Marine and Tropical Sciences Research Facility

Water Quality Research: Baseline Synthesis and Year 1 Summary

Australian Government

Department of the Environment, Water, Heritage and the Arts

Reef & Rainforest RESEARCH CENTRE

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Baseline Synthesis and Year 1 Summary

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Executive Summary

In the period since the release of the Reef Water Quality Protection Plan in 2003 research has been published this both changes and advances our understanding of water quality issues for the Great Barrier Reef (GBR). This report summarises the research and identifies key water quality issues that need to be addressed in the future. The Marine and Tropical Sciences Research Facility (MTSRF) will play a pivotal role in investigating these priority research needs.

Sources

The exact sources of contaminants resulting from land uses and land management practices are now well known. The effects of small scale controlling processes in soil erosion have been established (e.g. pasture cover, patchiness: Bartley *et al*. 2006). Most dissolved inorganic nitrogen (DIN, primarily nitrate) in streams which drain cropping areas comes from fertiliser residues (Rohde *et al.* 2006a; Faithful *et al.* 2007) with ninety percent of DIN originating from this source in the Tully/Murray Region (Mitchell *et al.* 2006; Armour *et al.* 2007). The herbicide residues most commonly found in surface waters in the GBR region (diuron, atrazine, ametryn and hexazinone) derive largely from sugarcane cultivation (Rohde *et al.* 2006a; Faithful *et al.* 2007; Lewis *et al.* 2007a). High suspended sediment concentrations derive from rangeland grazing in the Dry Tropics and urban development sites (Bainbridge *et al.* 2006a; 2006b; Rohde *et al.* 2006a), whereas sediment fluxes are relatively low from cropping landuses (especially sugarcane cultivation) due to changes in management practices over the last twenty years (Rayment 2003; Bainbridge *et al.* 2006b; Rohde *et al.* 2006a; Faithful *et al.* 2007).

Loads

Our understanding of the transport and trapping of contaminants as they move through the GBR catchments from paddock to river mouth has improved greatly. With this understanding comes a more accurate knowledge of the changes in delivery of contaminants from the GBR catchments to the GBR lagoon due to land use change (Brodie *et al.* 2003; Furnas 2003; Cogle *et al.* 2006) resulting from improved monitoring and modelling. Steps in the transport pathway such as bedload storage (Bartley *et al.* 2007a) and overbank flow (Wallace *et al.* 2007a) have now been better quantified. The dynamics of substances such as dissolved organic nitrogen (DON), which were previously neglected, are now being considered. Models such as SedNet/ANNEX are being greatly improved in their predictive ability (Cogle *et al.* 2006; Armour *et al.* 2007; Kinsey-Henderson and Sherman 2007) and validated through comparison with monitoring results (Fentie *et al.* 2005a; Armour *et al.* 2007; Mitchell *et al.* 2007a; Sherman *et al.* 2007).

Pesticides

Pesticides have recently been recognised as a greater potential threat to GBR ecosystems (mangroves, wetland plant communities, seagrass, coral reefs, phytoplankton communities) than was realised before 2003. Pesticide residues, especially herbicides, are ubiquitous in many GBR region waterbodies including streams, wetlands, estuaries, and coastal and reefal waters (e.g. Packett *et al.* 2005; Rohde *et al.* 2006a; Faithful *et al.* 2007; Lewis *et al.* 2007a). In marine waters, residues at biologically active concentrations have been found up to sixty kilometres offshore (Rohde *et al.* 2006a) in the wet season and in low but detectable concentrations in the dry season (Shaw and Müller 2005). These herbicides are shown to have biological effects on coral zooxanthellae, seagrass and microalgae at concentrations below 1 µg/L (e.g. Jones and Kerswell 2003; Jones *et al.* 2003; Harrington *et al.* 2005; Jones

2005; Negri *et al.* 2005; Markley *et al.* 2007; Cantin *et al.* in press). The long-term effect on ecosystem performance of the continuous presence of such residues is not known.

Flood plumes and exposure

The large increase in the availability of new satellite remote sensing platforms (e.g. MODIS, MERIS, ASTER, SPOT-5, QUICKBIRD, IKONOS, SEAWIFS) added to existing platforms (LANDSAT, AVHRR) has allowed the possibility of tracking flood plume dispersal in the GBR lagoon on a daily basis. The use of such images combined with traditional concurrent surface vessel sampling and image analysis for parameters such as suspended sediments and chlorophyll *a* (A. Dekker, pers. comm.) has allowed the assessment of the degree of exposure of GBR reefs (and other ecosystems) to be quantified (Brodie *et al.* 2006; Rohde *et al.* 2006a; Brodie *et al.* 2007a). In addition, analysis of the datasets collected in long-term studies of GBR water quality have allowed fine scale assessment of water quality in the GBR lagoon (Furnas 2003; De'ath 2005; Devlin and Brodie 2005; Furnas *et al.* 2005; Brodie *et al.* 2007a; De'ath In prep). Use of these combined datasets (flood plume and long-term water quality) has allowed modelling to link river discharge of contaminants to reef ecosystem exposure and to assess possible effects (Devlin *et al.* 2003; Wolanski and De'ath 2005; Wooldridge *et al.* 2006).

Effects

Our understanding of the effects of land-sourced contaminants on GBR species and ecosystems has been expanded enormously in the period since 2003. Dieback of the mangrove *Avicennia marina* in the Mackay region has been attributed to herbicide residues, particularly diuron (Duke *et al.* 2005). The effects of nutrients on GBR seagrass health have proved complex to understand, but it is now clear that the effects are different to those shown for temperate seagrass and the threat from increased nutrients may be less in tropical cases (Mellors *et al.* 2005; Schaffelke *et al.* 2005; Waycott *et al.* 2005). Strong links between coral reef health and water quality conditions have been shown (Fabricius 2005; Fabricius *et al.* 2005) including sedimentation stress (Philipp and Fabricius 2003; Weber *et al.* 2006) and the effects of muddy marine snow (Fabricius *et al.* 2003; Wolanski *et al.* 2003b). Links between nutrient enrichment and crown-of-thorns starfish (COTs) population outbreaks are now well supported in both anthropogenically enriched systems such as the GBR (Brodie *et al.* 2005) and naturally enriched systems such as the northern Pacific (Houk *et al.* 2007). Comparisons of the degree and stage of reef degradation, and the severity of human activity within the GBR compared to other global reef systems, shows that although the GBR is in relatively good condition it is by no means pristine, and is well along the path to the degradation seen in many other reef systems (Pandolfi *et al.* 2003; Brodie *et al.* 2007a; Bruno and Selig 2007).

Indicators

The use of coral cores to show the presence of a 'terrestrial signal' in the GBR, and hence changes in the delivery of materials from the land to the GBR with catchment development, are now well established. Ba/Ca ratios as an indicator of suspended sediment delivery from the Burdekin has been established (McCulloch *et al.* 2003a; Lewis *et al.* 2007b), as well as other metals that indicate specific changes in grazing practices (Lewis *et al.* 2007b). Additional coral proxies of water quality are currently being developed (Alibert *et al.* 2003; Wyndham *et al.* 2004; Sinclair 2005; Marion *et al.* 2005). Changes in the delivery of water due to vegetation change or loss in catchments have also been investigated using coral cores, and some dispute currently exists over the interpretation of this record (McCulloch 2004; Lough 2007). Changes in nitrogen delivery to reefs associated with increasing fertiliser use for sugarcane cultivation have been demonstrated from coral cores off Mackay (Jupiter *et al.* 2007; Marion 2007).

Cooper and Fabricius (2007) have used physical coral indicators to investigate the productively of reefs through the water quality gradient in the Whitsunday Island group. The species composition of foraminifera also shows a relationship with water quality conditions along this gradient (Nobes and Uthicke 2007). This tool has previously been applied to coral reefs in the Caribbean (Uthicke *et al.* 2006).

Models

In the context of extreme climatic variation and the large scale of the GBR and its catchment, modelling is essential in the interpretation of short-term monitoring data. The SedNet and ANNEX model group has been widely used at the catchment and sub-catchment scale for the entire GBR catchment area and has also been repeated and developed for regional catchments (e.g. Brodie *et al.* 2003; Cogle *et al.* 2006; Armour *et al.* 2007; Kinsey-Henderson and Sherman 2007) to predict sediment and nutrient generation, transport and delivery to the GBR lagoon. Limited modelling has occurred to connect land-sourced pollutants to marine effects (Wolanski *et al.* 2004; Wooldridge *et al.* 2006), however this is a critical area for further development to help set management targets. Considerable improvements have also been made in our ability to include socio-economic factors into modelling efforts (Roebeling 2006) which is also critical to prioritise catchment management implementation. In very recent times, a large array of conceptual models has been developed to better underpin monitoring programs and form the basis for numerical modelling (Prange 2007; Haynes *et al.* In press).

Contents

Acronyms and Abbreviations

ACTFR .... Australian Centre for Tropical Freshwater Research
AgSIP .... Agricultural State Investment Projects
AIMS .... Australian Institute of Marine Science
ANU .... Australian National University
ARC .... Aboriginal Rainforest Council
Ba .... Barium
BMP .... Best Management Practice
BSES .... Bureau of Sugar Experiment Stations
CCI .... Coastal Catchment Initiative
COTs .... Crown-of-thorns starfish
CRC .... Cooperative Research Centre
CSIRO .... Commonwealth Scientific and Industrial Research Organisation
DEW .... Department of the Environment and Water Resources (now Department of the Environment, Water, Heritage and the Arts)
DIN .... Dissolved inorganic nitrogen
DNRW .... Department of Natural Resources and Water
DON .... Dissolved organic nitrogen
DPI&F .... Department of Primary Industries and Fisheries
DSS .... Decision support system
EPA .... Environmental Protection Agency
ERM .... Ecological response modelling
FNQ .... Far North Queensland
FNQ-NRM .... Far North Queensland Natural Resource Management Board (now Terrain NRM Ltd)
FRC .... Fisheries Research Corporation
FSS .... Fine suspended sediment
GBR .... Great Barrier Reef
GBRCA .... Great Barrier Reef Catchment Area
GBRMPA .... Great Barrier Reef Marine Park Authority
GBRWQ .... Great Barrier Reef Water Quality
GU .... Griffith University
IOC .... International Oceanographic Commission
IRC .... Integrated report card
IRCF .... Integrated report card framework
JCU .... James Cook University
MLA .... Meat and Livestock Australia
MTSRF .... Marine and Tropical Sciences Research Facility
N .... Nitrogen
NAPSWQ .... National Action Plan for Solidity and Water Quality
NOx .... Nitrate + Nitrite
NRM .... Natural Resource Management
P .... Phosphorus
PDF .... Portable document format
RWQPP .... Reef Water Quality Protection Plan
SMART .... Specific, measurable, achievable, relevant and timed

SEAP............................Stream and Estuary Assessment Program
SIGNAL........................Stream Invertebrate Grade Number – 'Average Level'
SIP................................State Investment Package
SoE ....State of the Environment
SRDC ....Sugar Research and Development Corporation
SS.................................Suspended sediment
SSC ....Suspended sediment concentration
TSS ....Total suspended solids
URS..............................URS Corporation
WfHC............................Water for a Healthy Country
WQIP............................Water Quality Improvement Program
WQSIP ....Water Quality State Investment Package
WRP ....Water Resource Plan

1. Current Research Overview

1.1 Introduction

In the period from the establishment of the Great Barrier Reef Marine Park (1978) to the late 1990s, an increasing amount of research and monitoring effort was devoted to documenting and understanding the nature and importance of water quality issues for the Great Barrier Reef (GBR). Attention became focussed on land-based runoff as it was realised that the biggest source of pollution was runoff from the Great Barrier Reef Catchment Area (GBRCA). Conferences with a principal theme of GBR water quality were held in the 1980s, 1990 (Townsville), 1995 (Rockhampton), 1998 (Brisbane), 2001 (Townsville) and 2003 (Townsville), all of which produced papers published as proceedings that helped to consolidate our knowledge of the issue. By 2000 it was realised that a specific water quality management plan for the GBR was necessary. In order to produce such a plan, a number of knowledge synthesis and analysis documents were produced between 2000 and 2003 including the Water Quality Action Plan (Brodie *et al.* 2001); the report *Great Barrier Reef water quality: Current issues and management strategies* report (Haynes *et al*. 2001); the report by Williams *et al.* 2002 entitled *The current level of scientific understanding on impacts of terrestrial run-off on the Great Barrier Reef World Heritage Area*; a report on the study of land sourced pollutants and their impacts on water quality by Baker (2003); the Productivity Commission (2003) report; and the book *Catchments and corals: Terrestrial runoff to the GBR* by Furnas 2003. These documents consolidated our understanding of water quality issues for the GBR and thus provided the background for, and were instrumental in the development of the Reef Water Quality Protection Plan 2003 ('Reef Plan') (RWQPP) (ANON 2003).

In the period since the release of the RWQPP a number of large scale research, monitoring and management programs with some emphasis on GBR water quality have been implemented. These include the CSIRO Water for a Healthy County GBR program; the National Action Plan for Salinity and Water Quality with projects at Queensland State level (the State Investment Package, or SIP) and NRM regional level (e.g. water quality monitoring programs in the Mackay-Whitsunday and Burdekin regions); the *Catchment to Reef* joint program of the CRCs for Reef and Rainforest; the Water Quality Improvement Plan programs (DEW Coastal Catchments Initiative) in the Douglas Shire, and the Tully, Burdekin, Townsville-Thuringowa, Mackay-Whitsunday, Fitzroy and Burnett-Mary regions; GBRMPA Marine Monitoring Program (Water Quality); the Coastal CRC program; the Reef CRC program as well as core activities of government agencies such as the DNRW, DPI&F, EPA, CSIRO, GBRMPA and AIMS. Most recently the establishment of the Australian Government's Marine and Tropical Sciences Research Facility (MTSRF) has pulled together much of this activity and potentially may allow us to integrate the research in a way which has not been done previously.

These research programs have greatly increased our understanding of GBR water quality issues. The purpose of this Baseline Synthesis and Year 1 Summary report is to review, synthesise and analyse the work carried out since the release of the RWQPP in 2003. We will highlight research results that have changed our understanding since 2003 and hence may be critical in revising the aims or priorities of the RWQPP given the new understanding.

2. GBR Catchments and Lagoon Water Quality Research Synthesis

This section outlines the current status and understanding of catchment health (Section 2.1), catchment water quality influences with respect to the marine environment (2.2), the transport, extent, fate and effects of these terrestrial materials within the marine environment (2.3), and an overview of emerging issues (2.4).

2.2 Catchment health

Despite the clear connections between the catchments and coastal waters, our approach to understanding the two parts of the system needs to be partitioned because the health of the catchments is largely driven by ambient conditions while the health of coastal waters is mostly influenced by large events. Furthermore, as water quality monitoring has been driven by concerns about the health of the GBR, monitoring effort has been focused at the ends of rivers. Consequently, we now know a substantial amount about end-of-river contaminant loads, especially during flood events (Furnas 2003), but we know much less about water quality and its effects on ecosystems within catchments.

There has been growing concern about catchment health in its own right. Reef catchments support high biodiversity and endemicity of freshwater fish (Pusey *et al.* 2004), some of the highest diversity of freshwater invertebrates in the world (Pearson *et al.* 1986, Vinson and Hawkins 2003, Pearson 2005), and many species of aquatic plants (Mackay *et al.* 2007). Sources of information are now diverse, although much work on catchment health is unpublished. Nevertheless, substantial advances in publication are taking place as a result of recent initiatives, but any review of these studies must inevitably be incomplete given that many of them remain largely unavailable for general access. Some current work on catchment / waterway health is summarised in Table 1.

The importance of the catchments to Reef health was recognised in the Reef Plan, although there is still a belief that achieving end-of-river targets will be the answer to reef health. This view misses some important points, for example:

- The end of a river does not represent the entirety of its catchment, as many of the floodplain discharges are separate from the main river;
- The influence of chronic delivery of contaminants during the non-flood period is largely unknown;
- Good end-of-river water quality may be achievable despite poor habitat and water quality in the catchment (e.g. invasive weeds or dams can arrest contaminant transport); and
- Freshwater and marine systems are part of a continuum, especially for elements of the biota that must use both (e.g. barramundi), and so require good conditions throughout.

2.1.1 Current status and understanding of catchment health

Current understanding of catchment health is partly summarised in two recent figures. Figure 1 provides a view of a typical catchment in the Wet Tropics and outlines some major natural processes and human influences on them. There are now some quantitative data and substantial qualitative information to support the notions expressed. Current MTSRF research is providing information to flesh out some of these boxes. A modified Figure 1 will also apply to Dry Tropics systems, as discussed at a recent MTSRF workshop on ecosystem modelling (Wallace *et al.* 2007b), as the processes are similar.

Table 1: Current and recent research and monitoring activities in GBR catchments.

Projects	**Authors / agencies**
State of the Rivers Surveys and Water Resource Plans (e.g. Burdekin WRP)	DNRW
AUSRIVAS river health surveys	DNRW
Extensive surveys of fish, wet and dry tropics	Pusey *et al.*, Griffith University (GU)
Extensive surveys invertebrates, wet and dry tropics	Pearson *et al.*, James Cook University (JCU)
Stream conservation values	Burrows *et al*. 2004, Australian Centre for Tropical Freshwater Research (ACTFR)
Invasive fish species	Burrows, ACTFR; Webb, JCU
Herbert Integration Study	Scott *et al*. 2007, CSIRO
Intensive study of the Herbert floodplain	Butler *et al.*, ACTFR
Studies of the Russell-Mulgrave catchments as part of the *Catchment to Reef* program	Connolly *et al*. 2007b, c, d; Arthington and Pearson 2007; Pearson *et al.* 2007a, b; JCU, GU
Extensive water quality studies in the Tully catchment	Faithful *et al.* 2006; ACTFR
Water quality and biota studies in the Douglas Shire	Kroon *et al.*, CSIRO
Studies on stream bank stabilisation	Kapitzke *et al.* 1998, JCU
Impacts of recreation and tourism on Wet Tropics streams	Pearson *et al.* 1998, ACTFR
Overviews of Wet Tropics waterways, their water quality and their biota	Connolly and Pearson 2004; Connolly *et al.* 2007a, b, c, d; Pearson and Stork 2007
Outputs of the Reef and Rainforest CRCs' *Catchment to Reef* program.	Connolly *et al.* 2007 a, b, c, d; Mackay *et al.* 2007; Pusey *et al.* 2007; Arthington and Pearson 2007, GU, JCU
Studies in the Fitzroy catchment (mostly orientated to estuarine systems)	For example, Dobbie *et al.* 2002, Ford *et al.* 2006, Coastal CRC
MTSRF Project 3.7.3 *Status and trends of water quality and ecosystem health of fresh waters in the Wet Tropics*	Connolly *et al*. 2007c, JCU
Queensland SEAP investigations	Queensland Government
Regional investigations / management protocols	Mackay-Whitsunday, Burdekin and Far North Queensland NRM Boards; Cardwell Shire Floodplain Program; etc.
Conceptual models of catchment function – MTSRF workshop	Wallace *et al*. 2007b

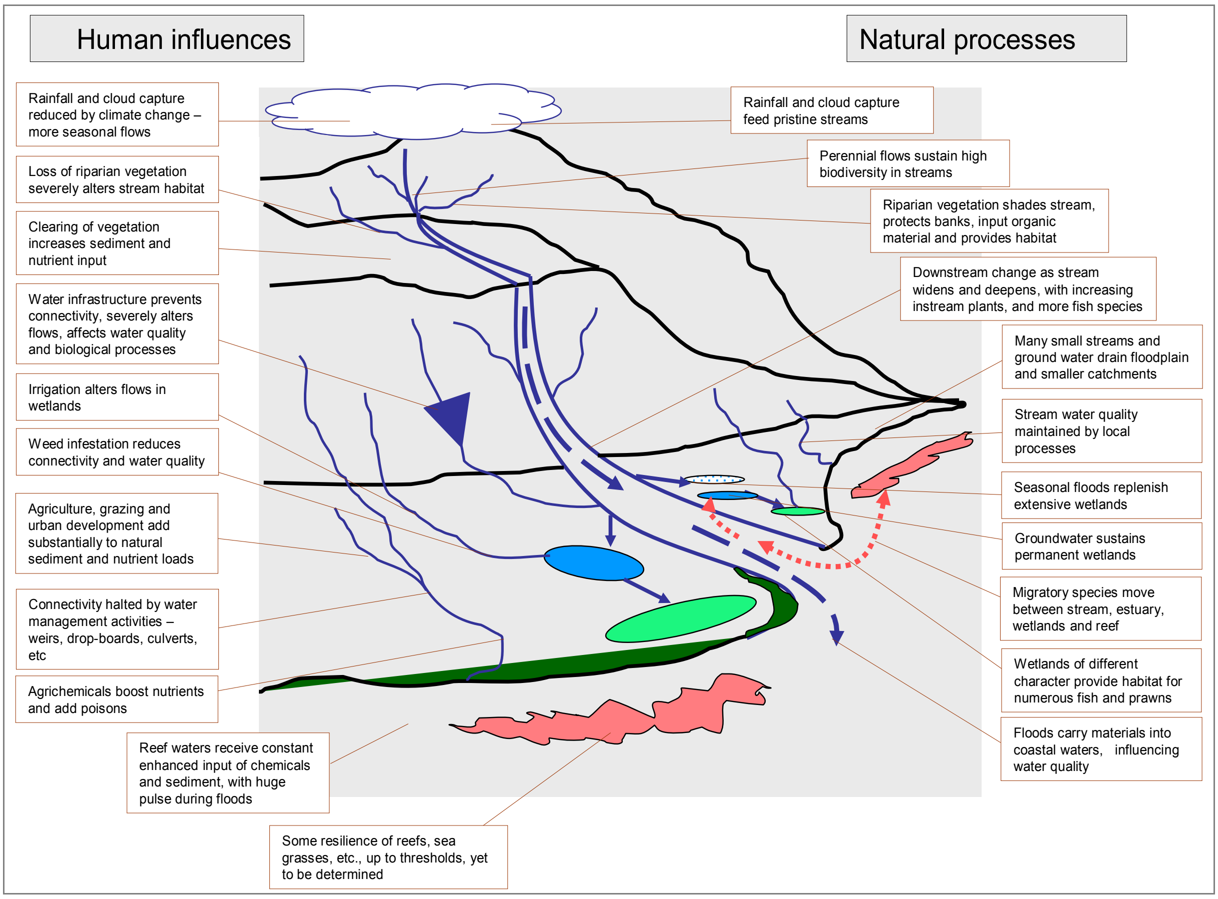

Figure 1: Natural processes and human influences in GBR catchments (from Pearson and Stork 2007).

While the holistic catchment view is important to understanding large-scale processes and management issues (e.g. flow regimes, end-of-river outputs), it is at smaller scales that we must understand many ambient processes (e.g. oxygen dynamics). Figure 2 focuses on the scale of stream reach or individual water body and outlines some of the natural biophysical processes and human influences that affect ecological health. The figure is not exhaustive, but does include many of the important aspects of ecosystem function in agricultural parts of GBR catchments. The complexity of interactions of many variables to create the resultant effects on ecosystem health (e.g. biodiversity) suggests risk factors and variables that need to be measured to gain proper understanding of system function. Again, MTSRF research seeks to understand some of these relationships.

2.1.2 *Recent key findings on ecosystem health*

Recent reviews on within-catchment water quality and ecosystem health have focussed on the Wet Tropics (e.g. Pearson and Stork 2007, Brodie *et al.* 2008, Connolly *et al.* 2007a, b, Connolly and Pearson 2004, Faithful *et al.* 2006), and it is on these reviews that this section is largely based. Studies in other regions (e.g. the Burdekin Water Resource Plan [WRP]) are currently unavailable or relate to estuarine systems.

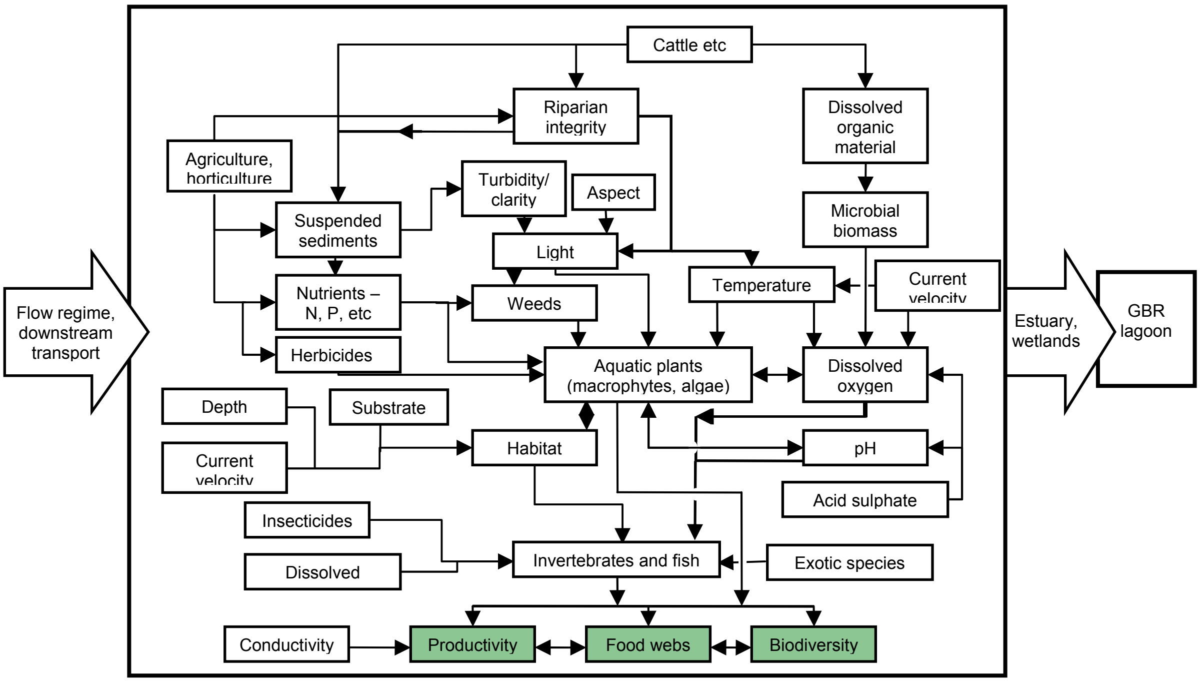

Figure 2: Some biophysical interactions affecting ambient water quality in tropical agricultural landscapes. The large box represents typical processes and interactions in a stream reach, a discrete waterhole or a habitat within them. The large arrows represent flow-related connectivity. Connectivity with the terrestrial landscape is implicit in some of the smaller boxes. The shaded boxes represent ecosystem process, structure and composition that reflect system health (from Brodie *et al.* 2008).

