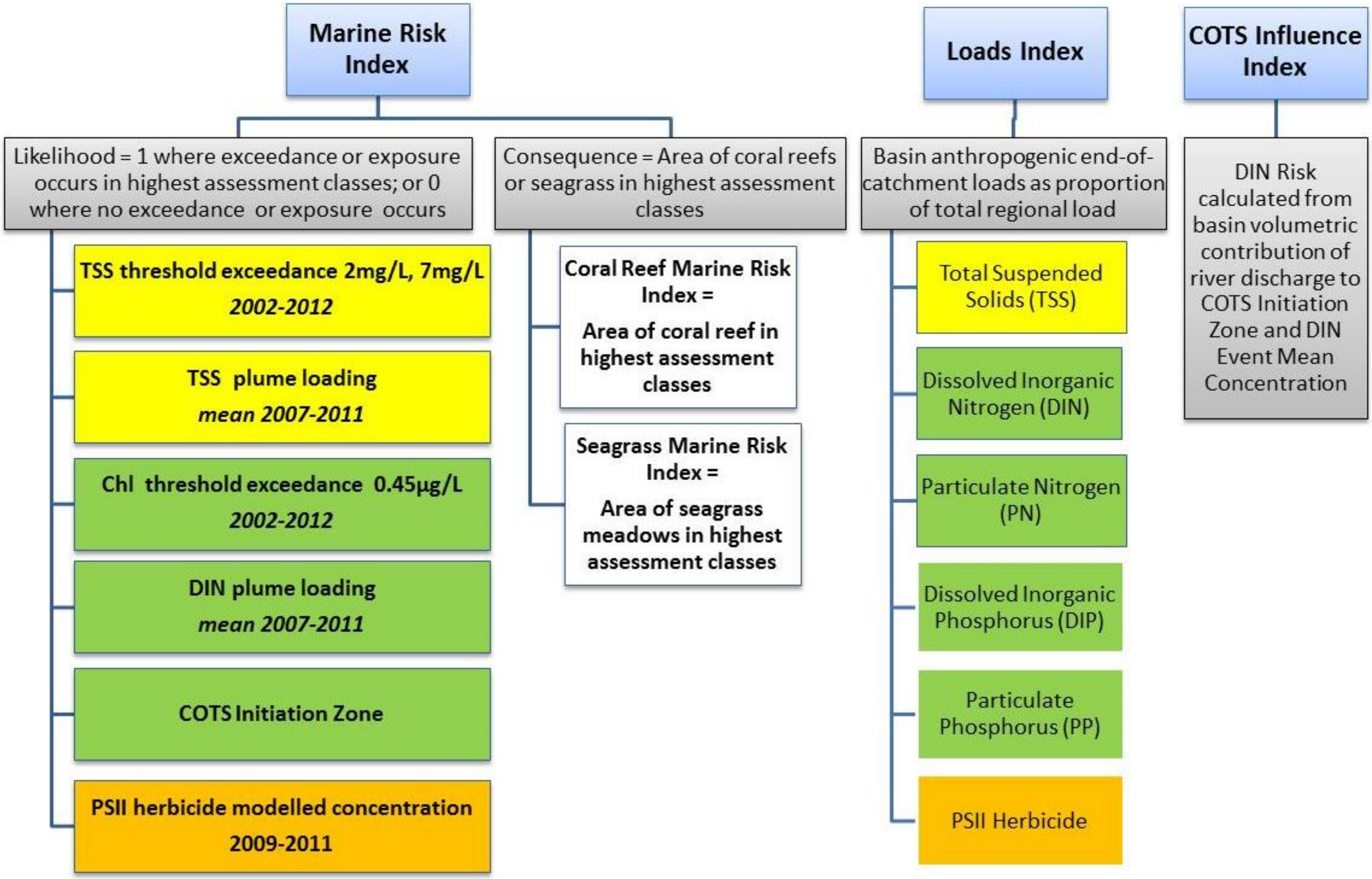


Figure 2.1. The risk assessment framework used in this project showing the components of the Marine Risk Index to represent marine water quality ecological risk to coral reefs and seagrass meadows, a Loads Index to represent catchment influences on GBR water quality using end-of-catchment anthropogenic pollutant loads and a COTS Influence Index to factor in the importance of river discharges on the COTS Initiation Zone for coral reefs. The colours represent groups of variables: yellow = sediment related variables, green = nutrient related variables and orange = PSII herbicide related variables.

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). A description of each of the variables, classification and analysis technique is presented in Brodie et al., (2013a).

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. 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., 2013b), we have limited certainty around this assumption. Similarly we consider dissolved inorganic nutrients to be of somewhat more important than particulate nutrients because they are immediately and completely bioavailable for algal growth (see Furnas et al., 2013b). Particulate forms mostly become bioavailable over longer time frames, and dissolved organic forms typically have limited and delayed bioavailability (see Furnas et al., 2013b). However, in our assessment in the ranking of end-of-catchment pollutant loads, we have considered PN, PP, DIN and DIP to be equally relevant given our current limitations in understanding.

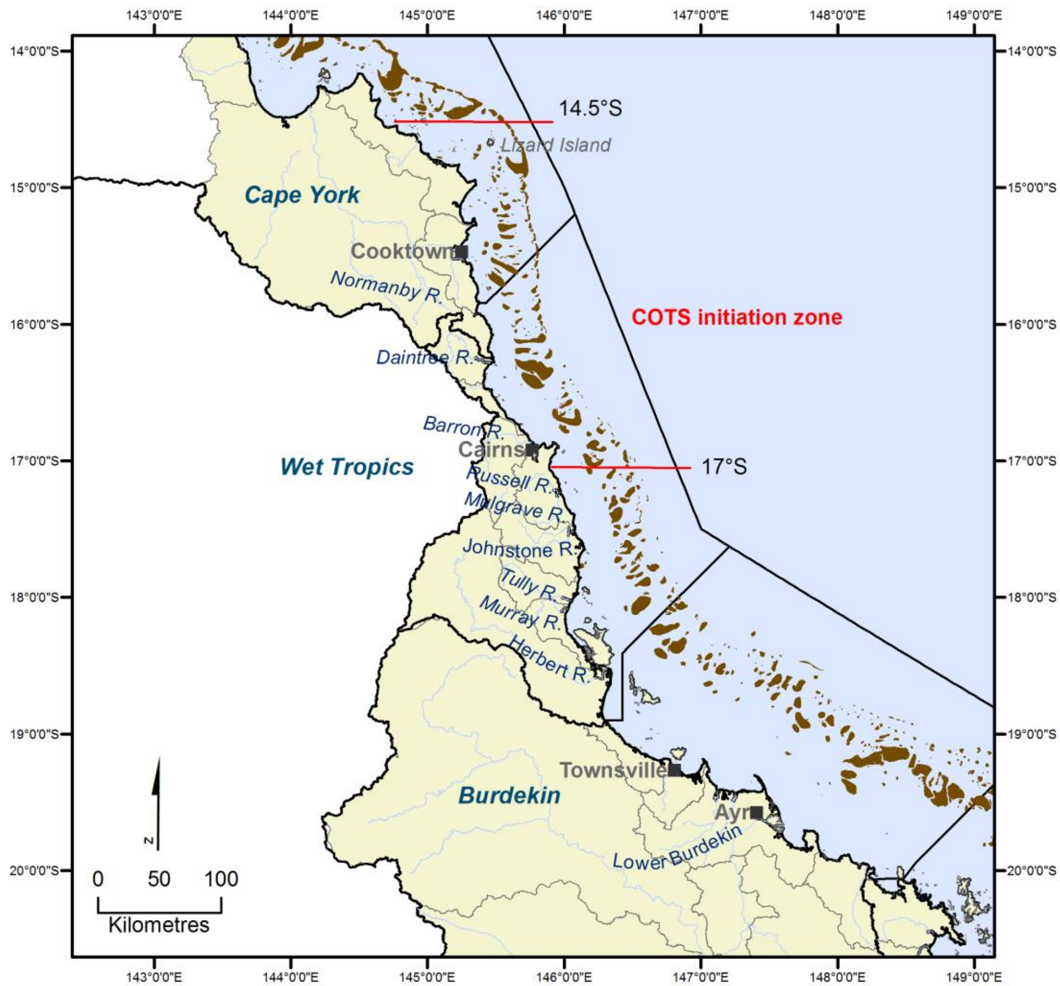


Figure 2.2. Location of the COTS Outbreak Initiation Zone, defined as a high risk area for COTS primary outbreaks based on current understanding of the outbreak initiation zone between 14.5°S and 17°S. Refer to Furnas et al. (2013a) for further explanation.

Table 2.1. 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 2012. 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 Brando et al. (2013).
Frequency of exceedance % for a 2 mg/L threshold (a)	<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.
Frequency of exceedance for a 7mg/L threshold (b)	0	<1	1-10	10-20	20-100	Threshold is equivalent to a turbidity of 5 nephelometric turbidity units (NTU). Shown to have various ecosystem effects including coral reef stress, declines in seagrass cover (Collier et al. 2012), fish habitat choice, home range movement and (above 7.5 nephelometric turbidity units) foraging and predator-prey relationships (Wenger et al., 2013).
TSS Plume Loading (mean 2007-2011)	Category 1		Category 2	Category 3		The frequency and extent of the influence of flood plumes containing differing concentrations of total suspended solids is used to provide an estimation of the extent of surface exposure of coral reefs and seagrass during wet season conditions. Modelled using an assessment of plume frequency from satellite imagery and monitored end-of-catchment loads in each wet season (Dec to Apr, inclusive) from 2007 to 2011 (Devlin et al., 2013). The mean of the five annual maps was selected as a way of factoring in inter-annual variability in river discharge, although it is recognised that this period was characterised by several extreme rainfall events.

Variables	Assessment Class					Data source/methodology
	Very Low 1	**Low 2**	**Medium 3**	**High 4**	**Very High 5**	
Nutrients						
Chlorophyll *a* concentration (µg/L)						Assessment classes were based on daily observations of Chlorophyll *a* concentrations over the period 1 Nov 2002 to 30 April 2012. Data was interpolated across reefs (which are masked during image processing) using Euclidean Allocation in ArcGIS. Classification is based on the number of valid observations in the full observation period. Method for extraction described in Brando et al. (2013).
Frequency of exceedance % for a 0.45 µg/L threshold	<1	1-10	10-20	20-50	50-100	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 annual chlorophyll concentrations remain below this concentration.
Dissolved Inorganic Nitrogen (DIN) Plume Loading (mean 2007-2011)	Category 1		Category 2	Category 3		Elevated 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). Modelled using an assessment of plume frequency from satellite imagery and monitored end-of-catchment loads in each wet season (Dec to Apr, inclusive) from 2007 to 2011 (Devlin et al., 2013). The mean of the five annual maps was selected as a way of factoring in inter-annual variability in river discharge, although it is recognised that this period was characterised by several extreme rainfall events.
COTS Initiation Zone	Out of the zone				In the Zone	Shows an area defined to be highest risk in initiating COTS outbreaks, defined as the area between Latitude 14.5°S and 17°S and described in Furnas et al. (2013a). Data from this area shows prolonged periods of high Chlorphyll *a* concentrations that exceed 0.8 µg/L, which is important for COTS larval survival.
PSII Herbicides						

Variables	Assessment Class					Data source/methodology
	Very Low 1	**Low 2**	**Medium 3**	**High 4**	**Very High 5**	
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. in review) 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; 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).

2.2.1 Habitat mapping

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

The seagrass habitat map used (supplied by TropWATER James Cook University) is comprised of a composite of the survey data up to 2010 (observed habitat) and 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.

2.2.2 Defining basin 'zones of influence'

Zones of influence for rivers in the Wet Tropics region were defined using output from the AIMS hydrodynamic model for the 2010-11 wet season (December to April inclusive). The rivers that are modelled in the region include the Daintree, Barron, Russell-Mulgrave, Johnstone, Tully and Herbert. Mean tracer concentrations for all Wet Tropics rivers were interpolated onto a regular grid and saved as geotiffs (cell size = 0.036 x 0.036 decimal degrees, GCS_WGS1984 ; supplied by N. Woolf, University of Queensland).

Salinity values produced by the same hydrodynamic model were used to estimate an appropriate tracer threshold. This was undertaken by looking for the maximum tracer concentration that occurred in water with salinities ranging from 34 to 25 for each of 10 rivers modelled in the GBR (maximum being used to avoid the many situations where modelled salinity and tracer concentration were decoupled). Mean tracer thresholds were then calculated for each salinity level as presented in Table 2.2.

Table 2.2. For each salinity (34 to 25), the maximum tracer concentration that occurred within each river plume during the 2010 - 2011 wet season.

Salinity	River										
	Normanby	Daintree	Barron	Russell-Mulgrave	Johnstone	Tully	Herbert	Burdekin	Haughton	Fitzroy	Mean
34	0.009	0.016	0.003	0.006	0.004	0.004	0.000	0.005	0.000	0.021	0.007
33	0.021	0.017	0.005	0.012	0.009	0.009	0.002	0.027	0.004	0.045	0.015
32	0.038	0.020	0.014	0.019	0.014	0.020	0.005	0.054	0.016	0.072	0.027
31	0.113	0.030	0.027	0.060	0.046	0.055	0.022	0.080	0.035	0.099	0.057
30	0.087	0.054	0.052	0.079	0.062	0.102	0.049	0.106	0.065	0.127	0.078
29	0.117	0.084	0.072	0.104	0.100	0.132	0.078	0.136	0.096	0.154	0.107
28	0.145	0.114	0.098	0.148	0.108	0.194	0.107	0.168	0.122	0.181	0.138
27	0.172	0.151	0.118	0.153	0.140	0.242	0.119	0.198	0.154	0.207	0.165
26	0.203	0.166	0.166	0.183	0.190	0.359	0.156	0.229	0.187	0.236	0.208
25	0.225	0.204	0.178	0.229	0.203	0.355	0.199	0.259	0.132	0.265	0.225

To select a mean tracer threshold, we visually compared the various salinity levels to a frequency map of weekly plume extent for the 2010-11 wet season. This is defined as the extent of primary plus secondary plume waters, derived from supervised classification of remote sensing imagery (see method in Álvarez-Romero et al., 2013). As an indication of the correlation with plume frequency, 34ppt corresponded to a plume frequency of ~10%, 33ppt to 30-50% and 32ppt to >50%. It was agreed that the 30-50% frequency was the most appropriate extent for defining wet season runoff influence for each basin, however, further analysis of this selection is recommended to provide greater confidence in this approach for future applications.

The wet-season mean tracer rasters were used to create vector masks of the area in which tracer concentration exceeded the 33ppt threshold (Spatial Analyst > Reclassify, then Raster to Polygon conversion). The 'combined rivers' area was a union of the zones of influence for the individual Wet Tropics rivers.

2.3 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, end-of-catchment pollutant loads and a COTS influence factor.

2.3.1 Marine Risk Index

To estimate ecological risk in this assessment, we selected seven water quality variables that represent key runoff-transported pollutants of greatest concern to two GBR ecosystems: 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 in each basin zone of influence (see explanation below). The variables included ecologically relevant thresholds for concentrations of total suspended solids (TSS) and chlorophyll *a* from daily remote sensing observations, and the distribution of key pollutants including TSS, dissolved inorganic nitrogen (DIN) and photosystem II-inhibiting herbicides (PSII herbicides) (see Lewis et al., 2013) in the marine environment during flood conditions (based on an assessment of flood plume frequency and predicted distribution of end-of-catchment loads). A spatial variable was included that represents the area of the GBR lagoon where primary crown-of-thorns starfish (COTS) outbreaks have been observed in northern parts of the GBR, approximately between Lizard Island and Cairns (Furnas et al., 2013a). COTS outbreaks are an important cause of coral loss on the GBR and appear to be a response to excess nutrient runoff from certain catchments that impact this 'COTS initiation zone' (Furnas et al., 2013a).

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 2.3. 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 each basin Zone of Influence in ArcGIS.

Table 2.3. 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 2.1.

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	1-10	10-20	20-50	50-100
Score	*1/7*	*0*	*0.25*	*0.5*	*0.75*	*1.0*
TSS threshold exceedance 7 mg/L (5NTU) Frequency of exceedance (%)		0	<1	1-10	10-20	20-100
Score	*1/7*	*0*	*0*	*0.33*	*0.66*	*1.0*
TSS Plume Loading (mean 2007-2011)		Category 1		Category 2	Category 3	
Score	*1/7*	*0.33* [2]		*0.66*	*1.0* [3]	
Chl threshold exceedance (0.45µg/L) Frequency of exceedance (%)		<1	1-10	10-20	20-50	50-100
Score	*1/7*	*0*	*0.25*	*0.5*	*0.75*	*1.0*
DIN Plume Loading (mean 2007-2011)		Category 1		Category 2	Category 3	

Variables	Overall weighting	Assessment Class				
		Very Low 1	**Low 2**	**Medium 3**	**High 4**	**Very High 5**
Score	*1/7*	*0.33* [2]		*0.66*	*1.0* [3]	
COTS Initiation Zone		Outside Zone				Within Zone
Score	*1/7*	*0*				*1.0*
PSII Herbicide modelled concentration (2009-2011) (µg/L)		0.025-0.1	0.1-0.5	0.5-2.3	2.3-10	>10
Score	*1/7*	*0.25*	*0.5*	*0.75*	*1.0*	*No occurrence*

[2] This class covers Very Low and Low; [3] This class covers High and Very High.

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 2.3.

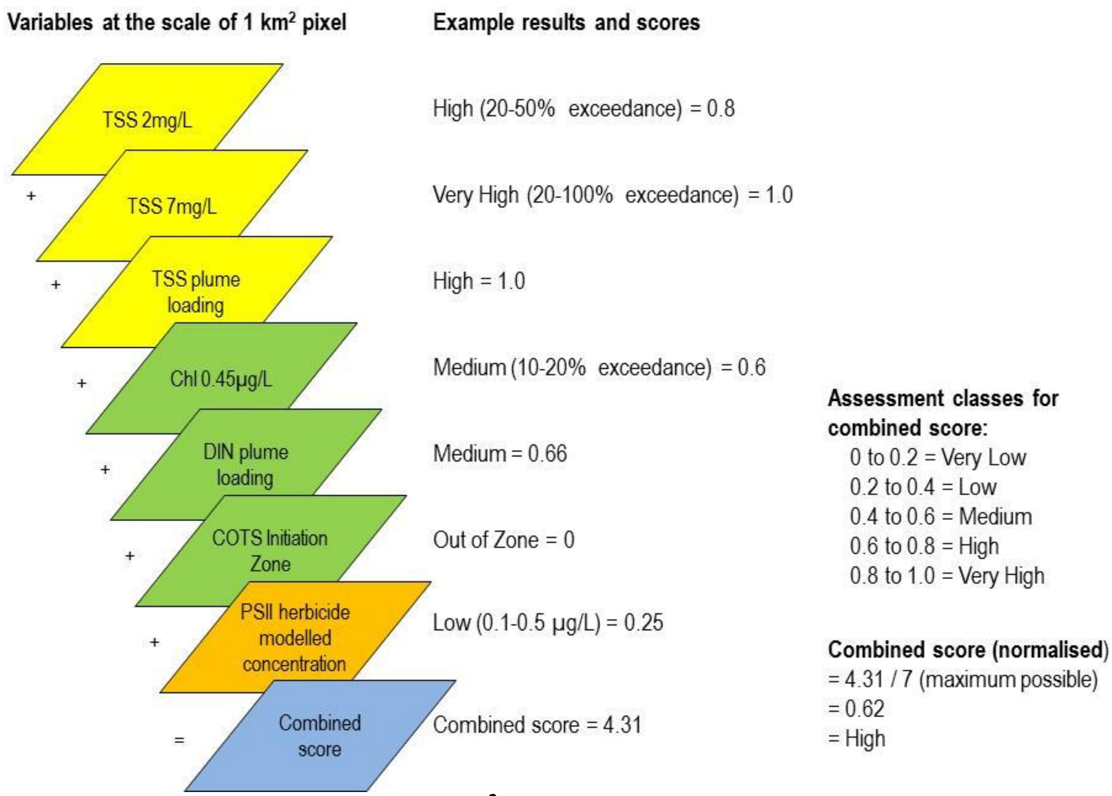


Figure 2.3. Example of the results in one pixel (1km^2) in ArcGIS. The result for coincident cells from each layer is summed to give a combined score, normalised and classified into five assessment classes (Very Low to Very High). In this example the combined score gives the cell a score within the High 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. Source: Brodie et al. (2013a).

