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JAMES COOK UNIVERSITY
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Assessment of the relative risk of degraded water quality to ecosystems of the Great Barrier Reef

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Assessment of the relative risk of degraded water quality to ecosystems of the Great Barrier Reef

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Lead by Jon Brodie, Jane Waterhouse and Jeffrey Maynard with many contributing authors

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Context to the report

The Queensland Government's Reef Water Quality Program provided funding for this up-to-date assessment of the relative risks of degraded water quality to ecosystems of the Great Barrier Reef to inform the development of Reef Plan 2013. The assessment, and its supplementary studies, informed the development of the 2013 Scientific Consensus Statement and, in particular, formed the basis of Chapter 3 of that statement. The Scientific Consensus Statement underpinned the management strategies and their priorities in Reef Plan 2013, including setting investment priorities for the Australian Government's Reef Rescue 2 program. This report, its supporting studies and the information collated for this assessment, will be a "living resource" that will continue to inform discussion of Reef Plan and other related management, investment and monitoring priorities at regional level in the reef catchments as their Water Quality Improvement Plans are updated.

The Queensland Government is committed to ongoing investment in Reef Plan science and, as new information becomes available, government policy will be adapted to take account of it. The report is provided in good faith, on the understanding that the information is not used out of the context explained above.

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Disclaimers

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Executive Summary

A risk assessment method was developed and applied to the Great Barrier Reef (GBR) to provide robust and scientifically defensible information for policy makers and 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). This information was used to inform management prioritisation for Reef Rescue 2 and Reef Plan 3. The risk assessment method needed to take account of the fact that catchment-associated risk will vary with distance from the river mouth, with coastal habitats nearest to river mouths most impacted by poor marine water quality.

The main water quality pollutants of concern for the GBR are enhanced levels of suspended sediments, excess nutrients and pesticides 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 report is presented in 2 main parts: Part A describes the risk assessment method and reports the main findings; Part B provides the overall conclusions which are also informed by a number of supporting studies which are provided as a separate report (Waterhouse, 2013). The key findings of all parts of the report and supporting studies are summarised below.

Part A: Risk assessment

The risk assessment method is described in Part A of this report and used a combination of qualitative and semi-quantitative information about the influence of individual catchments in the 6 natural resource management (NRM) regions on coral reefs and seagrass ecosystems. The marine boundaries used for each NRM region are those accepted officially by the Great Barrier Reef Marine Park Authority. The area of GBR lagoon waters within each marine NRM region were also reported in recognition of other important habitats and populations that exist in these areas.

The relative risk of degraded water quality among NRM regions was determined by combining information on end-of-catchment pollutant loads and the estimated ecological risk of water quality to coral reefs and seagrass meadows in the GBR. Modelled end-of-catchment pollutant loads (generated from the Source Catchments model framework for the Paddock to Reef Program) were obtained for each NRM region for key pollutants, and only the anthropogenic portions of total pollutant loads were considered in relating the relative risk to NRM regions. The anthropogenic load is calculated as the difference between the long term average annual load, and the estimated pre-European annual load. This information was used to define a 'Loads Index'.

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 each NRM region 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 NRM regions, and was used to generate a 'Marine Risk Index' for coral reefs and seagrass meadows.

A suite of water quality variables were chosen that represent the pollutants of greatest concern with regards to agricultural runoff and potential impacts on GBR ecosystems. The selection of variables was informed by the supporting studies described in Part B of this report (Waterhouse, 2013), and 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 spatial variable was included that represents the area of the GBR lagoon where primary crown-of-thorns starfish (COTS) outbreaks have been observed. 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'. In recognition of the importance of the influence of catchment discharges in driving COTS outbreaks, an index of regional contributions of river discharges to the COTS initiation zone is also included for coral reefs (COTS Influence Index).

The three indexes were then combined to generate a Relative Risk Index, which ultimately ranks the relative risk of degraded water quality to coral reefs and seagrass meadows in the GBR among NRM regions.

Supporting Studies (see chapters within Waterhouse, 2013)

The supporting studies of the project informed the selection of variables and methods of analysis used in the risk assessment. The studies also strengthen our understanding of the consequences of pollutant impacts on coral reefs and seagrasses. In particular: Chapter 1 emphasises the importance of nutrients in the initiation of COTS primary outbreaks and therefore loss of coral cover; Chapter 2 confirms the relative importance between nitrogen and phosphorus in driving productivity in the GBR lagoon; Chapter 3 reviews the effects of sediments and sedimentation on coral reef communities; Chapter 4 provides new information on the relative risk of PSII herbicides to coastal and marine ecosystems, identifying the highest risk areas to be in freshwater and coastal wetlands, estuarine areas and coastal seagrass and inshore reef communities; Chapter 5 develops relationships between flood plume frequency and end of catchment pollutant loadings to define plume water types related to water quality characteristics; Chapter 6 provides a case study that shows a correlation between plume water types and seagrass cover with a supporting review on the impacts of water quality on seagrass in an appendix (Chapter 7); and Chapter 8 summarises the results of water quality and phytoplankton samples collected in variable flood plume conditions between 2010 and 2012 to improve our understanding of phytoplankton population dynamics.

Key findings of the Supporting Studies include:

- A variety of experimental, modelling and observational evidence circumstantially, but strongly, supports the hypothesis that COTS primary outbreaks are initiated by an episode of greatly enhanced larval survival during conditions producing increased food availability for the filter-feeding pelagic larval stages (Chapter 1). The four primary COTS outbreaks originating in the Lizard Island - Cairns region (14.5-17°S) since 1960 follow 2-5 years after wet seasons when early season (November-February) aggregate discharges from the Burdekin to Daintree Rivers exceeded 10 Km^3.

- Hydrodynamic modelling and estimates of DIN loads were used to rank the individual contribution of significant rivers between the Daintree (16°S) and Burdekin (19°S) to regional runoff influences on the Lizard

Island – Cairns initiation region (Chapter 1). The initiation region is divided into two areas – north and south of Undine Reef (16°S). On a runoff volumetric basis, the Daintree has the largest influence followed by the Russell-Mulgrave and Tully. With DIN loads included, the Russell-Mulgrave and Tully Rivers are the most important in the northern part of the initiation region (14.5-16°S). For the southern sub-region (16-17°S) of the initiation region the Daintree, Barron and Burdekin Rivers ranked highest, indicating the additional significant influence of northward transport of the Burdekin River plume. When DIN loads are included, the influence of the Burdekin increases greatly, particularly in the southern part of the initiation region (16-17°S).

- Dissolved inorganic and particulate forms of nutrients discharged into the GBR are both important in driving ecological effects but increased nitrogen inputs are more important than phosphorus inputs (Chapter 2). Dissolved inorganic forms of nitrogen and phosphorus are considered to be of greatest concern compared to dissolved organic and particulate forms of nutrients, as they are immediately and completely bioavailable for algal growth. Particulate forms mostly become bioavailable over longer time frames, and dissolved organic forms typically have limited and delayed bioavailability.

- Across the 35 basins in the GBR catchment area, the highest annual average loads of total suspended solids are derived from the Burdekin River (3,306 kt/year), Fitzroy River (1,805 kt/year), Herbert River (482 kt/year), Mary River (362 kt/year) and Don River (330 kt/year) (Chapter 3). Recent research has highlighted gully and streambank erosion as the dominant sediment erosion processes occurring in the larger dry tropical river catchments of the GBR and Gulf of Carpentaria. Prior to these field studies, catchment modelling had identified hillslope erosion as the dominant source of sediment in these catchments. The very fine sediment fraction (<10 µm) has a shorter residence time than coarser sediment, and is less likely to be captured in storage pathways, such as reservoirs.

- Floodplume studies have found most sediment exported from GBR rivers (e.g. Burdekin, Fitzroy, Tully and Burnett Rivers and the Mackay Whitsunday rivers) is deposited within close proximity of the river mouth/estuary, near-shore zone and inner shelf of the GBR, with potential for remobilisation during subsequent wind and tide driven resuspension events. Such resuspension events can result in higher turbidity levels than measured in initial flood plumes. The delivery of this new sediment to the inner shelf sediment wedge plays a critical role on inshore turbidity regimes, with a recent study highlighting the influence of increased river flow/sediment loads on temporal variation in inshore turbidity.

- Turbidity reduces light for benthic organisms such as seagrass and corals (Chapter 3). Coastal coral reefs do grow in turbid water conditions at shallow depths, however biodiversity declines as a function of increased turbidity throughout the GBR. Variability in light conditions may be a greater stress than chronically reduced light, as energy demands to adjust to varying light conditions result in suboptimal energy gains.

- Sediment properties strongly influence the effects of sedimentation on corals. Nutrient enriched fine terrestrial silts found along the inshore GBR are most detrimental. Early life stages (e.g. fertilisation, settlement) of corals are particularly susceptible to poor water quality and sedimentation.

- Coral reefs most vulnerable to damage from turbidity and sedimentation are those found in locations with weak currents such as embayments (e.g. Keppel Bay, Cleveland Bay, Missionary Bay) and sheltered zones on deeper reef slopes, in places where fish abundances are low, and in regions that are frequently affected by other forms of disturbance such as cyclones, bleaching or crown-of-thorns starfish predation.

- Seagrass meadows are widespread and ecologically critical parts of the Great Barrier Reef Marine Park (Chapter 7). Recent, widespread loss of seagrass has conclusively demonstrated their sensitivity to water quality, and the ecological ramifications of seagrass loss including dugong and turtle mortality. Seagrass meadow distribution, abundance, productivity, composition and resilience are structured by chronic and acute water quality impacts.

- Both suspended sediments and nutrient-stimulated blooms of epiphytes and plankton attenuate light and reduce light penetration to seagrass canopies. Light thresholds associated with event-based loss of seagrass have been derived during recent runoff events. PSII herbicides, which are found above guideline levels in the GBR, reduce photosynthetic efficiency in seagrass.

- Little is known about the types and concentrations of contaminants bound to sediment discharged by rivers into the GBR and the risk that these pose to GBR ecosystems.

- An assessment of pesticide risk to the GBR (Chapter 4) considered pesticides within two groupings: (1) the additive effects of PSII herbicides (diuron, atrazine, hexazinone, ametryn, tebuthiuron and simazine) normalised via two methods (toxicity equivalent: TEQ and multiple substances potentially affected fraction: ms-PAF) and compared to consequence values based on expert opinion and (2) the individual risk of other pesticides compared to their respective trigger value (in a hierarchical framework from the Great Barrier Reef Marine Park Water Quality Guideline trigger values, the Australian and New Zealand Water Quality Guidelines and other internationally-derived values). It was concluded that the Mackay Whitsunday and Burdekin region are considered to be at highest risk from PSII herbicides, followed by the Wet Tropics, Fitzroy and Burnett Mary regions. However, the risk of only a fraction of pesticides has been assessed, with only 6 out of the 34 pesticides currently detected included in the assessment, and therefore the effect of pesticides is most likely to have been underestimated.

- Concentrations of a range of pesticides exceed water quality guidelines in many fresh and estuarine waterbodies downstream of cropping lands. Of the five ecosystems that were considered within the Great Barrier Reef, it is suggested that the freshwater reaches of rivers and freshwater/coastal wetlands have the highest risk from pesticides (PSII herbicides and some non-PSII pesticides) followed by the estuarine reaches of the rivers, the coastal nearshore zone which includes intertidal and subtidal seagrass meadows, the inner shelf and the mid and outer shelf.

- Plume loading maps have been produced for dissolved inorganic nitrogen and total suspended solids for the period 2007 and 2011 (Chapter 5). These maps provide an indication of the relative influence of these pollutants in the GBR during flood plume conditions, classified from low to high. The area of coral reef and seagrass in each class varies considerably between NRM regions, reflecting the differences in the dispersal of pollutants and the locations of the ecosystems.

- Innovative remote sensing methods to map water clarity can also be used as an interpretative tool for understanding changes in seagrass meadow area and abundance at large spatial scales. This method was tested in Cleveland Bay, near Townsville in the northern GBR area (Chapter 6). Methods have been developed to map plume water types in the GBR by using MODIS true colour images reclassified in function of their dominant colour. Water types entering into the GBR lagoon though river discharges have been described as primary, secondary and tertiary, each characterised by different concentrations of Coloured Dissolved Organic Matter (CDOM), total suspended solids (TSS) and chlorophyll. Substantial seagrass loss has occurred in Cleveland Bay over the period 2008 to 2011 and changes in seagrass area and biomass were monitored annually for selected meadows; there was a strong correlation between total bay-wide meadow area and biomass and exposure to primary water (high TSS and CDOM, low light) at an annual time-scale and also at a 5 year time scale.

- Analysing the species composition and size class of phytoplankton associated with various stages of plume development may help provide the missing link between increased nutrient loads, higher nutrient concentrations, changed water quality conditions and possible changes to food web/primary production in GBR waters including COTS outbreaks. Thus it is essential that we have greater knowledge on the drivers and consequences of changes in water quality, and the associated phytoplankton response. Chapter 8 presents current information from both local and international sources on the potential relationship between phytoplankton communities and COTS populations, including results of water quality and phytoplankton community analysis from samples collected in Wet Tropics flood plumes between 2010 and 2012.

Part B: Relative risk of degraded water quality to GBR ecosystems

The results of the Relative Risk Index were combined with the outcomes of the Supporting Studies and published literature to assess the overall relative risk of degraded water quality to GBR ecosystems (Part B of this report). A tabulated summary of the overall outcomes is presented in Table i and illustrated in Figure i. In this table we used the individual assessments of each variable used in the ecological risk assessment to highlight where the variables dominate among the regions. The primary rank for each variable is listed, with an indication of whether it dominates in terms of coral reef or seagrass area, or both. The Marine Risk Index for coral reefs and seagrass is then shown for the results of the combined analysis of water quality variables. The regional anthropogenic loads as a proportion of the total GBR load for TSS, DIN and PSII herbicides are shown to identify the primary sources of anthropogenic loads delivered to the GBR, in addition to the Loads Index which combines this information. Additional information includes facts related to the influence of river discharges to the COTS Initiation Zone and additional pesticide information. The Relative Risk Index which represents the overall results of the risk assessment (Part A) is shown as the critical underpinning for the overall conclusions. This is then informed by the management issues and associated land uses which were derived from published evidence and expert judgement of the assessment team (informed by the preceding columns). The overall ranking of relative risk was developed by the assessment on the basis of the overall content of the table.

The information has been coupled with the summary of pollutant sources from land uses in each region to generate the management priorities identified Table ii. However, cost effective solutions for all of these management issues are not necessarily currently available for all of these priorities. These issues are discussed further in the Reef Plan Scientific Consensus Statement 2013 (see Thorburn et al. 2013).

Even though the nutrient related variables of Chlorophyll threshold exceedance and DIN plume loading were ranked highest in the Fitzroy region, there is insufficient knowledge of the sources of DIN in the Fitzroy region to make recommendations about management priorities to address nutrients in the region. Further knowledge of the role of particulate nitrogen, which is largely derived from both cropping and grazing lands, and the processing of this into dissolved inorganic nitrogen is important for making future management recommendations in the large grazing catchments of the Fitzroy region.

Overall conclusions:

The main finding of the study was that increased loads of suspended sediments, nutrients (nitrogen and phosphorus) and pesticides all pose a high risk to some parts of the GBR. However, the risk differs between the individual pollutants, between the source catchments, and with distance from the coast as per the conclusions below. These findings are represented in the map shown in Figure ii.

- Overall, increased concentrations of nitrogen from catchments between the Daintree and Burdekin Rivers pose the greatest risk to coral reefs. Runoff from these rivers during extreme and early wet seasons is associated with outbreak cycles of the coral-eating COTS on the northern GBR shelf (15 to 17°S) that subsequently generate secondary outbreaks throughout the central and southern GBR. GBR-wide loss of coral cover due to COTS is estimated to be 1.4% per year over the last 25 years, and a new outbreak is underway. It is estimated that COTS have affected >1000 of the ~3000 reefs within the GBR over the last 60 years.

- Of equal importance is the risk to seagrass meadows from suspended sediments (TSS) discharged from rivers in excess of natural erosion rates, especially the fine fractions (clays). Whether carried in flood plumes, or re-suspended by wave action, suspended particulate matter creates a turbid water column that reduces the light required by seagrass and corals. High turbidity has been estimated to affect ~200 inshore reefs and most seagrass areas. The Burdekin and Fitzroy regions present the greatest risk to the GBR from increased suspended sediment loads.
- Loss of seagrass habitat as a result of cyclones, floods and degraded water quality appears to be associated with higher mortality of dugong and turtles.
- The risk to coastal seagrass beds (and freshwater and estuarine wetlands) from the six commonly used PSII herbicides (pesticides) was assessed as highest in the Mackay Whitsunday and Burdekin regions, followed by the Wet Tropics, Fitzroy and Burnett Mary regions to. Concentrations of a range of pesticides exceed water quality guidelines (thresholds) in many fresh and estuarine waterbodies downstream of cropping lands. However, the risk of only a fraction of pesticides has been assessed. Only 6 out of the 34 pesticides currently detected included in the assessment, and therefore the effect of pesticides is most likely underestimated.
- The ranking of the relative risk of degraded water quality between the NRM regions in the GBR is: Wet Tropics > Fitzroy > Burdekin > Mackay Whitsunday > Burnett Mary > Cape York. Priority areas for management of degraded water quality in the GBR are: Wet Tropics for nitrogen management; Mackay Whitsunday and lower Burdekin for PSII herbicide management; and Burdekin and Fitzroy for suspended sediment management.
- The regional ranking of risk to coral reefs from degraded water quality is: Wet Tropics > Fitzroy > Mackay Whitsunday > Burdekin> Cape York > Burnett Mary, while that for seagrass beds is: Burdekin > Wet Tropics > Fitzroy > Mackay Whitsunday > Burnett Mary > Cape York. The combined assessment of water quality variables in the GBR used the total area of habitat affected in the highest relative risk areas and end-of-catchment anthropogenic loads of nutrients, sediments and pesticides added to the GBR lagoon. Importantly in the Mackay Whitsunday Region, 40% of the seagrass area is in the highest relative risk class compared to less than 10% for all other regions. However the highly valuable seagrass meadows in Hervey Bay, and the importance to associated dugong and turtle populations in the Burnett Mary Region, were not included in the ranking analysis.

The risk assessment presented in this report has generated the most comprehensive assessment of the relative risk of degraded water quality to GBR ecosystems undertaken to date. However, it is important to reiterate that the rankings between NRM regions are relative, and do not represent absolute differences in the risk to GBR ecosystems. In this regard, even the lowest ranked regions of the Burnett Mary and Cape York region may pose a risk to GBR ecosystems, but relative to the other NRM regions they are considered to be of lower risk. This information can be useful in guiding investment priorities but should not be used in isolation from other knowledge related to regionally specific priorities supported by additional evidence, socio economic influences and limitations to the assessment that may have led to uncertainties in the results. The limitations to the assessment are described in Section 4 of this report, together with suggestions to improve upon the work presented herein.

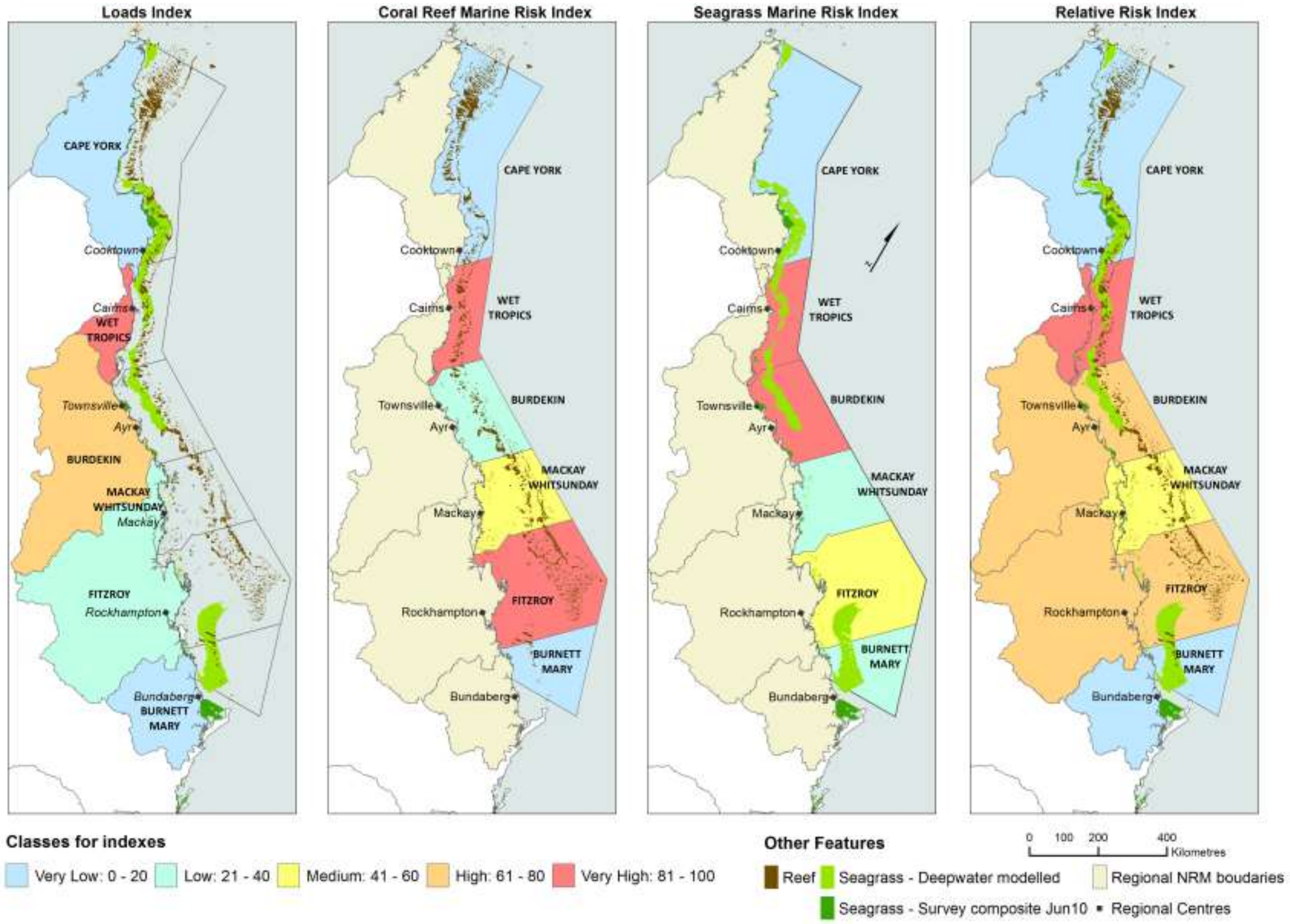

Figure i. Map summarising the results of the Loads Index, Marine Risk Indexes (coral reefs and seagrass) and the Relative Risk Index. The assessment for coral reefs also includes the COTS Influence Index associated with the extent of the influence of regional river discharge to the COTS Initiation Zone; the scores are 100 for the Wet Tropics, and 16 for the Burdekin region. The method for deriving and combining the indexes is provided in Section 2.4.4.

Table i. Summary of the outcomes of the overall assessment of the relative risk of water quality in the GBR. Note that the Burnett Mary Region is shaded in grey to represent the fact that most reefs and seagrass meadows in this region were not included formally in the analysis and thus the validity of the result has high uncertainty.

Region	**Dominant variables in marine assessment** *Variables where max area is in Region*	**Marine Risk Index**		**Regional Anthropogenic Load as a proportion of the Total GBR Load (%)**			**Loads Index**	**Additional Factors**	**Relative Risk Index**	**Management Issues**	**Associated land uses**	**Overall Ranking of Relative Risk**
	CR = Coral Reef *SG = Seagrass*	**Coral Reef**	**Seagrass**	**TSS**	**DIN**	**PSII Herb**						
Cape York	COTS Initiation Zone (CR)	12	4	3	<1	<1	0	Influence from catchment runoff is predominantly from Wet Tropics Rivers	9	The data in this Region are highly uncertain due to limited validation of marine datasets.		**LOW**
Wet Tropics		100	83	9	20	61	100	86% volumetric contribution to COTS Initiation Zone	100	Nutrients Pesticides	Sugarcane Bananas	**VERY HIGH**
Burdekin	TSS 2mg/L (SG, CR) TSS 7mg/L (SG) TSS Plume loading (CR, SG) Chl 0.45µg/L (SG) DIN Plume loading (SG)	40	100	32	11	13	62	14% volumetric contribution to COTS Initiation Zone High risk from PSII herbicides to Ramsar listed freshwater wetlands in the lower Burdekin catchments	76	Sediments Pesticides Nutrients	Grazing Sugarcane (coastal)	**HIGH**
Mackay Whitsunday	Pesticide exposure (CR, SG)	54	37	4	6	12	25	High risk from PSII herbicides in Sandy Creek	50	Pesticides Nutrients	Sugarcane	**MODERATE**
Fitzroy	TSS 7mg/L (CR) Chl 0.45µg/L (CR) DIN Plume loading (CR)	86	59	17	5	4	28	Monitored loads of PSII herbicides were high in 2011 (not reflected in modelled baseline)	80	Sediments Pesticides *Nutrients*[1]	Grazing Cropping	**HIGH**
Burnett Mary	All variables rank relatively low	11	23	4	4	9	20	The Mary River has the fourth highest total and anthropogenic TSS load of all GBR catchments	19	Sediments	Grazing	**UNCERTAIN**
										All variables rank relatively low, however, there is high uncertainty in this result given the lack of data on the full extent and condition of corals and seagrass (which are outside the GBRWHA) available for this assessment.		

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[1] There is insufficient knowledge of the sources of DIN in the Fitzroy region to make recommendations about management priorities for these. Further knowledge of the role of particulate nitrogen, which is largely derived from grazing lands, and the processing of this into DIN is important for making future management recommendations in the large grazing catchments of the Fitzroy region.

Table ii. Summary of management priorities for reducing the relative risk of pollutants to the GBR.

Relative Priority	**Management Priorities**			
	Region	**Pollutant Management**	**Key land uses**	**Comments**
1	Wet Tropics	Fertiliser nitrogen reduction	Sugarcane, Bananas	Note that these actions should not be prioritised at the exclusion of other practices that are already in place to manage losses of other pollutants in the Regions
	Burdekin	Erosion management in Burdekin	Grazing	
	Fitzroy	Erosion management in Fitzroy	Grazing, Cropping	
2	Burdekin	Pesticide reduction in (lower) Burdekin and Haughton	Sugarcane	
	Mackay Whitsunday	Pesticide reduction in all catchments	Sugarcane	
	Burdekin	Fertiliser nitrogen reduction in (lower) Burdekin and Haughton	Sugarcane	
3	Mackay Whitsunday	Fertiliser nitrogen reduction	Sugarcane	
	Burnett Mary	Erosion management in all catchments	Grazing	
	Wet Tropics	Pesticide reduction in all catchments	Sugarcane	
	Fitzroy	Pesticide reduction in all catchments	Grazing, Cropping	
4	Burnett Mary	Further information is required to inform the assessment, including data on the full extent and condition of corals and seagrass (which are outside the GBRWHA) in the region.		Habitat mapping, ecological value assessment and monitoring of ecosystem condition is required
5	Cape York	Further information is required to understand local influences.		As a relatively low impacted area, management efforts should aim to maintain the current values of the region

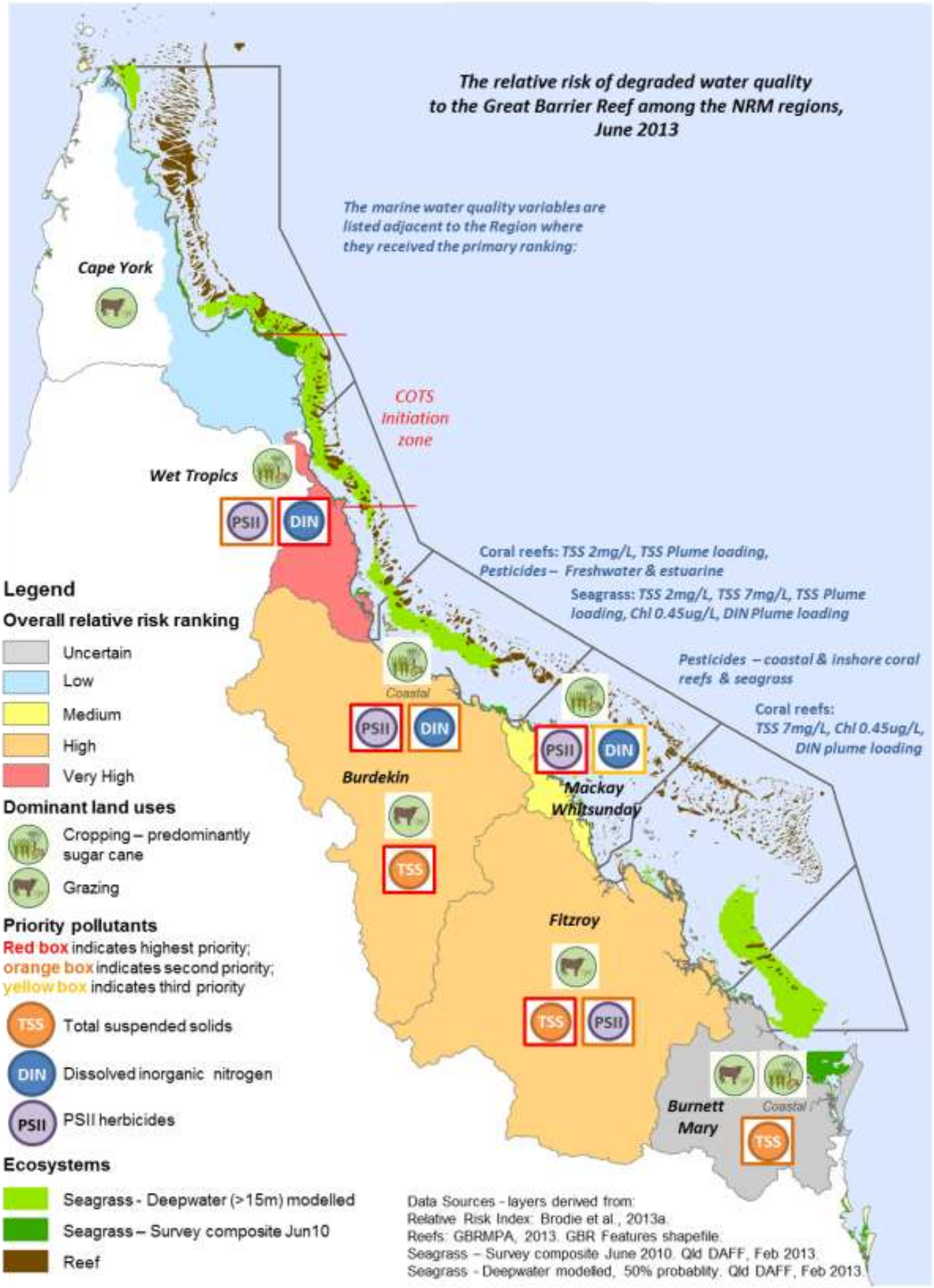


Figure ii. Illustration of the overall outcomes of the assessment of the relative risk of degraded water quality to Great Barrier Reef coral reefs and seagrass. The map shows the dominant land uses and priority pollutants and results of the overall relative risk ranking in each NRM region.

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, the magnitude of river discharges, the distance from river mouths, wind and current directions and, the mobility of different pollutant types, and of course the different land-uses in the 6 natural resource management (NRM) regions of the Great Barrier Reef (GBR) catchment. This differential exposure to land-sourced pollutants has important consequences for the likely degree of degradation that habitats such as coral reefs and seagrass meadows may suffer as a result of land-sourced pollution and an assessment of exposure is required to prioritise management of such pollution on a regional basis.

To date the prioritisation of potential management responses between different pollutants, different land uses and industries, and different NRM regions has used methods such as Multiple Criteria Analysis (MCA) (Brodie and Waterhouse, 2009; Brodie et al. 2009; Cotsell et al. 2009; Greiner et al. 2005; Waterhouse et al. 2012). The methodologies used to date, though the best available at the time, were limited for reasons summarised in Table 1.1. While these analyses have proved useful for ongoing prioritisation of investment under Reef Plan, more specifically Reef Rescue and the selection of priority management areas under the Reef Protection Package, more sophisticated analyses are now needed to more confidently prioritise between pollutants, across the individual catchments. In addition it is worth noting that the availability of data related to seagrass meadows for these assessments remains relatively sparse.

The assessment approach described in this report is listed in the final column of Table 1.1 below. In 2011, the Australian Government funded a scoping project through the National Environment Research Program (NERP *Project 4.3: Ecological risk assessment of pesticides, nutrients and sediments on water quality and ecosystem health*) to review the methodology used in previous ecological risk assessment approaches for water quality in the GBR and make recommendations for a revised and improved assessment approach. The project team outlined a tiered risk assessment methodology that was recommended to provide a systematic, objective and transparent approach to quantify the relative risk of pesticides, nutrients and sediment to the GBR (Hayes et al. 2012). A meta-database was compiled to determine the availability of data for the risk assessment. However, due to timing and data and resource limitations, the proposed method was not able to be adopted by the Queensland Department of Environment and Heritage Protection (DEHP). Subsequently in 2012, the DEHP agreed to fund a second phase to the project through the Reef Protection Package Science Program (http://www.reefwisefarming.qld.gov.au/information/science.html) that required delivery of an assessment of the relative risk of pollutants to the GBR by March 2013. The approach that was selected for this project builds on previous assessments (Table 1.1). It still uses an MCA approach; however is improved with new input data, revised criteria and the application of a spatial multi criteria analysis tool, Multi-Criteria Analysis Shell for Spatial Decision Support (MCAS-S) developed by ABARES (refer to http://www.daff.gov.au/abares/data/mcass).

Table 1.1. Summary of the elements included in past and current assessments of the risk of water quality to the GBR used to inform Reef Plan management prioritisation.

Element	**Reef Plan** *Greiner et al. 2005*	**Reef Rescue** *Cotsell et al. 2009*	**Reef Protection Package** *Waterhouse et al. 2012*	**Reef Plan 3 / Reef Rescue 2** *This report*
Method	MCA	MCA	MCA	MCA plus interpretive studies
Data availability	Very limited	Limited	Moderate	Good
Analysis end point	Coral reefs and seagrass	Coral reefs	Coral reefs, seagrass, water column	Coral reefs, seagrass, plus freshwater to marine ecosystems for pesticides
Relative importance of pollutants	No	No	No	Yes
Pesticide data	Very limited	Limited	Limited	Yes, with limitations
Marine exposure estimate	Limited – from Devlin et al. 2003	Moderate – from Maughan and Brodie, 2009	Moderate – from Maughan and Brodie, 2009	Good – from recent work by Devlin et al. 2013a; Alvarez Romero et al. 2013
Socio and economic values included	Yes	Yes	No	No
Spatial coverage	All GBR, however Burnett Mary marine area outside of GBRMP excluded	All GBR, however Burnett Mary marine area outside of GBRMP excluded	Cape York and Burnett Mary excluded	All GBR, however Burnett Mary marine area outside of GBRMP excluded

The objective of the project was to estimate the relative risk of pollutants in the GBR catchments to GBR ecosystem health. The assessment used a combination of qualitative and semi-quantitative information about the influence of individual catchments in the 6 NRM regions (Figure 1.1) on key GBR ecosystems (coral reefs and seagrass meadows). The marine boundaries used for each NRM region are those accepted officially by the Great Barrier Reef Marine Park Authority. The area of GBR lagoon waters within each marine NRM region were also reported in recognition of other important habitats and populations that exist in these areas.. Qualitative conclusions were drawn about coastal and estuarine wetlands where information was available. Unlike the risk assessment undertaken for Reef Plan in 2004 (Greiner et al. 2005), this assessment does not take into account the social and economic value of the assets such as tourism and fishing values.

This report is presented in 2 main parts:

Part A: Assessment of the relative risk of degraded water quality to ecosystems of the GBR.

Part B: Overall conclusions of the differential risk between sediments, nutrients and pesticides and between land uses, industries and catchments/regions in the GBR.

Supporting Studies (Waterhouse, 2013) were also a key component of this risk assessment and provided supporting evidence to determine differential risk between sediments, nutrients and pesticides and between land uses, industries and catchments.

The actual assessment of the relative risk of pollutants to the GBR ecosystems (Part A) is supported by a number of these specific studies that have either developed or confirmed our understanding of the characteristics of key pollutants that influence the risk to the GBR ecosystems (Supporting Studies). The results of these studies are presented as individual chapters in the Supporting Studies report and include:

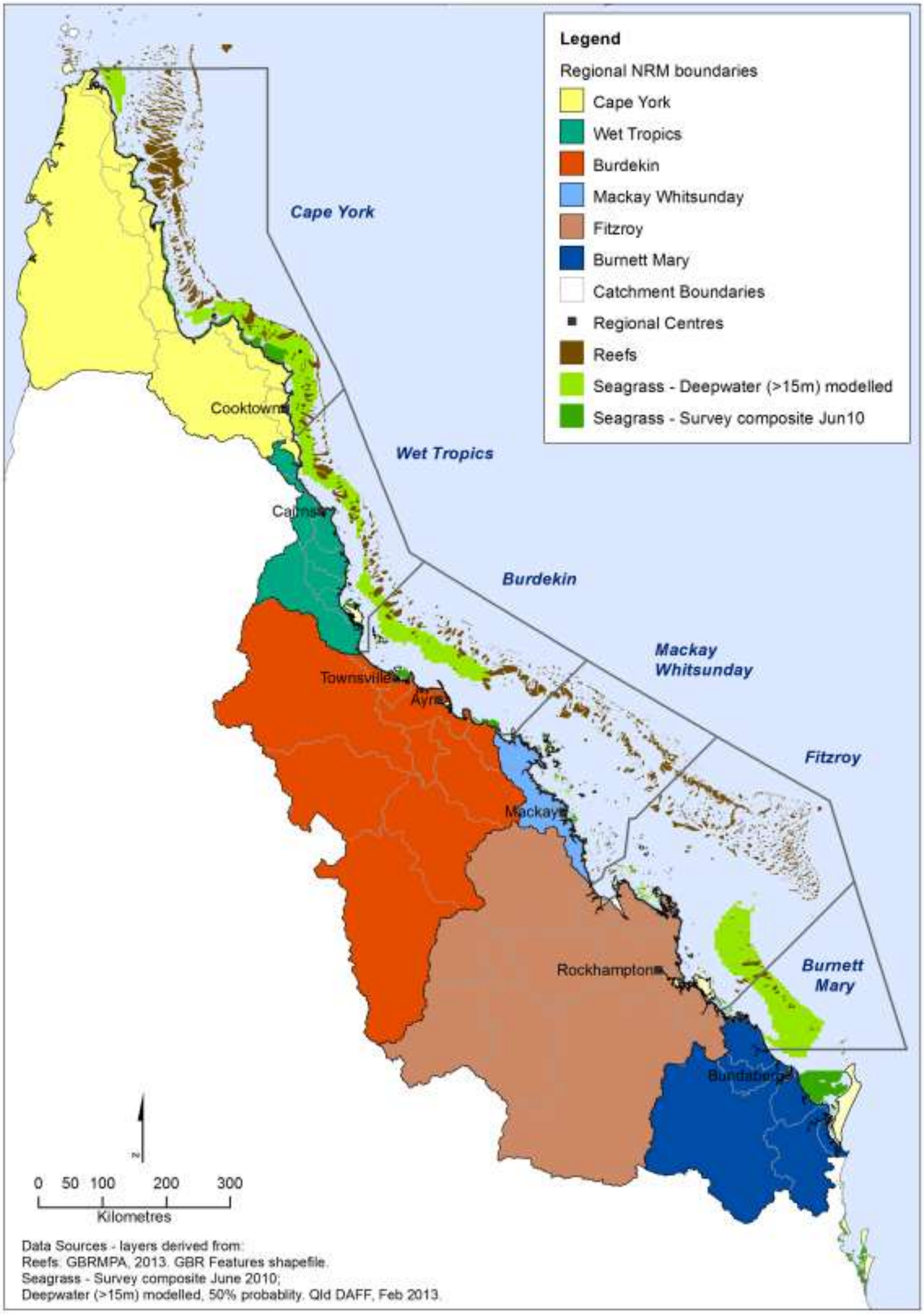
1. Linkages between river runoff, phytoplankton blooms and primary outbreaks of crown-of-thorns starfish in the Northern Great Barrier Reef.
2. The Redfield Ratio and potential nutrient limitation of phytoplankton in the Great Barrier Reef.
3. Review of increased suspended sediment delivery to the Great Barrier Reef and the effects of subsequent sedimentation and light reduction on coral reefs.
4. Assessing the risk of additive pesticide exposure in Great Barrier Reef ecosystems.
5. Mapping of exposure to flood plumes, water types and exposure to pollutants (DIN, TSS) in the Great Barrier Reef: toward the production of operational risk maps for the World's most iconic marine ecosystem.
6. Assessment of seagrass and water quality influences in the Great Barrier Reef: A case study linking annual measurements of seagrass change to satellite water clarity data (Cleveland Bay, Queensland).
7. Review of the risks to seagrasses of the Great Barrier Reef caused by declining water quality.
8. Analysis of phytoplankton community structure in flood events in the Great Barrier Reef.

Together, the results of these assessments allow conclusions to be drawn about the relative risk of pollutants to the GBR and relate these back to land uses and catchments (Part B, Section 3).

All of these Chapters and this overall report have been reviewed by independent experts, with the exception of the report on phytoplankton in Chapter 8 of the Supporting Studies. Only a small amount funding was provided under this project to undertake the actual analysis of water quality and phytoplankton populations in flood conditions collected between 2010 and 2012. As limited funding was provided to report on the outcomes of these analyses, the report of this work provided in Chapter 8 is preliminary and has not been peer reviewed. It is intended that these results will be considered in the context of a broader review funded through NERP which is also related to knowledge of GBR phytoplankton populations and the links to nutrient dynamics and COTS outbreaks. These results will be published at a later date.