2.1.3 *Special nature of the tropics*

Elevated temperatures and high light levels for most of the year make the tropics very different from the temperate zone. Biological productivity can continue throughout the year in the tropics and at a greater rate than elsewhere for much of the year. Therefore, biological processes are often greatly enhanced in tropical waterways. For example, increased photosynthesis leads to greater oxygen extremes through a 24-hour cycle, with a greater chance of fish kills in weedy slow-flowing waterways (Pearson 2007a). Additionally, Australia is very different from the rest of the world hydrologically (Peel *et al.* 2001), and the tropics are the most hydrologically active region of the continent (Bonnell 1998). Wet Tropics rivers typically have perennial flows, with major wet season floods that are unpredictable in their timing, while rivers in the dry tropics (e.g. the Burdekin) have major floods every few years, and cease to flow in some years. The tropics are also important for their special and high biodiversity (see above).

2.1.4 *Major habitats and their ecology*

Ecosystem health issues vary according to the type of habitat, particularly the flow regime, position in the catchment and surrounding vegetation (Figure 1). Substantial work on tropical waterways reflects these factors, and any consideration of health needs to be clear about the differences between major types of systems. Thus, the influences and processes illustrated in Figure 2 vary in extent and intensity depending on catchment and water body characteristics.

Streams and rivers are characterised foremost by their unidirectional flow. In the Australian tropics the pattern of flow involves a contrast between the high flows of the wet season and the low flows of the dry season. The contrast between wet and dry tropics relate particularly to the level of flow in the dry seasons – in the wet tropics good flows are maintained throughout, sustaining normal fluvial processes while in the dry tropics, dry season flows are low or cease altogether. At this stage, dry tropical rivers become still water bodies. Good year-round flow dilutes impacts of agricultural inputs, so wet tropics streams can maintain biodiversity even when surrounded by agricultural land (Connolly *et al.* 2007d, Rayner 2007). Nevertheless, human activity can detrimentally affect these waterways, especially through removal of riparian vegetation (Connolly *et al.* 2007d, Pusey *et al.* 2007). Loss of biodiversity of the riparian vegetation and of stream animals may be implicated in substantial effects on ecosystem health (Bastian *et al.* 2007, 2008; Boyero *et al.* 2006, 2007). Stream flows may not be sufficient to adequately dilute point sources of pollution such as sugar mills (Pearson and Penridge 1987, Connolly *et al*. 2007d).

Riverine lagoons occur in the dry season in dry tropics rivers when the flow is very low or absent. Conditions in these lagoons relate to local processes, including inputs from occasional storm rains. The health of theses systems is governed by a variety of variables, including inputs of nutrients and organic matter, depth and stratification, degree of shade, plant productivity, invasion by weeds and exotic fish, access to livestock and the effects on oxygen status of the water body. Dynamics of these biophysical interactions have been described for several systems by the Australian Centre for Tropical Freshwater Research (ACTFR) (unpublished reports), and in postgraduate projects on water quality and phytoplankton and invertebrates (Betts 2005). 'Health' measures vary between systems, partly as a result of natural processes, but particularly as a result of damage to the riparian zone and concentrated access by cattle.

Deep lakes are largely absent from the GBR catchment. Crater lakes are protected in national parks (although still subject to fish translocations) and sand-dune systems are remote from major impacts, apart from sand mining. Most large standing water bodies occur as riverine lagoons (Figure 1) or floodplain lakes and swamps. Like the riverine lagoons they are typically influenced by annual floods and connectivity, followed by long periods of disconnection and still water, when local influences are paramount. For example, small rain events frequently flush nutrients and organic materials from fields into waterways and create turnover in waterbodies, causing severe hypoxia problems and, occasionally, fish kills (Pearson *et al.* 2003, Scott *et al.* 2007). Many shallow lakes and swamps dry out in the dry season, but nevertheless provide extensive and important temporary habitat for plants, invertebrates, fish, amphibians, reptiles and birds. The health of these systems has been compromised by in-filling, flow modification, local inputs from agriculture and grazing, loss of riparian vegetation, invasions by weeds and exotic fish, etc. (e.g. Perna 2005, Perna and Burrows 2005).

Estuaries are highly dynamic systems that receive fresh water from the catchment and saline water from the sea. Dissolved and suspended materials come from both directions. The health of these systems has come under some scrutiny in southeastern Queensland through the Coastal CRC, with GBR focus in the Fitzroy catchment (e.g. Dobbie *et al.* 2002, Ford *et al.* 2006). Otherwise, there has been little focus on the health of estuaries in the GBR catchment, especially following the closure of the Coastal CRC, although there is recognition of this gap in knowledge (e.g. Gehrke and Sheaves 2006, Johnston and Sheaves 2007, Wolanski 2007). The state of research in estuaries was noted in the recent MTSRF workshop (Wallace *et al.* 2007b).

2.1.5 Ambient water quality vs. export loads

Material transport to downstream environments is dominated by high flows (Furnas 2003). Concentrations of materials such as suspended sediments and nutrients in flow events can be used to quantify contaminant loads from catchments to coastal waters (Furnas 2003) and may also give an indication of whole-of-catchment conditions (McKergow *et al.* 2005a, b), although quantities released via local floodplain drainage and when rivers break their banks are largely unknown. Most of the contaminants associated with major storm events pass through the freshwater system so rapidly that they have little effect on stream ecosystems. Conversely, concentrations of materials measured in ambient conditions indicate the conditions that persist for much of the year, and that have greatest influence the health of stream ecosystems. During this period, major interactions between microbes, plants, animals and water chemistry occur, and water chemistry and biology are closely connected. The coming of the flow pulse itself also has important effects on river ecology. The first inflow, with its high concentrations of organic carbon, suspended particulate matter, nutrients and hence biological oxygen demand, can cause hypoxia and fish kills (Pearson *et al.* 2003). Thus, flood events are typically most important with regard to contaminant exports, while the intervening periods are more important to the ecology of waterways. Moreover, perennial streams with constant dilution of local effects and with strong influence of whole-of-catchment effects contrast substantially with waterholes and wetlands in which flow is intermittent and local effects predominate. Different monitoring strategies are required to address these different issues.

2.1.6 Human influences on habitats and water quality

Agriculture

Agriculture is regarded as the chief source of anthropogenic contamination of GBR catchments. This is inevitable because of the very large proportion of the catchment that is under agriculture. Agricultural activities include grazing, which occupies the major area and is the source of most sediment and attached nutrients, and cropping, which is concentrated mainly on costal floodplains and is the major source of dissolved nutrients and pesticides. Agricultural inputs to waterways are typically regarded as diffuse, because they are derived from large catchment areas, although individual farms, feedlots, paddocks and drains can act as point sources within the drainage system. Agriculture has caused substantial damage to riparian zones, with detrimental effects on instream biota (Pusey and Arthington 2003, Pusey *et al.* 2007, Connolly *et al.* 2007d) and has greatly increased inputs of sediments, organic matter and nitrogen and phosphorus to downstream aquatic ecosystems, mainly particulate components from grazing lands, and dissolved inorganic nitrogen from cropping (Brodie and Mitchell 2005, 2006; Bramley and Johnson 1996; Mitchell *et al.* 2001; Bramley and Roth 2002; Bainbridge *et al*. 2006b; Faithful *et al.* 2006; Rohde *et al.* 2006a), even when only a small percentage (e.g. five percent) of the catchment area is under cultivation (Faithful *et al.* 2006; Mitchell *et al.* 2006; Rohde *et al.* 2006a). Other contaminants derived from agriculture can include a wide array of pesticides. Some monitoring of pesticide concentrations in waterways has been done in the past, especially by the Queensland Department of Natural Resources and Water (H. Hunter pers. comm.). While land clearing is the major impact on catchment ecosystems, how the land is subsequently managed has a great bearing on the health of waterways. Concentrations of sediments and nutrients in fresh waters are typically proportional to the area of land under agriculture; however the level of contaminants can be reduced by good management practice, as demonstrated by Connolly *et al.* (2007b).

Industry

Major industries in the catchments of the GBR include sugar milling in the wetter catchments and irrigation areas, aquaculture developments, metal refining in the Townsville and Gladstone region, and power generation (coal-fired in the southern GBR, hydro in the Wet Tropics). It is unknown whether there are any substantial impacts on GBR waterways, although examples of local contamination are known, such as high concentrations of sulphate derived from mine spoil and/or coal burning near Collinsville. Sugar mill impacts on stream health have been severe because of the heated effluent and its organic content (Pearson and Penridge 1987, 1992). More recently, good effluent management has apparently reduced the problem, although no recent work on stream health downstream of mills has been published and Connolly *et al*. (2007d) noted some possible impacts of a mill on Babinda Creek.

Aquaculture development has progressed over the last two decades along the coast of the GBR catchment. Discharges are typically via tidal creeks to the sea, and while impacts on catchment water quality are likely to be minor, it is possible that impacts on the estuarine environment are substantial. It is largely unknown what the impacts of the displacement of wetlands have been.

Hydroelectric power stations are located on the Barron and Tully rivers. Their influences on the river system and water quality occur mainly through flow management.

Mining

There have been extensive small-scale mining operations through much of the GBR catchment, including gold, tin, nickel and uranium mines. Because of poor management in the past, the impacts often belied their size, particularly the alluvial mining within stream beds that released large quantities of sediment that rendered stream beds uninhabitable, with low fish diversity (e.g. Hortle and Pearson 1990), and water quality of very low standard. Some operations also released toxicants which had severe effects, at least locally (e.g. arsenic associated with tin mining near Herberton). Currently, there are few such activities occurring. The major mines in the region are coal mines inland from Mackay and Rockhampton. Published reports on any impacts of mining activities are lacking.

Urban development

The hardening of the landscape with buildings, roads, car parks and their accompanying drainage works leads to major changes in flow regime that cause much more rapid runoff and more peaked flows in waterways. Urban stormwater is typically of poor quality and the first-flush effect is particularly pronounced in hardened catchments in which runoff from the first rains after a dry spell carries a very high proportion of catchment contaminants. More prolonged rain usually provides dilution and improved runoff quality, unless it is sufficiently intense and causes flooding, in which case water quality can suddenly become poor again due to accelerated erosion and failure of effluent and waste containment systems (e.g. sewage overflows). Such flows deliver a range of contaminants into waterways, including many chemicals from transportation and small industry, nutrients and pesticides from parks and gardens, metals from galvanised roofing, and general rubbish. The major potential point source of pollution in waterways is sewage treatment plants that can deliver an effluent that is rich in organic matter and nutrients. Impacts on waterways include the boosting of microbial and weed growth as well as hypoxia. There is no recent published information on the impacts of urban development in the GBR catchment, although anecdotal evidence suggests that poor control of new development works has led to substantial land erosion and contamination of waterways by sediments in the Cairns and Townsville regions.

Recreation and tourism

Compared with broad-scale agricultural and urban land use, and intensive activities such as industry and mining, recreational activities associated with waterways might appear to be minor issues. However, freshwater streams provide an important focus for recreation and ecotourism and even moderate recreational activity in small forest streams has been shown to be readily measurable by reference to nutrient concentrations in the water. Pearson and others (1998) demonstrated that there was a direct relationship between numbers of swimmers in stream swimming holes and the water quality. Much of the effect was due to disturbance of sediments and mobilisation of nutrients that might otherwise have remained on the stream bottom or have been washed out during flow events. While nutrient values were not high compared with those found in agricultural or urban areas, they could be greatly in excess of ambient values. The effect on the biota was unknown, but it was thought likely that the increased nutrients would enhance algal production in light areas and microbial processing of organic matter through the streams with knock-on effects on the animal assemblages (Pearson and Connolly 2000). While there was no evidence that the effect was of major importance, it was pointed out that in many cases it was key habitats that were affected. There is no recent published work on this issue.

Water infrastructure and flow

There are numerous dams and associated lakes in the GBR catchment, some of which are very large, with major impacts on large rivers (e.g. Burdekin), while some are small and impact only on small parts of the catchment (e.g. Paluma). Dams and weirs provide water storage for delivery downstream or elsewhere. Immediate habitat impacts include the drowning of running water systems, providing lagoons and lakes where previously there were streams and rivers, impeding connectivity for migrating organisms, and drowning important riparian zones that provide habitat and connectivity for terrestrial and semi-terrestrial organisms. Habitats downstream are affected by reduced flows during flow events and, if the river channel is used to deliver water downstream, by increased flows during dry periods. Such alterations in flow regime can have severe effects on breeding regimes of fish, turtles, etc., and can have indirect effects such as the encouragement of weed infestation. There may also be several impacts of water infrastructure on water quality. Deep water stratifies thermally, often producing cool hypoxic conditions at the bottom of the water body, rendering much of it uninhabitable by fish and other biota. When this water is released downstream or mixes with the overlying water column, there are severe effects on the biota. Still waterbodies can be prone to algal blooms, especially when there are excess nutrients available, so in some circumstances water in storages can become toxic to domestic stock and wildlife.

Loss of flow in rivers may reduce the degree of flushing necessary to maintain oxygenated conditions; conversely, supplemented flow may cause flushing where normally still waterbodies would develop. In either case, alteration in the normal flow regime produces a different environment with a changed water quality regime and associated biota. Most rivers in the GBR catchment that have dams on them are affected in one or all of these ways, although there is mostly only anecdotal evidence to support this. Only in situations where dams are high in the catchment (e.g. Paluma) are effects relatively small at the whole-catchment scale.

Much of the stored water in Queensland is used for irrigation. Such use changes the delivery of water through a catchment by increasing flows when streams might be dry, both upstream of the irrigated land (via natural delivery pathways) and downstream (via drains). Drains typically are contaminated with nutrients, pesticides and sometimes sediments, which affect downstream waterways and wetlands. Such impacts can be negative in promoting weed growth and hypoxia (e.g. in the Burdekin floodplain – Perna 2005, Perna and Burrows 2005) and in making temporary wetlands permanent, but can be positive in supplementing available habitat (e.g. for wetland birds – Zunker 2003).

Other infrastructure includes road crossings that can be sources of sediment and other contaminant input to streams. There is no available information on this issue. There is limited information on the effects of culverts and bridges on connectivity within streams: in small lowland streams and wetlands, culverts prevent migrations of some fish species (Perna 2005, Kapitzke 2007), and it is possible that there are similar impacts in otherwise quite pristine upland streams.

Aerial inputs

While upland streams appear to be upstream of most human influence, it is possible that air-borne contaminants have effects on water quality and the integrity of the stream biota. This might happen down-wind of industrial complexes (e.g. Paluma is down-wind of the Yabulu nickel refinery) and pesticide spraying, and much of the Wet Tropics is down-wind of sugarcane fields, most of which used to be burnt before harvesting. Burning is now much less common through the Wet Tropics, so any impact has been reduced, but continues in some areas, such as the Burdekin. The effects, if any, on stream water quality of aerial inputs are unknown, but could be significant in otherwise pristine streams with exceptionally high water quality.

Climate

Climate is the major factor determining the nature of streams. Streams in the Wet Tropics have perennial flows as a result of reliable rainfall through most of the year, while at the periphery of the region and beyond (north, south and west) many streams cease to flow during the dry season. This gradient of flow regime (which may occur over only a few kilometres) affects the nature of the biota occupying the streams. With climate change in progress, it is uncertain what the effects on streams in the tropics will be. It is probable that rainfall will become more extreme and more seasonal, possibly reducing the proportion of perennial streams in the region. It is also possible that the cloud cover that supplies an important source of water in the dry season through 'cloud capture' (as opposed to rainfall) (McJannet and Wallace 2006) will be raised by higher temperature such that no cloud capture will occur. Changes to the nature of forest and forest stream ecosystems might therefore be predicted. Climate interacts with all of the issues discussed above, and is a looming topic of concern in GBR catchments (Pearson 2007b).

2.1.7 Major agents causing impacts and issues for ecosystem health

The above mentioned influences are the source of and operate via a range of specific agents, which are generally the components of the system that can be managed. For example, sediments may be derived from grazing, mining or urban development, but typically have similar effects whatever their source (Pearson 1999).

Aquatic and riparian habitat modification

Waterway habitats may be greatly modified by engineering works, such as channelisation, bridge construction, sand and gravel extraction, water abstraction and so on. Changes to the substratum, depth and/or width have major effects on what fauna are able to live, breed or pass through a waterway, and may directly affect water quality by removing or creating riffles (which tend to bring oxygen levels towards saturation) and pools (in which plants may cause large fluctuations in oxygen concentration). However, the most widespread modifications to habitat are caused by changes to the flow regime, removal of riparian vegetation and weed invasions.

Quantitative information on many of the roles of the riparian vegetation is patchy; however, it is generally regarded as very important because it creates shade, stabilises banks, provides a filter for materials in overbank and in-soil flow, provides inputs to waterways that contribute to food webs (leaf litter, fruits, terrestrial insects, etc.) and habitat (woody debris), and provides habitat for terrestrial and semi-aquatic animals and plants (Pusey and Arthington 2003, Bengsen and Pearson 2006, Keir *et al.* 2007). Loss of riparian vegetation, or changes to it therefore may have an over-riding influence on aquatic habitats and water quality. For example, riparian condition was found to be a major driver of fish and invertebrate community composition in the Russell-Mulgrave catchment (Arthington and Pearson 2007; Connolly *et al.* 2007d).

Water quality may be influenced in several ways. Loss of vegetation on the bank facilitates erosion and sedimentation that is exacerbated by livestock accessing the waterway across the bank. Loss of vegetation may speed up over-land flow, and transport of contaminants, especially sediments and associated nutrients, to the waterway. The filtering role is frequently most effective with a combination of vegetation types as trees may not be as effective as grasses in arresting overland transport of sediments. Transport of dissolved material through the soils may be partly off-set by absorption by tree roots. The shade provided by riparian canopies can be vital in reducing light levels and the temperature of the water, reducing plant growth and metabolic activity (Preite 2005). In the absence of shade, emergent, submerged and floating plants may completely change a habitat and its water quality, particularly through their impact on the oxygen regime (Perna 2005).

Invasive species

Exotic weeds typically invade when there is a loss of the riparian vegetation, but may occur anywhere that there is unshaded water. By replacing native vegetation, they reduce the normal inputs to the waterway, and displace habitat for native species. In slow-flowing and still-water areas floating plants such as water hyacinth (*Eichhornia crassipes*) may form a thick mat over the whole water body, leading to hypoxia and loss of many fish species (Perna 2005, Perna and Burrows 2005). In almost any type of waterway, banks and shallows are typically invaded by para grass (Urochloa mutica) that replaces normal bank and under-bank habitats, and invades and narrows channels to such an extent that flow velocity is increased, the channel is incised, and habitat greatly changed (Bunn *et al.* 1998). In the more disturbed parts of the Russell-Mulgrave system, riparian weeds are a major issue (Mackay *et al.* 2007, Connolly *et al.* 2007b).

The exotic fish tilapia (*Oreochromis mossambicus*) are of major concern in the Wet Tropics, as are other related cichlid fishes of African origin which, it is feared, might displace native species (Burrows 2004). Currently it appears that introduced fishes do especially well in disturbed habitats, but are not yet implicated in displacement of native species in more pristine systems (Webb 2003). While exotic fish species are present in the Russell-Mulgrave system, for example, it appears that they might not be displacing native species, especially where natural habitats are least disturbed (Pusey *et al.* 2007).

Dissolved oxygen

Dissolved oxygen is perhaps the major health issue in the GBR catchments. While it is rarely a problem in fast flowing perennial streams (unless there is severe pollution – e.g. Pearson and Penridge 1987), in slow-flowing and still-water systems it is the variable that most closely defines health, partly because lack of oxygen is what most often kills fish and invertebrates, and because it is an integrating variable. The dynamics of oxygen (and pH) in catchment waterways are complex, and dependent on a range of natural and human-influenced variables (Pearson *et al.* 2003). Figure 1 illustrates some of the factors that directly affect dissolved oxygen and its daily cycling. Natural oxygen status can best be achieved by maintaining riparian zones, curtailing weed growth, preventing the input of nutrients and organic material, and by removing blockages to flow. While the tropical Australian invertebrate and fish fauna appear very resilient to low dissolved oxygen status (Pearson *et al.* 2003; Connolly *et al.* 2004), their tolerance thresholds can be breached, as evidenced by the occasional fish kills that occur in floodplain waterways. Substantial headway has been made in our understanding of oxygen dynamics and its impacts on fish (Flint 2007; Pearson *et al.* 2003). In particular, recent extensive work at James Cook University by B. Butler, D. Burrows and R. G. Pearson (currently unpublished) is producing a unique understanding of the tolerances of tropical freshwater fish of many species and difference stages of development to hypoxia.

Nutrients, ammonia and organic material

Nutrients such as nitrogen and phosphorus are essential to plant growth and are typically applied to crops to improve crop production. Phosphorus is typically attached to sediment particles, while the main nitrogen contaminants – nitrate and nitrite – are mostly dissolved in the water. Nutrients promote plant growth and microbial breakdown of organic material (Pearson and Connolly 2000) and may thereby contribute substantially to deoxygenation of waterways. Ammonia is a transitional breakdown product from organic material, but is also applied to fields as fertiliser. It is toxic to freshwater organisms, including important fish species such as the rainbowfish (*Melanotaenia splendida)* and barramundi (*Lates calcarifer*) (Økelsrud and Pearson 2007).

Sediments

Sediment transport and deposition are normal processes in waterways and are responsible for creating large tracts of the landscape (floodplains, wetlands, beaches, etc). However, abnormal rates of erosion due to land clearing, riparian degradation, mining, cropping, urban development, etc., cause substantial impacts in freshwater and marine environments. Within stream, deposition of fine material may fill interstices in the substratum and reduce habitat availability, as well as clogging the gills of aquatic animals and smothering plants. The effect is usually reduction in sizes of populations and biodiversity (Hortle and Pearson 1990), although most species show resistance to short-term effects (Connolly and Pearson 2007). Continuous fine suspended material may reduce normal productivity, as appears to be the case in the Burdekin River downstream of the Burdekin Dam.

Flow regime

Flow effects are largely discussed above. However it is worth reiterating that the flow regime is the major factor determining the character of freshwater systems – whether it is perennial, highly seasonal or episodic surface flow, or groundwater flow. Its overriding influence on processes is indicated in Figure 2 and has been alluded to in many reports on ecology and health in GBR catchments (e.g. Pearson *et al.* 2003; Pearson 2005, Pearson and Stork 2007, Connolly *et al*. 2007b, d, Brodie *et al.* 2008. While major floods are important in flushing river systems, carrying out geomorphologic work (e.g. see Brizga *et al.* 2000, 2001), delivering materials to the marine environment, providing ecological connectivity (Perna 2005, Perna and Burrows 2005) and resetting local ecological conditions, lesser flows are important in maintaining or influencing ambient conditions. In perennial streams, the flow dilutes contaminants and maintains crucial habitats (Connolly *et al.* 2007d); in intermittent systems the absence of flow allows development of individual conditions between water bodies. Minor flows into still waters can cause major impacts, as discussed above. It would appear that many floodplain lagoons are in poor condition because of local characteristics that preclude regular flushing and encourages growth of weeds and microbes (Perna 2005, Perna and Burrows 2005). Rehabilitation requires removal of weeds and improved land management practices to reduce inputs of fertiliser and organic material.

Pesticides

Many different types of pesticides are applied to agricultural lands to combat weeds, insects and other pests (Brodie *et al.* 2008). While there has been some monitoring of concentrations of pesticides in catchment waters, there has been little attempt to understand the ecological effects of pesticides in waterways.

Kevan and Pearson (1993) was an early attempt to gauge the impacts. Subsequently, work by the ACTFR in the Burdekin floodplain examined herbicide use and effects, but this work remains unpublished. Lack of information on the ecological effects of pesticides is a major omission from current research programs.

2.1.8 Trends in catchment health

There is no doubt that trends in habitat extent and quality have been downwards across many catchments in the Wet Tropics (Connolly *et al.* 2007b). While upland forest streams are quite well protected and have suffered least, lowland systems have suffered decline in extent (up to 75% loss of wetlands in some catchments – National Land and Water Audit) of vegetation cover in their catchments and in their riparian cover. Meanwhile they now receive run-off and through-flow from agriculture, with elevated levels of sediment, nutrients and organic material, as well as pesticides and other chemicals. Further, they have been invaded by noxious riparian and aquatic weeds. Hence some streams and wetlands support only a fraction of what would be normal biota. Nevertheless, some systems still sustain a diverse fauna, for example the Mulgrave River has a diverse fish fauna, including several endemic elements (Rayner 2007). Clearly the fauna can be quite resilient, and it can bounce back after devastation by very poor conditions, as has been demonstrated in the Burdekin floodplain following weed removal: the diversity of fish species jumped from three to sixteen in only a few months (Perna 2005). Such recovery from disturbance is a healthy trend, but it does depend on there being suitable refuge areas to sustain species throughout the times of greatest disturbance. Possibilities for improvement in health was also demonstrated in contrasting Russell and Mulgrave catchments, in which better management practice resulted in positive instream biodiversity (Arthington and Pearson 2007; Connolly *et al.* 2007d).

A notable trend over the last few years has been the recognition of the importance of catchment health as well as the influence of catchment on GBR waters. This has been demonstrated by the increased involvement in catchment management by local authorities, Natural Resource Management bodies, Government departments and agencies (e.g. the GBRMPA and Queensland SEAP program) and other groups (examples in Table 1). It has also been recognised that while many issues are quite well understood, there is still a need for basic scientific research to answer specific questions, and for researchers to provide support to the managing organisations.

2.1.9 Innovation

Outputs from recent research into catchment health have included innovative projects in understanding tropical waterways and developing new monitoring protocols for them. The *Catchment to Reef* program has focussed directly at these goals (Arthington and Pearson 2007) and the MTSRF program is continuing this work. There has been a strong effort to link closely with the users and beneficiaries of the research, which has been characterised by strong partnerships between researchers, agencies and land managers (e.g. Faithful *et al.* 2006, Mitchell *et al.* 2007b). One outcome has been the recognition that interpretive materials are required for use within local communities. To that end, the joint *Catchment to Reef* program produced a range of products including newsletters, an interpretive poster and booklet (Connolly *et al.* 2005), a book on nutrients in the landscape (Kelley *et al.* 2006), which have been very well received by the community, as well as a website from which to access these items and further information (http://www.catchmenttoreef.com.au/Start.html).

