



Managing Water Quality on the Great Barrier Reef

An Overview of MTSRF
Research Outputs, 2006-2010



Compiled by
Jane Waterhouse and Michelle Devlin



Australian Government

Department of Sustainability, Environment,
Water, Population and Communities



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Contents

Acronyms and Abbreviations.....	ii
Acknowledgements	ii
About this Report.....	iii
1. Background	4
1.1 Research focus	5
2. Water quality research highlights, 2006-2010	6
2.1 Priority pollutants and priority areas for water quality management	6
2.2 Catchment-to-reef connections	8
2.3 Pesticides.....	10
2.4 Monitoring and evaluation	14
2.5 Climate change and water quality interactions.....	15
3. Project highlights	18
3.1 Using coral reef organisms as indicators of water quality and ecosystem condition.....	18
3.2 Connectivity and risk: tracing contaminants from the catchment to the reef.....	19
3.3 Freshwater indicators and thresholds of concern	21
3.4 Wetlands and floodplains: connectivity and hydrological function	22
3.5 Socio-economic constraints to and incentives for the adoption of land use and management options for water quality	22
3.6 More reliable and accurate estimates of pollutant loads entering the Great Barrier Reef lagoon	23
3.7 Related research from within the MTSRF Research Programme	23
4. Outcomes for management.....	25
5. References	27

Acronyms and Abbreviations

AIMS	Australian Institute of Marine Science
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEEDI	Queensland Department of Employment, Economic Development and Innovation
DEWHA	Commonwealth Department of the Environment, Water, Heritage and the Arts (now Sustainability, Environment, Water, Population and Communities)
DERM	Queensland Department of Environment and Resource Management
DIN	Dissolved Inorganic Nitrogen
DPC	Queensland Department of the Premier and Cabinet
GBR	Great Barrier Reef
GBRMPA	Great Barrier Reef Marine Park Authority
GU	Griffith University
JCU	James Cook University
LRE	Loads Regression Estimator
MTSRF	Marine and Tropical Sciences Research Facility
NRM	Natural Resource Management
PS-II	Photosystem II
RRRC	Reef & Rainforest Research Centre Ltd
SEWPaC	Commonwealth Department of Sustainability, Environment, Water, Population and Communities
SST	Sea Surface Temperature
WWF	World Wide Fund for Nature

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About this Report

This report provides an overview of the key findings of research conducted under the Australian Government's Marine and Tropical Sciences Research Facility (MTSRF) relevant to management of water quality in the Great Barrier Reef (GBR). The MTSRF research theme *Halting and Reversing the Decline in Water Quality* (Program 7) was comprised of five major projects undertaken collaboratively by researchers from the Australian Institute of Marine Science (AIMS), James Cook University (JCU), the Australian Centre for Tropical Freshwater Research (at JCU), the CSIRO and Griffith University.

The intent of MTSRF-funded water quality research was pragmatic: to increase practical understanding and to develop effective tools for the management of water quality in the GBR region. There has been a strong focus on the development of indicators for use in adaptive management of both freshwater and marine systems.

This report is presented in two parts: a synthesis of the highlights of the MTSRF water quality research theme, and an overview of the achievements of each of the five individual projects within that theme. Management implications of many of the research findings presented here are also relevant for tropical reef ecosystems beyond the GBR.

A key achievement of the MTSRF has been the strong cooperation and collaboration that has been facilitated between research institutions in project development and implementation. Many of the findings presented in this report were derived from large collaborative projects funded by several sources in addition to the MTSRF, and research institutions have also contributed significant in-kind resources. Publications specifically generated through MTSRF funding are identified in the reference list.

This report provides the overview as one product of several in a series of information products that summarise MTSRF research findings relevant to managing water quality in the GBR. Other products include:

- 'Improved understanding of biophysical and socio-economic connections between catchment and reef ecosystems (Wet and Dry Tropics case studies)', compiled by M. Devlin and J. Waterhouse (Devlin and Waterhouse, 2010);
- 'Optimising water quality and impact monitoring, evaluation and reporting', compiled by J. Waterhouse (Waterhouse, 2010a).
- 'Thresholds of major pollutants with regard to impacts on instream and marine ecosystems', compiled by J. Waterhouse (Waterhouse, 2010b);
- 'Identification of priority pollutants and priority areas in the Great Barrier Reef Catchment', compiled by J. Waterhouse and J. Brodie (Waterhouse and Brodie, 2011);
- 'Review of MTSRF research advancing understanding of the source, transport and impacts of pesticides on the Great Barrier Reef and in associated ecological systems', compiled by M. Devlin and S. Lewis (Devlin and Lewis, in press);
- 'Water quality and climate change: managing for resilience', compiled by J. Johnson and K. Martin (Johnson and Martin, 2011a); and
- 'Managing for resilience of the Great Barrier Reef: Socio-economic influences', compiled by J. Johnson and K. Martin (Johnson and Martin, 2011b).

Visit http://www.rrrc.org.au/publications/synthesis_products.html to access and download these documents.

1. Background

High quality water is vital to the ongoing health of the Great Barrier Reef (GBR) and the adjacent catchments, including the Wet Tropics rainforests. It is also essential for the communities, industries and ecosystems that rely on the sustained health of these natural ecosystems. Management of water quality impacts on GBR marine and catchment ecosystems involves a complex system of biophysical and socio-economic elements and relies on robust understanding of interactions and responses in the system.

While point-source pollutants of water quality are managed primarily through legislation, diffuse water quality pollutants represent a greater challenge for both legislative and non-legislative management approaches. Diffuse water quality impacts are driven by intensive agricultural enterprises such as sugarcane and horticulture, particularly on Wet Tropics coastal floodplains, and extensive rangeland grazing of the large Dry Tropics catchments. These are distinct farming systems and landscapes with particular behavioral characteristics. The primary issues of concern from the perspective of water quality impacts on the GBR and catchment ecosystems are nutrients and pesticides from intensive cropping activities (predominantly sugarcane) and sediment and associated particulate nutrients from dryland grazing activities. However, the issues impacting catchment health are highly complex, with the distinctive characteristics of each catchment influencing the overall water quality and subsequent severity of impact. Wet Tropics catchments have frequent storm and runoff events in generally short, steep catchments, that is, direct and frequent linkages to coastal environments, while in the Dry Tropics major flow events may occur at intervals of decades, with long lag times for the transport of material through these large catchments. In addition, coral reefs and seagrass beds in the GBR are likely to reflect and respond to these distinct regional differences (Devantier *et al.* 2006). Thus GBR and adjacent catchment ecosystems are enormous, complex, dynamic and variable.

Institutionally the picture is equally complex. Many institutions operating at different scales contribute to managing water quality in the GBR region, including Australian and Queensland government agencies, a large number of local governments, six regional NRM bodies, a variety of agricultural industry peak bodies, tourism and fishing sectors, conservation and Indigenous groups, and many local groups with diverse interests and activities relevant to GBR water quality.

Many of the challenges facing managers of GBR catchments and marine ecosystems require improved knowledge of the biophysical and socio-economic nature of the system, cause and effect relationships and ecosystem responses to pressures and optimal techniques for performance assessment. There is a clear need for ongoing research if management approaches are to continue improving.

Over the past four years, major government funded initiatives have been put in place to restore, rehabilitate and protect catchment habitat through the adoption of best management practices and prioritisation of catchment activities that would reduce sediment, nutrient and pesticide runoff (DPC, 2009). These efforts have been informed by the outcomes of research supported by the MTSRF, in conjunction with other collaborative research programs such as the CSIRO Water for a Healthy Country GBR Program, the Australian Government's Coastal Catchments Initiative, the Reef Water Quality Partnership and various Queensland Government research programs. This report summarises the highlights of this MTSRF-funded research.

1.1 Research focus

MTSRF-funded research relevant to water quality management in the GBR has focused on several priority areas:

- Identification of **priority pollutants and priority areas for management** to focus investment in areas of high pollutant generation and delivery, and estimation of the **exposure of GBR ecosystems** to these pollutants;
- Investigation of the **source, transport and impact of pesticides** on GBR ecosystems;
- Development of improved approaches for the **estimation of end-of-catchment loads**;
- Development and testing of robust **indicators for water quality in freshwater, estuarine and marine ecosystems** to improve water quality monitoring and evaluation, and determination of **pollutant thresholds of potential concern** for exposure of key ecosystems to sedimentation, light, nutrients and herbicides, to inform target-setting;
- Application of catchment-specific tracers to determine the **links between terrestrial and marine water quality** to identify areas of the GBR lagoon at greatest **risk of exposure** to land-based pollutants;
- Investigation of **ecological dynamics in the wetlands and floodplains** of catchments adjacent to the GBR to identify and introduce sustainable environmental targets;
- Development of **predictive tools** that incorporate the likely impacts of changes in land use, management and climate on flow and water quality regimes, to inform **target-setting**;
- Assessment of the **socio economic outcomes of agricultural management practices** including scenario modeling of cost effectiveness and water quality benefit;
- Investigation of the **evaluation and reporting of water quality management responses**; and
- Examination of the **interactions between water quality and climate change** and how water quality influences GBR resilience.

The integral linkages between the MTSRF research program and a number of other initiatives related to water quality management in the GBR have enabled research results to be of immediate benefit. A number of cases in which MTSRF-funded research has informed policy and monitoring and evaluation initiatives are highlighted in this report. In particular, research outcomes have provided valuable information to assist the evaluation of the Reef Plan and the Reef Rescue Program, informed the establishment of the Queensland Government *Great Barrier Reef Protection Amendment Act (2009)* (Reef Protection Package), and assisted regional NRM planning.