The information generated from this assessment will be invaluable to the review of the Department of Environment and Heritage Protection Reef Water Quality Program (formerly Reef Protection Package) and the development of Reef Plan 2013 (Reef Plan 3). In addition, it provides an integral component of the overall investment prioritisation being undertaken for Reef Plan 3 (incorporating Reef Rescue 2) illustrated in Figure 1.2. The investment prioritisation will take the assessment from this project in association with more detailed catchment assessments of the analysis of sub catchment pollutant loads to identify catchment hot spots for pollutant sources, and an assessment of the 'solvability' of management issues in different NRM regions and catchment areas. The solvability assessment will be based on recent management practice adoption data for the sugar cane and grazing industries in the GBR catchments, and the cost effectiveness of improvements in water quality of the various practices. Together these assessments will provide robust, targeted scientific evidence of sources of high risk reef pollutants in the GBR catchment, with information to guide the best return on investment. This will enable better prioritisation of Reef Plan, Reef Water Quality Program and Reef Rescue 2 actions.

The outcomes of this project also inform one chapter of the Reef Plan Scientific Consensus Statement (SCS) 2013; *Chapter 3 Relative risks to the GBR from degraded water quality* (Brodie et al., 2013b) The SCS chapters and scope are illustrated in Figure 1.3. The evidence in these chapters also informs the methods and interpretation of results for this assessment and is referred to throughout this report.



Data Sources - layers derived from:
Reefs: GBRMPA, 2013. GBR Features shapefile.
Seagrass - Survey composite June 2010;
Deepwater (>15m) modelled, 50% probablity. Qld DAFF, Feb 2013.

Figure 1.1. Map showing the assessment boundaries considered in this risk assessment.

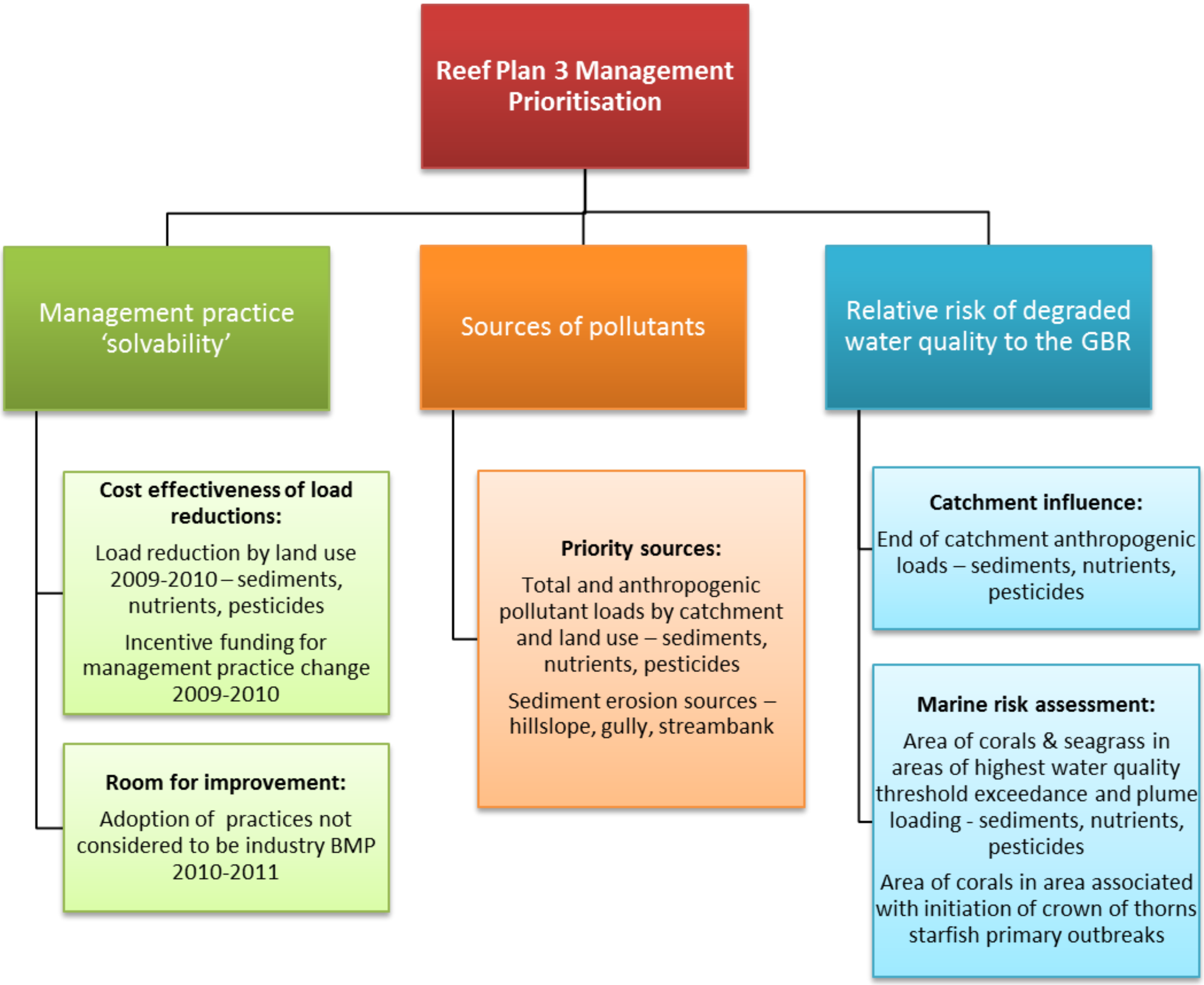
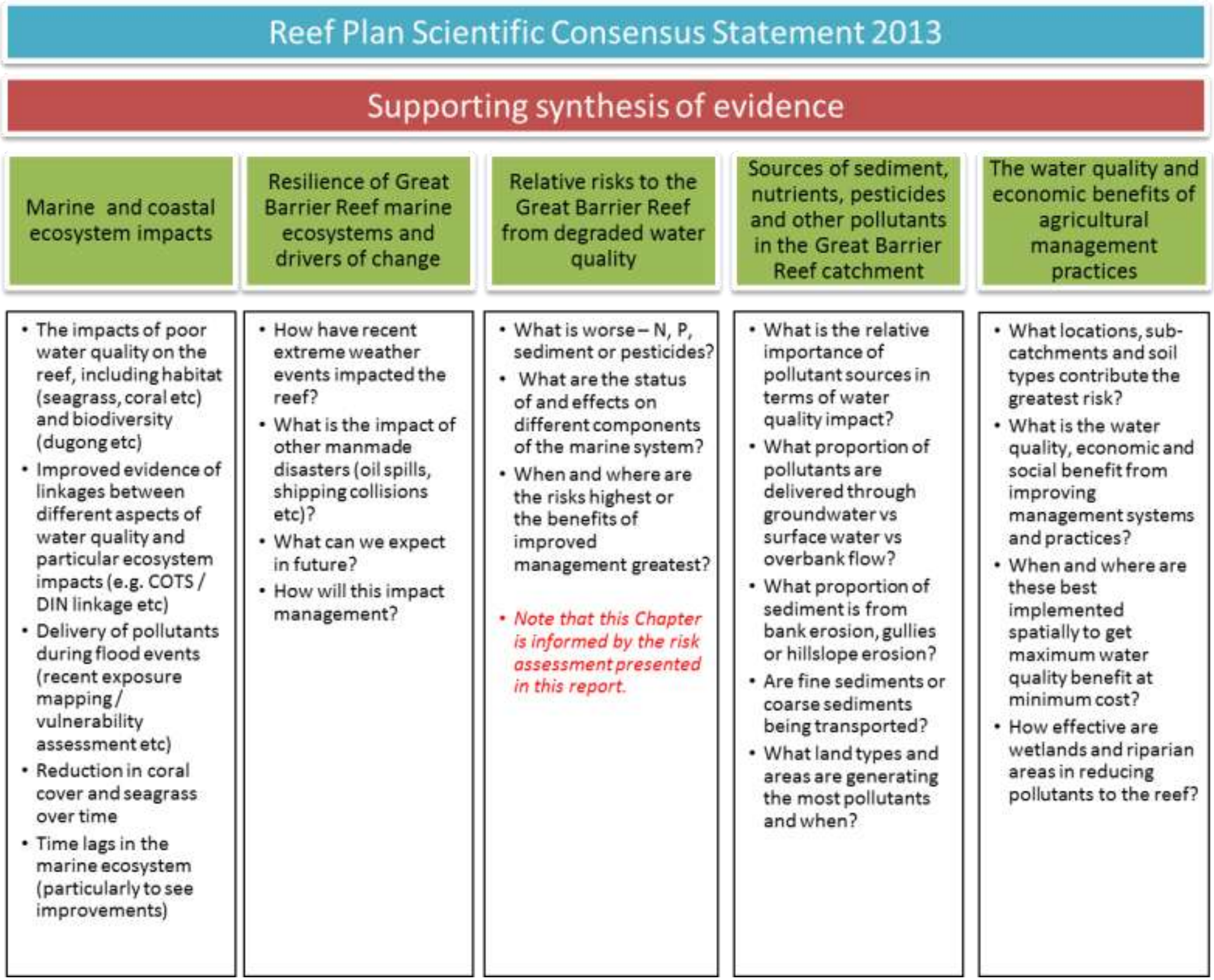


Figure 1.2. **Assessment framework for the overall Reef Plan 3 and Reef Rescue 2 management prioritisation process. The *Management practice 'solvability'* assessment will be delivered by the Australian Government for Reef Rescue 2 and includes analysis of the management practice adoption and cost effectiveness data developed through the Reef Plan Paddock to Reef Program. The *Sources of pollutants* assessment is being conducted as a collaborative effort between the Australian Government and the Queensland Government catchment modelling team. This project delivers the *Relative risk of degraded water quality to the GBR* assessment described in this report.**



Reef Plan Scientific Consensus Statement 2013

Supporting synthesis of evidence

Marine and coastal ecosystem impacts	Resilience of Great Barrier Reef marine ecosystems and drivers of change	Relative risks to the Great Barrier Reef from degraded water quality	Sources of sediment, nutrients, pesticides and other pollutants in the Great Barrier Reef catchment	The water quality and economic benefits of agricultural management practices
• The impacts of poor water quality on the reef, including habitat (seagrass, coral etc) and biodiversity (dugong etc) • Improved evidence of linkages between different aspects of water quality and particular ecosystem impacts (e.g. COTS / DIN linkage etc) • Delivery of pollutants during flood events (recent exposure mapping / vulnerability assessment etc) • Reduction in coral cover and seagrass over time • Time lags in the marine ecosystem (particularly to see improvements)	• How have recent extreme weather events impacted the reef? • What is the impact of other manmade disasters (oil spills, shipping collisions etc)? • What can we expect in future? • How will this impact management?	• What is worse – N, P, sediment or pesticides? • What are the status of and effects on different components of the marine system? • When and where are the risks highest or the benefits of improved management greatest? • *Note that this Chapter is informed by the risk assessment presented in this report.*	• What is the relative importance of pollutant sources in terms of water quality impact? • What proportion of pollutants are delivered through groundwater vs surface water vs overbank flow? • What proportion of sediment is from bank erosion, gullies or hillslope erosion? • Are fine sediments or coarse sediments being transported? • What land types and areas are generating the most pollutants and when?	• What locations, sub-catchments and soil types contribute the greatest risk? • What is the water quality, economic and social benefit from improving management systems and practices? • When and where are these best implemented spatially to get maximum water quality benefit at minimum cost? • How effective are wetlands and riparian areas in reducing pollutants to the reef?

Figure 1.3. Scope of the Reef Plan Scientific Consensus Statement 2013 in relation to this risk assessment project.

Part A: Assessment of the relative risk of degraded water quality to ecosystems of the GBR

2 Assessment of the risk of pollutants to ecosystems of the Great Barrier Reef including differential risk between sediments, nutrients and pesticides, and among NRM regions

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2.1 Summary of findings

Using the best available knowledge at the time and risk assessment methods that are appropriate within the resources of this study, we have investigated three key aspects of the relative risk of water quality to the GBR: (a) the relative importance of different pollutants to GBR ecosystems (coral reefs and seagrass meadows), (b) the combined risk of degraded water quality on GBR ecosystems, and (c) the relative risk of degraded water quality in the GBR through consideration of the combined risk and influence of end-of-catchment anthropogenic pollutant loads (ie. the current load less the estimated pre-European load) on GBR ecosystems.

The risk assessment method used a combination of qualitative and semi-quantitative information about the influence of individual catchments in the 6 natural resource management (NRM) regions on coral reefs and seagrass ecosystems. The area of GBR lagoon waters within each marine NRM region were also reported in recognition of other important habitats and populations that exist in these areas.

A suite of water quality variables were chosen that represent the pollutants of greatest concern with regards to agricultural runoff and potential impacts on GBR ecosystems. These include ecologically - relevant thresholds for concentrations of total suspended solids (TSS) and chlorophyll *a* (Chl) 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 was included that represents the area of the GBR lagoon where primary crown-of-thorns starfish (COTS) outbreaks have been observed. 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’. Anthropogenic end of catchment loads were included to link the outcomes of the marine assessment to catchment management. In recognition of the importance of the influence of catchment discharges in driving COTS outbreaks, an index of regional contributions of river discharges to the COTS initiation zone is also included for coral reefs.

For each variable, thresholds above which potential impacts have been observed were defined and classified into three to five classes (from lowest to highest), largely on the basis of the time (or probability) the ecosystem is likely to be exposed to concentrations above the threshold; these are defined as ‘assessment classes’.

Key findings:

Relative importance of different pollutants on GBR ecosystems

- The area of coral reefs at highest risk from all of the sediment and nutrient variables (except for the COTS initiation zone) was greatest in the Burdekin and Fitzroy regions. The other regions (Cape York, Wet Tropics, Mackay Whitsunday and Burnett Mary) each had ~20% or less of the coral reef area affected for each variable.

- The area of seagrass at highest risk from the sediment and nutrient-related variables was greatest in the Burdekin region. The area of seagrass within the Wet Tropics region is second greatest for all sediment-related variables but the areas are less than one quarter of the areas affected in the Burdekin region in all cases. For the nutrient variables, the second greatest areas of seagrass within the highest assessment classes are in the Fitzroy.

- The COTS Initiation Zone straddles the boundary between the Cape York and Wet Tropics regions, with approximately 60% of reefs within the Zone located in the Cape York region.

- Of the NRM regions examined in the assessment, the Mackay Whitsunday region presents the highest ecological risk from pesticides with the Photosystem II (PSII) herbicide risk of 'High' and 'Medium' extending off the mouths of the Pioneer and O'Connell Rivers and Sandy Creek. This is followed by the Burdekin (due to the Barratta Creek and Haughton Rivers but not the Burdekin River itself), Wet Tropics, Fitzroy and Burnett Mary NRM regions. It should be noted that the risk to 'pesticides' here is represented by PSII herbicides as these are the dominant pesticides detected in catchments, however a total of 34 pesticides (herbicides, insecticides and fungicides) have been detected. In addition the high risks of PSII herbicides to wetland, estuarine and coastal habitats (which provide important ecosystem services to the GBR including fish nursery habitats), were not included in this stage of the assessment, but they are recognised as important and addressed in Supporting Studies Chapter 4 (Lewis et al. 2013a) and Part B of this report.

Combined risk of degraded water quality to GBR ecosystems

- When all water quality variables are combined, the risk is greatest for coral reefs in the Fitzroy and Mackay Whitsunday regions, and for seagrass in the Burdekin and Fitzroy regions. In most cases, the proportion of the habitat area in each region that is in the highest risk areas are less than 10%, except in the case of seagrass meadows in the Mackay Whitsunday region where 37% of the area of seagrass in the region is affected. This may have significant implications at a regional scale and warrants further consideration. These high risk areas often include highly valued tourism and recreation sites of the GBR. Examples include Fitzroy Island, Hinchinbrook Island, Magnetic Island, many of the islands in the Whitsunday Group and the Keppel Island group. Inshore seagrass meadows are also of critical importance to dugong and green turtle populations in the GBR.

Relative risk of degraded water quality to GBR ecosystems

- A combined assessment of anthropogenic end of catchment pollutant loads and the ecological risk of water quality variables in the marine environment allows us to draw conclusions about the overall risk of pollutants to the GBR. In summary, the greatest risk to each habitat in terms of the potential water quality impact from all of the assessment variables in the GBR and end -of -catchment anthropogenic loads of DIN, TSS and PSII herbicides is:

    - **Coral reefs:** Wet Tropics region, followed by the Fitzroy region. The rank of the remaining regions is the Mackay Whitsunday, Burdekin, Cape York and Burnett Mary region.

    - **Seagrass meadows**: Burdekin region, followed by the Wet Tropics. The rank of the remaining regions is the Fitzroy, Mackay Whitsunday, Burnett Mary and Cape York region.

    - **Coral reefs and seagrass meadows combined:** Wet Tropics, followed by the Fitzroy (80% of this influence) and Burdekin (76%). The relative risk to the Mackay Whitsunday region is half the greatest risk, followed by the Burnett Mary and Cape York regions. It must be reiterated that these are relative assessments and therefore indicates that the Burnett Mary and Cape York are low relative to the other regions, but may be exposed to a range of risks that still warrant management to maintain the ecosystem values in these regions.

The risk assessment presented in this Section has generated the most comprehensive assessment of the relative risk of degraded water quality to GBR ecosystems undertaken to date. It is important to reiterate that the rankings between NRM regions are relative, and do not represent absolute differences. In this regard, even the lowest ranked regions of the Burnett Mary and Cape York region may pose a risk to GBR ecosystems, but relative to the other NRM regions they are considered to be of lower risk. This information can be useful in guiding investment priorities but should not be used in isolation from other knowledge related to regionally specific priorities, socio economic influences and limitations to the assessment that may have led to uncertainties in the results. The limitations to the assessment are described in Section 4 of this report, together with ways to improve upon the work presented herein.

2.2 Introduction

This section of the report presents the results of the most recent effort to assess the relative risk of the influence of sediments, nutrients and pesticides on key GBR ecosystems. As outlined in Section 1, the assessment considers the most relevant influences of water quality in the GBR - sediments, nutrients and pesticides.

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.

2.2.1 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 (eg. 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).

In an initial stage of the current project, an approach using a tiered risk assessment methodology that would provide a systematic, objective and transparent approach to quantify the relative risk of contaminants to the GBR ecosystems was developed (Hayes et al. 2012). This tiered ERA approach would have allowed a ranking of the rivers draining into in the GBR based on exceedance of water quality guidelines at marine sites whose water quality could be confidently attributed to individual rivers, and across the GBR lagoon as whole. However, this approach was not able to be used due to limitations in data availability and limitations with time and resources. Hence a simpler methodology suitable for the existing datasets, resources and timeframes has been developed based on a modification of the typical ERA framework.

In this assessment the relative risk of degraded water quality among NRM regions was determined by combining information on the estimated ecological risk of water quality to coral reefs and seagrass meadows in the GBR and end-of-catchment pollutant loads. This approach attempts to relate the water quality conditions in the GBR to catchment based influences, albeit in a relatively crude way.

Ecological risk is assessed using a relatively simple approach. 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. 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 pesticides on seagrass health. Evidence shows that one of the greatest drivers of seagrass health is the availability of light, which is reduced by increased suspended sediment and the secondary effects of increased nutrients such as increased growth of epiphytes and phytoplankton (Collier et al. 2012). However, in the absence of more regionally - and species-specific knowledge of pollutant impacts on seagrass, the same threshold concentrations have been used for coral reefs and seagrass meadows in this assessment. It is also recognised that the consequence of the exposure of species or habitats to a range of water quality conditions is complicated by the influence of multiple pressures, and many external influences including weather conditions, however it is difficult to factor these into the risk assessment in any quantitative way.

Given the above and recognising the inconsistencies in the spatial and temporal availability of the water quality data, 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'.

Modelled end-of-catchment pollutant loads (generated from the Source Catchments model framework for the Paddock to Reef Program) were obtained for each NRM region for key pollutants, and only the anthropogenic portions of total pollutant loads were considered. The anthropogenic load is calculated as the difference between the long term average annual load, and the estimated pre-European annual load. This information was used to define a 'Loads Index'.

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 the loading of key pollutants including TSS, dissolved inorganic nitrogen and photosystem II-inhibiting herbicides (PSII herbicides) 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. 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'. In recognition of the importance of the influence of catchment discharges in driving COTS outbreaks, an index of regional contributions of river discharges to the COTS initiation zone is also included for coral reefs (COTS Influence Index).

The three indexes were then combined to generate a Relative Risk Index for coral reefs and seagrass, which ultimately ranks the relative risk of degraded water quality to coral reefs and seagrass meadows in the GBR among NRM regions. The framework and how it relates to the typical ERA framework is shown in Figure 2.1. As described in the Introduction, the outputs of this assessment provide an integral component of the overall management and investment prioritisation being undertaken for Reef Plan 3 (incorporating Reef Rescue 2). A more detailed illustration of the overall process incorporating this assessment is shown in Figure 2.2.

The geographic boundaries of the assessment and the spatial distribution of the marine habitats in the assessment (coral reefs and seagrass - based on best available information) are shown in Figure 1.1. The area of GBR lagoon waters in each NRM region was also included as it contains other important habitats and biological populations such as fish and benthic organisms, however this was not included in the overall Relative Risk Index as assumptions regarding the importance of the potential impact on the wide range of ecosystems in the GBR are unknown. The marine boundaries used for each NRM region are those accepted officially by the Great Barrier Reef Marine Park Authority.

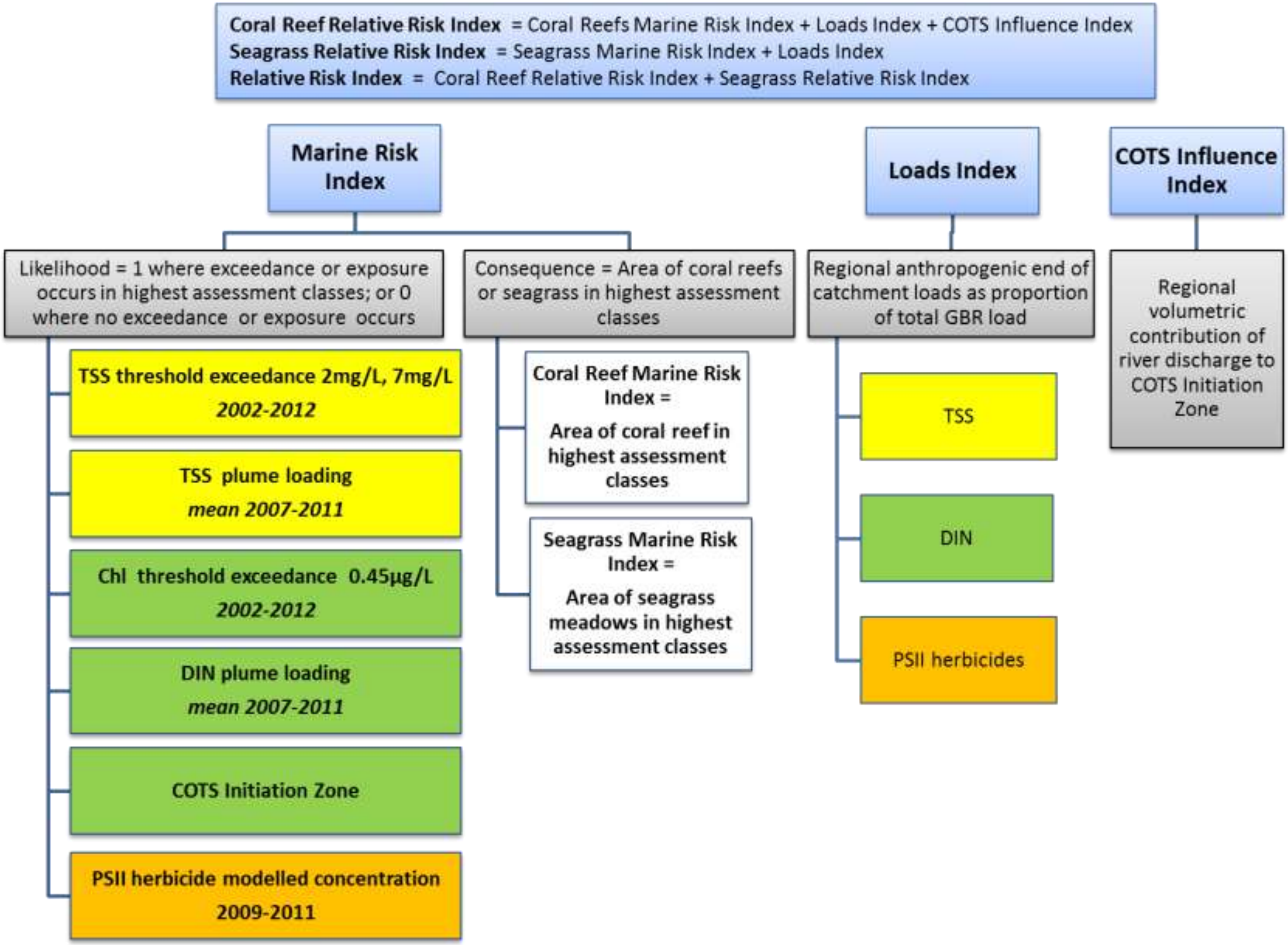
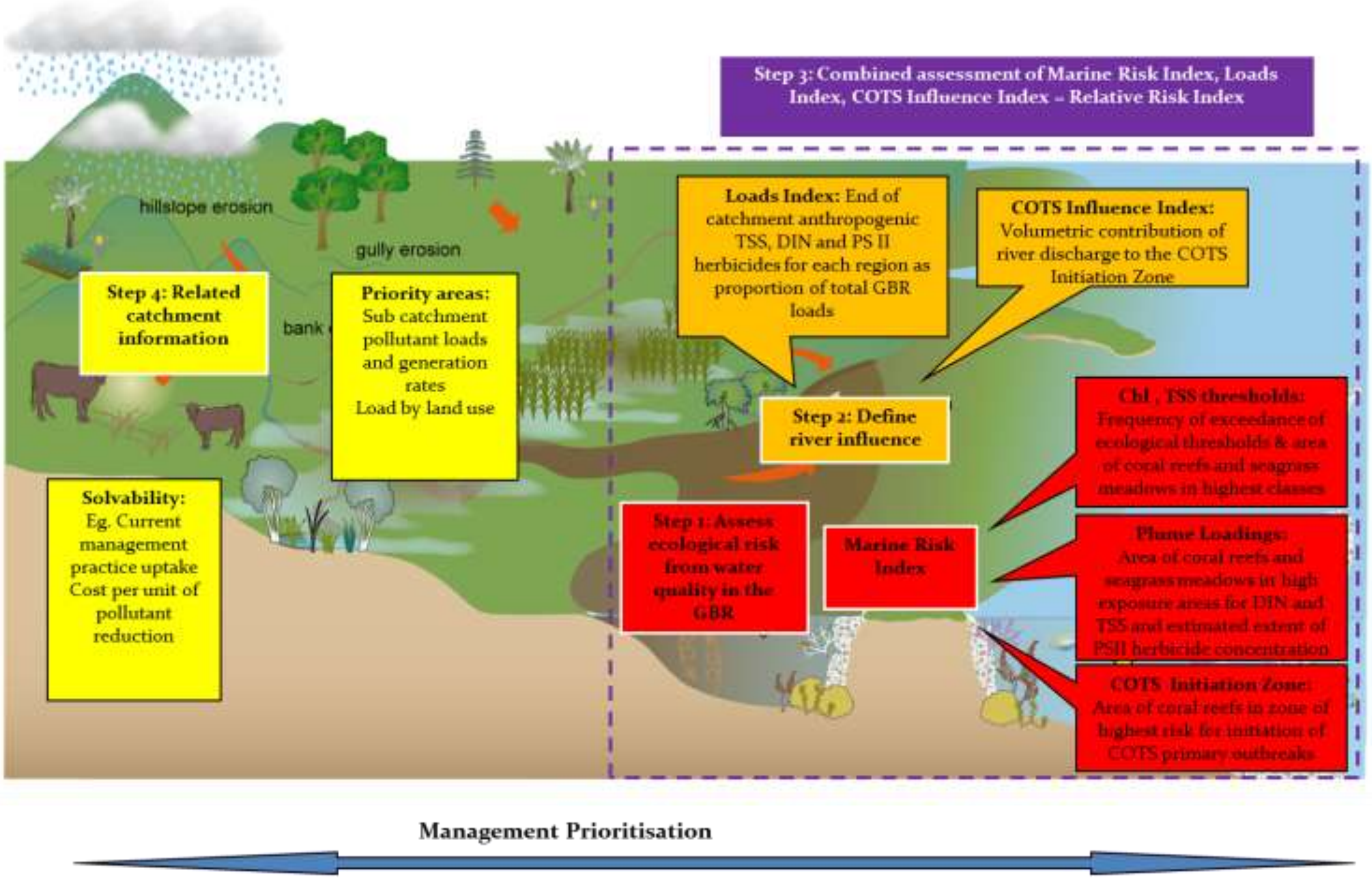


Figure 2.1. The risk assessment framework used in this project showing the components of the Marine Risk Index to represent marine water quality ecological risk to coral reefs and seagrass meadows, a Loads Index to represent catchment influences on GBR water quality using end of catchment anthropogenic pollutant loads and a COTS Influence Index to factor in the importance of river discharges on the COTS Initiation Zone for coral reefs.



- Step 1: Assess ecological risk by NRM regions, pollutants and coral reefs & seagrass meadows – based on presence of habitat & exceedance of thresholds / exposure – Marine Risk Index
- Step 2: Assess river influence by Regions, pollutants and habitats = Loads Index + COTS Influence Index (for coral reefs only)
- Step 3: Combined assessment of the Marine Risk Index + Loads Index + COTS Influence Index (coral reefs only) = Relative Risk Index - by region and habitats
- Step 4: Combine related information on priority pollutant sources and land use with Relative Risk Index to generate management priorities and overall relative risk ranking among NRM regions

Figure 2.2. The overall framework being used for Reef Plan 3 (incorporating Reef Rescue 2) management and investment prioritisation. This project contributes Steps 1 to 3 and part of Step 4. An additional assessment of the 'solvability' of management issues in different NRM regions and catchment areas is being conducted by the Australian Government. The assessment is based on recent management practice adoption data for the sugar cane and grazing industries in the GBR catchments, and the cost effectiveness of improvements in water quality of the various practices.

2.3 Methods

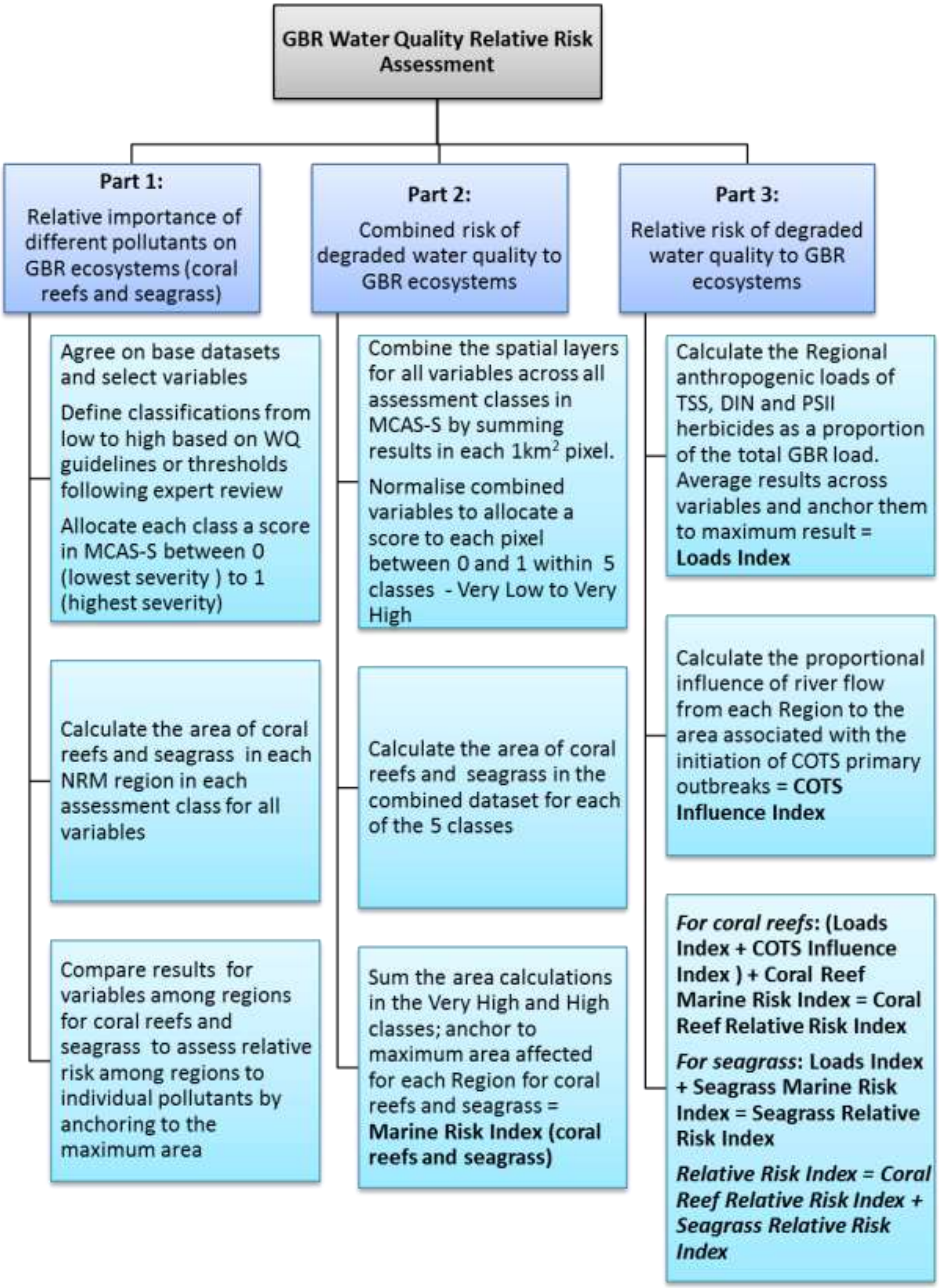
A 3-part approach of estimating the relative risk of pollutants to the GBR at a regional level was applied (illustrated in Figure 2.3):

1. Assessment of the relative importance of different pollutants on GBR ecosystems (coral reefs and seagrass). This identifies the areas where each water quality variable is considered to pose the greatest relative risk to coral reefs and seagrass between the NRM regions. The output can be used to guide priorities for management of individual pollutants between NRM regions. The methods are described in Section 2.3.3.
2. Combined risk of degraded water quality to GBR ecosystems. The combined assessment takes into account all assessment classes for each variable to generate a Marine Risk Index for coral reefs and seagrass. The areas within the Risk Index represent the areas of highest relative risk to degraded water quality in the GBR and identify the areas where coral reefs and seagrass are most likely to be under pressure from degraded water quality. The methods are described in Section 2.3.4.
3. The relative risk of degraded water quality to GBR ecosystems. This relates the results of Part 1 and Part 2 to land based influences using an assessment of end-of-catchment anthropogenic loads and river discharges (Loads Index and COTS Influence Index). These results inform the regional management priorities required to address the risks identified in Part 1 and Part 2 in terms of where to focus effort on which pollutants. The methods are described in Section 2.3.5.

Justification for the selection and classification of variables is provided in Section 2.3.1. Section 2.3.2 describes the habitat areas in each region.

2.3.1 Selecting and classifying variables

We have chosen a suite of water quality variables that represent the pollutants of greatest concern with regards to agricultural runoff and potential impacts on GBR ecosystems. Ecological impacts of terrestrial runoff on coral reefs and seagrasses beds can be experienced as either acute, short term changes associated with formation of high-nutrient, high-sediment, low salinity flood plumes or the more chronic impacts associated with changes in long-term water quality concentration (Devlin et al. 2012). The ecological impact of terrestrial pollutants varies not only with the type of pollutant, the magnitude and extent of the riverine influence but also with the ecosystems being affected and the frequency and duration of plume occurrence (e.g. Devlin et al. 2013a). Long time series of pollutant concentration data provides a way of assessing chronic stress, while river plume models can help to develop risk maps by defining areas which may experience acute or chronic high exposure to pollutants or stressors (Alvarez-Romero et al. 2013). Details of the pollutant movement and frequency of inundation can be key measurements in attributing water quality decline to ecosystem change. This assessment uses a combination of variables that represent chronic and acute stress.



GBR Water Quality Relative Risk Assessment

Part 1:
Relative importance of different pollutants on GBR ecosystems (coral reefs and seagrass)

Agree on base datasets and select variables

Define classifications from low to high based on WQ guidelines or thresholds following expert review

Allocate each class a score in MCAS-S between 0 (lowest severity) to 1 (highest severity)

Calculate the area of coral reefs and seagrass in each NRM region in each assessment class for all variables

Compare results for variables among regions for coral reefs and seagrass to assess relative risk among regions to individual pollutants by anchoring to the maximum area

Part 2:
Combined risk of degraded water quality to GBR ecosystems

Combine the spatial layers for all variables across all assessment classes in MCAS-S by summing results in each 1km^2 pixel.

Normalise combined variables to allocate a score to each pixel between 0 and 1 within 5 classes - Very Low to Very High

Calculate the area of coral reefs and seagrass in the combined dataset for each of the 5 classes

Sum the area calculations in the Very High and High classes; anchor to maximum area affected for each Region for coral reefs and seagrass = **Marine Risk Index (coral reefs and seagrass)**

Part 3:
Relative risk of degraded water quality to GBR ecosystems

Calculate the Regional anthropogenic loads of TSS, DIN and PSII herbicides as a proportion of the total GBR load. Average results across variables and anchor them to maximum result = **Loads Index**

Calculate the proportional influence of river flow from each Region to the area associated with the initiation of COTS primary outbreaks = **COTS Influence Index**

***For coral reefs*: (Loads Index + COTS Influence Index) + Coral Reef Marine Risk Index = Coral Reef Relative Risk Index**

***For seagrass*: Loads Index + Seagrass Marine Risk Index = Seagrass Relative Risk Index**

Relative Risk Index = Coral Reef Relative Risk Index + Seagrass Relative Risk Index

Figure 2.3. Illustration of the steps in the assessment of the relative risk of water quality pollutants to GBR ecosystems.

The selected variables are summarised in Table 2.1. These 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 Chapter 1 of the Supporting Studies, 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 are, based on current understanding, a response to excess nutrient runoff from certain catchments that reaches this 'COTS initiation zone' (Fabricius et al. 2010). The relevance of each of these variables is described below. 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).

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). The classification of each variable is described in Section 2.3.1a, 2.3.1b and 2.3.1c below. The selected variables and thresholds represent long-term conditions (chronic exposure) and wet season pollutant loadings in flood plumes (acute exposure).

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 pesticide concentration data. The decision to select DIN as primary nutrient variable within the assessment is supported by the conclusions of Chapter 2 of the Supporting Studies (Furnas et al. 2013b) which considered the relative importance of nutrient forms and of nitrogen and phosphorus in the GBR. The analysis indicates that dissolved inorganic and particulate forms of nutrients discharged into the GBR are both important in driving ecological effects but increased nitrogen inputs are more important than phosphorus inputs. Dissolved inorganic forms of nitrogen and phosphorus are considered to be of greatest concern compared to dissolved organic and particulate forms of nutrients, as they are immediately and completely bioavailable for algal growth (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).

For each of the variables shown in Table 2.1 a classified spatial data layer was prepared. ArcGIS was the primary tool used for spatial analysis, however, the Multi-Criteria Analysis Shell for Spatial Decision Support (MCAS-S[1]) was also used for some aspects of the assessment. MCAS-S was initially the preferred tool as it was also used for the associated Reef Rescue 2 Investment Prioritisation process conducted by the Australian Government. However, MCAS-S is a raster-based tool that therefore loses a degree of resolution of some spatial layers depending on the selected grid size. Using a 1 km^2 grid, this was problematic for the assessment of the area of coral reefs because the area was considerably different after the raster conversion. A number of approaches were tested to overcome these limitations including a presence/absence approach for coral reefs within a grid cell, but this resulted in significant overestimation of the areas especially in the inshore areas where reef sizes are typically small or there are many fringing reefs. The differences between regions were not comparable and therefore, significantly distorted the results of the assessment. Therefore ArcGIS was used for all area estimates (in km^2) for all variables as it is possible to calculate the area within the reef polygon; seagrass habitat is already on a 1 km^2 grid.

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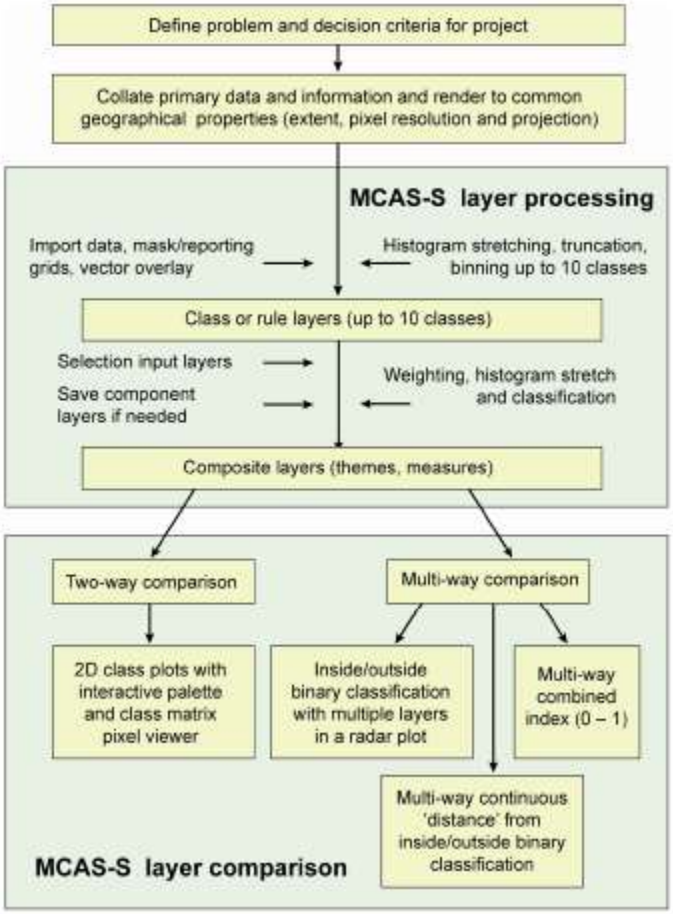
[1] MCAS-S: Multi-Criteria Analysis Shell for Spatial Decision Support developed by ABARES, refer to http://www.daff.gov.au/abares/data/mcass

MCAS-S is a useful tool for spatial analysis of datasets that has adopted much of the functionality of the ArcGIS interface but that allows independent data processing and is relatively easy to use. MCAS-S functionality promotes participatory processes that require the understanding of relationships between decision- making requirements and the available data. Of particular value in this regard are software features that enable interactive cognitive and 'live up-date' mapping of alternative views (Lesslie et al. 2008).