The area of coral reefs and seagrass meadows in each of the five assessment classes of the combined layer in each basin Zone of Influence was 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 and COTS Influence 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 Wet Tropics region. These aspects of the method are described in further detail in Brodie et al. (2013a).

2.3.2 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 (Hateley et al., 2014), were obtained for each basin for key pollutants: TSS, DIN, PN, DIP, PP and PSII herbicides. 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 (Hateley et al., 2014). This resulted in a consistent set of end-of-catchment pollutant loads for each of the basins in the Wet Tropics region (Hateley et al., 2014), which is part of a larger project that models all of the 35 GBR catchments (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 2009) 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 the current wet season in 2013. In addition, functionality from the previous iteration catchment modelling, SedNet/ANNEX (for example see Cogle et al. 2006), was incorporated into Source Catchments to represent hillslope, gully and streambank erosion and floodplain deposition processes.

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 basin proportional contributions were then anchored (to normalise to a standard scale) and summed to generate a combined **Loads Index** for TSS, speciated N and P, and PSII herbicides for each basin. 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 four pollutants relative to each other.

It is recognised that assessment of the input of PSII herbicides from each region can be expressed in a number of ways, and while loads allow comparison between basins, it is the toxicity and therefore concentration that is most relevant to the receiving environment. However, PSII herbicides concentration data is currently limited across the GBR including within the Wet Tropics region. Therefore, in the final conclusions relating to PSII herbicides risk in this assessment, additional evidence is drawn from a combination of load and concentration data from specific locations, assessed in Lewis et al. (2013).

2.3.3 COTS Influence Index

In recognition of the importance of the influence of catchment discharges (mainly due to DIN) in driving COTS outbreaks (see Furnas et al., 2013a and Brinkman et al., 2014), an index of regional contributions of river discharges to the COTS Initiation Zone was also included for coral reefs; the 'COTS Influence Index'. This index was included as a factor in the Marine Risk Index (see 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 2.2 has been identified as the area of highest risk with respect to initiating COTS primary outbreaks.

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 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. Daily river discharges (ML day^{-1}) 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.

The Mossman and Murray Rivers are not modelled individually; however the annual discharge from these rivers is relatively small. To calculate the Relative Risk Index, these rivers are combined with the associated basins, so the Mossman is combined with the Daintree River outputs (Daintree-Mossman), and the Murray is combined with the Tully River outputs (Tully-Murray).

Relative Risk Index

To provide an overall relative ecological risk ranking between the Wet Tropics basins, the Marine Risk Indexes for coral reefs and seagrass meadows were summed with the Loads Index, and for coral reefs only, the COTS Influence 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.

2.4 Recognising and assessing uncertainties in the data

Given the limited time and resources available for this study, differences in uncertainty and hence our confidence in the data can only be assessed highly subjectively and no specific quantitative estimates were considered. If such qualitative assessments of uncertainty in our methodologies and data were undertaken, uncertainty would be assessed as varying as much within as among basins. 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.

While the COTS influence assessment has been improved with the incorporation of an expanded timeframe of 4 years (compared to Brodie et al., 2013a), there are some issues with the model associated with the input data that represent river flow. The flow data currently used in the model are the flows measured at the most downstream flow gauging station on each river. However, these stations are often some distance up the river from the river mouth, and hence do not capture the full flow of the river. In addition, at a basin scale many streams are not gauged at all. As an example, the Johnstone basin consists of five major catchments: the Moresby River, Maria Creek, Liverpool Creek, North Johnstone River and South Johnstone River. The gauges in this basin used for flow estimation are only located on the North Johnstone and South Johnstone Rivers, both of which are a considerable distance from the mouth of the combined Johnstone River. Also however, there are no gauges used on the other three catchments (at least not on the model). Therefore, the flow data used in the model will be considerably less than the total basin flow resulting in an underestimate of the influence of the Johnstone basin in the COTS influence assessment. Of equal importance, the gauges on the Russell and Mulgrave Rivers are located at a considerable distance upstream so that the monitored flows in these cases are only a small proportion of the total basin flow. Accordingly the influence of the Russell-Mulgrave basin in the COTS influence assessment is also an underestimate. This is being partly rectified through installation of new gauging and sampling sites at the mouths of the Russell and Mulgrave Rivers through DSITIA.

The zones of influence defined for the modelled rivers in the Wet Tropics region are an estimate only and the method requires refinement. There are a number of limitations to the existing approach:

- The limitations associated with the estimates of river discharge for the COTS modelling (described above) also apply to this output.
- Each river is modelled individually ('turned on' in the model one at a time) so there is no influence 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 modelled grid is coarse*** (4 km^2 x 4 km^2)***, resulting in poor coverage of the coastal zone in some locations.*** This means that any environmental gradient within 4 x 4 km^2 resolution is missed, as well as any coast feature < 4km, so ***some areas of coastal fringing coral reefs and seagrass are not incorporated in the assessment.*** The output for each river is applied with the assumption that there is equal influence throughout the zone of influence. TropWATER is currently leading a process to combine outputs of the hydrodynamic model with remote sensing data to incorporate a distance weighting which factors in the transport and processing of the pollutant temporally and spatially.
- 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 one year of data and should be extended to account for inter-annual variability.

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/moderate certainty
- TSS plume loading – low/moderate certainty
- Remote sensing chlorophyll – Low certainty
- DIN Plume loading – low/moderate certainty
- PSII concentration model – low certainty
- COTS Initiation Zone - high certainty
- COTS Influence Index – low/moderate certainty
- River loads – moderate/high certainty

- Coral reef areas – high certainty
- Seagrass areas – monitored: low/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, aswell as recent improvements to the 2013 risk assessment, are presented in Section 5.

3 Results

3.1 River zones of influence and habitat areas

The marine area defined for the WQIP is shown in Figure 3.1 and broadly includes the marine NRM region as defined GBRMPA. However, this is refined in the analysis of relative risk by defining zones of influence for the Wet Tropics rivers. The zone of influence defined for the rivers modelled in the Wet Tropics region include the Daintree, Barron, Russell-Mulgrave, Johnstone, Tully and Herbert Rivers. These are shown in Figure 3.1. It is important to recognise that the Burdekin River, which is outside of the Wet Tropics NRM region, also influences the Wet Tropics marine area in years where there are large river flows. While this is acknowledged in this assessment, the impact of the Burdekin is not directly accounted for in assessing relative risk to the coral reef and seagrass habitats, apart from in the COTS assessment described below.

The combined zone of influence (all river zones overlaid) has an area of 11,828 km^2, which is relatively small compared to the area of the marine NRM region which is estimated at 31,534 km^2. The largest zone of influence is from the Tully River, followed by the Daintree and Russell-Mulgrave Rivers. The model indicates that the areas of influence from the Herbert and Johnstone Rivers are similar, and that the Barron River is comparatively low. When considered in the context of annual river discharge (Table 2.2), it is expected that the result for the Herbert, Johnstone and Russell-Mulgrave Rivers are likely to be an underestimate. 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. However, the largest zones do contain the largest areas of coral reefs and seagrass.

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.

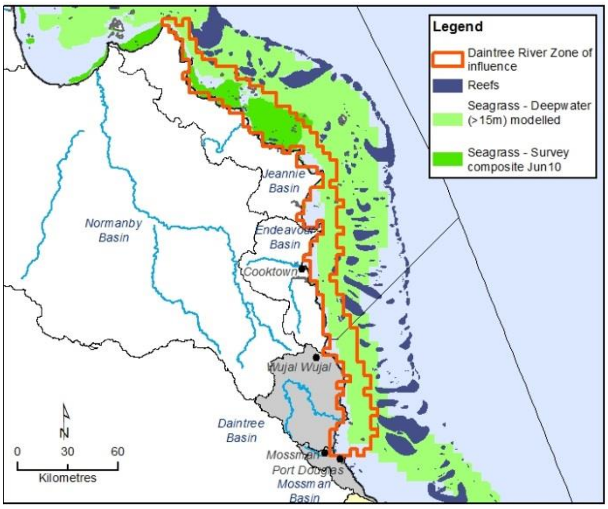
The distribution of coral reefs and seagrass used in the risk assessment are shown in Figure 3.1, and Table 3.1 shows the area of coral reef, seagrass and zone of influence for the rivers modelled in the Wet Tropics region. The total area of coral reef in the GBR is estimated around 24,000 km^2. The total area of coral reefs in the marine NRM region for the Wet Tropics is 2,427km^2 (Figure 3.2) whereas the area of coral reefs in the combined zones of influence (see Figure 3.2) is ~219km^2 as the area typically does not extend into the midshelf or offshore areas. From the mapping data used in this assessment, the zone of influence for the Daintree basin has the highest area of coral reef estimated at approximately 134km^2.

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 seagrass (surveyed and modelled) in the marine NRM region for the Wet Tropics is 4,868 km^2, which accounts for ~14% of the total arear reported for the GBR, and is similar to the total area of seagrass in the combined zones of influence (4,686km^2; see Figure 3.1). The zone of the influence for the Daintree basin has the highest area of seagrass estimated at approximately 1,171 km^2 from monitoring surveys, and 3,785 km^2 deepwater seagrass (>15m) from model predictions.

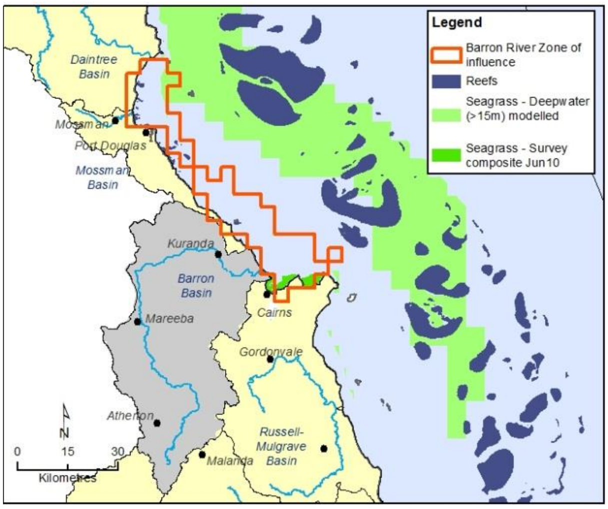
Data confidence: High for coral reefs, and low/moderate for seagrass given spatial and temporal coverage of the monitoring. The potential extent of deepwater seagrass is modelled and we have used the 50% probability assessment.

Table 3.1. The total area (km^2) of the zone of influence, mapped coral reef, and mapped and modelled seagrass for the modelled river basins in the Wet Tropics region.

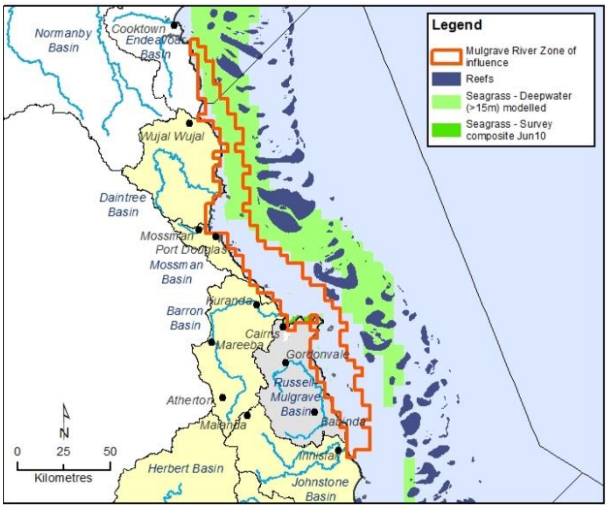
River	Mean Annual Discharge (ML)	Zone of Influence (km^2)	Reef (km^2)	Seagrass (km^2)		
				Survey composite	Deepwater (>15m) modelled	Total
Daintree	2,639,319	4,913	134	1,171	2,614	3,785
Barron	793,802	860	20	26	36	62
Russell-Mulgrave	3,684,046	3,851	41	29	925	953
Johnstone	4,559,029	2,649	39	32	24	56
Tully	3,488,088	6,998	88	157	1,449	1,606
Herbert	4,273,490	2,707	40	136	50	186
Area of combined zones of influence		11,828	**219**	**1,357**	**3,329**	**4,686**



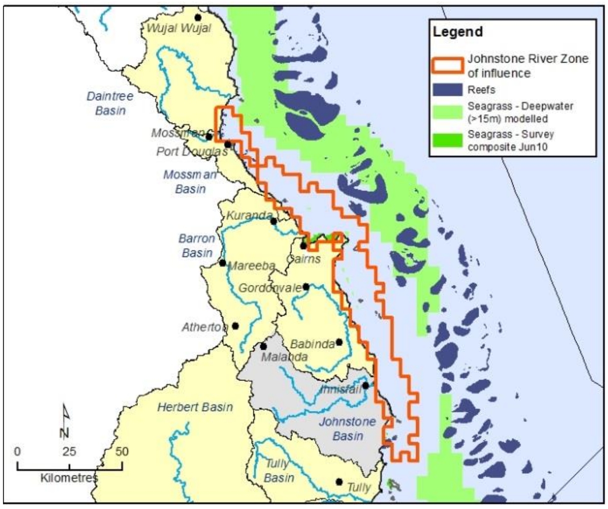
a) **Daintree River**



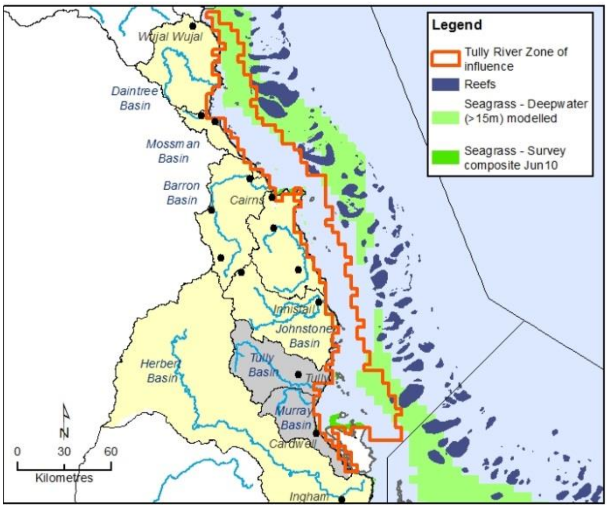
b) **Barron River**



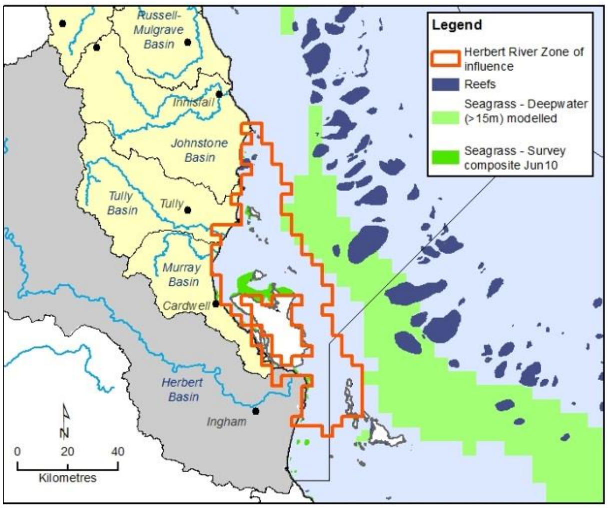
c) **Russell-Mulgrave River**



c) **Johnstone River**



e) **Tully River**



f) **Herbert River**

Figure 3.1. Zones of influence for rivers modelled in the Wet Tropics region, based on application of a threshold to the wet season mean of the tracer data that equates to a salinity of 33ppt, 2010-2011. The method for deriving these zones is described in Section 2.2.1.

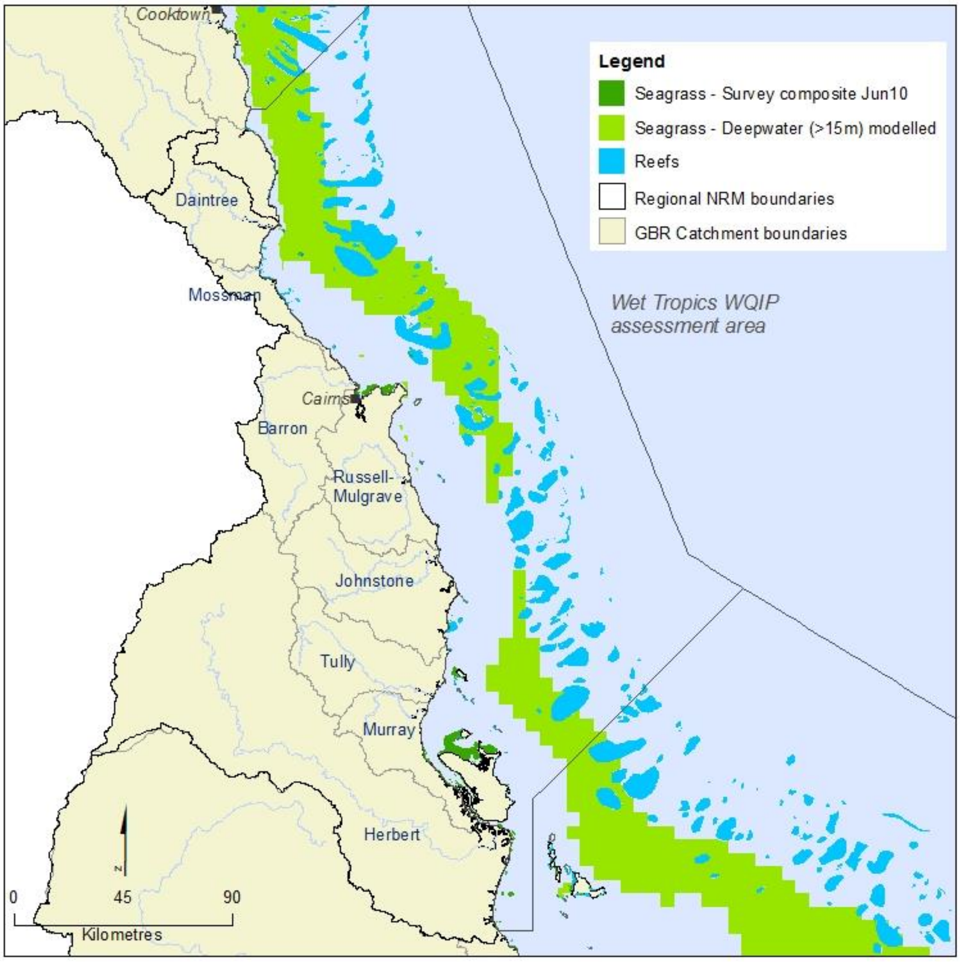


Figure 3.2. Locations of coral reefs and seagrass meadows used for the risk assessment. Coral reef outlines used are per the GBRMPA Spatial Data Centre official reefs spatial data layer 2013. Seagrass areas are observed (composite of surveyed data as at June 2010) and modelled deepwater seagrass habitat after Coles et al. (2009).