This report provides a brief general overview of the achievements of the MTSRF water quality research program. Further insights and details can be obtained from the synthesis report series¹ that covers the major advances and outputs of the program.

¹ http://www.rrrc.org.au/publications/synthesis_products.html

2. Water quality research highlights, 2006-2010

2.1 Priority pollutants and priority areas for water quality management

Several MTSRF projects contributed to advances in our current understanding of priority pollutants and priority areas for water quality management in the GBR. Three projects supported by the MTSRF, Reef Rescue initiative (both SEWPaC) and the Queensland Department of the Environment and Resource Management (DERM) collaborated to collate and assess information about pollutants in the GBR region. The Reef Rescue-funded project involved an assessment of the best estimate of pollutant loads delivered to the GBR for input to the Reef Rescue Multi Criteria Analysis for determining investment priorities. This information was used as the basis of two reports funded by DERM, firstly to undertake a relative risk assessment of contaminant loads between the GBR catchment Natural Resource Management (NRM) regions, and subsequently, load estimations at a basin and sub-basin scale for the Wet Tropics, Burdekin, Mackay-Whitsunday and Fitzroy regions.

The priority pollutants – those derived from anthropogenic land uses and considered most likely to pose a threat to the quality of runoff water entering the GBR ecosystem – are suspended sediments, dissolved inorganic nitrogen (DIN) and PS-II herbicides. Current pollutant load estimations do enable ‘hot spots’ of pollutant delivery to the GBR to be identified within a reasonable degree of certainty, and to date management prioritisation is based on these estimates (see Brodie *et al.* 2009a). The assessment in Brodie and Waterhouse (2009) indicates that in terms of the contribution and influence of land-based pollutants, the Wet Tropics and Mackay-Whitsunday regions rank the highest priority (High), with the Burdekin and Fitzroy catchments relatively high priority (Medium-High) and the Burnett-Mary catchments of moderate priority (Figure 1). Cape York catchments were not included in the assessment but would be expected to be of relatively low priority.

The results of regional pollutant load assessments indicate that:

- The areas of the highest generation of pollutant loads are:
 - DIN: Sugarcane in the Burdekin and Wet Tropics regions;
 - Suspended sediments: Grazing lands in the Burdekin and Fitzroy regions; and
 - PS-II herbicides: Sugarcane in the Wet Tropics and Mackay Whitsunday regions.
- A large proportion of the anthropogenic load of DIN (~80%) is derived from sugarcane fertiliser losses (Wet Tropics 84%, lower Burdekin 80%, Mackay-Whitsunday 88%), except in the Fitzroy region where almost all of the DIN load is from cereal grains and cotton.
- Hillslope erosion contributes the most suspended sediment to the overall load across the GBR catchments in comparison to bank and gully erosion.
- Diuron is the dominant herbicide found in the Wet Tropics, lower Burdekin and Mackay-Whitsunday region and is generally associated with areas of sugarcane, but is also found in other cropping areas.
- Tebuthiuron is the dominant herbicide in the Burdekin and Fitzroy regions associated with grazing lands. Atrazine is associated with other crops (including grains and cotton) in the Fitzroy region.

In addition to these findings, the key achievements of MTSRF research that have assisted us to understand priority pollutants and priority areas for management intervention in the GBR catchments are summarised in the companion report *Identification of priority pollutants and priority areas in the Great Barrier Reef catchments* (Waterhouse and Brodie, 2011).

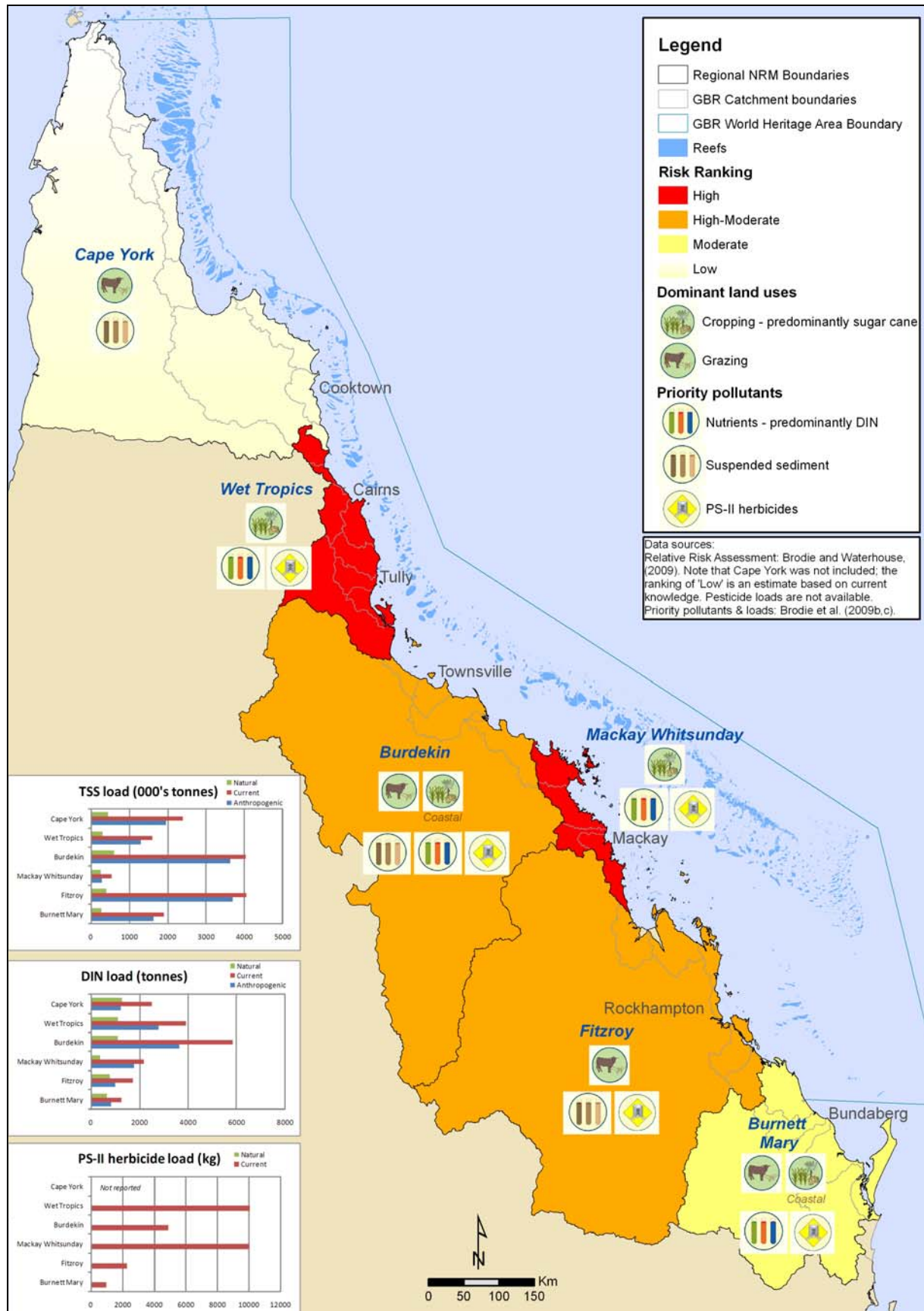


Figure 1: Summary of priority pollutants, pollutant loads and priority areas for water quality management in the GBR catchments (from Waterhouse and Brodie, 2010).

Many of these findings have already been used by managers who are making decisions about directing effort and guiding investment priorities in the GBR region. Important examples are the present management responses associated with Reef Rescue initiatives and the Reef Protection Package, which focuses on the areas and industries identified in the overall risk assessment of priority pollutants and priority areas generated through MTSRF funding. The report also identifies a number of future research priorities designed to overcome remaining uncertainties in the dataset.

2.2 Catchment-to-reef connections

A conceptual understanding of catchment-to-reef processes was well established for some locations on the GBR prior to the commencement of the MTSRF water quality program, as summarised in a MTSRF synthesis report of current knowledge in 2006 (Brodie *et al.* 2008a). However, some significant gaps existed in our overall understanding of the connectivity between systems. Since then, major government-funded initiatives have been put in place to restore, rehabilitate and protect catchment habitat through the adoption of best management practices and prioritisation of catchment activities that would reduce sediment, nutrient and pesticide runoff (DPC, 2009). These efforts have been informed by the outcomes of research supported by the MTSRF, in conjunction with other collaborative research programs such as the CSIRO Water for a Healthy Country GBR Program, the Australian Government Coastal Catchments Initiative, the Reef Water Quality Partnership and various Queensland Government research programs.