As described in Lesslie et al. (2008), MCAS-S requires the user to prepare raw spatial data for a project in a raster format of consistent geographical extent, pixel resolution and projection. Primary data can then be selected from the menu and dragged into a display workspace whereupon the spatial data layer can be classified using a variety of simple classification methods and tools for tailoring input data. With the creation of individual class or rule layers, the user can apply them in weighted combinations to construct composite layers contributing to themes of interest. Key functions for combining and comparing spatial layers are represented schematically in Figure 2.4.



MCAS-S Key Functions

A *composite* layer can be created as a summary of several input layers. The weighted contribution of any selected layer to any composite can be set. The composite map dynamically updates as the user changes the weightings on input layers and shows a hierarchical, cognitive 'map' showing the development of individual layers culminating in a final summary layer representing a theme. Relationships among themes, specific views and particular indicators may be examined using several methods.

Two-way comparison enables the user to create a two-way comparison map, explore the association among input classes, and define a colour ramp and value scale to highlight association of high or low values, or feature a particular geographical region.

Multi-way comparison is used when the spatial association of two or more data layers is required. The multi-way analysis uses the radar plot as the basis for visualisation.

Figure 2.4. Flow chart for MCAS-S showing stages and functionality. Source: Derived from Lesslie et al. (2008).

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) *Frequency of exceedance %*						Based on daily 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).
Threshold a: 2 mg/L	<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. Refer Section 2.3.1a(i)
Threshold b: 7mg/L	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). Refer Section 2.3.1a(ii).
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 (Nov to May) from 2007 to 2011 (Devlin et al, 2013a). 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. Refer Section 2.3.1c(v).

Variables	Assessment Class					Data source/methodology
	Very Low 1	**Low 2**	**Medium 3**	**High 4**	**Very High 5**	
Nutrients						
Chlorophyll concentration (µg/L) *Frequency of exceedance %*						Assessment classes were based on daily observations of Chlorophyll 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).
0.45 µg/L	<1	1-10	10-20	20-50	50-100	Chlorophyll 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. Refer Section 2.3.1b(iii).
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 (Nov to May) from 2007 to 2011 (Devlin et al, 2013a). 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. Refer Section 2.3.1c(v).
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 Chl concentrations that exceed 0.8 µg/L, which is important for COTS larval survival. Refer Section 2.3.1b(iv).

Variables	Assessment Class					Data source/methodology
	Very Low 1	Low 2	Medium 3	High 4	Very High 5	
Pesticides						
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. (2013a). Refer Section 2.3.1b(iv). **>0.025-0.1 µg/L**: No observable effect; **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. in review) and microalgae (Magnusson et al. 2008, 2010). The effect on primary production is minor. **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. **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. in review) 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. **> 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).

a) Exceedance of suspended solids concentration thresholds

The effects of elevated concentrations of suspended solids on GBR ecosystems including coral, seagrass and algal communities are described in Chapter 3 of the Supporting Studies (Brodie et al. 2013a). The greatest influence of increased turbidity caused by resuspension of sediment in waters of depths less than 12 metres is reduced light for benthic phototropic communities including coral reefs and seagrass (Larcombe et al. 1995; Anthony et al. 2004; Orpin et al. 2004; Alongi and McKinnon, 2005). This resuspension driven turbidity persists for many months of the year in GBR coastal waters. Suspended solids in flood plumes also reduce light for benthic communities but the effects are only present for short periods, typically days to weeks. Hence, a long - term time series is most relevant in the assessment of chronic effects of elevated suspended solids and turbidity on habitats. However, typically the resuspended sediment is that which was delivered as a sediment loading during the previous wet season and potentially earlier wet seasons as well. Hence, there is a strong connection between turbidity and river loadings of sediment (Fabricius et al. 2013). The TSS plume loading modelling (Devlin et al. 2013a) allows us to assess loadings and in a sense predict the likely conditions of suspended sediment in various areas of the GBR lagoon. When fine sediment is delivered to shallow areas less than 12 metres, it is a good indicator for likely resuspension later in the year. Therefore, both the concentration data and the loading data are relevant to this assessment. The actual exposure of benthic organisms (for example in Cleveland Bay) to flood plume turbidity is more relevant for the assessment of acute effects (see Devlin et al. 2013b).

Method:

Using remote sensing imagery in the period 2002 to 2012, we defined the areas where the TSS concentration exceeded of the different ecologically-relevant threshold values at different frequency intervals (see Table 2.2). The method for the retrieval and processing of the remote sensing data is described in Brando et al. (2013) and is summarised below.

Data collected by MODIS Aqua provide a time series from 1 November 2002 to 30 April 2012 of water quality estimates with spatial coverage at 1 km^2 resolution for the whole-of-GBR lagoon, nominally on a daily basis (except overcast days). The water quality estimates were retrieved from the MODIS Aqua time series using two coupled physics-based inversion algorithms developed to accurately retrieve water quality parameters for the optically complex waters of the GBR lagoon (Brando et al. 2008; Schroeder et al. 2008; Brando et al. 2010a,b; Brando et al. 2012; Schroeder et al. 2012). This was necessary because chlorophyll concentrations retrieved with the MODIS standard algorithms provided by NASA are up to two-fold inaccurate in GBR waters (Qin, Dekker et al. 2007), while CSIRO’s regionally parameterised algorithms account for the significant variation in concentrations of Colour Dissolved Organic Matter (CDOM) and TSS and achieve more accurate retrievals (Brando e al. 2010a,b). For this work the whole MODIS Aqua time series was reprocessed with the most recent updates in NASA’s software (SeaDAS version 6.4), incorporating the improved knowledge of instrument temporal calibration to improve temporal stability of the time series of the MODIS Aqua ageing sensor.

The comparison of MODIS Aqua retrievals of Chl, CDOM and turbidity data to *in situ* data showed that the a-LMI water quality algorithm coupled with the ANN atmospheric correction is more accurate than NASA’s algorithms for GBR waters (Brando et al. 2013). The parameterisation and validation on the remote sensing retrievals was mainly based on observations performed in coastal and lagoonal waters during the dry season between Keppel Bay and the Wet Tropics region. The accuracy of the retrieval is likely to be lower in shallow and turbid waters systems such as Princess Charlotte Bay, Broadsound and Shoalwater Bay, as there is no data available for parameterisation and validation. Details on the algorithm’s theoretical basis, parameterisation and validation are provided in Brando et al. (2013).

The frequency of exceedance of the TSS threshold was calculated by analysing ‘daily’ observations of TSS concentrations at a scale of 1 km^2 pixels. The assessment classes were defined using the total potential number of observations, and the maximum number of valid observations in the assessment period (Table 2.2). The low number of valid observations is a result of the strict quality control criteria applied to the imagery: pixels with cloud or cloud shadow, low view and illumination angles (solar zenith and observer zenith higher than 60 degrees) are flagged and dismissed as are pixels where the atmospheric correction failed. In the wet season a valid observation is obtained approximately 1 in every 5 days (23%), while for the dry season valid observations were obtained approximately 2 of every 5 days (41%), equating to less than 2 valid observations every 5 days over the full year (32%). In a ten-year period, the total potential number of observations is 3,650. The assessment classeswere defined using expert opinion, informed by Jenks natural breaks on the basis of the frequency of exceedance of the thresholds (<1%, 10%, 20%, 50% and 100%) as a proportion of the total number of valid observations.

Table 2.2. Number of valid remote sensing observations (in the context of the total potential observations) throughout the assessment period, and the frequency of exceedances used to define assessment classes for the assessments. The selected variables are all Annual and highlighted in grey shading.

Item	Number of observations		
	Wet season 10 yrs	**Dry Season 10 yrs**	**Annual 10 yrs**
No Pixels (maximum potential observations) 1 pixel = 1 day	1820	1820	3650
Valid observations (pixels with data in assessment period)	427	755	1182
Actual as proportion of potential observations	23%	41%	32%
Frequency of exceedance (based on valid observations)			
<1% exceeding thresholds	<4	<7	<10
10% exceeding threshold	43	76	118
20% exceeding threshold	85	151	236
50% exceeding threshold	214	378	591
100% exceeding threshold	427	755	1182

Assessment classes:

Several ecologically-relevant values were explored for TSS using the wet season, dry season and annual datasets over the 10-year period. The threshold concentrations considered in the assessment are the GBR Water Quality Guideline value of 2 mg/L and turbidity 5 NTU (which equates to TSS 6.6 mg/L but is rounded to 7 mg/L for reporting only). The justification for these is described below and further detailed in Chapter 3 the Supporting Studies (Brodie et al. 2013a).

i Threshold a - TSS 2 mg/L

The assessment classes for TSS were obtained from the annual dataset from the frequency of exceedance (expressed as a percentage) of the *Threshold a* concentration of 2 mg/L (1.5 NTU) which is the TSS Water Quality Guideline value (GBRMPA, 2009). Fabricius (2011) reviewed the factors determining the vulnerability of specific coral reefs to damage from turbidity and sedimentation. The study found that well-flushed locations with strong currents, shallow reef crests surrounded by a deep water body, and reefs inhabited by healthy populations of fishes are likely to have the highest levels of resistance and resilience to degradation from sedimentation and high or variable turbidity. In contrast, damage is most likely to occur in locations with weak currents such as embayments (e.g. Keppel Bay, Cleveland Bay, Missionary Bay), and within these sheltered zones on deeper reef slopes, in places where fish abundances are low, and in regions that are frequently affected by other forms of disturbance such as cyclones , bleaching or crown-of-thorns starfish predation. Despite these complications, water clarity with an annual mean of less than 10 m Secchi depth (or TSS concentration greater than 2 mg/L), has been found to relate to strongly altered ecosystem properties throughout the GBR. These values have therefore been adopted as Water Quality Guidelines for inshore waters by the Great Barrier Reef Marine Park Authority (GBRMPA, 2009).

As described above, the degree of exposure of an organism or ecosystem to a stressor is typically a function of the both amount (= concentration, level or load) of the stressor, and the length of time it is in contact with the stressor (Figure 2.5). A reef may be exposed to a high level of a stressor for a short period of time, or to lower levels for longer periods. When quantifying exposure levels, it is therefore important to determine peak concentrations (potentially leading to damage or mortality within hours to days), as well as to quantify long-term mean (or median) concentrations and the duration of exposure. This complicates the definition of exposure thresholds in turbidity and sedimentation given their values may change by one to two orders of magnitude between days, seasons and years. It is for these reasons that we have considered two different thresholds of TSS in this assessment.

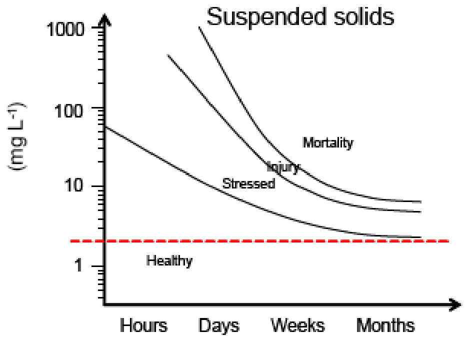


Figure 2.5. Conceptual representation of the exposure of corals to turbidity and suspended solids concentration, and the severity of response, are a function of exposure time and the concentration of the stressor (from Fabricius 2011). The red dotted line shows the GBR WQ Guideline value for TSS of 2 mg/L.

The data extracted from the remote sensing assessment was classified into the assessment classes shown in Table 2.1 are based on the total number of daily observations that exceeded the threshold value over the 10-year assessment period as a proportion of the total number of valid observations (Table 2.2).

ii Threshold b - TSS 7 mg/L (turbidity 5 NTU)

The annual assessment data for TSS 6.6 mg/L (rounded to 7 mg/L for reporting here) was used in the analysis and was correlated with effects on several ecosystems:

- Coral reefs - Cooper et al. (2008) suggest long-term turbidity concentrations >3 NTU lead to sub-lethal stress, whereas long-term turbidity concentrations >5 NTU correspond to severe stress effects on corals at shallow depths.
- Seagrass – change in seagrass cover at Picnic Bay showed a strong correlation between a decline in seagrass cover and mean turbidity greater than 4 NTU over several days (Collier et al. 2012; Chapter 6 of Supporting Studies, Devlin et al. 2013b). However, this effect was observed using a small dataset and requires further investigation.

- Fish – Wenger et al. (2013) showed that turbidity of 5 NTU was the threshold for fish habitat choice and home range movement, and further Wenger et al. (2012) showed that 7.5 NTU was the threshold for foraging ability and changes in predator prey relationships.

The data extracted from the remote sensing assessment was classified into the 'frequency of exceedance' classes shown in Table 2.2. These classes then were used to establish the relative severity classes (very low to very high) shown in Table 2.1 and are based on the proportion of daily observations that exceeded the threshold value over the 10-year assessment period. Note that the classes are different to those for threshold 1 and reflect the increased severity of the impacts associated with this higher TSS concentration threshold.

b) Chlorophyll concentration exceedance

Chlorophyll (Chl) concentrations are relevant year round as an indication of nutrient enrichment in marine waters. Chl concentrations are particularly relevant when considering drivers of Crown of Thorn Starfish (COTS) outbreaks. The threshold concentrations for Chl related to adverse effects on coral reefs are well established, but only preliminary results are available to relate Chl concentrations to seagrass health. Further discussion of the impacts of nutrient enriched waters on GBR ecosystems is described in the *Reef Plan SCS Chapter 1 Marine and coastal ecosystem impacts* (Schaffelke et al. 2013).

Method:

Using remote sensing imagery in the period 2002 to 2012, we defined the areas where the Chl concentration exceeded of the different ecologically-relevant threshold values at different frequency intervals (see Table 2.2). The method for the retrieval and processing of the remote sensing data is described in Brando et al. (2013) and is the same as that applied for TSS exceedance described in Section 2.3.1a above.

Assessment classes:

Several ecologically-relevant values were explored for Chl using the wet season, dry season and annual datasets over the 10-year period. These ranged between 0.13 µg/L which considered to be insignificant in terms of potential ecological impacts, various concentrations within the GBR Water Quality Guidelines (seasonal and cross shelf differences) including 0.45 µg/L, and the highest threshold of 2 µg/L which is known to be associated with severe ecosystem impacts. Based on expert opinion and data availability the final concentration included in the assessment was Chl 0.45 µg/L, described below.

iii Chl 0.45 µg/L

Syntheses and interpretation of long-term Chl a and turbidity datasets were presented in De'ath and Fabricius (2008) to underpin the development of the GBR Water Quality Guidelines. For Chl, an analysis of the response of macroalgal cover, species richness of hard corals, and species richness of phototrophic and heterotrophic octocorals, coupled with an assessment of the spatial distribution of water quality, concluded that there would be significant benefits ecological status of reefs in the GBR if the mean annual Chl concentration was kept below 0.45 µg/L in both coastal and inner shelf zones in all regions.

In addition, a variety of experimental, modelling and observational evidence indicates that initiation of COTS outbreaks is coupled to enhanced survival of the pelagic larval phase as a result of increased food availability, particularly if Chl concentrations are greater than 0.45 µg/L.

For these reasons we selected the value of Chl 0.45 µg/L as the most appropriate threshold representing long-term average conditions.

There is less information available on the relationship between seagrass health and chlorophyll concentrations however it is clear that elevated chlorophyll concentrations increase light attenuation and reduce light availability to seagrasses (Chapter 7 of Supporting Studies, Collier, 2013). However, preliminary assessments by Collier et al. (in review) show that decline in seagrass cover is correlated with increasing average daily Chl concentrations above 0.3 µg/L, however, there is insufficient information to differentiate this response from those observed at the Guideline value of 0.45 µg/L. This value has been adopted in the GBR Water Quality Guidelines as also relevant to seagrass, and in the absence of any further information has also been used in this risk assessment for seagrass.

The data extracted from the remote sensing assessment was classified into the 'frequency of exceedance' classes shown in Table 2.2. These classes were used to establish the relative severity classes (very low to very high) shown in Table 2.1 and are based on the total number of daily observations that exceeded the threshold value over the 10-year assessment period.

iv COTS specific assessments

Two of the potential threshold concentrations for Chl obtained from the remote sensing data were based on the relationship between survival of COTS larvae and Chl concentrations (see Fabricius et al. 2010 and Figure 2.6 below). These values were Chl concentration of 0.8 µg/L where COTS larval survival starts to increase, and 2 µg/L where 100% COTS larval survivorship occurs.

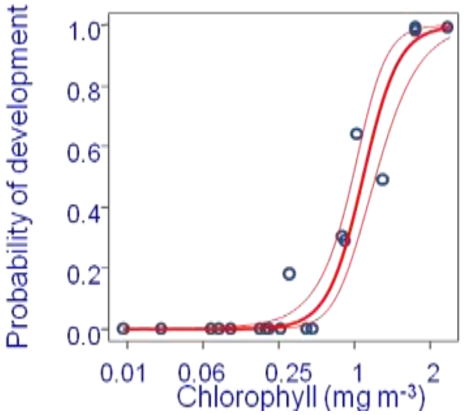


Figure 2.6. Relationship between chlorophyll concentrations and the probability of development of COTS through larval survival. Note: mg m^{-3} is equivalent to µg/L. Source: Fabricius et al. (2010).

The case study analysis presented in Chapter 1 of the Supporting Studies (Furnas et al. 2013a) strongly supports the hypothesis that river discharge (and associated nutrient loads) is the primary driver of regional chlorophyll concentrations within the GBR lagoon. The critical factor is the amount of discharge during the early part of the wet season (November-February) when COTS larvae are present in the water column. There appears to be an important threshold on the order of 10,000,000 ML (10 km^3) of discharge in this period to produce sufficient phytoplankton at the proper time to sustain high COTS larval survival and promote a subsequent COTS outbreak. Further development of a COTS outbreak, however, depends on there being sufficient coral cover to sustain local adult populations.

Based on this information and the importance of the timing of wet season discharges, it would have been beneficial to undertake further analysis of the long term Chl dataset for the period 1 November to 28 February each year over the 10 years of available data. However, given the limitation of time and resources associated with the project it was not able to be completed in time for this assessment.

In the absence of this more detailed assessment of Chl concentrations in specific periods, a high risk area for the initiation of COTS primary outbreaks has been defined. A variety of experimental, modelling and observational evidence indicates COTS primary outbreaks are initiated by an episode of greatly enhanced larval survival due to increased food availability (chlorophyll concentrations >0.45 µg/L) for the filter-feeding pelagic larval stage (Brodie et al. 2005). Observational evidence indicates that primary COTS outbreaks originate on reefs within a ~250 km sector between Cairns and Lizard Island (17.2°–14.5°S latitudes). Primary COTS outbreaks in the Cairns-Lizard Island region since 1960 (n=4) have occurred 2-5 years after wet seasons when aggregate early wet season (November-February) discharge from the Burdekin to Daintree Rivers exceeded 10 km^3. The 2-5 year delay is consistent with the time it takes for COTS to grow up from small (<0.5 cm) recruiting juveniles with cryptic behaviour at settlement to conspicuously large (>50 cm) and non-cryptic adults of breeding size that produce large feeding scars. The available data and more recent satellite imagery shows that extensive flooding from central GBR and Wet Tropics rivers leads both to large nutrient inputs (Furnas, 2003) and widespread phytoplankton growth (blooms) over large areas of the GBR shelf, including the region between Cairns and Lizard Island. Regional chlorophyll concentrations in the nominal outbreak initiation region (1989-2012) are inversely related to regional salinity which is most strongly influenced by wet season rainfall and river runoff (more rainfall = more runoff = lower salinities). Regional chlorophyll concentrations during the critical pelagic larval period (Nov-Feb) are positively correlated with estimates of concurrent river runoff at both the local and regional scales (Furnas et al. 2013a). The 'high-risk' area for primary COTS outbreaks between 14.5°S and 17°S contains approximately 200 reefs with an aggregate outer reef slope circumference close to 2,000 km (GBRMPA GIS Group, personal communication).

In this assessment, we have used a binary assessment approach where the reefs are either within or outside of the COTS Initiation Zone. As shown in Table 2.1, the areas are either classified as Very Low or Very High depending on whether the reefs are located within the COTS Initiation Zone.

c) Pollutant loading in river plumes

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

Land sourced runoff containing elevated nutrient concentrations results in flood plumes in the GBR lagoon which may result in a range of impacts on coral communities (Fabricius et al. 2005; Fabricius, 2011; Brodie et al. 2011). Dissolved inorganic and particulate forms of nutrients discharged into the GBR are both important in driving ecological effects but increased nitrogen inputs are more important than phosphorus inputs (see Chapter 2 of the Supporting Studies, Furnas et al. 2013b). Dissolved inorganic forms of nitrogen and phosphorus are considered to be of greatest concern compared to dissolved organic and particulate forms of nutrients, as they are immediately and completely bioavailable for algal growth. Particulate forms mostly become bioavailable over longer time frames, and dissolved organic forms typically have limited and delayed bioavailability (Furnas et al. 2013b).

Most studies in GBR waters show that high levels of dissolved inorganic nitrogen and phosphorus can cause significant physiological changes in corals, but do not kill or greatly harm individual coral colonies (reviewed in

Fabricius, 2005). However, exposure to dissolved inorganic nitrogen can lead to declining calcification, higher concentrations of photo-pigments (affecting the energy and nutrient transfer between zooxanthellae and host; Marubini and Davies, 1996), and potentially higher rates of coral diseases (Bruno et al. 2003). Macroalgae and heterotrophic filter-feeders benefit more from dissolved inorganic and particulate organic nutrients than do corals. As a result, corals that can grow at extremely low food concentrations may be out-competed by macroalgae and/or more heterotrophic communities that grow best in high nutrient environments (Fabricius, 2011). Densities of benthic filter feeders – such as sponges, bryozoans, bivalves, barnacles and ascidians – increase in response to nutrient enrichment (Costa Jr et al. 2000). In high densities some filter feeders, such as internal macro-bioeroders, can substantially weaken the structure of coral reefs and increase their susceptibility to storm damage. Critically, more recent research shows that direct interactions between nutrients species such as nitrate and enhanced coral bleaching susceptibility will be important as a clear example of direct synergy between climate change stress and nutrient enrichment stress (Wooldridge 2009a; Wooldridge and Done 2009).

The impacts of nutrients on seagrass are less well known and there has been limited, detailed exploration of nutrient dynamics and nutrient limitation in the GBR, with notable exceptions (Udy et al. 1999; Mellors, 2003). Therefore, nutrients as an environmental driver has so far been difficult to elucidate because of other over-riding factors such as light limitation, which tends to be a primary driver (Collier and Waycott 2009). Nutrient enrichment can stimulate seagrass growth (Udy and Dennison 1997; Udy et al. 1999) if other factors, such as light availability, are not limiting (Chapter 7 of the Supporting Studies, Collier, 2013). Although a theoretical nutrient toxicity level does exist, nutrient over-enrichment tends to impact at ecosystem scales and follow a path of eutrophication with excessive production of organic matter. In addition, nutrients favour the growth of plankton, macroalgae and epiphytic algae, all of which attenuate light to seagrass leaves (Collier, 2013). In the GBR some very high epiphyte loads occur on seagrass meadows of the GBR (Mckenzie et al. 2012) and are likely to reduce light reaching seagrass leaves. However, to date, these have largely been seasonal blooms, and epiphyte cover has not correlated well with seagrass abundance (Mckenzie et al. 2012). Although nutrient enrichment has been linked to high algal cover (Campbell et al. 2002), seagrass loss has rarely been attributed to nutrient over-enrichment. Further discussion of the impact of flood plumes and degraded water quality on seagrass ecosystems in the GBR is included in Chapter 6 of the Supporting Studies.

The impacts of elevated suspended solids to coral reefs and seagrass meadows were described above in Section 2.3.1a. It is important to note that particulate matter in plumes changes from ‘clay’ (or mineral)-based material in inshore regions, to organic matter (algal material) in offshore regions. These different types of particulate matter can have different effects on coral reefs and seagrass meadows as described in Chapter 3 of the Supporting Studies (Brodie et al. 2013a).

Further discussion of the impacts of TSS and DIN on GBR ecosystems is provided in SCS Chapter 1 (Schaffelke et al. 2013). Given the importance of flood plumes in delivering TSS and DIN to the GBR, the following variables related to plume loadings have been included in the assessment.

v DIN and TSS Plume Loading (mean 2007-2011)

Method:

Plume loading maps have been developed for TSS and DIN over the period 2007 to 2011. To date the method has not been developed for phosphorus due to limitations in our understanding of the relationship between end of catchment loads of phosphorus and marine concentrations due to complex dynamics in phosphorus processing in marine waters. However, in the assessment of the relative importance of nitrogen and phosphorus (Chapter 2 of the Supporting Studies, Furnas et al. 2013b) it was concluded that increased nitrogen inputs are more important than phosphorus inputs in driving ecological effects in the GBR.

The method for assessing plume loadings is described by Alvarez Romero et al. (2013), with further detail in Chapter 5 of the Supporting Studies (Devlin et al. 2013a). The method involves:

i. Classification of GBR surface waters into colour classes corresponding to plume surface water, non-plume surface water, cloud and sun glint areas;

ii. Creation of weekly plume colour class maps and mean annual color classes by overlaying maps created in *(i)*. Weekly composites maps minimize the amount of area without data per image due to masking of dense cloud cover, common during the wet season (Brodie et al. 2010), and intense sun glint;

iii. Creation of maps of annual frequency of occurrence of plumes, by overlaying weekly composites created in *(ii)*. These maps help evaluating the annual frequency of occurrence of plumes, representing the number of weeks plumes are present (*i.e.* classified as plume surface water) in every pixel/areas of the GBR and during wet seasons;

iv. Creation of spatially distributed TSS and DIN loading maps. This step involves: (a) the calculation of the percentage of the TSS and DIN load delivered by each of the 7 GBR priority rivers (Joo et al. 2012; Reef Plan 2003) in relation to the total TSS and DIN load from the catchments in Wet Tropics, Burdekin, Mackay Whitsundays and Fitzroy NRMs, and (b) the creation of grids representing the annual average distribution of TSS and DIN load delivered by the seven major rivers in the study region by multiplying their proportional contribution to the region-wide TSS and DIN loads with a cost-distance grid (see Alvarez-Romero et al. 2013) defining the maximum area of influence and the dispersal of pollutants in the sea. The individual spatially distributed grids (one per river) are then summed to represent the full TSS load per cell; the overlap of two or more grids defined cells influenced by multiple rivers;

v. The production of annual risk maps for TSS and DIN loading within the GBR by multiplying the annual frequency of plume occurrence grid *(iii above)* by the grid representing the sum of spatially distributed TSS and DIN loads for all rivers *(iv above)*. Exposure values are finally grouped in 5 categories of exposure (from very low to very high) to investigate spatial variation in exposure; and

vi. Annual exposure maps were then reclassified into three categories of risk (high, medium, low – see Table 2.1). For this assessment the mean of the 5 annual maps in the period 2007 to 2011 was selected as a way of factoring in some inter-annual variability, although it is recognised that this period was characterised by several extreme rainfall events.

The above assessment approach was not completed for Cape York because of outstanding issues with validation of true colour in this area. However, in recognition that there is some influence of river plumes in the Cape York region, a more crude estimate of TSS and DIN plume loading in this region has been applied which is summarised here and described in more detail in Chapter 5 of the Supporting Studies (Devlin et al. 2013a). This involved:

a) Defining the primary and secondary plume types in the GBR for 2011 (see Alvarez-Romero et al. 2013; Devlin et al. 2013a).

b) For TSS plume loading: Using the extent of the primary plume type in Cape York to define the extent of surface exposure. This is where coastal waters are characterised by elevated Colour Dissolved Organic Matter (CDOM) and TSS, with TSS concentrations dropping out rapidly as the heavier particulate material flocculates and settles to the sea floor. This area was then allocated as Low exposure as a conservative estimate given that there is limited information on the frequency of the occurrence of these conditions, and low confidence in the remote sensing outputs in this Region. The remaining area in the Region was assessed as having no plume exposure.

c) For DIN plume loading: Using the extent of the secondary plume type in Cape York to define the extent of plume exposure. This is where intermediate waters are characterised by a region where CDOM is elevated, TSS concentrations are reduced due to sedimentation, and the increased availability of light and nutrient availability prompt phytoplankton growth measured by elevated Chl concentrations. This area was then allocated as Low exposure as a conservative estimate given that there is limited information on the frequency of the occurrence of these conditions, and low confidence in the remote sensing outputs in this Region. The remaining area in the Region was assessed as having no plume exposure.

Note that this assessment for Cape York is not included in the overall normalisation of loads for the model described in Step (iv) above, however, exposure scores for pollutants, particularly DIN, are typically low for the northern GBR and would not add significantly to the calculation of the normalised loads.

We also assessed the option of just using the plume loading maps from 2011 as a representation of a year of peak flood conditions, and for comparability to the pesticide exposure maps. However, it was concluded that the results were too biased to the influence from the large rivers of the Burdekin and Fitzroy which experienced flow conditions well above long term median records in 2011. Accordingly, the mean of the full set of available data (2007-2011) was used to represent variation in the characteristics of river discharges and hence flood plumes between the catchments between years.

Assessment classes:

The following three relative pollutant loading classes were allocated: Low, Medium and High. As an indication of the relative differences between these classes, preliminary satellite/in-situ match-up analyses have been performed to validate the 2007-2011 annual exposure maps and relate *in situ* data to the plume loading (exposure) classes and described in Chapter 5 of the Supporting Studies (Devlin et al. 2013a). There is a strong correlation between the in situ data and the assessment classes for DIN and TSS. For example, DIN concentrations increased linearly ($R^2 = 0.95$) with the highest concentrations corresponding to the highest DIN exposure category. This reflects the conservative mixing that has been described for DIN in the GBR lagoon (Devlin and Brodie, 2005; Devlin et al. 2012). TSS concentrations still increased along an increasing gradient of the level of exposure, with a rapid rise in concentrations in the highest exposure categories ($R^2 = 0.95$). This exponential increase reflects the sedimentation of the larger, heavier particles in the low salinity zones, and the transport of the finer sediment over much larger spatial scales. This sediment process is described for the Burdekin (Bainbridge et al. 2012), Tully (Devlin and Schaffelke, 2009) and reflects the higher risk associated with the availability of the finer sediment over longer time scales (Fabricius et al. 2012; Brodie et al. 2012b).

d) Pesticide concentrations

vi PSII Herbicide modelled concentration 2009-2011

Waters of the GBR lagoon are contaminated with a range of pesticides including herbicides, insecticides and fungicides. Pesticides, unlike nutrients, sediments and metals, have no natural sources and their concentrations have been positively correlated with low salinity associated with river runoff (Lewis et al. 2009; Kennedy et al. 2012a). Therefore, the occurrence of pesticides in the GBR can be attributed with great confidence to agriculture in the catchments that result in river discharge into the GBR lagoon. Of the 34 pesticides that have been detected in catchments draining to the GBR, several persistent and mobile PSII herbicides dominate the pesticides identified in water samples and passive samplers in both near-shore and offshore sites on the GBR. Further information describing the relevance of PSII herbicides to this assessment is described in Chapter 4 of the Supporting Studies (Lewis et al. 2013a).

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

Method:

A full description of this method is provided in Chapter 4 of the Supporting Studies (Lewis et al. 2013a). A modelling approach based on the relationship between CDOM and sea surface salinity (Schroeder et al. 2012), was used with the results of in situ end of catchment and GBR lagoon pesticide concentration results for the 2009-2010 and 2010-2011 wet seasons.

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

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

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

Assessment classes:

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

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

- **Very High**: >10 µg/L causes reduced growth and mortality in seagrass (Gao et al. 2011) and loss of symbionts (bleaching) in corals (Jones et al. 2003; Negri et al. 2005). The effect on health and survival of foundation species of the GBR can be catastrophic.

- **High:** 2.3 – 10 µg/L Photosynthesis is reduced by between 50% and 90% in corals (Jones and Kerswell, 2003; Negri et al. 2011); seagrass (Chesworth et al. 2004; Gao et al. 2011; Flores et al. in review) and microalgae (Magnusson et al. 2008, 2010). A 50% reduction of growth and biomass of tropical microalgae was also reported in this concentration range (Magnusson et al. 2008). The community structure of tropical microalgae is significantly affected and this causes significant changes in the tolerance of microbial communities to herbicides (Magnusson et al. 2012). The effect on primary production is major.

- **Medium:** 0.5-2.3 µg/L Photosynthesis is reduced by between 10% and 50% in corals (Negri et al. 2011); seagrass (Haynes et al. 2000; Chesworth et al. 2004; Gao et al. 2011; Flores et al. 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.

- **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. in review) and microalgae (Magnusson et al. 2008, 2010). The effect on primary production is minor.

- **Very Low:** 0.025-0.1 µg/L No observed effect on photosynthesis in corals (Negri et al. 2011); seagrass (Haynes et al. 2000; Flores et al. in review) and microalgae (Magnusson et al. 2008, 2010).

- **No Risk:** < 0.025 µg/L

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

Further explanations of the methods are provided in Chapter 4 of the Supporting Studies (Lewis et al. 2013a).

e) Recognising and assessing uncertainties in the selection of variables

For all variables, any relative differences in uncertainty and hence our confidence in the data can only be assessed highly subjectively. If such qualitative assessments of uncertainty in our methodologies and data were undertaken, uncertainty would be assessed as varying as much within as among NRM regions. As we compare results for NRM regions in the final combined relative risk assessment, the various methodologies used to generate the data are considered to have roughly the same uncertainty and with the limited time and resources, no specific estimates were considered.

Further discussion of the uncertainties and limitations of the assessment are presented in Part B of this report, Section 4.

2.3.2 Estimating habitat area

The habitats considered in the assessment were for coral reefs and seagrass meadows, based on the best available information. The area of GBR lagoon waters in each NRM region was also included in the assessments as it contains other important habitats and biological populations such as phytoplankton, fish and benthic organisms. The area estimates in each Region are based on the GBRMPA Spatial Data Centre's coral reefs spatial data file (December 2012) and seagrass spatial data files supplied by TropWATER James Cook University. The seagrass habitat map used 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.

2.3.3 Assessment Method - Part 1: Differential risk between pollutants on GBR ecosystems

The relative risk of different pollutants between regions was estimated by calculating the area of coral reefs, seagrass meadows and GBR lagoon waters associated with an NRM region within each of the assessment classes for each variable. As the first step, the assessment classes for each variable were allocated score in MCAS-S between 0 (lowest severity) and 1 (highest severity) at the 1 km^2 pixel scale. These are shown in Table 2.3 below. 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, seagrass meadows and GBR lagoon waters were then reported for each assessment class in each region in ArcGIS.

To compare results between regions, only the areas affected in the highest assessment class for each variable was considered as these were determined through expert opinion to be the most ecologically relevant in determining risk, except for PSII herbicides where the highest and second highest assessment classes were included in recognition of the toxicity of both of these classes. The output is a map and a table showing the area (km^2) of coral reef, seagrass and GBR lagoon waters within each assessment class for all variables in all NRM regions. The assessment classes used in this part of the analysis are highlighted in grey in Table 2.3. For example, the TSS threshold of 2 mg/L used in the assessment is the highest frequency of exceedance class of 50 to 100% (Very High).

The results were then anchored for comparison; the maximum area is set as an anchor point and given a value of 100, and all other area calculations are then expressed as a proportion of the maximum (values between 0 and 100). For example, for the TSS threshold of 2 mg/L the area of coral reef within the highest assessment class (Very High – 50-100% exceedance of the threshold) is 9 km^2 in the Burdekin, 6 km^2 in the Fitzroy, and all other regions have less than 2 km^2 of coral reef in the area of the Very High assessment class. In this case the maximum area of 9 km^2 is in the Burdekin, so the Burdekin is allocated a value of 100. The other areas are then reported as a proportion of the maximum value of 9 km^2; the Fitzroy is therefore 61% and all other regions are less than 15%. It can then be concluded that the area of coral reefs in the Fitzroy region within the Very High assessment class for TSS threshold of 2 mg/L is 61% of that in the Burdekin region.

Table 2.3. Summary of the classes used to assess the differential risk between pollutants on GBR ecosystems (Part 1), and the weightings given to each assessment class for the MCAS-S combined assessment (Part 2). The cells shaded in grey show the classes included in assessing the relative risk between variables (Part 1). The overall weighting for the water quality variables used in the combined assessment are also shown. 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
MCAS-S[1] 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	20-50 50-100
MCAS-S score	*1/7*	*0*	*0*	*0.33*	*0.66*	*1.0*
TSS Plume Loading (mean 2007-2011)		Category 1		Category 2	Category 3	
MCAS-S 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
MCAS-S score	*1/7*	*0*	*0.25*	*0.5*	*0.75*	*1.0*
DIN Plume Loading (mean 2007-2011)		Category 1		Category 2	Category 3	
MCAS-S score	*1/7*	*0.33* [2]		*0.66*	*1.0* [3]	
COTS Initiation Zone		Outside Zone				Within Zone
MCAS-S 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
MCAS-S score	*1/7*	*0.25*	*0.5*	*0.75*	*1.0*	*No occurrence*

[1] MCAS-S: Multi-Criteria Analysis Shell for Spatial Decision Support developed by ABARES, refer to http://www.daff.gov.au/abares/data/mcass; [2] This class covers Very Low and Low; [3] This class covers High and Very High.

2.3.4 Assessment Method - Part 2: Combined risk of degraded water quality to GBR ecosystems

To consider the combined risk of the selected water quality variables to marine ecosystems, the spatial layers for the individual variables described above were combined and the scores allocated to each assessment class for each variable were summed at the 1 km^2 pixel scale (see Figure 2.7). Anchoring and normalising the data to the uni-directional scale ensures that the ranges in data values (very different among variables) are standard and can be summed to produce a single score for each pixel. Pixels with no data were not included in the final averaging. It is recognised that this approach to standardising the assessment classes has limitations when considering the equivalency of the assessment classes for each variable.

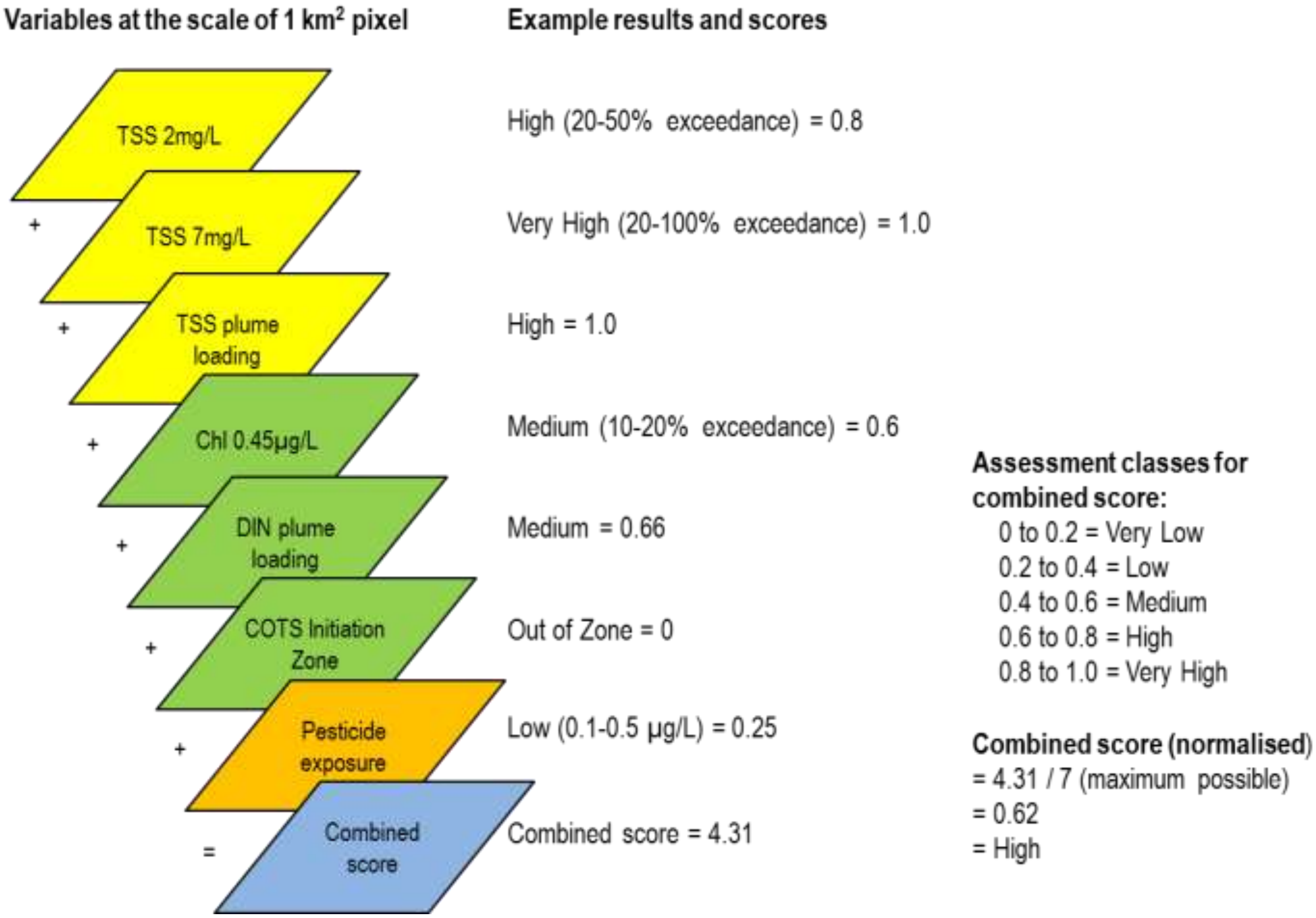


Figure 2.7. Example of the results in one pixel from a Composite in MCAS-S. The result for the pixel from each layer is summed to give a combined score. These scores are then classified into five assessment classes (Very Low to Very High). In this example the combined score gives the pixel a score within the High assessment class in terms of relative risk of degraded water quality.