3.2 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 between in the Wet Tropics 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 Wet Tropics 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 Wet Tropics region.

a) Sediments

Total suspended solids threshold exceedance, Threshold a – 2 mg/L

As shown in Table 2.1, five assessment classes were used for TSS 2 mg/L based on the frequency of exceedance of this concentration (in days) in the period 2002 to 2012, expressed as a percentage of the total number of valid daily observations ranging from Very Low to Very High. The results of the assessment are shown in Figure 3.3. The areas of greatest exceedance are located around Hinchinbrook Island extending to the north, which is mostly influenced by the Herbert, Murray and Tully Rivers. There are no coral reefs in the Very High assessment class, but there is a small area of seagrass in this area (~20km^2).This correlation may be associated with the higher sediment loads from the Herbert River and the area of grazing lands in the Upper Herbert catchment, however, further validation of these results are required. The elevated exceedance around Rockingham Bay may be partly associated with naturally high turbidity (it is a relatively shallow area) or uncertainties in the remote sensing results which have not been resolved. Further validation of the algorithm in this area is required to improve the confidence in this result. There is also a relatively narrow band of High exceedance along the entire coastline. These inshore areas are locations with some of the highest use and visitation rates; this is a result common to all individual variables and is reviewed in the discussion.

Data confidence: Low/moderate due to limited validation of remote sensing data in nearshore coastal areas, particularly in the shallow and naturally turbid areas such as Rockingham Bay.

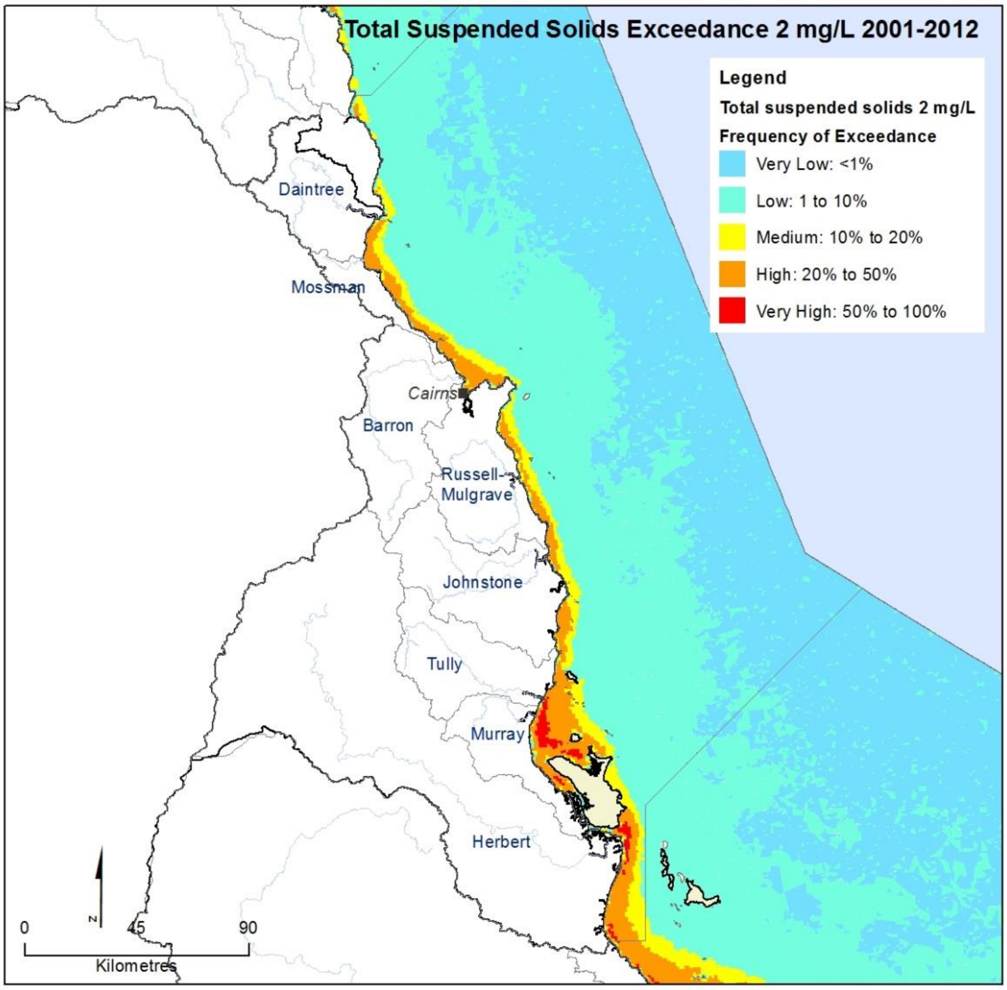


Figure 3.3. Results for the assessment of frequency of exceedance of TSS 2 mg/L using daily remote sensing data 2002-2012. Results for the assessment are based on frequency of exceedance of TSS 2 mg/L (see methods in Table 2.1).

Total suspended solids threshold exceedance, Threshold b - 7 mg/L (turbidity 5NTU)

As shown in Table 2.1, five assessment classes were used for TSS 7 mg/L (5NTU) based on the frequency of exceedance of this concentration (in days) in the period 2002 to 2012, expressed as a percentage of the total number of valid daily observations ranging from Very Low to Very High. Note that the assessment classes are different from those for TSS 2 mg/L to reflect the greater severity of the higher concentration; however, there were no pixels where the frequency of exceedance was greater than 50%. The results of the assessment are shown in Figure 3.4. There are very few areas within the Very High and High class but the results follow a similar, but reduced extent, to the TSS 2 mg/L exceedance threshold except in the Trinity Inlet area which is showing exceedance of this threshold and not the lower threshold. This reveals an error in the remote sensing data likely associated with shallow, naturally turbid waters. The areas of greatest exceedance are located around Hinchinbrook Island which is mostly influenced by the Herbert River, and in some conditions, the Tully and Murray Rivers. However, there are no coral reefs in the region in the High or Very High exceedance classes, and only ~50km^2 seagrass beds in the High class. As noted above, the elevated exceedance around Rockingham Bay may be partly associated with naturally high turbidity (it is a relatively shallow area) or uncertainties in the remote sensing results which have not been resolved. Further validation of the algorithm in this area is required to improve the confidence in this result.

Data confidence: Low/moderate due to limited validation of remote sensing data in nearshore coastal areas, particularly in the shallow and naturally turbid areas such as Rockingham Bay.

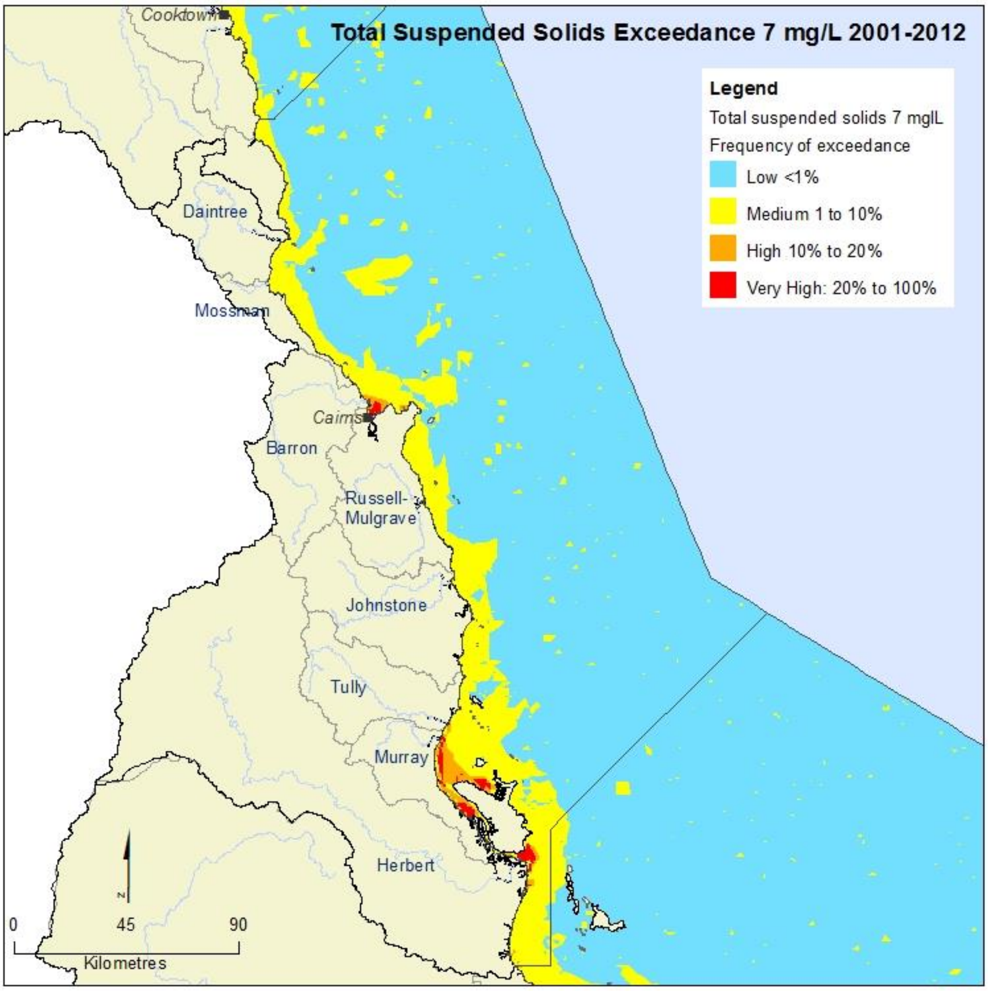


Figure 3.4. Results for the assessment of frequency of exceedance of TSS 7 mg/L using daily remote sensing data 2002-2012. Results for the assessment are based on frequency of exceedance of TSS 7 mg/L (see methods in Table 2.1).

TSS plume loading (mean 2007-2011)

As shown in Table 2.1, three assessment classes (Low, Medium and 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 (Devlin et al., 2013). The results of the assessment are shown in Figure 3.5. The areas within the highest assessment class (High) are located south of Hinchinbrook Island; this area includes ~50 km^2 of seagrass beds. There is pattern of moderate exposure extending south of Cairns containing areas of coral reef (~24 km^2 within the marine NRM region) and seagrass beds (~224km^2). The majority of the remainder of the region is in the Low category.

However, there are some limitations for this version of the plume loading model in this region. Only a selection of GBR river loads is modelled and in the Wet Tropics region, which includes the Barron, Johnstone, Tully and Herbert. Accordingly, the distribution from the Daintree, Mossman, Russell-Mulgrave and Murray are not represented in the TSS plume loading map. This limitation is currently being addressed through further development and improvement of the model through M. Devlin and others at TropWATER.

Data confidence: Low/moderate as the incorporation of load data from all rivers was not possible when the model was developed. Therefore the output is likely to be an underestimate in the areas of higher plume loading at the Murray River and at the medium and low plume loading at the Russell-Mulgrave and at the Daintree and Mossman Rivers, respectively.

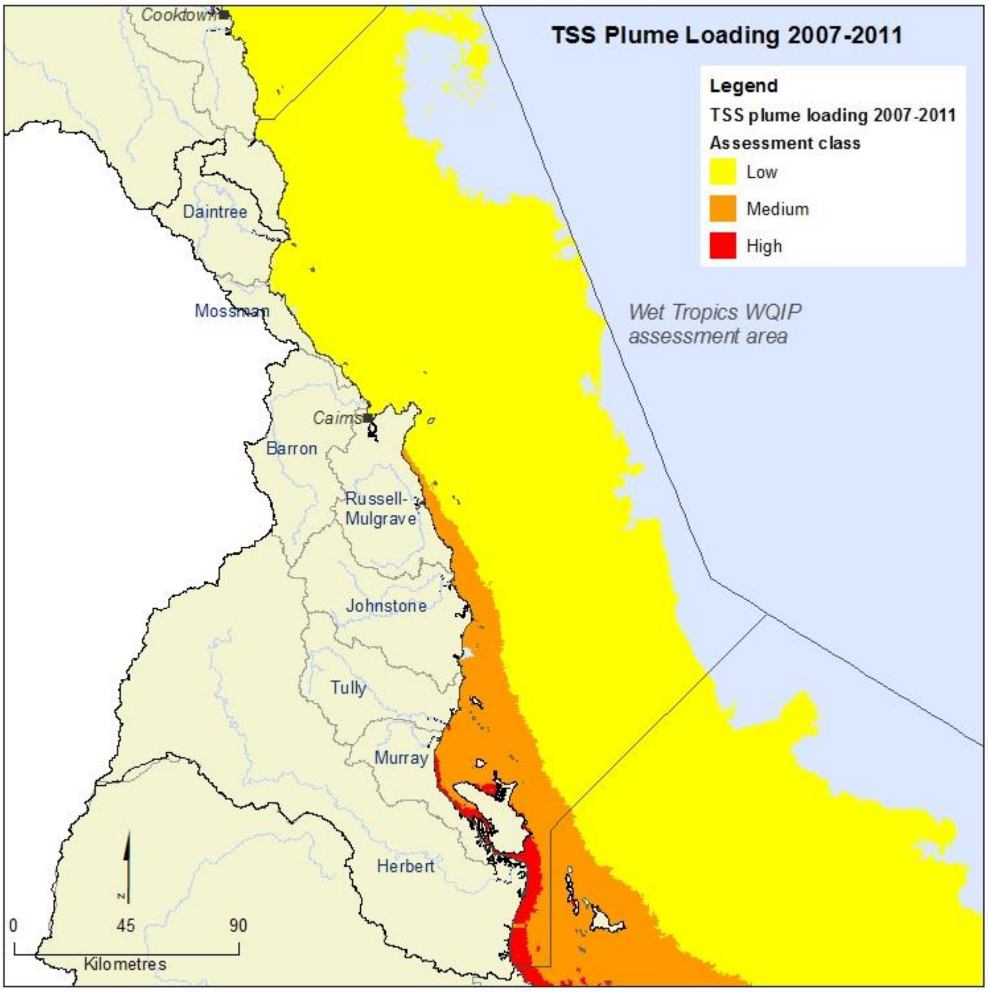


Figure 3.5. Results for the assessment of TSS plume loading (mean of annual assessments 2007 to 2011). The assessment classes are relative and derived from an interpolation of a multi-year analysis that combines scaled river loads data and flood plume frequency analysis from remote sensing data (see methods Table 2.1).

b) Nutrients

Chlorophyll threshold exceedance 0.45 µg/L

Chlorophyll *a* (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 Chl *a* 0.45 µg/L based on the frequency of exceedance of this concentration (in days) in the period 2002 to 2012, expressed as a percentage of the total number of valid daily observations ranging from Very Low to Very High. The results of the assessment are shown in Figure 3.6. The areas within the Very High class are constrained to the area around Hinchinbrook Island which is locally influenced by the Herbert, Murray and Tully Rivers, but also receives water from the Burdekin region. This area contains seagrass habitats (~20k m^2) but limited coral reefs. The elevated exceedance around Rockingham Bay may be partly associated with naturally high turbidity (it is a relatively shallow area) or uncertainties in the remote sensing results which have not been resolved. Further validation of the algorithm in this area is required to improve the confidence in this result. The areas of High exceedance form a band approximately 20km wide along the entire coast, incorporating areas of seagrass (~205 km^2 within the marine NRM region) and inshore coral reefs (~65 km^2 within the marine NRM region). This line is closely correlated with bathymetry and potential resuspension.

Data confidence: Low due to probable limitations of the functionality of the algorithm in highly turbid waters and limited validation of remote sensing data in this region to take this into account.

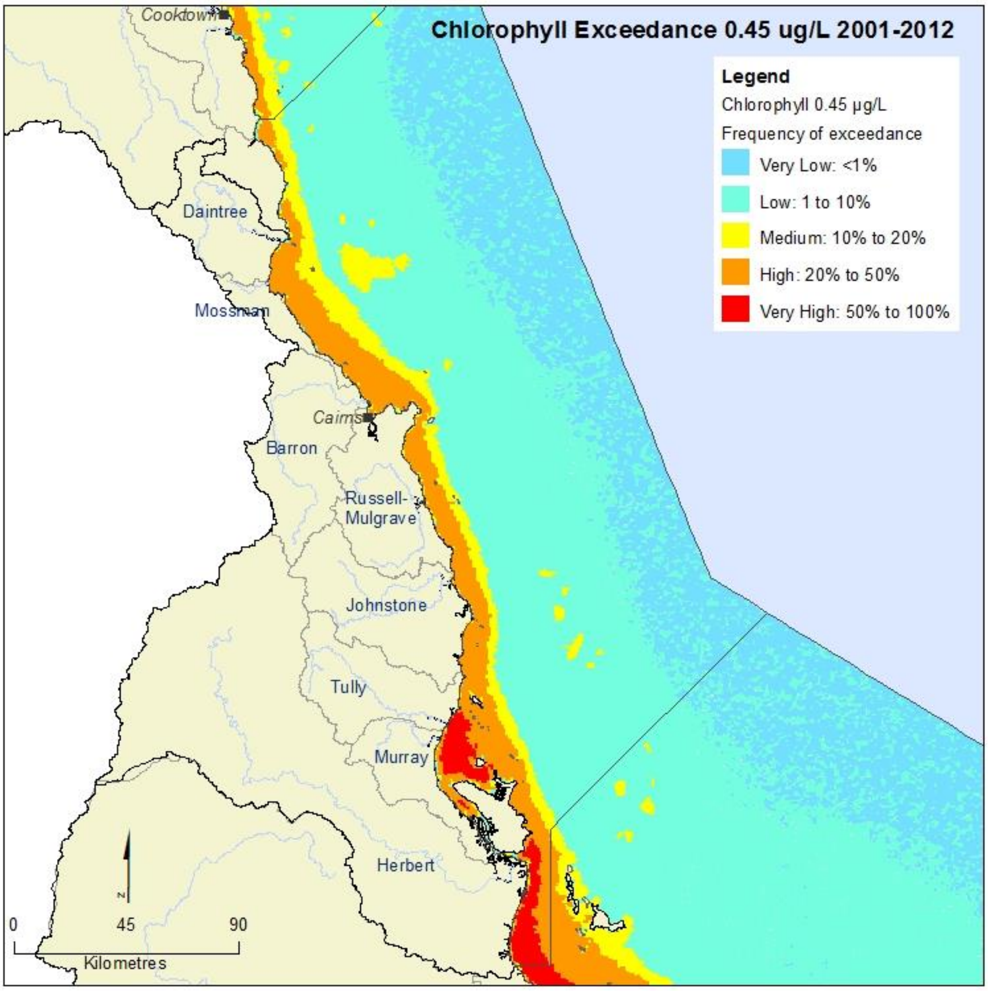


Figure 3.6. Results for the assessment of frequency of exceedance of Chl a 0.45 µg/L using daily remote sensing data 2002-2012. Results for the assessment are based on frequency of exceedance of Chl a 0.45 µg/L (see methods in Table 2.1).