In the four years since 2006 there has been a greater research focus on the role of the catchment, and in particular wetlands, in whole-of-system understanding for the GBR. This has begun to address the need to achieve broader marine connectivity understanding and to further define connections between the physical and biological components of both freshwater and marine ecosystems. Under the MTSRF, the role of freshwater systems, riparian zones and wetlands have been studied as important ecological systems in their own right (e.g. Pearson *et al.* 2010; Arthington and Pearson, 2007). MTSRF-funded research also continued to investigate the impact of pollutants on important catchment and marine ecosystems (e.g. Pearson *et al.* 2010; Fabricius, 2011a, 2011b; Cooper *et al.* 2009; Waycott and McKenzie, 2010), including the development of pollutant thresholds to inform the development of water quality guidelines for the GBR (De'ath and Fabricius, 2008, 2010) and further guidance on the selection of monitoring indicators (e.g. Fabricius *et al.* 2010a, 2010b; Pearson *et al.* 2010). Investigations of the delivery of pollutants to the GBR have been an important research area, in particular, the delivery of sediment from the Burdekin catchment (e.g. Bainbridge *et al.* 2010; Lewis *et al.* 2009a) and the delivery of nutrients from Wet Tropics catchments (e.g. Wallace *et al.* 2010a; Karim *et al.* 2010a, 2010b; Bainbridge *et al.* 2009). The role of wetlands, small tributaries and overbank flow have been investigated to increase understanding of how these estuarine environments and processes affect the contaminant flow into marine waters (Wallace *et al.* 2010a; Karim *et al.* 2010a, 2010b). New load estimates have been calculated (e.g. Brodie *et al.* 2009a, 2009b; Brodie and Waterhouse, 2009) based on new statistical approaches (e.g. Kuhnert and Henderson, 2010) and better understanding of where the water goes (e.g. Wallace *et al.* 2010b), and how much actually moves into offshore environments. A new approach to risk assessment of pollutants in the GBR has been considered based on higher *in situ* data frequency and more accurate mapping of plume characteristics (Devlin *et al.* 2010). In collaboration with the Reef Rescue Marine Monitoring Program, a more accurate assessment of exposure to terrestrial discharge at a regional level has been made, based on improved knowledge of plume extent and concentrations and the frequency of inundation to biological systems (Devlin *et al.* 2010). The past four years of marine monitoring has seen a comprehensive integration of marine ecosystem status data, high frequency logger data and the use of appropriate remote

sensing techniques to provide a better understanding of the changes in water quality and potential impacts from contaminants on the GBR.

The companion synthesis report *Improved understanding of biophysical and socio-economic connections between catchment and reef ecosystems: Wet and Dry Tropics case studies* (Devlin and Waterhouse, 2010) summarises and synthesises this research, using case studies in the Burdekin and Tully catchments to demonstrate current understanding of pollutant generation, transport and fate in the GBR and its catchments. The highlights of relevant MTSRF-funded research in these case study areas are shown in Figures 2 and 3.

Advances in our understanding of the connectivity between catchment scale processes and the GBR enable more effective monitoring and evaluation of management targets defined in the updated Reef Plan (DPC, 2009) and Reef Rescue Program (Australian Government, 2007). Four years of MTSRF-funded research has successfully identified water quality indicators that can be linked to land-based changes. The development of these water quality indicators and changes in our monitoring and evaluation techniques are covered in more detail in the companion synthesis reports *Optimising water quality and impact monitoring, evaluation and reporting programs* (Waterhouse, 2010a) and *Thresholds of major pollutants with regard to impacts on instream and marine ecosystems* (Waterhouse, 2010b) and summarised further below.

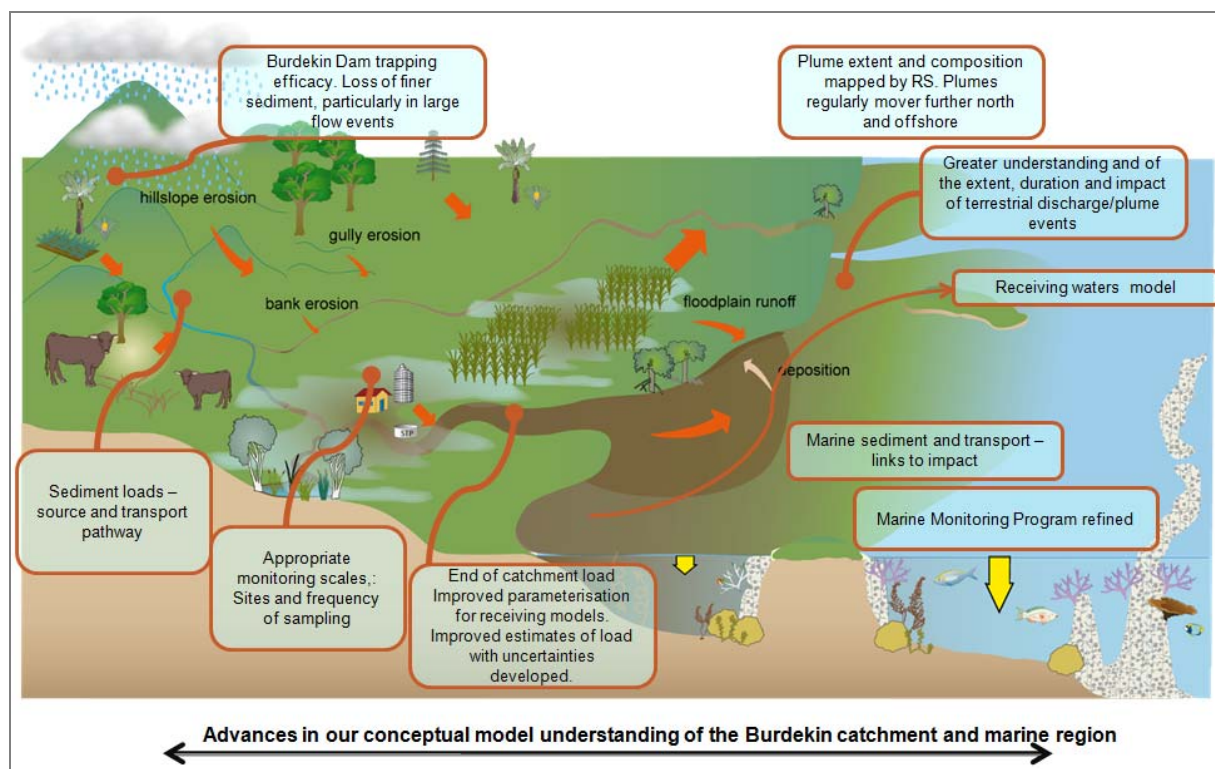


Figure 2: Advances in conceptual understanding of water quality in the Burdekin catchment and marine region (base model developed by Prange, 2007). Source: Devlin and Waterhouse (2010).

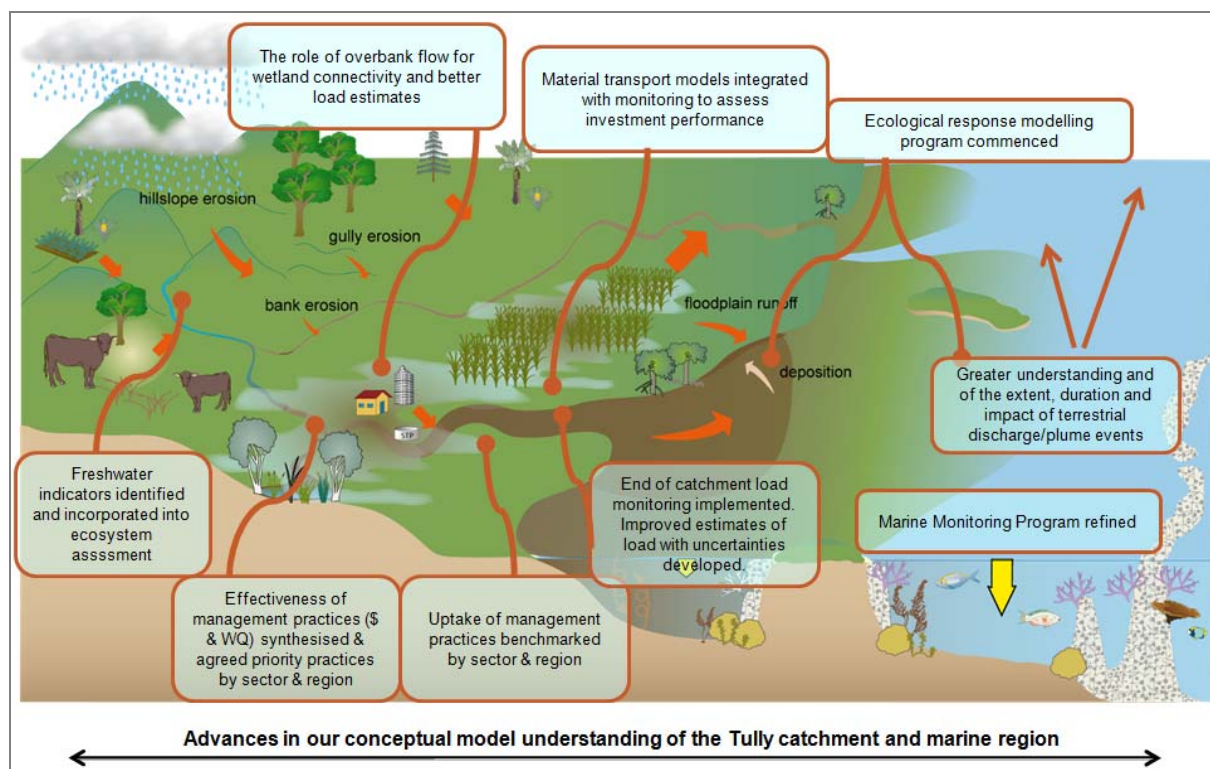


Figure 3: Advances in conceptual understanding of water quality in the Tully catchment and marine region (base model derived from Prange, 2007). Source: Devlin and Waterhouse (2010).