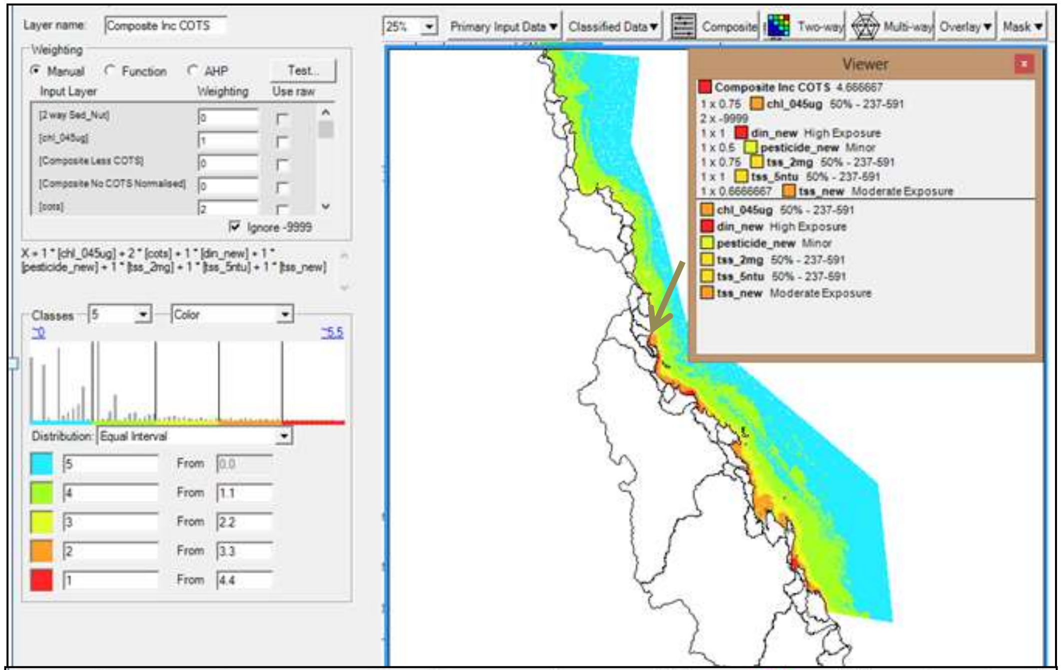
The classifications, scores and overall weightings for this assessment were based on expert opinion and are shown in Table 2.3. Ideally the classes for each variable would be scaled so that they are equivalent in terms of potential ecological impacts to provide comparable weightings between variables. However, it is recognised that this may not be the case for all variables given the inconsistencies in the temporal and spatial characteristics of the datasets. As temporal and spatial resolution of 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.

The data layers were then combined using the *Composite tool* in MCAS-S which essentially sums the results of the scores for each 1 km^2 pixel in each spatial layer to create a combined spatial layer. Figure 2.8 illustrates the use of the MCAS-S tool. The result of the summed pixels can then be normalised in MCAS-S to generate a score between 0 and 1 for each pixel (see example in Figure 2.9). The results for each pixel were further classified into five even break classes ranging from Very Low to Very High to provide a classification of relative risk of degraded water quality. A more detailed classification of 10 classes was also tested but the spread of the data resulted in limited benefit from using more than five classes. An example of the process applied in MCAS-S is shown in Figure 2.7.

The area of coral reefs, seagrass meadows and GBR lagoon waters within each of the five assessment classes was calculated in ArcGIS and tabulated for comparison between regions. A **Marine Risk Index** was defined by summing the areas of coral reefs, seagrass and GBR lagoon waters in the Very High and High assessment classes of the combined layer, and anchoring those results to the maximum area among regions. This enabled an assessment of the relative differences between regions in terms of combined water quality risk for coral reefs, seagrass and GBR lagoon waters. The Very High and High assessment classes were determined (by expert opinion) to be the most ecologically relevant for the assessment. It is recognised that these classes are relative and that the areas of coral reefs and seagrass meadows in the lower assessment classes may also be important depending on temporal and spatial variability of the exposure to exceedance in the water quality variables. A more detailed assessment of these patterns in the lower assessment classes was outside of the scope of this project but 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.

The final output is a Coral Reef Marine Risk Index and a Seagrass Marine Risk Index.

A number of options for combining the variables were considered which essentially weighted each variable differently, described in Appendix 2. All of these were performed using the *Composite tool* in MCAS-S described above. The selected option involved combining all variables individually with an equal weighting (1/7) and summed. The maximum score for each pixel is therefore 7 (Figure 2.8), and this value is then normalised between 0 and 1 (Figure 2.9). This approach essentially weights the variables differently because there are 3 sediment related variables, 3 nutrient related variables and 1 pesticide related variable which were considered to be appropriate by the assessment team given current evidence of the relative importance of nutrients and sediments compared to pesticides in the GBR. An example of this combination in MCAS-S is shown in Figure 2.7.



Layer name: Composite Inc COTS

Weighting: ● Manual ○ Function ○ AHP

Input Layer	Weighting	Use raw
[2 way Sed_Nut]	0	☐
[chl_045ug]	1	☐
[Composite Less COTS]	0	☐
[Composite No COTS Normalised]	0	☐
[cots]	2	☐

☑ Ignore -9999

X = 1 * [chl_045ug] + 2 * [cots] + 1 * [din_new] + 1 * [pesticide_new] + 1 * [tss_2mg] + 1 * [tss_5ntu] + 1 * [tss_new]

Classes: 5 · Color · 0 · 5.5

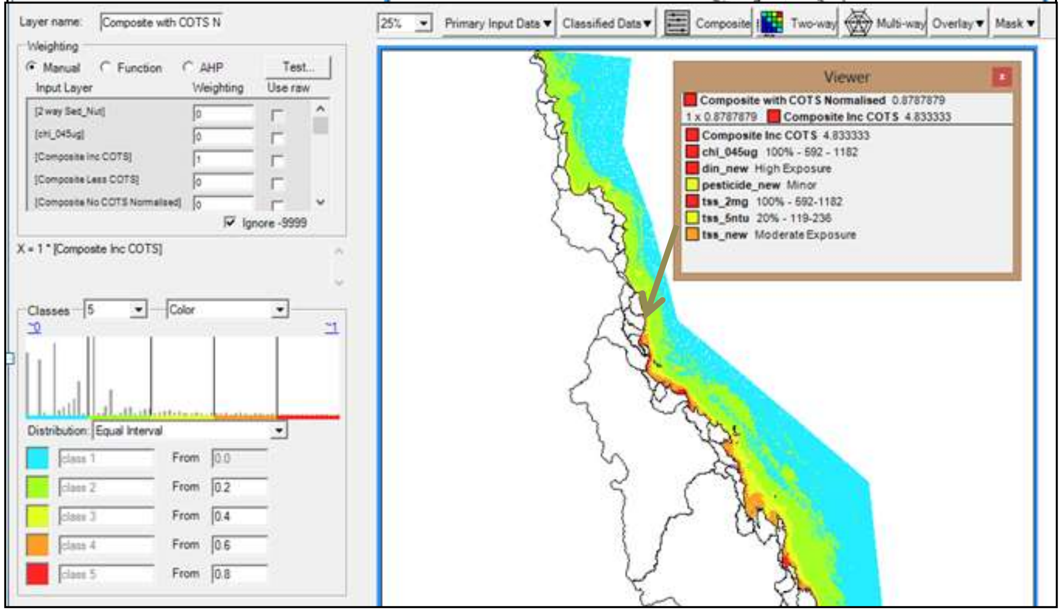
Distribution: Equal Interval

🟦	5	From	0.0
🟩	4	From	1.1
🟨	3	From	2.2
🟧	2	From	3.3
🟥	1	From	4.4

```
Composite Inc COTS  4.666667
1 x 0.75  chl_045ug  50% - 237-591
2 x -9999
1 x 1  din_new  High Exposure
1 x 0.5  pesticide_new  Minor
1 x 0.75  tss_2mg  50% - 237-591
1 x 1  tss_5ntu  50% - 237-591
1 x 0.6666667  tss_new  Moderate Exposure
```

```
chl_045ug  50% - 237-591
din_new  High Exposure
pesticide_new  Minor
tss_2mg  50% - 237-591
tss_5ntu  50% - 237-591
tss_new  Moderate Exposure
```

Figure 2.8. Example of the results in one pixel (near the arrow) from a Composite in MCAS-S where all individual variables are combined equally (formula shown in the panel to the left). The score for each variable is shown in the Viewer: the upper box shows the combined score for each variable where variables with no result or zero are allocated a value of -9999 (and not counted), the lower box identifies the input scores for each variable in the selected pixel (in this example the COTS Initiation Zone did not receive a score as the pixel is outside the Zone). The scores can then be normalised as shown in Figure 2.9.



Layer name: Composite with COTS N

Weighting: ● Manual ○ Function ○ AHP

Input Layer	Weighting	Use raw
[2 way Sed_Nut]	0	☐
[chl_045ug]	0	☐
[Composite Inc COTS]	1	☐
[Composite Less COTS]	0	☐
[Composite No COTS Normalised]	0	☐

☑ Ignore -9999

X = 1 * [Composite Inc COTS]

Classes: 5 · Color · 0 · 1

Distribution: Equal Interval

🟦	class 1	From	0.0
🟩	class 2	From	0.2
🟨	class 3	From	0.4
🟧	class 4	From	0.6
🟥	class 5	From	0.8

```
Composite with COTS Normalised  0.8787879
1 x 0.8787879  Composite Inc COTS  4.833333
```

```
Composite Inc COTS  4.833333
chl_045ug  100% - 592 - 1182
din_new  High Exposure
pesticide_new  Minor
tss_2mg  100% - 592-1182
tss_5ntu  20% - 119-236
tss_new  Moderate Exposure
```

Figure 2.9. Example of the results in one pixel (near the arrow) from a normalised Composite in MCAS-S where all individual variables are combined equally (shown in the panel to the left). The classes and distribution of pixels within these classes for the combined layer is shown at the bottom of the left panel. This combined class for each variable is shown in the Viewer: the upper box shows the combined score for the selected pixel, the lower box identifies the scores for each input variable in the selected pixel.

2.3.5 Assessment Method - Part 3: Relative risk of degraded water quality to GBR ecosystems

To inform management priorities that aim to address the risks identified in Part 1 and 2, it is necessary to understand the influence of river discharge in each of the regions, as these discharges carry a majority of the pollutants into the GBR lagoon.

To relate the results of the Marine Risk Index (described in Section 2.3.4) to land based influences, anthropogenic end-of-catchment loads were expressed as the proportion of total GBR load for each Region to generate a **Loads Index** for each region. This recognises that while the total GBR load is important in influencing the marine water quality conditions, it is only the anthropogenic proportion that can be factored into management. The regional proportional contributions were then anchored (to normalise to a standard scale) and averaged to generate a Loads Index for TSS, DIN and PSII herbicides for each NRM region. 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 three pollutants relative to each other.

End-of-catchment anthropogenic loads were obtained from the results of the Source Catchments model framework which have been produced as part of the Paddock to Reef Program (Waters et al. in press). 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. This resulted in a consistent set of end of catchment pollutant loads for each of the 35 GBR catchments. 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.

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

An index specific to the potential influence of river DIN loads on the initiation of COTS primary outbreaks in the GBR was added (see Furnas et al. 2013a). DIN runoff is considered to be an important factor as approximately 40% of the loss of coral cover in the GBR since 1987 has been attributed to COTS predation (De’ath et al. 2012). A COTS outbreak initiation zone has been defined between Lizard Island (14.5°S) and Cairns (17°S). On total volumetric basis, most (86%) of the estimated freshwater input (direct and indirect) to the Zone comes from Wet Tropics rivers, with the remaining 14% from the Burdekin River (Furnas et al. 2013a). These estimates were used to create a **COTS Influence Index**.

To provide an overall relative ecological risk ranking between the NRM regions, 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 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 region.

Once the relative risks and pollutants are known, the load information for each catchment allows us to track back to management priorities. A detailed assessment of the load contributions at a catchment scale was outside of the scope of this assessment, however, the SCS chapters on sources of pollutants (Kroon et al. 2013) and management practice effectiveness (Thorburn et al. 2013) provide a solid foundation for this analysis to be progressed.

2.4 Results

2.4.1 Habitat and regional NRM areas

The distribution of coral reefs and seagrass used in the risk assessment are shown in Figure 2.10, and the inset table shows the area of coral reef, seagrass and area of GBR lagoon waters in each marine NRM region. The total area of the Great Barrier Reef Marine Park in this spatial dataset is 345,804 km^2; this represents a difference of well less than half of 1% the published area assessment from the GBRMPA of 345,400km^2. The very slight difference between the area estimates used here from ArcGIS and the published area assessments are a result of slightly different estimates of the areas around coastlines and the Marine Park boundary. We consider the difference here to be negligible.

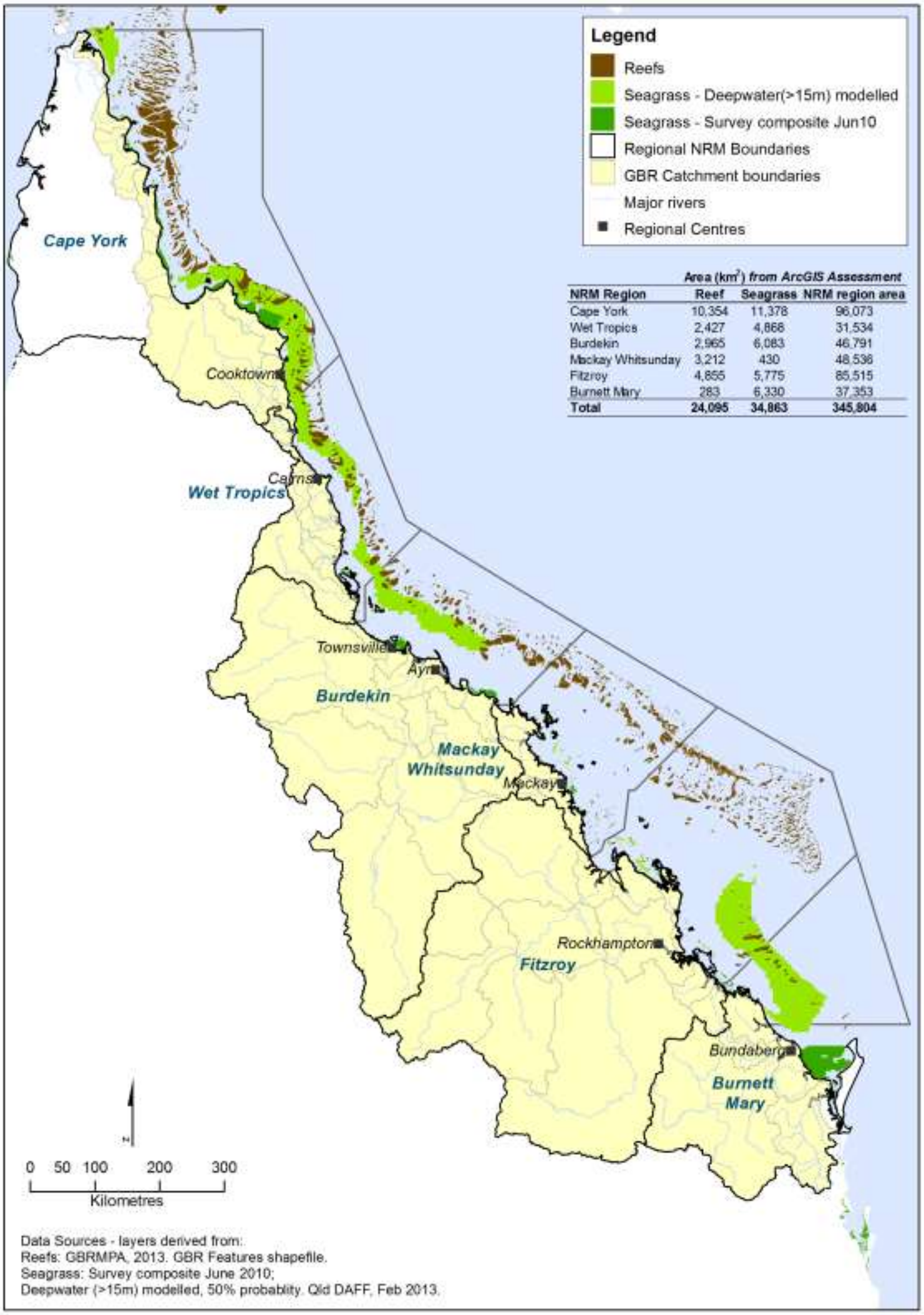
The total area of coral reef in the GBR is estimated around 24,000 km^2. The Regions with the largest areas of coral reef are Cape York (10,354 km^2), Fitzroy (4,855 km^2), and Mackay Whitsunday (3,213 km^2). Approximately 35,000km^2 of seagrass has been mapped in the coastal waters around Queensland and Torres Strait since the mid 1980s. Surveys and statistical modelling of seagrass in offshore waters deeper than 15m shows 37,454 square kilometres 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 Cape York marine NRM region also has the highest area of seagrass with 11,378km^2. The regions with the second and third-highest seagrass area are the Burnett Mary (6,330 km^2) and the Burdekin (6,083 km^2), respectively. The area of seagrass in the Mackay Whitsunday region is relatively low compared to other Regions with only approximately 430 km^2. Deepwater seagrasses are sparse in the Mackay Whitsunday region, particularly south of Mackay, where tidal velocities are high and no major deepwater seagrass meadows exist (Coles et al. 2009). High current stress, low Secchi readings and coarse mobile sediments generally make this an unsuitable habitat for seagrass growth.

It is important to note that the habitats of the Burnett Mary region are under estimated in this assessment, as the GBR Marine Park and World Heritage Area boundary does not include all of the habitat areas that would be affected by the catchments of the Burnett Mary region. In particular, there is a large area of seagrass to the south of the boundary in Hervey Bay which is known to provide important habitat, and foraging grounds, for species that also inhabit the GBR Marine Park. The total area estimate for seagrass in the Burnett Mary region is around 8,000km^2 (McKenzie et al. 2010b). These limitations are discussed further in Part B Section 4.

2.4.2 Part 1: Relative importance of different pollutants to GBR ecosystems

The following section presents the results of the individual variables considered in this assessment (refer to Section 2.3.3 for a description of the methods). 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 the NRM regions. The output can be used to guide priorities for management of individual pollutants between NRM regions.



	Area (km^2) from ArcGIS Assessment		
NRM Region	Reef	Seagrass	NRM region area
Cape York	10,354	11,378	96,073
Wet Tropics	2,427	4,868	31,534
Burdekin	2,965	6,083	46,791
Mackay Whitsunday	3,212	430	48,536
Fitzroy	4,855	5,775	85,515
Burnett Mary	283	6,330	37,353
Total	**24,095**	**34,863**	**345,804**

Data Sources - layers derived from:
Reefs: GBRMPA, 2013. GBR Features shapefile.
Seagrass: Survey composite June 2010;
Deepwater (>15m) modelled, 50% probablity. Qld DAFF, Feb 2013.

Figure 2.10. 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). Inset table shows the area of coral reef, seagrass, those habitats combined and region for each marine NRM region.

The area of coral reefs, seagrass and GBR lagoon waters is shown for all assessment classes for all variables in this section. Area calculations are rounded to the nearest whole km^2 for ease of reporting but does include summed portions of some 1 km^2 pixels. For each variable there is a table of results, and a map shows the areas within each assessment class for each variable. Within the map, a graph compares the areas of coral reef and seagrass affected by the highest class and a comparison of these areas with the total (whole of GBR) areas of habitat affected among the NRM regions is presented as a pie chart.

Note that in this section the regions are simply referred to as their name, for example 'the Burdekin' rather than 'the Burdekin region' to improve readability.

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. However, as the Very Low class receives a score of 0, it is not reported here. The results of the assessment are shown in Table 2.4 and Figure 2.11. The areas within the Very High class are constrained to the coast and concentrated in the Burdekin and Fitzroy. 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.

Key findings:

- The area of coral reef in the Very High class of TSS exceedance at 2 mg/L is greatest in the Burdekin (9 km^2), and second-greatest in the Fitzroy (6 km^2) (see inset in Figure 2.11). The greatest area within the High class is in the Fitzroy (103 km^2) and Mackay Whitsunday is second (90 km^2). The proportion of coral reefs in each region in the Very High class is less than 1%. More than 95% of the coral reefs within in each region are within the lowest classes (Very Low and Low) for exceedance of TSS 2 mg/L.

- The area of seagrass within in the Very High class of TSS exceedance at 2 mg/L is also greatest in the Burdekin (209 km^2), which is ~10 times greater than the second-greatest area in the Wet Tropics (22 km^2) (see inset Figure 2.11). In the High class Cape York has the greatest area of seagrass (747 km^2), with Fitzroy second (300 km^2). The proportion of seagrass meadows in each region in the Very High class is less than 5%. More than 59% of the seagrass meadows within in each region are within the combined Very Low and Low class for exceedance of TSS 2 mg/L and a large proportion of these are deepwater meadows (>15m). The proportion of seagrass within all other categories is similar across regions (all less than 10%) with the notable exception of Mackay Whitsunday which has 18% and 16% within the Medium and High classes respectively.

- The pie chart insets in Figure 2.11 show the area of coral reef and seagrass within each region as a percentage of total area (GBR-wide) of coral reef and seagrass within the Very High class of TSS exceedance at 2 mg/L. The area of coral reef in the Very High class in Burdekin represents 52% of the total GBR coral reef area within the Very High class, and the area of seagrass in the Very High class in the Burdekin represents 78% of the total GBR seagrass area within the Very High class. The lowest areas of coral reefs and seagrass in both the Very High and High classes are in the Burnett Mary (<5 km^2 for coral and 55km^2 for seagrass).

- The area of GBR lagoon waters in the Very High class of TSS exceedance at 2 mg/L is greatest in the Burdekin (932 km^2), and second in the Fitzroy (502 km^2). The greatest area in the High class is in the

Fitzroy (3,390 km^2) with Mackay Whitsunday second (2,122 km^2). The proportion of GBR lagoon waters in each region in the Very High class is less than 5%.

- When summed, the area of coral reef within the High and Very High classes (frequency of exceedance 20-50% and 50-100%) of TSS exceedance at 2 mg/L represents 0.8% (Cape York) to 2.8% (Mackay Whitsunday) of the total coral reef area in the regions; seagrass ranges from 0.9% (Burnett-Mary) to 17% (Mackay Whitsunday) of the seagrass area in the regions, and GBR lagoon waters from 1% (Burnett-Mary) to 5% (Burdekin) of the total region area. The lowest total areas in the Very High and High classes are in Burnett Mary, however the assessment area is bound to the GBRWHA and therefore does not incorporate coral reefs that have not been fully mapped within the region, or the large seagrass meadows in Hervey Bay the large seagrass meadows in Hervey Bay.

Table 2.4. Area of coral reefs, seagrass meadows and GBR lagoon waters within the Low to Very High assessment classes for TSS 2 mg/L and the percent of the NRM region that the area represents. Results for the assessment are based on frequency of exceedance of TSS 2 mg/L using daily remote sensing data 2002-2012 (see methods in Section 2.3.1a(i)).

TSS 2 mg/L	Low		Medium		High		Very High	
Frequency of exceedance class	1-10%		10-20%		20-50%		50-100%	
NRM Regions	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region
Coral Reefs								
Cape York	10,163	98	71	1	84	1	0	0
Wet Tropics	2,355	97	17	1	46	2	0	0
Burdekin	2,930	99	2	<1	9	<1	9	<1
Mackay Whitsunday	2,886	90	191	6	90	3	1	<1
Fitzroy	4,559	94	173	4	103	2	6	<1
Burnett-Mary	277	98	1	<1	3	1	2	1
Seagrass								
Cape York	8,949	79	463	4	747	7	0	0
Wet Tropics	4,450	91	57	1	117	2	22	<1
Burdekin	4,289	71	54	1	165	3	209	3
Mackay Whitsunday	255	59	79	18	70	16	4	1
Fitzroy	5,042	87	159	3	300	5	11	<1
Burnett-Mary	5,926	94	24	<1	35	1	20	<1
GBR lagoon waters								
Cape York	92,137	96	2,016	2	1,809	2	0	0
Wet Tropics	28,647	91	1,238	4	1,446	5	147	<1
Burdekin	43,582	93	734	2	1,497	3	932	2
Mackay Whitsunday	43,948	91	2,274	5	2,122	4	131	<1
Fitzroy	79,095	92	2,440	3	3,390	4	502	1
Burnett-Mary	36,514	98	412	1	233	1	145	<1

The results presented here and used in the risk assessment have been compared with spatial patterns in secchi depth shown in De'ath and Fabricius (2008). The visual comparison of our outputs for TSS exceedance at 2 mg/L and those from De'ath and Fabricius (2008) are shown in Appendix 1 along with a similar comparison for Chl 0.45 µg/L. The spatial patterns are very similar suggesting the remotely sensed data used here are at least comparable to the long term patterns measured in situ.

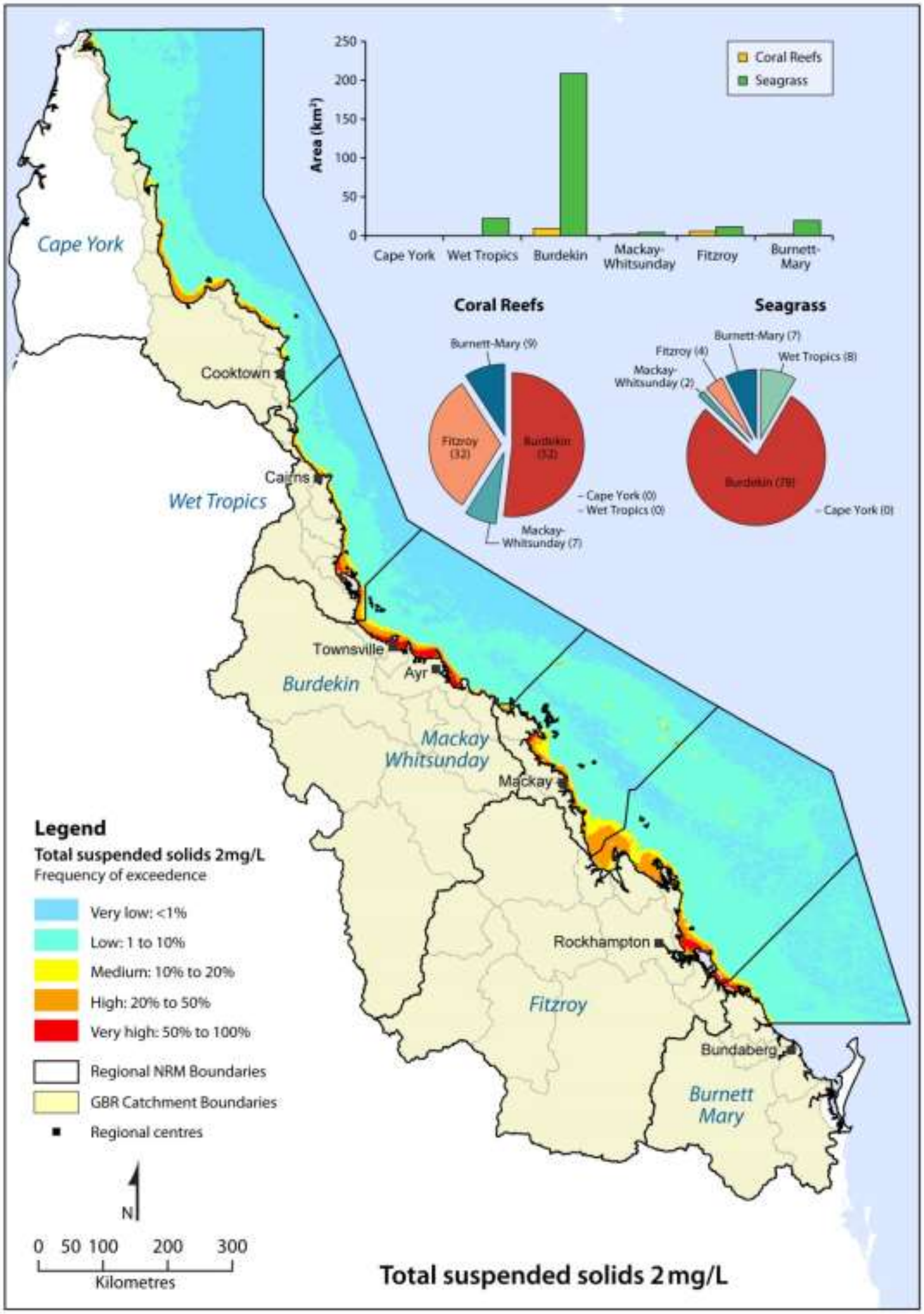


Figure 2.11. Results for the assessment of frequency of exceedance of TSS 2 mg/L using daily remote sensing data 2002-2012. Results for the assessment are based on frequency of exceedance of TSS 2 mg/L (see methods in Section 2.3.1a(i)). Inset bar chart compares coral reef and seagrass area within the Very High class (50-100% exceedance); pie charts show the area of coral reef and seagrass within each region as a percentage of total area (GBR-wide) of coral reef and seagrass within the Very High class.

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, but only the results of the Medium to Very High classes are presented as the most relevant here. 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 Table 2.5 and Figure 2.12. The area exposed in the Very High class is constrained to the coast (see map forming Figure 2.12) and concentrated in the Fitzroy region.

Table 2.5. Area of coral reefs, seagrass meadows and GBR lagoon waters within the Medium to Very High assessment classes for TSS 7 mg/L (5 NTU) and the percent of the NRM region that the area represents. Results for the assessment are based on frequency of exceedance of TSS 7 mg/L (5 NTU) using daily remote sensing data 2002-2012 (see methods in Section 2.3.1a(ii)).

TSS 7 mg/L	Medium		High		Very High	
Frequency of exceedance class	1-10%		10-20%		20-100%	
NRM Regions	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region
Coral Reefs						
Cape York	1,280	12	3	<1	0	0
Wet Tropics	423	17	0	0	0	0
Burdekin	105	4	<1	<1	<1	<1
Mackay Whitsunday	747	23	5	<1	0	0
Fitzroy	775	16	25	1	11	<1
Burnett Mary	58	20	0	0	0	0
Seagrass						
Cape York	2,437	21	30	<1	0	0
Wet Tropics	624	13	50	1	9	<1
Burdekin	600	10	96	2	35	1
Mackay Whitsunday	219	51	16	4	0	0
Fitzroy	484	8	29	<1	9	<1
Burnett Mary	393	6	6	<1	0	0
GBR lagoon waters						
Cape York	9,661	10	80	<1	0	0
Wet Tropics	5,063	16	204	1	30	<1
Burdekin	7,381	16	451	1	170	<1
Mackay Whitsunday	6,026	12	185	<1	17	<1
Fitzroy	9,329	11	1,094	1	504	1
Burnett Mary	2,062	6	26	<1	0	0

Key findings:

- The area of coral reef in the Very High class of TSS exceedance at 7 mg/L is greatest in the Fitzroy (11 km^2); all other regions have less than 1 km^2 or zero (see inset in Figure 2.8). The greatest area within the High class is in the Fitzroy (25 km^2) and Mackay Whitsunday is second (5 km^2). The proportion of coral reefs in each region in the High and Very High class is less than 1%. More than 80% of the coral reefs within each region are within the lowest classes where the frequency of exceedance of TSS 7 mg/L was <1% (not shown here). The lowest areas of coral reefs in all assessment classes are in Burnett Mary.

- The area of seagrass within in the Very High class of TSS exceedance at 7 mg/L is also greatest in the Burdekin (35 km^2), with 9 km^2 within in both the Wet Tropics and Fitzroy (see inset Figure 2.12). In the High class Burdekin has the greatest area of seagrass (96 km^2), with Wet Tropics second (50 km^2). The proportion of seagrass meadows in each region in the High class is less than 5%, and less than 1% in the Very High class. More than 80% of the seagrass meadows within all regions except Mackay Whitsunday are within the lowest classes where the frequency of exceedance of TSS 7 mg/L was <1% (not shown here). In Mackay Whitsunday 55% of the seagrass is within the Medium to Very High classes.

- The area of GBR lagoon waters in the Very High class of TSS exceedance at 7 mg/L is greatest in the Fitzroy (504 km^2), and second in the Burdekin (170 km^2). The greatest area in the High class is in the Fitzroy (1,094 km^2) with Mackay Burdekin second (451 km^2). The proportion of GBR lagoon waters in each region in the Very High class is less than 1%. More than 80% of the GBR lagoon waters within in each region are within the lowest classes where the frequency of exceedance of TSS 7 mg/L was <1% (not shown here).

- The pie chart insets in Figure 2.12 show the area of coral reef and seagrass within each region as a percentage of total area (GBR-wide) of coral reef and seagrass within the Very High class of TSS exceedance at 7 mg/. The area of coral reef in the Very High class in Fitzroy represents 97% of the total GBR coral reef area within the Very High class, and the area of seagrass in the Very High class in the Burdekin represents 65% of the total GBR seagrass area within the Very High class.

- When summed the area of coral reef within the High and Very High of TSS exceedance at 7 mg/L represents 0% (Wet Tropics) to 0.7% (Fitzroy) of the total coral reef area in the regions; seagrass ranges from 0.1% (Burnett Mary) to 3.7% (Mackay Whitsunday) of the total seagrass area in the regions, and GBR lagoon waters from 0.1% (Burnett Mary) to 1.9% (Fitzroy) of the total region area. The total areas in the High and Very High classes are lowest in Burnett Mary; however the assessment area is bound to the GBRWHA and therefore does not incorporate coral reefs that have not been fully mapped within the region, or the large seagrass meadows in Hervey Bay.

For both concentrations of TSS exceedance, there is a distinct area of exceedance of the Medium class in the coastal areas in the Cape York region north of Cooktown and Princess Charlotte Bay. Further validation of this result is required, however recent studies by Brooks et al. (2013) indicate that suspended sediment loads from the Normanby River are likely influence this area. Similar patterns exist in the coastal areas around Shoalwater Bay in the northern part of the Fitzroy region which are also known to be naturally turbid and uncertainties in the remote sensing results in these areas have not been resolved. While these uncertainties may be important for regionally specific analyses, they are not considered to be significant enough to influence the overall conclusions of this assessment.

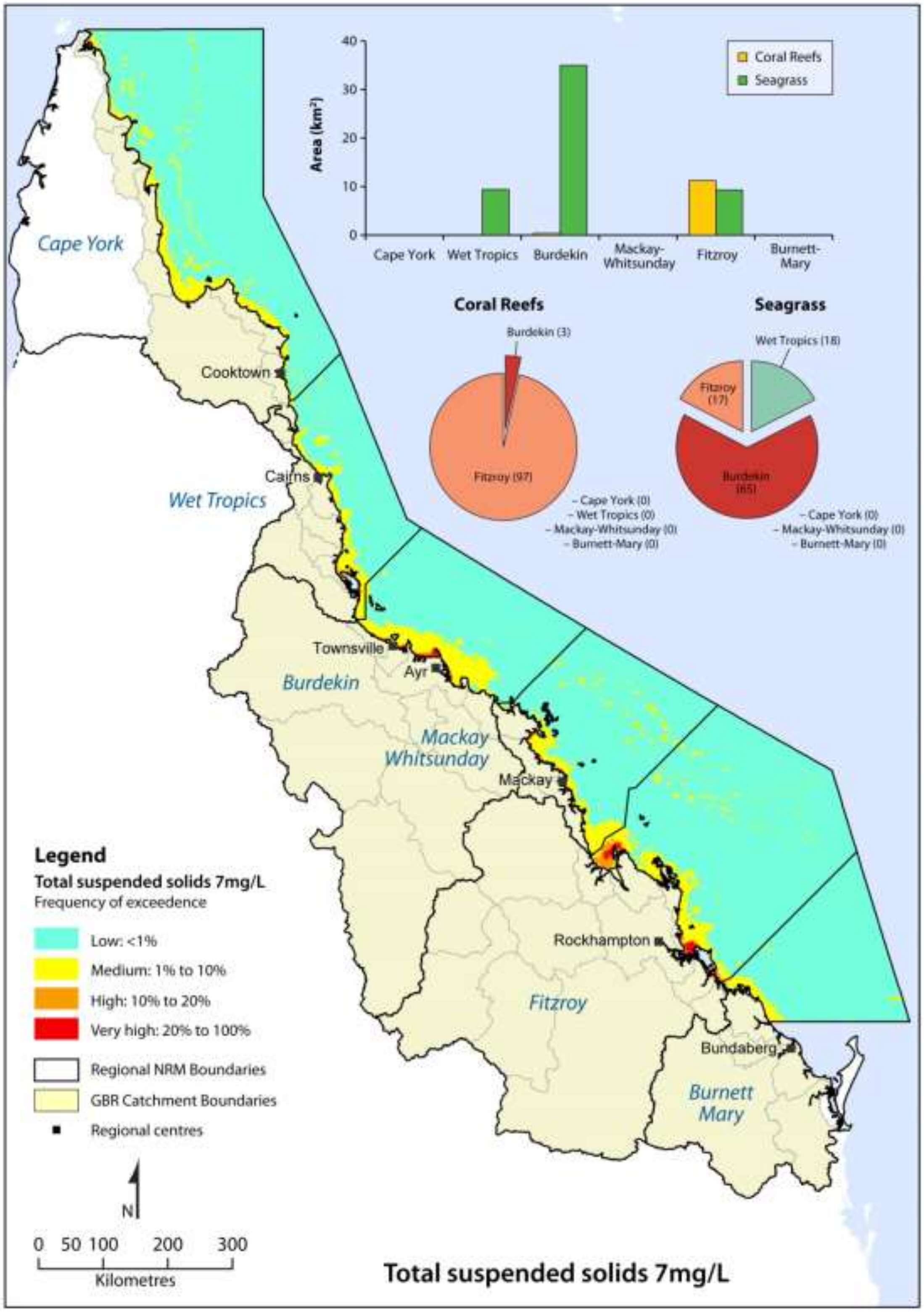


Figure 2.12. Results for the assessment of frequency of exceedance of TSS 7 mg/L (5NTU) using daily remote sensing data 2002-2012. Results for the assessment are based on frequency of exceedance of TSS 7 mg/L (5NTU) (see methods in Section 2.3.1a(i)). Inset bar chart compares coral reef and seagrass area within the Very High class (50-100% exceedance); pie charts show the area of coral reef and seagrass within each region as a percentage of total area (GBR-wide) of coral reef and seagrass within the Very High class.

TSS plume loading (mean 2007-2011)

As shown in Table 2.1, three assessment classes were used for TSS plume loading based on plume frequency information from remote sensing and scaled river load data. To factor in inter-annual variability, we used the mean result of assessments completed annually from 2007 to 2011. The results of the assessment are shown in Table 2.6 and Figure 2.13. Note that there are areas within the GBRWHA that are assessed as being outside of the area of plume loading influence which are not reported in this assessment. The areas within the highest assessment class (High) are inshore (Figure 2.13) and mostly concentrated in the Burdekin region.

Table 2.6. Area of coral reefs, seagrass and GBR lagoon waters within the assessment classes for TSS mean plume loadings between 2007 and 2011, and the percent of the NRM region that the area represents. The assessment classes are relative and derived from a combination of scaled river loads data and flood plume frequency analysis from remote sensing data (see methods in Section 2.3.1b).

TSS plume loadings	Low		Medium		High	
NRM Regions	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region
Coral Reefs						
Cape York	8,903	86	0	0	0	0
Wet Tropics	2,267	93	23	1	2	<1
Burdekin	2,746	93	35	1	20	1
Mackay Whitsunday	401	12	229	7	1	0
Fitzroy	694	14	161	3	6	0
Burnett Mary	268	95	3	1	0	0
Seagrass						
Cape York	11,433	100	0	0	0	0
Wet Tropics	4,535	93	223	5	48	1
Burdekin	5,113	84	354	6	610	10
Mackay Whitsunday	<1	<1	407	95	4	1
Fitzroy	5,244	91	490	8	30	1
Burnett Mary	5,750	91	341	5	0	0
GBR lagoon waters						
Cape York	54,536	57	0	0	0	0
Wet Tropics	21,464	68	2,817	9	445	1
Burdekin	21,899	47	7,160	15	4,553	10
Mackay Whitsunday	13,004	27	12,331	25	136	0
Fitzroy	26,488	31	13,506	16	763	1
Burnett Mary	10,172	27	1,802	5	0	0

Key findings:

- The area of coral reef in the High class for TSS plume loading is greatest in the Burdekin (20 km^2), and second-greatest in the Fitzroy (6 km^2) (see inset in Figure 2.13). The greatest area within the Medium class is in Mackay Whitsunday (229 km^2) and Fitzroy is second (161 km^2). The proportion of coral reefs in each region in the High class is less than 1%. More than 85% of the coral reef area in the Cape York, Wet Tropics and Burdekin are within the Low class, and approximately 80% of the area of coral reefs in the Mackay Whitsunday and Fitzroy are outside the mapped plume loading area. There is no occurrence of coral reefs in the High class in Cape York and Burnett Mary, but there are limitations to the method applied to for Cape York described in Section 2.3.1c, and the area of coral reefs in the Burnett Mary is not considered to be accurate.