DIN plume loading (mean 2007-2011)

As shown in Table 2.1, three assessment classes were used for DIN mean plume loading based on an interpolated map derived from plume frequency information from remote sensing and scaled river load data (Devlin et al., 2013). The results of the assessment are shown in Figure 3.7. The areas within the highest assessment class (High) extends from the southern limit of the marine NRM region up to the proximities of the Russell-Mulgrave River mouth; this area includes ~25 km^2 of coral reef and ~192 km^2 of seagrass beds. There is pattern of Moderate exposure extending south of Cairns containing areas of coral reef (~74 km^2 within the marine NRM region) and seagrass beds (~917 km^2). The majority of the remainder of the region is in the Low category.

The same limitations mentioned for the TSS plume loading maps applies to the DIN plume loading model in this region, and they are currently being addressed through further development and improvement of the model through M. Devlin and others at TropWATER.

Data confidence: Low/moderate as the incorporation of load data from all rivers was not possible when the model was developed. Therefore the output is likely to be an underestimate in the areas medium to low plume loading at the Russell-Mulgrave, Mossman and Daintree Rivers.

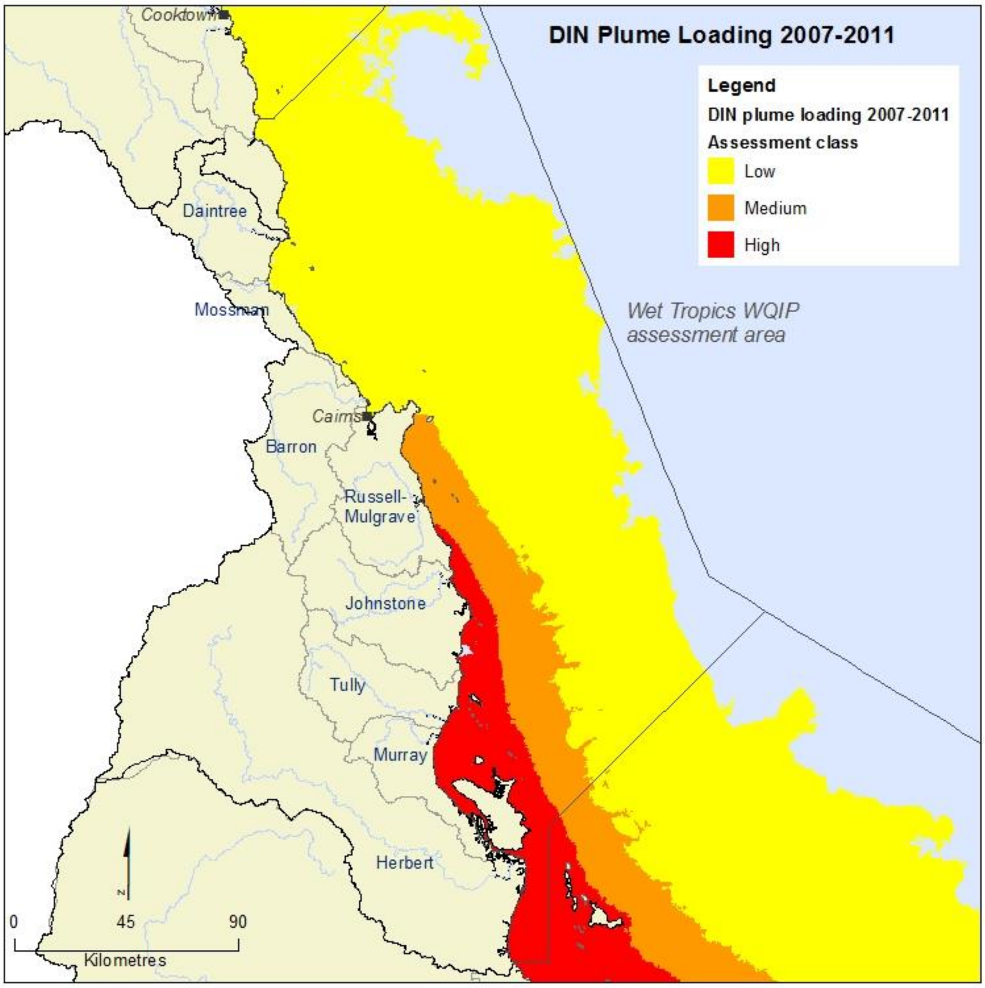


Figure 3.7. Results for the assessment of DIN plume loading (mean of annual assessments 2007 to 2011). The assessment classes are relative and derived from an interpolation of a multi-year analysis that combines scaled river loads data and flood plume frequency analysis from remote sensing data (see methods in Section 2.1.2).

COTS Initiation Zone

As shown in Table 2.1, this variable is added to factor in the importance of the geographic location of the COTS Initiation Zone (described in Section 2.2 and shown in Figure 2.2). This variable is only relevant to reefs, and reef areas are given a score of 1 (inside the zone) or 0 (outside of the zone). The greatest area of reefs inside the COTS Initiation Zone are in the northern part of the Wet Tropics region, within the Daintree-Mossman zone of influence (~106 km^2) compared to less than 30 km^2 for each of the other basins, except for the Herbert zone of influence where there are none.

Data confidence: High as explained in Furnas et al., (2013a), Fabricius et al., (2010) and Brodie et al., (2005).

c) PSII Herbicides

PSII Herbicide modelled concentration, 2009-2011

As shown in Table 2.1, six assessment classes were used for PSII herbicides based on the toxicity of diuron calculated in several studies on coral and seagrass species (see Lewis et al., 2013) ranging from No Risk to Very High. These were then used for assessing the results of an estimate of the relationship between additive PSII herbicide concentrations and CDOM (salinity proxy) in flood plume conditions; see Section 2.1.3). The results of the assessment are shown in Figure 3.8. All of the marine areas in the Wet Tropics region are in the Low, Very Low or No Risk class. The Low Risk areas extend from the river mouths are largest where the influence of multiple rivers merge; for example, the Johnstone and Russell-Mulgrave, and the Herbert, Murray and Tully. These areas include ~30 km^2 of coral reefs and 247 km^2 seagrass (within the marine NRM region).

Data confidence: Low/moderate due to limited availability of PSII herbicide concentration data in rivers and the marine environment during flood events.

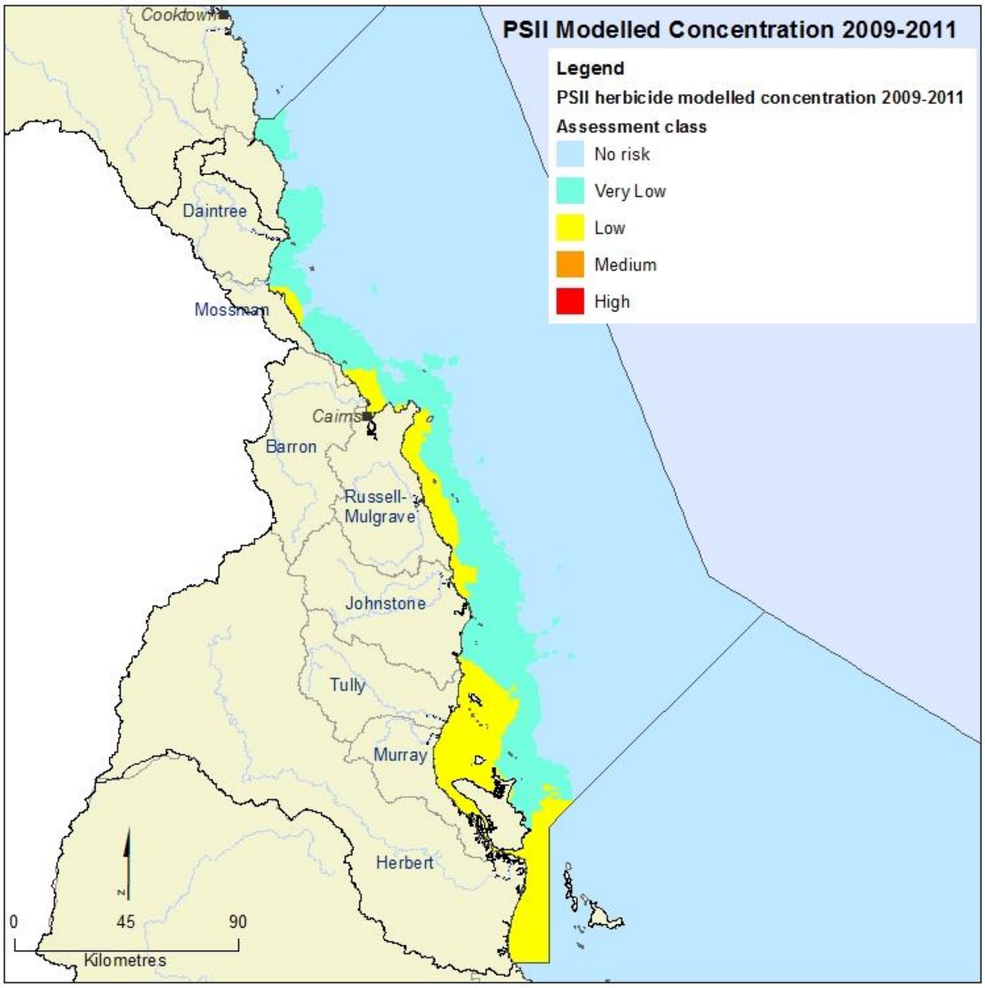


Figure 3.8. Results for the assessment of exposure to PSII herbicides based on an estimate of the relationship between additive PSII herbicide concentrations (2010-11 and 2011-12 water years) and CDOM (salinity proxy) in flood plume conditions (2012-13 wet season). Results for the assessment are based on the exposure assessment undertaken by Lewis et al. (2013) and shown in Table 2.1.

d) Relative differences between pollutants

The assessment of individual variables presented above (a – sediment, b - nutrients and c - PSII herbicides) can be used to guide priorities for management of individual pollutants between the Wet Tropics basins to some degree, but should in conjunction with further expert opinion and local technical expertise due to the data limitations noted above for each variable.

Table 3.2 shows the area of coral reefs and seagrass in the highest assessment class for each variable. In summary:

- The largest areas of coral reef in the combined high and very high assessment classes (summed) for the TSS 2mg/L and TSS 7mg/L are in the zones of influence of the Daintree and Tully Rivers. The largest areas of seagrass in the combined high and very high assessment classes (summed) for the TSS >7mg/L and plume loading are in the zones of influence of the Tully and Herbert Rivers, and there are large areas of seagrass in the Daintree-Mossman zone of influence for TSS 2 mg/L. There are some concerns regarding the validity of the remote sensing data in the coastal areas extending north from the Daintree River that require further validation which would affect this result.
- The greatest area of coral reefs in the COTS Initiation Zone are in the zone of influence for the Daintree River.
- The largest areas of coral reef and seagrass in the moderate assessment class for the PSII herbicide modelled concentration (this is the highest assessment class recorded in this region) are in the zones of influence of the Tully and Herbert Rivers.

This assessment indicates that it is not possible to draw conclusions about the relative importance of pollutants between the basins in the Wet Tropics region with the current datasets, but there are patterns in the areas of greatest potential risk in the coral reefs and seagrass in the zones of influence of the Daintree, Tully and Herbert Rivers.

It is possible to compare results among basins and variables using an approach that presents the results relative to the maximum area of coral reefs and seagrass among the zones of influence. The basin with the maximum area of coral reefs and seagrass in the highest assessment classes for each variable are set as an anchor point and given a value of 1. All other results of habitat areas are then expressed as a proportion of the maximum (values between 0 and 1), as shown in Table 3.2. This shows relative differences between Wet Tropics basins. For example, for the TSS threshold of 2 mg/L the area of coral reef within the highest assessment classes (Very High and High – >20% exceedance of the threshold) is greatest for the Tully-Murray basins, so this basin is allocated a score of 1.0. The results from the other basins are then reported as a proportion of the maximum value; the Johnstone and Daintree-Mossman areas of coral reef in the highest classes therefore 0.8 or 80% of the value of the Tully-Murray. It can therefore be expressed as the area of coral reefs in the Johnstone basin within the Very High and High assessment class for TSS threshold of 2 mg/L is 80% of that in the Tully-Murray basin.

This approach was used in the GBR wide assessment (Brodie et al., 2013a) and identified distinct differences between NRM regions. However, at a basin scale, it is difficult to draw clear conclusions from the results. This could be due to the similarity of the patterns across the region and the distribution of the habitats in proximity to the inshore areas which tend to be the areas of greatest exceedance of the selected variables. In addition, further confidence in the zones of influence and the input datasets would be required for greater certainty in the results.

Table 3.2. The area of coral reefs and seagrass for each basin Zone of Influence affected by the highest assessment classes for the water quality variables included in the risk analysis. The greatest areas for each variable are highlighted in red. Refer to Table 2.1 for further explanation of the variables.

	TSS 2mg/L Exceedance	TSS 7mg/L Exceedance	TSS Plume Loading	Chl 0.45μg/L Exceedance	DIN Plume Loading	PSII Herbicide modelled concentration	COTS Initiation Zone
Assessment classes	**High + Very High**	**High + Very High**	**High**	**High + Very High**	**High**	**Moderate**	**Inside Zone**
Coral Reefs							
Daintree-Mossman	26	2.0	0	50	0.0	3	106
Barron	15	0.1	0	18	0.0	6	10
Russell-Mulgrave	15	0.1	0	26	0.0	8	18
Johnstone	24	0.1	0	32	8	8	10
Tully-Murray	30	0.5	0	46	21	20	31
Herbert	16	0.0	1.8	28	32	13	0.0
Seagrass (Survey & Deepwater modelled)							
Daintree-Mossman	603	26	0	1,285	0	0	
Barron	322	15	0	50	0	20	
Russell-Mulgrave	22	15	0	200	0	29	
Johnstone	20	15	0	45	3	29	
Tully-Murray	23	68	14	235	160	208	
Herbert	119	54	22	107	162	152	

Table 3.3. Anchored scores for the area of coral reefs and seagrass for each basin zone of influence affected by the highest assessment classes for the water quality variables included in the risk analysis. The basin that had the largest area affected was given a score of 1; all other basins are expressed as a proportion based on the area affected in the basin relative to the area in the basin with the maximum area affected. To highlight differences between basins, cells are shaded (graduated) in red. Refer to Table 2.1 for further explanation of the variables.

	TSS 2mg/L Exceedance	TSS 7mg/L Exceedance	TSS Plume Loading	Chl 0.45μg/L Exceedance	DIN Plume Loading	PSII Herbicide modelled concentration	COTS Initiation Zone
Assessment classes	**High + Very High**	**High + Very High**	**High**	**High + Very High**	**High**	**Moderate**	**Inside Zone**
Coral Reefs							
Daintree-Mossman	0.8	1.0	0.0	1.0	0.0	0.1	1.0
Barron	0.5	0.0	0.0	0.4	0.0	0.3	0.1
Russell-Mulgrave	0.5	0.0	0.0	0.5	0.0	0.4	0.2
Johnstone	0.8	0.0	0.0	0.7	0.2	0.4	0.1
Tully-Murray	1.0	0.3	0.0	0.9	0.6	1.0	0.3
Herbert	0.5	0.0	1.0	0.6	1.0	0.6	0.0
Seagrass (Survey & Deepwater modelled)							
Daintree-Mossman	1.0	0.0	0.0	0.2	0.0	0.1	
Barron	0.1	0.2	0.0	0.9	0.0	0.1	
Russell-Mulgrave	0.1	0.2	0.6	0.2	0.7	0.1	
Johnstone	0.1	0.2	1.0	1.0	1.0	1.0	
Tully-Murray	0.4	1.0	0.0	0.5	0.2	0.7	
Herbert	0.3	0.8	1.0	0.0	0.8	0.0	

3.3 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 Wet Tropics 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 3.4, for the whole region in Figure 3.9 and for each river zone of influence in Figure 3.10.

Table 3.4. Area of coral reefs and seagrass meadows within the 5 relative risk classes in each basin 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 three first greatest areas/highest scores are shaded with scale of red.