2.3 Pesticides

Pesticide residues, especially herbicides, are widespread in waterbodies of the GBR region, including streams, wetlands, estuaries, coastal and reefal waters (e.g. Lewis *et al.* 2007, 2009b; Packett *et al.* 2005, 2009; Rohde *et al.* 2006, 2008; Mitchell *et al.* 2005; Shaw *et al.* 2010; Davis *et al.* 2008; Bainbridge *et al.* 2009). Residues commonly detected are the PS-II herbicides including atrazine, diuron, ametryn, hexazinone and tebuthiuron (Lewis *et al.* 2009b). These substances would not have been present at all before agricultural development of the catchments. MTSRF-funded researchers investigated several aspects of pesticides in the GBR including review of current knowledge (Lewis *et al.* 2009b), marine ecotoxicology (e.g. Negri *et al.* 2009, 2011) and a preliminary risk assessment (e.g. Lewis *et al.* in press). In the risk assessment proposed by Lewis and colleagues (in press), two separate normalisations were calculated to determine specific areas of risk in the GBR lagoon. The two procedures included the proposed additive GBR Guideline index and a proposed additive PS-II inhibition guideline index, the latter incorporating measured effect concentrations using pulse amplitude modulation chlorophyll *a* fluorescence techniques. The choice of method for pesticide assessment requires further discussion as the use of additive herbicide thresholds show that the area of risk for most regions is greatly increased under the proposed additive PS-II inhibition guideline (Lewis *et al.* in press).

PS-II herbicides are a priority contaminant because they are residual herbicides, relatively soluble and mobile and hence have a higher propensity to reach the marine environment at detectable concentrations. They have a longer half-life than many other herbicides and are widely used in agricultural practices throughout the GBR catchment. Recent MTSRF-supported work on pesticide monitoring in paddocks, rivers and in the marine environment has progressed our understanding of the extent and persistence of pesticides in freshwater

and marine areas (Lewis *et al.* 2009b; Bainbridge *et al.* 2009; Shaw *et al.* 2010). Concentrations of pesticides in rivers and streams are highest in areas of intensive agricultural activity, including sugarcane, but also from grazing lands (tebuthiuron) (Lewis *et al.* 2009b; Brodie and Waterhouse, 2009). Concentrations of pesticides in marine waters are likely to be highest off these rivers with intensive agriculture. This is supported by the data collected within the Reef Rescue Marine Monitoring Program (e.g. Paxman *et al.* 2009; Johnson *et al.* 2010).

Concentrations of pesticides are variable over time and space and thus it can be difficult to define the full impact of pesticide concentrations at any given sampling point. Complex transport mechanisms and variability within receiving waters can make it difficult to define the overall risk area within GBR waters. Work commenced by Lewis and others through the MTSRF in the definition and areal extent of risk and impact from pesticides is ongoing. A synthesis of MTSRF research on pesticides in the GBR has been prepared as part of the MTSRF water quality synthesis report series *Review of MTSRF research advancing understanding of the source, transport and impacts of pesticides on the Great Barrier Reef and in associated ecological systems* (Devlin and Lewis, in press).

Key peer-reviewed findings from MTSRF-funded research include:

- The herbicide residues atrazine and diuron have been identified in water samples taken from flood plumes in the GBR lagoon at concentrations that are known to have negative effects on seagrass and corals (Devlin *et al.* 2009; Lewis *et al.* 2009b).
- Diuron and atrazine are the most commonly detected herbicides in GBR waters and concentrations in flood plumes exceed, at times, laboratory-based lowest observable effect concentrations for marine plants and/or ecological protection guidelines for the Great Barrier Reef Marine Park (Lewis *et al.* 2009b, in press; Magnusson *et al.* 2010).
- Other herbicides detected in the GBR lagoon waters include hexazinone, ametryn, simazine, tebuthiuron, bromacil and metolachlor while residues of the insecticide imidacloprid have also been detected in some parts of the GBR (Davis *et al.* 2008; Kennedy *et al.* in press; Lewis *et al.* 2009b, in press; Shaw and Müller, 2005; Shaw *et al.* 2010).
- Monitoring on the GBR lagoon following wet season discharge showed that 80% of the time when herbicides are detected, more than one is present (Paxman *et al.* 2009; Johnson *et al.* 2010; Kennedy *et al.* in press; Lewis *et al.* in press). These herbicides have been shown to act in an additive manner with regards to photosystem II inhibition.
- Inshore areas of the GBR lagoon may be negatively affected from additive herbicide exposure which could reduce the resilience of this important ecosystem (Lewis *et al.* in press).
- Herbicide residues (atrazine and diuron) persist in the lagoon at low concentrations even during non-flooding seasons (Shaw and Müller, 2005). While the possible long-term effects of this chronic low-level exposure on the GBR ecosystem are unknown, laboratory tests have indicated that sublethal concentrations of diuron can negatively affect the reproductive capacity of corals (Cantin *et al.* 2007), and reduce the rate of energy acquisition for young (recruit) corals (Cantin *et al.* 2009).
- Herbicide residues in some parts of the GBR lagoon can persist at concentrations above GBR photosystem II thresholds for at least one month of the year which suggests potential for chronic effects (Lewis *et al.* in press)
- A summary of the detection and known impact of pesticides detected for GBR biota is provided in Table 1.

- Laboratory work has also shown impacts of pesticides on reef ecosystems from a cellular to system change within coral, seagrass and algal communities. For example, a shift in the community structure of benthic biofilms was observed following exposure to environmentally relevant concentrations of diuron over a four week period, resulting in enhanced tolerance to herbicides over time (Magnusson, 2009; Magnusson *et al.* 2008; Magnusson *et al.* in press). These results strongly suggest that inter-specific differences in herbicide sensitivity may alter the primary productivity or other functional characteristics of tropical ecosystems.
- Recent studies have shown that the combined effects of elevated temperature and reduced water quality (presence of herbicides) were detrimental to the coral *Acropora millepora* in exposure experiments and that the effects of elevated sea surface temperatures (SSTs) and herbicide on photosynthetic efficiency of coral symbionts are additive (Negri *et al.* 2011).
- An innovative multiple biomarker approach has linked patterns in land use with patterns of contamination observed in north Queensland's riverine ecosystems. For example, barramundi caught from five northern Queensland rivers – the Herbert, Johnstone, Endeavour, Lockhart and Pascoe – were tested for exposure to a range of anthropogenic chemicals (Humphrey *et al.* 2007). Analysis of muscle tissue in barramundi from the Johnstone and Herbert rivers indicated exposure to pesticides, particularly insecticides of the organophosphorus and carbamate variety, both of which are difficult to detect in water samples. An organophosphorus insecticide called chlorpyrifos was the most heavily used pesticide in the Johnstone and Herbert catchments (Hamilton and Haydon, 1996), principally by the sugar and banana growing industries. In addition, significantly increased rates of DNA damage were found in barramundi from the Johnstone River relative to those from the other rivers. This may be linked to genotoxic concentrations of polycyclic aromatic hydrocarbons (PAH) detected in water samples from the Johnstone River.

The scientific evidence advanced by MTSRF research, plus a large body of national and international research, indicates that there is a risk that agricultural chemical residues are negatively affecting the resilience of inshore coral reefs (see Devlin and Lewis, in press). MTSRF-funded research has identified that the application, supply and exposure of ecosystems to pesticide contamination has the potential to impact on the freshwater and marine environment (e.g. Lewis *et al.* 2009b; Negri *et al.* 2011), and is a major management issue for the long term protection of the GBR. This work has advanced our understanding of the sources of pesticides from GBR catchments (e.g. Brodie *et al.* 2009a), the transport mechanisms of pesticides to marine waters (e.g. Lewis *et al.* in press), the level and extent of exposure from pesticides within the GBR lagoon (e.g. Kennedy *et al.* in press) and the potential impacts of environmentally relevant pesticide concentrations which have been detected in the GBR (e.g. Negri *et al.* 2009, 2011). Resilience of the GBR inshore system is affected by loads of pesticides delivered from catchments in the wet season and floods result in concentration spikes of pesticides in the GBR lagoon (Lewis *et al.* 2009b). These wet season floods deliver not only agricultural pollutants but also sediments and low-salinity conditions to these inshore reefs during the warmest part of the year, when corals and seagrasses may already be suffering temperature stress, and corals may be attempting to spawn (sexual reproduction generally occurs in November and December each year). Runoff of pesticides and herbicides is therefore likely to be contributing to degradation of ecosystem resilience of the inshore reefs in the GBR. These processes are summarised in the conceptual diagram presented in Figure 4 relating to the source, delivery and impact of pesticides in the GBR.

Table 1: Summary of the detection and known impact of pesticides detected for GBR biota. Source: Devlin and Lewis (in press).