- The area of seagrass within the High class for TSS plume loading is also greatest in the Burdekin (610 km^2), which is considerably larger than the second-greatest area in the Wet Tropics (48 km^2) (see inset Figure 2.13). In the Medium class Fitzroy has the greatest area of seagrass (490 km^2) with Mackay Whitsunday second (407 km^2). The proportion of seagrass meadows in each region within the High class is less than 1%, except for Burdekin which is 10%. Approximately 95% of the seagrass area in Mackay Whitsunday region is in the Medium class, and all other regions are less than 10%, which is associated with the distribution of seagrass in the region which is predominantly inshore (see 2.4.1 for further explanation). For all other regions, more than 80% of the seagrass in the region is within the Low class. There is no occurrence of seagrass meadows in the High class in Cape York and Burnett Mary, but there are limitations to the method applied to for Cape York described in Section 2.3.1c, and large seagrass meadows exist outside of the GBRWHA boundary and were not included in this assessment.

- The pie chart insets in Figure 2.13 show the area of coral reef and seagrass within each region as a percentage of total area (GBR-wide) of coral reef and seagrass within the High class for TSS plume. The area of coral reef and seagrass in the Burdekin represents 68% and 88% of the total GBR coral reef area and seagrass area respectively of habitats within the High class across the GBR.

- The total extent of influence of all TSS plume loading classes varies between the regions but is greater than 50% of the total region area in all cases except for Burnett Mary which is 32%. Large proportions (>70%) of the Wet Tropics and Burdekin are within the total area of TSS exposure. The area of GBR lagoon waters in the High class is greatest in the Burdekin (4,553 km^2), and second in the Fitzroy (763 km^2), associated with large river discharges in the assessment period (Figure 2.13). The greatest area in the Medium class is in the Fitzroy (13,506 km^2) with Mackay Whitsunday second (12,331 km^2). The proportion of GBR lagoon waters in each region in the High class is less than 1%, except for the Burdekin which is 10%. In Cape York, 43% of the area is outside of the estimated plume loading area, although there are obvious uncertainties in the method used for this Region which must be taken into account (see Section 2.3.1c).

- When summed the coral reef area in the Medium and High classes for TSS plume loading represents 0% (Cape York) to 7.1% (Mackay Whitsunday) of the total coral reef area in the regions; seagrass ranges from 0% (Cape York) to 95% (Mackay Whitsunday) of the total seagrass area in the regions, and GBR lagoon waters from 0% (Cape York) to 26% (Mackay Whitsunday) of the total region area. The areas of lowest exposure are within the Cape York and Burnett Mary regions, although these results cannot be concluded with a great degree of certainty due to limited or no validation in those locations.

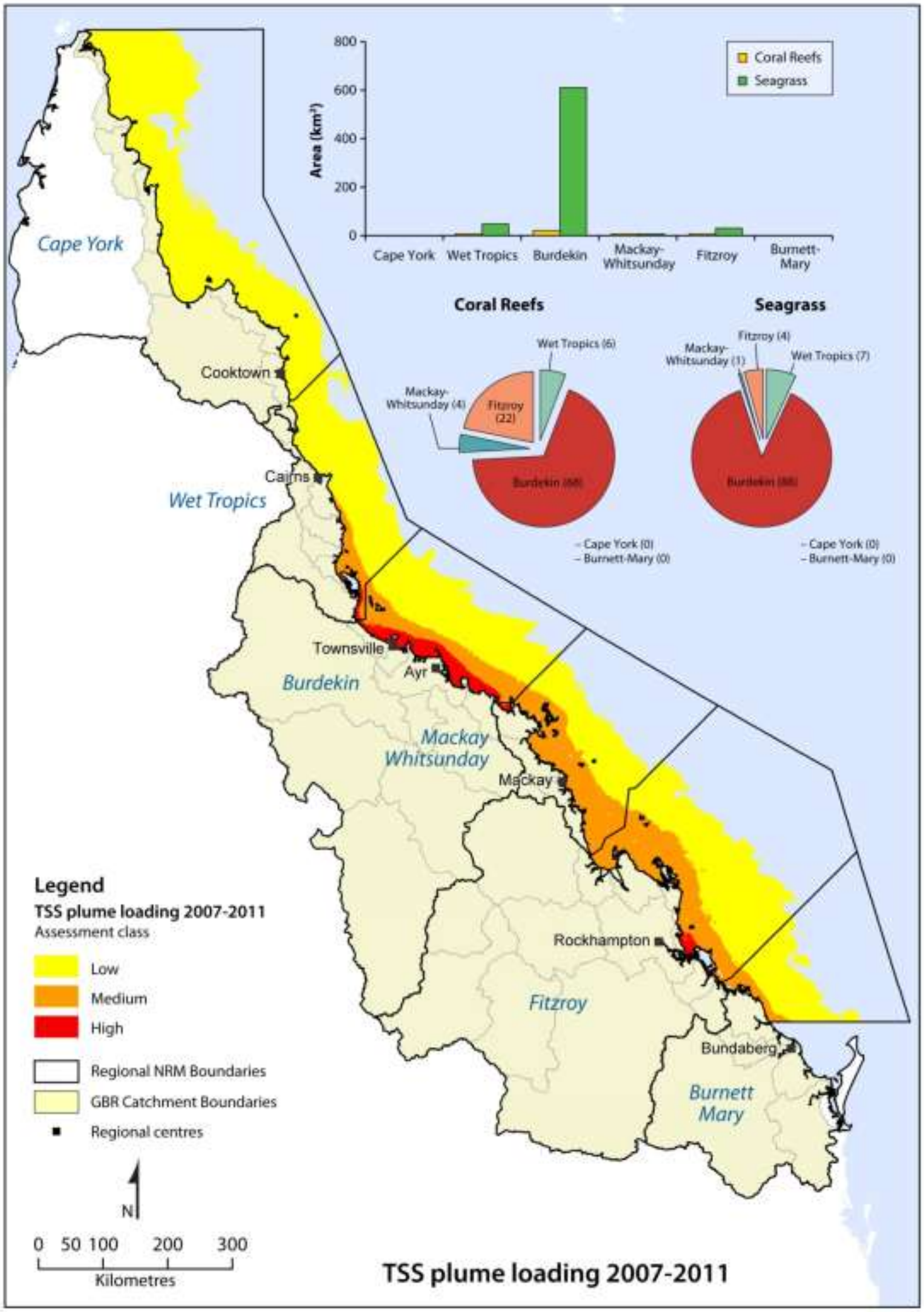


Figure 2.13. Results for the assessment of TSS plume loading (mean of annual assessments 2007 to 2011). The assessment classes are relative and derived from a combination of scaled river loads data and flood plume frequency analysis from remote sensing data (see methods in Section 2.3.1c). Inset bar chart compares coral reef and seagrass area within the High class; pie charts show the area of coral reef and seagrass within each region as a percentage of total area (GBR-wide) of coral reef and seagrass within the High class.

b) Nutrients

Chlorophyll threshold exceedance 0.45 µg/L

Chlorophyll (Chl) 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 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. However, as the Very Low class receives a score of 0, it is not reported here.The results of the assessment are shown in Table 2.7 and Figure 2.14. The areas within the Very High class are constrained to the coast and concentrated in the Burdekin and Fitzroy, as was the case for TSS 2 mg/L (Section 2.4.2a). 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.

Table 2.7. Area of coral reefs, seagrass meadows and GBR lagoon waters within the Low to Very High assessment classes for Chl 0.45 µg/L and the percent of the NRM region that the area represents. Results for the assessment are based on frequency of exceedance of Chl 0.45 µg/L using daily remote sensing data 2002-2012 (see methods in Section 2.3.1b).

Chl 0.45 µg/L	Low		Medium		High		Very High	
Frequency of exceedance class	1-10%		10-20%		20-50%		50-100%	
NRM Regions	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region
Coral Reefs								
Cape York	8,364	81	1,324	13	614	6	<1	<1
Wet Tropics	2,063	85	288	12	65	3	<1	<1
Burdekin	2,623	88	256	9	34	1	12	<1
Mackay Whitsunday	707	22	1,599	50	846	26	10	<1
Fitzroy	2,463	51	1,620	33	707	15	46	1
Burnett-Mary	216	76	54	19	8	3	4	1
Seagrass								
Cape York	6,527	57	2,410	21	2,410	21	14	<1
Wet Tropics	4,055	83	554	11	204	4	45	1
Burdekin	5,435	89	79	1	231	4	315	5
Mackay Whitsunday	46	11	114	27	223	52	23	5
Fitzroy	5,042	87	291	5	230	4	196	3
Burnett-Mary	5,942	94	217	3	110	2	47	1
GBR lagoon waters								
Cape York	47,149	49	7,632	8	6,225	6	24	<1
Wet Tropics	17,750	56	2,033	6	3,218	10	617	2
Burdekin	29,989	64	2,072	4	2,439	5	2,202	5
Mackay Whitsunday	26,845	55	10,641	22	7,431	15	632	1
Fitzroy	63,314	74	9,886	12	7,601	9	2,140	3
Burnett-Mary	34,563	93	1,013	3	829	2	419	1

Key findings:

- The area of coral reef in the Very High class of Chl exceedance of 0.45 µg/L is greatest in the Fitzroy (46 km^2), and second-greatest in the Burdekin (12 km^2) (see inset in Figure 2.14). The greatest area within the High class is in Mackay Whitsunday (846 km^2) and Fitzroy is second (707 km^2). The proportion of coral reefs in each region in the Very High class is less than 1%. More than 75% of the coral reefs in Cape York, Wet Tropics, Burdekin and Burnett Mary are within the Low class, and 50% of the Fitzroy is within the Low class of frequency of exceedance of 0.45 µg/L.
- The area of seagrass within in the Very High class Chl exceedance of 0.45 µg/L is greatest in the Burdekin (315 km^2), and the second-greatest area is the Fitzroy (196 km^2) (see inset Figure 2.10). In the High class Cape York has the greatest area of seagrass (2,410 km^2) with the Wet Tropics, Burdekin, Mackay Whitsunday and Fitzroy all similar with 200-230 km^2 of seagrass in the High class of Chl 0.45 µg/L exceedance. The proportion of seagrass meadows in each region in the Very High class is less than 5%. More than 80% of the seagrass meadows within the Wet Tropics, Burdekin, Fitzroy and Burnett Mary are within the Low class. The proportion of seagrass within the Medium and High categories in Cape York is around 20%. In Mackay Whitsunday 52% of the seagrass is within the High class of Chl exceedance.
- The lowest areas of coral reefs and seagrass in the Very High and High classes of Chl exceedance of 0.45 µg/L are in Burnett Mary (12 km^2 and 157 km^2 respectively).
- The pie chart insets in Figure 2.14 show the area of coral reef and seagrass within each region as a percentage of total area (GBR-wide) of coral reef and seagrass within the Very High class of Chl exceedance of 0.45 µg/L. The area of coral reef in the Very High class in Fitzroy represents 63% of the total GBR coral reef area within the Very High class, and the area of seagrass in the Very High class in the Burdekin represents 49% of the total GBR seagrass area within the Very High class.
- The area of GBR lagoon waters in the Very High class of Chl exceedance of 0.45 µg/L is greatest in the Burdekin (2,202 km^2), and second in the Fitzroy (2,140 km^2). The greatest area in the High class is in the Fitzroy (7,601 km^2) with Mackay Whitsunday second (7,431 km^2). The proportion of GBR lagoon waters in each region in the Very High class is less than 5%.
- When summed, the area of coral reef within the High and Very High classes (frequency of exceedance 20-50% and 50-100%) of Chl exceedance of 0.45 µg/L represents 1.54% (Burdekin) to 26.6% (Mackay Whitsunday) of the total coral reef area in the regions; seagrass ranges from 2.5% (Burnett Mary) to 57% (Mackay Whitsunday) of the total seagrass area in the regions, and GBR lagoon waters from 3.3% (Burnett Mary) to 17% (Mackay Whitsunday) of the total region area. The lowest total areas in the Very High and High classes are in Burnett Mary, however the assessment area is bound to the GBRWHA and therefore does not incorporate coral reefs that have not been fully mapped within the region, or the large seagrass meadows in Hervey Bay the large seagrass meadows in Hervey Bay.

The results presented here and used in the risk assessment have been compared with spatial patterns in Chlorophyll shown in De'ath and Fabricius (2008). The visual comparison of our outputs for Chl 0.45 µg/L and those from De'ath and Fabricius (2008) are shown in Appendix 1 along with a similar comparison for TSS 2 mg/L. The spatial patterns are similar suggesting that the remotely sensed data used here are robust with a few key exceptions. In a similar pattern as TSS 2mg/L exceedance using remote sensing data, there is a distinct area of exceedance of the Medium class in coastal areas in the Cape York region north of Cooktown and Princess Charlotte Bay. Further validation of this result is required and may be associated with high turbidity interfering with the quantification of chlorophyll when TSS concentrations. Further assessment is required to quantify the concentrations of TSS that influence the Chl assessment. Similar patterns exist in the coastal areas around Shoalwater Bay in the northern part of the Fitzroy region which are also known to be naturally turbid, thereby potentially interfering with the Chl signal, and uncertainties in the remote sensing results in these areas have not been resolved. Similarly to TSS, these uncertainties are not considered to be significant enough to influence the overall conclusions of this assessment but may be important for regionally specific analyses in any further assessment of the data.

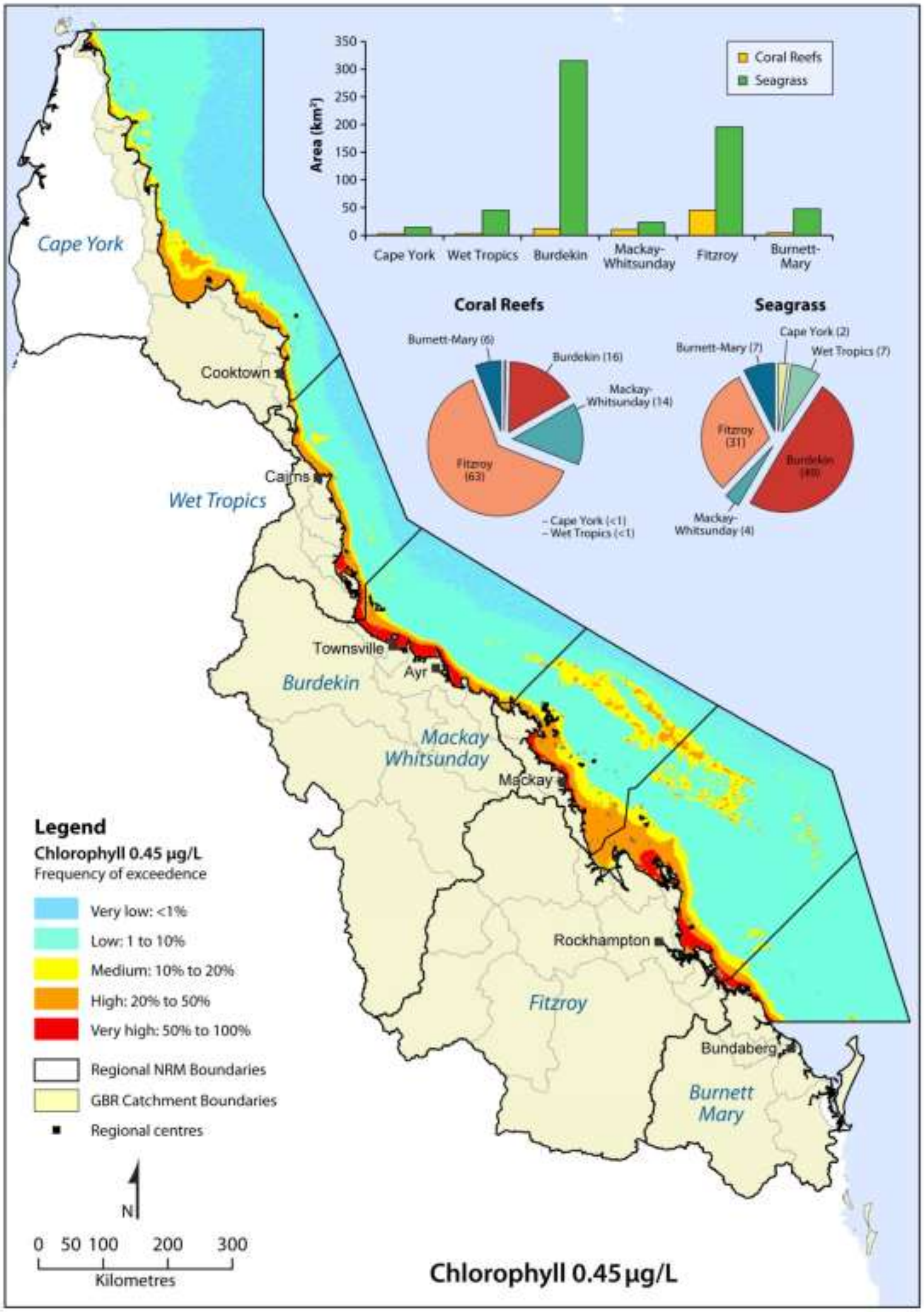


Figure 2.14. Results for the assessment of frequency of exceedance of Chl 0.45 µg/L using daily remote sensing data 2002-2012. Results for the assessment are based on frequency of exceedance of Chl 0.45 µg/L (see methods in Section 2.3.1b). Inset bar chart compares coral reef and seagrass area within the Very High class (50-100% exceedance); pie charts show the area of coral reef and seagrass within each region as a percentage of total area (GBR-wide) of coral reef and seagrass within the Very High class.

DIN plume loading (mean 2007-2011)

As shown in Table 2.1, three assessment classes were used for DIN mean plume loading based on plume frequency information from remote sensing and scaled river load data. To factor in inter-annual variability, we used the mean result of assessments completed annually from 2007 to 2011. The results of the assessment are shown in Table 2.8 and Figure 2.15. Note that there are areas within the GBRWHA that are assessed as being outside of the area of plume loading influence which are not reported in this assessment. The areas within the highest assessment class (High) are constrained inshore (Figure 2.15) and mostly concentrated in the inshore southern portion of the Wet Tropics region and in the inshore areas of the Burdekin, Fitzroy and Burnett Mary regions.

Table 2.8. Area of coral reefs, seagrass and GBR lagoon waters within the assessment classes for DIN mean plume loadings between 2007 and 2011, and the percent of the NRM region that the area represents. The assessment classes are relative and derived from a combination of scaled river loads data and flood plume frequency analysis from remote sensing data (see methods in Section 2.3.1c).

DIN plume loadings	Low		Medium		High	
NRM Regions	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region
Coral Reefs						
Cape York	6,351	61	0	0	0	0
Wet Tropics	2,262	93	74	3	25	1
Burdekin	2,698	91	49	2	54	2
Mackay Whitsunday	393	12	230	7	8	<1
Fitzroy	584	12	140	3	138	3
Burnett Mary	242	86	26	9	3	1
Seagrass						
Cape York	10,911	96	0	0	0	0
Wet Tropics	3,754	77	917	19	191	4
Burdekin	4,106	67	1,328	22	642	11
Mackay Whitsunday	<1	<1	360	84	51	12
Fitzroy	1,926	33	3,320	57	519	9
Burnett Mary	5,081	80	808	13	204	3
GBR lagoon waters						
Cape York	38,149	40	0	0	0	0
Wet Tropics	19,832	63	3,081	10	2,792	9
Burdekin	19,917	43	6,553	14	7,140	15
Mackay Whitsunday	9,893	20	14,725	30	898	2
Fitzroy	14,949	17	15,308	18	10,527	12
Burnett Mary	8,454	23	2,174	6	1,344	4

Key findings:

- The area of coral reef in the High class of DIN plume loading is greatest in the Fitzroy (138 km^2), and second-greatest in the Burdekin (54 km^2) (see inset in Figure 2.15). The greatest area within the Medium class is in Mackay Whitsunday (230 km^2) and Fitzroy is second (140 km^2). The proportion of coral reefs in each region in the High class is less than 5%. More than 85% of the coral reef area in the Wet Tropics, Burdekin and Burnett Mary are within the Low class, and approximately 80% of the area of coral reefs in the Mackay Whitsunday and Fitzroy are outside the mapped plume loading area. There is no or limited occurrence of coral reefs in the High class in Cape York and Burnett Mary, but there are limitations to the method applied to for Cape York described in Section 2.3.1c, and the area of coral reefs in the Burnett Mary is not considered to be accurate.

- The area of seagrass within the High class of DIN plume loading is also greatest in the Burdekin (642 km^2), and the second-greatest area is in the Fitzroy (519 km^2) (see inset Figure 2.15). In the Medium class Fitzroy has the greatest area of seagrass (3,320 km^2) with Burdekin second (1,328 km^2). The proportion of seagrass meadows in each region within the High class is less than 12% (Mackay Whitsunday). The proportion of the seagrass in each region that is in the Medium class is relatively high for Mackay Whitsunday (84%) and Fitzroy (57%). For all other regions, more than 60% of the seagrass in the region is within the Low class. There is no occurrence of seagrass meadows in the High class in Cape York, but there are limitations to the method applied to for Cape York described in Section 2.3.1c. In addition, the large seagrass meadows in the Burnett Mary region that are outside of the GBRWHA boundary were not included in this assessment.

- The pie chart insets in Figure 2.15 show the area of coral reef and seagrass within each region as a percentage of total area (GBR-wide) of coral reef and seagrass within the High class of DIN plume loading. The area of coral reef in the High class in Fitzroy represents 61% of the total GBR coral reef area within the High class, and the area of seagrass in the High class in the Burdekin represents 40% of the total GBR seagrass area within the High class.

- The total extent of influence of all DIN plume loading assessment classes varies between the regions but is greater than 30% of the total region area in all cases, with 82% of the Wet Tropics and 72% of the Burdekin within the total area of DIN plume loading. Approximately half of the Fitzroy and Mackay Whitsunday are in the exposure area, around 40% of the Cape York region and 32% of the Burnett Mary region. The area of GBR lagoon waters in the High class is greatest in the Fitzroy (10,527 km^2), and second in the Burdekin (7,140 km^2), associated with large river discharges in the assessment period (Figure 2.15). The greatest area in the Medium class is also in the Fitzroy (15,308 km^2) with Mackay Whitsunday second (14,725 km^2). The proportion of GBR lagoon waters in each region in the High class ranges between 9 to 15% in the Burdekin, Wet Tropics and Fitzroy; the area of GBR lagoon waters in the High class in the other regions is less than 5%. In Cape York, 60% of the area is outside of the estimated plume loading area, although there are obvious uncertainties in the method used for this Region which must be taken into account (see Section 2.3.1c).

When summed the area of coral reef in the Medium and High classes of DIN plume loading represents 0% (Cape York) to 10% (Burnett Mary) of the total coral reef area in the regions; and seagrass area ranges from 0% (Cape York) to 96% (Mackay Whitsunday) of the total seagrass area in the regions. The lowest total areas within the plume loading influence area are within the Cape York and Burnett Mary regions, although these results cannot be concluded with a great degree of certainty due to limited or no validation in those locations.

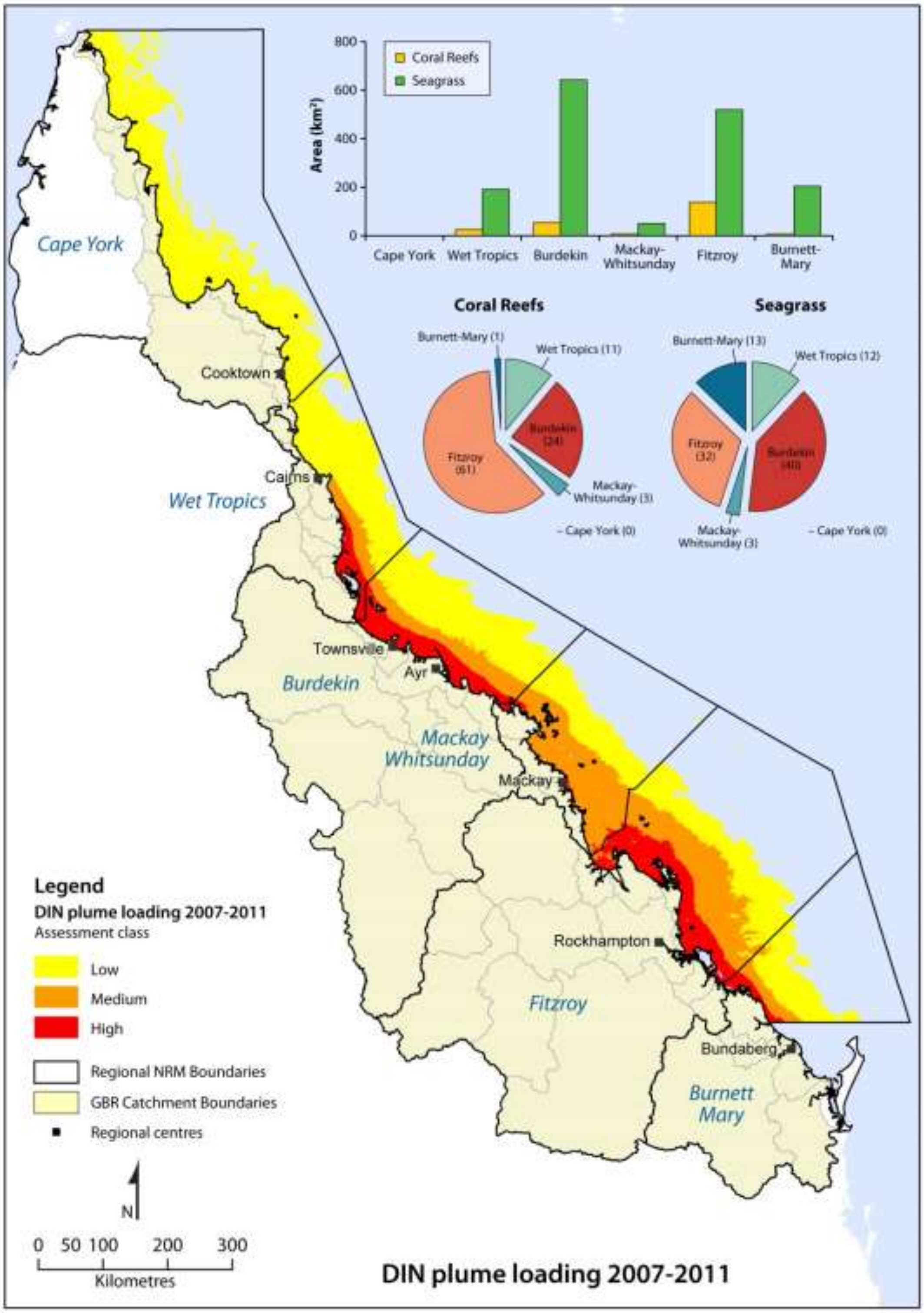


Figure 2.15. Results for the assessment of DIN plume loading (mean of annual assessments 2007 to 2011). The assessment classes are relative and derived from a combination of scaled river loads data and flood plume frequency analysis from remote sensing data (see methods in Section 2.3.1c). Inset bar chart compares coral reef and seagrass area within the High class; pie charts show the area of coral reef and seagrass within each region as a percentage of total area (GBR-wide) of coral reef and seagrass within the High class.

COTS Initiation Zone

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 the methods Section 2.3.1b and Chapter 1 of the Supporting Studies (Furnas et al. 2013a). This area is assessed here as the coral reef area between 14.5°S and 17°S inside the GBR Marine Park boundary. The areas affected by this zone are within the Cape York and Wet Tropics regions (see Figure 2.16). The total area of reefs affected is 3,284 km^2, of which 59% of the area is in the Cape York region. This accounts for 11% and 34% of the coral reefs in the Cape York and Wet Tropics regions respectively. 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 Section 2.4.4(b).

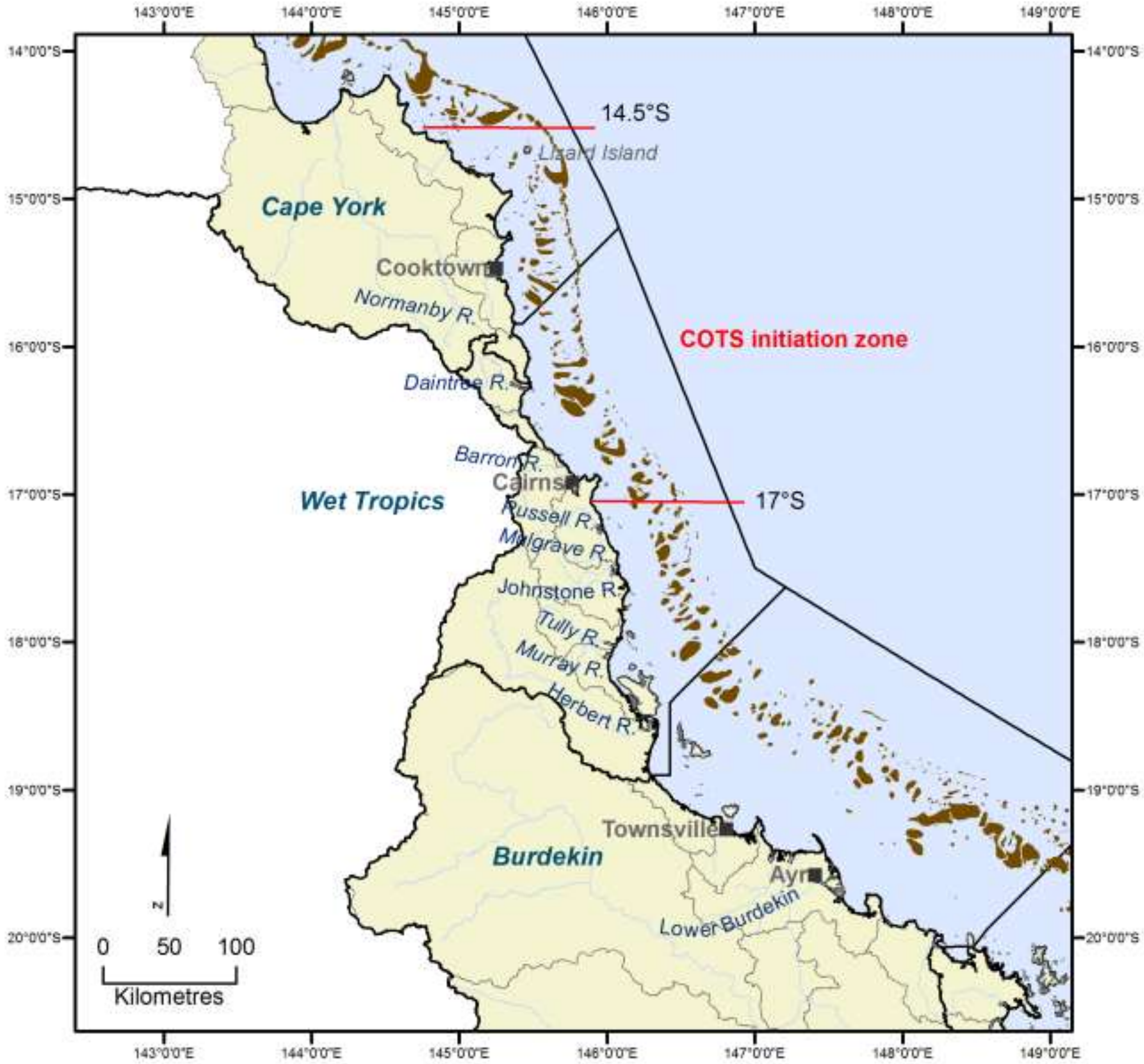


Figure 2.16. Location of the COTS Outbreak Initiation Zone, defined as a high risk area for COTS primary outbreaks based on current understanding of the outbreak initiation zone between 14.5ºS and 17ºS. Refer to Furnas et al. (2013a) for further explanation.

c) *Pesticides*

PSII Herbicide modelled concentration, 2009-2011

As shown in Table 2.1, five assessment classes were used for PSII herbicides based on the toxicity of diuron calculated in several studies on coral and seagrass species (see Chapter 4 of the Supporting Studies, Lewis et al. 2013a) ranging from Very Low 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 between January 2010 and March 2011 (in the 2009-2010 and 2010-2011 wet seasons; see Section 2.3.1c and Chapter 4 of the Supporting Studies). Note that no assessment has been undertaken for Cape York due to limited data availability, and was therefore assessed to be No risk; however, the risk in this region is unknown. The results of the assessment are shown in Table 2.9 and Figure 2.17. There are no marine areas in the Very High class, and marine areas within the Medium and High class are constrained inshore and only occur in the Mackay Whitsunday region (see Figure 2.17). The strong delineation between the regions in the mapping is due to regionally specific analysis of the data, which is explained further in Chapter 4 of the Supporting Studies.

Table 2.9. Area of coral reefs, seagrass and GBR lagoon waters within the Very Low to High assessment classes for exposure to PSII herbicides in 2009-2011 and the percent of the NRM region that the area represents. No areas were within the Very High assessment class (>10 µg/L). Results for the assessment are based on the exposure assessment undertaken by Lewis et al. (2013a) and described in Section 2.3.1c.

	Very Low		Low		Medium		High	
PSII herbicide concentration	<0.1 µg/L		0.1 - 0.5 µg/L		0.5 - 2.3 µg/L		2.3 - 10 µg/L	
NRM Regions	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region	Area (km^2)	% of habitat in region
Coral Reefs								
Cape York	0	0	0	0	0	0	0	0
Wet Tropics	134	6	30	1	0	0	0	0
Burdekin	<1	<1	0	0	0	0	0	0
Mackay Whitsunday	127	4	113	4	18	1	6	<1
Fitzroy	28	1	6	<1	0	0	0	0
Burnett Mary	5	2	1	<1	0	0	0	0
Seagrass								
Cape York	0	0	0	0	0	0	0	0
Wet Tropics	744	15	247	5	0	0	0	0
Burdekin	10	<1	0	0	0	0	0	0
Mackay Whitsunday	84	19	205	48	82	19	57	13
Fitzroy	14	<1	<1	<1	0	0	0	0
Burnett Mary	40	1	45	1	0	0	0	0
GBR lagoon waters								
Cape York	0	0	0	0	0	0	0	0
Wet Tropics	4,360	14	3,015	10	0	0	0	0
Burdekin	1,124	2	0	0	0	0	0	0
Mackay Whitsunday	3,790	8	4,377	9	1,573	3	509	1
Fitzroy	1,295	2	751	1	0	0	0	0
Burnett Mary	427	1	357	1	0	0	0	0

Key findings:

- There were no areas within the Very High assessment class (>10 µg/L) of PSII herbicide modelled concentration in the GBR lagoon.
- The extent of PSII herbicide exposure for the High and Medium classes of PSII herbicide modelled concentration only occurs in the Mackay Whitsunday region (Figure 2.17 and inset bar graph). Under this scenario of High and Medium class conditions, up to 70% of phototrophic species would be affected with up to 20% of phototrophic species experiencing major impacts. This includes considerable inhibition of photosystem II as well as reductions in growth of coral reef and seagrass species. It should be remembered that these areas only characterise the additive risk of six PSII herbicides which is only a portion of the 34 pesticides that have been recorded in catchments at the end-of system (Chapter 4 of the Supporting Studies).
- The area of coral reef in the High class of PSII herbicide modelled concentration in the Mackay Whitsunday region is 6 km^2, with 18 km^2 in the Medium class, both representing less than 1% of the coral reef in the region (see Figure 2.17). The greatest areas within the Low class are in Mackay Whitsunday (113 km^2) and Wet Tropics (30 km^2), both representing less than 5% of the coral reef area in each region. In all regions that were assessed the greatest areas of coral reefs are in the Very Low class, with 134 km^2 in the Wet Tropics, 127 km^2 in Mackay Whitsunday and less than 30 km^2 in the Fitzroy, Burnett Mary and Burdekin.
- The area of seagrass within in the High class of PSII herbicide modelled concentration is greatest in the Mackay Whitsunday (57 km^2), 82 km^2 in the Medium class (see inset Figure 2.17), representing 19% and 13% of the seagrass in the region respectively. The greatest areas within the Low class are in the Wet Tropics (247 km^2) and Mackay Whitsunday (205 km^2). This area in Mackay Whitsunday includes almost 50% of the seagrass meadows in the region. In all regions that were assessed, the greatest areas of seagrass are in the Very Low class, with 744 km^2 in the Wet Tropics, 84 km^2 in Mackay Whitsunday and less than 40 km^2 in the Fitzroy, Burnett Mary and Burdekin. This represents 19% of the seagrass in Mackay Whitsunday, and 15% of the seagrass in Wet Tropics.
- The total area of GBR lagoon waters in the Very Low to High classes of PSII herbicide modelled concentration is estimated to be 21,500 km^2. Approximately 50% of this area is in the Very Low class, 40% in the Low class and less than 10% in the Medium and High classes. In this assessment the Burdekin region is only exposed to PSII herbicide concentrations in the Very Low class, however it is noted that the influence of PSII herbicides is significant in the freshwater and estuarine environments in the Lower Burdekin (see below plus Chapter 4 of the Supporting Studies).

A limitation of this risk assessment was that only the major river within each region was assessed using the adopted method, i.e. Wet Tropics: Tully River; Burdekin: Burdekin River; Mackay Whitsunday: Pioneer River; Fitzroy: Fitzroy River; Burnett-Mary: Burnett River, in comparison to the plume loading assessment of TSS and DIN which accounted for annual flood plume assessments from all GBR catchments from 2007 to 2011. Therefore, the exposure area of PSII herbicides may be an underestimate.

Additional analysis using an ms-PAF method was undertaken for comparison with this assessment in Chapter 4 of the Supporting Studies (Lewis et al. 2013a). This method is a modification of the species sensitivity distribution methods used to calculate water quality guidelines for individual chemicals (e.g. ANZECC and ARMCANZ, 2000; GBRMPA, 2009). The ms-PAF method expands on the single chemical approach by incorporating multiple substances from a mixture into the calculation. It calculates the potentially affected fraction (PAF) which is the percentage of species (s) that will theoretically be affected at a specified environmental concentration of each component of the mixture. Similar to the herbicide equivalent method, ms-PAF thresholds were allocated to each of the risk classifications.

The ms-PAF method also showed that the risk of herbicides in the Mackay Whitsunday region was also Medium to High and when multiple exposures were considered as well as discharge, the Pioneer River was considered to present the highest risk of PSII inhibiting herbicides in the GBR lagoon. The other NRM regions of the GBR fell within the Low or Very Low risk categories with the Wet Tropics having the next highest risk of PSII inhibitor herbicides to coral reefs and seagrass meadows. Overall, the two methods showed good agreement in their assessment of the risk posed by PSII inhibiting herbicides in the GBR lagoon from individual plumes.

While this assessment has provided a general regional prioritisation of risk for PSII inhibiting herbicides, we note that some of the smaller creeks in the regions were not properly assessed as shown by the analysis of the monitoring data in Table 2.10. For example, on occasion, Barratta Creek in the Burdekin region displayed chronic exposures of PSII herbicides that were rated as Very High (and hence a high risk to the Ramsar wetland and to Bowling Green Bay) and Sandy Creek in the Mackay Whitsunday region regularly had chronic exposures rated as High - Medium in 2009-2010.

The ms-PAF assessment showed that Barratta Creek within the Burdekin region reached a Very High risk (more than 70% phototrophic species with minor impacts and more than 20% of phototrophic species experiencing major impacts to populations) for one of the analysed periods; this result is of concern given that Barratta Creek feeds into high value Ramsar-listed wetlands. Indeed the smaller coastal creeks that contain relatively large areas of intensive agriculture (> 20%) such as Barratta and Sandy Creeks yielded the highest pesticide concentrations in monitoring programs.

It should be noted that this assessment of risk of PSII herbicides did not take into consideration the period of exposure to PSII herbicides within each region, as is considered for other water quality variables. Toxicity of PSII herbicides is time dependent (Vallotton et al. 2008), i.e. the toxicity of PSII herbicides to phototrophs increases with an increasing exposure duration. For this risk assessment, acute exposure was used to assess the potential impacts to seagrass and corals, however, for regions in where the exposure period lasts days or weeks, the risk from PSII herbicides would have been underestimated.

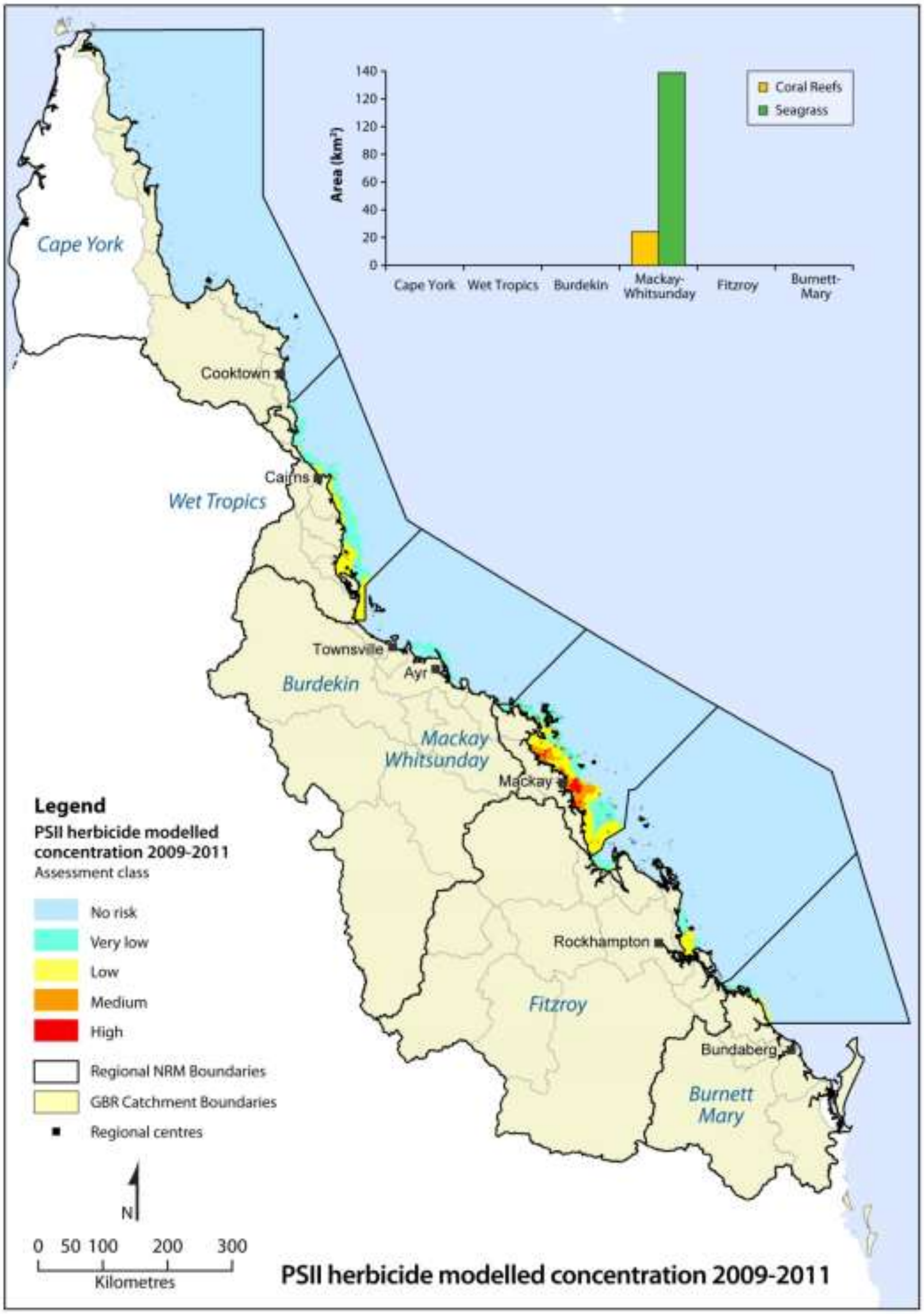


Figure 2.17. Results for the assessment of exposure to PSII herbicides based on an estimate of the relationship between additive PSII herbicide concentrations and CDOM (salinity proxy) in flood plume conditions from January 2010 to March 2011. Results for the assessment are based on the exposure assessment undertaken by Lewis et al. (2013a) and described in Section 2.3.1c. Inset bar chart compares reef and seagrass area exposed for the High class. Note that Cape York is assessed to be No risk but was not included in the remote sensing analysis and is therefore unknown.