2.1.10 Knowledge gaps

The issues outlined above need addressing by coordinated management and monitoring activities, using tools that are appropriate to the questions being asked. The requirement for new knowledge to enhance understanding of catchments, and hence their management, have partly been identified above. In summary they include:

- **Integration:** There is a need for better coordination of efforts in management and research. Water quality issues have been the responsibility of several agencies, and many researchers, community groups, etc., have been running disconnected programs. Better alignment will improve the direction and adoption of research discoveries, management applications and policy change. Some indication that this is happening is through the GBRMPA-led Reef Partnership, the Queensland SEAP program, MTSRF-led research, and collaborations between research providers such as the CSIRO, James Cook University and Griffith University – e.g. Wallace *et al.* (2007b).
- **New monitoring tools:** New tools are required for water quality assessment against benchmarks. Water quality monitoring has frequently not been well carried out because important variables (e.g. time of day or year) are ignored. Much of the current monitoring is focused on major events and end-of-river, which have little bearing on the health of catchment waterways. Monitoring frameworks are required to address the issues of *why*, *what*, *when*, *how* and *who* to monitor water quality and system health. The *Catchment to Reef* and MTSRF programs are addressing these issues.
- **Geographic extent of knowledge:** Expansion of the increasingly detailed understanding of Wet Tropics streams and rivers from *Catchment to Reef* and MTSRF programs to include the Dry Tropics and standing water bodies.
- **Holistic assessment of system health:** Holistic assessment of system health is required because water quality *per se* is only one of several important issues such as habitat degradation, riparian condition, invasive species and normal variation in natural processes.
- **Sublethal stress:** There is a need for tools to detect sublethal stress in aquatic organisms exposed to impacts that can short-cut the often slow traditional methods of detecting environmental impacts. There is also a need for more sensitive and unambiguous indicators of environmental quality, such as measurements of the physiological stress that develops in organisms long before conditions become so bad that populations or communities change substantially or crash. Current work by B. Butler, D. Burrows and R. G Pearson of James Cook University (a DEW project) is addressing this issue for fish response to dissolved oxygen in tropical Australia.
- **Quantifying connectivity:** Understanding connectivity between catchments and the GBR (Figure 1) is a requirement for achieving successful outcomes. This connectivity is partly driven by the hydrological cycle whereby water is delivered from the sea to the land via the atmosphere, and then returns to the sea via surface and subsurface drainage. Major aspects of this cycle are the timing of events and the materials that the water picks up along its journey and delivers downstream. But other aspects of connectivity are also very important, particularly the biological links between the sea and fresh waters, and among the waterways of the catchment. While we know that many species use both marine and brackish or freshwater systems during their life cycles, the quantitative importance of these connections, and impediments to them, are largely unknown.
- **Need for models of ecosystem function:** The above discussion involves conceptual models of how different parts of the catchment-to-reef ecosystems function. However, to

facilitate our understanding of management needs, especially to enable response to unexpected change, and to assist in prioritisation of efforts in restoration and rehabilitation, more explicit and quantitative models of stream, river, estuary and wetland function is required. Extending and quantifying the models discussed here will underpin management in all parts of the catchment-to-reef continuum. The recent MTSRF workshop (Wallace *et al.* 2007b) and other initiatives have made substantial progress in this direction.

- **Need to quantify roles of the riparian zone:** While the importance of the riparian zone is well known, a pressing research need is to quantify its roles to facilitate management activities aimed at controlling water quality while simultaneously sustaining processes vital for river ecosystem health. There is a clear need for tools to quantify the filtering role of the riparian ribbon and the effects of different land uses, including sugar and banana growing and forestry, and their contributions to sediment and nutrient run-off, as well as to provide guidelines towards enhancing future performance.
- **Need to quantify roles of wetlands:** There is much written about the role of the coastal wetlands: they support unique plant and animal communities, contribute substantially to biodiversity and provide breeding and nurturing habitats for key species (e.g. barramundi). These wetlands also store fresh waters over long periods of time, both arresting flows to the sea and enhancing prospects for perennial aquatic habitat. In slowing flows and promoting plant growth, wetlands can strip sediments and nutrients from the water that is eventually delivered to the coast. However, few of these processes have been quantified, even at a small scale. We do not have the hydrological models to indicate how much flood run-off is captured, and we do not know what proportion of contaminants is retained temporarily or in the long term. These processes require further research to provide guidance to managers of riparian and wetland environments, particularly with regard to where the major rehabilitation effort and funding should be expended. The MTSRF is supporting some research in this direction.
- **Understanding the role of groundwater:** Many systems are maintained by groundwater through the dry season, such that the character of the water quality varies substantially between seasons. Currently we know very little about groundwater-fed systems.
- **Identifying and managing new impacts (e.g. climate change):** While we have a good appreciation of the types of impacts affecting the catchment-to-reef continuum (Figure 1), our lack of quantitative understanding of the mechanisms involved hampers our ability to predict the effects of novel impacts or novel combinations of impacts. For example, we do not have good models of how different climate change scenarios might directly affect pristine ecosystems, let alone interact with current impacts. Climate change may also lead to new interactions, as crops more suitable to the new climatic conditions in an area may raise a range of issues not previously encountered in a particular region. We do not have enough detailed information on particular crops and their impacts to predict the effects of change. Again, conceptual models of the processes that are involved in the impact of different land uses are required, followed by quantification of the models.

2.2 Catchment water quality influences with respect to the marine environment

This section reviews current and recent research being conducted within the GBRCA on the linkages between catchment land use and downstream (GBR wetlands and lagoon) water quality.

2.2.1 Current status and understanding of catchment water quality influences

Recent research and monitoring has been primarily driven through two avenues:

1. Current research programs with a focus on GBR water quality, such as the MTSRF and CSIRO Water for a Healthy Country-GBR Catchments Theme; and the
2. DEW Water Quality Improvement Plan process (to deliver on the Reef Plan), which is being delivered at a regional scale through the regional NRM bodies (Wet Tropics, Burdekin, Mackay-Whitsunday, Fitzroy and Burnett Mary NRM regions), and more recently, through the Townsville and Thuringowa City Council's Creek to Coral Program (first urban Water Quality Improvement Program [WQIP]).

2.2.2 Effects of land use at the paddock scale

Over the last five years a range of research has been conducted at the paddock scale to investigate the impact of different land use practices and management on the quality of receiving waters. These projects have tended to have a research focus on one particular land use, and have often been established through regional collaborative arrangements developed between interested growers / graziers, key industry groups (BSES, Canegrowers, GrowCom), Federal / State Government initiatives and associated extension staff (such as the SRDC, AgSIP and DPI&F Reef Extension program) and research organisations (the CSIRO and universities). The regional NRM body WQIP process has built on and contributed to existing paddock-scale research projects, and has provided broader frameworks that will aid in the rollout of the Best Management Practices (BMPs) and further water quality plot-scale research.

Intensive agriculture

Most paddock-scale research has focused on the more intensive land uses such as sugarcane and horticulture. The following is a summary of projects (current or recent) being conducted along the GBR coastline:

- Wet Tropics groundwater (Rasiah *et al.* 2007; Rasiah *et al.* In prep);
- Tully plot-scale runoff for cane and horticulture (banana) industries (Faithful *et al*. 2006);
- Pine plantation runoff (Faithful *et al.* 2005);
- Lower Burdekin Cane BMPs (Hesp 2006; Thorburn and Attard 2007; Thorburn *et al.* 2007; Thorburn *et al.* submitted);
- BSES Lower Burdekin sugarcane paddock runoff (Ham 2006);
- Burdekin Coastal Catchment Initiative (CCI) pesticide study (Lewis *et al.* 2007a);
- Mackay-Whitsunday Cane BMP trial (Masters *et al*. In prep);
- AgSIP Bundaberg (Stork *et al.* 2007).

Paddock-scale research investigating the application and loss pathways (e.g. volatilisation, denitrification and runoff) of nutrients and pesticides in intensive agriculture systems has tended in the past to focus on the productivity outcomes of improved practices, rather than an explicit focus on potential water quality impacts. However, recent plot scale runoff projects, such as those investigating runoff from varying management practices in the sugar and banana industries (Armour *et al.* 2006; Faithful *et al*. 2006; Ham 2006; Lewis *et al.* 2007a) have found considerable concentrations of nutrients (nitrate) and pesticides in farm runoff. With Schroeder and others' (2005; 2006) 'six-easy-steps' for nutrient management in sugarcane production, and other regional collaborative arrangements (such as Thorburn *et al.* 2007) the recommendation of nutrient management BMP is much further advanced than recommendations for pesticides. However, current research (Rohde *et al.* 2006a; Faithful *et al.* 2007; Lewis *et al*. 2007a) indicates that changes in current pesticide management will be required. More recent trials are being conducted under the WQIP framework investigating both nutrient and pesticide runoff from a series of recommended BMP, such as the Mackay-Whitsunday rainfall simulation trial of sugarcane BMP (see Figure 3) (Masters *et al*. In prep). This type of research quantifies the water quality benefits from the implementation of BMPs, and it is likely that we will see more of these trials across the GBRCA through the WQIP process.

Figure 3: Rainfall simulator set up to investigate proposed sugarcane BMP and resultant water quality outcomes in the Mackay-Whitsunday region (sourced from Masters *et al.* In prep).

Grazing

Paddock- and small catchment-scale research is being conducted on the water quality impacts of the grazing industry. Current research projects, such as the DPI&F Wambiana Grazing Trials (O'Reagain *et al.* 2005) and that at Virginia Park (Bartley *et al.* 2007a) in the Burdekin catchment are building on previous studies that investigated the relationship between ground cover and runoff water quality in semi-arid rangeland systems (e.g. Scanlan *et al.* 1996; Roth 2004; McIvor *et al.* 2005). The CSIRO research at Virginia Park has shown that rates of hillslope erosion are strongly linked to not just the absolute degree of pasture cover, but also the patchiness of the cover (Bartley *et al.* 2006). The use of SedNet at this small sub-catchment scale has further shown the degree of small-scale patchiness in erosional processes and sediment delivery to streams (Kinsey-Henderson *et al.* 2005; Bartley *et al.* 2006). The likely long time-lags of sediment delivery through a large catchment like the Burdekin were also highlighted (Bartley *et al.* 2007a), although this is obviously particle size dependant. The Wambiana Grazing Trial compares different grazing strategies (i.e. light, heavy, rotational and wet season spell stocking regimes) and the impact of each strategy upon land condition, economics and production. This trial has also identified the significant time-lags in runoff water quality benefits as a result of improved catchment condition that can occur in the Dry Tropics (Bainbridge *et al.* 2006b).

These projects are more closely aligned with current and proposed grazing BMPs in an attempt to improve our knowledge of the linkages between grazing BMP and improved water quality, which has been identified as a current research gap by Coughlin *et al*. (2006).

Socio-economic research on the impediments to change

Socio-economic research into the cost effectiveness of the recommended BMPs for the major industries (sugarcane, horticulture, grazing and forestry) within the GBRCA has been conducted across the entire region (Roebeling 2006; Roebeling *et al.* 2005; 2007a), and more recently, specifically for the Douglas Shire and Tully/Murray WQIP processes (Roebeling *et al*. 2004; 2007b; Bohnet *et al*. 2006; 2007; Roebeling and van Grieken 2007; Roebeling and Webster 2007). This approach also incorporates production system simulation models (such as APSIM) and the SedNet and ANNEX models (Roebeling *et al.* 2007a). Socio-economic research has also been conducted by Lankester and Greiner (2007) for the Burdekin WQIP focusing specifically on the grazing industry within this region. This study found that a suite of incentive measures would be required to encourage the adoption of BMPs within this region.

2.2.3 Land use and pollutant losses

Recent research has allowed us to more clearly identify and quantify the losses of suspended sediments, nutrients and pesticides from different land uses and land management practices. Very strong relationships between fertilised land uses (sugarcane, banana) and in particular loss of nitrate (and sometimes ammonia) have been shown in the Tully basin (Mitchell *et al.* 2006; Faithful *et al.* 2007). This relationship is illustrated in Figure 4, where the relationship between fertiliser-additive land use and average nitrate concentrations has been plotted (Mitchell *et al*. 2006), and also in the boxplots from the Tully and Mackay-Whitsunday regions that show average nitrate and nitrite concentrations for sugarcane sub-catchments compared to other land uses within these two regions (Figures 5 and 6) (Rohde *et al*. 2006a; Faithful *et al.* 2007). This relationship has also been shown in the Russell-Mulgrave catchment (Connolly *et al*. In prep), Lower Burdekin (Bainbridge *et al.* 2006b) and Mackay-Whitsunday catchments (Rohde *et al.* 2006a). The loss of herbicide residues – particularly diuron, atrazine, hexazinone and ametryn – from sugarcane cultivation has been firmly established (Packett *et al.* 2005; Rohde *et al*. 2006a; Faithful *et al.* 2007; Lewis *et al.* 2007a; Stork *et al.* 2007) in the dominant sugarcane regions from Bundaberg to Tully. In contrast losses of suspended sediment from sugarcane cultivation has been shown to be relatively low, reflecting fifteen years of improved soil conservation measures including green cane harvesting, trash blanketing and reduced tillage (Rayment 2003; McJannet *et al*. 2005; Bainbridge *et al.* 2006b; Rohde *et al*. 2006a; Faithful *et al*. 2007). However, there is still some evidence of elevated erosion in sugarcane cultivation areas compared to forested areas as shown from the results of Hateley (2007), who identified the sources of sediments collected from waterways draining different land uses within the Tully River catchment. In contrast, rangeland beef grazing lands lose large quantities of suspended sediment through erosion associated with low vegetation cover (Brodie *et al.* 2003; McKergow *et a*l. 2005a; O'Reagain *et al.* 2005; Bainbridge *et al*. 2006a; 2006b; Bartley *et al*. 2006; Dougall *et al.* 2006; Fentie *et al.* 2006). However, the likely improvements in suspended sediment conditions due to better vegetation (pastures and trees) management are not well quantified (Coughlin *et al.* 2006; Gordon and Nelson submitted).

This research has also highlighted the difference in the pollutants of concern between the wet and dry catchments within the GBRCA. 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 (Furnas 2003; Fabricius *et al*. 2005; DeVantier *et al*. 2006). Whilst the significantly larger Fitzroy and Burdekin River catchments (each ~135 000 km^2), dominated by unimproved savannah / woodland rangeland grazing, are identified as considerable contributors of suspended sediment to the GBR lagoon (Mitchell and Furnas 2001; Furnas 2003; O'Reagain *et al.* 2005; Bainbridge *et al*. 2006b; Packett 2007; Waters and Packett 2007).

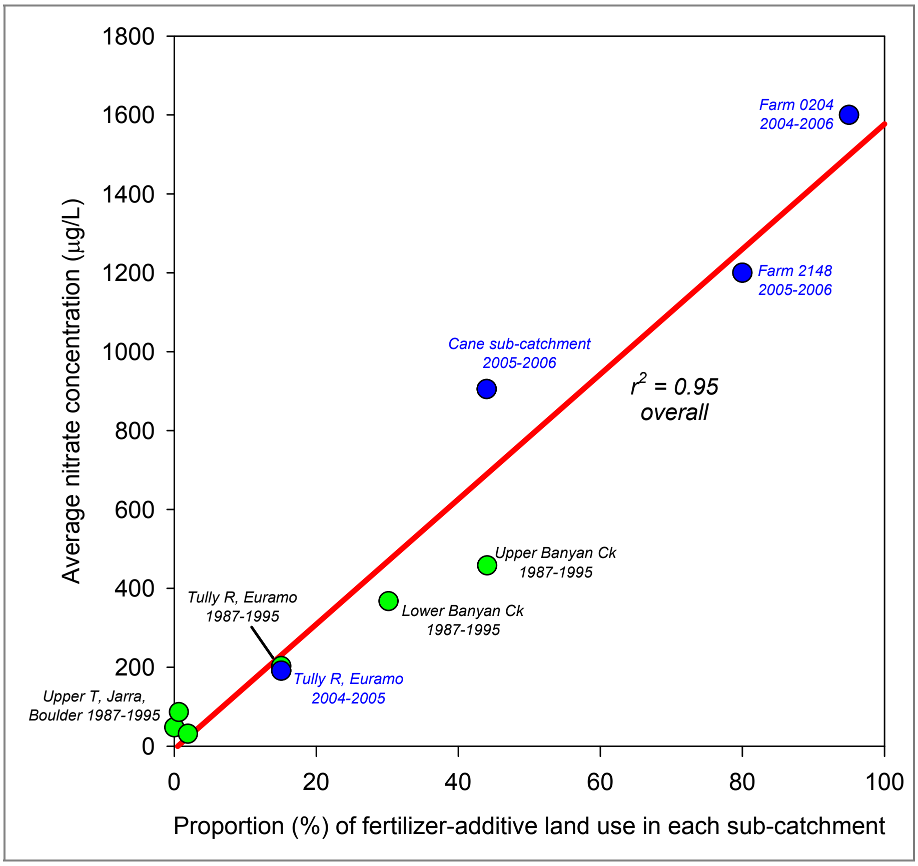

Figure 4: Relationship between fertiliser-additive land use and average (mean) nitrate concentration (sourced from Mitchell *et al.* 2006). Green symbols are AIMS-BSES wet season data; Blue symbols represent wet season data from Faithful *et al.* (2007) (cane sub-catchment) and Faithful *et al.* (2006) (Farm 2148 – 80% bananas; Farm 0204 – 95% sugarcane; Tully River; Euramo).

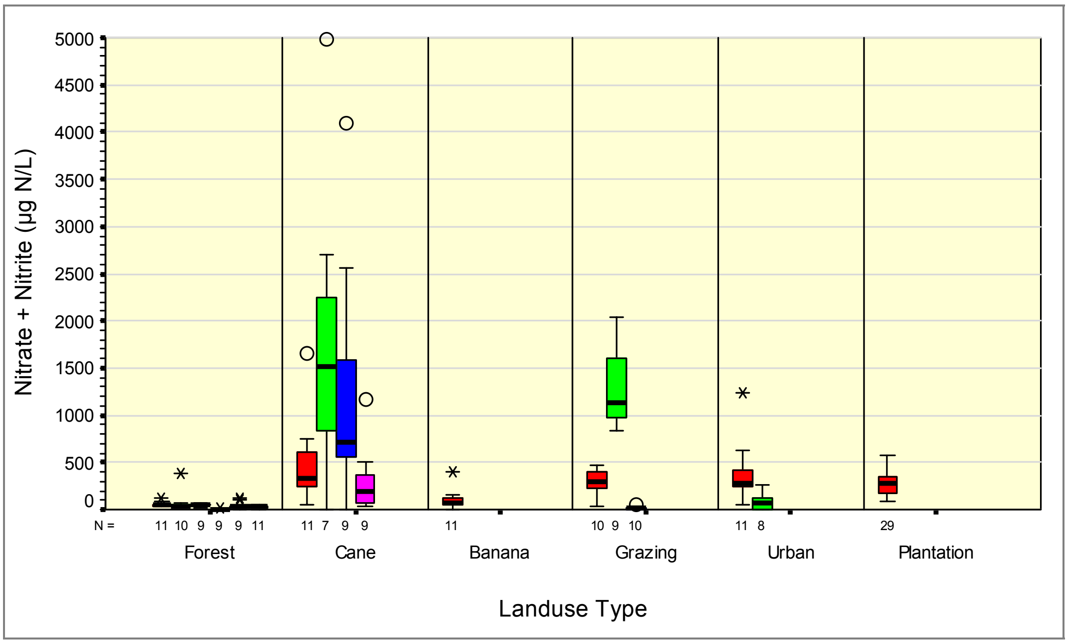

Figure 5: A boxplot showing the relative distribution of nitrate + nitrite (NO_X) (µg N/L) in river and creek flows for the five land use activities within the Tully-Murray Rivers region between December 2005 and July 2006. Plantation NO_X data, collected from Whitfield Creek was also included for comparison, sourced from Faithful *et al.* (2006) (sourced from Faithful *et al.* 2007).

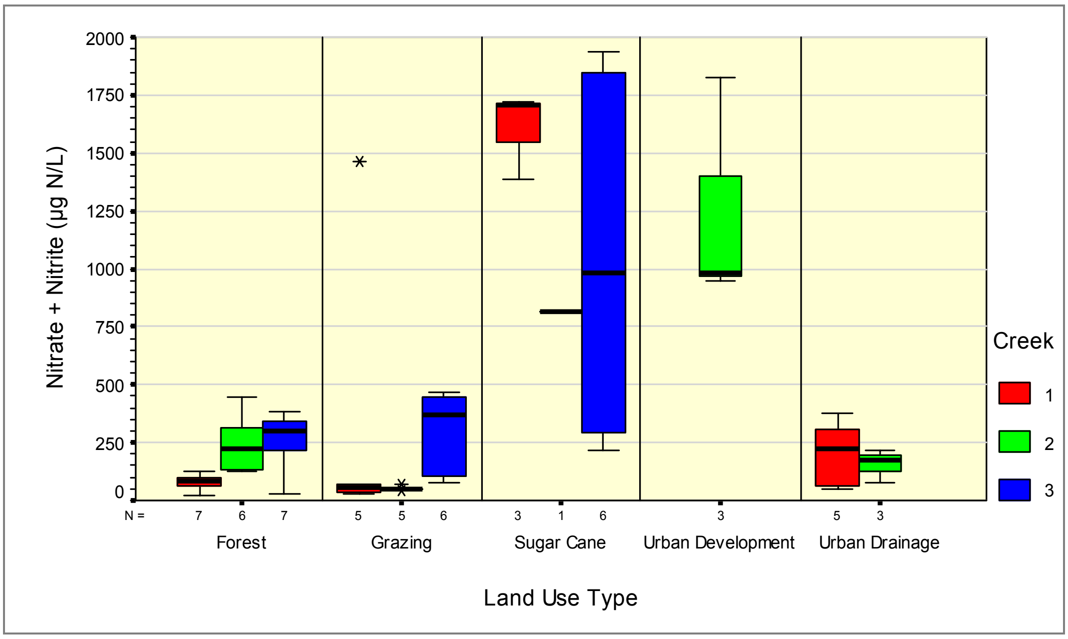

Figure 6: A boxplot showing the relative distribution of nitrate + nitrite (NO_X) (µg N/L) in river and creek flows for the five land use activities within the Mackay-Whitsunday region for the 2004/2005 wet season (sourced from Rohde *et al.* 2006a).

2.2.4 Catchment pollutant transport and trapping

Extensive research and monitoring programs in the Burdekin catchment over the last five years have shown that different landscapes are producing vastly different amounts of suspended sediments, most likely dependent on geology / soil type, elevation, climate and vegetation as well as grazing management styles (Brodie *et al.* 2003; O'Reagain *et al.* 2005; Bainbridge *et al.* 2006a; 2006b). This has confirmed modelling results that predicted similar large spatial differences in erosion and sediment delivery (Brodie *et al.* 2003; McKergow *et al.* 2005a; Fentie *et al*. 2006). Comparisons between modelled predictions (using SedNet and ANNEX) and measured suspended sediment and nutrient species concentrations in the Burdekin show fair correlation for suspended sediment, good correlation for dissolved nitrogen and phosphorus species but poor correlations for particulate nutrient species (Mitchell *et al.* 2007a; Sherman *et al*. 2007). Comparisons in the Tully and Murray catchments have shown similar patterns of correlation (Armour *et al.* 2007; Hateley *et al*. 2007) while studies in the Fitzroy catchment for sediment delivery showed good correlations at catchment-wide scale (Dougall *et al*. 2006).

2.3 Marine environment

This section reviews recent research efforts (since 2003) in the marine and estuarine environment of the GBR lagoon as well as experimental laboratory studies on organisms of the GBR.

2.3.1 Current status and understanding of marine water quality

Transport and extent

Knowledge of the transport of terrestrially-sourced dissolved and particulate materials to the marine environment during high flow events has considerably increased in the last five years. Improvements in satellite technology (tracing of freshwater plumes, sediments and chlorophyll *a*; Brodie *et al.* 2006; 2007a), coral records (both physical and geochemical records to assess the exposure of coral reefs to freshwater plumes and to quantify changes in sediment and nutrient loads; McCulloch *et al.* 2003a; Sinclair and McCulloch 2004; Lewis *et al.* 2007b; Lough 2007; Marion 2007) and increased laboratory sensitivity and instruments to measure pollutants (in particular passive samplers and the direct measurement of pesticides and nutrients; Rohde *et al*. 2006a; Shaw and Müller 2005; Devlin and Brodie 2005) have all provided an enhanced understanding of pollutant risk for the marine ecosystems of the GBR.

From these studies and technological advances, we now know that river water plumes may reach further offshore in the GBR than originally thought (A. Dekker pers comm., 2007), and that pesticides (namely herbicides) pose a considerable threat to freshwater and marine ecosystems. Elevated nutrient concentrations (considerably above ambient levels) have also been detected several kilometres (up to hundreds of kilometres) from the mouths of major GBR catchments (Devlin and Brodie 2005; Brodie *et al*. 2006; Rohde *et al.* 2006a; Schaffelke and Slivkoff 2007). In addition, coral records are able to quantify the increased sediment and nutrient loads exported from the waterways of the GBR catchments (McCulloch *et al.* 2003a; Lewis *et al*. 2007b; Marion 2007). While sediment and nutrient loads have increased, coral luminescence records show no evidence for increased delivery of freshwater to the GBR since European settlement (Lough 2007), despite catchment hardening (and lower infiltration potential) from cattle grazing (e.g. Scanlan *et al*. 1996; Roth 2004). However, other evidence using rainfall and runoff records suggests that freshwater runoff may have increased by as much as 78% after the clearing of forested lands (Siriwardena *et al.* 2006). It has also been revealed that palaeo-channels of the GBR lagoon (e.g. Fielding *et al.* 2003) provide a potential mechanism for the transport of terrestrial materials in the GBR lagoon through "wonky holes" (Stieglitz 2005).

The fate of sediments

Over the last five years, several studies have emerged that have investigated the fate of sediments and nutrients in the GBR lagoon. The fate of terrestrial sediments have been investigated off the Burdekin (Orpin *et al*. 2004), Fitzroy (Bostock *et al.* 2006a; 2006b) and the Tully-Murray rivers (Land 2004) while sediment resuspension / transport on the GBR shelf during storm events have also received some attention (Larcombe and Carter 2004; Wolanski *et al.* 2005). The fate of nutrient species in the GBR lagoon have also been considered by 'budget' modelling involving the cycling of microbial organisms (Algoni and McKinnon 2005; Furnas *et al.* 2005), the accumulation of nutrients in seagrasses (Mellors *et al*., 2005) and using chlorophyll *a* concentrations (Brodie *et al.* 2007a). Phosphorus and carbon budgets and sources have also been investigated in the marine environment (Brunskill *et al.* 2002; McCulloch *et al.* 2003b; Monbet *et al*. 2007).

From these studies we now know that cyclone and storm events play a critical role in the transport and deposition of terrestrial sediment in the marine environment, and that most sediments exported from rivers are retained in close proximity to the river mouths (Brodie *et al.* 2004; Orpin *et al.* 2004; Pfitzner *et al*. 2004; Devlin and Brodie 2005; Brodie *et al*. 2006; Bostock *et al*. 2006a; 2006b; Rohde *et al*. 2006a; Packett 2007; Wolanski *et al*. 2007). However, the final fate of fine sediments and colloidal materials is still contentious, although these materials (depending on grain size) are probably stored in estuaries, mangroves, in low energy north-facing bays and on the mid-shelf. We believe that the clay-sized sediment fraction (< 2μm), which is carried as wash load in waterways, would travel large distances in the marine environment and mainly be deposited on the mid-shelf. The silt-sized fraction (2μm to 63μm) is largely carried in the suspended load by waterways and would probably be deposited in coastal areas such as mangroves, estuaries and north-facing embayments. Research is continuing on these important sediment fractions. The fate of nutrients is considerably more complex as nutrients are cycled rapidly in the marine environment with products including chlorophyll *a* and dissolved organic nitrogen. Bioavailable nutrients discharged from rivers are taken up into phytoplankton as soon as there is enough light following removal of suspended sediments from the plume by sedimentation (Furnas 2003; Devlin and Brodie 2005). The resultant algal bloom thus takes a few days to fully develop which is evident from satellite images (Figures 7 and 8; Brodie *et al.* 2006; Brodie unpublished data).