GBR biota	Detection and known impact								
	Pesticides	Insecticides	Fungicides	PS-II herbicides					
				Inhibition of photosynthesis	Growth inhibition	Reduced energy acquisition	Reduced reproduction	Bleaching	Effects enhanced by:
Microalgae				Y	Y				
Crustose coralline algae				Y					Sediments
Seagrass				Y					
Foraminifera				Y					High temperatures
Coral (symbionts)				Y	Y			Y	High temperatures
Coral (host)		Inhibit larval settlement	Inhibit larval settlement			Y	Y	Y	
Crabs	Y	Multiple biomarkers for stress							
Fish		Multiple biomarkers for stress							
Turtles	Y								
Dugongs	Y								

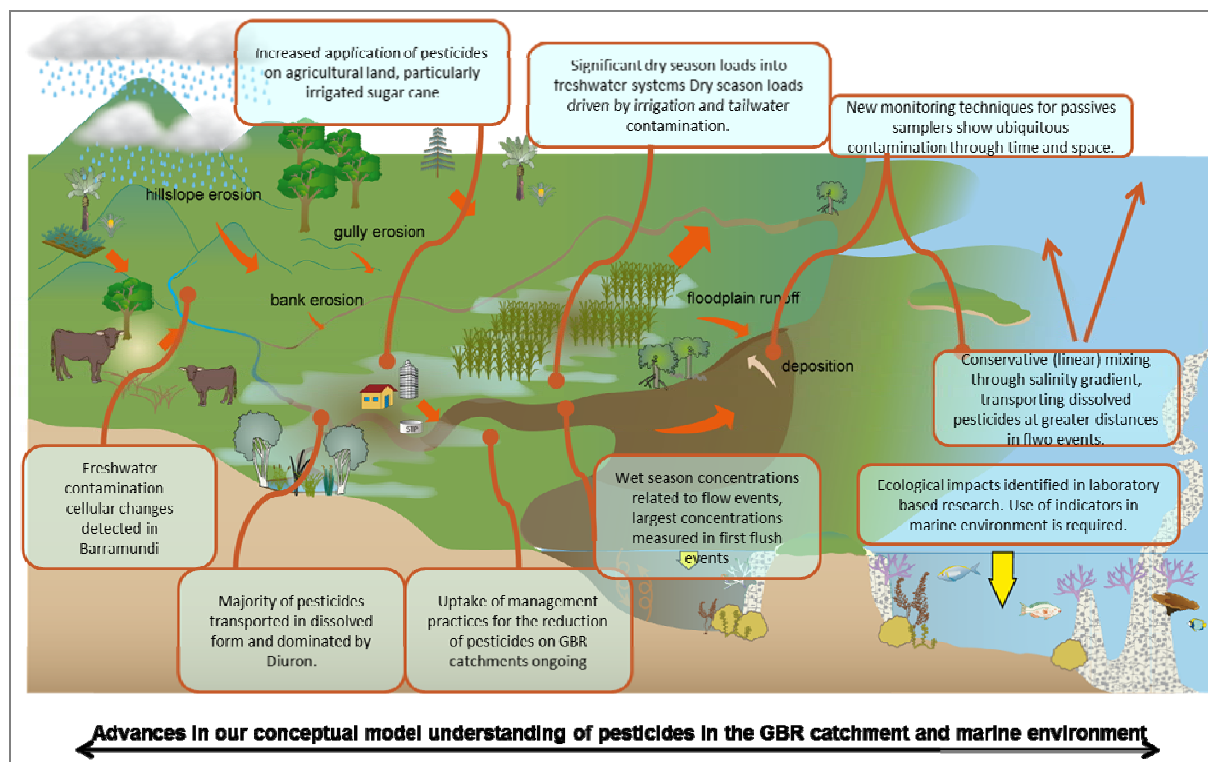


Figure 4: Advances in conceptual understanding of sources, transport and impact of pesticides in the GBR (base model derived from Prange, 2007). Source: Devlin and Lewis (in press).

2.4 Monitoring and evaluation

MTSRF-funded research has generated significant outcomes for informing the design and implementation of GBR water quality monitoring, evaluation and reporting programs. In particular, a monitoring and evaluation framework that incorporates biophysical, social and economic aspects of the system at multiple scales has been developed. This framework includes a range of monitoring and modelling activities to combine system attributes at several scales from plot/paddock, to sub catchment, catchment and regional scales and, ultimately, across the entire GBR. Suitable indicators for measuring ecosystem status and response have been developed and tested for the GBR and its catchments. The indicators incorporate all aspects of the system that managers need to evaluate the performance of management actions in the catchment, and the response to these actions in the GBR ecosystem. These indicators include measures of management practice status and change, catchment health, catchment loads, estuarine health, marine water quality and marine ecosystem health. This suite of indicators is summarised in Figure 5. In some cases, thresholds for these indicators have been established, and form the basis for the definition of guidelines to trigger a management response (see also Waterhouse (2010b) for a synthesis of MTSRF research on thresholds of major pollutants with regard to impacts on instream and marine ecosystems). The best ways to report indicators have also been considered.

MTSRF-funded research has helped overcome some of the important constraints that previously hampered GBR water quality monitoring and evaluation programs. Specifically, best estimates of current contaminant loads delivered to the GBR have been generated (Kroon *et al.* 2010; Brodie *et al.* 2009a, 2009b), techniques for improved estimation of loads have been developed (e.g. Wallace *et al.* 2009, 2010b; Kuhnert *et al.* 2008, 2009; Kuhnert and Henderson, 2010; Wang *et al.* 2009; Lewis *et al.* 2009a), more efficient and robust indicators have been developed and tested for freshwater (Pearson *et al.* 2010), estuarine (Sheaves *et al.* 2010) and marine ecosystems (Cooper *et al.* 2009; Fabricius *et al.* 2010a,

2010b), indicators of social and economic status and governance arrangements are being developed (van Grieken *et al.* 2010a, 2010b; Lynam *et al.* 2010; Taylor and Robinson, 2010) and receiving water models are being established (Brinkman *et al.* 2010; Maughan and Brodie, 2009). In addition, thresholds of concern for priority pollutants have been established for marine ecosystems (GBRMPA, 2009; De'ath and Fabricius, 2010) and used as the basis for the Great Barrier Reef Water Quality Guidelines (GBRMPA, 2009). Pollutant thresholds for freshwater and wetland ecosystems have also been investigated (Pearson *et al.* 2010; Wallace *et al.* 2010a). Waterhouse (2010a) provided an overview of these outcomes, with particular emphasis on aspects that have and can be applied in GBR monitoring programs. These findings are also applicable in similar tropical environments elsewhere in Australia and internationally.

2.5 Climate change and water quality interactions

Climate change has been recognised as one of the greatest threats to coral reefs around the world, including the GBR. A reduction in global carbon emissions is the only long-term solution to the problems caused by climate change, however effective management and strategic investment in enhancing reef resilience through improvements to water quality will help mitigate some of the risks in the short term, giving natural communities time to adapt to a changing environment.

MTSRF-funded research has increased understanding of the response of GBR ecosystems to predicted climate changes, such as increasing sea surface temperatures, ocean acidification and secondary influences of increasing incidents of coral disease. This information is summarised in the companion synthesis report *Water quality and climate change: managing for resilience* (Johnson and Martin, 2011a). In addition, the complex interactions between climate change and water quality, and the mechanisms behind how water quality influences reef resilience have been examined closely and significant new knowledge has emerged (Johnson and Martin, 2011a). Collectively, this new information has been used by MTSRF researchers to develop models that can deal with the complex nature of these relationships to predict how reefs might respond to increasing severity of thermal events, increasing incidents of coral disease, ocean acidification and ultimately the interactions between ecosystem health, water quality and resilience.

For example, recent research indicates that improving water quality will increase resilience of the GBR to future climate change. Specifically, Wooldridge has shown a correlation between the upper thermal bleaching limit of corals and exposure to dissolved inorganic nitrogen (DIN), which suggests that reducing DIN output may enhance the resilience of inshore corals to forecast increases in sea surface temperature (Wooldridge, 2009a, 2009b). This provides evidence that while the issue of building and maintaining GBR resilience to climate change is complex, it is amenable to management influence.