Basins and habitat	**Area (km^2)**							**Based on sum of Risk areas**	**Based on area VH+H**
Coral Reefs	**V Low**	**Low**	**Moderate**	**High**	**V High**	**Total**	**High & V High**	**% of Total risk areas (High & V High)**	**Marine Risk Index**
Daintree-Mossman	2	54	65	13	0	134	13	10	0.44
Barron	<1	2	5	13	0	20	13	64	0.43
Russell Mulgrave	1	8	17	14	0	40	14	33	0.45
Johnstone	<1	10	7	20	0	38	20	53	0.67
Tully-Murray	1	39	16	30	0	87	30	35	1.00
Herbert	<1	13	9	19	0	40	19	46	0.62
Combined zones of influence	**2**	**95**	**78**	**41**	**0**	**217**	**41**	**19**	
						Max	*30*		

Seagrass (monitored and deepwater modelled)	**V Low**	**Low**	**Moderate**	**High**	**V High**	**Total**	**High & V High**	**% of Total risk areas (High & V High)**	**Marine Risk Index**
Daintree-Mossman	2	644	554	5	0	1,206	5	<1	0.04
Barron	3	2,539	85	13	0	2,639	13	<1	0.10
Russell Mulgrave	<1	16	49	13	0	79	13	16	0.10
Johnstone	<1	9	29	16	0	55	16	29	0.13
Tully-Murray	1	863	90	86	39	1,079	125	12	1.00
Herbert	<1	1,316	149	78	40	1,584	118	7	0.95
Combined zones of influence	**6**	**3,797**	**727**	**106**	**46**	**4,681**	**152**	**3**	
						Max	*125*		

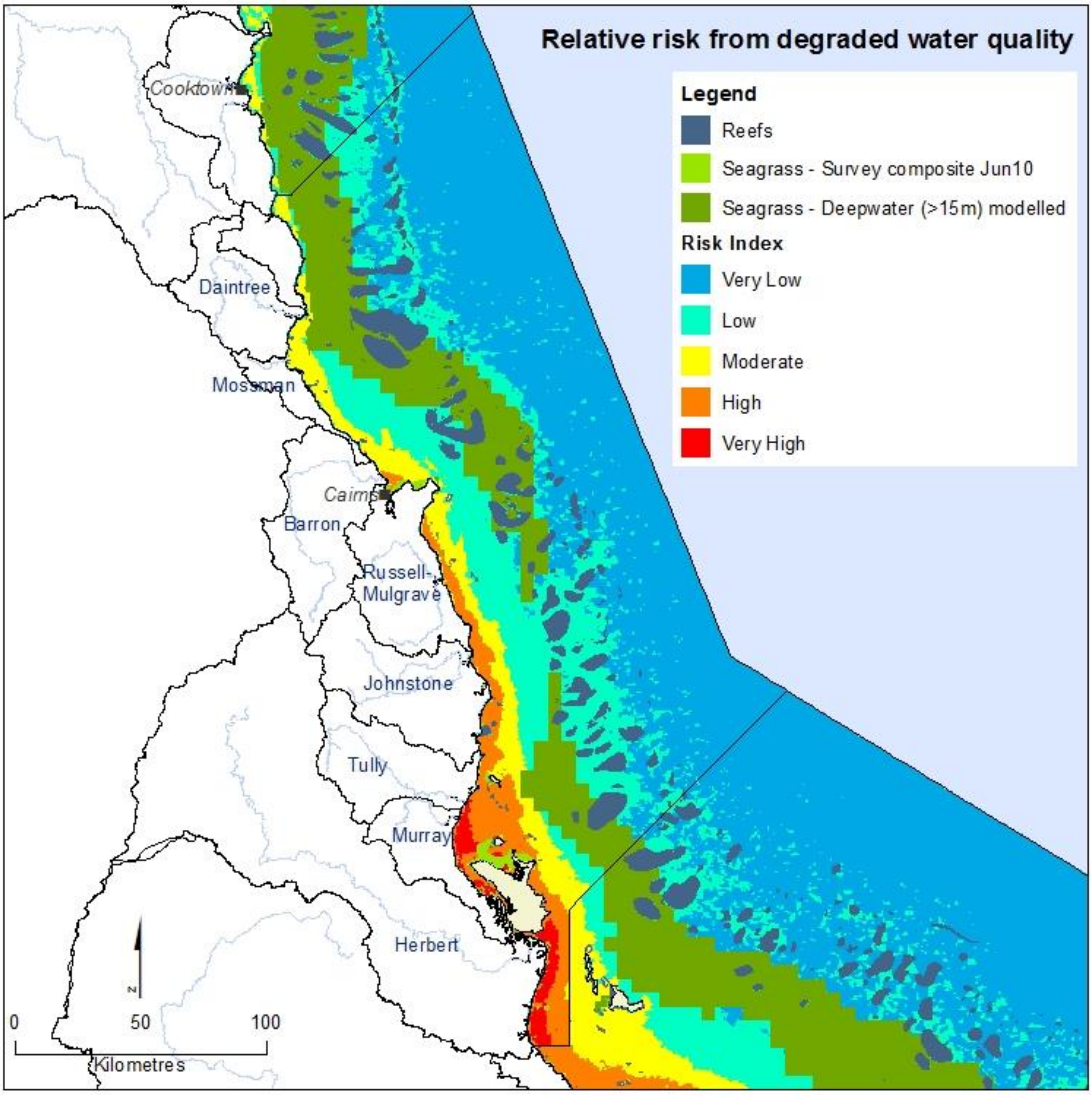
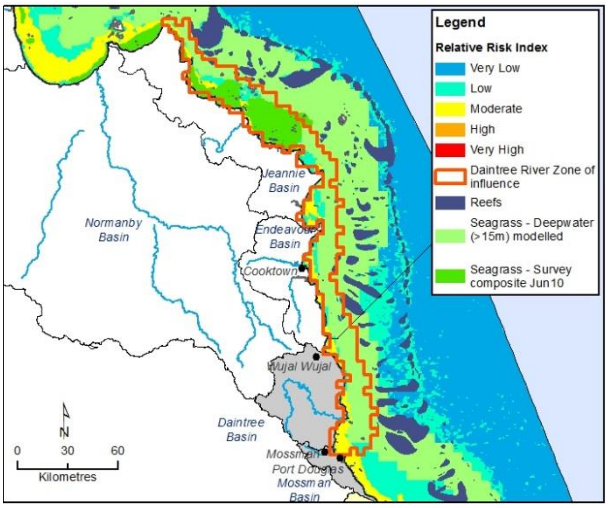
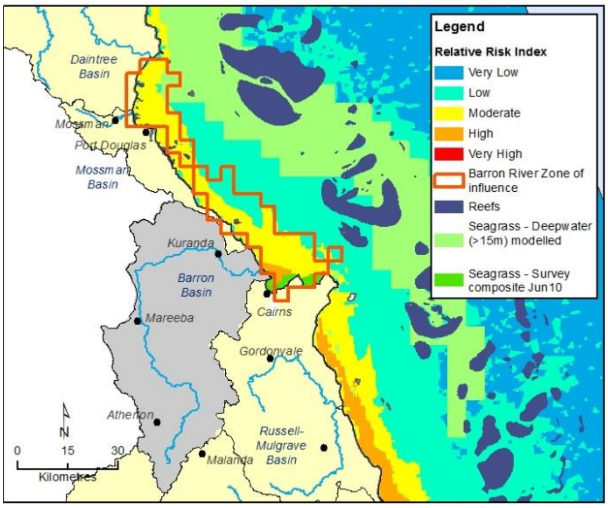


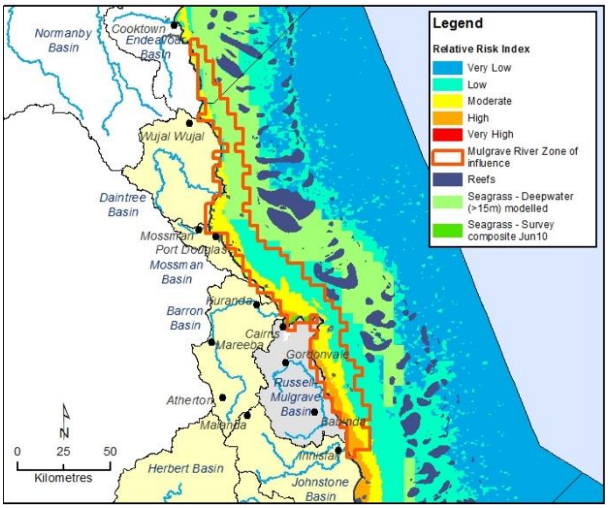
Figure 3.9. Combined assessment (1 km^2 resolution) of the relative risk of water quality variables. The areas (in km^2) of habitat types within each class are shown in Table 3.4.



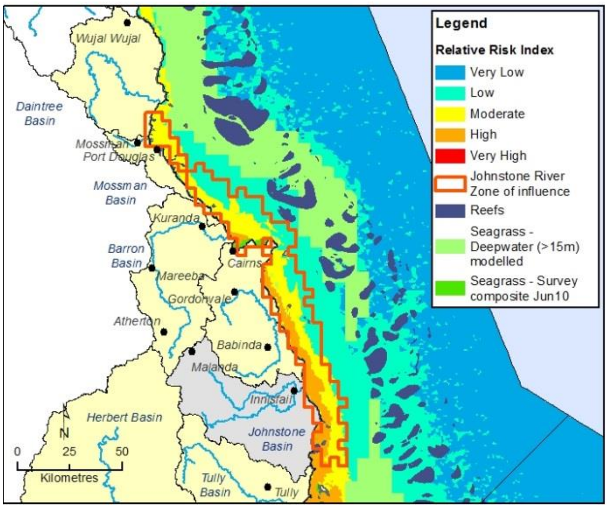
a) **Daintree River**



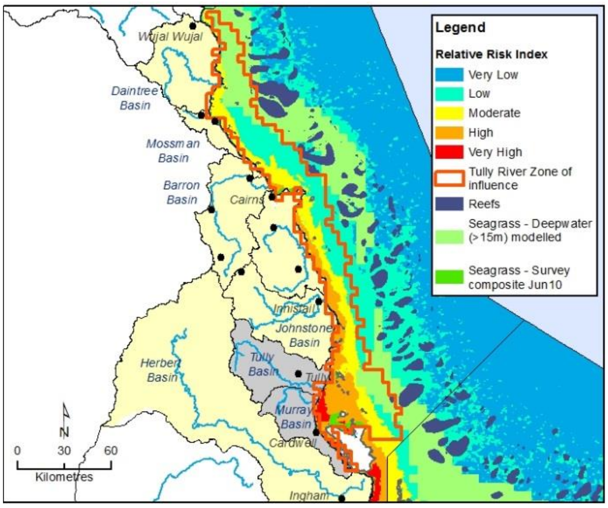
b) **Barron River**



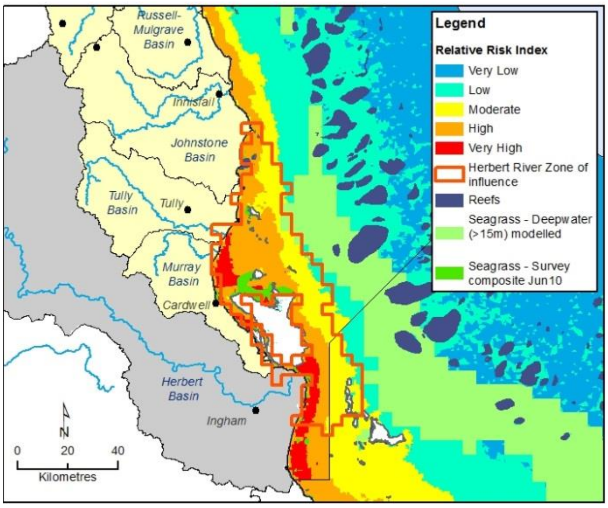
c) **Russell-Mulgrave River**



b) **Johnstone River**



e) **Tully River**



f) **Herbert River**

Figure 3.10. Combined assessment (1 km^2 resolution) of the relative risk of water quality variables for each river zone of influence. The areas (in km^2) of habitat types within each class are shown in Table 3.4.

The key findings are:

- The areas in the Very High relative risk class were located in the coastal areas around Hinchinbrook Island, extending north to the Tully River mouth and south to the regional boundary at the southern part of the Herbert basin. This area is locally influenced by the Herbert, Murray and Tully Rivers, but also receives water from the Burdekin region. The southern boundary is most likely strongly influenced by the boundaries of the PSII herbicide assessment which was conducted within individual marine NRM regions, thereby showing an unrealistic boundary of the Very High risk areas in the southern part of the region.
- There are no coral reefs in the Very High relative risk class. The greatest area of coral reef within the High relative risk class is in the Tully River zone of influence (~30 km^2). This zone extends almost the entire length of the marine NRM region and is generally constrained to the inshore reef areas. The combined area of the zones of influence contain approximately 41 km^2 of coral reefs in the High relative risk class.
- Seagrass only occurs in the Very High relative risk class in the Tully and Herbert River zones of influence (~40 km^2 each). This is the seagrass meadows located in the areas to the north of Hinchinbrook Island. The greatest areas of seagrass within the Very High and High relative risk classes is in the Tully and Herbert River zones of influence (~120 km^2 each), also in the meadows north of Hinchinbrook.
- There are only small areas of habitat (<5 km^2) in all basin zones of influence in the Very Low relative risk class.
- In the combined area of zones of influence, the greatest areas of habitats are in the Low relative risk class.
- When considering the proportion of the total risk area in each zone of influence that is in the Very High and High relative risk classes, the following findings may be important:
  - Coral reefs: 64% of the area in the Barron zone of influence is in the Very High and High relative risk class; the Johnstone is 53% and Herbert is 46%.
  - Seagrass: 29% of the area in the Johnstone zone of influence is in the Very High and High relative risk class, and the Russell-Mulgrave is 16%.

While the areas of coral reef and seagrass within the highest assessment classes for individual variables and the Marine Risk Index are relatively small, they often include highly valued tourism and recreation sites of the GBR. Examples include Hinchinbrook Island, Goold Island, the Brooks Islands, and the Family Island group including Bedarra Island and Dunk Island. In the case of seagrass meadows, many of the highest risk areas overlap with dugong protection areas (DPAs) around Hinchinbrook and Taylors Beach, which are assigned because of the large populations of dugongs feeding in the associated seagrass meadows.

In summary, when all water quality variables are combined into the Marine Risk Index, the risk is greatest for coral reefs in the Tully River zone of influence, and for seagrass in the Tully-Murray and Herbert River zones of influence. 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 Wet Tropics basins.

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

The pollutant load information allows managers to relate the Marine Risk 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 load contributions from each basin to the total regional loads. The data is derived from the report of the Source Catchments modelling for the Wet Tropics region, prepared by Hateley et al. (2014).

It is recognised that concentrations of PSII herbicides are more ecologically relevant than loads. It is recognised that the concentrations of PSII herbicides are more ecologically relevant than loads for GBR ecosystems. While this is true for any pollutant, it is most relevant to PSII herbicides in this study given the known responses of ecosystems to herbicide toxicity. The pollutant load helps to understand the ecological implications of a pollutant in the environment. Hydrodynamics, the status of the water body receiving the load and the biogeochemical process play an important role in determining if that load will or not be of any harm to the environment. For determining risk to aquatic biota from PSII herbicides, assessing toxic effects from concentration data normalised to represent 'additive' PSII herbicide toxicity is a more ecologically relevant method than an assessment of the PSII load transported to the marine environment generated through the Source Catchments model. The Source Catchments model is based on an annual average load of the total sum of the five common PSII herbicides (i.e. diuron, atrazine, ametryn, hexazinone and tebuthiuron) and does not consider the differences in toxicity between these herbicides. However, the PSII modelled load does provide an indication of the contribution of PSII herbicides from each basin based on an 'average' year, i.e. a long term average that adjusts for extreme weather conditions. While our risk analysis includes the toxic PSII concentration based on monitoring data from the Tully River, we have limited concentration data that is comparable between the basins and so our risk scores are likely to be on the conservative side. Indeed, the ecologically relevant targets analysis (Brodie et al., 2014) suggested that the event mean concentration of the 'first flush' herbicides likely put the areas just offshore the mouths of the Mossman, Russell Mulgrave, Johnstone, Tully and Murray basins in the 'medium risk' category and the Herbert Basin in the 'high risk' category.

The estimated pollutant loads for the basins in the Wet Tropics are shown in Table 3.5, and graphed in Figures 3.11 to 3.16.

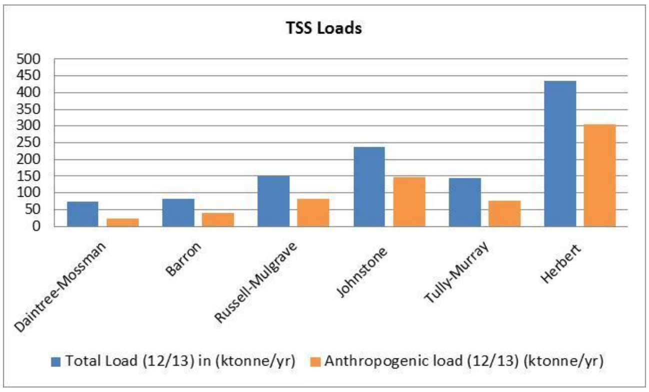
Data confidence: Moderate/high due to considerable and ongoing improvements to the Source Catchments modelling. The available monitoring data in the Wet Tropics region shows good correlation with the end-of-catchment monitoring data.

Table 3.5. Total and anthropogenic loads for TSS, DIN and PSII herbicides from Wet Tropics basins, and as percentages of the total regional load and regional anthropogenic load.

TSS loads ($kt.y^{-1}$)					
Basin Name	**Pre-Development Load**	**Total Load (12/13)**	**Anthropogenic load (12/13)**	**Anthropogenic load % of Regional Total Load**	**Ranking**
Daintree-Mossman	51	75	24	2	6
Barron	42	82	40	4	5
Russell-Mulgrave	67	150	83	7	3
Johnstone	88	236	148	13	2
Tully-Murray	67	144	77	7	4
Herbert	130	434	304	27	1
Regional total	**445**	**1122**	**677**	**60**	

DIN loads ($t.y^{-1}$)					
Basin Name	**Pre-Development**	**Total Load (12/13)**	**Anthropogenic load (12/13)**	**Anthropogenic load % of Regional Total Load**	**Ranking**
Daintree-Mossman	378	480	102	2	5
Barron	47	89	42	1	6
Russell-Mulgrave	438	652	214	5	3
Johnstone	506	1304	798	19	1
Tully-Murray	510	959	449	11	2
Herbert	535	695	160	4	4
Regional total	**2,414**	**4180**	**1766**	**42**	

PSII loads ($kg.y^{-1}$)					
Basin Name	**Pre-Development**	**Total Load (12/13)**	**Anthropogenic load (12/13)**	**Anthropogenic load % of Regional Total Load**	**Ranking**
Daintree-Mossman	0	311	311	5	5
Barron	0	239	239	4	6
Russell-Mulgrave	0	1114	1114	18	4
Johnstone	0	1264	1264	20	3
Tully-Murray	0	1590	1590	25	2
Herbert	0	1850	1850	29	1
Regional total	**0**	**6367**	**6367**	**100**	



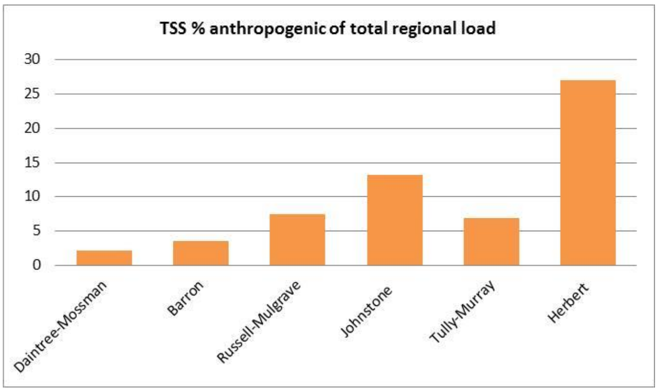
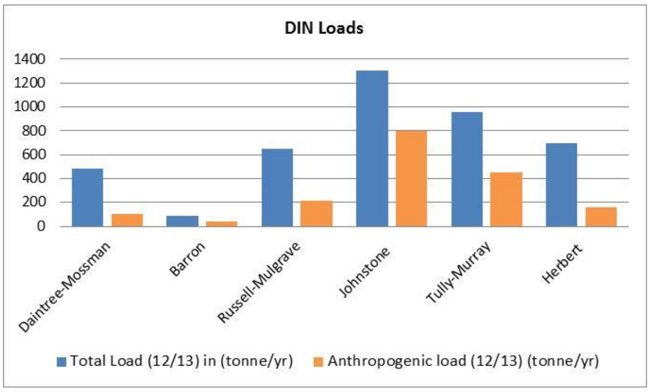


Figure 3.11. Annual load estimates for TSS from the basins in the Wet Tropics region. The graphs show (a) Total (12/13) and anthropogenic loads (12/13) (kilotonnes), and (b) the proportion that the anthropogenic TSS from each basin contributes to the regional Total TSS Load.