Table 2.10. Risk assessment of individual events from the Wet Tropics, Burdekin/Haughton, Mackay Whitsunday, Fitzroy and Burnett NRM regions during the 2009-2010 wet season. Events assessed using satellite imagery are indicated by an asterisk. The Exposure Coverage Ratio accounts for repeated exposure to event and flood event plumes (an approximation of the aerial extent of each flood plume was calculated and compared to that of the appropriate flood plume with the satellite image and expressed as a ratio). Refer to Chapter 4 of the Supporting Studies (Lewis et al. 2013a) for further explanation of the methods used in this assessment.

Event Details				Risk Assessment		
Site	**Event No**	**Duration**	**Discharge (GL)**	**Exposure Type**	**Risk Category**	**Exposure Coverage Ratio**
Wet Tropics						
South Johnstone River	1*	25 d 3 h	89.7	Chronic	Very Low	1.0
	2	22 d 14 h	137.6	Chronic	Very Low	1.5
Tully River	1*	19 d 22 h	244.1	Chronic	Low	1.0
	2	13 d 6 h	215.4	Chronic	Low	0.9
	3	23 d 22 h	540.5	Chronic	Very Low	2.2
Burdekin/Haughton						
Barratta Creek	1	15 d 22 h	5.6	Chronic	Very High	0.2
	2	12 d 18 h	92.2	Chronic	Moderate	3.5
	3	16 d 3 h	55.5	Chronic	Very Low	2.1
	4	17 d 10 h	30.7	Chronic	Very Low	1.2
Burdekin River	1	46 d 7 h	4738.8	Chronic	Very Low	1.1
Mackay Whitsunday						
Pioneer River	1	7 d 19 h	74	Chronic	High	0.4
	2*	4 d 23 h	196	Chronic	Moderate	1.0
	3	13 d 17 h	332	Chronic	Very Low	1.7
Sandy Creek	1	5 d 23 h	44	Chronic	High	0.7
	2*	4 d 21 h	60	Chronic	Moderate	1.0
	3	4 d 11 h	30	Chronic	Moderate	0.5
	4	3 d 13 h	33	Acute	Moderate	0.6
	5	4 d	30	Chronic	Moderate	0.5
	6	7 d 3 h	63	Chronic	Low	1.1
Fitzroy						
Fitzroy River	1*	10 d 21 h	1419.3	Chronic	Very Low	1.0
	2	23 d 9 h	4408.9	Chronic	Low	3.1
	3	14 d 16 h	3072.7	Chronic	Very Low	2.2
	4	24 d 15 h	1815.4	Chronic	Very Low	1.3
Burnett						
Burnett River	1*	33 days, 2 hour	856.0	Chronic	Very Low	1.0

d) Comparisons among variables and Regions

The assessment of individual variables presented in Section 2.4.2 above (a – sediment, b - nutrients and c - PSII herbicides) can be used to guide priorities for management of individual pollutants between NRM regions. The different ways of reporting TSS and nutrient variables provide different perspectives of either acute (surface exposure mapping) or chronic (long term exceedance) effects of the variables on coral reefs and seagrass.

To compare results among regions, the areas of coral reefs, seagrass, and GBR lagoon waters in the highest assessment class for each variable (see Table 2.1 and 2.3) has been set as an anchor point (see Methods Section 2.3.2) and given a value of 100. All other area calculations were then expressed as a percentage of the maximum (values between 0 and 100), as shown in Table 2.11, to show relative differences between regions. Summaries of these results are provided below.

Table 2.11. Anchored scores for the area of coral reefs and seagrass for each NRM region affected by the highest assessment classes for the water quality variables included in the risk analysis (final output of Part 1 in Figure 2.3). In the case of PSII herbicides, the two highest assessment classes ware used. The Region that had the largest area affected was given a score of 100; all other Regions are expressed as a percentage based on the area affected in each Region relative to the area in the Region with the maximum area affected. To highlight differences between Regions, cells with the greatest and second-greatest areas affected are shaded dark and light grey respectively. Refer to Table 2.1 for further explanation of the variables.

	Sediments			Nutrients			Pesticides
NRM regions	TSS exceedance 2mg/L	TSS exceedance 7mg/L	TSS plume loading 07-11	Chl exceedance 0.45 ug/L	DIN plume loading 07-11	COTS Initiation Zone	PSII herbicide modelled concentration
Coral Reefs							
Cape York	0	0	0	0	0	100	0
Wet Tropics	0	0	9	1	18	70	0
Burdekin	100	4	100	26	39	0	0
Mackay Whitsunday	14	0	6	22	6	0	100
Fitzroy	61	100	32	100	100	0	0
Burnett Mary	18	0	0	9	2	0	0
Seagrass						N/A	
Cape York	0	0	0	5	0		0
Wet Tropics	11	27	8	14	30		0
Burdekin	100	100	100	100	100		0
Mackay Whitsunday	2	0	1	7	8		100
Fitzroy	5	27	5	62	81		0
Burnett Mary	9	0	0	15	32		0
GBR lagoon waters						N/A	
Cape York	0	0	0	1	0		0
Wet Tropics	16	6	10	28	27		0
Burdekin	100	34	100	100	68		0
Mackay Whitsunday	14	3	3	29	9		100
Fitzroy	54	100	17	97	100		0
Burnett Mary	16	0	0	19	13		0

Sediments

Assessment of the exceedance of TSS 2 mg/L (annual) results provides an indication of suspended sediment conditions in the GBR against the Water Quality Guidelines year round. The areas within the highest assessment classes are constrained to the coast and mostly concentrated in the Burdekin and Fitzroy regions. This is a similar pattern for the exceedance of the higher categories of the greater concentration of TSS 7 mg/L which is known to have measurable effects on coral and seagrass health, and fish behaviour (refer to Chapter 3 of the Supporting Studies Brodie et al. 2013a) and is therefore of greater significance when considering potential ecosystem impacts.

For TSS exceedance of 2 mg/L, the area of coral reef in the highest assessment class (Very High) is relatively small but is greatest in the Burdekin region, and second-greatest in the Fitzroy region (61%). For the higher concentration of TSS exceedance of 7 mg/L, the area within the Very High class is extremely constrained to the coast, and is by far the greatest in the Fitzroy region.

The area of seagrass within the Very High class of TSS exceedance of 2 mg/L and 7 mg/L is greatest in the Burdekin region. The area of seagrass in these areas is significantly larger than the areas in other regions; in both cases the next greatest area is the Wet Tropics region with less than one quarter of the seagrass area affected compared to the Burdekin.

The plume loading mapping for TSS over the period 2007 to 2011 provides an indication of the extent of the influence of flood plumes on the GBR in terms of frequency and extent of influence of flood plumes with differing characteristics of suspended sediment concentrations. The area of coral reef and seagrass in the highest assessment class (High) is by far the greatest in the Burdekin region.

The area of seagrass affected by all of the sediment variables is greatest in the Burdekin. The area of seagrass within the Wet Tropics is second for all variables but is less than one quarter of the areas affected in the Burdekin in all cases.

The area of GBR lagoon waters within the highest assessment classes for the sediment variables follows the same pattern as for coral reefs. The area of GBR lagoon waters within the Very High assessment class for TSS exceedance of 2 mg/L is greatest in the Burdekin and is double that of the Fitzroy. For TSS exceedance of 7 mg/L (5 NTU) the area affected in the Very High assessment class is greatest in the Fitzroy, and triple of that in the Burdekin. For all three sediment variables all of the other regions have less than 17% of the area affected in the Burdekin and Fitzroy.

Nutrients

Assessment of Chl exceedance of 0.45 µg/L results provides an indication of nutrient conditions in the GBR against the Water Quality Guidelines year round. The area of coral reefs affected by the highest assessment classes of the nutrient variables (Chl exceedance 0.45 µg/L Very High, and DIN plume loading 2007-2011 High) is greatest in the Fitzroy and then the Burdekin region, but in both cases the area within the Burdekin is less than 40% of that in the Fitzroy. All other regions have less than one quarter of the coral reef area within the highest assessment classes compared to the Fitzroy.

The area of seagrass within the highest assessment classes of the nutrient variables is greatest in the Burdekin region, and then the Fitzroy, but in both cases the relative difference is not as great as that for coral reefs (62% for Chl exeedance of 0.45 µg/L and 81% for DIN plume loading). The other regions have less than one third of the seagrass area within the highest assessment classes compared to the Burdekin and in the case of Cape York is less than 5%.

The area GBR lagoon waters within the highest assessment class for Chl excedance of 0.45 µg/L is greatest and very similar in the Burdekin and Fitzroy; these regions switch for DIN plume loading with Fitzroy having the greatest area of regional waters affected and the Burdekin region being second (68%). The other regions have less than one third of area of GBR lagoon waters within the highest assessment classes compared to the maximum, and in the case of Cape York is less than 1%.

Only coral reefs in the Cape York and Wet Tropics regions are counted within the COTS Initiation Zone. The area of coral reefs is 0% for all other regions. The maximum area of coral reefs within the COTS Initiation Zone is in Cape York, and the area in Wet Tropics is equivalent to 70% of this area.

PSII Herbicides

Based on the methods used here, coral reefs, seagrass, and GBR lagoon waters are only affected by the highest assessment classes of pesticides (Very High and High) in the Mackay Whitsunday region. This is a result unique to pesticides. However, it should be noted that the high risks of PSII herbicides to wetland, estuarine and coastal habitats, which provide important ecosystem services to the GBR including fish nursery habitats, were not included in this assessment. However, further investigation was conducted in the support studies of pesticide risk included as Chapter 4 of the Supporting Studies (Lewis et al. 2013a. It showed that the ecosystems of highest risk from pesticides are those coastal habitats (e.g. wetlands, estuaries, mangroves and seagrass) which provide important ecological services to GBR biota, including nursery habitats, primary productivity and nutrient cycling. The assessment concluded that the risk of pesticides in the GBR can be classified into five separate areas of ecological importance with assessments ranging from Very Low to Very High.

- Within the *freshwater reaches of rivers and freshwater/coastal wetlands*, the risk of pesticides (PSII herbicides and some non-PSII pesticides) is rated in the Very High class (>70% of phototrophic species affected), High (5 – 40% of phototrophic species affected) and Medium class (5 – 40% of phototrophic species affected depending on the region and stream) particularly for the coastal stream networks that drain a relatively large area (> 20%) of intensive agriculture such as Barratta and Sandy Creeks.
- In the *estuarine reaches of the rivers*, the risk of pesticides is largely in the High to Low category (1 – 70% of phototrophic species affected). A similar risk occurs for the *coastal marine environment* including intertidal and subtidal seagrass meadows (major reduction in photosynthesis by between 50% and 90% seagrass and microalgae (High) and up to 10% photosynthesis reduction (Low)).
- *Coral reefs and seagrass meadows on the inner shelf* whichincludes but not limited to areas extending up to 20 km from the coast, generally fall into the Low (reduction in photosynthesis by between 10% and 50% in corals, seagrass and microalgae) to Very Low categories (no observed effect on corals, seagrass or microalgae; < 40% of phototrophic species affected) depending on the region and adjacent catchment(s).
- The risk to *coral reefs on the mid and outer shelf* is considered Very Low to no risk (< 1% phototrophic species affected).

For all variables included in the risk assessment except for PSII herbicides, at least two (for COTS Initiation Zone) and otherwise 4 or 5 other regions have areas of coral reefs, seagrass and GBR lagoon waters in the highest assessment classes of the water quality variables. The common exception is Cape York; no coral reef area is affected by the highest assessment classes of all sediment variables, or Chl 0.45 µg/L and DIN plume loading. Further, no seagrass or GBR lagoon waters in Cape York are within the highest assessment classes of all sediment variables, and DIN plume loading 2007-2011 (see Table 2.11).

2.4.3 Part 2: Combined risk of degraded water quality to GBR ecosystems

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 GBR and hence where coral reefs and seagrass are most likely to be under pressure from degraded water quality.

To consider the combined risk of the selected water quality variables to coral reefs and seagrass, the results for the individual variables described above were summed at the 1 km^2 pixel scale and normalised between 0 and 1 using the Multi-Criteria Analysis Shell for Spatial Decision Support (MCAS-S) (see methods Section 2.3.4). The results were further classified into five even break classes ranging from Very Low to Very High. The results of combining the variables are shown in Figure 2.18 and the area of coral reefs, seagrass meadows and GBR lagoon waters within each of those 5 classes is shown in Table 2.12.

A Marine Risk Index was calculated by summing the areas of coral reefs, seagrass and GBR lagoon waters in the Very High and High classes and anchoring those results to the maximum areas. This shows relative differences between regions (see final column in Table 2.12) by comparing the total area of habitat at risk among regions. However, the proportion of coral reefs and seagrass in each region that is within the Marine Risk Index is also presented as this is most relevant for determining management priorities within a region.

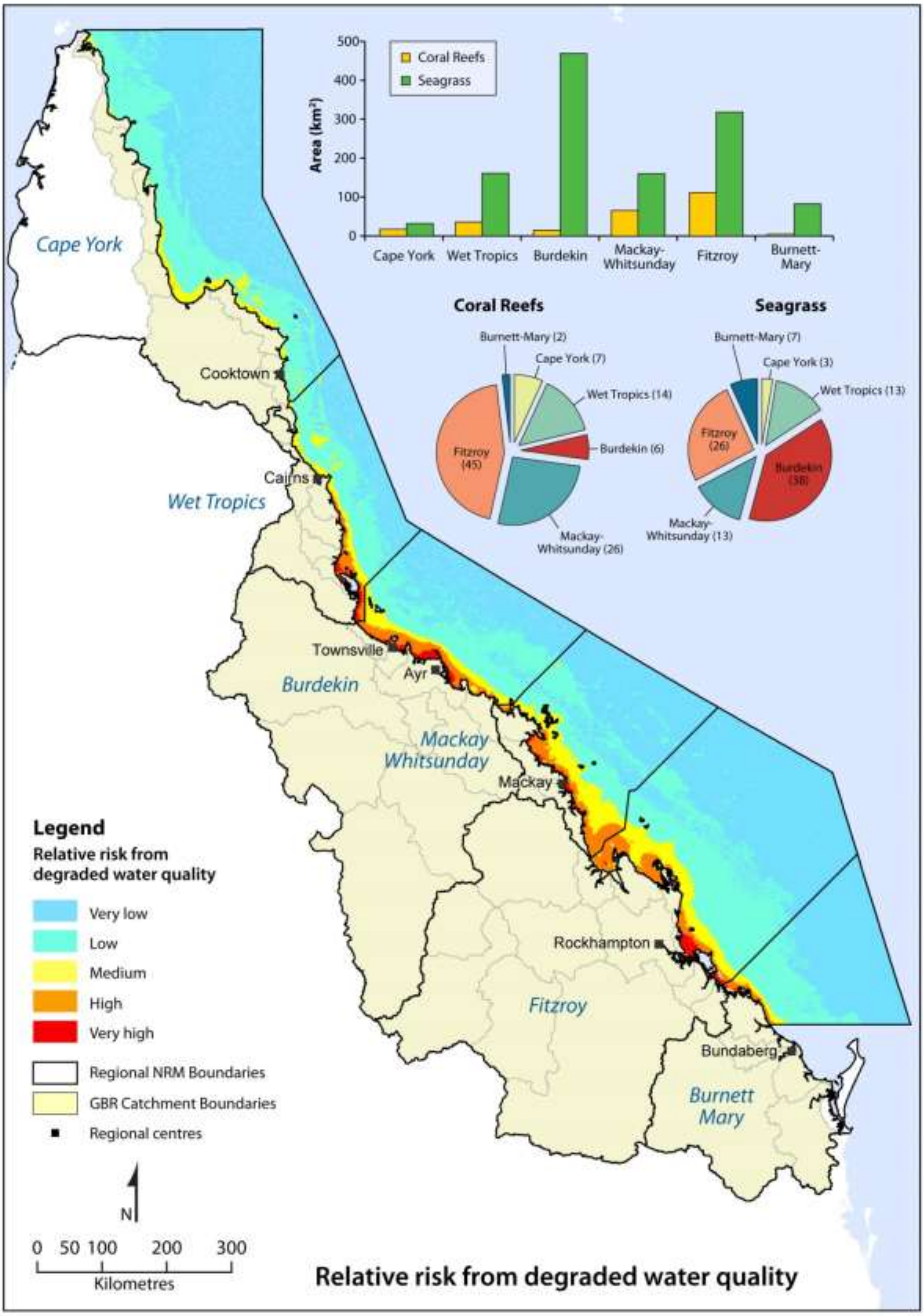


Figure 2.18. Combined assessment (1 km^2 resolution) of the relative risk of water quality variables (output of Part 2 shown in Figure 2.2). The areas (in km^2) of habitat types within each class are shown in Table 2.12. The Marine Risk Index for coral reefs and seagrass is defined from the combined areas of the High and Very High relative risk classes. Inset bar chart shows reef and seagrass areas in the Marine Risk Index by Region; pie charts show affected coral reef and seagrass areas for each Region as a percentage of the total GBR coral reef and seagrass areas in the Marine Risk Index.

Table 2.12. Area of coral reefs, seagrass meadows, and GBR lagoon waters within the 5 relative risk classes. 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 100. The greatest area/highest scores are shaded dark grey, second is shaded light grey.

Habitat **NRM Regions**	**V Low**	**Low**	**Medium**	**High**	**V High**	**Total**	**Sum High & V High**	**% of habitat in Region (High & V High)**	**Marine Risk Index**
	Area (km^2)								
Coral Reefs									
Cape York	3,585	6,147	546	17	0	10,295	17	<1	15
Wet Tropics	121	1,809	448	36	<1	2,415	36	1	32
Burdekin	704	2,206	24	14	<1	2,948	15	<1	13
Mackay Whitsunday	2,147	826	133	61	5	3,171	66	2	59
Fitzroy	3,726	964	38	103	8	4,840	111	2	100
Burnett Mary	10	265	1	5	0	282	5	2	4
Seagrass									
Cape York	1,258	8,711	1,329	32	0	11,330	32	<1	7
Wet Tropics	175	4,240	278	102	59	4,855	161	3	34
Burdekin	1,281	4,160	150	333	136	6,060	470	8	100
Mackay Whitsunday	5	21	210	136	25	396	160	37	34
Fitzroy	201	5,050	177	303	15	5,746	319	6	68
Burnett Mary	458	5,561	210	76	7	6,313	83	1	18
GBR lagoon waters									
Cape York	59,433	30,785	3,823	73	0	94,114	73	<1	2
Wet Tropics	13,544	12,558	2,698	1,777	462	31,038	2,239	7	51
Burdekin	22,258	17,138	3,313	2,794	777	46,280	3,571	8	82
Mackay Whitsunday	26,300	12,309	5,964	3,433	326	48,332	3,759	8	86
Fitzroy	48,084	26,371	6,482	3,696	660	85,293	4,355	5	100
Burnett Mary	26,127	9,565	848	658	54	37,252	712	2	16

Key findings:

- The greatest area of coral reef within the Very High and High relative risk classes is in the Fitzroy region (see inset Figure 2.18 and Figure 2.19). These classes are summed for the Marine Risk Index and reflect that less than one third of the coral reef area affected in the Fitzroy is affected in all other regions except Mackay Whitsunday (59%). However, the proportion of coral reefs in each region that are within the High and Very High classes are approximately equal for all regions and is less than 2%.

- The area of coral reef in the Very High class of relative risk is greatest in the Fitzroy (8 km^2), and second-greatest in Mackay Whitsunday (5 km^2). Less than 1 km^2 of coral reef area is within the Very High class for the other four regions (Table 2.12). The greatest area within the High class is in Fitzroy (103 km^2) and Mackay Whitsunday is second (61 km^2), and less than 72 km^2 in total for all of the other regions combined (Table 2.12 and Figure 2.19). In the Medium class (not in the Marine Risk Index but shown in Table 2.12) the greatest area of coral reef is within Cape York (546 km^2) and second in the Wet Tropics (448 km^2). However, the relatively large area of coral reefs within the Medium class in Cape York is assessed with low confidence due to issues with the remote sensing of

Chl and TSS exceedance identified in the above, in addition to the method used for allocating DIN and TSS plume loading in the Region; all of these factors require further validation. The largest areas of coral reefs are within in the Very Low or Low classes for all regions.

- The greatest area of seagrass within the Very High and High relative risk classes is in the Burdekin region (see inset Figure 2.18 and Figure 2.19). These classes are summed for the Risk Index and reflect that less than one third of the seagrass area affected in the Burdekin is affected in all other regions except Fitzroy (68%). The proportion of seagrass in each region that is within the Very High and High classes is less than 10% of the total seagrass area within all regions except for Mackay Whitsunday which is 37%.

- The area of seagrass in the Very High relative risk class is greatest in the Burdekin (136 km^2), and second-greatest in the Wet Tropics (59 km^2), and less than 47 km^2 of seagrass area is within all of the other four regions combined (Figure 2.18, 2.19 and Table 2.12). The greatest area within the High class is in Burdekin (333 km^2), second-greatest in the Fitzroy (303 km^2), and less than 346 km^2 in all of the other regions combined. When the sum of the area in the Very High and High classes are expressed as a percentage of the total seagrass area in each region, the proportion is highest in Mackay Whitsunday at 37%, and second-highest in the Burdekin (8%) and Fitzroy (6%). However, the total area of seagrass affected is far greater in the Burdekin and Fitzroy; the differences in percentages indicate how much greater the total seagrass areas are in the Burdekin and Fitzroy regions (6,060 km^2 and 5,746 km^2 respectively; Figure 2.10) compared to 430 km^2 for the Mackay Whitsunday region. In the Medium class (not in the Marine Risk Index but shown in Table 2.12) the greatest area of seagrass is by far the greatest in Cape York (1,329 km^2). However, as noted above further validation of the datasets in the Cape York region is required.

- The greatest area of GBR lagoon waters within the Very High and High relative risk classes is in the Fitzroy (Figure 2.18). These classes are summed for the Marine Risk Index and reflect that the area of GBR lagoon waters in the Marine Risk Index are reasonably comparable for the Fitzroy (100%), Mackay Whitsunday (86%) and Burdekin (82%). The result in the Wet Tropics is approximately half of the area affected in the Fitzroy, 16% in Burnett Mary and less than 5% in Cape York.

- The area of GBR lagoon waters in the Very High relative risk class is greatest in the Burdekin (777 km^2) and second in the Fitzroy (660 km^2). The greatest area within the High class is in the Fitzroy (3,696 km^2), Mackay Whitsunday (3,433 km^2) and Burdekin (2,794 km^2) regions (Table 2.12 and Figure 2.19). When the sum of the area in the Very High and High classes are expressed as a percentage of the total area in the regions, the percentage is less than 10% for all regions. For the Medium class, unlike coral reefs and seagrass where the greatest area is within the Cape York region (not in the Marine Risk Index but shown in Table 2.12), the greatest total area affected is in the Fitzroy (6,482 km^2) and Mackay Whitsunday (5,964 km^2) regions.

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 Fitzroy Island, Hinchinbrook Island, Magnetic Island, many of the islands in the Whitsunday Group and the Keppel Island group. In the case of seagrass meadows, many of the highest risk areas overlap with dugong protection areas (DPAs), which are assigned because of the large populations of dugongs feeding in the associated seagrass meadows.

In summary, the 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 NRM regions. When all water quality variables are combined into the Marine Risk Index, the risk is greatest for coral reefs in the Fitzroy and Mackay Whitsunday regions, and for seagrass in the Burdekin and Fitzroy regions. The total areas influenced by the Marine Risk Index are greatest in the Fitzroy, Mackay Whitsunday and Burdekin regions, which may be important for habitats other than corals and seagrass. In most cases, the proportion of the habitat area in each Region that is within the High and Very High relative risk classes (forming the Marine Risk Index) is less than 10%, except in the case of seagrass meadows in the Mackay Whitsunday region where 37% of the area of seagrass in the region is within the Marine Risk Index area.

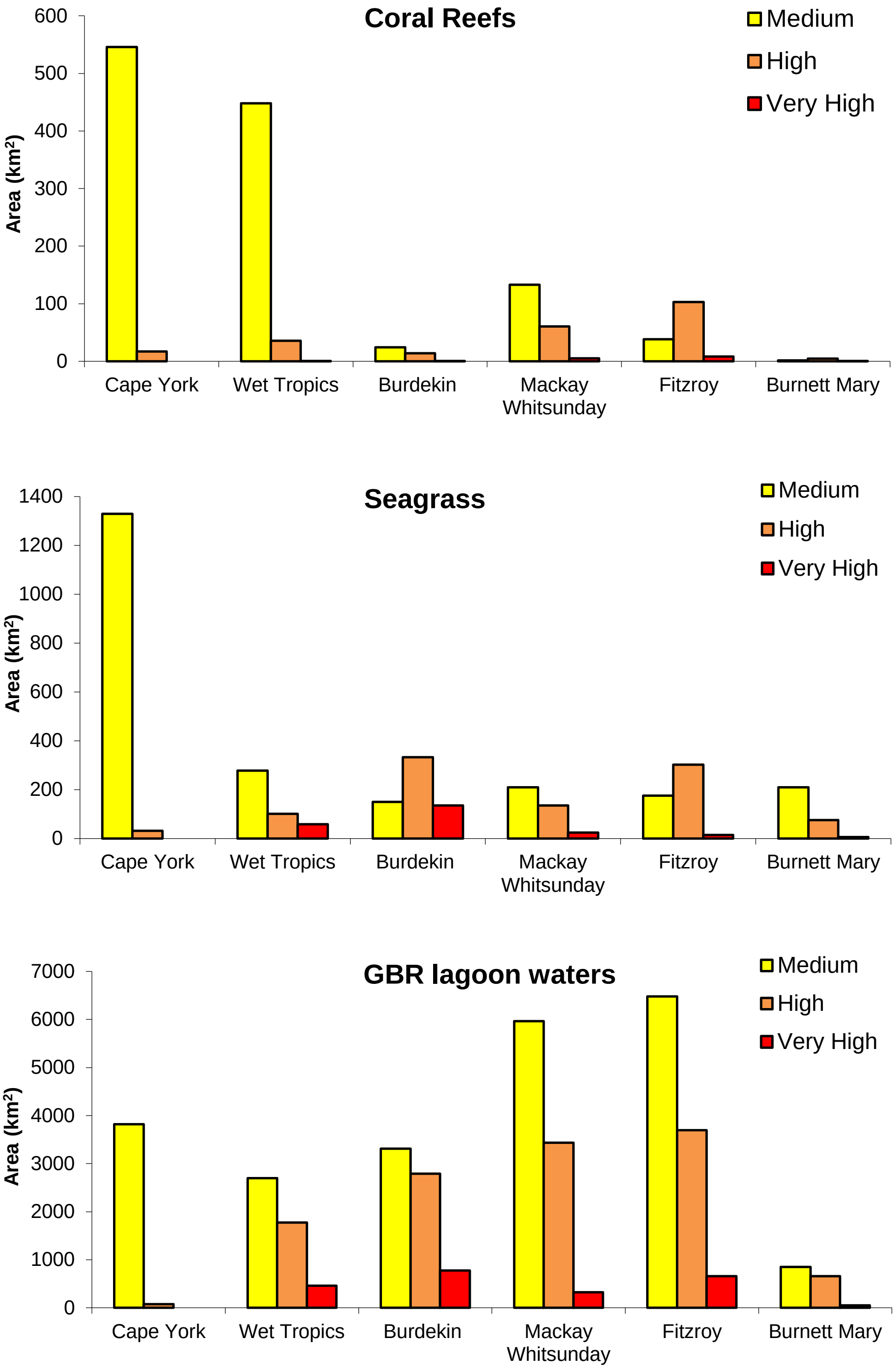


Figure 2.19. Area of coral reefs, seagrass, and GBR lagoon waters within the Medium, High and Very High relative risk classes from the combined water quality assessment. The y-axis scale differs among the plots.

2.4.4 Part 3: Relative risk of degraded water quality to GBR ecosystems

To inform management priorities to address the risks identified above, it is necessary to understand the influence of river discharge in each of the Regions, as these discharges carry a majority of the anthropogenic pollutant load into the GBR lagoon. The results of this part of the assessment are presented in two components: a) assessment of the pollutant loads and b) combining the marine relative risk (Marine Risk Index) with the pollutant load information (Loads Index).

a) Assessment of end-of-catchment pollutant loads

Understanding the sources of pollutants is important for management prioritisation, and when considering river discharges to the GBR, the anthropogenic pollutant loads are the most relevant. However, in the case of pesticides, it is the toxicity and therefore concentration that is most relevant but concentration data is limited across the GBR. Therefore, in the final conclusions relating to pesticide risk the evidence is drawn from a combination of load and concentration data from specific locations.

To relate the results of the Marine Risk Index to catchment influences, the anthropogenic loads were expressed as the proportion of total GBR load for each Region for TSS, DIN, and PSII herbicides (Table 2.13). This recognises that while the total GBR load is important in influencing the marine water quality conditions, it is only the anthropogenic proportion that can be factored into management. These proportional contributions were then anchored (to normalise to a standard scale) and averaged to generate a Loads Index (Table 2.14). This assumes that the relative importance of each load is equal, which in reality is unlikely to be the case, although there is currently insufficient knowledge to weight the importance of the three pollutants relative to each other.

Once the marine relative risks and relative pollutant loads are known, the pollutant load information allows managers to track back to management priorities within catchments and land uses. To inform these decisions, further analysis of catchment pollutant loads could be undertaken for TSS, DIN, and PSII herbicides and include: comparisons between catchments and among regions of the total and anthropogenic load contributions to GBR total loads, and identification of the top 5 catchments in terms of the anthropogenic load expressed as a proportion of the GBR total load. For example, based on modelling:

- The top 5 contributors to the total GBR TSS anthropogenic load are (from 1-5) [Catchment (Region, catchment load)]: Burdekin River (Burdekin, 2318 kilotonnes), Fitzroy River (Fitzroy, 1362 kilotonnes), Herbert River (Wet Tropics, 352 kilotonnes), Mary River (Burnett-Mary, 301 kilotonnes), and the Don River (Burdekin, 211 kilotonnes).

- The top 5 contributors to the total GBR DIN anthropogenic load are (from 1-5): the Johnstone River (Wet Tropics, 851 tonnes), Fitzroy River (Fitzroy, 475 tonnes), Haughton River (Burdekin, 474 tonnes), Burdekin River (Burdekin, 401 tonnes), and the Tully River (Wet Tropics, 345 tonnes).

- The top 5 contributors to the total GBR PSII herbicide load are (from 1-5): Herbert River (Wet Tropics, 2,660 kg,), Johnstone River (Wet Tropics, 2401 kg), Mulgrave-Russell River (Wet Tropics, 1,776 kg), Tully River (Wet Tropics, 1,740 kg), and the Haughton River (Burdekin, 1,426 kg). However, these figures are currently under review and show distinct differences from monitoring data (see below) which reflects annual variability.

- There are 7 rivers with average anthropogenic contributions of combined TSS, DIN and PSII herbicides loads exceeding 5%, ordered from highest to lowest average contribution here: (1) Burdekin River (17% average), (2) Fitzroy River (12%), (3) Johnstone River (12%), (4) Herbert River (10%), Haughton River (7.1%), Tully River (7.3%) and the Mulgrave-Russell River (5.7%).

More detailed analyses of the load data are outside of the scope of this assessment but are recommended to be undertaken to guide future management priorities.

For PSII herbicides the concentrations are more ecologically relevant than loads. For determining risk to aquatic biota from PS II herbicides, assessing toxic effects from concentration data (Section 2.4.5) is a more ecologically relevant method than an assessment of the PSII load transported to the marine environment. These issues are illustrated with the most recent annual loads based on monitoring data from the 2010-11 monitoring year. By region, Fitzroy was the greatest contributor (66%), followed by Mackay Whitsunday (15%), Burdekin/Haughton (10%), Wet Tropics (6%) and Burnett (3%). The greatest contributor of total PSII herbicide loads was the Fitzroy River (8,532 kg, 66% of total GBR load), followed by the Pioneer River (1,254 kg, 10%), Burdekin River (886 kg, 7%), Sandy Creek (701 kg, 5%), Tully River (455 kg, 4%), Burnett River (446 kg, 3%), Barratta Creek (358 kg, 3%), Herbert River (287 kg, 2%) and Johnstone River (58 kg, <1%). However, the PSII modelled load does provide an indication of the contribution of PSII herbicides from each catchment based on an 'average' year, i.e. a long term average that adjusts for extreme weather conditions.

Table 2.13. Total and total anthropogenic loads for DIN, TSS and pesticides from rivers discharging into the marine NRM regions and, for each region, as percentages of the total GBR load, and total regional and GBR anthropogenic load.

Parameter NRM Regions	Total Load	Anthropogenic Load	Regional Anthropogenic load % of Total GBR Load
TSS (000s tonnes)			
Cape York	495	229	3
Wet Tropics	1,228	782	9
Burdekin	4,104	2,807	32
Mackay Whitsunday	514	363	4
Fitzroy	2,034	1,487	17
Burnett Mary	475	382	4
Total	**8,850**	**6,051**	
DIN (tonnes)			
Cape York	492	5	<1
Wet Tropics	4,437	2,023	20
Burdekin	2,352	1,114	11
Mackay Whitsunday	901	627	6
Fitzroy	1,272	503	5
Burnett Mary	563	442	4
Total	**10,018**	**4,714**	
PSII Herbicides (kg)			
Cape York		5	<1
Wet Tropics		10,229	61
Burdekin		2,219	13
Mackay Whitsunday		2,045	12
Fitzroy		638	4
Burnett Mary		1,556	9
Total		**16,692**	

To generate a Loads Index from the information presented in Table 2.13, we averaged the Regional anthropogenic load contributions as a proportion of the total GBR load for TSS, DIN and PSII herbicides. These results were then anchored it to the maximum value to generate a relative assessment of load contributions to the GBR, forming a Loads Index for each Region (Table 2.14). The assessment shows the greatest relative contribution of combined end of catchment loads to the GBR is from the Wet Tropics region, followed by the Burdekin region. The contributions from the Mackay Whitsunday, Fitzroy and Burnett Mary regions are similar and are around one quarter of the contributions of the Wet Tropics. The load contributions from the Cape York region are minor compared to all other regions.

Table 2.14. Loads Index for TSS, DIN and PSII Herbicides derived from the average of the Regional anthropogenic load contributions to the total GBR load. The Region that had the largest average load was given a score of 100; all other Regions are expressed as a percentage based on the area affected in each Region relative to the area in the Region with the largest average. Source: Derived from Waters et al. (in press).

	Regional Anthropogenic Load as a proportion of the Total GBR Load					
Region	**TSS**	**DIN**	**PSII**	**Average**	**Loads Index**	**Loads Index Rank**
Cape York	2.6	0.05	0.03	0.04	0	6
Wet Tropics	8.8	20.2	61.3	30.1	100	1
Burdekin	31.7	11.2	13.3	18.7	62	2
Mackay Whitsunday	4.1	6.3	12.2	7.5	25	4
Fitzroy	16.8	5	3.8	8.5	28	3
Burnett Mary	4.3	4.4	9.3	6.0	20	5
			Max	*30.1*		

An important factor in attributing the Marine Risk Index to the influence of the Regions or individual rivers is that the rivers in each Region may influence a greater area than just that within the marine NRM region boundary which has been directly assigned to each of the 6 NRM regions. The sheer size and episodic nature of river flow in the large catchments of the Burdekin and Fitzroy regions means that marine areas and habitats outside of the associated marine NRM regions may also be affected by these rivers. For example, satellite imagery during periods of high flow has shown that the Burdekin River influences areas as far north as the Wet Tropics marine NRM region, and that the Fitzroy River may influence the Mackay Whitsunday marine NRM region. Without more detailed analysis of river flow and hydrodynamics in the GBR, it is necessary to make the assumption that the rivers in each catchment NRM region only contribute to the risk in the corresponding marine NRM region. This is noted as a limitation to this aspect of the assessment, and suggestions on how this might be addressed for future assessments are included in Section 4.

However, 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 in Chapter 1 of the Supporting Studies (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). Furnas et al. (2013a) defined the volumetric contribution of river discharge and DIN loading from 8 rivers to the COTS Initiation Zone between Lizard Island in Cairns (Chapter 1 of the Supporting Studies, Table 1.3c).

For this assessment, we used the total volumetric contribution of river discharge to the COTS Initiation Zone (Table 2.15). An assessment of modelled DIN load data was also investigated but the uncertainties associated with limited validation with monitoring results were considered to be too limiting at this time. These included: the Normanby River in the Cape York region; the Daintree, Barron, Russell-Mulgrave, Johnstone, Tully and Herbert Rivers in the Wet Tropics region; and the Burdekin River in the Burdekin region. The greatest contribution was identified from the Daintree River, and all other contributions were normalised against the Daintree to show relative contributions (Table 2.15). The proportion that each Region contributes was then calculated by summing all values and presenting each region as a percentage of the total. The majority of the estimated influence (86%) is from the Wet Tropics rivers and a small proportion (14%) from the Burdekin River (Table 2.15 below). This information was incorporated into an additional factor, the 'COTS Influence Index' by anchoring these results which are then 100% for the Wet Tropics region, 16% for the Burdekin region and zero contribution from all other Regions. While this assessment relies on many assumptions associated with DIN loads in river discharges and differences in inter annual variability, it does provide a way of recognising the relative influence of the regional river discharges to the ecologically important initiation area of COTS primary outbreaks.

Table 2.15. Relative volumetric contribution of individual rivers to the COTS outbreak initiation zone between Cairns and Lizard Island. The relative contributions of different rivers were normalised against the largest riverine contribution to the region, the Daintree. The COTS Load Influence is based on the proportional contribution of the Regions to the COTS Initiation Zone, and then anchored to the maximum value and expressed as a relative percentage (0-100).

River	Volumetric Contribution to the COTS Initiation Zone	NRM region	COTS Load Influence by NRM region	COTS Load Index (Anchored to max COTS Load Influence) by NRM region
Normanby	0	Cape York	0	0
Daintree	100	Wet Tropics	86	100
Barron	52			
Russell-Mulgrave	59			
Johnstone	29			
Tully	57			
Herbert	7			
Burdekin	49	Burdekin	14	16
Total	**353**			
		Mackay Whitsunday	0	0
		Fitzroy	0	0
		Burnett Mary	0	0

b) Combined assessment: Relative Risk Index

Using the information obtained through the above analyses for the marine water quality variables and end of catchment pollutant loads, it is possible to make an assessment of the management priorities for minimising the risk of water quality impacts in the GBR. This section presents an option for a quantitative combined assessment to inform water quality management priorities across the NRM regions in the GBR. In this assessment the limitation identified above related to the assumption that river influence from an NRM region is constrained to that same marine NRM region is recognised.

As described in the methods (Section 2.3.5), to provide an overall ranking of relative risk between the NRM regions 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 (Table 2.16). For coral reefs, the two loads related indexes, i.e. the COTS Influence Index and the Loads Index, were combined by summing the scores and then anchoring the result. For seagrass only the Loads Index and the Marine Risk Index are used. 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 2.17); summarised in Figure 2.20.

Table 2.16. 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 Region that had the maximum value was given a score of 100; all other Regions are expressed as a percentage based on the value in each Region relative to the area in the Region with the maximum value.

Coral Reefs **NRM region**	**Coral Reef Marine Risk Index**	**Loads & COTS Index**	**Sum of Indexes**	**Coral Reef Relative Risk Index (Anchored)**	**Rank**
Cape York	15	0	15	12	5
Wet Tropics	32	100	132	100	1
Burdekin	13	39	52	40	4
Mackay Whitsunday	59	13	72	54	3
Fitzroy	100	14	114	86	2
Burnett Mary	4	10	14	11	6
		Max	*132*		

Seagrass **NRM region**	**Seagrass Marine Risk Index**	**Loads Index**	**Sum of Indexes**	**Seagrass Relative Risk Index (Anchored)**	**Rank**
Cape York	7	0	7	4	6
Wet Tropics	34	100	134	83	2
Burdekin	100	62	162	100	1
Mackay Whitsunday	34	25	59	37	4
Fitzroy	68	28	96	59	3
Burnett Mary	18	20	38	23	5
		Max	*162*		

Table 2.17. Results of the overall risk assessment using a sum of the anchored Indexes for coral reefs and seagrass (final output from Part 3 in Figure 2.3). The Region that had the largest sum of indexes was given a score of 100; all other Regions are expressed as a percentage based on sum of indexes in each Region relative to the sum in the Region with the maximum sum of indexes.