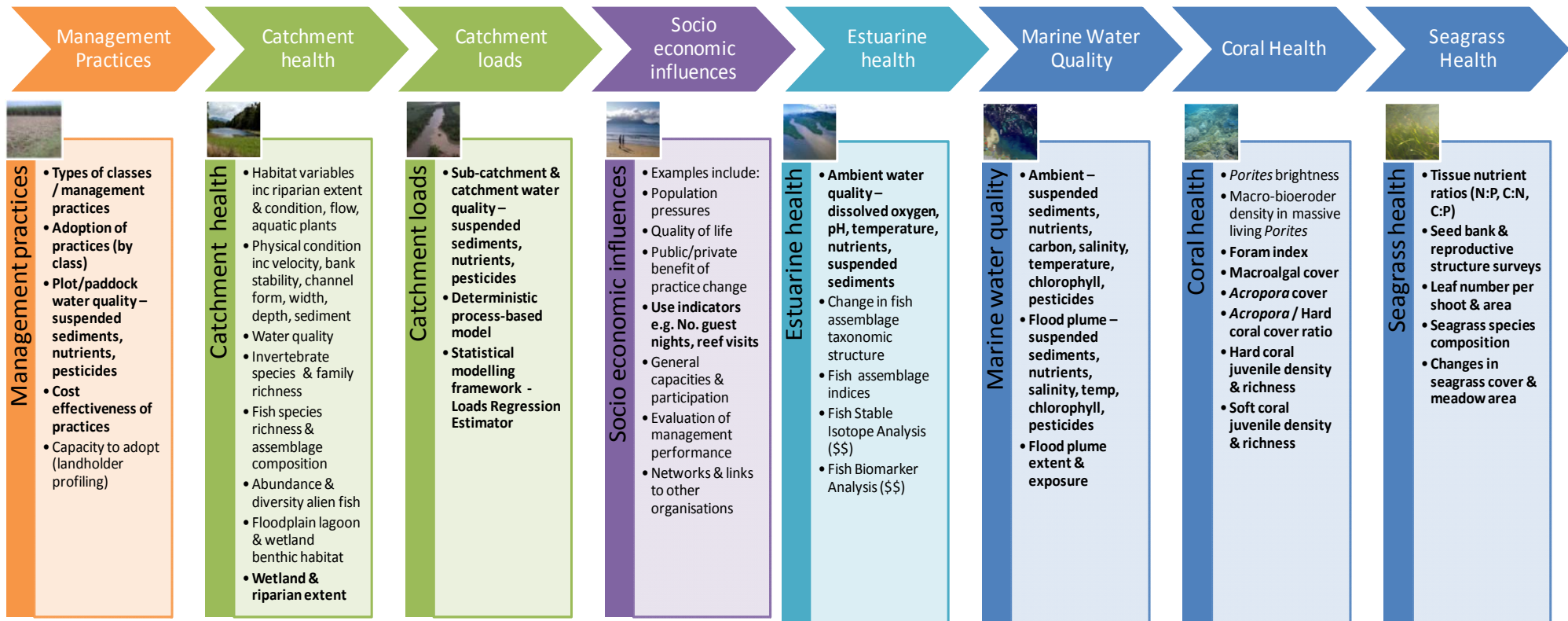


Figure 5: Summary of the recommended suite of indicators for monitoring water quality and ecosystem health in the GBR and its catchments developed and tested through the MTSRF. Indicators highlighted in bold have already been adopted by the Reef Plan Paddock to Reef Integrated Monitoring, Modelling and Reporting Program. Source: Waterhouse (2010a).

MTSRF-funded research has also increased understanding of how GBR communities are likely to be affected by changes to the GBR ecosystem due to climate change, and provided insight into how strategies to improve water quality and enhance ecosystem resilience can be most effectively implemented (summarised in the companion synthesis report *Managing for resilience of the Great Barrier Reef: Socio-economic influences*, Johnson and Martin, 2011b). In addition, the complex interactions between different social systems and how they respond to change have been examined (e.g. Lynam *et al.* 2010). Recent compulsory compliance mechanisms and limited resources for implementation of improved management practices in the GBR catchment means that it is important to select cost-effective practices that have the highest likelihood of delivering positive water quality outcomes and of having high adoption rates. This has motivated several studies within the MTSRF to examine the cost-effectiveness of recommended management practices and rates of uptake for the major industries that are significant sources of sediment and nutrients (e.g. sugarcane, horticulture and grazing) across the GBR catchments (Roebeling 2006; Roebeling *et al.* 2007a, 2007b, 2009a, 2009b; Roebeling and van Grieken 2009; van Grieken *et al.* 2008, 2009, 2010a, 2010b).

Achieving improved water quality also requires strategic and effective planning that considers potential barriers, such as the rate of BMP uptake (e.g. Emtage *et al.* 2009; Emtage and Shrestha, 2010), landholder profiles and typologies and suitable incentives for uptake (in van Grieken *et al.* 2009; Emtage and Herbohn, 2008) and existing institutional and governance arrangements (Robinson *et al.* 2009). In addition, coordinated action and institutional partnerships between state and federal agencies, NRM bodies, agricultural industries, land holders and research providers are required to minimise the risks associated with certain land uses (Taylor and Robinson, 2010).

Managing for GBR resilience requires an understanding of the current pressures and future threats to the GBR ecosystem, and variables that can be used to measure impacts. Current research has focused on key water quality parameters and only a single variable for climate change impacts – coral bleaching. This has many ancillary issues that need to be considered for a comprehensive approach to understanding climate change threats and impacts, and future research needs to identify a suite of suitable climate change variables that can measure ecosystem response and possible changes in resilience.

3. Project highlights

The MTSRF water quality program comprised five major projects, led by several researchers from the Australian Institute of Marine Science, the Australian Centre for Tropical Freshwater Research (at JCU), James Cook University, CSIRO and Griffith University. The highlights of the program are presented above; this section presents the achievements of each of these projects, closing with a summary of significant science outputs for each project.

3.1 Using coral reef organisms as indicators of water quality and ecosystem condition

MTSRF Project 3.7.1 led by Dr Katharina Fabricius, AIMS

http://www.rrrc.org.au/mtsrf/theme_3/project_3_7_1.html

This project confirmed that decreases in water quality cause profound multi-faceted trophic shifts (from phototrophic to heterotrophic communities) and community shifts (from reef-building coral dominated communities to sites dominated by macroalgae and abiotic substrata) on the inshore GBR. Twenty-six environmental variables are strongly and specifically related to water quality conditions on the inshore GBR, and their potential usefulness as indicators of water quality for monitoring programs were investigated. Turbidity was by far the best predictor of biota and should be the first priority for monitoring water quality on the inshore GBR. For example, colonies of massive *Porites* corals are darker in colour, and the density of macrobioeroders on living surfaces is higher, on reefs which experience higher turbidity and river-influenced waters. Less diverse symbiont-bearing benthic foram communities are also observed on these reefs, and the ratio of phototrophic to heterotrophic foram taxa declines. In contrast, total macroalgal cover steeply increases from almost none in clear water reefs to >50% cover in turbid water. Both total cover and the cover of specific genera of hard corals and octocorals declines as turbidity increases, and so does the taxonomic richness and juvenile densities and richness in both hard corals and octocorals. In cases where direct turbidity measurements are impractical or too expensive, bioindicators may be a cost-effective alternative for monitoring changes in water quality. This research project has delivered a final list of 11 bioindicators useful for water quality monitoring on the GBR: *Porites* brightness, macro-bioeroder density in massive living *Porites*, Foram Index, macroalgal cover, *Acropora* cover, *Acropora*/Hard coral cover ratio, *Turbinaria* cover, juvenile hard coral density and richness, and juvenile soft coral density and richness. Additionally, Secchi depth readings taken every visit serve as a twelfth indicator for water quality. A new multivariate approach to synthesising and integrating across multiple and unrelated indicators into one comprehensive and easy to use indicator system is now being tested. This new technique is derived from the indicator work conducted in this MTSRF project over the last four years, and if successful could become widely applicable for ecological indicator initiatives around the world.

The project also identified the organism groups in marine biofilms (bacterial biofilms on sediments, microphytobenthos layers on sediments, and foraminifera on sediment and other reef substrata) that consistently change along water quality gradients. The effects of light and nutrients on growth, mortality and photosynthesis were tested for several foraminiferan species both in laboratory experiments and in the field (through sampling under the Reef Rescue Marine Monitoring Program and experimental field transplants). Both foraminiferan growth rates and C/N ratios are reflective of local water quality conditions. Analyses of the influence of various stressors on foraminiferan distribution have improved our understanding of the thresholds of potential concern for pollutant exposure for individual organism groups and biofilm communities generally. Further experiments investigating interactions between water quality and climate change suggest that for at least one foram species, additive effects

of the two stressors exist, and foram growth rates can be negatively affected by increased nutrient concentrations and increased temperature. Most species tested are clearly susceptible to bleaching at temperatures only slightly above current summer maxima, and thermal thresholds have been established for several foraminiferan species. In an immediate demonstration of the usefulness of this new monitoring tool, a foram index has been incorporated into the Reef Rescue Marine Monitoring Program from 2010. In addition, researchers funded through the MTSRF Transition Program are currently investigating changes in water quality over the past 200 years by analysing changes in foraminiferan communities in dated sediment cores.

Through this project and Project 1.1.1 *Identification of indicators and thresholds of concern for ecosystem health on a bioregional scale for the Great Barrier Reef* indicators of seagrass health have been developed. This is supported by research on the responses of seagrasses to changing environments including increased nutrients, reduced light and increased temperature. The studies concluded that no single indicator is sufficient to interpret the cause of change to seagrass status in the GBR, however by evaluating the response stages of seagrass meadows a reasonable understanding of reasons for decline is gained.

Overall, this project has considerably furthered our understanding as to how poor water quality from river runoff affects a wide range of attributes of GBR communities. Research quantifying the responses of corals and other reef-associated organisms to changing nutrients and sediments permitted the development of a set of indicators that is currently being tested within the Reef Rescue Marine Monitoring Program. Research results from this project have been published in over thirty peer-reviewed scientific papers and ten student theses, formed the basis for the Great Barrier Reef Marine Park Authority's Water Quality Guidelines (GBRMPA, 2009), substantially contributed to and underpinned the Scientific Consensus Statement on Water Quality Issues in the GBR (Brodie *et al.* 2008b, 2008c), substantially contributed to GBRMPA's first Outlook Report, and informed the Reef Rescue initiative as well as the Queensland Government's Reef Regulations. Perhaps most importantly, this MTSRF research project has contributed to a more informed and less confrontational public debate on this highly controversial issue, helping to build community consensus for better environmental management.