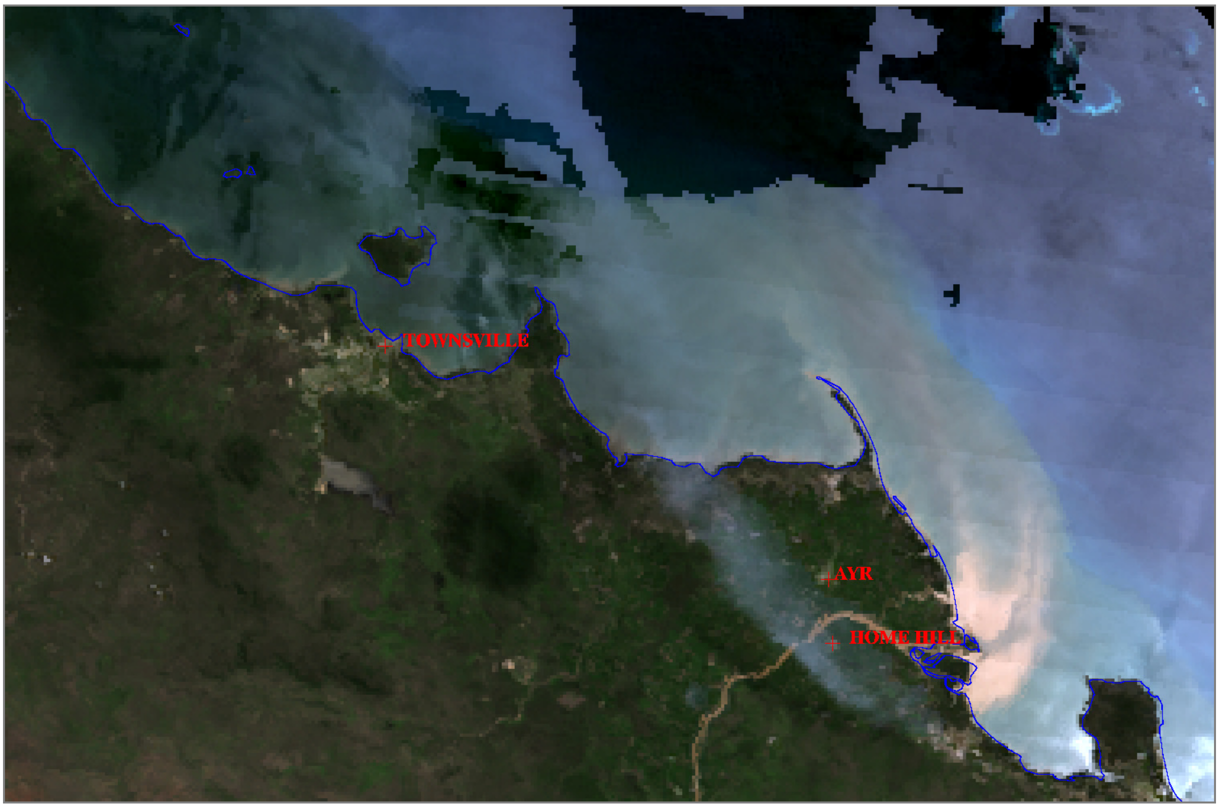

Figure 7: Satellite image of flood plumes from the Burdekin and Haughton rivers and Barratta Creek on 9 February 2007. The data show the plume moved primarily in a northward direction, although the Burdekin plume took a southward direction later in the flow event.

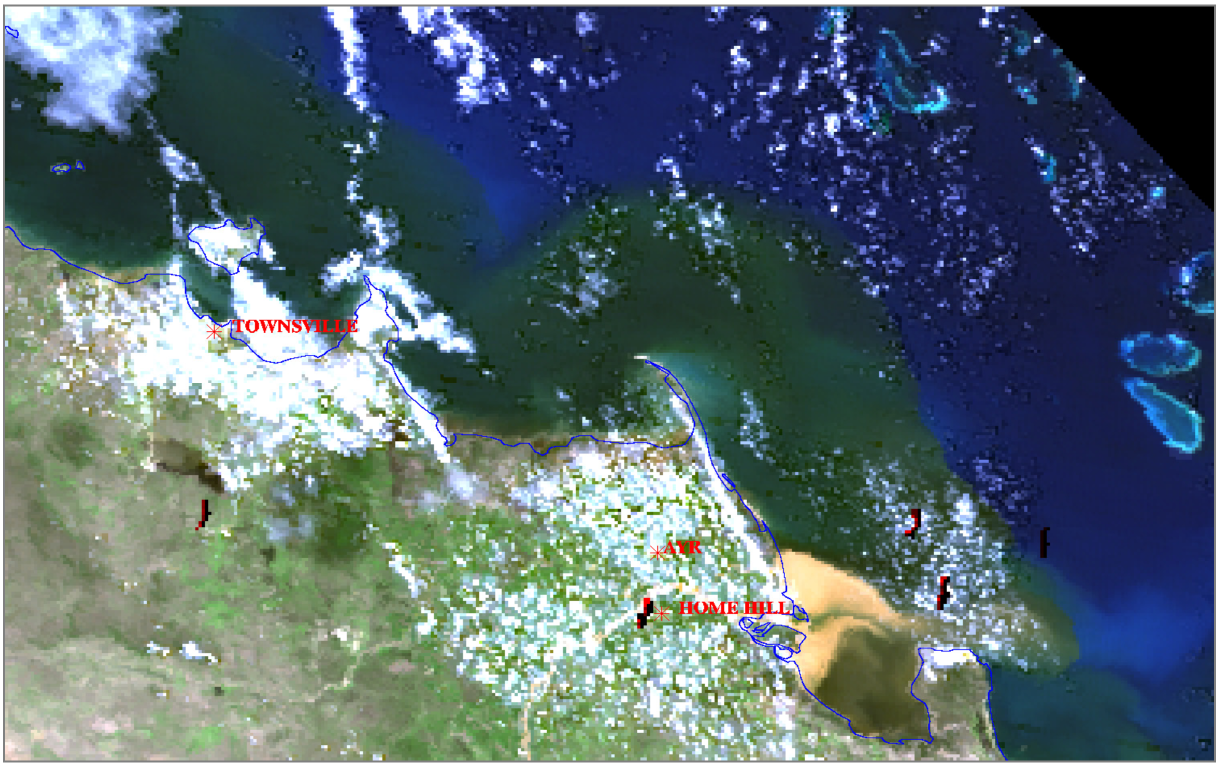

Figure 8: Satellite image of flood plumes from the Burdekin and Haughton rivers and Barratta Creek two days later on 11 February 2007. The image shows that within a couple of days the flood plume 'turns green', which indicates increased biological productivity.

Effects

The effects of terrestrial runoff to the GBR lagoon have received widespread attention during the last five years (e.g. Pandolfi *et al.* 2003; Bellwood *et al.* 2004; Fabricius 2005; Schaffelke *et al.* 2005). In particular, knowledge of the effects of sediments (Fabricius *et al.* 2003; 2005; Philipp and Fabricius 2003; Birrell *et al.* 2005; Hutchings *et al.* 2005; Wolanski *et al.* 2005; Weber *et al.* 2006), nutrients (Brodie *et al.* 2005; Fabricius *et al.* 2005; DeVantier *et al.* 2006) and pesticides (Jones *et al.* 2003; Jones and Kerswell 2003; Bell and Duke 2005; Duke *et al.* 2005; Harrington *et al.* 2005; Haynes *et al.* 2005; Jones 2005; Negri *et al.* 2005; Waycott *et al.* 2005; Markey *et al.* 2007; Cantin *et al.* in press) on organisms of the GBR has substantially increased, although any direct impacts of terrestrial materials to marine ecosystems have remained a complex issue.

While the majority of the GBR is considered in reasonable health (Miller and Sweatman 2004), some cornerstone publications have examined the endangerment of organisms in the GBR and described the apparent biodiversity loss of inshore reefs adjacent to catchments with intensive agriculture (Pandolfi *et al.* 2003; Fabricius *et al.* 2005; DeVantier *et al.* 2006; Bruno and Selig 2007). In addition, several studies have demonstrated the risks of increased nutrients (e.g. increased frequency of COTs outbreaks: Brodie *et al.* [2005]; change in nitrogen isotope composition of corals due to fertiliser runoff: Marion [2007]) and laboratory studies have shown the high toxicity of several commonly used pesticides in the GBR catchments on marine organisms. These findings are particularly valuable to set water quality targets for terrestrial pollutant export to the GBR lagoon. Coral records have provided tangible evidence of increased sediment and nutrient loads to the GBR lagoon since European settlement around 1860 (McCulloch *et al.* 2003a; Sinclair and McCulloch 2004; Mellors *et al.* 2005; Jupiter *et al.* 2007; Lewis *et al.* 2007b; Marion 2007). Indeed, a water quality gradient exists through the Whitsunday Island Group (van Woesik *et al.* 1999) and a clear correlation between water quality parameters and reef condition is evident throughout such gradients (Fabricius and De'ath 2004; Fabricius *et al.* 2005).

Innovation

Several innovations within the last five years have helped to provide valuable insights into the transport, fate and potential effects of pollutants to the GBR lagoon. Improvements in satellite technology allow for high frequency (sub-daily) and high resolution mapping of freshwater plumes in the marine environment (e.g. see Figures 7 and 8; Brodie *et al.* 2006). The development of algorithms to process the satellite data also allow for concentrations of suspended solids, chlorophyll *a* and salinity to be estimated with increasing degrees of confidence (Dekker, unpublished data; Brodie *et al.* 2006; Brodie *et al.* in prep). The innovation of passive samplers provides valuable data on the extent and the concentrations of pesticides in the marine environment (Shaw and Müller 2005).

The improvements in laser ablation technology are providing high resolution coral records that reflect and quantify the historical deterioration of water quality in the GBR lagoon as a result of increased agricultural activity (McCulloch *et al.* 2003a; Jupiter 2006; Jupiter *et al.* 2007). In addition, the development of a technique to analyse nitrogen isotopes in corals provides evidence of changing water quality in the GBR lagoon from increased fertiliser usage in the sugarcane and horticultural industries (Marion 2007). Currently, additional geochemical coral proxies are being developed to assess long-term water quality change in the GBR lagoon (Alibert *et al.* 2003; Wyndham *et al.* 2004; Sinclair and McCulloch 2004; Sinclair 2005).

The development of simplified conceptual models has greatly improved communications between scientists and managers. Some of these models have also been developed for educational booklets that have circulated amongst the general community, graziers and farmers (Connolly *et al.* 2005; Kelley *et al.* 2006). The development of a technique to assess the health of corals via colour (Coral Watch – Health Chart: Marshall *et al.* 2005) is another simple tool that has resulted in widespread community monitoring of coral reefs. This tool provides rapid assessment of the health of coral reefs and may also provide early indications of coral reef decline / improvement. This tool also allows for the accumulation of data from several reefs and will provide a longer-term assessment of coral reef health. Additional tools to monitor coral reef health are currently being developed by AIMS (Cooper and Fabricius 2007; Fabricius *et al.* 2007a). In addition, another reliable tool to assess GBR water quality is being developed using species of foraminifera (foram index: Uthicke *et al.* 2006; Nobes and Uthicke 2007).

2.3.2 Summary

- The majority of suspended sediments are initially deposited very close to the river mouth before being remobilised by prevailing southeasterly winds and by storm events and then becoming trapped in estuaries, north-facing embayments and mangroves. The clay sediment fraction may travel larger distances in the marine environment and become deposited on the mid-shelf below resuspension depths.
- Dissolved materials (including nutrients and pesticides) travel much further in the marine environment and are elevated several orders of magnitude above ambient concentrations in the freshwater plume. After turbidity decreases in the plume, nutrients are rapidly consumed by phytoplankton and algal blooms become evident in the marine waters. Satellite images and plume sampling reveal that algal blooms develop when weather conditions clear and full sunlight becomes available for increased photosynthesis (usually two to five days after the peak discharge occurs).
- Coral geochemical records provide compelling evidence that sediment and nutrient loads from GBR catchments have increased by several fold since European settlement.
- The coral luminescence record reveals no evidence of increased freshwater runoff to GBR lagoon from catchment hardening, although coupled rainfall and runoff records suggest the freshwater runoff has increased significantly.
- Distinct water quality gradients are measurable through the Whitsunday Island Group with a range of indicator species, including forams, coral colour and biodiversity. A clear correlation between water quality parameters and reef condition is evident through this gradient.

2.4 Emerging issues

2.4.1 Pesticides – A new threat to the ecosystems of the Great Barrier Reef?

The GBRCA is for the most part used for rangeland beef grazing and cropping, principally sugarcane cultivation, closer to the coast. Organochlorine, organophosphate and other types of pesticides have been widely used in agricultural crops of the coastal plain however many of the more persistent compounds were phased out and replaced from the 1980s onwards (Cavanagh 2003). While residues of highly persistent organochlorine pesticides such as dieldrin, aldrin and DDT can still be detected in coastal sediments and biota, these residues are believed to be from use in the 1950s to 1980s and not from contemporary use. More recently (from the 1970s) a number of herbicides have come into widespread use in the sugar industry, especially those that are associated with minimum tillage practices where weeds are suppressed through herbicide use rather than traditional tillage (Johnson and Ebert 2000).

Monitoring programs in fresh and marine waters, sediment and biota carried out since the 1990s in all parts of the GBR and GBRCA have found that residues of some of these herbicides, particularly diuron, atrazine, hexazinone, ametryn and 2,4-D are ubiquitous in areas adjacent to sugarcane cultivation regions (Rohde *et al.* 2006a; Faithful *et al.* 2007; Lewis *et al.* 2007a). Other detected herbicide residues appear to be associated with other industries, e.g. simazine with forestry, and tebuthiuron with tree clearing in grazing lands (Lewis *et al.* 2007a). Some herbicides widely used in sugarcane cultivation and other industries such as glyphosate and paraquat have not been detected in off-farm water bodies. Herbicide residues in concentrations possibly able to impact marine plant communities such as mangroves, macroalgae, seagrass and coral zooxanthellae have been detected up to a hundred kilometres offshore in parts of the GBR during river discharge events (i.e. in flood plumes) and in lower concentrations in non-discharge periods (Shaw and Müller 2005; Rohde *et al*. 2006a).

Off-site transport of pesticides to water bodies can occur via various pathways such as runoff, erosion and volatilisation. These are primarily dependant on the type of pesticide, according to its properties, as well as environmental conditions. The environmental fate of pesticides, their application rates and toxic potency to non-target organisms are key factors for evaluating potential ecosystem impacts (Lewis *et al.* 2007a). Extreme climatic conditions in tropical systems such as the GBRCA can have profound influence on the potential for pesticide off-site migration. High rainfall regimes facilitate increased dissolved and soil associated transport to river systems. Similarly, high annual temperatures in tropical systems have been shown to result in substantially increased volatilisation, and subsequent cold condensation over water bodies may be expected (Simpson *et al.* 2001). On the other hand, degradation rates of pesticides are thought to be substantially increased in warmer climates and hence may reduce their potential to reach the GBR. However, the fate of pesticides in tropical systems is poorly understood to date. Furthermore, there is a considerable lack of information on pesticide application rates within the GBRCA which contributes to uncertainties regarding their potential impact on ecosystems such as the GBR.

The toxicity of these herbicide residues to a number of relevant GBR biota has been tested (Jones *et al.* 2003; Jones and Kerswell 2003; Bell and Duke 2005; Duke *et al*. 2005; Harrington *et al*. 2005; Haynes *et a*l. 2005; Jones 2005; Negri *et al.* 2005; Waycott *et al.* 2005; Markey *et al.* 2007; Cantin *et al*. 2007). The herbicides diuron, atrazine, hexazinone, ametryn, simazine and tebuthiuron all inhibit photosynthesis through their effect on photosystem II in plants and this effect occurs at low concentrations – of the order of 0.1-10 µg/L. Tested marine plant types that showed reductions in photosynthesis at these low concentrations include zooxanthellae (in corals), seagrasses, benthic microalgae and coralline algae. Mangrove species (particularly *Avicennia marina)* were sensitive but at much higher concentrations (Bell and Duke 2005).

While plants can recover from this effect when the herbicide is removed the long-term and chronic exposure effects on plant growth and reproduction are still being evaluated. Some of the herbicides tested also showed a toxic effect to the animal half of the coral / zooxanthellae symbiosis, especially on reproductive ability (Jones *et al*. 2003; Jones and Kerswell 2003; Jones 2005; Markey *et al.* 2007; Cantin *et al*. 2007).

The combination of the concentrations measured in monitoring programs with the known effects levels from toxicity studies suggests that there is some level of risk to GBR marine biota, especially plant communities, from herbicide residues (Schaffelke *et al*. 2005). However a comprehensive risk assessment is yet to be made. Considerable further studies, including monitoring, pesticide behaviour studies and toxicity assessments need to be carried out before such a risk assessment can be considered accurate. The only situation where it has been claimed that effects are occurring currently is during the mangrove die-back events near Mackay which affects the mangrove *A. marina*. Mangrove die-back may have been associated with high diuron loads sourced from sugarcane cultivation usage in the local catchments – principally the Pioneer River (Bell and Duke 2005; Duke *et al.* 2005).

However the causal relationship is still complex and studies are continuing to clarify the relationship between diuron delivery and loads, and mangrove die-back (Wake 2006). Stress on GBR ecosystems from herbicide residues are also closely linked to and interact with other stresses. These include other water quality stressors such as suspended sediments and elevated nutrient loadings as well as the stresses of elevated water temperatures associated with global climate change.

Management of the herbicide issue has barely begun as the potential problems have only recently been realised. Two of the main management options appear to be:

1. Better management application methods, including targeted spray options that use less herbicide and hence suffer lower loss rates; and/or
2. A shift to non-residual or other effective herbicides which are not easily lost from the paddock.

There are a number of cost penalties to the farmer with both these options and the possibility of government subsidies to assist in the transition is being explored.

3. Knowledge Gaps

A number of the most important knowledge gaps of GBR water quality include:

- Despite regional collaborative efforts between industry, research, Government and the regional NRM bodies to develop BMPs for the major industries (sugarcane, grazing and horticulture) within the GBRCA, there is still a lack of quantitative evidence linking these BMPs with water quality benefits to downstream waterbodies. How strong is this linkage between the adoption of BMPs and resultant improvements in water quality, and in what time frame can changes in water quality be detected at different scales (i.e. paddock to sub-catchment monitoring)?
- What is the primary cause of gully erosion in the landscape (particularly the extensive gully networks in the semi-arid dry tropics catchments), and what are the most effective remedial management practices to stabilise new and existing gullies?
- What is the role of riparian vegetation in stabilising stream bank erosion on different sized streams? For example, is riparian vegetation more effective at stabilising the banks of lower order streams than the banks of the major river channels (such as the Burdekin, Tully or Daintree rivers which often have high, steep river banks)? As a result, how effective are recommended grazing BMPs that focus on the fencing-off of riparian vegetation at different stream orders?
- Anastomosing / anabranching floodplains are highly prized as cattle fattening country as the floodplain gets inundated during most flow events (even if those flow events are infrequent) and is therefore highly productive. The key questions are, What grazing land and/or riparian zone management practices will best maintain the productivity AND biodiversity (both terrestrial and aquatic) and the material trapping capacity of these systems? Out of this question forms a series of sub-questions:
  - What is the optimal combination of fencing and off-stream watering points for different types of floodplains?
  - Are all anastomosing / anabranching river systems the same?
  - Do different floodplain morphologies require different management approaches?
  - What impact does floodplain clearing have on productivity, biodiversity and material trapping at a range of time-scales?
- Considerable ranges of suspended sediment (SS) concentrations (100-14,000 mg/L) have been measured from different sub-catchments within the Dry Tropics region (e.g. Burdekin and Fitzroy rivers). What is the major driver(s) for this large variability in terms of natural (soils and geology, elevation and rainfall intensity and duration) and/or anthropogenic (land management such as stocking rates, fencing and spelling, and resultant ground cover) factors?
- Only a small proportion (perhaps five percent) of the SS load of major rivers is transported large distances in the marine environment during major discharge events (evident from satellite images and flood plume monitoring). What is the specific origin in catchments of this small but high risk component, and how do geology, soil type and land management practices interact to produce this presumably fine-grained, washload (non-settling) SS? Areas of catchments producing this component of the SS load will be of high management priority.
- What are the residence times of varying particle size fractions of SS being transported through the catchment? How variable are these times between these different particle sizes (i.e. transit time of sands which are more likely to be stored in the system than finer material such as silts)?
- Does increased SS loads due to increased erosion from agricultural and urban development in major rivers lead to increased regional turbidity generated by

resuspension in inshore areas of the GBR lagoon (with depths generally less than ten metres)? This old question argued over by geologists / physicists (Larcombe, Ridd and colleagues) and biologists / oceanographers/ geochemists (Wolanski, Fabricius, McCulloch and colleagues) is critically in need of a definitive answer if we are to justify our strategies to reduce erosion on GBR catchments as a major RWQPP action.

- Is the Burdekin Falls Dam a highly efficient SS trap as predicted by the SedNet model with predicted trapping of 75% of inflow SS on a long-term basis? If this is the case then there is no priority to manage soil erosion above the Dam to protect the GBR from SS delivery as little of this SS will ever reach the river mouth. If however the Dam is only a low efficiency trap (as suggested from some limited monitoring data) then management of these areas above the Dam (the majority of the area of the Burdekin catchment) may still be a priority for GBR water quality management.
- How important is the dissolved organic nitrogen (DON) fraction of the nitrogen load in agriculturally developed catchments of the GBR catchment area? DON was previously considered to be relatively refractory and non-bioavailable on a very limited theoretical basis. However DON is a large component of the nitrogen load in many rivers and the degree of its bioavailability will be a critical factor in assessing the risk to both fresh and marine ecosystems from nitrogen driven eutrophication. In addition, the bio-availability of particulate nitrogen and phosphorus also needs to be further investigated in the GBR catchments and lagoon.
- What are the specific impacts of pesticides (particularly herbicides) on the GBR ecosystems? Presently there is a lack of toxicity data for organisms specific to the GBR. Much of the current research has been focused particularly on corals with comparatively little data on mangroves, seagrass and micro-organisms. In addition, the synergistic effects of mixtures of pesticides are relatively unknown, as well as the exposure times for effects.
- One issue not being addressed in any research program is the relative risks to GBR ecosystems of the individual terrestrial-sourced pollutants. Current risk modelling assumes all pollutants of concern (e.g. nitrate, suspended sediments, diuron) are of equal risk. Clearly this is not the case. This lack of knowledge prevents us from prioritising management options for each of these individual pollutants in the catchments. To prioritise accurately we need to know the degree of deviation from natural plus potential consequences. Currently we are prioritising pollutant management on the basis of deviation from natural only. This is not satisfactory.

4. Research and Monitoring: Coordination and Integration Needs

Currently and over the last few years (since the RWQPP was published in 2003) we estimate in the order of $AUD100 million is being spent on research, scientific synthesis and analysis and technical studies relating to land-sourced water quality and the GBR. Almost 100% of this funding is ultimately sourced from the Commonwealth and Queensland Governments. An incomplete list of the programs and projects we are referring to is as follows:

- MTSRF Water Quality Theme;
- GBRMPA Marine Monitoring Program;
- CSIRO WfHC GBR Program;
- NAPSWQ – State Investment Program – AgSIP, WQSIP, Salinity SIP;
- *Catchment to Reef* Joint CRC Program;
- CRC Reef projects;
- Regional WQIP water quality monitoring, research and synthesis projects – Douglas Shire, Tully/Murray, Townsville-Thuringowa, Burdekin, Mackay-Whitsunday, Fitzroy, Burnett-Mary;
- Regional NRM group water quality monitoring (separate from WQIP) – FNQ, Burdekin, Mackay-Whitsunday, Fitzroy;
- Coastal CRC projects – particularly in the Fitzroy region;
- SRDC funded fertiliser use projects (BSES and DPI&F);
- Queensland DNRW (GBRI5) catchment loads program;
- Wetland DSS;
- Nutrient Management Zones project;
- GBR Environmental Metrics project – DNRW;
- Queensland Pesticide Risk Assessment project – Hydrobiology;
- Pesticide Audit and Reporting System project – URS;
- AIMS core program studies in GBR water quality;
- Core program studies of DNRW, DPI&F, EPA;
- GBRMPA water quality guidelines project;
- MLA funded grazing management studies – DPI&F and CSIRO.

This is a most impressive list of technical activity but currently there is no formal process or structure to bring the data from these studies together and integrate the information for the implementation of the RWQPP. Unfortunately, even closely related projects (e.g. those relating to pesticides) have not been coordinated in any formal way. Inefficiencies and duplication arise because of this lack of coordination and integration.

The RQWPP actually needs a formal 'Technical Implementation Plan' so the integrated information from the above listed studies can be used to implement the RWQPP on-ground. The existing RWQPP is a policy document, as was obviously required at the time of its development, but does not really contain the technical details needed for its implementation on-ground.

This is still a missing link in moving from policy to on-ground implementation. To provide the technical information for implementation of the RWQPP a formal scientific coordination and integration structure is required – this needs to be separate from the policy coordination bodies (e.g. IOC) and needs to have the scientific credibility to provide advice on critical scientific needs for the implementation of the RWQPP. The Scientific Advisory Panel of the Reef Partnership has taken on a small part of this role by default but is not adequately resourced to carry the whole role, and is not clearly supported by the governments to have this role.

Recommendations for the future of the RWQPP are that two new activities are required for successful implementation:

1. The development of a Technical Implementation Plan that will sit under the RWQPP and guide on-ground implementation; and
2. The establishment of a scientific coordination and integration structure that is resourced and funded by the governments to provide scientific knowledge and advice for the implementation of the RWQPP.

5. System Modelling and Synthesis within the GBR

5.1 Background

The RWQPP seeks to introduce BMPs in the GBR catchment with the aim of reducing the input of contaminants, such as sediment, nutrients and pesticides, into the GBR lagoon. A three-tiered monitoring program is being put in place to measure the changes in management practice, the trends over time in the loads of contaminants entering the lagoon from the various GBR catchments, and the improvement in the ecological condition of the GBR lagoon. A major challenge will be to link the information from these three programs so that the effect of changes in land management on the reef's ecological condition can be quantified. This will require the development of predictive models. Additionally, many recent studies have identified the need for integration and synthesis of water quality research results so that the 'big picture' can be used to guide management. Modelling has also been identified as the most useful tool for this integration.

5.1.1 Report cards

Browne *et al.* (2007) have been reviewing report card approaches to assist in the development of an Integrated Report Card (IRC) system for the GBR region to report on the condition and trends in catchment and marine health. A conceptual and statistical framework for the water quality component of this IRC has also been developed through the MTSRF program (Kuhnert *et al*. 2007). The IRC for the GBR region will further assist in the integration and synthesis of current water quality research.

5.1.2 Modelling

A considerable amount of modelling has been undertaken in the GBR region (and is continuing), ranging from the building of conceptual models (e.g. Haynes *et al*. in press) to complex process models (e.g. Wolanski and De'ath 2005). However, most of the current modelling effort is uncoordinated across institutions and researchers. Table 2 summarises the range of approaches that are currently being utilised within the GBR region.