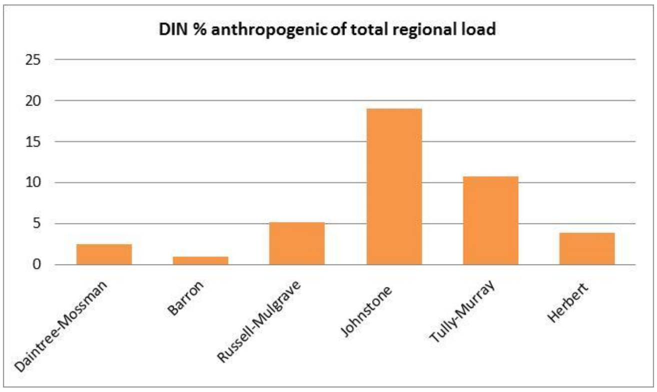
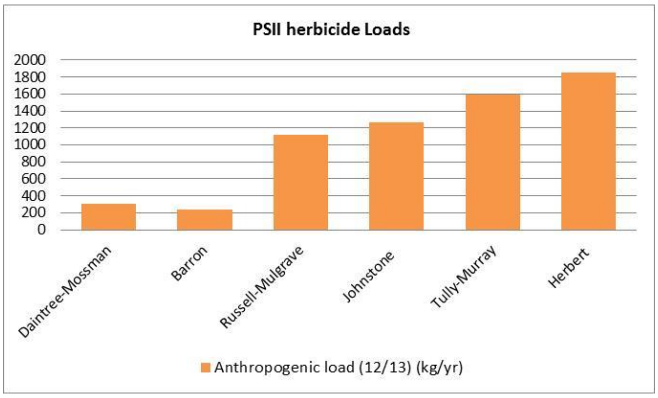


Figure 3.12. Annual load estimates for DIN from the basins in the Wet Tropics region. The graphs show (a) Total (12/13) and anthropogenic loads (12/13) (tonnes), and (b) the proportion that the anthropogenic DIN from each basin contributes to the regional Total DIN Load.



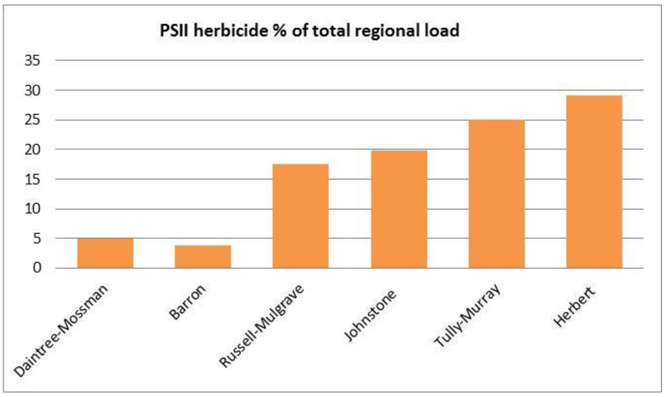


Figure 3.13. Annual load estimates for PSII herbicides from the basins in the Wet Tropics region. The graphs show (a) anthropogenic loads (12/13) (kg), and (b) the proportion that the anthropogenic PSII herbicides from each basin contributes to the regional Total PSII herbicides Load.

Table 3.6. Total and anthropogenic loads for PN, DIP and PP loads from Wet Tropics basins, and as percentages of the total regional load and regional anthropogenic load.

PN loads ($t.y^{-1}$)					
Basin Name	**Pre-Development**	**Total Load (12/13)**	**Anthropogenic load (12/13)**	**Anthropogenic load % of Regional Total Load**	**Ranking**
Daintree-Mossman	229	335	106	3	6
Barron	66	173	107	3	5
Russell-Mulgrave	276	521	245	7	3
Johnstone	340	1025	685	19	1
Tully-Murray	307	549	242	7	4
Herbert	319	987	668	19	2
Regional total	1,537	**3589**	**2052**	**57**	

DIP loads ($t.y^{-1}$)					
Basin Name	**Pre-Development**	**Total Load (12/13)**	**Anthropogenic load (12/13)**	**Anthropogenic load % of Regional Total Load**	**Ranking**
Daintree-Mossman	21	28	7	3	4
Barron	5	12	7	3	4
Russell-Mulgrave	25	40	15	7	3
Johnstone	28	47	19	9	1
Tully-Murray	28	48	20	9	1
Herbert	30	45	15	7	3
Regional total	**21**	**28**	**7**	**37**	

PP loads ($t.y^{-1}$)					
Basin Name	**Pre-Development**	**Total Load (12/13)**	**Anthropogenic load (12/13)**	**Anthropogenic load % of Regional Total Load**	**Ranking**
Daintree-Mossman	48	66	18	2	6
Barron	23	59	36	3	5
Russell-Mulgrave	65	152	87	8	3
Johnstone	104	352	248	22	2
Tully-Murray	64	137	73	7	4
Herbert	97	353	256	23	1
Regional total	401	1118	717	64	

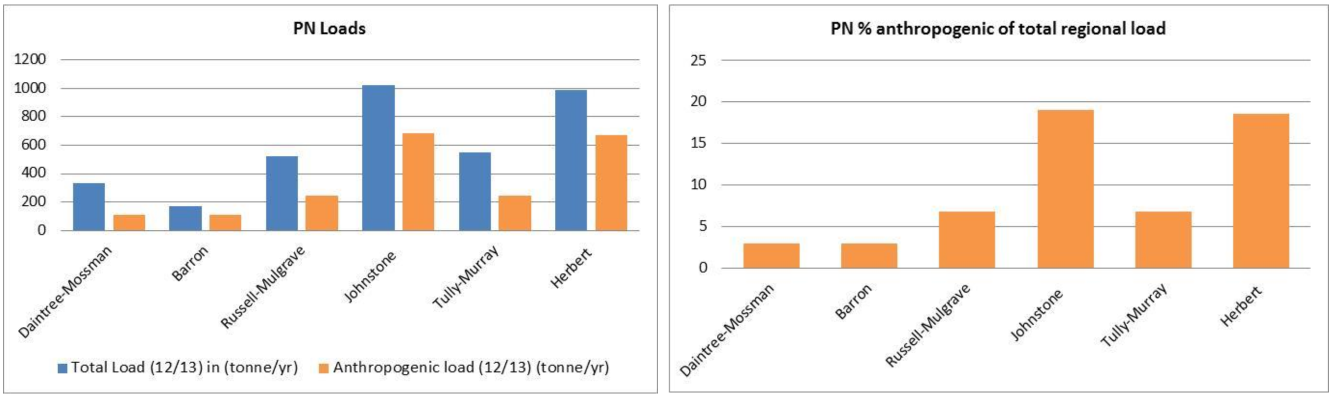


Figure 3.14. Annual load estimates for Particulate Nitrogen (PN) from the basins in the Wet Tropics region. The graphs show (a) Total (12/13) and anthropogenic loads (12/13) (tonnes), and (b) the proportion that the anthropogenic PN from each basin contributes to the regional Total PN Load.

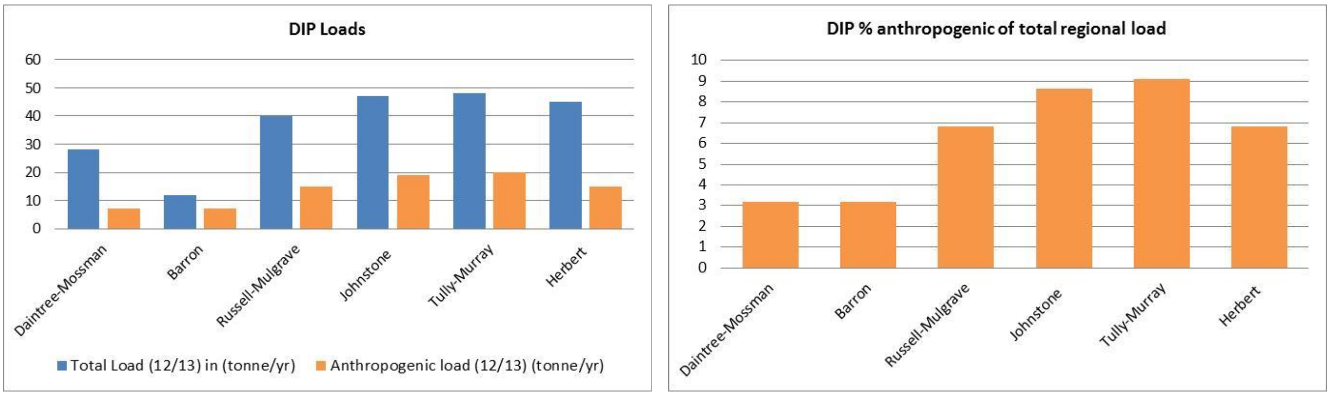


Figure 3.15. Annual load estimates for Dissolved Inorganic Phosphorus (DIP) from the basins in the Wet Tropics region. The graphs show (a) Total (12/13) and anthropogenic loads (12/13) (tonnes), and (b) the proportion that the anthropogenic DIP from each basin contributes to the regional Total DIP Load.

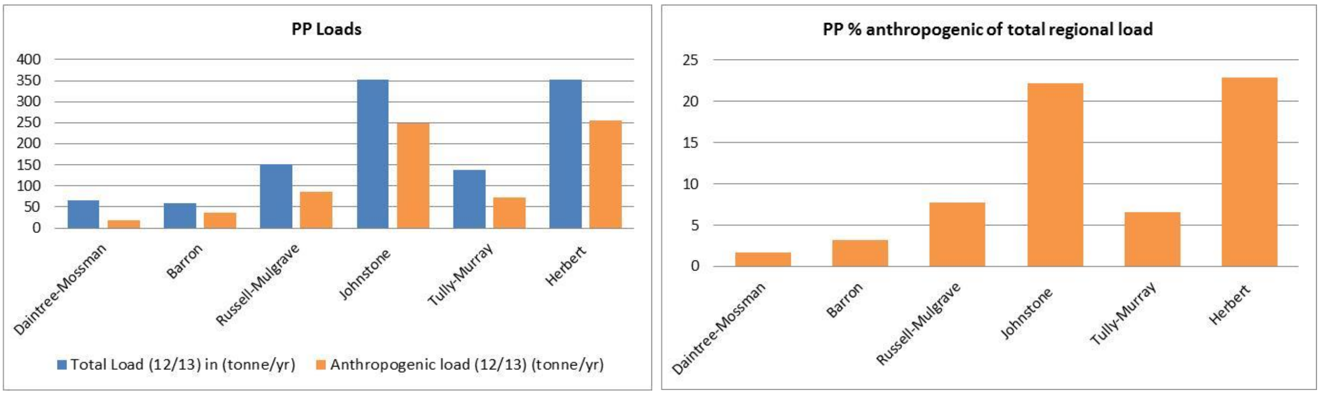


Figure 3.16. Annual load estimates for Particulate Phosphorus (PP) from the basins in the Wet Tropics region. The graphs show (a) Total (12/13) and anthropogenic loads (12/13) (tonnes), and (b) the proportion that the anthropogenic PP from each basin contributes to the regional Total PP Load.

The key findings from the 2012-2013 end-of-catchment pollutant load estimates for the Wet Tropics region are:

- Within the Wet Tropics region, the Johnstone and Herbert basins were the highest contributors for all constituents.
- **TSS:** The Herbert and Johnstone basins contributed a total of 60% of the total regional TSS load, with the majority of the load from the Herbert basin (38%). The Herbert basin contributes the greatest anthropogenic TSS load in the region, estimated at 304,000 tonnes per year. The anthropogenic contribution accounts for 27% of the total regional load. Compared to other basins in the region, the Herbert basin contributes at least twice as much of the anthropogenic load (Figure 3.11); the next greatest contribution is from the Johnstone basin (148,000 tonnes per year or ~13%) and the others contribute less than 10% of the anthropogenic proportion of the total load. The lowest contribution is from the Daintree-Mossman basin (~2%). In comparison to all other GBR basins, the Hebert basin is the third largest contributor of TSS to the total GBR TSS load, however, the Wet Tropics region only contributes 14% of the total GBR TSS load.
- **DIN:** The Johnstone basin contributes the highest total DIN load at 31%, followed by the Herbert basin at 18% and the Tully and Mulgrave-Russell basins at 16% each. The Johnstone basin contributes the greatest anthropogenic DIN loads in the region, estimated at 798 tonnes per year. The anthropogenic contribution accounts for ~19% of the total regional load. The Tully-Murray (11%) basins contribute almost half the load of the Johnstone basin (Figure 3.12). The other basins contribute 5% or less of the anthropogenic load to the regional total load. In comparison to other NRM regions, the Wet Tropics region has the greatest total DIN load (42%).
- **PSII herbicides:** The Herbert basin contributes the greatest PSII herbicide loads in the region, estimated at 1,850 kilograms per year (note that the total load is equal to the anthropogenic load). This accounts for approximately 29% of the regional load. The Tully-Murray basin also contributes 25% to the regional load (Figure 3.13), followed by the Johnstone (~20%) and Russell-Mulgrave (~18%) basins. The Barron and Daintree-Mossman basins contribute <5% of the regional load. In comparison to other NRM regions, the Wet Tropics region has the greatest PSII herbicide load (51%).
- **PN:** The Johnstone basin contributed 30% of the PN load, followed by the Herbert at 27%. The Johnstone and Herbert basins contribute the greatest anthropogenic PN loads in the region, estimated at around 670 tonnes each. These anthropogenic contributions account for approximately 19% of the total regional load each. In comparison all other basins only contribute a small proportion to the regional anthropogenic load (<7%) (Figure 3.14). The total PN load from the Wet Tropics region to the total GBR PN load is 32%.
- **DIP:** Both the Johnstone and Herbert basins contributed similar amounts of total DIP loads, approximately 21% each. The Johnstone and Tully-Murray basins contribute the greatest anthropogenic DIP loads in the region, estimated at around 20 tonnes respectively. These anthropogenic contributions account for approximately 9% of the total regional load each. The anthropogenic loads from the Russell Mulgrave and Herbert basins are also similar at around 15 tonnes (Figure 3.15). The total DIP load from the Wet Tropics region to the total GBR DIP is 20%.
- **PP:** The Johnstone basin contributed 35% of the PP load. The Johnstone and Herbert basins contribute the greatest anthropogenic PP loads in the region, estimated at around 250 tonnes respectively. The anthropogenic contribution accounts for approximately 22% of the total regional load each. In comparison all other basins contribute a small proportion to the regional anthropogenic load (Figure 3.16). The total PP load from the Wet Tropics region to the total GBR PP load is 28%.

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 3.7. 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, PSII herbicides, PN, DIP and PP are summed for each basin, and then normalised to the maximum to give a relative assessment.

The assessment shows the greatest relative contributions of combined end of basin loads to the Wet Tropics region is from the Herbert and Johnstone basins. The anchored score indicates that the contribution from the Tully Murray basin is approximately 60% of that from the Herbert and Johnstone basins, and the contribution from the Russell-Mulgrave basin is approximately 47% of that of the Herbert and Johnstone basins. The Barron and Daintree are relatively low contributors to regional pollutant loads compared to the other basins (approximately 16% of that contributed by the Herbert and Johnstone basins).

Table 3.7. Loads Index for TSS, DIN, PSII Herbicides, 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 Hateley et al. (2014).

Basin	Basin Anthropogenic load as % of Wet Tropics Regional Total Load								
	TSS	DIN	PSII	PN	DIP	PP	Sum	Loads Index	Loads Index Rank
Daintree-Mossman	2	2	5	3	3	2	17	0.16	4
Barron	4	1	4	3	3	3	18	0.16	4
Mulgrave-Russell	7	5	17	7	7	8	51	0.47	3
Johnstone	13	19	20	19	9	22	102	0.94	1
Tully-Murray	7	11	25	7	9	7	65	0.60	2
Herbert	27	4	29	19	7	23	108	1.00	1
Total	**60**	**42**	**100**	**57**	**37**	**64**	**361**		
						MAX	*108*		

3.5 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 Wet Tropics 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 Burdekin River influences the marine areas located offshore from the Wet Tropics basins. 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 (Furnas et al., 2013a). This is considered to be an important factor 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, approximately 85% 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). 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 3.8). 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. The Normanby River generally flows north of Cape Melville and has 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 beyond Cape Grafton.

Table 3.8. Relative freshwater volumetric contributions of individual rivers to the COTS outbreak initiation region between Cairns (17°S) and Lizard Island (14.5°S). The relative contributions of individual rivers were normalized 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 3.8) were combined with estimated DIN concentrations to assess and rank the DIN exposure contributions from the major rivers (Table 3.9). A risk score was calculated for each river, for each year, and rivers were ranked according to their DIN risk score.

Data confidence: Low to moderate confidence due to the issues identified above with the flow data that has been utilised (see Section 2.4).

Table 3.9. 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.

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

Risk scores for each river were averaged across the 4 years of simulation to derive a mean risk, and the rivers were then ranked accordingly. In addition, a separate ranking was determined based only on the 6 major rivers of the Wet Tropics region (Table 3.10).

Table 3.10. Summary of DIN Risk scores, mean DIN Risk score and ranking based on the mean DIN Risk score for all rivers, and for the Wet Tropics (WT) sub-set of rivers. The results are then normalised to the maximum mean DIN Risk Score to generate the COTS Influence Index for All rivers, and Wet Tropics rivers only.