3.2 Connectivity and risk: tracing contaminants from the catchment to the reef

MTSRF Project 3.7.2 led by Jon Brodie, ACTFR
http://www.rrrc.org.au/mtsrf/theme_3/project_3_7_2.html

This project has been successful in tracing materials, particularly sediment and pesticides, from the terrestrial environment to the marine environment through the processes of generation, transport, transformation, trapping and risk. Inshore-offshore sediment transport in the Wet Tropics has also been investigated by identifying the relationships between sediment input and transport and regional turbidity regimes. Researchers have shown that the movement of sediment from the Burdekin catchment is dependent on the size and also the location of flood events. The Burdekin Dam plays an important role in trapping a high proportion of incoming suspended sediment, with the bulk of the suspended sediment delivered to the GBR lagoon sourced from the lower catchments below the dam (Bowen/Bogie catchment). The project has produced data on suspended sediment behavior in flood plumes by describing the pathway of the finer sediment and its potential impacts on the reef. This work has shown that the finer sediment signature is still present in secondary flood plume waters (though masked through organic flocculation processes), and further work can potentially start to connect plume behaviour and potential impacts with specific soil types/sources in the sub-catchments of the Burdekin River. Geochemical records from coral

cores have been successfully used as proxies to demonstrate long-term changes in catchment sediment loads, and to develop long-term histories of regional trends in agricultural and urban activities.

Sediment budget research in the Tully and Cleveland Bay areas has been successful in developing our understanding of the sediment pathways, and the long-term impact of increased sediment supply. Sediments sourced during high flow events are deposited in the bay, and are re-suspended during the dry season through the trade winds. This has the effect of increasing the long-term turbidity of the bay, with consequences for local coral and seagrass ecosystems. Science-based sediment reduction rates which may potentially promote seagrass and reef growth in this area have been proposed.

A major component of this project has been the identification of priority pollutants and priority areas for management of water quality in the GBR. The key findings are:

- The priority pollutants derived from anthropogenic land uses considered most likely to pose a threat to the quality of runoff water entering the GBR ecosystem are suspended sediment, dissolved inorganic nitrogen (DIN) and PS-II herbicides.
- There is a large difference in the pollutants of concern between the wet and dry catchments within the GBR catchment area.
- Due to the wetter climates and presence of intensive agricultural land uses (sugar cane and horticulture) and their associated fertiliser and pesticide usage, the Wet Tropics and Mackay-Whitsunday areas have been identified as regions of high nutrient and pesticide runoff concern.
- The significantly larger Fitzroy and Burdekin River catchments (each ~135,000 km²) dominated by unimproved savannah/woodland rangeland grazing, are identified as considerable contributors of suspended sediment to the GBR lagoon.
- Concentrations of pesticides in rivers and streams are highest in areas of intensive agricultural activity, including sugar cane, but also from grazing lands (tebuthiuron). Concentrations of pesticides in marine waters are likely to be highest off these rivers with intensive agriculture. This is supported by the data collected within the Reef Rescue Marine Monitoring Program.

The total priority pollutant loads (sediments, nutrients and pesticides) from each region have been calculated based on a combination of long-term monitoring data and recent SedNet/ANNEX model outputs. 'Hot spot' areas or catchments have been identified, as well as the key land uses in each region which would benefit from further management intervention.

In conjunction with activities undertaken as part of Project 3.7.1, this project, in collaboration with other programs, has identified that the application, supply and exposure of ecosystems to pesticide contamination has the potential to impact on the freshwater and marine environment, and is a major management issue for the long term protection of the GBR. Pesticide research in the MTSRF has considerably advanced our understanding of the sources of pesticides from GBR catchments, the transport mechanisms of pesticides to marine waters, the level and extent of exposure from pesticides within the GBR lagoon and the potential impacts from the environmentally relevant pesticide concentrations which have been detected in the GBR.

3.3 Freshwater indicators and thresholds of concern

MTSRF Project 3.7.3 led by Professor Richard Pearson (JCU) and Professor Angela Arthington (GU)

http://www.rrrc.org.au/mtsrf/theme_3/project_3_7_3.html

This project sought to measure and understand the ecological processes, linkages and interdependencies that govern the condition, health, trend and resilience of rivers and their floodplain wetlands in GBR catchments, as a basis for development of cost-effective biophysical monitoring tools to help sustain these habitats and their dependent environmental assets. Researchers produced a conceptual biophysical model that identified potential indicators of wetland health, and probable thresholds of concern, in terms of contaminant concentrations, ecological processes and biodiversity. The major indicators identified are related to pressures including types of land use, general water quality and contaminants, hydrological regime and connectivity, channel and habitat structure, riparian vegetation condition and alien species of plants and fish. Stressor-response relationships along gradients of disturbance (supported by data from laboratory trials and the literature) have helped to identify 'thresholds of concern', i.e. points along each disturbance gradient where ecological changes of scientific or management concern become apparent.

The most serious factors currently affecting health in Wet Tropics streams and wetlands are changes to habitats, including flow modification, invasion by exotic weeds and loss of riparian vegetation, which can cause major changes to waterway morphology, habitat complexity, food availability, gas exchange with the atmosphere and, therefore, biodiversity. Dry Tropics streams and wetlands are impacted by similar influences but due to varying land uses and a dominance of cattle grazing, are generally more exposed to issues related to sedimentation. Many Dry Tropics rivers cease to flow in the dry season, contracting to isolated lagoons which provide refugia for the biota. The gradient of flow regime from mid-Wet Tropics to Dry Tropics is very clearly reflected in their biodiversity, with even the smaller rivers of the Wet Tropics supporting many more fish species than the large Dry Tropics systems. Flow regime has a high influence on fish populations. The relationship between the structure and dynamics of the larval fish assemblage in lowland riverine Wet Tropics habitats and the underlying variability of the habitat and its condition are shaped primarily by the prevailing flow regime.

The fauna in the wetlands of the Tully-Murray floodplain and in streams of the Russell-Mulgrave catchment is in moderate to good condition. It appears that the fauna is resistant to the immense changes in land use that have taken place across the floodplains in the last century, mostly because of perennial flows. Less well-flushed systems (e.g. on the Herbert floodplain) do not fare so well. Potential indicators of ecosystem health, such as abundance and diversity of zooplankton and benthic invertebrates, tend to correlate very closely with habitat changes, which themselves are quite straightforward to monitor (e.g. floods, riparian condition, alien species and weeds). Fish provide a robust indication of lagoon condition and, importantly, connectivity, while fish and especially invertebrates are good indicators of condition in streams.

3.4 Wetlands and floodplains: connectivity and hydrological function

MTSRF Project 3.7.4 led by Dr Jim Wallace, CSIRO
http://www.rrrc.org.au/mtsrf/theme_3/project_3_7_4.html

This project successfully quantified the role of over-bank floods on the transport of sediments and nutrients and their transport across floodplains in the Wet Tropics. This work was instrumental in the prediction of how the hydrological response and connectivity of floodplain wetlands are affected by land use and water management. Researchers have shown that the nutrient loads being delivered during flood events from the Tully-Murray catchments to the GBR lagoon have been significantly underestimated: over-bank flood contributions were found to increase the mean annual loads of phosphorus and nitrogen loads by 30-50% above previous river-based estimates.

Model simulations provided a means of identifying the degree of connectivity of different wetlands, ranging from those wetlands that are more permanently connected with streams and drains, to those that are connected only when there are large over-bank floods. This information has been integrated into the biological indicator work to help understand movement of freshwater fish. Understanding of the ecological functions of wetlands has been enhanced by this improved knowledge of over bank flow and the reoccurrence of connectivity between wetlands. Variations in wetland connectivity could affect the movement of aquatic biota during floods, and the variability of habitat and biodiversity of individual wetlands. Knowledge of the appropriate corridors and links will be instrumental in any future management of wetlands and/or selection for rehabilitation and restoration.

3.5 Socio-economic constraints to and incentives for the adoption of land use and management options for water quality

MTSRF Project 3.7.5 led by Martijn van Grieken, CSIRO
http://www.rrrc.org.au/mtsrf/theme_3/project_3_7_5.html

This study has provided an economic assessment of instruments promoting adoption of land management practices by landholders for the Tully Murray catchment in the Wet Tropics and the Burdekin catchment in the Dry Tropics. The objectives of this study were to determine the private economic consequences of management practice adoption, determine the effectiveness of management practice adoption in reducing nutrient supply, and assess the effectiveness of taxes and subsidies to promote the adoption of management practices. Researchers combined a financial analysis of management practices in sugarcane, beef cattle production, banana cultivation and production forestry at the paddock scale and a farm household modelling approach for various types of producers at the farm scale. The results showed that improved nutrient, pesticide and soil management in the sugarcane industry would lead to increased productivity benefits, but at a significant investment cost. Improved practices (i.e. reduced stocking rates) in the grazing industry would cause a loss of productivity, although in some cases, reductions in stock rates may lead to benefits (through increased gross margins).

Researchers then made some predictions about how different types of farmers, or farming agents, will respond to different policy interventions, by developing a typology of farmers in the study area. This has permitted qualitative and quantitative estimation of regional socioeconomic and environmental consequences of implementing a specific policy in terms of local income, employment and nitrogen runoff. The conclusion of this work is that while financial motives are important in explaining adoption of management practices, there are a wide range of other nonfinancial factors explaining the current non-adoption of management practices by a significant number of farmers.