At the paddock scale, models that connect agricultural practices to loss of suspended sediment, nutrients and pesticides have been greatly advanced. These models include APSIM which is being used in sugarcane cultivation modelling (Stewart *et al*. 2006; Thorburn *et al*. 2001; 2002; 2005) and HOWLEAKY which has been used in cotton and grains (Rattray *et al.* 2004; 2006).

At the sub-catchment scale, models such as SedNet have been adapted to work at fine scale (Kinsey-Henderson *et al.* 2005; Bartley *et al.* 2007a) providing detailed sediment generation and transport information. At the catchment scale a large amount of modelling has been performed to improve the predictive and explanatory capabilities of the SedNet and ANNEX models. Both models have been run at the scale of the GBRCA, with the earlier run (Brodie *et al.* 2003; McKergow *et al*. 2005a, b) used to identify hotspots of sediment and nutrient generation within the catchments, whilst the latest run (Short Term Modelling Project: Cogle *et al*. 2006; Dougall *et al.* 2006; Fentie *et al.* 2006; Hateley *et al.* 2006; Rohde *et al.* 2006b) has focused on improvements to the model and improving regional modelling capability. In addition, SedNet and ANNEX were used in a number of regional projects specifically in the Herbert River (Bartley *et al.* 2003), Douglas Shire WQIP (Bartley *et al.* 2004b) and in the Bowen sub-catchment of the Burdekin River (Bartley *et al.* 2004a). Considerably improved versions of SedNet and ANNEX have recently been used in the WQIP process in the Tully-

Murray region (Armour *et al*. 2007) and the Burdekin catchment (Kinsey-Henderson and Sherman 2007).

Table 2: Recent and current modelling efforts in the GBR catchment and lagoon.

Model Type	Name	Institutions	Example Publications
Empirical MCA	Exposure ranking	GBRMPA	Devlin *et al.* 2003
Empirical MCA	Catchment risk ranking	CSIRO Sustainable Ecosystems, GBRMPA, ACTFR	Greiner *et al.* 2003; 2005
Reef effects process	Ecohydrological model (HOME)	AIMS	Wolanski and De'ath 2005; Wolanski *et al.* 2003a; 2004
Catchment models	SedNet, ANNEX, EMSS	CSIRO Land and Water, ACTFR, CRC Catchment Hydrology, DNRW	McKergow *et al*. 2005a, b; Bartley *et al*. 2003, 2004a, b; Cogle *et al.* 2006
Catchment to reef process models		AIMS, ACTFR	Wooldridge *et al.* 2006
GBR lagoon hydrodynamic		JCU and AIMS AIMS and others	Luick *et al*. 2007 Brinkman *et al*. 2002; Legrand *et al*. 2006
GBR effects correlations	Crown-of-thorns starfish modelling	AIMS, ACTFR	Brodie *et al*. 2005
Catchment to reef Bayesian models	Bayesian Belief Network	Monash University, ACTFR	Thomas *et al*. 2005
Catchment to reef socio-economic models		CSIRO Sustainable Ecosystems	Roebeling *et al.* 2005; Smajgl *et al.* 2007; Heckbert and Smajgl 2005; Hajkowicz *et al*. 2005
Crop efficiency modelling		Sugar CRC	Mallawaarachchi *et al.* 2002
Empirical flux modelling from monitoring data		AIMS	Furnas 2003
Conceptual models	Sediment/nutrient reef effects; Catchment to reef	AIMS GBRMPA and others	Fabricius 2007; Haynes *et al.* 2007; Prange *et al.* 2007; Bass *et al*. in prep.
Paddock scale	APSIM HOWLEAKY	CSIRO Sustainable Ecosystems DNRW	Thorburn *et al.* 2001; 2005; 2006 Rattray *et al.* 2004; 2006

Attempts have been made to quantify the uncertainty of SedNet model outputs (Newham *et al.* 2003; Fentie *et al.* 2005a, b; Herr and Kuhnert 2007); however this information has not yet been broadly applied to SedNet users. Attempts have also been made to validate SedNet and ANNEX outputs through comparisons with monitoring data (Bartley *et al.* 2007b; Mitchell *et al.* 2007a; Sherman *et al*. 2007; Bainbridge *et al.* 2007), however such comparisons are somewhat problematic as the models are based on long-term averages (i.e. ~30 years) while only short-term monitoring data (<10 years) is available for comparison.

One of the more difficult modelling challenges is to model the dispersal of land-sourced materials in the marine environment and connect this to ecosystem effects. This has been attempted in the GBR region for nitrate discharge (Wooldridge *et al.* 2006) as a driver of phytoplankton biomass (expressed as chlorophyll *a*). Other models use changed turbidity and nutrient status to predict and explain reef degradation (Wolanski *et al.* 2003b; Wolanski *et al.* 2004; Wolanski and De'ath 2005). Traditional hydro-dynamic modelling of the GBR lagoon has improved in the last few years (Brinkman *et al.* 2002; Legrand *et al.* 2006) and other modelling (Luick *et al.* 2007; Wang *et al.* 2007) has shown that water residence time in the GBR lagoon can be between one month to one year.

For prioritising management actions in catchments it is essential to have a socio-economic component to the models and this has recently begun to be incorporated through the WQIP process in the Douglas Shire (Roebeling *et al.* 2004; Roebeling 2006), Tully-Murray region (Roebeling and van Grieken 2007; Roebeling *et al.* 2007b) and across the GBR (Hakjowicz *et al.* 2005; Smajgl and Gehrke, 2007; Smajgl *et al.* 2007).

Currently the only approach being explored to use a single modelling framework from catchment to marine environments uses the Bayesian belief network (Thomas *et al.* 2005), however this approach appears to have great promise and a number of other researchers are now planning to use this framework.

Conceptual models

The following diagrams show initial conceptual models of catchment processes (Figure 9), with a focus on sediment transport in the catchment and marine environment (Figure 10). Many parallel efforts to develop conceptual models of catchment to reef processes are currently underway, including those of the Reef Water Quality Partnership, GBRMPA and Queensland EPA. More detailed models (series of flow charts) of these processes can be found in Haynes *et al.* (2007).

Figure 11 summarises major variables and interactions affecting ambient water quality in Australian tropical fresh waters (Brodie *et al*. 2008). The diagram is not exhaustive in its coverage, but serves to demonstrate the inter-related nature of water quality processes and measures, and their influence on the ecological system. It also indicates that these processes occur as part of a continuum from the catchment to the sea, determined by the flow regime of the system. In perennial streams and rivers the inputs and outputs of surface waters are continuous, whereas in floodplain lagoons and riverine waterholes in the dry tropics, inputs and downstream outputs may be local or non-existent.

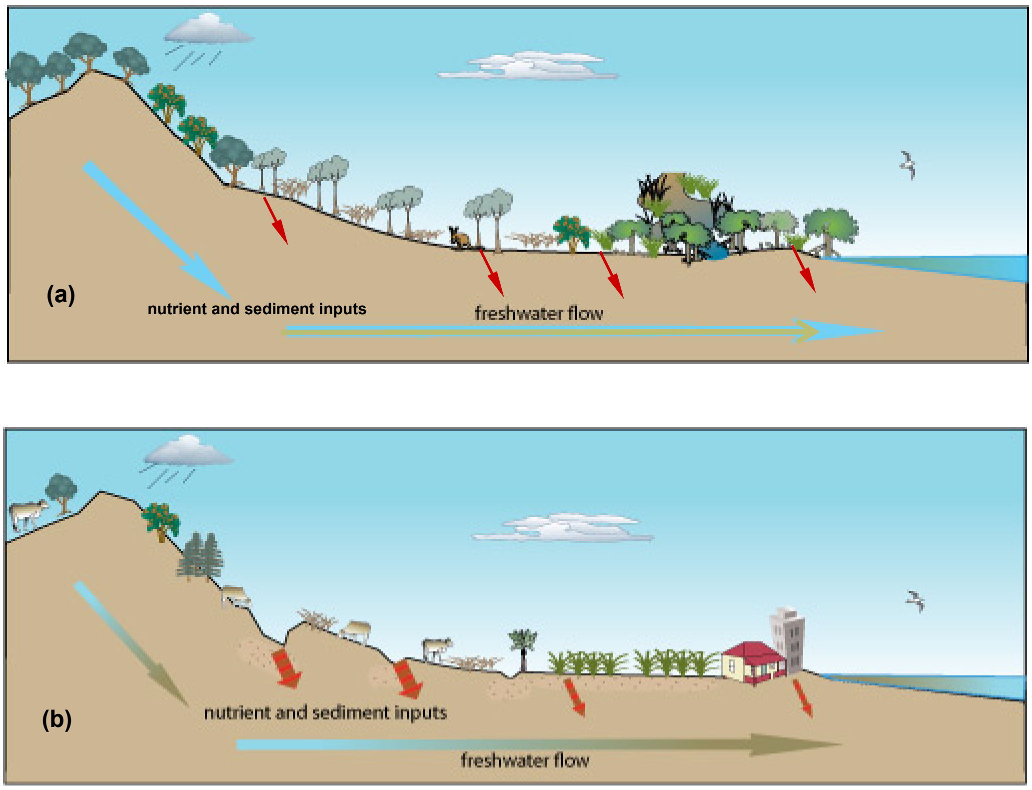

Figure 9(a-b): Conceptual models of catchment land use activities in (a) pre-European and (b) current conditions (from Bass *et al.* in prep).

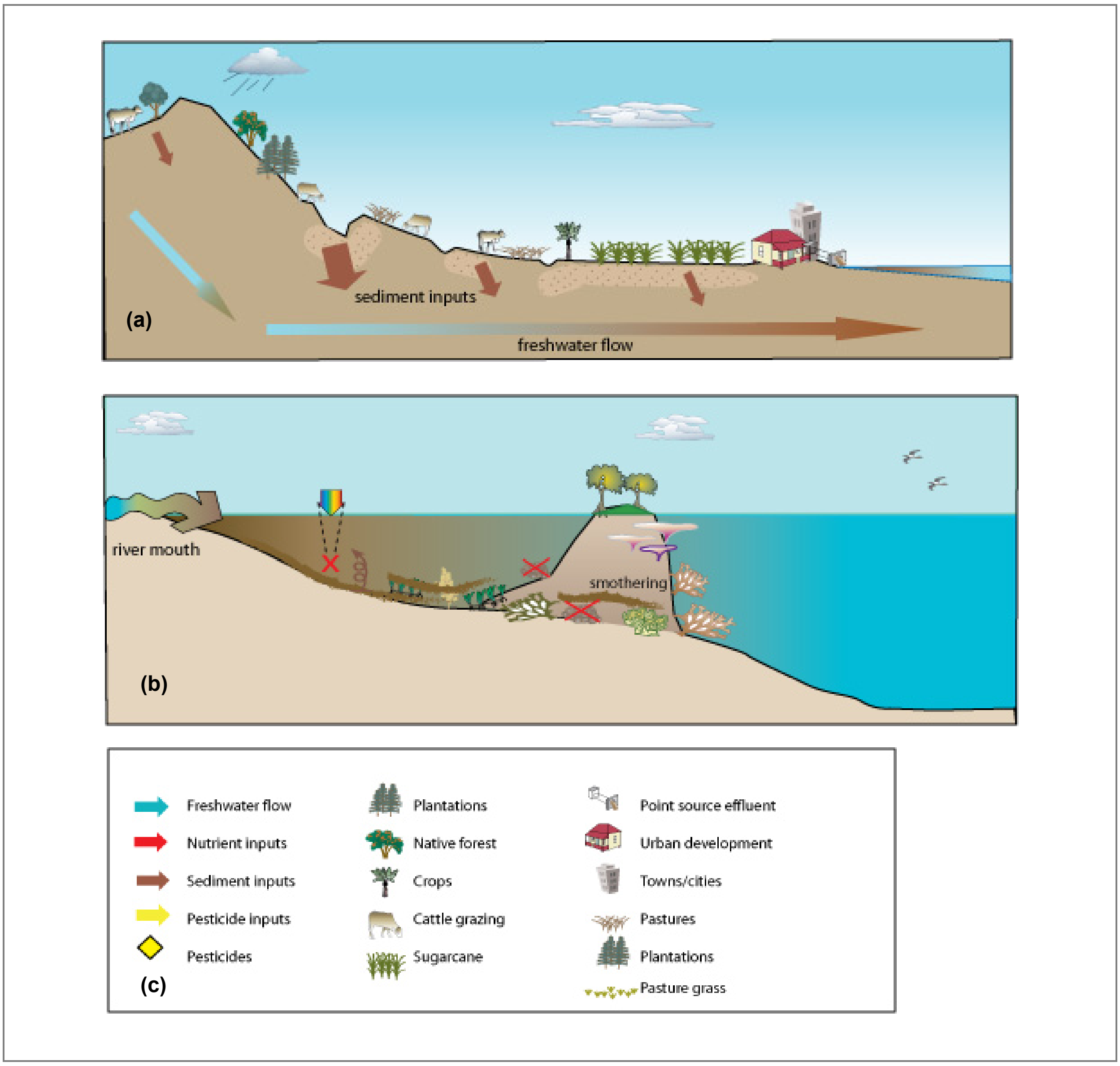

Figure 10(a-c): Conceptual models of sediment loss and transport in the Burdekin rangelands and coastal floodplain, with amount of loss indicated by arrow size (a), and (b) resultant impact on marine ecosystems in the receiving waters. Figure 10(c) provides a legend for the conceptual model (from Bass *et al.* in prep).

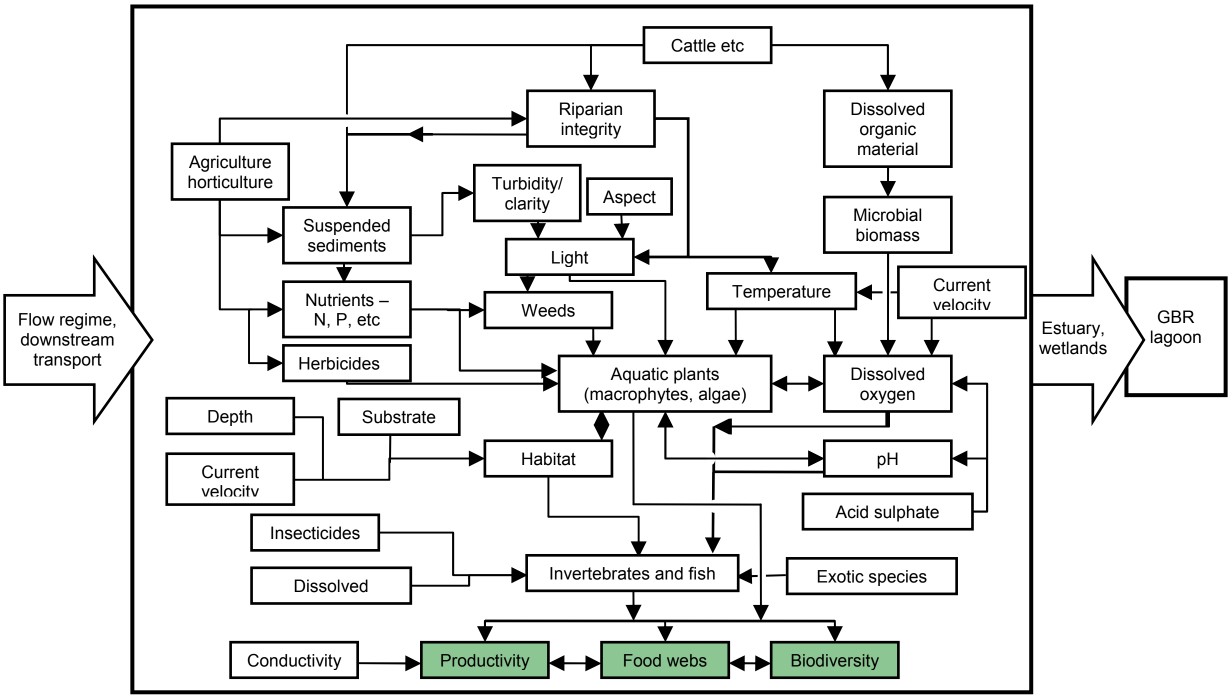

Figure 11: Biophysical interactions affecting ambient water quality in tropical agricultural landscapes. Note that not all factors or interactions can be shown, for example, riparian integrity has a number of influences on ecological responses that are not indicated here; and there is no indication of the influences of urban infrastructure, mines, etc. The large box represents typical processes and interactions in a stream reach, a discrete waterhole or a habitat within them. Large arrows represent flow-related connectivity. The shaded boxes represent different types of ecological response. Connectivity with the terrestrial landscape is implicit in some of the smaller boxes.

The following models represent the movements and fate of sediments (Figures 12 and 14) as well as the cycling of nutrients (Figures 13 and 15) in the marine environment. These models were developed as part of the Coastal CRC reports for the Fitzroy River and are directly applicable to other large semi-arid catchments of the GBR.

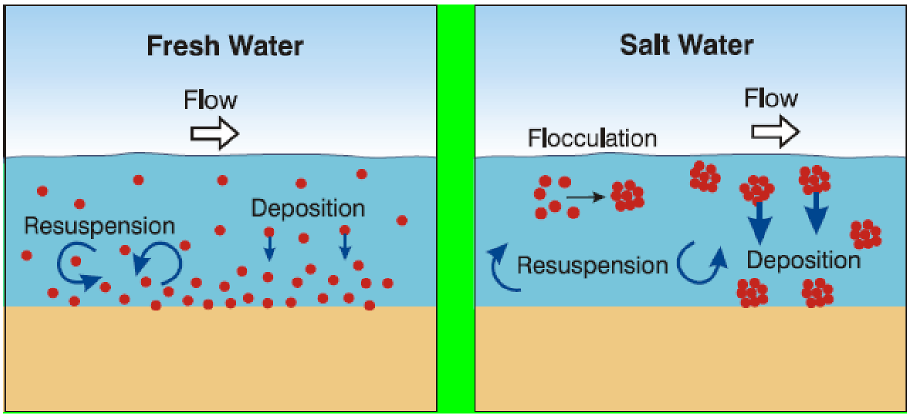

Figure 12: Conceptual model of the factors which control suspended sediment concentrations in large estuaries of the GBR catchments (example from the Fitzroy catchment from Webster *et al.* 2003).

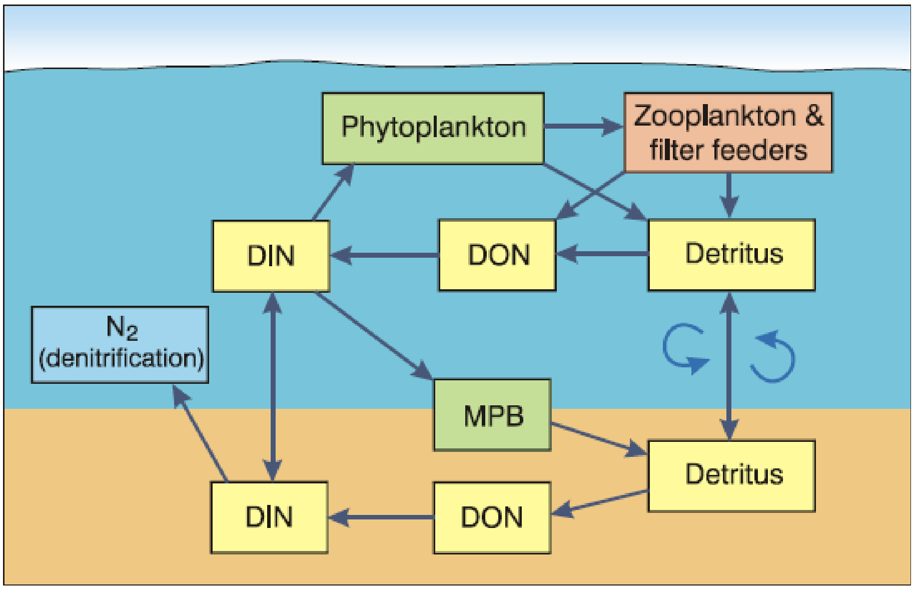

Figure 13: Conceptual model of the biogeochemical processes affecting the nitrogen cycle in the estuarine waters (example from the Fitzroy catchment from Webster *et al.* 2003).

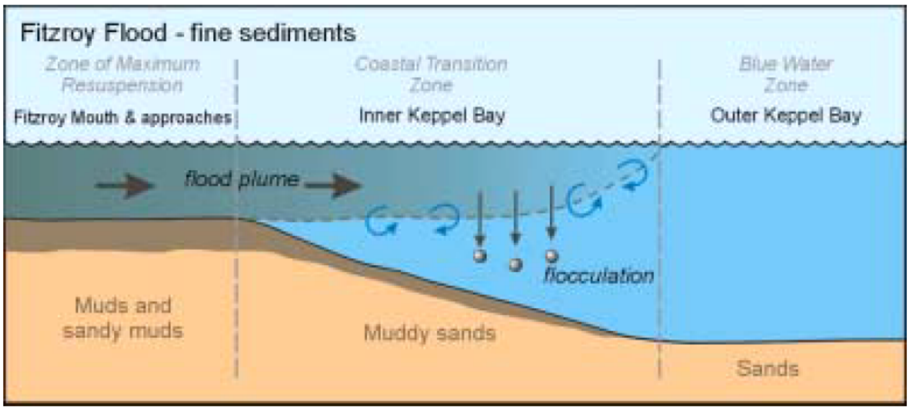

Figure 14: Conceptual model showing the removal of sediments in a flood plume (example from the Fitzroy River, from Robson *et al.* 2006).

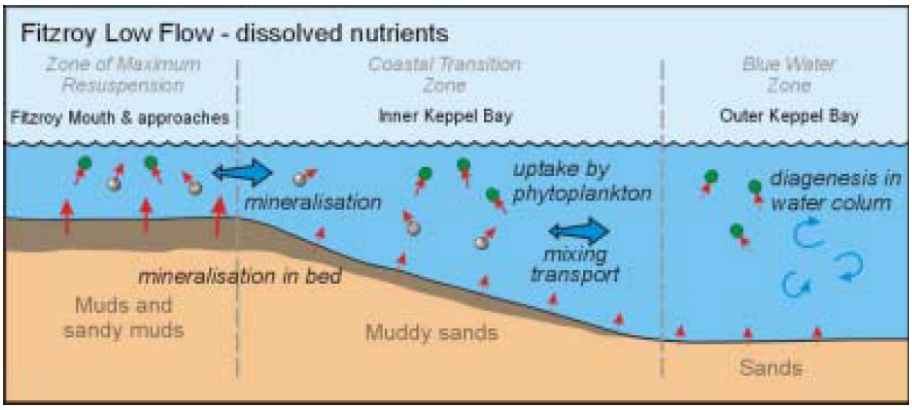

Figure 15: Conceptual model showing the cycling of nutrients in the marine environment (example from the Fitzroy River, from Robson *et al.* 2006).

Gehrke and Sheaves (2006) have developed the draft Marine Catchment Basin concept that links the six key domains of the upper and lower catchment with the open ocean waters (Figure 16). Land, wetland and river interactions are represented in the upper catchment, floodplain and estuary and these connect with the marine environment via the freshwater plume that mixes with the deeper ocean waters. Lateral interactions occur in each domain, but with differing hydrological and ecological characteristics. Longitudinal interactions between the domains mix waters of different chemistry and acts as a conduit for materials and freshwater and marine biota. It is recognised that details of the Marine Catchment Basin concept would be different in wet and dry tropical systems and that hydrological and ecological sub-models would need to be specified for each domain and system.

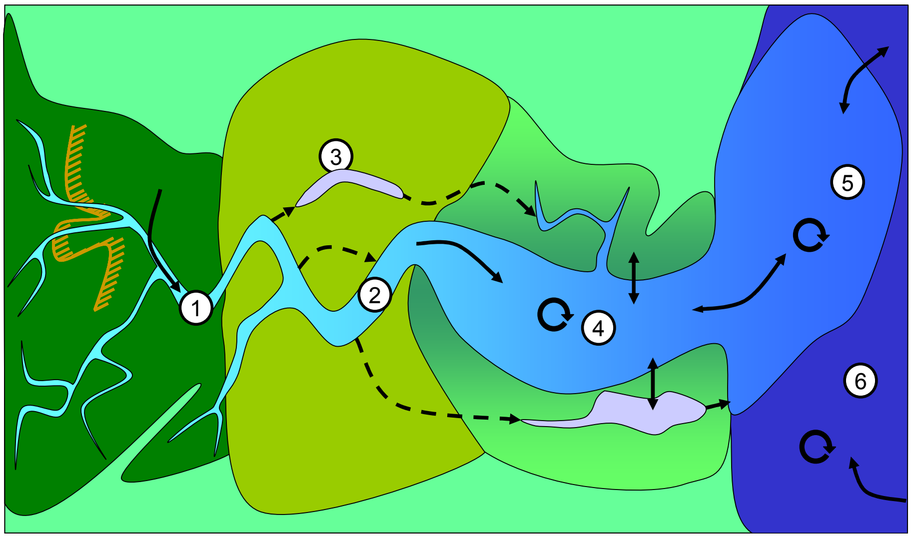

Figure 16: The Marine Catchment Basin concept showing the major sub-components of the catchment, floodplain, estuary and marine continuum. (1) River reaches upstream of the lowland floodplain; (2) lowland river reaches adjacent to (3) well-developed floodplain with freshwater wetlands; (4) estuarine reaches with salt-tolerant riparian vegetation and brackish wetlands; (5) river plume extending seaward; and (6) coastal waters outside the river plume. Arrows indicate direction of major material transport within numbered zones. Circular arrows show major zones of material recycling. Modified from Gehrke and Sheaves (2006) who adapted the original concept of Caddy (2000).

The following conceptual model (Figure 17) highlights the effects of increased loads of sediments and nutrients on corals of the GBR (from Fabricius 2007).