	DIN Risk score					Normalised to max value		Ranking - based on mean	
	2008/09	2010/11	2011/12	2012/13	**Mean**	All rivers	**WT only**	All rivers	**WT only**
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	0.34	6	4
Barron	0.04	0.03	0.03	0.01	**0.02**	0.03	0.10	7	5
Russell- Mulgrave	0.15	0.22	0.22	0.15	**0.19**	0.22	0.75	3	2
Johnstone	0.27	0.30	0.30	0.18	**0.25**	0.30	1.00	2	1
Tully	0.14	0.21	0.21	0.13	**0.17**	0.21	0.70	4	2
Herbert	0.29	0.12	0.12	0.00	**0.10**	0.12	0.42	5	3
Burdekin	1.37	1.00	1.00	0.00	**0.84**	1.00		1	
				Max All Rivers	*0.84*				
				Max Wet Tropics	*0.25*				

The following conclusions are drawn:

- Rankings based on volumetric contributions were generally consistent between years, with the Daintree dominating freshwater delivery into the region, typically followed in ranking by the Russell-Mulgrave, Tully and Barron Rivers (Figure 3.17).
- Overall, the Johnstone, Russell-Mulgrave, Tully, and Burdekin Rivers are the dominant rivers contributing to the DIN pool in the outbreak region. Together these rivers contributed >85% of the total DIN input to the region, based on mean DIN contributions over the 4 years modelled (Figure 3.18).
- 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 (Figure 3.18).
- For all years modelled, the Johnstone River ranks in the highest 3 DIN contributors (Table 3.9), and this is reflected in the ranking based on mean risk scores (Table 3.10) where the Johnstone River ranks second behind the Burdekin River when considering all rivers.
- When considering only the Wet Tropics rivers (e.g. Daintree, Barron, Russell-Mulgrave, Johnstone, Tully and Herbert Rivers) the Johnstone is estimated to present the largest risk of contributing to the DIN pool in the COTS Initiation Zone. The high level of DIN risk from the Johnstone River is related to the large volume discharged (mean = 3.2 km^3 over the 4 years of simulation) but also due to the high estimated concentration of DIN in the discharge (321 µg N/L).
- The Russell-Mulgrave and Tully Rivers rank consecutively lower than the Johnstone River for DIN risk, however the mean risk values for these three rivers are similar. When comparing discharges and volumetric contributions to the outbreak region from these three Rivers, the Russell-Mulgrave consistently out ranks the Tully and Johnstone Rivers (in that order), however, when combined with DIN load data, the mean risk values for the Russell-Mulgrave, Tully and Johnstone Rivers are similar. This indicates that for these rivers, it is the DIN load rather than discharge that is the primary determinant of the DIN risk score for these rivers.
- The COTS Influence Index reflects the rankings noted above, showing that the DIN risk score for the Russell-Mulgrave and Tully Rivers is 70-75% of that of the Johnstone River, the Herbert River is 42%, Daintree is 34% and the Barron is 10%.
- 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 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).

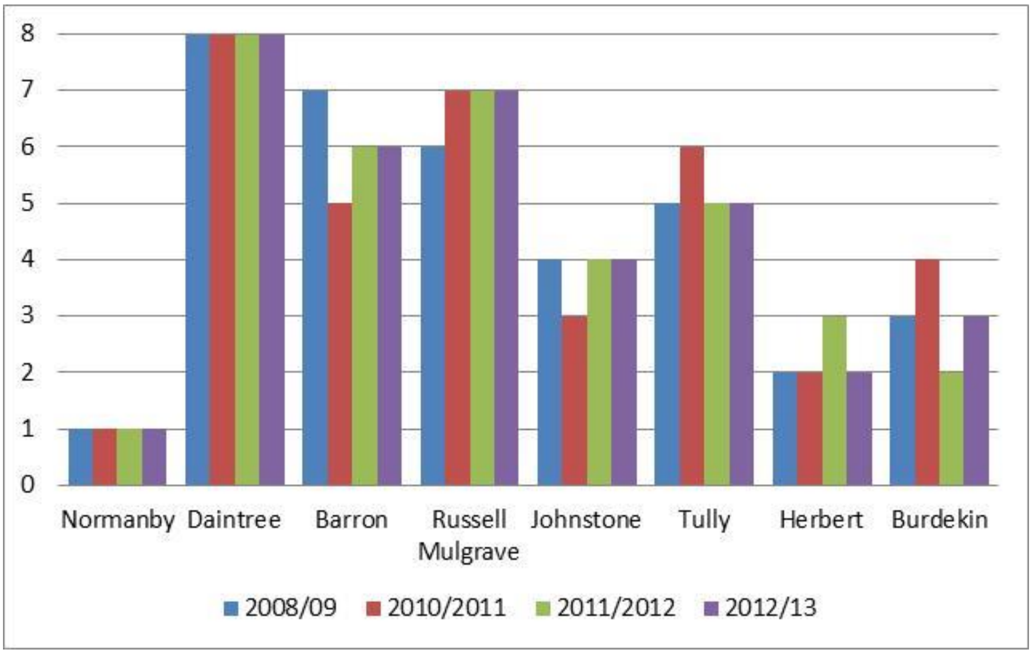


Figure 3.17. Relative volumetric contribution of individual rivers to the COTS outbreak initiation zone between Cairns and Lizard Island, 2008/09 to 2012/13 from 1 (lowest) to 8 (highest).

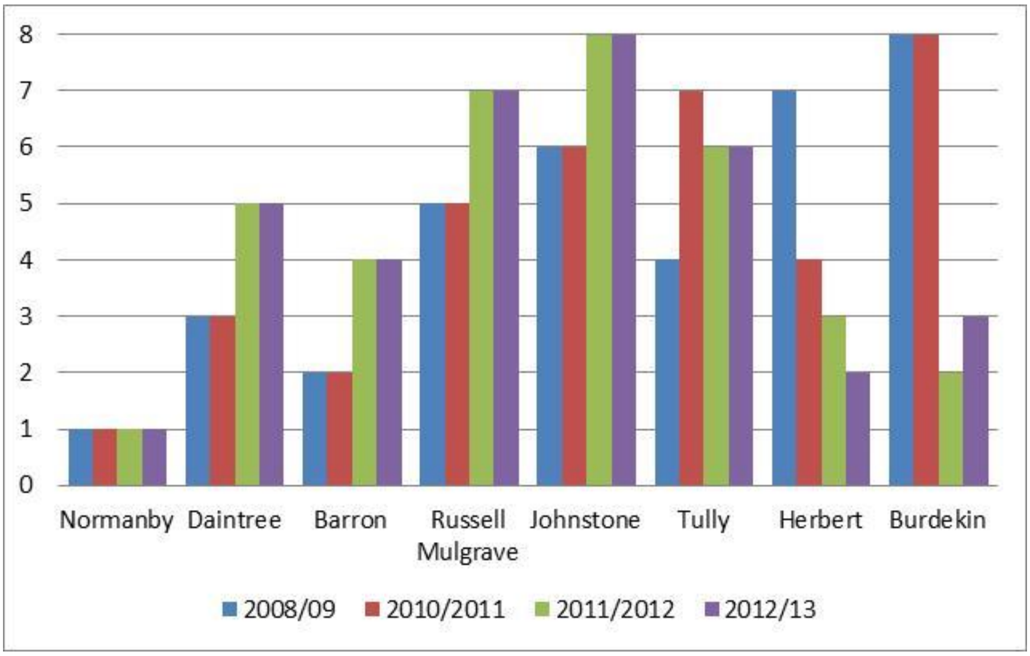


Figure 3.18. Relative DIN risk of individual rivers to the COTS outbreak initiation zone between Cairns and Lizard Island, 2008/09 to 2012/13 from 1 (lowest) to 8 (highest).

3.6 Combined assessment: Relative Risk Index

Using the information obtained through the above analyses for the marine water quality variables and end of basin pollutant loads, it is possible to make an assessment of the management priorities for minimising the risk of water quality impacts in the Wet Tropics region. This section presents an option for a quantitative combined assessment to inform water quality management priorities among the basins in the Wet Tropics region. However, 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, COTS Influence Index (for coral reefs) and the Marine Risk Index for coral reefs and seagrass meadows were combined to generate a Coral Reef Relative Risk Index and Seagrass Relative Risk Index.

For coral reefs, the two loads related indexes, i.e. the COTS Influence Index and the Loads Index, plus the Marine Risk Index were combined by summing the scores and then anchoring the result for each basin (Table 3.11, Table 3.12). For seagrass, only the Loads Index and the Marine Risk Index were used (Table 3.12).

Table 3.11. The Loads Index used for Coral Reefs derived by summing the Loads Index and the COTS Influence Index, and anchoring the combined score.

Loads Index – Coral Reefs	Loads Index	COTS Influence Index	Sum	Anchored combined index	Ranking
Daintree-Mossman	0.16	0.34	0.50	0.26	5
Barron	0.16	0.10	0.26	0.13	6
Russell-Mulgrave	0.47	0.75	1.22	0.63	4
Johnstone	0.94	1.00	1.94	1.00	1
Tully-Murray	0.60	0.70	1.30	0.67	3
Herbert	1.00	0.42	1.42	0.73	2
		MAX	*1.94*		

Table 3.12. Results of the overall risk assessment from summing the Loads, COTS Influence (for coral reefs only) and Marine Risk Index for coral reefs and seagrass. The basin that had the maximum value was given a score of 1; all other basins are expressed as a percentage based on the value in each basin relative to the area in the basin with the maximum value.

Coral Reefs Risk Index	Risk Index for Reefs	Loads & COTS Index	Sum of Indexes	Final Index Reefs (Anchored)	Rank
Daintree-Mossman	0.44	0.26	0.70	0.42	4
Barron	0.43	0.13	0.56	0.34	5
Russell-Mulgrave	0.45	0.63	1.08	0.64	3
Johnstone	0.67	1.00	1.67	1.00	1
Tully-Murray	1.00	0.67	1.67	1.00	1
Herbert	0.62	0.73	1.35	0.81	2
		Max	*1.67*		

Seagrass Risk Index	Risk Index for Seagrass	Loads Index	Sum of Indexes	Final Index Seagrass (Anchored)	Rank
Daintree-Mossman	0.04	0.16	0.20	0.10	6
Barron	0.10	0.16	0.27	0.14	5
Russell-Mulgrave	0.10	0.47	0.58	0.30	4
Johnstone	0.12	0.94	1.07	0.55	3
Tully-Murray	1.00	0.60	1.60	0.82	2
Herbert	0.95	1.00	1.95	1.00	1
		Max	*1.95*		

The final indexes for coral reefs and seagrass were then summed and anchored to provide an overall assessment of the relative risk of water quality to coral reefs and seagrass meadows – the Relative Risk Index (Table 3.13).

Table 3.13. Results of the overall risk assessment using a sum of the anchored Indexes for coral reefs and seagrass. The basin that had the largest sum of indexes was given a score of 1; all other basins are expressed as a percentage based on sum of indexes in each basin relative to the sum in the basin 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**
Daintree-Mossman	0.42	0.10	0.52	0.29	4
Barron	0.34	0.14	0.47	0.26	5
Russell-Mulgrave	0.64	0.30	0.94	0.52	3
Johnstone	1.00	0.55	1.55	0.85	2
Tully-Murray	1.00	0.82	1.82	1.00	1
Herbert	0.81	1.00	1.81	0.99	1
		Max	*1.82*		

These results show the greatest risk to each habitat in terms of the potential water quality impact from all of the assessment variables in the Wet Tropics region and end -of -catchment anthropogenic loads of TSS, DIN, PSII herbicides, PN, DIP and PP. The rankings are:

- **Coral reefs:** Highest ranking are the Tully-Murray and Johnstone basins. The rank of the remaining basins is Herbert (81% of the Tully-Murray and Johnstone), Russell-Mulgrave (64%), Daintree-Mossman (42%) and Barron (34%).
- **Seagrass meadows:** Highest ranking is the Herbert basin. The rank of the remaining basins is Tully-Murray (82% of the Herbert), Johnstone (55%), Russell-Mulgrave (30%), Barron (14%) and Daintree-Mossman (10%).
- **Coral reefs and seagrass meadows combined:** Highest ranking are Tully-Murray and Herbert basins. The rank of the remaining basins is Johnstone (85% of the Tully Murray and Herbert), Russell-Mulgrave (52%), Daintree-Mossman (29%) and Barron (26%).

Overall, the assessment shows that the highest ranking basins are the Tully-Murray, Herbert and Johnstone basins. The relative risk of the Russell-Mulgrave basin is about half of the relative score of the highest ranking basins for the combined assessment, but higher when only coral reefs are considered (64%). The Daintree-Mossman and Barron basins are showing to be of lower priority relative to the other basins in the region (around 25-30% of the relative score of the highest ranking basins for the combined reef and seagrass result). However, there are many uncertainties associated with the input datasets and method for combining these Indexes at a basin scale at this time (see Section 6); further discussion is recommended prior to making any management decisions based on these results. In particular, the input data for the Russell-Mulgrave basin loads and flow data are uncertain.

It is 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 Wet Tropics region.

4 Management prioritisation for the Wet Tropics region based on pollutant loads and potential influences

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.

4.1 Additional information to support the risk analysis

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.

<u>GBR catchment land use</u>

Land use characteristics of the Wet Tropics region are shown in Table 4.1, and mapped in Figure 4.1. This information is all derived from Hateley et al. (2014). The dominant land uses in the region by area are nature conservation and plantation forestry (approximately 11,000 km^2 or 51% of the total area), grazing (7,250 km^2 or 33% of total area), with intensive agricultural industries (sugarcane, horticulture, bananas and cropping) totalling 2,191 km^2 (10% of total area) of which sugarcane is 1,797 km^2 (8% of total area) (DSITIA 2012a) (Table 4.1, Figure 4.1). Grazing is the major land use in the western part of the region, where it is generally drier and only a minor part of the coastal lowlands. In coastal areas, the main crops are sugarcane and bananas. Nature conservation is generally restricted to the mountainous regions.

At the GBR scale, the Wet Tropics region has the highest proportion of sugarcane with 33% of the total sugarcane area in the GBR catchment, followed by the Mackay-Whitsunday area with 31%, and the Burdekin with 20%. The Wet Tropics has the second highest proportion of horticulture (including bananas) in the GBR catchment with 32% (the Burnett Mary region has 39%). Grazing and cropping (not sugarcane) in the Wet Tropics only accounts for 2% and 1% respectively of the total GBR catchment area.

Between 1999 and 2009, there were some changes to land use in the Wet Tropics region. The area of land use change (relative to the change in intensity at the Australian Collaborative Land Use and Management Program, Secondary Level) was ~129,000 ha or 6% of the Wet Tropics region (DSITIA, 2012b). Of the total change, 70% went from more intense to less intense and the remaining 30% went to more intense from less intense. Almost 50% of the total change in area went from minimal use and management resource protection into protected areas such as National Parks and protected area estates. The next biggest change (13%) was a shift into production and plantation forestry from a mixture of beef grazing native vegetation and sugarcane (DSITIA 2012b).

Table 4.1. Estimated land use by area (km^2) in the Wet Tropics region (based on QLUMP data used in Source Catchments). Source: Hateley et al. (2014).

Land use	Units	Daintree	Mossman	Barron	Mulgrave-Russell	Johnstone	Tully	Murray	Herbert	Total
Bananas	(km^2)	0.3	<1	14	4	66	62	10	<1	156
	(%)	0.2	<1	9	2	42	40	6	<1	100
Cropping	(km^2)	1	0.2	109	1	6	0.3	0.4	32	150
	(%)	0.7	0.1	73	0.4	4	0.2	0.2	22	100
Forestry	(km^2)	677	0.7	397	7	9	41	108	404	1,643
	(%)	41	0.04	24	0.4	0.5	2	7	25	100
Grazing (inc dairy)	(km^2)	148	17	735	105	530	85	69	5,561	7,250
	(%)	2	0.2	10	1.4	7	1.2	1.0	77	100
Horticulture	(km^2)	2	1	43	11	13	8	6	4	88
	(%)	3	1	49	12	15	9	7	5	100
Nature conservatio	(km^2)	1,175	363	632	1,429	1,275	1,219	712	2,661	9,468
	(%)	12	4	7	15	13	13	8	28	100

Land use	Units	Daintree	Mossman	Barron	Mulgrave-Russell	Johnstone	Tully	Murray	Herbert	Total
n										
Sugar cane	(km^2)	44	48	56	249	280	203	158	759	1,797
	(%)	2	3	3	14	16	11	9	42	100
Urban/other	(km^2)	18	29	145	90	62	20	12	81	456
	(%)	4	6	32	20	14	4	3	18	100
Water	(km^2)	40	21	58	83	85	47	40	340	714
	(%)	6	3	8	12	12	7	6	48	100
Total	**(km^2)**	**2,107**	**479**	**2,189**	**1,979**	**2,326**	**1,685**	**1,115**	**9,842**	**21,722**

Table 4.2. Land use contribution to DIN loads for the Wet Tropics Basins.

Basin	Total (08/09) Load	Total Anthropogenic DIN Load	% contribution				
			Bananas	Sugar	Cropping	Horticulture	All cropping
Daintree	387	64	0%	7%	0%	0%	8%
Mossman	107	52	0%	39%	0%	0%	40%
Barron	90	43	3%	4%	10%	3%	20%
Russell-Mulgrave	695	258	1%	32%	0%	1%	35%
Johnstone	1,360	854	9%	56%	1%	1%	66%
Tully	702	358	13%	45%	0%	0%	58%
Murray	288	122	4%	46%	0%	1%	51%
Herbert	807	272	0%	40%	1%	0%	41%

Table 4.3. Land use contribution to PSII herbicide loads for the Wet Tropics Basins.

Basin	Total PSII herbicide Load	% contribution	
		Sugar	Cropping
Daintree	235	95.3%	4.7%
Mossman	150	98.8%	1.2%
Barron	269	33.6%	66.4%
Russell - Mulgrave	1,482	99.7%	0.3%
Johnstone	1,861	96.1%	3.9%
Tully	1,359	99.5%	0.5%
Murray	862	99.5%	0.5%
Herbert	2,378	97.1%	2.9%

As shown in Table 4.1, 4.2 and 4.3, the area and land use characteristics of the basins are quite different. To summarise:

- The **Daintree** River Basin has an area of 2,107 km^2 and consists of 56% natural/minimal use lands, 32% forestry, 7% grazing, 2% sugarcane, 1% urban and 2% other. The Source Catchments analysis suggests that 7% of the total DIN load is sourced to sugarcane land use, although this represents 26% of the anthropogenic DIN load exported from the basin (Table 4.2). Sugarcane contributes the vast majority (> 95%) of the PSII herbicide loads from the basin (Table 4.3). Sub-catchment 3 (Baird's Landing/Peirces Hill area) within the Daintree River Basin was identified as a hotspot contributing a higher proportion of SS loads. Water quality monitoring in the Daintree River Basin is limited to 1 year of load data from the Daintree River at Bairds site during the 2003/04 season (R. Bartley, Pers. Comm.).