Coral Reef and Seagrass **NRM Region**	**Coral Reef Relative Risk Index**	**Seagrass Relative Risk Index**	**Sum of Indexes**	**Relative Risk Index (Anchored)**	**Rank**
Cape York	12	4	16	9	6
Wet Tropics	100	83	183	100	1
Burdekin	40	100	140	76	3
Mackay Whitsunday	54	37	91	50	4
Fitzroy	86	59	145	80	2
Burnett Mary	11	23	34	19	5
		Max	*183*		

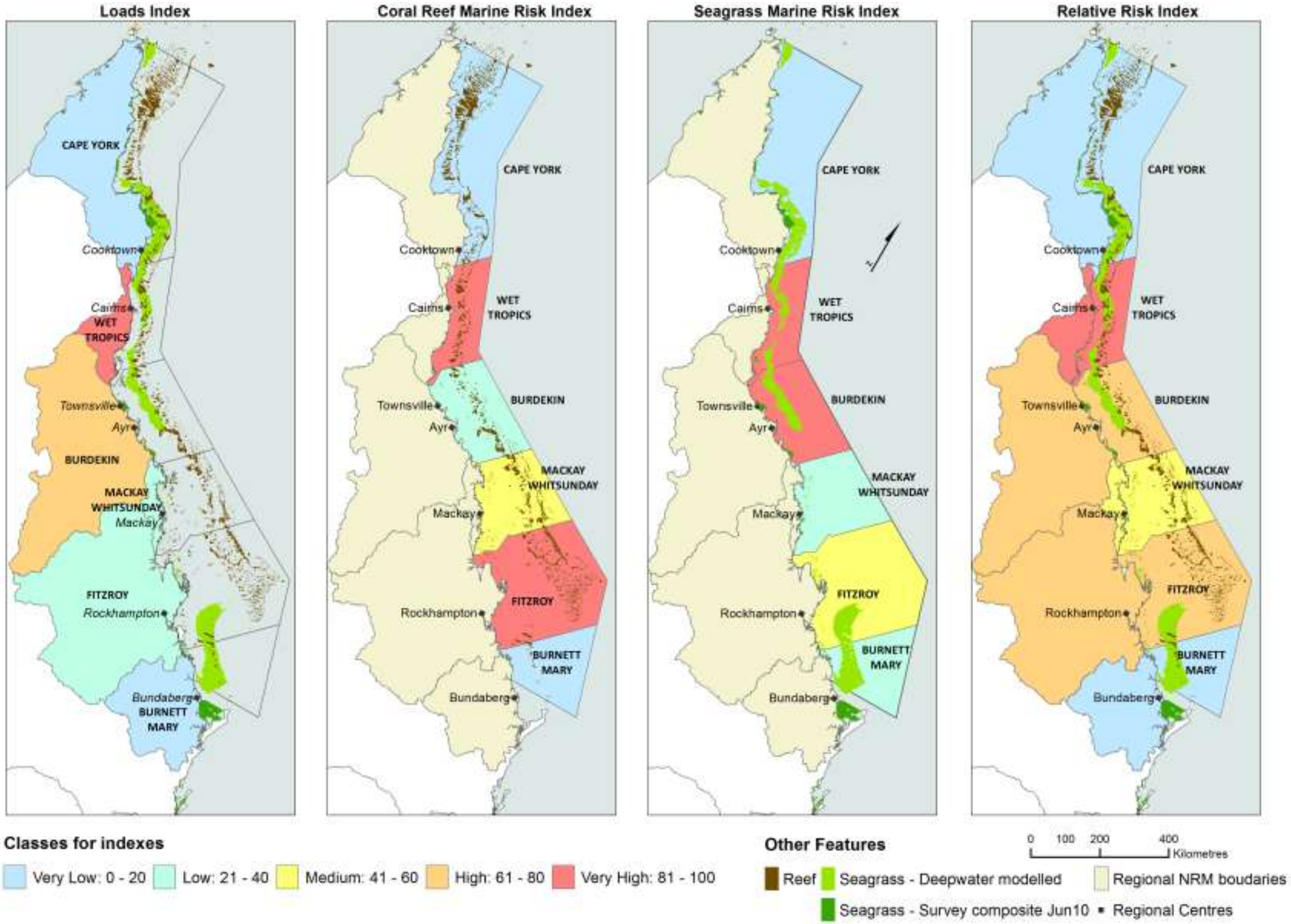


Figure 2.20. Map summarising the results of the Loads Index, Marine Risk Indexes (coral reefs and seagrass) and the Relative Risk Index. The assessment for coral reefs also includes the COTS Influence Index associated with the extent of the influence of regional river discharge to the COTS Initiation Zone; the scores are 100 for the Wet Tropics, and 16 for the Burdekin region. The method for deriving and combining the indexes is provided in Section 2.4.4.

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 GBR and end -of -catchment anthropogenic loads of DIN, TSS and PSII herbicide. These are:

- **Coral reefs:** Wet Tropics region, followed by the Fitzroy region. The rank of the remaining regions is the Mackay Whitsunday, Burdekin, Cape York and Burnett Mary region.
- **Seagrass meadows:** Burdekin region, followed by the Wet Tropics. The rank of the remaining regions is the Fitzroy, Mackay Whitsunday, Burnett Mary and Cape York region.
- **Coral reefs and seagrass meadows combined:** Wet Tropics, followed by the Fitzroy and Burdekin (both ~80% of the relative risk compared to the Wet Tropics). The relative risk to the Mackay Whitsunday region is half the greatest risk, followed by the Burnett Mary and Cape York regions. It must be reiterated that these are relative assessments and therefore indicates that the Burnett Mary and Cape York are low relative to the other regions, but may be exposed to a range of risks that still warrant management to maintain the ecosystem values in these regions.

A number of differences are also evident in cross shelf locations of reefs and seagrass, leading to the following conclusions:

- **Mid shelf reefs south of Cooktown:** DIN due to the link to the initiation of COTS outbreaks, and to a lesser extent, the effects of increased nutrients on bleaching susceptibility.
- **Inner shelf reefs south of Cooktown:** Primarily TSS, and secondly, DIN and PSII herbicides.
- **Seagrass:** Primarily TSS, and secondly PSII herbicides. The effects of nutrients are not fully understood but there is evidence of changes in seagrass cover linked to excess nutrients.

It is noted that the value of using this type of final assessment where all values are combined in the end 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 catchments based investments.

2.4.5 Conclusions

The results of the three main parts of the study show some clear patterns, and in many cases distinct differences, between the relative risk of the key pollutants to coral reefs and seagrass meadows among NRM regions. In summary:

- The area of coral reefs at greatest risk from all of the sediment and nutrient variables (except for the COTS Initiation Zone) was highest in the Burdekin and Fitzroy regions. The COTS Initiation Zone straddles the boundary between the Cape York and Wet Tropics regions, and approximately 60% of reefs within the Zone are located in the Cape York marine NRM region.
- The area of seagrass at greatest risk from all of the sediment and nutrient variables was highest in the Burdekin region and second highest in the Wet Tropics region, however, the areas are less than one quarter of the areas affected in the Burdekin region in all cases. The area of seagrass within the highest assessment classes of the nutrient variables is greatest in the Burdekin region, and then the Fitzroy.
- Of the NRM regions examined in the assessment, the Mackay Whitsunday region presents the highest ecological risk of pesticides with the PSII herbicide risk of ‘High’ and ‘Medium’ extending off

the mouths of the Pioneer and O'Connell Rivers and Sandy Creek. This is followed by the Burdekin (due to the Barratta Creek and Haughton Rivers but not the Burdekin River itself), Wet Tropics, Fitzroy and Burnett Mary regions. It should be noted that the risk to 'pesticides' here is represented by PSII herbicides as these are the dominant pesticides detected in catchments, however a total of 34 pesticides (herbicides, insecticides and fungicides) have been detected.

- A qualitative assessment of the potential risk of PSII herbicides to other GBR ecosystems showed that a variety of coastal habitats (e.g. wetlands, estuaries, mangroves and seagrass) which provide important ecological services (including nursery habitats, primary productivity and nutrient cycling) to GBR biota are at risk. The assessment classified the risk of pesticides in the GBR into five groups ranging from Very Low to Very High. Within the freshwater reaches of rivers and freshwater/coastal wetlands, the risk of pesticides (PSII herbicides and some non-PSII pesticides) was assessed to be Very High to Medium, particularly for the coastal stream networks that drain a relatively large area (> 20%) of intensive agriculture such as Barratta and Sandy Creeks. In the estuarine reaches of the rivers, the risk of pesticides was mostly within High to Low risk. A similar risk occurs for the coastal marine environment including intertidal and subtidal seagrass meadows. Coral reefs and seagrass meadows on the inner shelf (includes but not limited to areas extending up to 20 km from the coast) generally fell into the lowest risk classes depending on the region and adjacent catchment(s). The risk to coral reefs on the mid and outer shelf was considered Very Low to no risk.
- From a combined assessment of all of the water quality variables the risk was found to be greatest for coral reefs in the Fitzroy and Mackay Whitsunday regions, and for seagrass in the Burdekin and Fitzroy regions. In most cases, the proportion of the habitat area in each region within the High and Very High classes is less than 10%, except in the case of seagrass meadows in the Mackay Whitsunday region where 37% of the area of seagrass in the region is within the Marine Risk Index area. It should be noted that this assessment does not account for the potential synergistic or antagonistic effects that these multiple stressors when acting together may have on ecosystems.
- In many cases, these differences in relative risk to coral reefs and seagrasses between regions can be related to the characteristics of pollutant load inputs to the GBR lagoon. The largest sources of anthropogenic TSS loads is from rivers in the Burdekin region, the greatest contribution to the anthropogenic DIN load is from rivers in the Wet Tropics region, and the greatest contribution to the PSII herbicide load is from rivers in the Wet Tropics region. There are 7 rivers where the average of the summed anthropogenic contributions of TSS, DIN and PSII herbicides loads exceed 5% of the GBR total, ordered from highest to lowest average contribution here: (1) Burdekin River (17% average), (2) Fitzroy River (12%), (3) Johnstone River (12%), (4) Herbert River (10%), Haughton River (7%), Tully River (7%) and the Russell Mulgrave River (6%).
- The combination of the assessment of marine water quality relative risk and anthropogenic end-of-catchment pollutant loads allows us to draw conclusions about the overall risk of pollutants to the GBR. The ranking of the relative risk of degraded water quality between the NRM regions in the GBR is: Wet Tropics > Fitzroy > Burdekin > Mackay Whitsunday > Burnett Mary > Cape York. Priority areas for management of degraded water quality in the GBR are: Wet Tropics for nitrogen management; Mackay Whitsunday and lower Burdekin for PSII herbicide management; and Burdekin and Fitzroy for suspended sediment management.

While the areas of coral reef and seagrass affected in highest risk categories for individual variables and all of the variables combined are relatively small, they are often located in some of the highly valued tourism and recreation sites of the GBR. In addition, the habitats of the Burnett Mary region are considered to be undervalued in this assessment, as the GBR Marine Park and World Heritage Area boundary does not include all of the habitat areas that would be affected by the catchments of the Burnett Mary region. In particular, there is a large area of seagrass to the south of the boundary in Hervey Bay which is known to provide important habitat for species that also inhabit the GBR Marine Park that should be incorporated in any future assessments of the influence of water quality on regional habitats.

The final conclusions of the relative risk from water quality to GBR ecosystems are presented in Part B of this report drawing on the results of this assessment and the Supporting Studies (compiled as a separate report).

Part B: Overall conclusions of the relative risk between sediments, nutrients and pesticides and between land uses, industries and catchments in the GBR

3 Relative risk from degraded water quality to GBR ecosystems

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.

3.1 Additional information to support the assessment in Part A

Several limitations to the quantitative assessment (Part A of this report) are identified in Section 4; 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. The Supporting Studies have informed the selection of variables and methods of analysis used in the risk assessment described in Section 2. The Supporting Studies also strengthen our understanding of the consequences of pollutant impacts on coral reefs and seagrasses. In particular: Chapter 1 emphasises the importance of nutrients in the initiation of COTS and therefore loss of coral cover; Chapter 2 confirms the relative importance between nitrogen and phosphorus in driving productivity in the GBR lagoon; Chapter 3 reviews the effects of sediments and sedimentation on coral reef communities; Chapter 4 provides new information on the relative risk of PSII herbicides to coastal and marine ecosystems, identifying the highest risk areas to be in freshwater and coastal wetlands, estuarine areas and coastal seagrass and inshore reef communities; Chapter 5 develops relationships between flood plume frequency and end of catchment pollutant loadings to define plume water types related to water quality characteristics; and Chapter 6 provides a case study that shows a correlation between plume water types and seagrass cover with a supporting review on the impacts of water quality on seagrass in Chapter 7. A small amount of resources were also provided to analyse water quality and phytoplankton populations in flood conditions, provided as Chapter 8.

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

Seagrass meadows and dugong and green turtle populations

The links between the condition and extent of seagrass meadows in the GBR has important implications for populations of dugongs and green turtles in the GBR, and consideration of this relationship in this assessment is therefore critical. Loss of seagrass habitat as a result of severe weather events and degraded water quality has led to increased mortality of dugong and turtles in recent years. Cyclone Yasi in the central GBR and flooding in the southern GBR in 2011 resulted in devastating loss of seagrass (Coles et al. 2011; McKenzie and Unsworth, 2011; McKenzie et al. 2012) along the GBR coast from Hervey Bay to Cairns. This loss came on top of declining seagrass health in the central GBR (McKenzie et al. 2010a). The dugong population in the GBR is totally reliant on seagrass communities. Evidence shows that the southern dugong population was significantly reduced by commercial harvesting between 1847 and 1969 so the population is at best only about 25% what might be expected (Marsh et al. 2005). Given this population (reduced though it is) is a potential surrogate for the quantity of seagrass needed to maintain it, the loss of seagrass from the chronic impacts of water quality followed by the acute impact of the extreme cyclonic event and flooding in 2011 saw the southern dugong population reduce from an estimate of 2500 animals in 2005 to 600 in November 2011 (Sobtzick et al. 2012). It is considered that much of the change in population estimates between 2005 and 2011 can be explained by animals moving to locations outside the survey area to search for seagrasses (Sobtzick et al. 2012).

The number of recorded dugong and turtle strandings has also increased significantly in recent years. In 2011 there were over 180 recorded deaths of dugong on the Queensland coast (Meager and Limpus, 2012) believed to be due mainly to starvation associated with the loss of seagrass (Bell and Ariel, 2011). As shown in Figure 3.1, turtle deaths (mostly green turtles) on the Queensland coast nearly doubled between 2010 and 2011 (Meager and Limpus, 2012) have been attributed to a range of complications resulting from a lack of food. An assessment of the effects of the 2010-2011 flood events in the GBR show that the dugong deaths were potentially increasing both because of the chronic loss of seagrass (2009 and 2010) and increased dramatically in 2011 (GBRMPA, 2011).

This evidence, coupled with current knowledge of the impacts of degraded water quality on seagrass meadows in the GBR (see above and Chapter 7 of the Supporting Studies), strengthens the importance of the implications of increased suspended sediment discharge from land based sources to the GBR.

GBR catchment land use

Major land uses in the Great Barrier Reef region are shown in Figure 3.2. Grazing is the dominant agricultural land use. Sugarcane and horticultural crops dominate in the high rainfall and coastal irrigation areas. Large sections of summer and winter rain-fed grain crops and irrigated cotton are prevalent in the inland areas of the Fitzroy region.

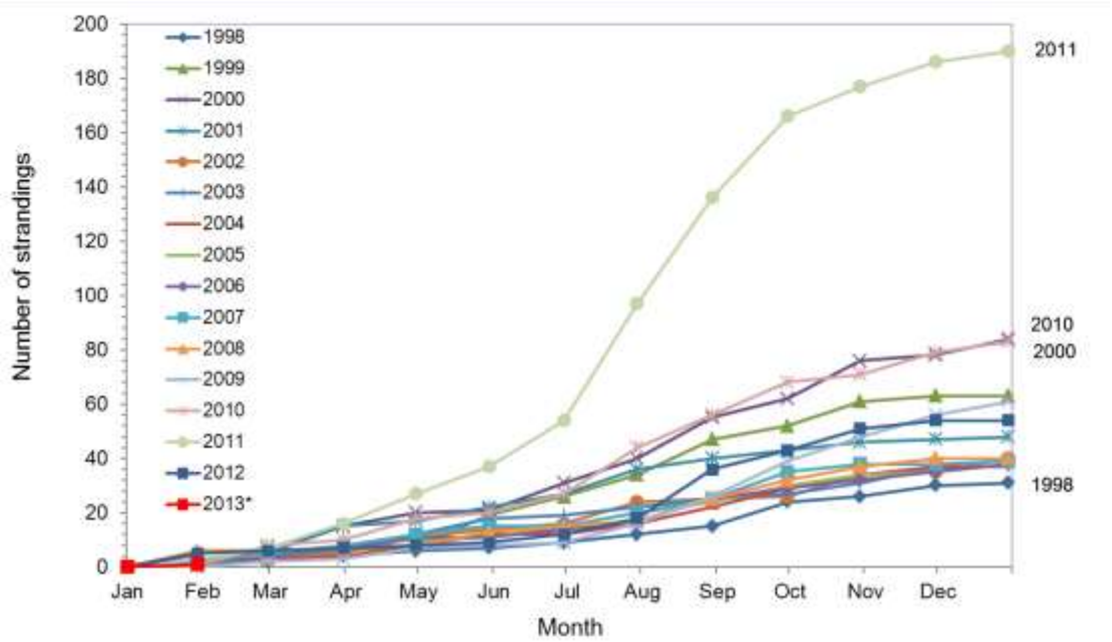
To relate the results of the Relative Risk Index to catchment management priorities, reference can be made to current knowledge of the pollutant contributions from different land uses in each Region. The latest information on pollutant sources in the GBR catchments is synthesised in SCS Chapter 4 *Sources of sediment, nutrients, pesticides and other pollutants in the Great Barrier Reef catchment* (Kroon et al. 2013). In summary:

- Grazing lands contribute 75% of the total TSS load. Land use, soil properties, the extensive area involved, river discharge flows and geomorphology all contribute to the loads. Provenance tracing shows that most sediment comes from a combination of gully and streambank erosion and subsoil erosion from hillslope rilling, rather than broad-scale hillslope sheetwash erosion.

- Eighty percent of DIN originates from the Wet Tropics, Burdekin and Mackay Whitsunday regions, primarily from fertilised land use and in particular, land used for sugarcane cultivation.

- Results from Source Catchments modelling suggest that over 90% of the modelled PSII herbicide load is from land used for sugarcane cultivation, with minor contributions from cropping and grazing lands, in particular from the Fitzroy catchment (Waters et al. in press).

(a) Dugong



(b) Turtle

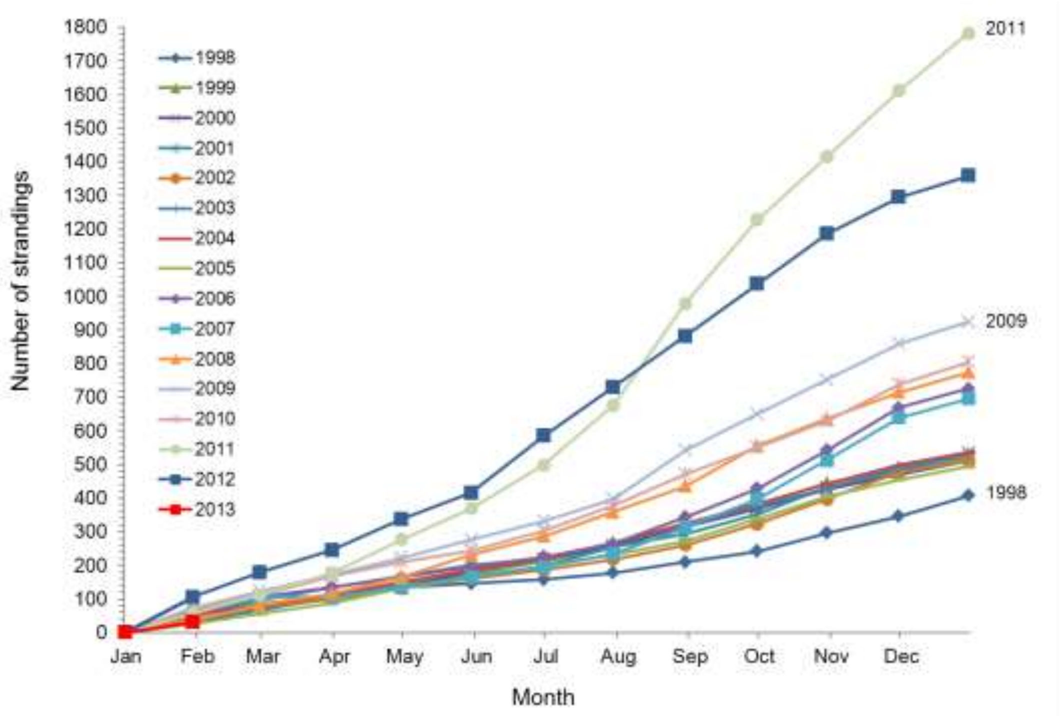


Figure 3.1. Monthly cumulative strandings by year for the Queensland East Coast, up to 31 January, 2013 for (a) dugong and (b) turtle (only cases confirmed in the field by a trained person, and later verified by an expert are included). Source: Meager and Limpus, 2012.

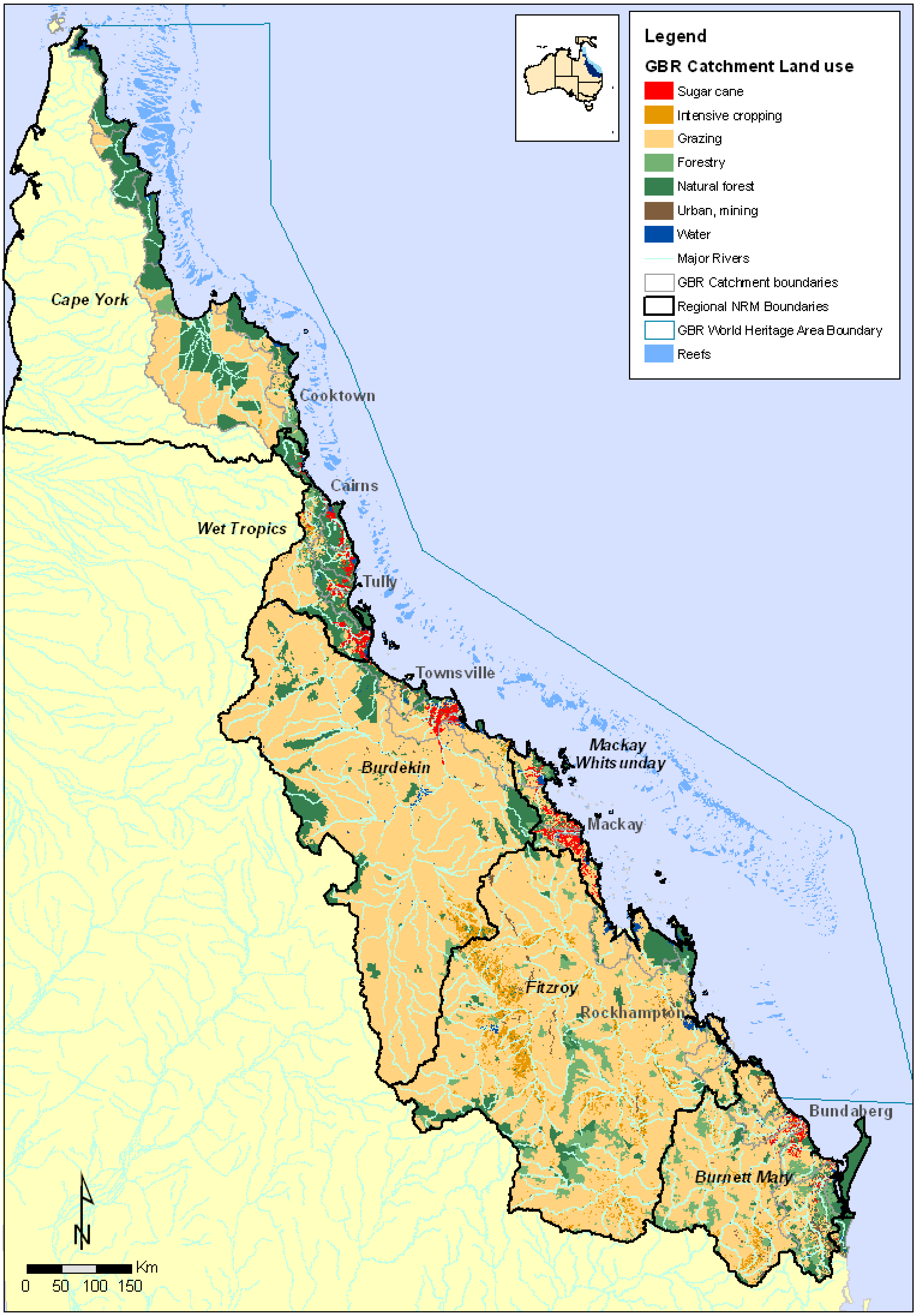


Figure 3.2. Land use map of the Great Barrier Reef catchment. Source: Waterhouse et al. (2012).

3.2 Overall assessment of the relative risk of degraded water quality to GBR ecosystems

Using the information from Part A and the Supporting Studies we have developed an overall summary of the relative importance of different pollutants to GBR ecosystems, and the relative risk of degraded water quality to GBR ecosystems among NRM regions. This information is presented in Table 3.1, and illustrated in Figure 3.3. In this table we have taken the results of the individual assessments of each variable in the ecological risk assessment to highlight where the variables dominate among the Regions. The primary rank for each variable is listed, with an indication of whether it dominates in terms of coral reef or seagrass area, or both. The Marine Risk Index for coral reefs and seagrass is then shown for the results of the combined analysis of water quality variables. The regional anthropogenic loads as a proportion of the total GBR load for TSS, DIN and PSII herbicides are shown to identify the primary sources of anthropogenic loads delivered to the GBR, in addition to the Loads Index which combines this information. Additional information includes facts related to the influence of river discharges to the COTS Initiation Zone and additional pesticide information. The Relative Risk Index which represents the overall results of the risk assessment in Part A is shown as the critical underpinning for the overall conclusions. This is then informed by the management issues and associated land uses which were derived from published evidence and expert judgement of the assessment team (informed by the preceding columns). The overall ranking of relative risk was developed by the assessment on the basis of the overall content of the table. Importantly, while the Burnett Mary ranked relatively low in the Relative Risk Index, this result is considered to be highly uncertain due to the fact that most reefs and seagrass meadows in this region (but outside of the GBRWHA) were not included formally in the analysis.

The information has also been coupled with the summary of pollutant sources from land uses in each region (above) to generate the management priorities identified Table 3.2. However, cost effective solutions for all of these management issues are not necessarily currently available for all of these priorities. These issues are discussed further in SCS *Chapter 5* regarding the effectiveness of management practices and outstanding information gaps in this field (Thorburn et al. 2013).

Even though the nutrient related variables of Chlorophyll threshold exceedance and DIN plume loading were ranked highest in the Fitzroy region, there is insufficient knowledge of the sources of dissolved inorganic nitrogen in the Region to make recommendations about management priorities for these. Further knowledge of the role of particulate nitrogen, which is largely derived from grazing lands, and the processing of this into dissolved inorganic nitrogen is important for making future management recommendations in the large grazing catchments of the Fitzroy region. Current research is showing differences in sediment and nutrient runoff from native brigalow scrub, newly planted legume based ley pastures and cropping lands which will be useful to guide management priorities in the future. Compared to the native brigalow scrub landscape, cropping exported more TSS and DIN, while grazing exported less total nitrogen and DIN, but more TSS (Thornton and Elledge, 2012). The legume pastures do appear to pose a risk to water quality as they contribute higher nutrient loads than grass only pasture systems, established grass-leucaena pastures, and the native brigalow scrub landscape representative of the environment in its pre-European condition (Elledge and Thornton, 2012).

In the Burnett Mary region all of the variables ranked relatively low, however, the assessment does not include large areas south of the GBRWHA boundary that contain coral reefs and large areas of seagrass (refer to Section 4). The end of catchment TSS total and anthropogenic annual average loads in the Mary River are the fourth highest of all GBR catchments. A majority of this is thought to be derived from grazing lands, although mixed cropping is also a potential contributor (Waters et al. in press). The TSS loads from the Burnett catchment and particularly the role of dams in sediment trapping requires further investigation. It is possible that a similar process of trapping of coarser sediments (>20 μM) that occurs in the Burdekin catchment (Lewis et al. 2013b) may also occur in the Burnett catchment, resulting in the bulk of the material discharged to the marine environment being the finer fraction. It is the finer sediment fraction that is more harmful to coral reefs (Weber et al. 2006, 2012) and seagrass (Collier et al. 2012). For these reasons sediment management in the Burnett Mary region is considered to be highest priority until a more thorough analysis is undertaken that includes all of the potential ecosystems at risk.

Table 3.1. Summary of the outcomes of the overall assessment of the relative risk of water quality in the GBR. Note that the Burnett Mary Region is shaded in grey to represent the fact that most reefs and seagrass meadows in this region were not included formally in the analysis and thus the validity of the result has high uncertainty.

Region	**Dominant variables in marine assessment** *Variables where max area is in Region*	**Marine Risk Index**		**Regional Anthropogenic Load as a proportion of the Total GBR Load (%)**			**Loads Index**	**Additional Factors**	**Relative Risk Index**	**Management Issues**	**Associated land uses**	**Overall Ranking of Relative Risk**
	CR = Coral Reef *SG = Seagrass*	**Coral Reef**	**Seagrass**	**TSS**	**DIN**	**PSII Herb**						
Cape York	COTS Initiation Zone (CR)	12	4	3	<1	<1	0	Influence from catchment runoff is predominantly from Wet Tropics Rivers	9	The data in this Region are highly uncertain due to limited validation of marine datasets.		**LOW**
Wet Tropics		100	83	9	20	61	100	86% volumetric contribution to COTS Initiation Zone	100	Nutrients Pesticides	Sugarcane Bananas	**VERY HIGH**
Burdekin	TSS 2mg/L (SG, CR) TSS 7mg/L (SG) TSS Plume loading (CR, SG) Chl 0.45µg/L (SG) DIN Plume loading (SG)	40	100	32	11	13	62	14% volumetric contribution to COTS Initiation Zone High risk from PSII herbicides to Ramsar listed freshwater wetlands in the lower Burdekin catchments	76	Sediments Nutrients Pesticides	Grazing Sugarcane (coastal)	**HIGH**
Mackay Whitsunday	Pesticide exposure (CR, SG)	54	37	4	6	12	25	High risk from PSII herbicides in Sandy Creek	50	Pesticides Nutrients	Sugarcane	**MODERATE**
Fitzroy	TSS 7mg/L (CR) Chl 0.45µg/L (CR) DIN Plume loading (CR)	86	59	17	5	4	28	Monitored loads of PSII herbicides were high in 2011 (not reflected in modelled baseline)	80	Sediments Pesticides *Nutrients*[1]	Grazing Cropping	**HIGH**
Burnett Mary	All variables rank relatively low	11	23	4	4	9	20	The Mary River has the fourth highest total and anthropogenic TSS load of all GBR catchments	19	Sediments	Grazing	**UNCERTAIN**
										All variables rank relatively low, however, there is high uncertainty in this result given the lack of data on the full extent and condition of corals and seagrass (which are outside the GBRWHA) available for this assessment.		

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[1] There is insufficient knowledge of the sources of DIN in the Fitzroy region to make recommendations about management priorities for these. Further knowledge of the role of particulate nitrogen, which is largely derived from grazing lands, and the processing of this into DIN is important for making future management recommendations in the large grazing catchments of the Fitzroy region.

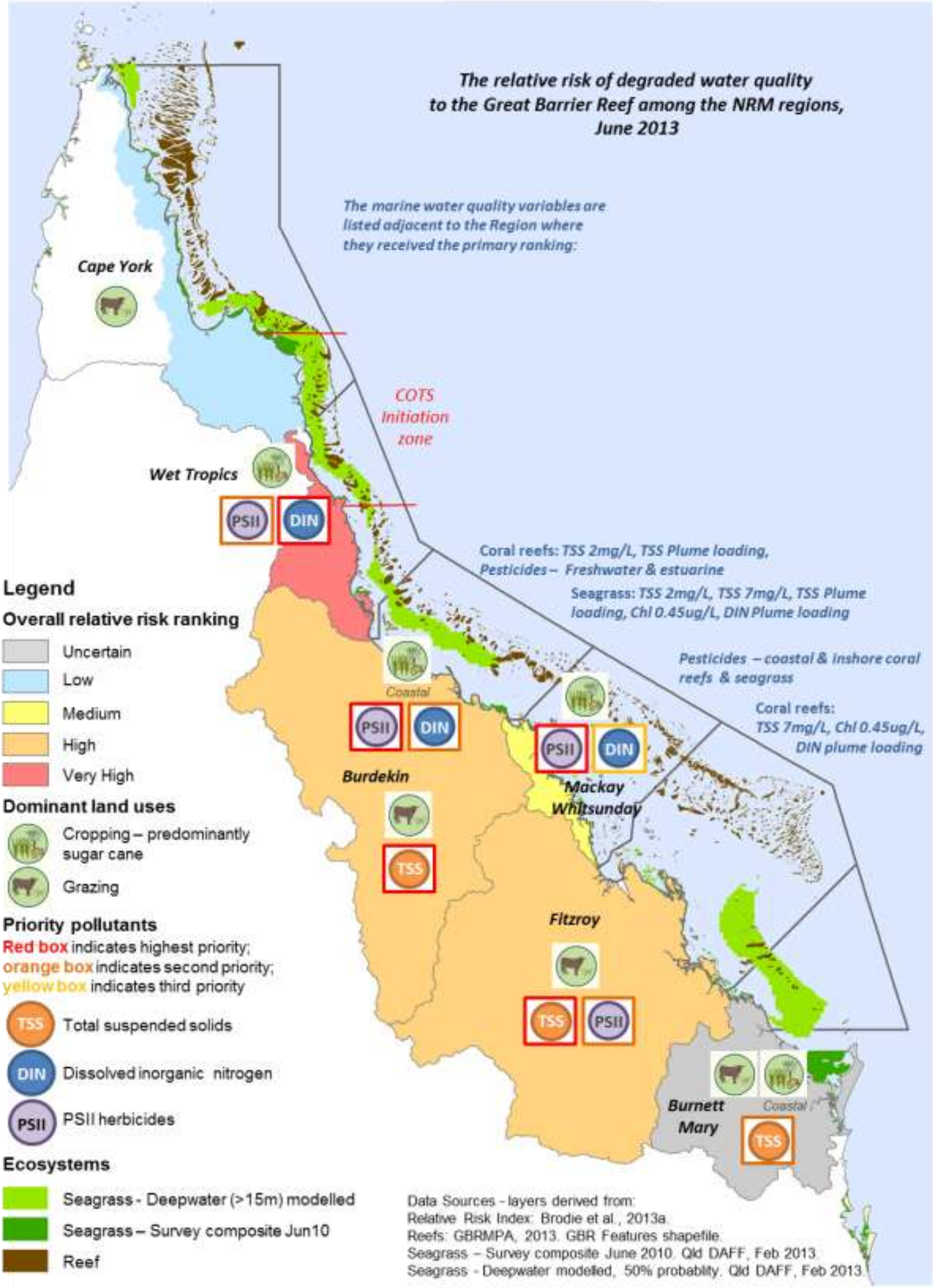

Figure 3.3. Illustration of the overall outcomes of the assessment of the relative risk of degraded water quality to Great Barrier Reef coral reefs and seagrass. The map shows the dominant land uses and priority pollutants and results of the overall relative risk ranking in each NRM region.

Table 3.2. Summary of management priorities for reducing the relative risk of degraded water quality to the GBR.

Relative Priority	Management Priorities			
	Region	**Pollutant Management**	**Key land uses**	**Comments**
1	Wet Tropics	Fertiliser nitrogen reduction	Sugarcane, Bananas	Note that these actions should not be prioritised at the exclusion of other practices that are already in place to manage losses of other pollutants in the Regions
	Burdekin	Erosion management in Burdekin	Grazing	
	Fitzroy	Erosion management in Fitzroy	Grazing, Cropping	
2	Burdekin	Pesticide reduction in (lower) Burdekin and Haughton	Sugarcane	
	Mackay Whitsunday	Pesticide reduction in all catchments	Sugarcane	
	Burdekin	Fertiliser nitrogen reduction in (lower) Burdekin and Haughton	Sugarcane	
3	Mackay Whitsunday	Fertiliser nitrogen reduction	Sugarcane	
	Burnett Mary	Erosion management in all catchments	Grazing	
	Wet Tropics	Pesticide reduction in all catchments	Sugarcane	
	Fitzroy	Pesticide reduction in all catchments	Grazing, Cropping	
4	Burnett Mary	Further information is required to inform the assessment, including data on the full extent and condition of corals and seagrass (which are outside the GBRWHA) in the Region.		Habitat mapping, ecological value assessment and monitoring of ecosystem condition is required
5	Cape York	Further information is required to understand local influences.		As a relatively low impacted area, management efforts should aim to maintain the current values of the region

3.3 Overall conclusions

Drawing on the information in this report, the overarching conclusion drawn from this project is that ***the greatest water quality risks to the GBR are from nitrogen discharge, associated with crown of thorns starfish outbreaks and their destructive effects on coral reefs, and fine sediment discharge which drives light reduction for seagrass ecosystems and inshore coral reefs. Pesticide inputs pose a risk to freshwater and some inshore and coastal habitats***.

The key points of supporting evidence for this statement are included below. These statements have been included in the *Reef Plan SCS Chapter 3 Relative risks to the GBR from degraded water quality* (Brodie et al. 2013b).

- Overall, increased concentrations of nitrogen from catchments between the Daintree and Burdekin Rivers pose the greatest risk to coral reefs. Runoff from these rivers during extreme and early wet seasons is associated with outbreak cycles of the coral-eating COTS on the northern GBR shelf (15 to 17°S) that subsequently generate secondary outbreaks throughout the central and southern GBR. GBR-wide loss of coral cover due to COTS is estimated to be 1.4% per year over the last 25 years, and a new outbreak is underway. It is estimated that COTS have affected >1000 of the ~3000 reefs within the GBR over the last 60 years.

- Of equal importance is the risk to seagrass meadows from suspended sediments discharged from rivers in excess of natural erosion rates, especially the fine fractions (clays). Whether carried in flood plumes, or resuspended by wave action, suspended particulate matter create a turbid water column that reduces the light required by seagrass and corals. High turbidity affects ~200 inshore reefs and most seagrass areas. Seagrass loss severely impacts green turtle and dugong populations. On a regional basis the Burdekin and Fitzroy regions present the greatest risk to the GBR in terms of sediment loads.

- Loss of seagrass habitat as a result of cyclones, floods and degraded water quality appears to be associated with higher mortality of dugong and turtles.

- At smaller scales, particularly in coastal seagrass habitats and freshwater and estuarine wetlands, pesticides can pose a high risk. Concentrations of a range of pesticides exceed water quality guidelines in many fresh and estuarine waterbodies downstream of cropping lands. Based on a risk assessment of the six commonly used PSII herbicides, the Mackay Whitsunday and Burdekin region are considered to be at highest risk, followed by the Wet Tropics, Fitzroy and Burnett Mary regions. However, the risk of only a fraction of pesticides has been assessed, with only 6 out of the 34 pesticides currently detected included in the assessment, and therefore the effect of pesticides is most likely to have been underestimated.

- The ranking of the relative risk of degraded water quality between the NRM regions in the GBR is: Wet Tropics > Fitzroy > Burdekin > Mackay Whitsunday > Burnett Mary > Cape York. Priority areas for management of degraded water quality in the GBR are: Wet Tropics for nitrogen management; Mackay Whitsunday and lower Burdekin for PSII herbicide management; and Burdekin and Fitzroy for suspended sediment management.

- From a combined assessment of water quality variables in the GBR (using the total area of habitat affected in the highest relative risk areas) and end-of-catchment anthropogenic loads of nutrients, sediments and PSII herbicides, the regional ranking of water quality risk to coral reefs is: Wet Tropics > Fitzroy > Mackay Whitsunday > Burdekin> Cape York > Burnett Mary. The regional ranking of water quality risk to seagrass is: Burdekin > Wet Tropics > Fitzroy > Mackay Whitsunday > Burnett Mary > Cape York. Importantly in the Mackay Whitsunday Region, 40% of the seagrass area is in the highest relative risk class compared to less than 10% for all other regions. However the highly valuable seagrass meadows in Hervey Bay, and the importance to associated dugong and turtle populations in the Burnett Mary Region, were not included in the ranking analysis.

- Runoff-associated risk varies with distance from rivers. Coastal reefs near river mouths will be most adapted to poor marine water quality especially highly turbid conditions.
- Enhanced sedimentation interferes with the normal functioning of benthic animal and plant communities. Effects include reducing free surfaces available for larval recruitment, reductions of early life stage survival, and slowed growth and reproduction by increasing energy expenditure on cleaning.
- Corals in areas of high nutrient concentrations are more susceptible to temperature-induced bleaching due to a lower temperature threshold (less than 2°C change) for bleaching.
- Macroalgal cover on reefs is inversely correlated with indices of water quality, increasing 5-fold with decreasing water clarity and 1.4-fold with increasing chlorophyll (nutrient availability). Enhanced macro-algal cover can affect coral cover and/or larval coral recruitment.
- Dissolved inorganic and particulate forms of nutrients discharged into the GBR are both important in driving ecological effects but increased nitrogen inputs are more important than phosphorus inputs. Dissolved inorganic forms of nitrogen and phosphorus are considered to be of greatest concern compared to dissolved organic and particulate forms of nutrients, as they are immediately and completely bioavailable for algal growth. Particulate forms mostly become bioavailable over longer time frames, and dissolved organic forms typically have limited and delayed bioavailability.
- Little is known about the types and concentrations of contaminants bound to sediment discharged by rivers into the GBR and the risk that these pose to GBR ecosystems.
- Other pollutants (e.g. microplastics, endocrine disrupting substances, oil and PAHs, pharmaceuticals and heavy metals) may pose risks to specific coastal sites or ecosystems, but our limited current knowledge of the extent and degree of their influence precludes a quantitative statement of risk to wider areas.