3.6 More reliable and accurate estimates of pollutant loads entering the Great Barrier Reef lagoon

MTSRF Project 3.7.7 led by Dr Petra Kuhnert, CSIRO
http://www.rrrc.org.au/mtsrf/theme_3/project_3_7_7.html

This project has generated a four-step methodology – the Loads Regression Estimator (LRE) – which allows better estimates of load through the calculation of the uncertainty associated with load data. The first step involves ‘regularising’ the flow, a process whereby a loess smoother, capturing peak flows, is used to predict flow at regular time intervals (e.g. hourly) and infill any gaps in the flow monitoring data. The second step in the methodology fits a generalised additive model to concentration (on the log-scale) to model the relationship between concentration and a series of flow terms that attempt to mimic key hydrological processes of the system with the aim of reducing knowledge uncertainty. The third step involves the estimation of the load, which is the result of multiplying the regularised flow by the concentration predicted at each regularised flow value, which is then summed over the water year. The fourth step involves the construction of the variance around the estimate of the load. The variance is structured so it not only incorporates errors in the concentration but errors in the flow rates (measurement and spatial). The LRE has been applied to twelve monitored rivers and nine pollutants to estimate annual loads with uncertainties. These estimations were then used to calculate more reliable and accurate long-term loads of pollutants being delivered to the Great Barrier Reef lagoon. The LRE has already been adopted by water quality monitoring programs and is being used to report on the status of, and trends in, pollutant loads.

3.7 Related research from within the MTSRF Research Programme

A number of other Themes within the MTSRF have generated outcomes that are relevant to water quality management in the GBR. Examples of these are summarised below.

Project 4.9.6 *Strategic NRM and land use planning* **Led by Dr Catherine Robinson, CSIRO**

This project developed SMART (Specific, Measurable, Achievable, Relevant and Timed) targets for the GBR catchments (McDonald and Roberts, 2006), where water quality targets are explicitly determined from achievable land management practices and set within an adaptive management framework. This process also allows analysis of management options by running and exploring scenarios, and can assess potential progress towards scientifically validated targets for various management options. In addition, the research team has provided important insights into evaluation and reporting of water quality management responses (see Taylor and Robinson, 2010 for an overview of this work).

Project 4.9.7 *Understanding and enhancing social resilience* **Led by Dr Tim Lynam, CSIRO**

In addition to the governance and institutional investigations outlined above, a complementary component of management evaluation research in the MTSRF was designed to enable agencies, such as regional NRM bodies or state government agencies, to explore likely impacts of interventions such as financial incentives or regulation to achieve water quality on the adaptive abilities of society (see Lynam *et al.* 2010). Based on the outcomes of a series of surveys with key stakeholders, a set of indicators of social resilience to environmental or other change in the GBR region were developed. These indicators are supported by a step-by-step user guide for applying this indicator framework, including survey templates and the most suitable assessment approaches, facilitating the application of this approach elsewhere.

Project 2.5i.4 *Tools to support resilience-based management in the face of climate change*

Led by Dr Scott Wooldridge, AIMS

This project provided quantitative insight into many of the management issues that presently face coral reef managers tasked with maintaining reef resilience in the face of climate change. The benefit of 20%, 40%, 60% and 80% reductions in end-of-river dissolved inorganic nitrogen (DIN) concentrations in raising the thermal tolerance (i.e. bleaching 'resistance') of inner-to-mid-shelf reef sites on the GBR was modelled alongside two alternative global CO₂ emission scenarios: (a) No mitigation ('business-as-usual'), and (ii) CO₂ mitigation leading to atmospheric stabilisation of CO₂ concentrations at 450 ppm early in the 22nd century. The 'ReefClim' software package was used to develop regional-scale sea surface temperature (SST) patterns for the GBR until 2100. The dominant feature of the projected SST warming from all climate models tested was a proportionately higher rate of warming in the central to southern GBR. Simulated reductions in end-of river DIN loads appear to offer considerable improvements in the future survival prospects of locally-impacted reefs. The model projections demonstrated that in the area between Cardwell and Bowling Green Bay, an 80% reduction in DIN permits the maintenance of the coral-dominated reef state for an additional ~50 years beyond current projections for the 'business-as-usual' (no mitigation) climate change scenario. Moreover, when coupled with the CO₂ mitigation (stabilisation at 450 ppm) climate change scenario, the enforcement of ~50% reduction in DIN is sufficient to ensure the long-term persistence of the impacted reefs. The outcomes of this work demonstrate that both local and global strategies are needed to prevent mortality risk and loss of resilience that currently characterises the inner-to-mid-shelf reefs of the Great Barrier Reef.

The e-Atlas

The e-Atlas is a new web-accessible integrated knowledge management system designed to provide a framework to facilitate effective use and sharing of information in order to enhance evidence-based decision making for effective management and the long-term sustainable use of the GBR and its catchments, the Wet Tropics rainforests and Torres Strait. The e-Atlas is a portal providing access to new data and information handling, spatial mapping and analytical tools to collate, integrate, share and analyse the vast array of biophysical and socio-economic data required to manage these environmentally, economically and culturally valuable systems effectively. Based on open-source software, the e-Atlas uses internationally recognised standards that enable its content to be interrogated and delivered into GIS systems, particularly those within federal and state government departments and agencies. For example, the e-Atlas contains the primary datasets measured as part of the Reef Rescue Marine Monitoring Program, and statistical analyses of long term water quality data sets. In addition, numerous maps included in the e-Atlas illustrate characteristics of North Queensland's ecosystems, particularly patterns and hotspots of biodiversity and threats, facilitating the identification and improvement of understanding of the major risk and resilience factors influencing the MTSRF region, and their ecological, social and economic impacts, and enhances capacity to evaluate and implement effective policy and management responses to ensure the long-term sustainability of North Queensland's natural assets.

4. Outcomes for management

The findings of the MTSRF research presented in this report are directly relevant to managers of the Great Barrier Reef World Heritage Area and its catchment. Some highlights of the management applications of the outcomes are provided below.

- The multi-scale, multi-disciplinary 'paddock to reef' monitoring and modelling framework developed by MTSRF researchers (see Bainbridge *et al.* 2009) has been used to inform the development of the Reef Plan Integrated Paddock to Reef Monitoring, Modelling and Reporting Program to support the evaluation of targets in the Reef Plan and Reef Rescue initiative. Many of the coral and seagrass indicators developed and tested through the program are already operational as part of the marine component of the program, the Reef Rescue Marine Monitoring Program (refer to Johnson *et al.* 2010). The whole of system monitoring approach was also used in the development of regional water quality plans, including the Water Quality Improvement Plans for the Tully, Barron, Townsville Thuringowa (Black Ross), Mackay-Whitsunday and Burnett-Mary regions. These programs assisted in the identification of priority pollutants and priority areas for management in each region. In conjunction with revised and improved pollutant load estimations (see below), the findings have informed the prioritisation of Reef Rescue expenditure in these regions.
- Of considerable significance, the management responses presently being implemented through Reef Rescue initiatives and the Queensland *Great Barrier Reef Protection Amendment Act (2009)* (Reef Protection Package) are focused on the areas and industries identified in the risk assessment of priority pollutants and priority areas completed through a collaborative MTSRF project (Brodie and Waterhouse, 2009; Brodie *et al.* 2009b).
- MTSRF-funded research on thresholds of concern for coral ecosystems (De'ath and Fabricius, 2010) provides the scientific basis for the Great Barrier Reef Water Quality Guidelines 2009 (GBRMPA, 2009). These guidelines are used for assessment of the annual results of the Marine Monitoring Program, for assessing annual status and relative change between monitoring periods (e.g Johnson *et al.* 2010). Remote sensing techniques that have evolved through development and testing in the Marine Monitoring Program enable broad-scale assessment of chlorophyll, turbidity and Colour Dissolved Organic Matter concentrations against these guidelines (Brando *et al.* 2010). The thresholds that are suggested for tissue nutrients in seagrasses (Waycott and McKenzie, 2010) are currently used to assess the seagrass monitoring results in the same program.
- The findings of the MTSRF catchment and instream health research (see Pearson *et al.* 2010) can be used to assess the condition of Wet Tropics streams and wetlands, which is of interest to the Queensland Government and regional NRM groups. Where thresholds were not able to be established due to considerable local and regional differences and/or insufficient datasets, the assessment provides a robust set of stressor-response relationships and a robust benchmark against which improvement in the ecological condition of streams and floodplain lagoons can be evaluated.
- A large proportion of the outcomes of these research programs have been incorporated into significant management documents, for example, the revised Scientific Consensus Statement on Water Quality in the Great Barrier Reef (Brodie *et al.* 2008b, 2008c). The Statement was developed by leading researchers to support the revision of the Reef Plan (DPC, 2009; www.reefplan.qld.gov.au) and implementation of the Australian Government's \$200 million Reef Rescue initiative. A large component of this knowledge was generated by the MTSRF in collaboration with other initiatives, with several authors of the Statement leading MTSRF research activities (J. Brodie, K. Fabricius, R. Pearson, I. Gordon and J. Waterhouse). Many of these MTSRF findings have also informed the first GBRMPA Outlook Report.

Many of the most significant influences of the MTSRF research on management decisions have been through the participation of MTSRF researchers in steering committees and technical groups coordinated by management agencies. MTSRF researchers are able to contribute their knowledge and synthesis of the research findings directly into the management processes; in many cases their contributions to discussion instigates interest which is subsequently supported through the provision of written evidence. Examples of these activities include the range of technical groups and forums coordinated for the regional Water Quality Improvement Plans, design workshops for the Paddock to Reef Program and ongoing participation in the associated Technical Advisory Group, the expert workshops convened for the Multi-Criteria Analysis for prioritising Reef Rescue investment, participation in various committees for the Queensland Wetlands Program, and involvement in several research prioritisation workshops which have informed the Reef Plan and Reef Rescue R&D Strategies.

5. References

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