- The **Mossman** River Basin has an area of 479 km^2 and consists of 76% natural/minimal use lands, 3% grazing, 10% sugarcane, 4% urban and 6% other. The Source Catchments analysis suggests that 39% of the total DIN load is sourced to sugarcane land use, although this represents 65% of the anthropogenic DIN load exported from the basin (Table 4.2). Sugarcane contributes the vast majority (99%) of the PSII herbicide loads from the basin (Table 4.3). There has been no dedicated monitoring for loads in the Mossman River Basin (that we are aware of).
- The **Barron** River Basin has an area of 2,189 km^2 and consists of 29% natural/minimal use lands, 31% grazing, 18% forestry, 8% other crops (including bananas), 3% sugarcane, 3% dairy, 5% urban and 4% other. The Source Catchments analysis suggests that 4% of the total DIN load is sourced to sugarcane land use while bananas and other crops contribute 25% of the total DIN load (Table 4.2). It is estimated that 55% of the DIN is derived from diffuse urban sources and wastewater treatment plants. Cropping, other than sugar contributes 66% of the PSII herbicide loads from the basin (Table 4.3).
- The **Russell**-**Mulgrave** River Basin has an area of 1,979 km^2 and consists of 72% natural/minimal use lands, 3% grazing, 1% other crops, 13% sugarcane, 2% dairy, 3% urban and 6% other. The Source Catchments analysis suggests that 32% of the total DIN load is sourced to sugarcane land use while bananas and other crops contribute 3% of the total DIN load. The model suggests that sugarcane in this basin contributes 60% of the anthropogenic DIN load exported from the basin (Table 4.2). Sugarcane contributes >99% of the PSII herbicide loads from the basin (Table 4.3). Sub-catchment 96 (Babinda/Miriwinni area) in this Basin has been identified as a hotspot for SS, DIN and PSII herbicides, while sub-catchment 95 (Babinda/Miriwinni area) of the basin is a hotspot for SS and PSII herbicides. In addition, sub-catchments 91 and 92 (Babinda/Miriwinni area) have been identified to contribute elevated PSII herbicide loads.
- The **Johnstone** River Basin has an area of 2,326 km^2 and consists of 55% natural/minimal use lands, 16% grazing, 1% other crops, 12% sugarcane, 3% bananas, 6% dairy, 2% urban and 4% other. The Source Catchments analysis suggests that 56% of the total DIN load is sourced to sugarcane land use while banana contribute 9% of the total DIN load from the Johnstone Basin (Table 4.2). The model suggests that sugarcane in this basin contributes 80% of the anthropogenic DIN load exported from the basin (Table 4.2). Sugarcane contributes 96% of the PSII herbicide loads from the basin (Table 4.3). Sub-catchments 115, 113, 122, 395 (Wangan/Mundoo) and 150 (Silkwood/El Arish) in this Basin has been identified as a hotspot for SS and DIN loads, while sub-catchment 141 (Rankin Falls area) of the basin is a hotspot for SS. In addition, sub-catchments 147 and 149 (Silkwood/El Arish) have been identified to contribute elevated DIN loads and sub-catchment 150 (Silkwood/El Arish) contribute high loads of PSII herbicides.
- The **Tully** River Basin has an area of 1,685 km^2 and consists of 75% natural/minimal use lands, 5% grazing, 1% other crops, 12% sugarcane, 4% bananas, 2% forestry, 1% urban and 3% other. The Source Catchments analysis suggests that 74% of the total DIN load is sourced to sugarcane land use while bananas contribute 21% of the total DIN load from the Tully Basin (Table 4.2). The model suggests that sugarcane in this basin contributes 88% of the anthropogenic DIN load exported from the basin (Table 4.2). Sugarcane contributes >99% of the PSII herbicide loads from the basin (Table 4.3). Sub-catchment 162 (Lower section of Travelling Dairy Creek) has been identified as a hotspot for SS, while sub-catchments 158 and 164 (Southwest of Tully) of the basin are hotspots for DIN and PSII herbicide loads. In addition, sub-catchment 393 (Southwest of Tully) contributes elevated PSII herbicide loads.
- The **Murray** River Basin has an area of 1,115 km^2 and consists of 64% natural/minimal use lands, 10% forestry, 6% grazing, 1% bananas, 1% other crops, 14% sugarcane, 1% urban and 4% other. The Source Catchments analysis suggests that 81% of the anthropogenic DIN load is sourced to sugarcane land use while bananas contribute 8% of the total DIN load from the Murray Basin (Table 4.2). Sugarcane contributes >99% of the PSII herbicide loads from the basin (Table 4.3). Sub-catchment 177 (Southwest of Tully) in this Basin has been identified as a hotspot for PSII herbicides.

- The **Herbert** River Basin has an area of 9,842 km^2 and consists of 27% natural/minimal use lands, 56% grazing, 8% sugarcane, 4% forestry and 4% other. The Source Catchments analysis suggests that 88% of the anthropogenic DIN load is sourced to sugarcane land use from the Herbert Basin (Table 4.2). Sugarcane contributes 97% of the PSII herbicide loads from the Herbert Basin (Table 4.3). Sub-catchment 194 (North of Ingham) has been identified as a hotspot for PSII herbicides.

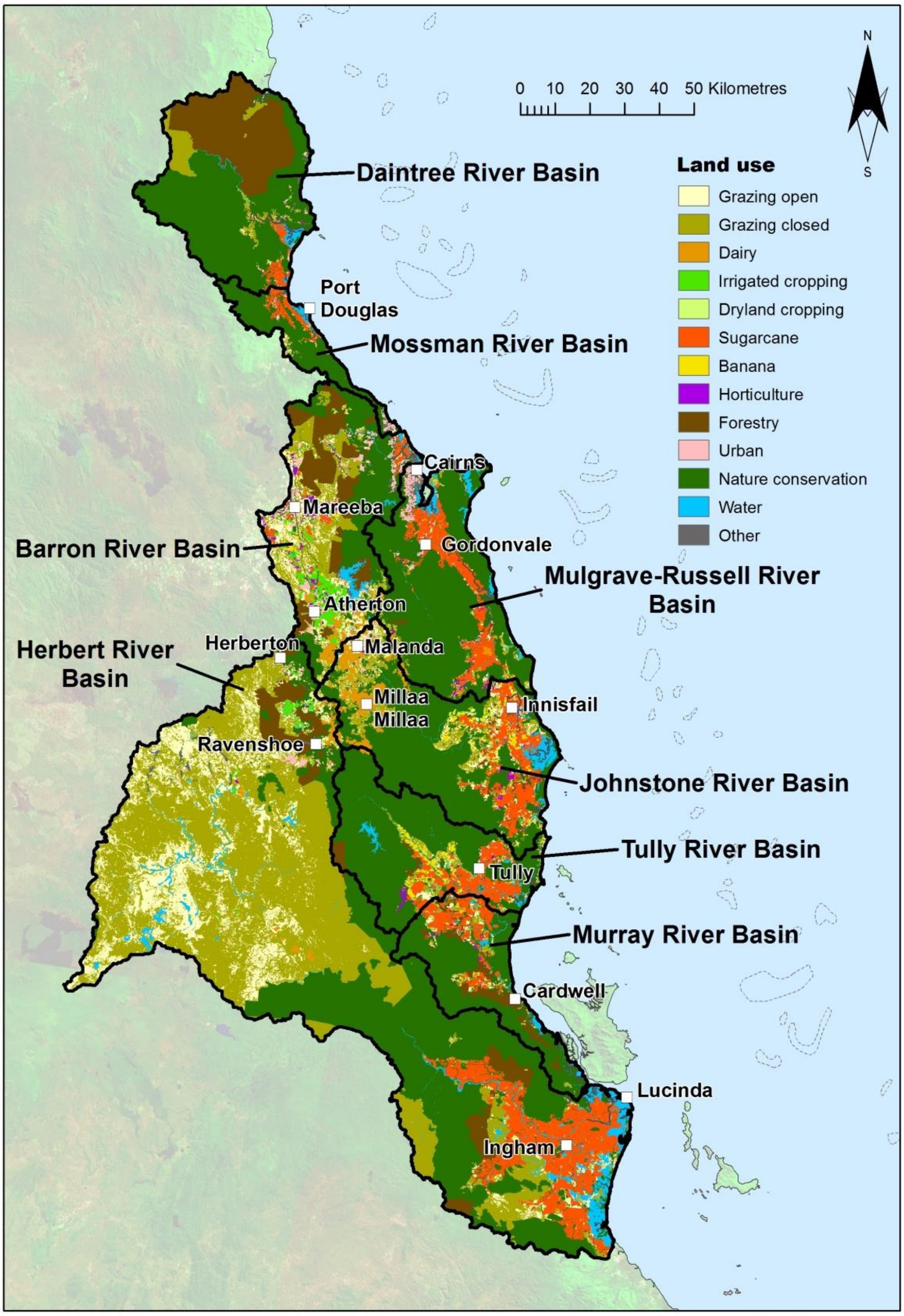


Figure 4.1. Land use map of the Wet Tropics region. Source: Hateley et al. (2014).

Urban land uses contribute a large range of pollutants including TSS, nutrients, pesticides and other pollutants such as heavy metals, hydrocarbons and pharmaceuticals. Overall, urban land uses contribute less than 10% of the total regional load for all constituents.

Point sources

Sewage discharges can be relevant at a local scale. There are several sewage treatment plants (STP) in the Wet Tropics region that discharge into the GBRWHA or adjacent waterways. The loads for these treatment plants are estimated in Table 4.4, and are based on an assessment by Hateley et al., (2014) where it is estimated that ~79% of the Total Nitrogen and Total Phosphorus is in dissolved inorganic form.

Table 4.4. Major sewage treatment plants in the Wet Tropics region.

Name of STP	Discharge point	Catchment	DIN (kg/yr)	DON (kg/yr)	DIP (kg/yr)	DOP (kg/yr)
Marlin Coast	Avondale Creek	Barron River	5,011	1,332	970	274
Northern	Barron River		8,758	2,328	1,922	542
Southern	Smith's Creek (Trinity Inlet)	Russell-Mulgrave River	22,104	5,876	3,520	993
Edmonton	Trinity Inlet		2,567	682	347	98

Point source (all)

	TN (t/yr)	DIN (t/yr)	DON (t/yr)	TP (t/yr)	DIP (t/yr)	DOP (t/yr)
Point source (all)	48	38	10	9	7	2

Emerging pollutants
A study was commissioned by Terrain to examine the sources and risk of 'emerging pollutants' in the Wet Tropics NRM region (O'Brien et al., 2014). Two specific sources and pollutants were examined: (1) pesticide residues from the mixed cropping land use in the Upper Barron River (i.e. above the Tinaroo Dam) and (2) pharmaceuticals, personal care products and pesticides from the Sewage Treatment Plants in the Cairns Region that discharge into Trinity Inlet.

Case study: Analysis of micropollutants in sewage discharges
Passive and grab sampling at the Edmonton and Southern wastewater treatment plants (WWTP) that drain into Trinity Inlet was conducted from December 2013 to March 2014 to examine the concentrations of various pesticides, pharmaceuticals and personal care products (PPCPs) in both untreated influent and treated sewage effluent. The treatment processes undertaken likely remove the chemicals that have an affinity for particulate/organic matter and/or are prone to photodegradation. The results obtained show that several of the monitored chemicals were removed during the treatment process and few remained in the treated effluent that is discharged into Trinity Inlet (note that there are potentially hundreds to thousands of chemicals for which analysis is not undertaken because of the limitations in analytical capacity at this time). Chemicals detected at both WWTPs include the artificial sweetener acesulfame, pesticides and pharmaceuticals (including antibiotics, analgesics, anti-convulsants, antidepressants, diuretics, and medical dyes). None of these chemicals were detected at concentrations known to cause environmental harm (where there are toxicity data available and also considering dilution within Trinity Inlet). Hence the risk of pesticides, pharmaceuticals and personal care products discharged from sewage treatment plants in the Cairns region into Trinity Inlet is considered to be low. The results of the study indicated that these emerging pollutants currently pose a relatively low risk in the Wet Tropics region compared to the more recognised pollutants of suspended sediments nutrients and PSII herbicides. It is recommended that episodic monitoring be carried out (i.e. every few years) on these emerging pollutants to ensure their risk remains negligible. Indeed as analytical capacity and toxicity studies advances in the coming years, a more quantifiable risk profile can be established for these constituents.

Case study: Pesticides upper Barron
A small scoping study was undertaken to assess the presence of pesticides at sampling locations above the Tinaroo Dam in the Upper Barron catchment (O'Brien and Lewis, 2014). A total of 14 pesticide residues, 3 herbicide degradation

products, 2 synthetic musks and 1 flame retardant were detected in the passive samplers and grab samples in the Upper Barron River between December 2013 and March 2014. The sampling captured low flow (mid-December to mid-January), high flow (mid-January to mid-February) and moderate flow (mid-February to mid-March) events. The residues detected included the herbicides ametryn, atrazine, diuron, hexazinone, metolachlor, metsulfuron methyl, pendimethalin, picloram, prometryn, simazine and tebuthiuron and the herbicide degradation products, 3,4-dichloroanaline (diuron metabolite), desethyl atrazine and desisopropyl atrazine (atrazine metabolites). The insecticides detected included chlorpyrifos, diazinon and imidacloprid and the synthetic musks detected were galaxolide and tonalide. Tris (2-chloro-1-methylethyl) phosphate (TCIPP) was the only detected flame retardant in the samples. Our analysis suggests that none of these chemicals were detected at concentrations known to cause environmental harm, although diazinon and chlorpyrifos exceeded 99% ecological protection trigger values during each of the three monthly monitoring periods undertaken. However, the 95% trigger values were not exceeded and are more appropriate to apply given this would be considered a moderately disturbed site. Overall, compared to other regions of the GBR, the pesticides (and other chemicals) in the Upper Barron Catchment that drain into Tinaroo Dam, are considered low risk.

4.2 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 Wet Tropics region:

1. In the combined assessment of the relative risk of marine water quality variables (Section 3.3) the areas in the Very High relative risk class were located in the coastal areas around Hinchinbrook Island, extending north to the Tully River mouth and south to the regional boundary at the southern part of the Herbert basin. When all water quality variables are combined into the Marine Risk Index, the risk is greatest for coral reefs in the Tully-Murray basins, and for seagrass in the Tully-Murray and Herbert basins. 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 Wet Tropics basins.
2. In the assessment of end-of-catchment pollutant loads (Section 3.4) the greatest relative contributions of combined end-of-catchment loads to the Wet Tropics region is from the Herbert and Johnstone basins. The anchored score indicates that the contribution from the Tully-Murray basin is approximately 60% of that from the Herbert and Johnstone basins, and the contribution from the Russell-Mulgrave basin is approximately 47% of that of the Herbert and Johnstone basins. The Barron and Daintree are relatively low contributors to regional pollutant loads compared to the other basins (approximately 16% of that contributed by the Herbert and Johnstone basins).
3. When considering only the Wet Tropics rivers (e.g. Daintree, Barron, Russell-Mulgrave, Johnstone, Tully and Herbert Rivers) the Johnstone is estimated to present the largest risk of contributing to the DIN pool in the COTS Initiation Zone. The high level of DIN risk from the Johnstone River is related to the large volume discharged (mean = 3.2 km^3 over the 4 years of simulation) and but also due to the high estimated concentration of DIN in the discharge (321 µg N/L).
4. The Russell-Mulgrave and Tully Rivers rank consecutively lower than the Johnstone River for DIN risk however the mean risk values for these three rivers are similar.
5. The COTS Influence Index reflects the rankings noted above, showing that the DIN risk score for the Russell-Mulgrave and Tully Rivers is 70-75% of that of the Johnstone River, the Herbert River is 42%, Daintree is 34% and the Barron is 10%.
6. The load contributions from the Daintree and Mossman basins are relatively low across the region. This correlates with a relatively high degree of hydrological connectivity in the basin as identified through the GBRMPA Blue Maps assessment. These basins may be suitable as higher priorities for maintaining current coastal systems to maintain current values.

Table 4.5. Summary of management priorities for reducing the relative risk of degraded water quality to the Wet Tropics region.

Relative Priority	Priority management areas for GBR outcomes		
	Basin	**Pollutant management**	**Key land uses**
Very High	1. Johnstone	Nitrogen	Sugar cane, bananas
	2. Tully Murray	Nitrogen	Sugar cane, bananas
	3. Herbert	Nitrogen	Sugar cane
	4. Russell Mulgrave	Nitrogen	Sugar cane
	5. Herbert	PSII herbicides	Sugar cane
	6. Tully Murray	PSII herbicides	Sugar cane
High	1. Johnstone	PSII herbicides	Sugar cane
	2. Herbert	Sediment / Phosphorus	Grazing Disused mining sites in the Upper Herbert
Moderate	1. Johnstone	Sediment / Phosphorus	Sugar cane
	2. Barron	Sediment	Tableland mixed cropping; urban (broader Cairns area)
	3. Russell Mulgrave	Sediment	Urban (broader Cairns area)
	4. Barron	Nutrients	Sugar cane, urban
	5. Daintree-Mossman	Nutrients	Sugar cane
	6. All basins	Phosphorus	Sugar cane, bananas, cropping, grazing, coastal urban
Lower	Barron, Daintree	PSII herbicides	Sugar cane

5 Improvements and 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.

We have applied a number of improvements from the 2013 risk assessment (Brodie et al., 2013a). These include:

1. Definition of zones of influence for each basin in an attempt to attribute marine risk back to individual basins.
2. Refinement of the COTS influence modelling using four years of data rather than one (2010-11) to consider inter-annual differences. This has revealed differences in the main influences between high flow and low flow years.
3. The contribution of DIN into the COTS Initiation Zone has been incorporated as opposed to just volumetric input. The annual DIN loads estimated by Lewis et al., (in review) take into account the whole basin.
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:

TSS and Chlorophyll *a* exceedance is based on daily observations over a 10 year monitoring period (with), while TSS and DIN plume loading is based on a mean of 2007 to 2011 (which were in fact relatively wet years in the long term record), and PSII herbicide concentration modelling is based on single flood events. 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 and DIN surface exposure) do factor in these events. In comparing the modelled results against empirical data, the relative contributions of individual NRM regions are in general agreement with monitoring data except during extreme wet seasons.

The marine hydrological modelling is conducted using a 4km grid, which has resulted in odd overlays with the coastal areas for the zones of influence. The analysis was conducted on these boundaries, and for future assessments, should be 'smoothed' to align with the coastline. While new spatial files have been prepared to represent these revised zones of influence, the analysis has not been conducted on these new boundaries and therefore may incorporate some errors with coastal fringing reefs or seagrass beds. However, these discrepancies are not expected to change the overall results in terms of relative rankings.

The assessed risk posed by pesticides is most probably an underestimate. Only a few of the pesticides detected in the GBR lagoon are considered. The risk posed by multiple pesticides, in combination with other contaminants found in flood plumes (e.g. elevated TSS and nutrients) and other environmental stressors (temperature) have not been assessed. Cumulative impacts from the multiple plumes that occur each year are also not accounted for. Toxicity of PSII herbicides is time dependent (Vallotton et al., 2008), i.e. the toxicity to phototrophs increases with exposure duration. For this risk assessment, only acute exposure was used to assess the potential impacts to seagrass and corals.

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 (Brodie et al., 2013a).

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 areas near Hinchinbrook Island which are naturally turbid, such as Rockingham Bay. Uncertainties in products derived from remote sensing of these areas have not been resolved. 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.

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 management priorities required to reduce pollutant impacts on the GBR. However, further consideration of the relative priorities between the Regions and industries requires incorporation of the current adoption of management practices, the feasibility of adopting the most effective practices in terms of water quality benefits, the relative cost effectiveness of these practices, existing management programs in place, and the range of management strategies available to address these issues. The Reef Plan 3 Management Prioritisation project will address these aspects to some degree over the coming months, although these aspects will always present a challenge to managers due to the complexity of the issues and varying degrees of knowledge of these aspects between the Regions and industries.

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. 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.
3. Validation of the remote sensing data for turbidity and chlorophyll, particularly in areas which are known to be naturally highly turbid or where existing validation data is limited such as in Cape York and Burnett Mary regions.
4. 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.
5. 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.

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