The risk assessment described in this report provides the best available assessment of the relative risk of degraded water quality to the GBR and can be used as the first step in prioritising management focused on regional ‘hot spots’ for pollutant sources, contributing industries and resulting impacts in the marine environment. It is recognised that there are several limitations to the assessment that are important to identify and priorities for future work; these are outlined in Section 4.

4 Limitations to the risk assessment and future improvements

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. 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 exceedance is based on daily observations over a 10 year monitoring period (with only 1 or 2 valid observations every 5 days), 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 exposure is based on single flood events. 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 micropollutants 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.

No quantitative assessment of uncertainty in the estimates of risk. For all variables, any relative differences in uncertainty and hence our confidence in the data can only be assessed highly subjectively. If such qualitative assessments of uncertainty in our methodologies and data were undertaken, uncertainty would be assessed as varying as much within as among NRM regions. As we compare results for NRM regions in the final combined relative risk assessment, the various methodologies used to generate the data are considered to have roughly the same uncertainty and with the limited time and resources, no specific estimates were considered.

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.

Risk has not been assessed equally across all regions due to limitations with habitat mapping and assessment boundaries. For example, there is less data on the extent and condition of corals and seagrasses of the Burnett Mary region which are outside the GBRWHA.

The wider Burnett Mary region contains a large area of seagrass to the south of the GBRWHA boundary in Hervey Bay which provides important habitat and foraging grounds for mobile species that also inhabit the GBRWHA. The total estimate of seagrass in the Burnett Mary marine NRM regions is 8,000km^2 (McKenzie et al. 2010b). The seagrass area in Hervey Bay supports the highest density dugong habitat south of the Torres Strait (Grech et al. 2011; see Figure 4.1). These seagrass meadows have been severely impacted by several high discharge events from the rivers in the Burnett Mary region in 1992 (Preen et al. 1994), again in 1999

(Campbell and McKenzie, 2004) and in 2011 (McKenzie and Unsworth, 2011; Coles et al. 2011). The loss of seagrass after these floods had dramatic effects on dugong mortality and migration (Preen et al. 1994).

Mon Repos near Bundaberg supports the largest concentration of nesting marine turtles on the eastern Australian mainland. This is the most significant loggerhead turtle nesting population in the South Pacific Ocean region. Successful breeding here is critical for the survival of this endangered species. The Eastern Australia loggerhead turtle population is recognised as a single genetic stock, with most females nesting at one of five rookeries (Mon Repos, Wreck Rock, Wreck Island, Erskine Island and Tryon Island). Among these, Mon Repos currently supports the biggest nesting population, with ~300 females nesting per year (Limpus et al. 1994; Limpus and Limpus 2003a,b). The Mon Repos nesting site was badly damaged in the Burnett River floods of 2011.

There are also important areas of coastal coral reef in the area south of the GBRWHA boundary (Zann, 2012) that has been impacted by river discharge events from Burnett Mary rivers. Finally, pesticides discharged from the Mary River have been found in estuarine and marine sections of Hervey Bay at concentrations potentially able to reduce photosynthesis in seagrass (McMahon et al. 2005). Given these considerations the conclusions of relative risk between regions is likely to be an underestimate for the Burnett Mary. These areas should be incorporated in any future assessments of the influence of water quality on regional habitats.

Coral communities in Hervey Bay and Great Sandy Strait were recently mapped by Zann (2012) shown in Figure 4.2. In addition, more detailed surveys of coral reefs in the coastal areas around Bundaberg were recently been completed by Central Queensland University (Alquezar et al. 2011) with support from the Burnett Mary Regional Group. The Woongarra Coast, located approximately 10km east of Bundaberg, is the most southerly set of coastal fringing reefs on the East Australian mainland and boasts some of the best coastal reef diving in Queensland. The reef section spans from Burnett Heads in the north to Elliott Heads in the south (~25km). The surveys identified a total of 34 substrate classes, in a range of biodiversity and coral condition. Coral communities at eight sites in Hervey Bay were also surveyed for the Wildlife Preservation Society of Queensland, Fraser Coast Branch in 2010 (De Vantier, 2010). The sites were located adjacent to the mainland coast from Gatakers Bay to Point Vernon, and off Woody and Little Woody Islands in the Great Sandy Strait. A total of 46 species of reef-building (hermatypic) corals were recorded, with the richest individual site at Woody Island (31 species). These areas should be incorporated in any future assessments of the influence of water quality on regional habitats. A similar argument could be made for the coral reef and seagrass habitats of the northern GBR in the Torres Strait.

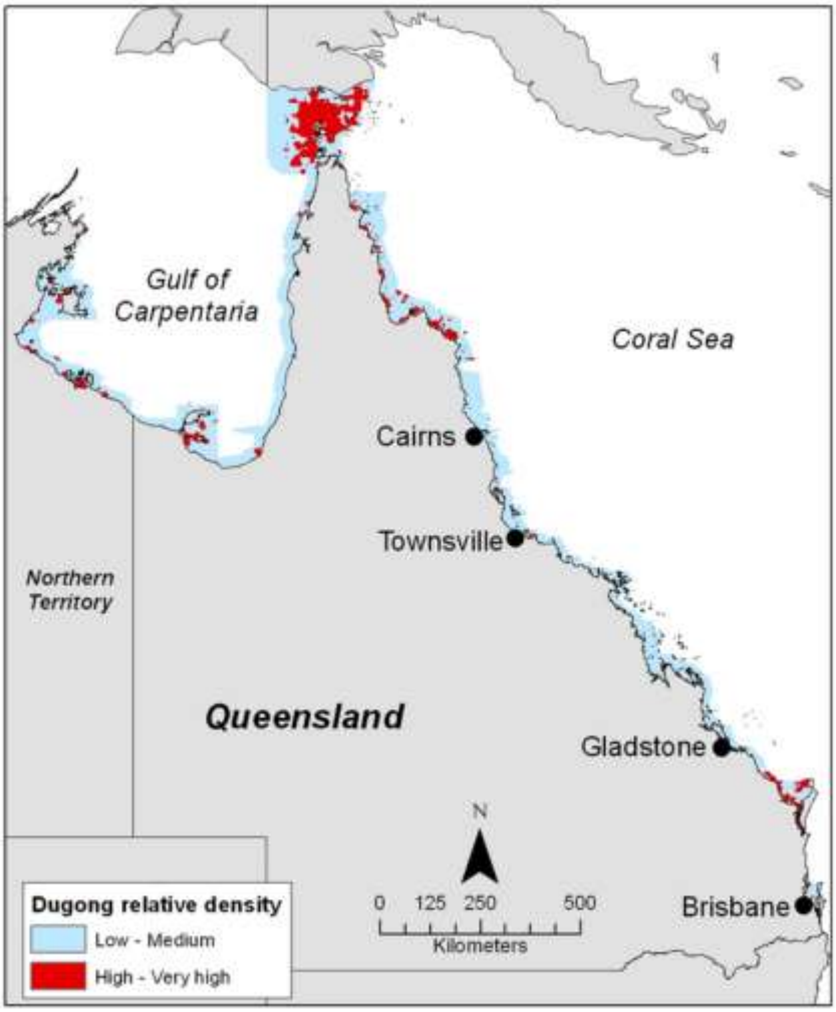

Figure 4.1. Dugong relative population density along the Queensland coast. Source: Grech et al. (2011).

The areas of greatest density are in the Torres Strait in the north, the far northern coast of the Great Barrier Reef, and the southern areas of Hervey Bay which are the highest density south of the Torres Strait. Derived from spatially-explicit population models of dugong distribution and relative density in northeast Australia. The spatially-explicit models were interpolated from a 20-year time series of systematic aerial surveys of dugongs at the scale of 2 km * 2 km planning units. Planning units were initially classified as low, medium, high and very high dugong density on the basis of the relative density of dugongs estimated from the models and a frequency analysis. The model of dugong distribution and relative density in the southern Great Barrier Reef region is from Grech and Marsh (2007).

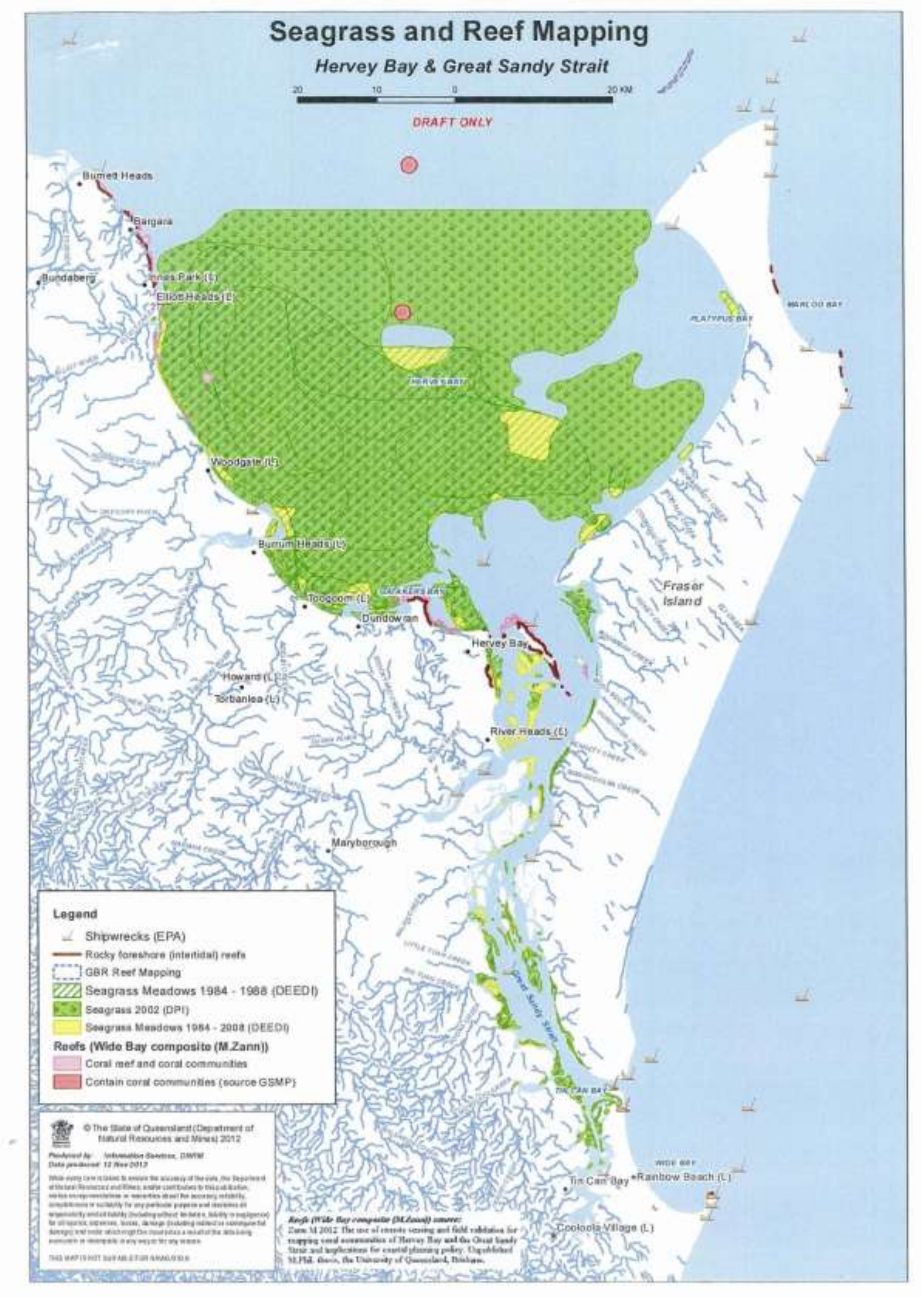

Figure 4.2. Seagrass and coral reef mapping in Hervey Bay and Great Sandy Straits. Source: Zann (2012). Note that the GBRWHA is just northward of the northern boundary of this map.

Estimates of regional river influences on the GBR are assumed to be constrained within adjacent marine NRM boundaries due to currently limited capacity to quantify the transport and dispersion of individual river plumes in the GBR lagoon. It is fully understood that river plumes, particularly from the large Burdekin and Fitzroy River catchments can cover large areas within the GBR lagoon. Observations (e.g. Wolanski and van Senden, 1983; hydrodynamic modelling (e.g. King et al. 2002) and satellite imagery (e.g. Devlin et al. 2012) during periods of high flow has shown that the Burdekin River influences the shelf into the Wet Tropics marine NRM region, and that the Fitzroy River plume may reach the Mackay Whitsunday marine NRM region.

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. The approach to classification used is also a potential weakness of MCA, 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 Cape York region north of Cooktown, coastal areas around Shoalwater Bay which are naturally turbid. 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. Definition of zones of river influence in the GBR for each catchment using hydrodynamic and pollution distribution models so that water quality risk from individual and combined pollutants can be attributed back to individual rivers. With this information it would be possible to estimate source-sink relationships for every pollutant, every river, and every part of the GBR lagoon. It is the ultimate intent of eReefs to deliver this type of information.
4. Collation of all existing information on the distribution and condition of coral reef and seagrass habitats in the Burnett Mary and Cape York regions, with support for resources to undertake further assessment if gaps are identified.
5. 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.
6. 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.
7. 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.

If a number of these limitations were overcome, it would be more feasible to undertake a risk assessment that enabled analysis of the absolute risk of degraded water quality to GBR ecosystems. The Ecological Risk Assessment framework provided in Hayes et al. (2012) provides a solid foundation for this improved approach. In the proposed methodology, Tiers 1-4 were designed to deal with increasingly higher quality data regarding exposure to, and effects of, pollutants. Importantly, the lower tiers would be able to handle any data so long as they were time stamped and location stamped and would not be reliant on data collected over long periods of time with high-frequency. In contrast, Tier 5 would require high quality time series data recorded at locations across the GBR lagoon, and a hind-casting technique to attribute risk back to individual rivers, in order to accurately characterise the relative risk of different rivers. The higher data requirements for the Tier 5 level of the risk assessment was the rationale for proposing a tiered risk assessment approach.

As described in Hayes et al. (2012) the proposed methodology also allows for two sets of loss functions to measure the consequences of exposure to pollutants. The first is a simple indicator function that identifies the probability of exceeding GBR water quality guidelines for each of the pollutants. The water quality guidelines provide environmental standards for water quality stressors that define specific ecological conditions that are protective for a variety of ecological end-points including, but not limited to, specific endpoints such as corals or seagrass. The second set of loss functions involves exposure-effect curves that describe the specific response of the risk assessment endpoint(s) to exposure to one or more pollutants, either individually or in concert. Application of the ERA methodology with the specific exposure effect curves provides for a potentially more accurate assessment but this is contingent on the availability of the more complex loss function for specific endpoints. The tiers are increasingly complex and are contingent upon increasing amounts of data and analysis. The extent to which pollutants will be progressed through each tier depends therefore on the availability of exposure and effects information.

Despite the limitations of the current assessment, the risk analysis described in this Section is considered to be the most quantitative and rigorous, as well as the most collaborative, ever undertaken for assessing the risk of degraded water quality to GBR ecosystems. This is associated with the availability of high resolution spatial data and more in depth analysis of the combination of water quality variables. As a logical next step, current knowledge of the effectiveness of management practices (in terms of water quality benefits and socio economic outcomes) across the main agricultural industries in the GBR catchments can be used to inform investment options to address these water quality priorities. The information presented in Reef Plan SCS on management practice effectiveness (Thorburn et al. 2013) provides the basis for this type of assessment.

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Appendix 1. Further information regarding remote sensing assessments

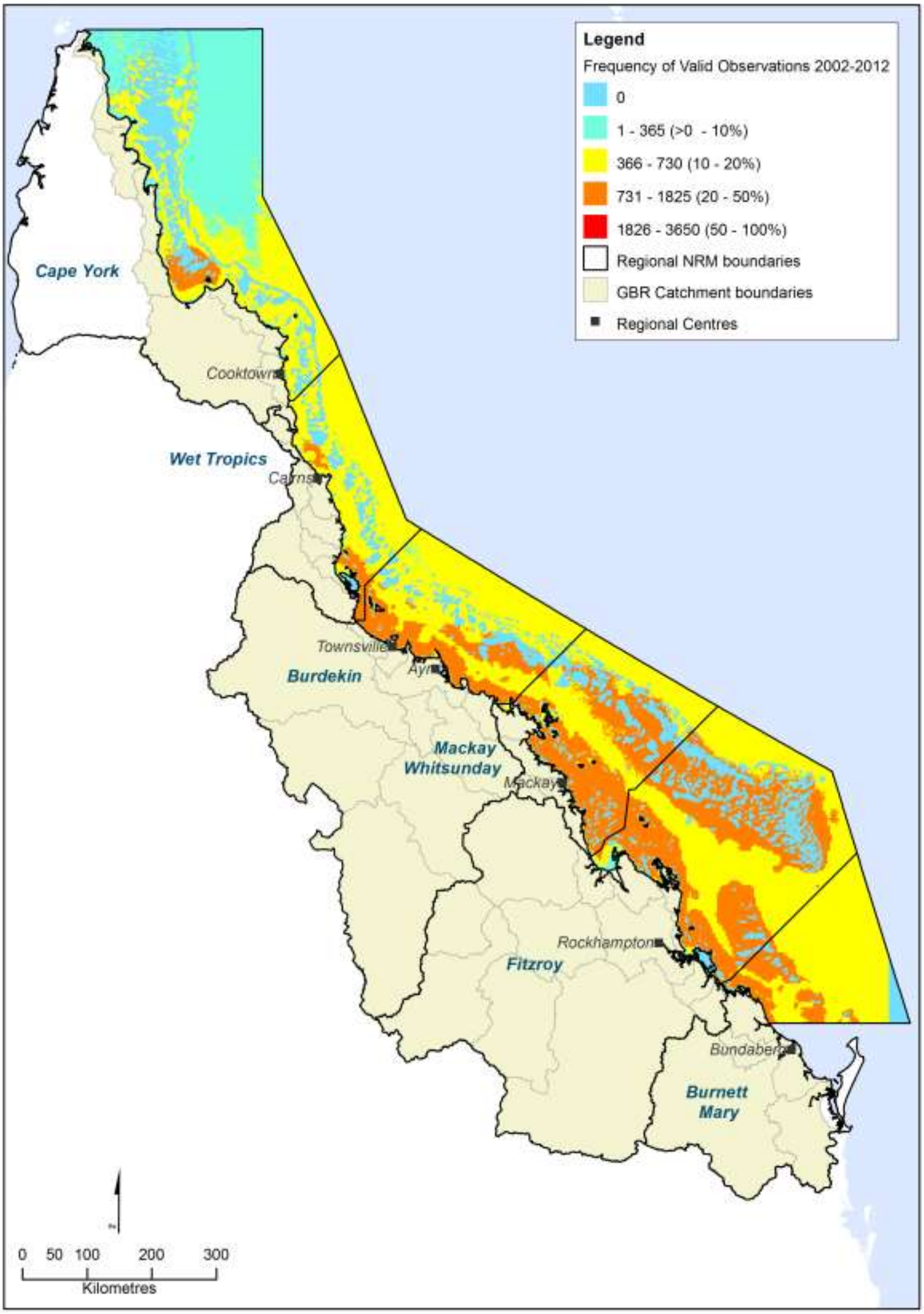


Figure Ap1a. Map showing the number of valid observations in the assessment period 2002-2012 where remote sensing images have been processed to estimate concentrations of Total suspended solids and Chlorophyll.

Figure Ap1b.Results of (a) TSS 2 mg/L assessment in this project (2002 to 2012) (see section 2.4.2) and (b) the secchi depth assessment presented in De'ath and Fabricius (2008). Visual comparison of the two assessment outputs suggests roughly comparable latitudinal and shelf-based spatial patterns. For (b) Locations that are presently at less than the water quality guideline trigger value of a minimum annual mean of 10 m Secchi depth are shown in green. Orange zones show areas that exceed the guideline trigger values, having Secchi depths of 5 – 10 m. Red zones show areas of greatest concern with Secchi depth <5 m. The level of opacity for the colouring in the right-most panel indicates the level of confidence in the estimates; faded areas have higher uncertainty (mostly offshore).

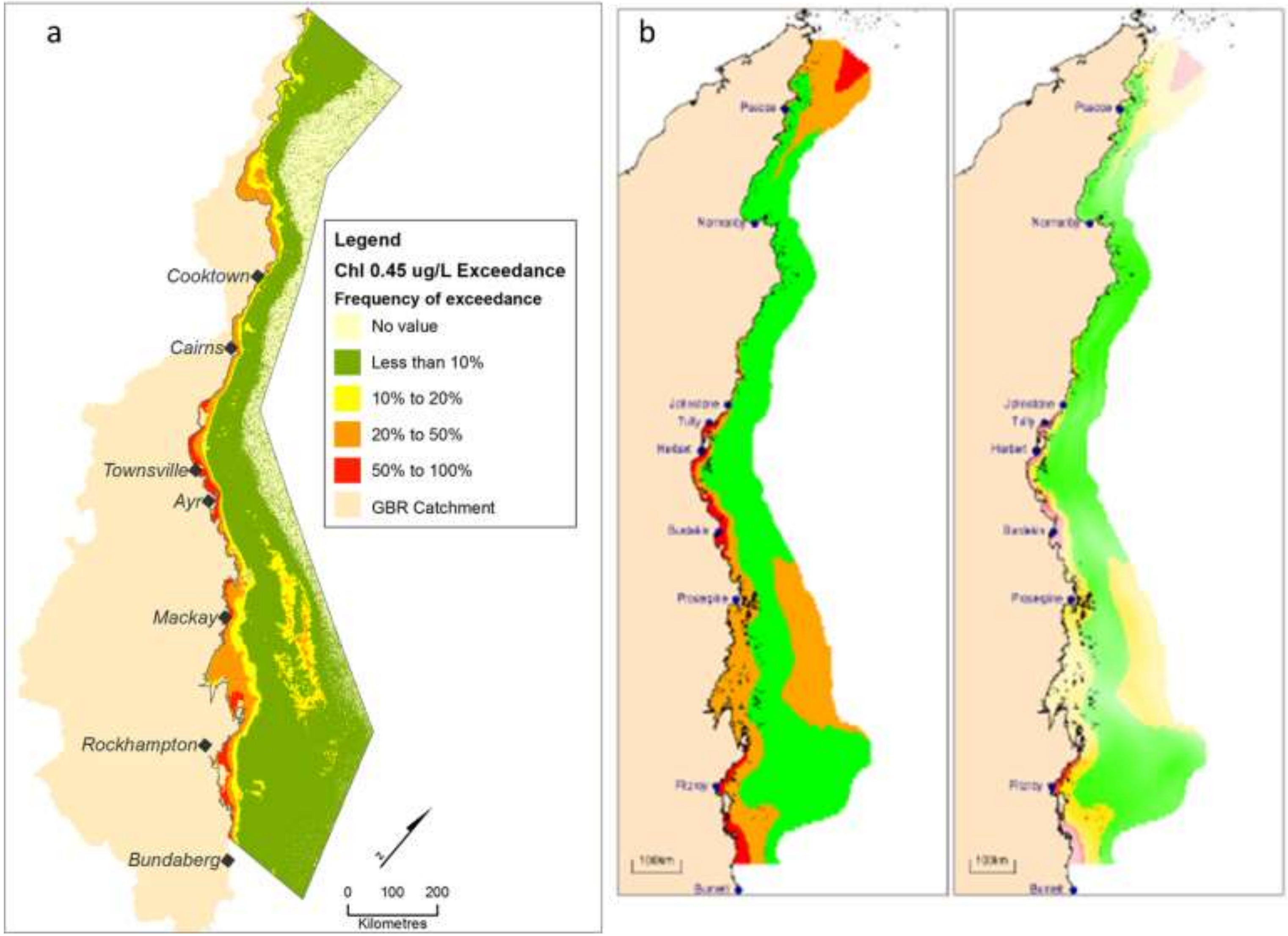
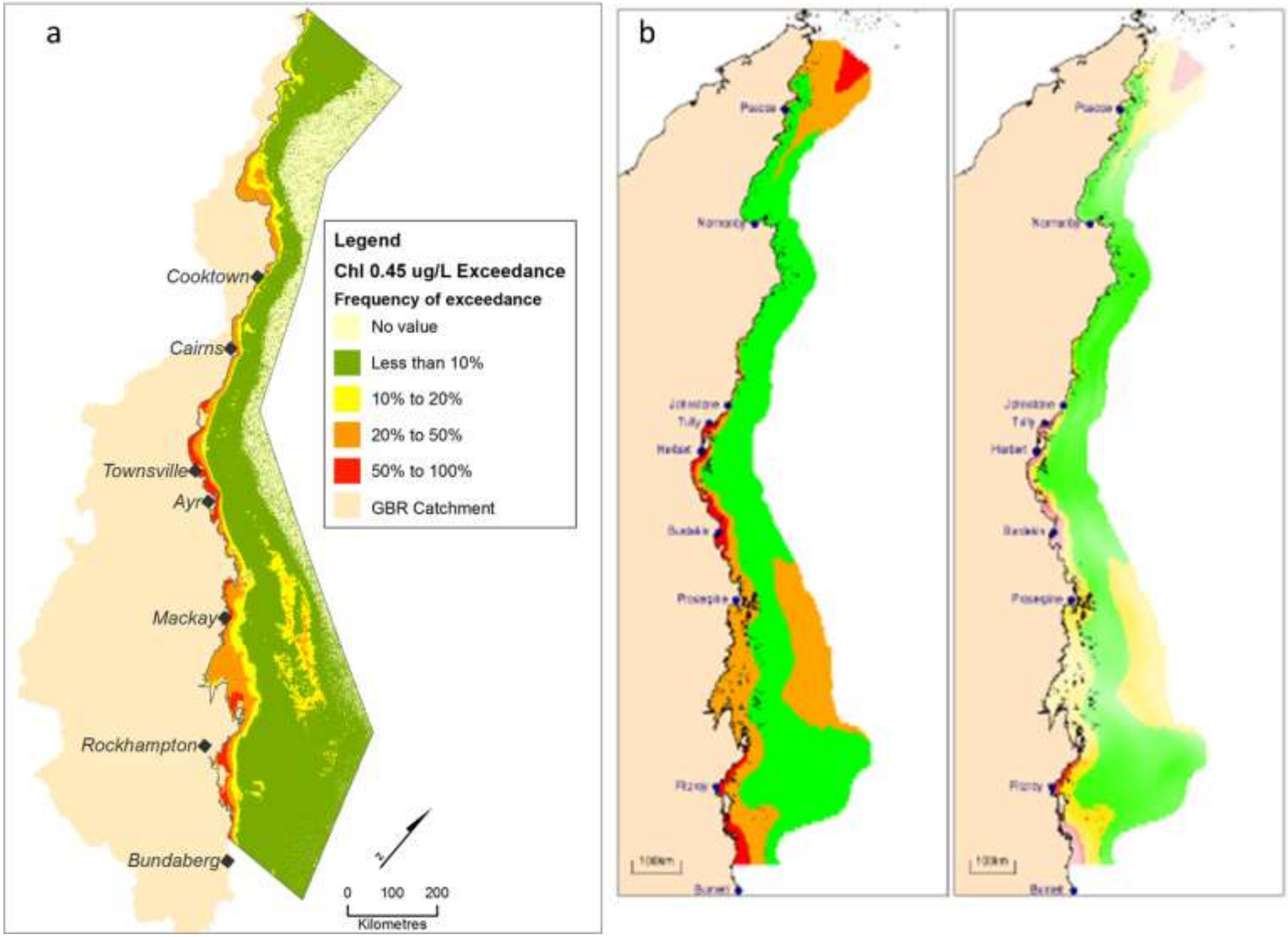


Figure Ap1c. a) Results of (a) the Chlorophyll 0.45 ug/L assessment in this project (2002 to 2012) and (b) the analysis of exceedance of Chlorophyll presented in De'ath and Fabricius (2008). Visual comparison of the two assessment outputs suggests roughly comparable latitudinal and shelf-based spatial patterns. For (b), locations that are presently at less than the water quality guideline trigger value of a maximum annual mean of 0.45 µg/L chlorophyll are shown in green. Orange zones show areas that exceed the guideline trigger values, having chlorophyll values of 0.45 – 0.8 µg/L. Red zones show areas of greatest concern with >0.8 µg/L chlorophyll. The level of opacity for the colouring in the right-most panel indicates the level of confidence in the estimates; faded areas have higher uncertainty (mostly offshore).



Appendix 2. Sensitivity analysis of options for combining water quality variables for determining relative risk

Three options for combining the water quality variables in the marine relative risk assessment were considered. These options essentially weighted each variable differently, and provide a very simple sensitivity analysis. All of these were performed using the *Composite tool* in MCAS-S described in Section 2.3.4 and Figures 2.7, 2.8 and 2.9 of this report. The overall weightings for each variable for each of the options are shown in Table A2.1.

1. *Option 1 (selected option): Combining all variables individually*. All variables were treated with equal weighting (1/7) and summed. The maximum score for each pixel is therefore 7, and this value is then normalised between 0 and 1. This approach essentially weights the variables differently because there are 3 sediment related variables, 3 nutrient related variables and 1 pesticide related variable which were considered to be appropriate by the assessment team given current evidence of the relative importance of nutrients and sediments compared to pesticides in the GBR.

2. *Option 2: Grouping the sediment and nutrient variables, then combining with pesticide exposure*. The results for TSS exceedance 2 mg/L and TSS 7 mg/L, and TSS plume loading 2007-2011 were averaged to produce a 'sediment' layer, and then the results for Chl exceedance 0.45 µg/L, DIN plume loading 2007-2011 and the COTS Initiation Zone were average to produce a 'nutrients' layer. The pesticide exposure layer formed the 'pesticide' layer. These layers were all normalised in MCAS-S, and then combined using the *Composite tool*. This essentially weights the sediments, nutrients and pesticides groupings equally but changes the weightings for individual variables as shown in Table A2.1. Experts considered that the weighting of COTS (1/9) was too low compared to pesticides (1/3), so Option 3 was tested.

3. *Option 3: Separating the COTS Initiation Zone to be a separate group from Option 2*. The incorporation of the COTS Initiation Zone recognises the importance of the destructive impacts of COTS on coral reefs in the GBR, and the significance of the water quality conditions in the region between Lizard Island and Cairns in initiating outbreaks. Removal of this layer reduced the overall risk in the Wet Tropics region. This approach kept the COTS Initiation Zone as a separate group with a weighting of ¼, comparable to other groupings. It was decided that an additional factor related to river influence on COTS outbreaks should be factored in a later stage of the assessment rather than weighting the COTS Initiation Zone equally to the groupings of sediments, nutrients and pesticides.

Each method was tested and mapped in MCAS-S and the results were compared by the assessment team. Figure A2.1 presents a comparison of the results for the Marine Risk Index for Option 1 and Option 2 showing only the High and Very High relative risk classes. The results of the area calculations for each relative risk class are shown in Table A2.2. The greatest differences between the options were evident in the lowest assessment classes and in the results for Mackay Whitsunday – attributable to the higher weighting given to PSII herbicide modelled concentration. This also resulted in a higher ranking for Mackay Whitsunday for coral reefs and seagrass.

The results for the Relative Risk Index for Option 2 are shown in Tables A2.3 and A2.4. When combined to produce the Relative Risk Index, the overall ranking among the Regions was elevated for Mackay Whitsunday which was ranked approximately equal to Burdekin and Fitzroy region (all ~70% of the risk assigned to the highest region, the Wet Tropics) in comparison to fourth for Option 1.

We selected Option 1 as the preferred approach given current evidence of the relative importance of nutrients and sediments compared to pesticides in the GBR. The effect of the inherent weighting of 3 for sediments, 3 for nutrients, and 1 for pesticides applied in Option 1 was most evident for the area of seagrass in the Very High and High assessment classes in the Mackay Whitsunday and Wet Tropics regions. In these regions the total area of the Very High and High assessment classes are greater in Option 2, and these areas contain mapped areas of seagrass meadows but limited coral reefs. For the Mackay Whitsunday region this means that an even greater proportion of seagrass meadows would have been in the area used to calculate the Marine Risk Index.

Table A2.1. Summary of options considered for combining and weighting the seven variables used in the risk assessment. The colours represent groupings of variables, where the variables within the group were averaged prior to combining with other groups.

Weighting Options	TSS threshold exceedance (2 mg/L)	TSS threshold exceedance (7 mg/L)	TSS Plume Loading (2007-2011)	Chl threshold exceedance (0.45µg/L)	DIN Plume Loading (2007-2011)	COTS Initiation Zone	PSII Herbicide modelled concentration (2009-2011)
Option 1 - Selected Option: Equal weighting of all individual variables by summing	1/7	1/7	1/7	1/7	1/7	1/7	1/7
Option 2: Grouping of variables into sediments, nutrients, pesticides by averaging and then summing the grouped layers	1/9	1/9	1/9	1/9	1/9	1/9	1/3
Grouped weighting	1/3			1/3			1/3
Option 3: Separating out the effect of COTS by adding the COTS layer after summing all other variables	1/12	1/12	1/12	1/8	1/8	1/4	1/4
Grouped weighting	1/4			1/4		1/4	1/4

Table A2.2. Results of the area of coral reef and seagrass for Option 1 (individual variables) and Option 2 (grouped variables) described above.

Option 1: Individual variables

	Area (km²)								
	V Low	**Low**	**Medium**	**High**	**V High**	**Total**	**Sum High & V High**	**% habitat in region (High & V High)**	**Marine Risk Index**
Coral Reefs									
Cape York	3,585	6,147	546	17	0	10,295	17	0%	15
Wet Tropics	121	1,809	448	36	0	2,415	36	1%	32
Burdekin	704	2,206	24	14	0	2,948	15	0%	13
Mackay Whitsunday	2,147	826	133	61	5	3,171	66	2%	59
Fitzroy	3,726	964	38	103	8	4,840	111	2%	100
Burnett Mary	10	265	1	5	0	282	5	2%	4
						Max	*111*		
Seagrass									
Cape York	1,258	8,711	1,329	32	0	11,330	32	0%	7
Wet Tropics	175	4,240	278	102	59	4,855	161	3%	34
Burdekin	1,281	4,160	150	333	136	6,060	470	8%	100
Mackay Whitsunday	5	21	210	136	25	396	160	37%	34
Fitzroy	201	5,050	177	303	15	5,746	319	6%	68
Burnett Mary	458	5,561	210	76	7	6,313	83	1%	18
						Max	*470*		

Option 2: Grouped variables

NRM region	**V Low**	**Low**	**Medium**	**High**	**V High**	**Total**	**Sum High & V High**	**% of habitat in region (High & V High)**	**Marine Risk Index**
Coral Reefs									
Cape York	6,642	3,100	573	0		10,316	0	0%	1
Wet Tropics	870	1,058	448	39	1	2,416	40	2%	47
Burdekin	2,560	353	23	13	0	2,950	14	0%	16
Mackay Whitsunday	2,226	730	129	72	13	3,169	85	3%	100
Fitzroy	3,959	736	59	79	6	4,839	85	2%	100
Burnett-Mary	196	80	2	3	1	282	4	1%	4
						Max	*85*		
Seagrass									
Cape York	5,679	4,575	1,106	3		11,363	3	0%	1
Wet Tropics	2,468	1,874	312	119	83	4,856	202	4%	52
Burdekin	4,063	1,380	237	350	39	6,069	389	6%	100
Mackay Whitsunday	0	11	139	152	104	407	256	60%	66
Fitzroy	1,820	3,433	270	237	1	5,760	238	4%	61
Burnett Mary	5,259	758	210	80	10	6,317	90	1%	23
						Max	*389*		

Table A2.3. 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 for Option 2 (grouped variables). The Region that had the maximum value was given a score of 100; all other Regions are expressed as a percentage based on the value in each Region relative to the area in the Region with the maximum value.

Coral Reefs **NRM region**	**Coral Reef Marine Risk Index**	**Loads & COTS Index**	**Sum of Indexes**	**Coral Reef Relative Risk Index (Anchored)**	**Rank Option 2**	**Comparison Rank Option 1**
Cape York	1	0	1	0	5	5
Wet Tropics	47	100	147	100	1	1
Burdekin	16	39	55	37	4	4
Mackay Whitsunday	100	13	113	77	3	3
Fitzroy	100	14	114	78	2	2
Burnett Mary	4	10	14	10	6	6
		Max	*147*			

Seagrass **NRM region**	**Seagrass Marine Risk Index**	**Loads Index**	**Sum of Indexes**	**Seagrass Relative Risk Index (Anchored)**	**Rank Option 2**	**Comparison Rank Option 1**
Cape York	1	0	1	1	6	6
Wet Tropics	52	100	152	94	2	2
Burdekin	100	62	162	100	1	1
Mackay Whitsunday	66	25	91	56	4	4
Fitzroy	61	28	89	55	3	3
Burnett Mary	23	20	43	27	5	5
		Max	*162*			

Table A2.4. Results of the overall risk assessment using a sum of the anchored Indexes for coral reefs and seagrass for Option 2 (grouped variables). The Region that had the largest sum of indexes was given a score of 100; all other Regions are expressed as a percentage based on sum of indexes in each Region relative to the sum in the Region with the maximum sum of indexes.

Coral Reef and Seagrass **NRM region**	**Coral Reef Relative Risk Index**	**Seagrass Relative Risk Index**	**Sum of Indexes**	**Relative Risk Index (Anchored)**	**Rank Option 2**	**Comparison Rank Option 1**
Cape York	0	1	1	0	6	6
Wet Tropics	100	94	194	100	1	1
Burdekin	37	100	137	71	3	3
Mackay Whitsunday	77	56	133	69	2	4
Fitzroy	78	55	133	69	2	2
Burnett Mary	10	27	37	19	5	5
		Max	*194*			

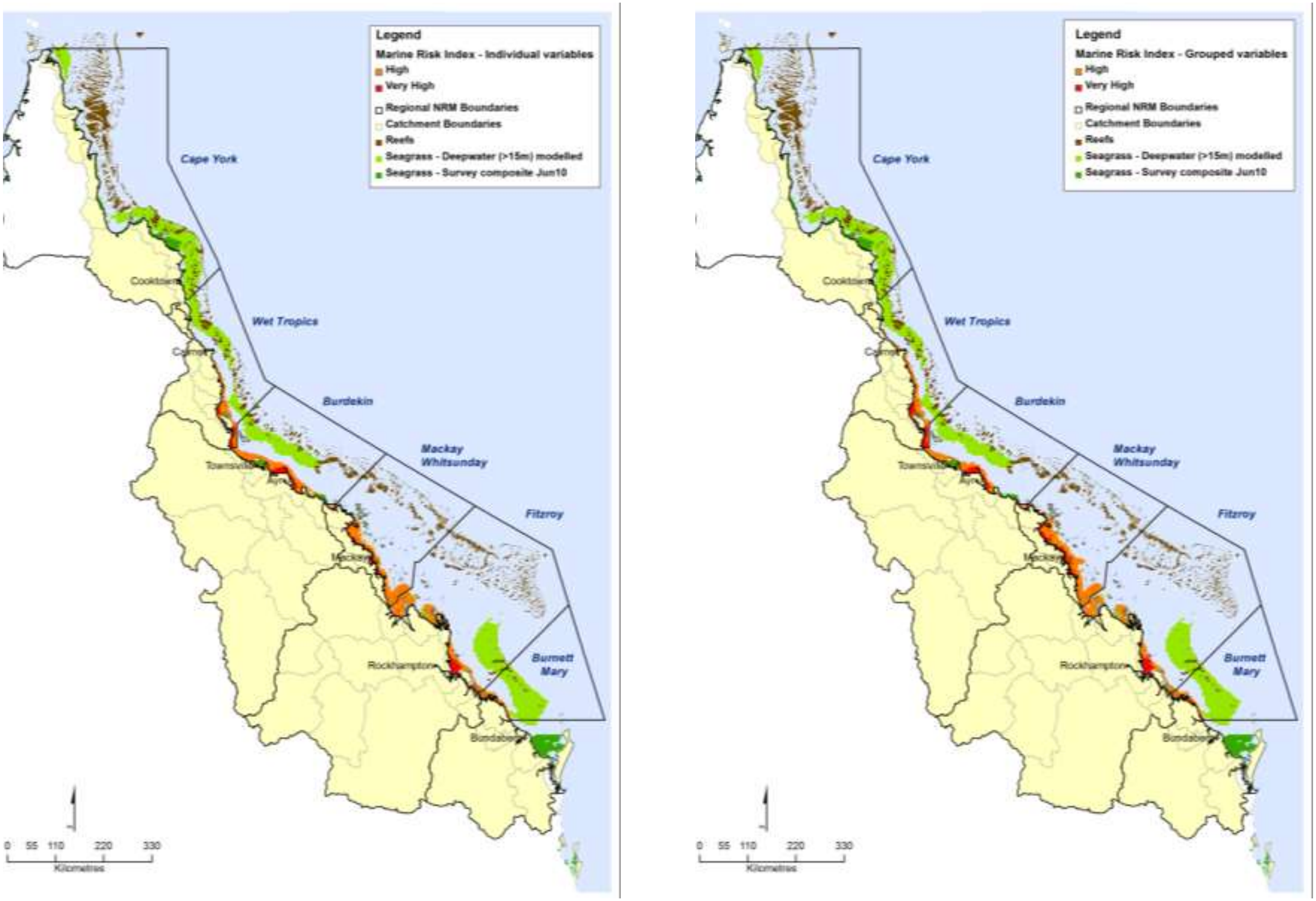


Figure A2.1. Comparison of the Marine Risk Index results for Option 1 (individual variables combined) and Option 2 (grouped variables for sediments, nutrients and then pesticides combined).