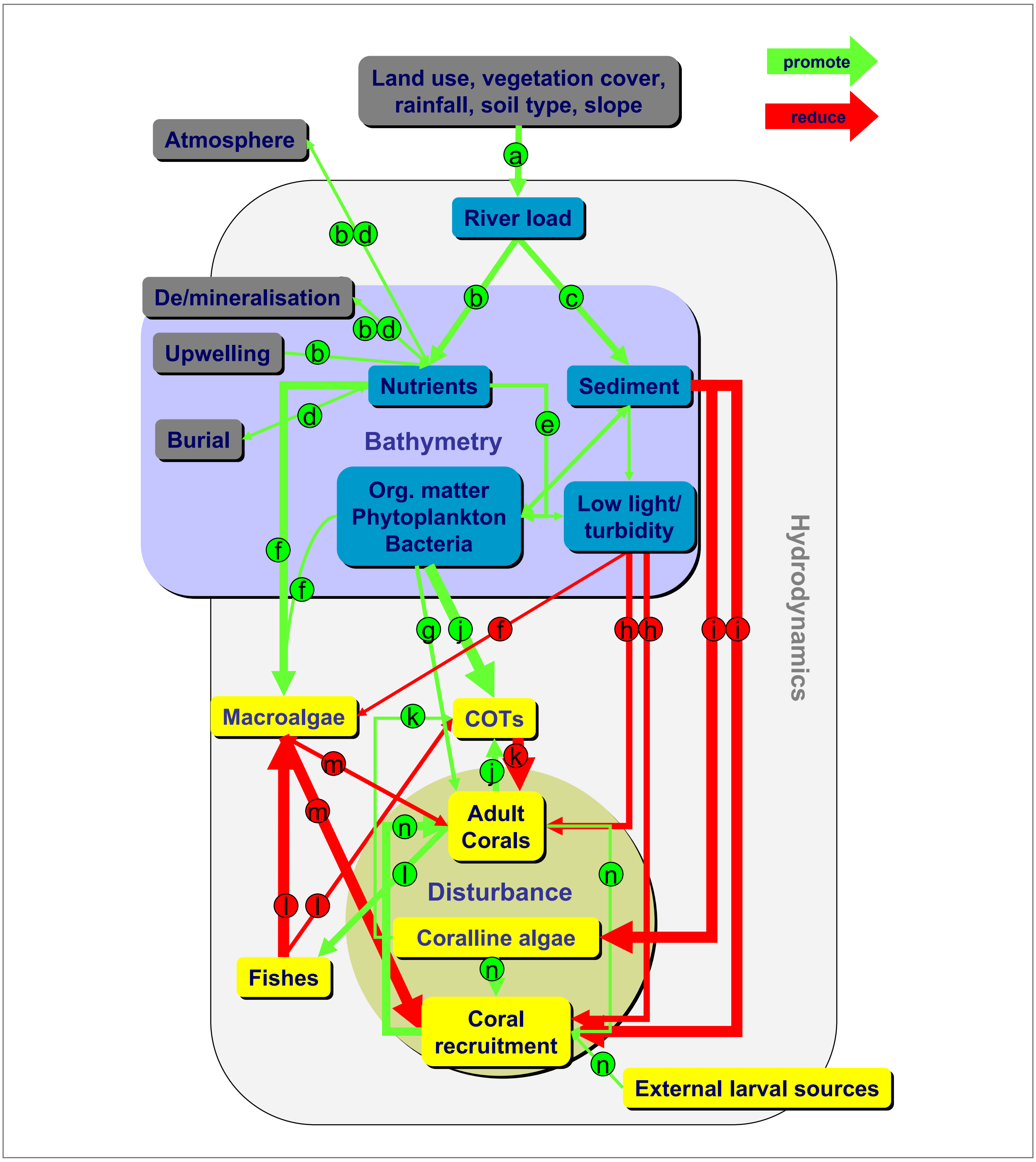

Figure 17: Conceptual model of the relationships between the four main water quality constituents (blue) and biotic responses (yellow). External and physical factors (grey boxes) further shape the relationships (from Fabricius 2007).

The following conceptual model (Figure 18) shows the movement of groundwater in the Burdekin River delta (from Charlesworth and Bristow 2004).

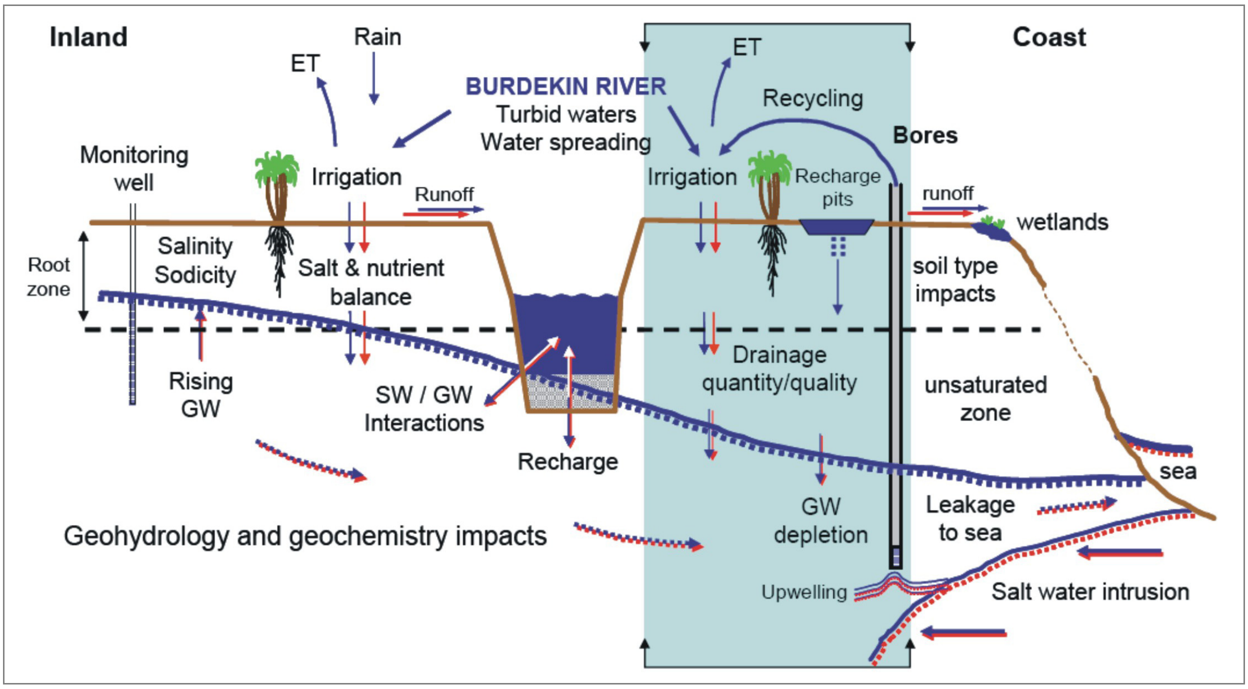

Figure 18: Conceptual model of groundwater movements in the lower Burdekin Area (from Charlesworth and Bristow 2004).

The following conceptual models (Figures 19 to 23) have been developed by Prange (2007) and present the processes of sediments, nutrients and pesticides in the marine environment and the recommendations of how targets are set to achieve water quality objectives.

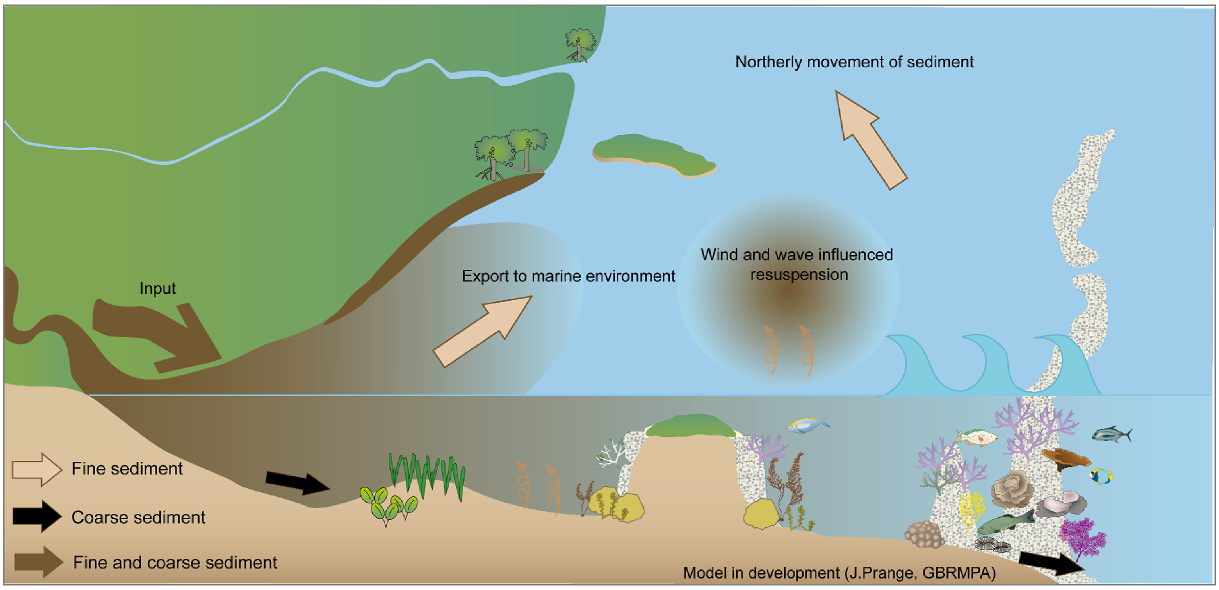

Figure 19: Model of sediment processes in the GBR lagoon (from Prange 2007).

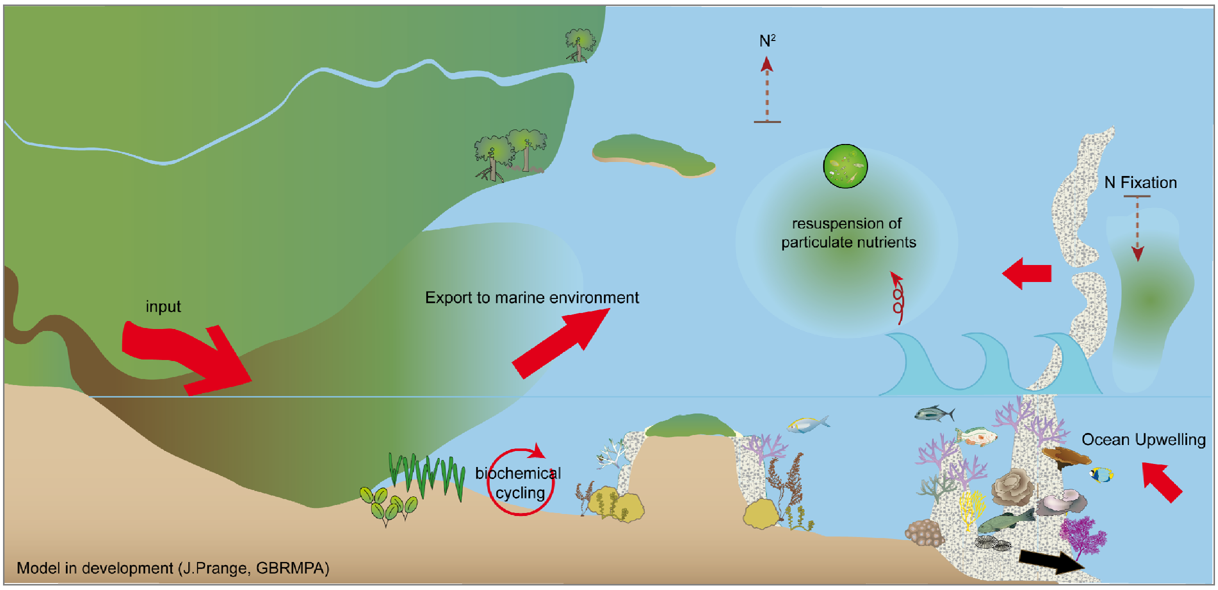

Figure 20: Model of nutrient processes in the GBR lagoon (from Prange 2007).

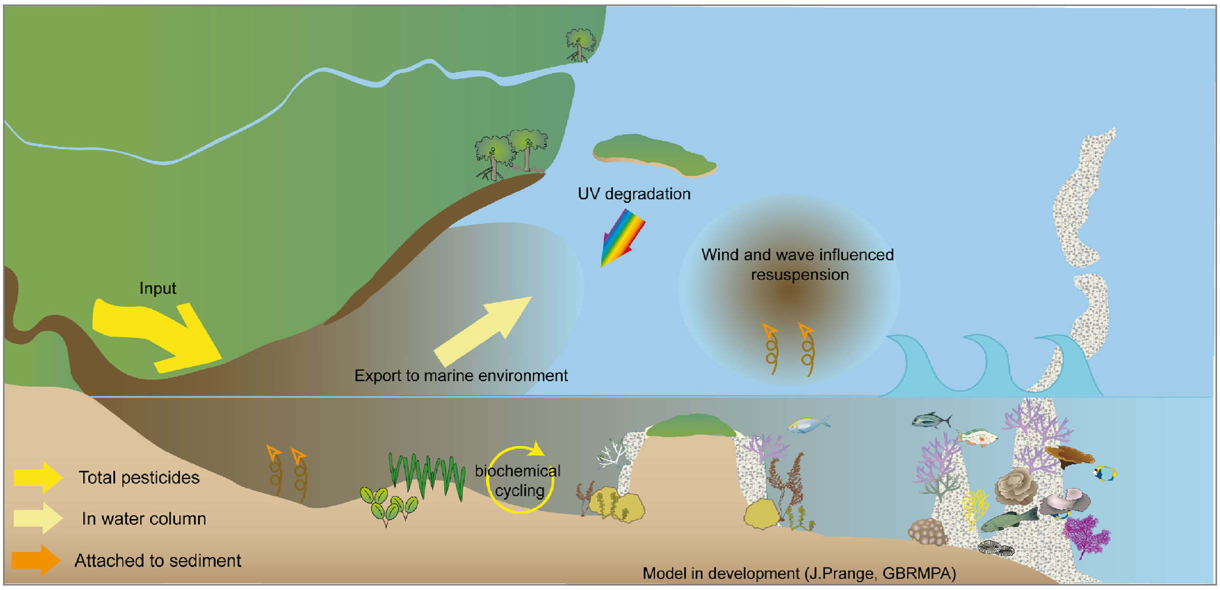

Figure 21: Model of pesticide processes in the GBR lagoon (from Prange 2007).

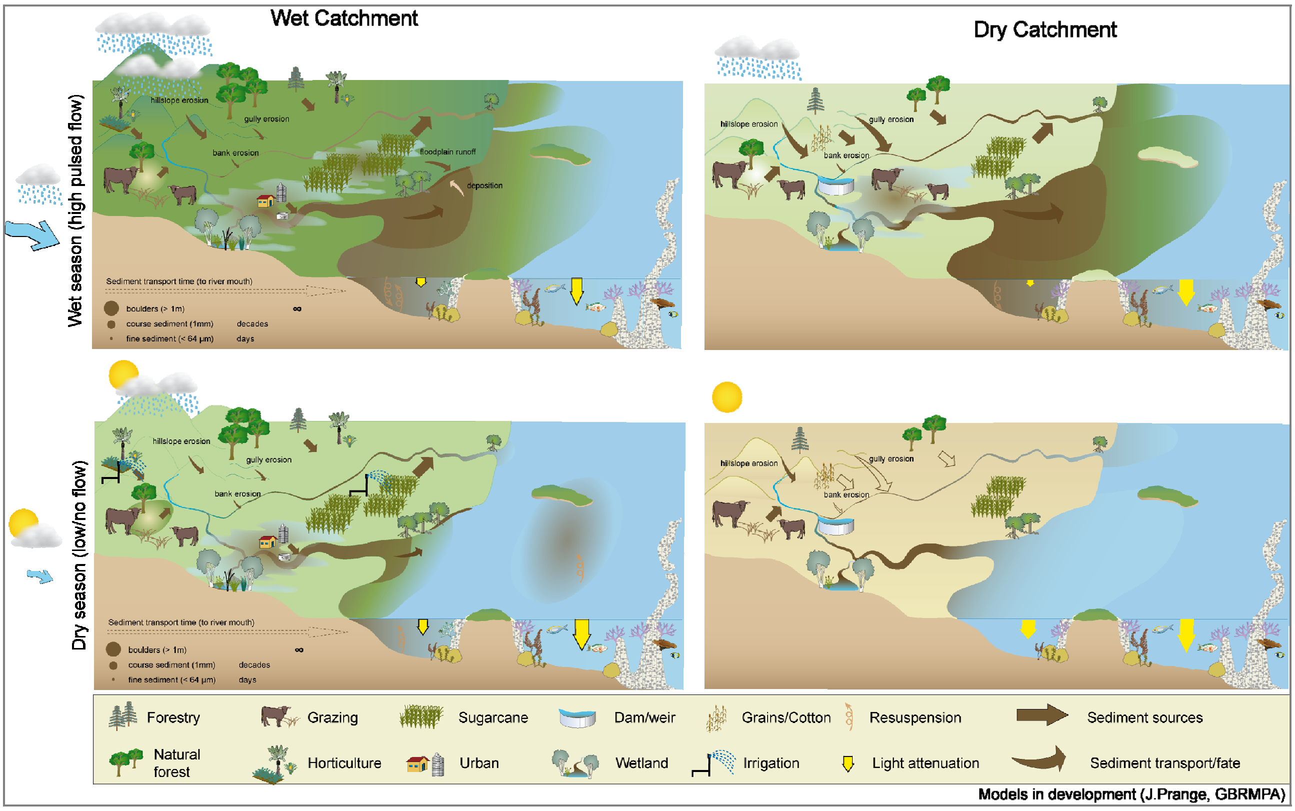

Figure 22: Model of sediment processes in both wet and dry catchments of the GBR (from Prange 2007).

Models (marine)

Several models have been developed to investigate the impacts of increased/continued agricultural land use on the ecosystems of the GBR (Wolanski *et al*. 2004; Wolanski and De'ath 2005), the nutrient enrichment of receiving marine waters since European settlement (Wooldridge *et al.* 2006) and the circulation/flushing times of GBR lagoonal waters (Legrand *et al.* 2006; Wang *et al.* 2007; Luick *et al.* 2007). A number of conceptual models have also been developed to highlight the effects of the different terrestrial materials on coral reefs and highlight the connectivity between the terrestrial and marine environment (e.g. Fabricius 2005; Connolly *et al.* 2005; Kelley *et al.* 2006). Models have also been generated to investigate the sediment and nutrient dynamics in the Fitzroy estuary (Webster *et al.* 2003; Radke *et al.* 2006; Robson *et al*. 2006).

These models not only indicate that nutrients have the potential to impact ecosystems of the GBR but also highlight the benefits of reducing nutrient loads from the catchments of the GBR (such as increasing the resilience of coral reefs to climate change). Luick *et al.* (2007) discovered that the flushing time for 'parcels' of water (conservative molecules) in the GBR lagoon ranged from one month to one year. This time is relatively long when considering that biological activity will consume nutrients within hours to days. However, calculations by Wang *et al.* (2007) suggest a flushing time of forty days for the inshore waters and ten days for the offshore waters.

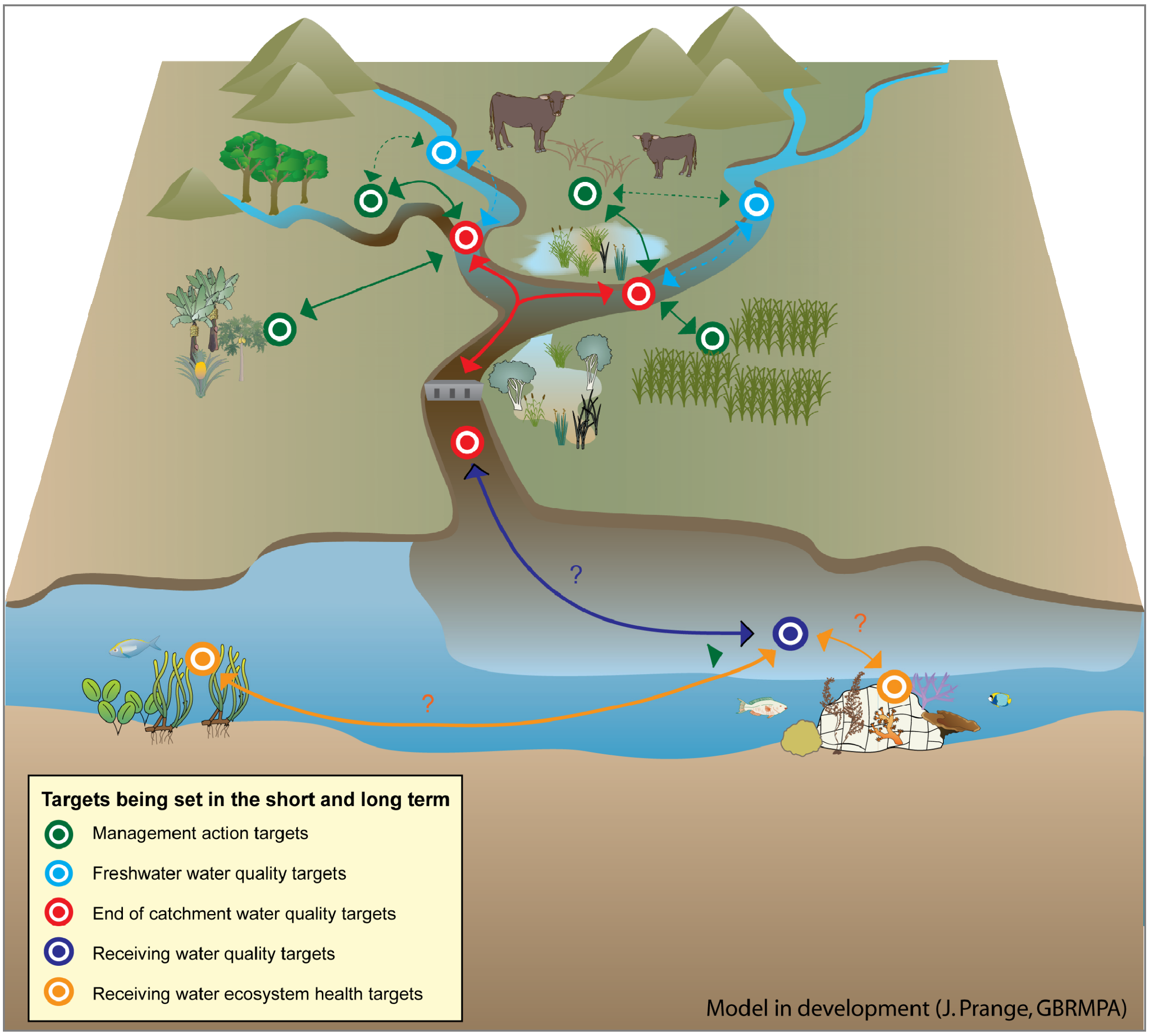

Figure 23: Model of recommendations for target setting to achieve water quality targets (from Prange 2007).

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Appendix 1: Summary of MTSRF Project 2006-2007

Theme 3: Halting and Reversing the Decline of Water Quality

Program 7: Halting and Reversing the Decline of Water Quality

The quality of water entering the Great Barrier Reef lagoon has been declining and is negatively affecting the condition of its ecosystems. There is an urgent need to elevate our certainty about the effectiveness of actions taken under the Reef Water Quality Protection Plan (Reef Plan), and for improved scientific understanding of how the condition of freshwater, estuarine and marine ecosystems are linked to terrestrial processes.

Project 3.7.1 Marine and Estuarine Indicators and Thesholds of Concern

Project Leader and Host Organisation: Dr Katharina Fabricius, AIMS (with JCU, GU, DPI&F)

This project will capitalise on, and take to completion, previous research efforts on the identification of indicators suitable as monitoring tools, conducted under the *Catchment to Reef* Joint CRC Program. This activity was the focus of Year 1 of the project. After review and prioritsation of the hundreds of potential indicators tested during the *Catchment to Reef* Joint CRC Program, the determine dose-response relationships and thresholds of potential concern for pollutant exposure of selected bioindicators will be determined. A better understanding of the significance of such thresholds for GBR water quality and ecosystem condition will be provided. Advanced statistical data synthesis will integrate previously collected large-scale data sets, towards developing a composite indicator system, to interpret water quality monitoring data and their link to ecosystem condition, and to improve estimates of river pollutant loads from discharge concentrations. The outcomes of the project will assist to refine the monitoring design of the Reef Plan Marine Monitoring Program, and will guide the selection of indicators for the Reef Water Quality Report Card.

Key objectives:

- To develop biofilm indicators for improved monitoring of water quality;
- To develop indicators for reef ecosystem condition;
- To develop indicators for seagrass condition in response to changing water quality; and
- To develop estuarine indicators for ecosystem condition.

Summary of Outputs for Project 3.7.1

Output: Final report on use of marine biofilms as indicators for changes in water quality (AIMS)

See: Nobes, K. and Uthicke, S. (2008) *Benthic Foraminifera of the Great Barrier Reef: A guide to species potentially useful as Water Quality Indicators.* Report to the Marine and Tropical Sciences Research Facility. Reef and Rainforest Research Centre Limited, Cairns (44pp.) (http://www.rrrc.org.au/publications/benthic_foraminifera.html).

Benthic foraminifera are established indicators for water quality in Florida and the Caribbean. This study summarised field and experimental work on benthic foraminifera as indicators for water quality in the Great Barrier Reef and is divided into two sections: the distribution of benthic foraminifera in four regions of the GBR and along a water quality gradient in the Whitsunday region; and manipulative laboratory experiments to determine whether the distribution of symbiont bearing foraminifera is controlled by light levels.

Over large geographic scales in the GBR, distinct benthic foraminiferan communities were recorded in the four regions of the GBR: Princess Charlotte Bay, the Wet Tropics, the Whitsunday Area and mid and outer shelf reefs. In addition, foraminiferan communities exhibited gradual changes along the water quality gradient in the Whitsunday region (Figure 1). Several species were associated with either high nutrient/high turbidity or low nutrient/low turbidity conditions.

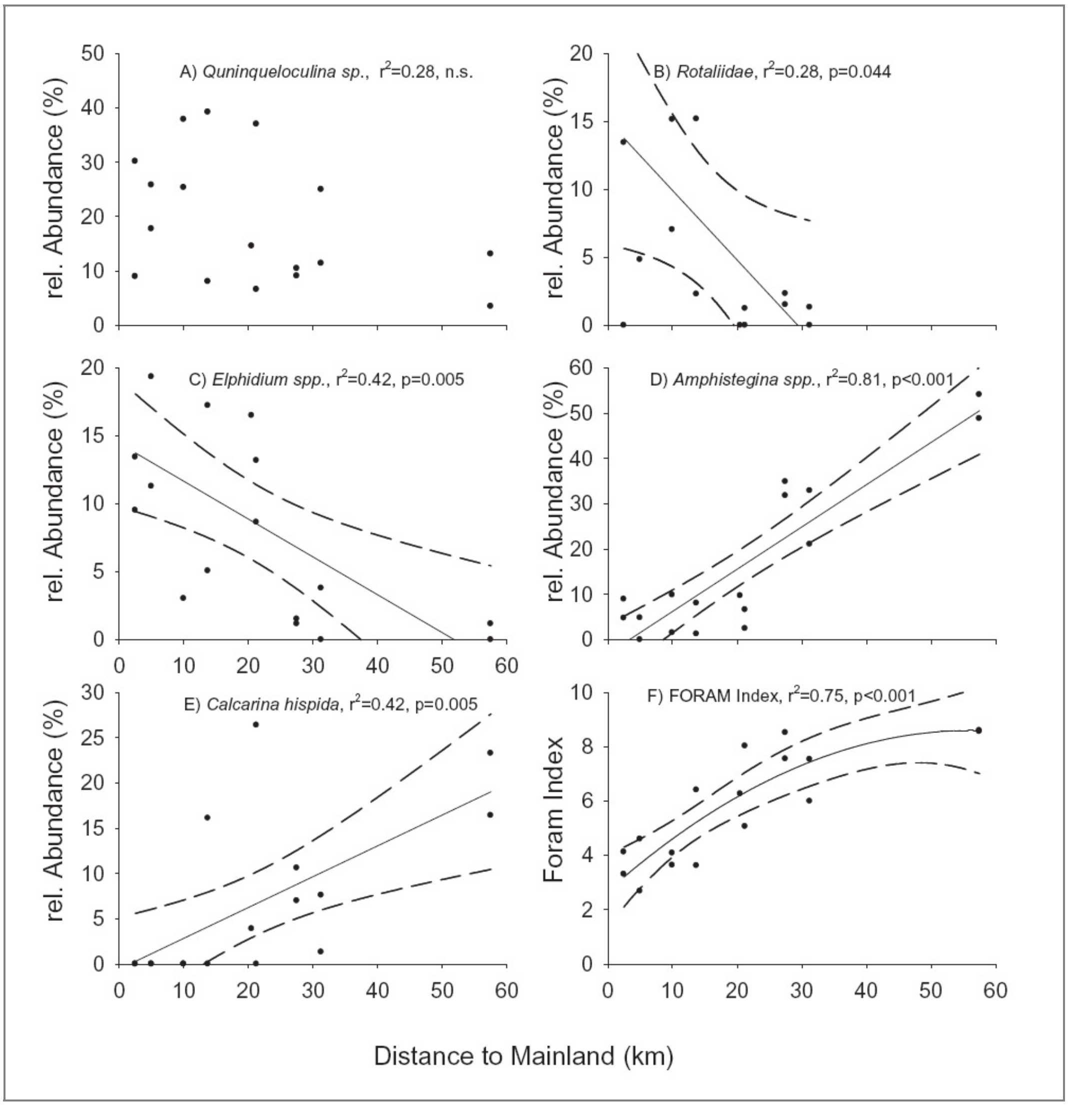

Figure 1: Linear regression analysis of selected foraminiferan taxa and the FORAM index (Hallock *et al.* 2003) as a function to the distance to the coastline. With exception of the FORAM index, inclusion of a polynomial term did not significantly improve the model. Dashed lines indicate 95% confidence intervals.

In general, large (algal symbiont bearing) foraminifera were more characteristic for clear water/low nutrient environments, while more turbid high-nutrient environments harbour heterotrophic taxa (free of algal symbionts). This is similar to previous findings in the Caribbean. However, not all species followed this pattern in the GBR. An application of the Caribbean FORAM index showed significantly increasing values along the Whitsunday Islands water quality gradient. It is concluded that it will be possible to apply the FORAM index to GBR reefs, after adaptations and fine-tuning of the index based on a better understanding of the physiology and ecology of GBR species. Because high turbidity and high nutrients are generally co-occurring along the water quality gradients, controlled manipulative experiments are needed to discern whether changes in light, in nutrients or the combined effect of both, determines the abundance of indicator taxa.

Detailed field surveys and controlled laboratory experiments were conducted to investigate whether light is the main factor regulating the distribution of several symbiotic foraminiferan species. The field surveys confirmed that the diversity of symbiotic taxa, and the abundances of most symbiont bearing species, increased along a water quality gradient away from the mainland in the Whitsundays region. Distance from the mainland alone explained nearly three times more of the variance than sampling depth and percent surface light in the distribution of species. In a laboratory experiment manipulating light levels, two of the three symbiotic genera tested, *Amphistegina* spp. and *Calcarina* spp. exhibited similar growth rates at 100%, 30% and 7% of sea surface light. This indicates a wide tolerance for light levels. In contrast, growth of *Heterostegina depressa* decreased significantly with increasing light intensity, suggesting that too much light inhibits growth in this species. All three foraminiferan taxa had the most efficient light use at the lowest light level tested, and their general photophysiology is characteristic of 'low light' plants. Reduced photosynthetic yield at high irradiance suggested that high light may exert stress on the photosystem of the symbionts.

In conclusion, both field and laboratory studies suggest that light is unlikely to be the controlling factor for the distribution of foraminifera that were selected as potential bioindicators for water quality. This raises the potential that foraminifera are specific indicators for enhanced nutrient availability, which will be investigated in further experiments. Furthermore, dose-response relationships will be quantified. Whether light is not a main controlling factor in other abundant symbiont bearing species will also need to be established. Further manipulative experiments *in situ* and in aquaria, have commenced as part of the next phase of the MTSRF project investigating the use of biofilms as indicators for water quality.

Two manuscripts on the role of foraminifera as indicators for water quality conditions have also been completed.

Output: Report on the use of physiological measures in coral reef organisms as indicators of water quality and ecosystem condition (AIMS).

See: Cooper, T. and Fabricius, K. (2007) *Coral-based Indicators of Changes in Water Quality on Nearshore Coral Reefs of the Great Barrier Reef.* Report to the Marine and Tropical Sciences Research Facility. Reef and Rainforest Research Centre Limited, Cairns (31pp.) (http://www.rrrc.org.au/publications/downloads/Project-371-Coral-based-Indicators-of-WQ-Change.pdf)

In this study, coral-based indicators at a range of spatial and temporal scales were quantitatively assessed and compared, and those most suitable for inclusion into a ‘toolbox’ for monitoring the health of nearshore reefs on the GBR are identified.

The aim of the report was to summarise research on a range of coral-based indicators at different spatial and temporal scales and identify those most suitable for inclusion into a 'toolbox' for monitoring the health of nearshore reefs on the GBR. The types of indicators investigated ranged from physiological responses to community-level measures in corals. A set of selection criteria defined for the candidate indicators were assessed for their use to indicate changes in the key components of water quality (i.e. sedimentation, turbidity and light attenuation, and nutrients). The systematic assessment of research presented in the report and in Fabricius *et al.* (2007) has resulted in the recommendation of seven coral-based measures to indicate changes in levels of sedimentation, turbidity and light attenuation, and nutrients on nearshore coral reefs. Seven coral-based indicators were identified that could be incorporated into a monitoring toolbox. These were:

1. Symbiont photo-physiology;
2. Colony brightness of massive *porites*;
3. Tissue thickness of massive *porites*;
4. Density of macro-bioeroders in living *porites*;
5. Changes in coral juvenile densities;
6. Changes in coral community structure; and
7. The maximum depth of coral reef development.

Of the investigated candidate measures to indicate stress, some have been shown to respond to a range of stressors, including unusual levels of temperature and salinity. For example, maximum quantum yield (Fv/Fm) decreases in response to sedimentation (Philipp and Fabricius 2003; Weber *et al.* 2006) but also following exposure to low salinity (Kerswell and Jones 2003) and elevated sea temperatures (Ulstrup *et al*. 2006). Among the water quality specific indicators, few were found to be specific for either sedimentation or turbidity or nutrients, and further work is needed to identify indicators for each of specific water quality conditions. Since elevated levels of sedimentation, turbidity and nutrients tend to co-occur in many nearshore environments, such greater specificity was considered secondary compared with identifying indicators that are specific for water quality.

Each of these measures has a different sensitivity and response time to changes in water quality. A combination of these measures, complemented by indicators based on biofilms and direct water quality measurements, is therefore recommended as a composite indicator system to assess changes in the exposure and condition of nearshore reefs on the GBR (Figure 2). The indicator measures were plotted against increasing levels of stressors in ascending order, from sublethal stress to mortality. These responses vary according to the magnitude and duration of exposure to the stressors. Similar responses to those presented in the short-term may occur following exposure to lower levels of stress over longer (months to years) periods of time but this remains to be determined. Exposure to the key components contributing to decreased water quality (i.e. elevated sediments, turbidity and nutrients, and reduced irradiance) will first invoke a response at the physiological level (i.e. the early warning indicators). At increasing exposure (either longer duration or higher levels), responses at the population and community level will become evident.

The challenge ahead will be to improve the understanding of patterns of variation and defining thresholds for the suite of indicators identified. For example, further work is required to provide estimates of seasonal and temporal variability in symbiont photo-physiology on nearshore coral reefs of the GBR. The relationship between the maximal depth of coral reef development and water quality requires further investigation because if deep corals on nearshore reefs are indeed light limited, then simple tools such as Secchi depth and monitoring coral reef depth may provide time-integrated information on strategies to improve water quality on the GBR. It has been beyond the scope of this study to examine and identify 'thresholds of concern', but clearly future research should focus on understanding the physiological, ecological and community responses to differing loads and duration of the key components of water quality. Moreover, priority should be given to studies that investigate the responses, adaptation and consequences of changes in water quality on corals and coral reefs that are exposed to a changing environment of temperatures and water carbonate saturation.

Further outputs of the study include a manuscript proposing the use of light, together with chlorophyll, as integrative and ecologically relevant proxy measure for changes in water quality, and the effect of light limitation on reef development in the Whitsundays.

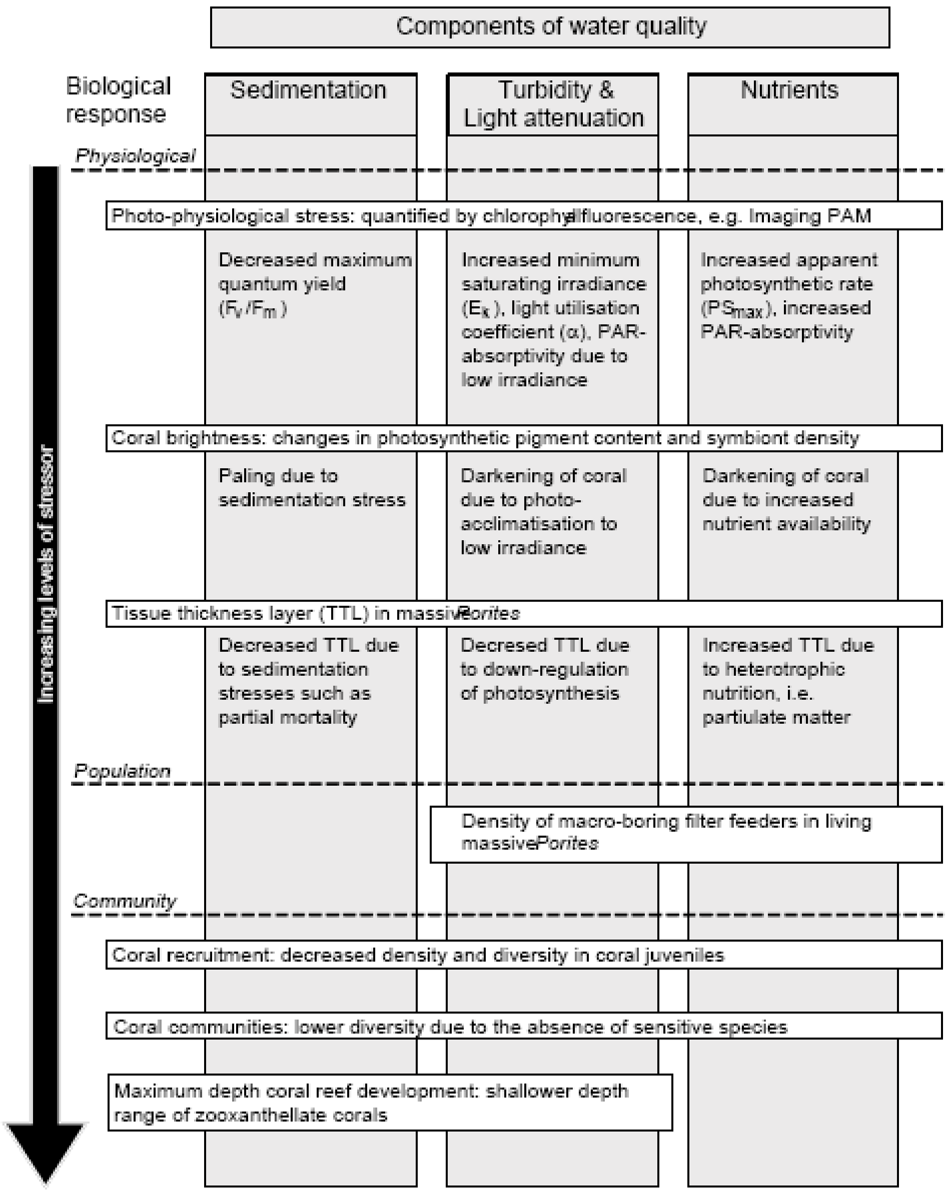

Figure 2: Biological measures to indicate increasing exposure to the key components of water quality. Indicator measures that can be used to assess all three stressors are displayed at the level of exposure at which the measure is useful. The grey boxes indicate cases where the indicator values differ depending on the type of stressor

Output: Report on the use of physiological measures in coral reef organisms as indicators of water quality and ecosystem condition (AIMS).

See: Fabricius, K., Uthicke, S., Humphrey, C. and Cooper, T. (2007) *Potential water quality specific indicators for the Reef Water Quality Protection Plan monitoring of estuaries and inshore coral reefs: Summary of benefits and costs.*

This document presents a summary of key aspects and the main recommendations for research to develop water quality specific biophysical indicators for the Reef Plan monitoring. The document contains a tabulated summary that lists and highlights those potential indicators that are highly specific, practical to use, ecologically relevant and associated with low to medium costs. A subset of these indicators is currently being used, and others are being trialled, by the AIMS Inshore Reef Monitoring group and others may be included into future Reef Plan monitoring programs.

Output: Report on relationships between Seagrass communities and sediment properties along the Queensland coast (DPI&F).

This component of the project forms a step towards refinement of seagrass monitoring techniques, and investigation of surrogate indicators, such as sediment properties. As a starting point, the conversion of all sediment properties data to quantitative measure apportioned by grain size has been completed for the whole Seagrass-Watch data set. The conversion is based on the CRC Reef Deepwater seagrass survey sediment data (for which both 'deck descriptions' (essentially on-site observations) and grain size analyses exist). This allowed to back-relate the deck description data collected through Seagrass Watch to sediment grain sizes. With this conversion completed, this extensive data set represents a valuable resource to quantitatively investigate the relationships between seagrass meadow properties (species composition, biomass, etc.) and sediment properties, as well as spatial and temporal factors. To complete such statistical analyses and the write-up of this complex and large research project will require more substantial investment than was available in Year 1.

Output: Report detailing the conceptual framework for reef ecosystem condition in relation to changing river discharges (AIMS).

See: Fabricius, K. E. (2007) *Conceptual model of the effects of terrestrial runoff on the ecology of corals and coral reefs of the Great Barrier Reef.* Report to the Marine and Tropical Sciences Research Facility. Reef and Rainforest Research Centre Limited, Cairns (24pp.) (http://www.rrrc.org.au/publications/downloads/Project-371-Conceptual-Model-Report.pdf

The objective of this study was to build a conceptual model to address the specific question: "How are changes in river loads linked to changes in lagoonal water quality and biogeochemical processes, and do these changes alter the condition and ecological properties of coral reefs"? The conceptual model summarises the present understanding of the processes involved the dynamics of nutrients, sediments, and their effect on the condition of inshore coral reefs of the GBR. The model combines published process understanding, budgets and reviews including Furnas *et al.* (1995); Furnas (2003); Wolanski *et al.* (2004); Alongi and McKinnon (2005); Fabricius (2005); Schaffelke *et al*. (2005) and Fabricius *et al.* (2007).

The study concludes that from the perspective of inshore coral reefs of the GBR, the four most relevant water quality drivers are inorganic nutrients, particulate organic matter, light reduction from turbidity, and sedimentation. Agrochemicals may also be important, but their exposure levels and ecosystems effects are still poorly understood. The main processes of direct impact are the inhibition of coral recruitment by moderate levels of sedimentation and light attenuation from turbidity. Coral larvae and newly settled juvenile stages, rather than adults, are at greatest risk from poor water quality. Sediment layers inhibit the successful recruitment of juvenile corals, either directly, or through negative effects on crustose coralline algae which are a preferred settlement substratum. The two main indirect effects are potentially increased frequencies of outbreaks of crown-of-thorns starfish (COTs) in response to phytoplankton availability, resulting in enhanced predation pressure on corals, and the proliferation of macroalgae in response to increased nutrient levels, resulting in more severe space competition. The severity of these water quality effects depend both on dose and on exposure times, and such dose-response relationships are found in the field along water quality gradients both naturally and in places where nutrient and sediment exposure levels are enhanced by human activity.

This conceptual model may now be used to populate a process-based numerical model to test scenarios / model risks in relation to changes in water quality, to design conceptual diagrams as communication tools, and to identify future research priorities.

Output: Final report on literature review on potentially useful ecological indicators of the condition of North Queensland's estuaries (JCU and GU).

See: Sheaves, M., Connolly, R. and Johnston, R. (2007) *Assessment of techniques for determining the health of tropical estuarine ecosystems.* Report to the Marine and Tropical Sciences Research Facility. Reef and Rainforest Research Centre Limited, Cairns (43pp.) (http://www.rrrc.org.au/publications/downloads/Q4-371-JCU-GU-Estuary-indicators-Review-June-07.pdf)

This study assessed techniques that can be employed to determine the ecosystem health of estuaries and coastal wetlands in Australia's tropical regions, evaluated the sensitivity of those techniques to detect the effects of specific stressors, and evaluated their ability to separate natural variations from deleterious anthropogenic impacts. In total, 565 references were collected, reviewed and synthesised, and a summary of recommendations have been provided.

The study showed that while there is a large amount of information about detecting impacts and measuring ecosystem health in temperate estuaries, the extent to which temperate approaches are transferable to tropical/subtropical systems is unclear. There have been no location-specific studies evaluating the appropriateness of extrapolation from temperate to tropical understanding. In particular, biochemical processes such as toxicity, persistence and accumulation rates are likely to differ between cooler temperate and warmer tropical systems). Contrasts in functioning of tropical compared to temperate estuaries are likely to be compounded by the much higher biological diversity present in tropical estuaries, which potentially leads to more complex ecological processes High diversity might also equate to high variability, adding another layer of complexity.

Ecosystem health is a combination of three factors: resistance, organisation and vigour, all of which are ultimately functions of ecological processes. Ecosystem health might therefore be considered as more closely aligned with the integrity of ecological processes than the health or abundance of individual species or groups of species. The study suggests that definitive measurement of ecosystem health requires approaches that provide measures of the integrity of ecological processes; there is a need to advance our understanding of the links between stressors and environmental outcomes.

Future estuarine indicator work will focus on fish. The work will be extended to include ecological processes that, together, should offer a more comprehensive indication of ecosystem health. Three estuarine fish indicators have been conceptualised that are likely to represent important components of ecosystem health: scavenging pressure, non-detritivore trophic composition, and predator success (Figure 3). The combination of a range of techniques and their use at multiple sites in close proximity but having different potential impacts provides an opportunity to greatly advance our ability to assess the health of estuaries and coastal wetlands of Australia's tropics.

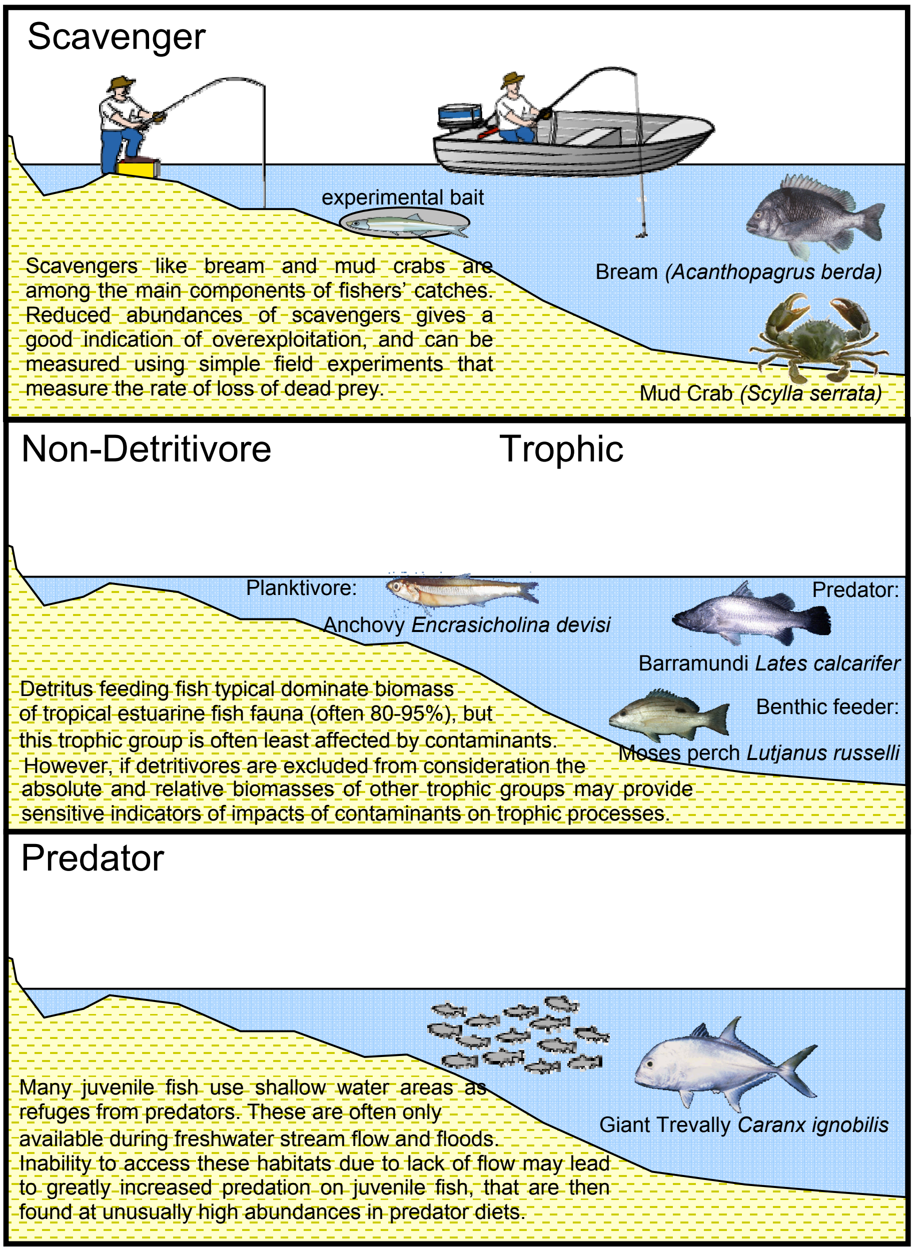

Figure 3: Three examples of simple biological indices with the potential to provide information on impacts crucial to ecologicaly processes in tropical estuaries.

Output: Final report on use of stress markers in barramundi as indicators of water quality (AIMS).

See: Humphrey, C., Codi King, S. and Klumpp, D. (2007) *The use of biomarkers in barramundi (Lates calcarifer) to monitor contaminants in estuaries of tropical North Queensland.* Report to the Marine and Tropical Sciences Research Facility. Reef and Rainforest Research Centre Limited, Cairns (30pp.) (http://www.rrrc.org.au/publications/downloads/Q3-371-Biomarkers-for-Barramundi-_2_.pdf)

Biomarkers are particularly valuable as early warning signals of environmental degradation and provide an inexpensive, rapid and highly sensitive means of identifying and evaluating exposure to, and/or effects of, environmental contaminants in complex ecosystems. By selecting a key component in the ecosystem, in this case barramundi a top-level predator, and measuring multiple biomarkers including measures of molecular, genetic and physiological impairment along with chemical analysis, the ecological relevance of environmental contaminants may be more readily elucidated and thus integrated into environmental management strategies (Brown *et al.* 2004; Galloway *et al*. 2004a, b).

In order to assess whether chemical contaminants were impacting upon the sensitive ecosystems of the northern GBR, barramundi (*Lates calcarifer*) were sampled from estuaries of five separate river systems, which represent varying degrees of impact from anthropogenic activities. A multibiomarker approach was used in conjunction with chemical analysis of water and sediment from the five systems to try and characterise the relationship between anthropogenic contamination and response of resident biota in estuaries along the north Queensland coast.

Water, sediment and barramundi (*Lates calcarifer*) samples were collected from five North Queensland estuaries along a perceived pollution gradient in 2002 were processed and analysed for trace organic contaminants such as polycyclic aromatic hydrocarbons, polychlorinated biphenyls, organochlorine and organophosphate insecticides and metals. In addition, the pollution induced responses of a suite of seven biochemical parameters (phase I biotransformation enzymes (e.g. EROD, P450), fluorescent aromatic compounds, DNA damage, RNA:DNA ratio and neurotransmission enzymes) and two condition indices (condition factor and hepatosomatic index) were measured in barramundi. The resulting database was subjected to uni- and multi-variate analyses in order to determine the most suitable biomarkers to assess pollution in North Queensland estuaries and to classify the environmental quality of the sites. Principal components analysis on the biochemical markers revealed that EROD, EROD/P450, DNA damage and to a lesser extent cholinesterase activity and fluorescent aromatic compounds were found to be responsive to contaminants in the environment while cytochrome P450, condition factor and the hepatosomatic index were found to be less responsive biomarkers. Of particular significance was the ability of the cholinesterase activity assay to detect the presence of organophosphate insecticides, compounds that are notoriously difficult to detect in environmental samples analytically. Discriminant analysis was used to classify the pollution status of the various estuaries. It appears that the best discrimination between the various sites was obtained using discriminant analysis on the biomarkers; however, further analysis using water quality parameters and levels of organic contaminants in water and sediment produced a similar pattern as found with the biomarkers.

This was the first study to employ multiple biomarkers in a resident fish species in Queensland, and has demonstrated the utility of applying a multibiomarker approach in conjunction with traditional analysis of contaminants in providing valuable information in environmental risk assessment.

Project 3.7.2 Connectivity and Risk: Tracing of Materials from the Upper Catchment to the Reef

Project Leader and Host Organisation: Jon Brodie, JCU (with AIMS, ADFA)

The goal of this project is to characterise and obtain a distinct ‘fingerprint’ of the fine sediments (mud fraction) entering the marine environment, using their isotopic and elemental properties, and link these to the sediment sources of the major terrestrial catchments. It will also examine historical changes in the delivery of terrestrial materials from the major river systems in the Townsville-Cairns region to the marine environment using coral and sediment cores. This will involve determining transport mechanism, residences time and fate of terrigenous sediments in the inshore as well as mid-reef regions of the Great Barrier Reef, and develop and apply new technologies to specifically trace pathways of the key nutrient elements phosphorus and nitrogen from the terrestrial catchments, through estuaries, inshore coastal zones to the mid-reef of the Great Barrier Reef.

Key objectives:

- Sediment tracing in the terrestrial environment;
- Sediment tracing in the marine environment;
- Inshore-offshore sediment transport in the Wet Tropics; and
- Floodplain sedimentation dynamics in Dry Tropics catchments.

The work in Year 1 of the project was focused on collecting primary data sources.

Summary of Outputs for Project 3.7.2

Output: Tracing of materials in the terrestrial environment; primary data collection (JCU).

The key tasks for this Output were to:

- Characterise and obtain a distinct ‘fingerprint’ of the fine sediments (mud fraction) delivered to the inshore regions of the Great Barrier Reef within the Burdekin and selected wet tropics catchments (Herbert, Tully, Johnstone and Russell-Mulgrave);
- Trace the transport and extent of the each sediment type through the main tributaries of the Burdekin and selected wet tropic catchments in the Townsville Cairns region; and
- Determine the sediment trapping capacity of estuaries and coastal zones as well the effects of the Burdekin Falls Dam during major flow events.

During the 2007 wet season, a suite of water samples (~80 samples) were collected from the tributaries throughout the Burdekin catchment (Figure 4) and from the freshwater plume from Burdekin (and Tully) River (Figure 5). These samples are currently being stored and the suspended sediments will be recovered and analysed for trace element and isotope composition by the end of 2007. Particle size analysis will be undertaken on 147 samples. Water samples taken from the Burdekin River freshwater plume were analysed for trace elements; preliminary analysis show the initial Barium (Ba) desorption at very low salinities (~1 ppt) followed by a consistent dilution trend of Ba over the remaining salinity gradient (Figure 6). This trend is consistent with the 2002 flood plume from the Burdekin River (M. McCulloch *pers. comm.*) and supports the interpretation of Barium/Calcium (Ba/Ca) ratios in corals as a proxy of sediment delivery to the Great Barrier Reef lagoon.

A comprehensive collection of daily satellite imagery from the 2007 flood plumes along the GBR allow the extent and movement of plumes to be traced over time as well as provide an understanding of biological processes occurring within the plume. Preliminary results suggest that the movements of the Burdekin plume may switch direction by 180 degrees within days. In addition, freshwater plumes throughout the GBR lagoon became a 'green' colour within two to three days of expsore to sunlight, providing an insight into the timeframes of biological activity in the flood plume (J. Brodie, unpub. data).

Samples for pesticide analysis were collected from the flood plumes from the Burdekin and Tully Rivers in 2007. Data from the Haughton River and Barratta Creek plumes (Figure 7) from February 2007 show the presence of diuron and atrazine in the plume waters. These concentrations were below marine guidelines, although these concentrations would possibly have been higher if this flood event had occurred earlier in the wet season (e.g. November-when pesticides are applied).

Suspended sediment samples collected from the Burdekin Falls Dam spillway have been analysed. It is calculated that 1.2 million tonnes of sediment was transported past the dam during the February-March wet season. Sediment loads will be calculated for the major waterways above the Burdekin Dam to assess dam trapping in the 2007 wet season once gauging and suspended sediment data become available. The comparably smaller flow event in 2006 suggests that the dam trapped approximated 80% of sediments (~ 1.8 million tonnes of sediment; Bainbridge *et al*. 2006b).

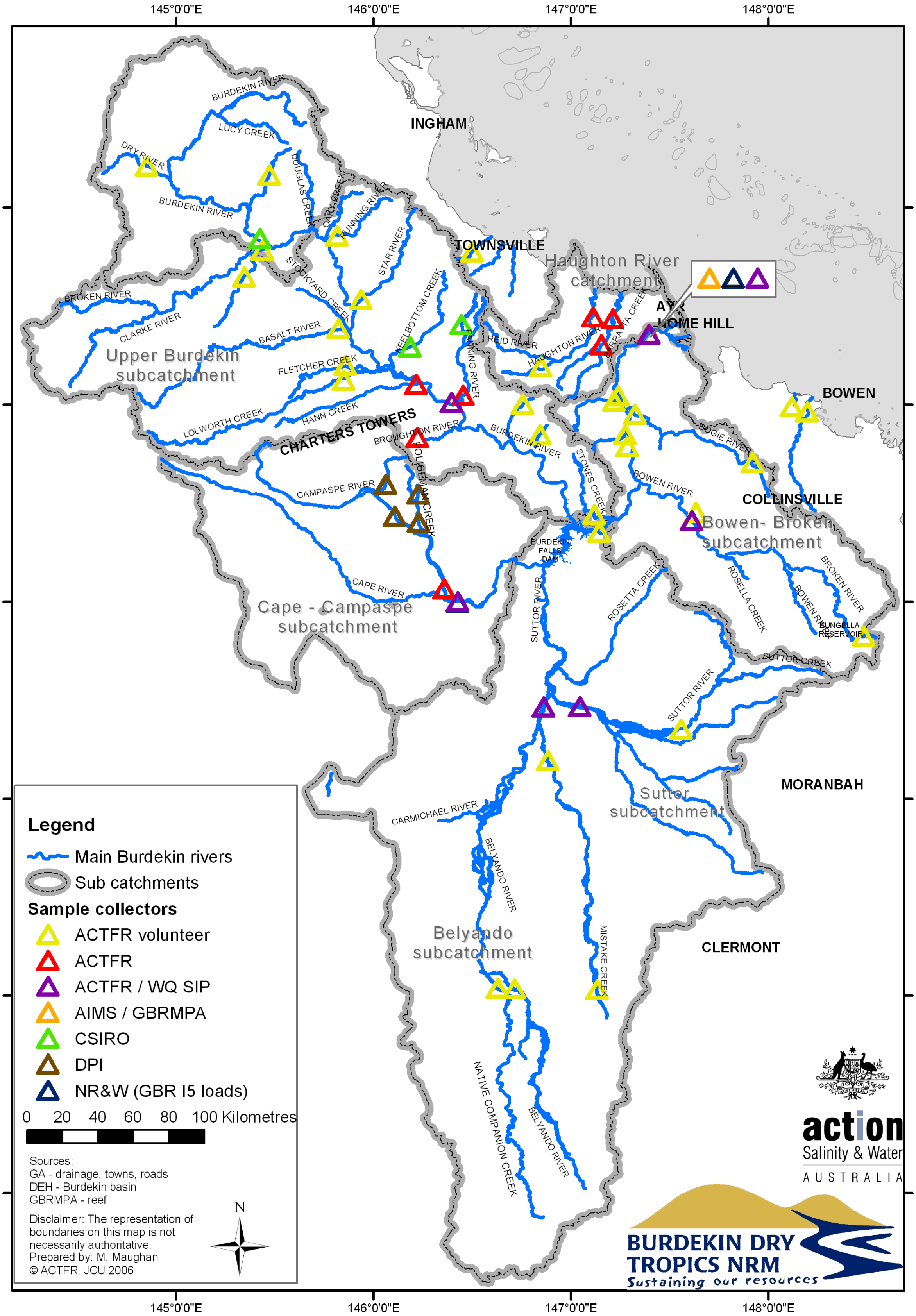

Figure 4: Sampling sites during the 2006/2007 Wet Season.

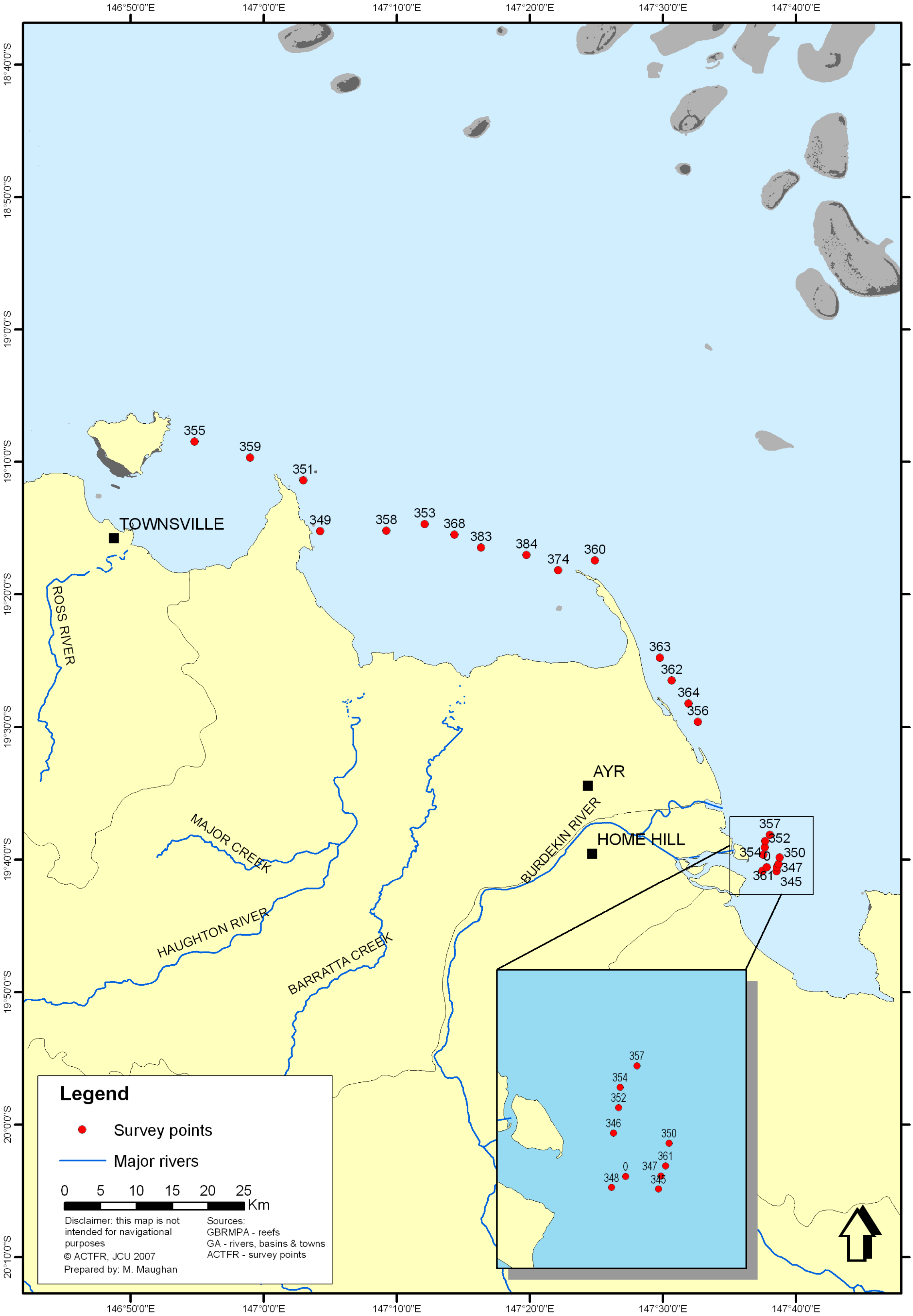

Figure 5: Map of water quality samples taken from the Burdekin River freshwater plume on the 6-7 February 2007.

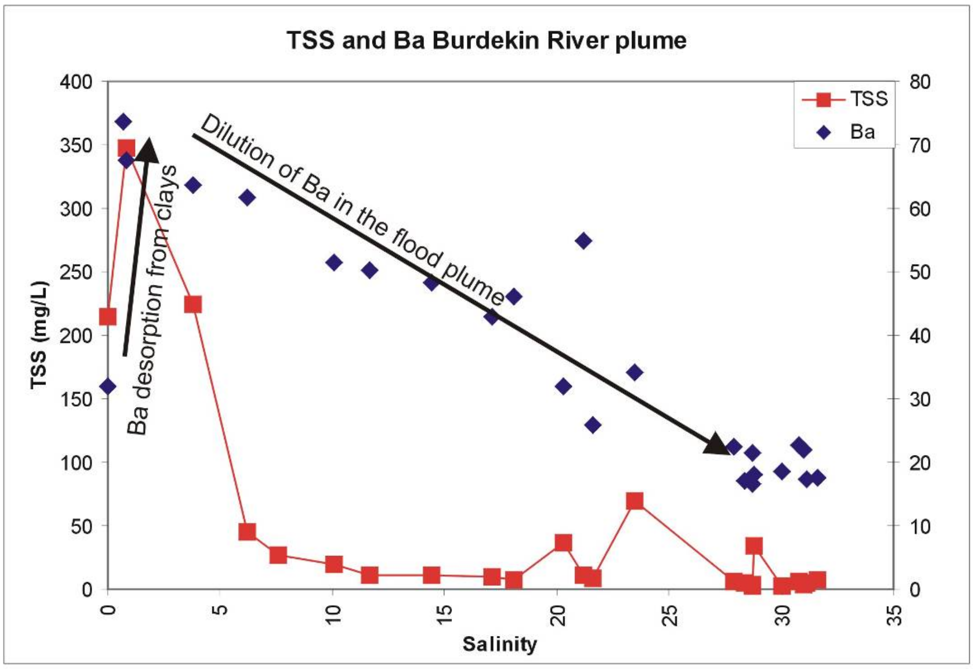

Figure 6: Graph of total suspended solids (TSS) and barium (Ba) concentrations over the salinity gradient in the Burdekin River flood plume. The data show that TSS concentrations decrease rapidly in the flood plume by the 10 ppt salinity zone where the majority of sediments have settled out in the plume. The Ba concentration follows a considerably different trend where Ba becomes desorbed from clays at low salinities and is then slowly diluted as the plume mixes with seawater. This trend supports the coral Ba/Ca proxy of sediment delivery to the GBR lagoon.

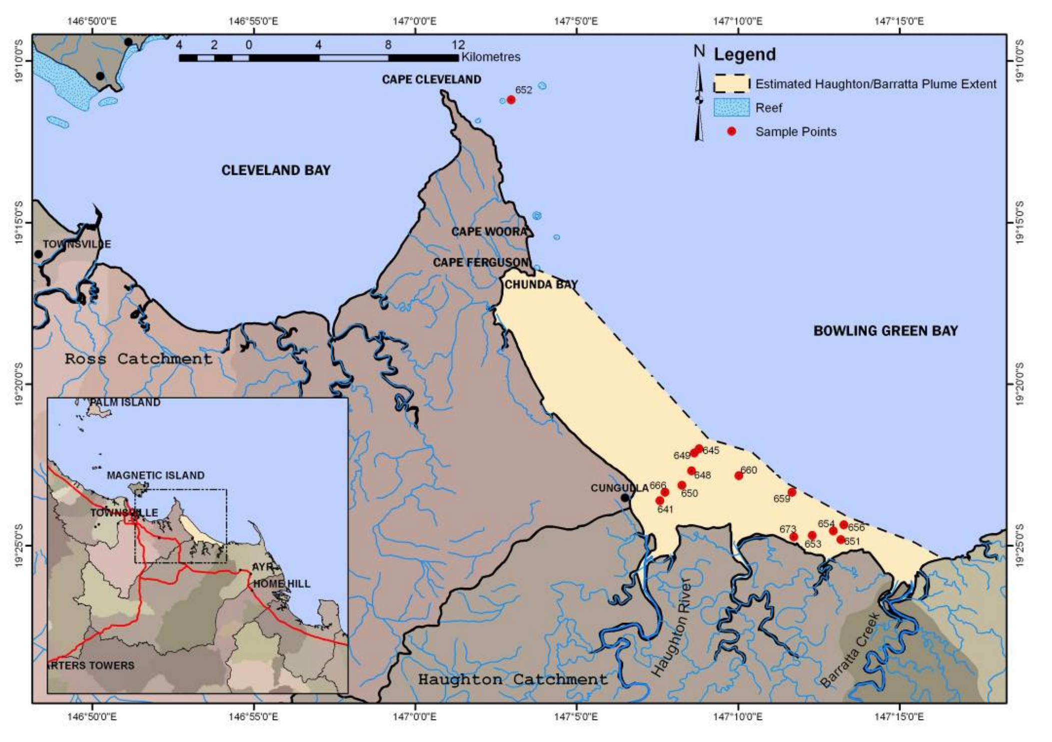

Figure 7: Map of sampling points for the Haughton River and Barratta Creek flood plume. The dotted line represents the estimated extent (by both visual and some GPS points) of the plume on the day (3 February 2007).

Output: Tracing of materials in the marine environment (ANU).

The key tasks for this objective are to:

- Examine historical changes in the delivery of terrestrial materials from the major river systems in the Townsville-Cairns region to the marine environment using coral and sediment cores;
- Characterise and obtain a distinct 'fingerprint' of the fine sediments (mud fraction) in the marine environment using their isotopic and elemental properties and to link these to the sediment sources of the major terrestrial catchments;
- Determine the transport mechanism, residence time and fate of terrigenous sediments in the inshore as well as mid-reef regions of the Great Barrier Reef; and
- Develop and apply new cutting-edge technologies to specifically trace the pathways of the key nutrient elements phosphorus and nitrogen from the terrestrial catchments, through estuaries, inshore coastal zones to the mid-reef of the Great Barrier Reef.

Townsville/Cairns Region

Due to the widespread flood plumes generated from the large wet season of February-March 2007, collection of additional coral cores in the region will be delayed until November 2007. This delay is required to allow for the incorporation of the latest flood signals into the coral skeletal record. However, a long coral core collected from Magnetic Island (collected 2002) was analysed (Figure 8). Lewis *et al.* (2007b) reported increased Ba/Ca and Manganese (Mn) concentrations since European settlement in the Burdekin River catchment (>1850s) in a long coral core record from Magnetic Island, although this analysis was performed at 2 yearly resolution. This new analysis was able to obtain a much higher resolution (~ two-weekly) made possible by the laser ablation ICP-MS machine. The coral shows historical changes in water quality in freshwater plumes from the Burdekin River and possibly local catchments which reflects changes in bulk sediment and top soil erosion in these catchments. The data support the findings of McCulloch *et al*. (2003a) for the Havannah Island coral Ba/Ca record. In addition, a coral record from Whitsunday Island was also analysed by LA-ICP-MS in March 2007. Results from this analysis are being processed.

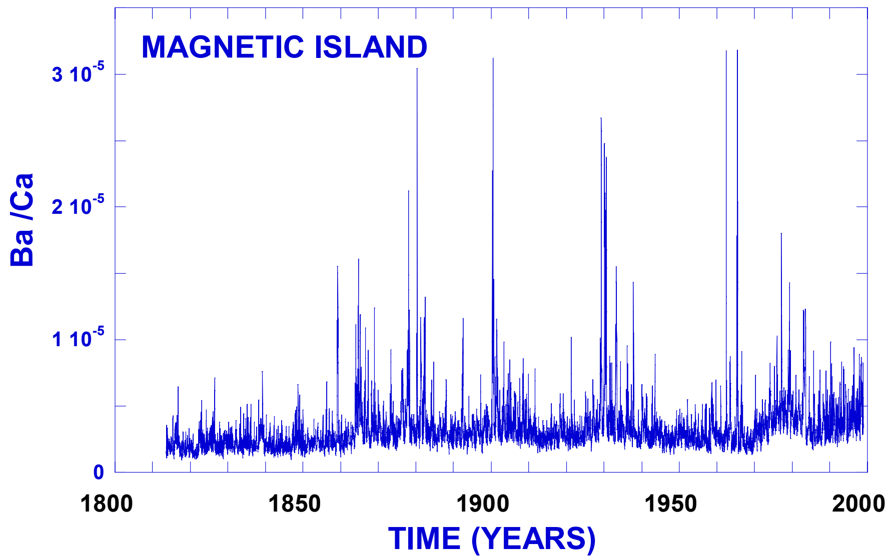

Figure 8: LA-ICP-MS Ba/Ca analysis of a Magnetic Island coral record supports the Havannah Island Ba/Ca (McCulloch *et al.,* 2003a) of increased sediment erosion in the Burdekin River catchment since European settlement in the 1850s.

Mackay-Whitsunday Region

This component of the project aims to investigate changes in water quality over the last 150 years using coral cores along a water quality gradient in the Mackay-Whitsunday region. Luminescent lines (flood bands) from two short coral cores (last thirty to forty years, ~1970-2005) and from one long coral core (1816-1991) from Whitsunday Island (one hundred samples in total) will be sampled for trace elements (Ba, Mn, Y, Th, Ca, rare earth elements: REE) and isotopes (O and N) to quantify changes in sediment and nutrient runoff since European settlement and the geographical extent of influence of such changes. Samples of flood plume water analysed for trace elements and phytoplankton composition.

Two short coral cores (~1960-2005) and one long core (~1816-1992) from Whitsunday Island were selected for laser ablation ICP-MS analysis at AIMS. The samples were prepared and one short core and the long core were analysed at ANU, Canberra in March 2007. Preliminary results show an annual temperature signature in the coral with Sr/Ca and U/Ca ratios (Figure 9).

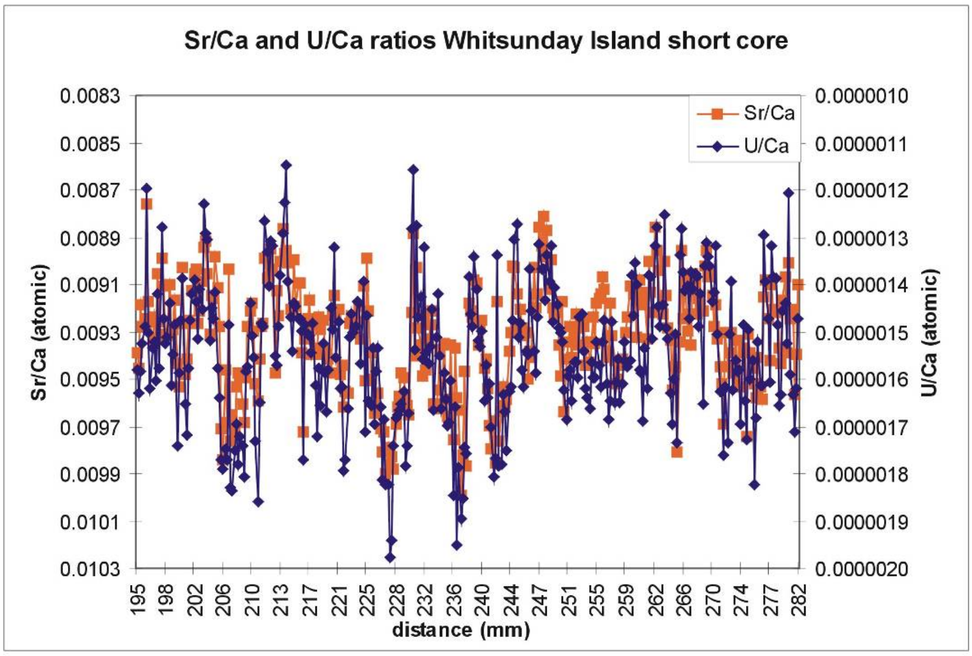

Figure 9: Sr/Ca and U/Ca ratios from the Whitsunday Island short core (W-34) collected by AIMS in 2005. This dataset shows approximately 10 years of growth. The Sr/Ca and U/Ca thermometers display excellent agreement which allows a robust chronology to be developed within the coral core.

Output: Inshore-offshore sediment transport in the Wet Tropics (AIMS).

See: Wolandski, E., Fabricius, K., Cooper, T. and Humphrey, C. (2007) Wet season fine sediment dynamics on the inner shelf of the Great Barrier Reef. *Journal of Estuarine, Coastal and Shelf Science* 77(4): 755-762.

The purpose of this task is to determine the existence of a nepheloid layer able to transport fine particulate matter (containing nutrients) from inshore to offshore in the Wet Tropics section of the GBR lagoon. Sediment transport mechanisms within the reef will be studied using arrays of nephelometers, sediment traps and current meters off the Tully and Johnstone rivers including Dunk and High Islands, and extending arrays out longshore and into the midshelf. These will be deployed for one month each in the wet and dry season over two years. The existence of a nepheloid layer to assist offshore transport of nutrients associated with the fine particles, longshore transport in relation to wind-waves and currents, facilitation resuspension and deposition events etc will be assessed. This work will be integrated with work on coral cores from the same region as well as the isotope tracing of the sediment sources.

Fine sediment dynamics were recorded in the coastal area off Tully River, North Queensland, during a moderate flood event in February 2007 (Figure 10). An estuarine circulation prevailed on the inner continental shelf with a surface seaward velocity peaking at 0.1 m s^{-1} and a near-bottom landward flow peaking at 0.05 m s^{-1}. Much of the riverine mud originating from eroding soils was exported onto the shelf during the rising stage of the flood in the first flush. Suspended sediment concentration during the river flood peaked at 0.2 kg m^{-3} near the surface and 0.4 kg m^{-3} at 10 m depth in coastal waters during calm weather. Particles settled onto the seafloor and some nearby inshore coral reefs, with rates of sedimentation averaging 254 ± 33 g m-2 d^{-1} during the study period. The deposited mud together with old seafloor sediments was resuspended during subsequent storms, resulting in suspended sediment concentrations of 0.5 kg m^{-3} near the surface and 2 kg m^{-3} at 10 m depth. During this time, diurnal irradiance dropped to almost zero for ten days during and after the flood, suppressing photosynthesis.

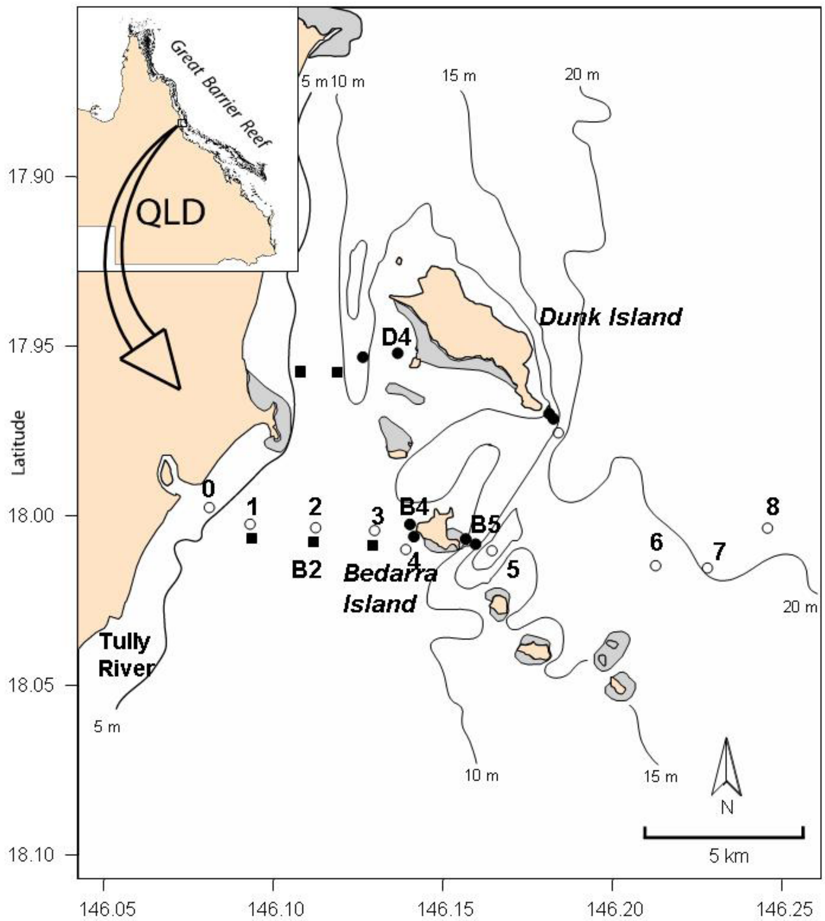

Figure 10: Map of the study area showing the bathymetry and the location of the CTD casts (○) and of the oceanographic moorings on the inner shelf (■) and on the islands' slopes (●).

As sketched in Figure 11, river plumes deposited mud directly all over the inner shelf of the GBR, including coral reefs ten kilometres offshore during the early rising stage of the river flood, as a result of the first flush of eroded soil from the river catchment. Deposition rates were larger inshore than offshore. This mud was later resuspended by wind-driven waves and redistributed by advection and diffusion due to strong longshore and cross-shore currents to a distance of at least twenty kilometres offshore. The mud deposited below the resuspension depth, which is about twelve metres in open waters and three metres in sheltered waters, may remain on the bottom except if shifted by cyclonic waves. Strong wind events will resuspend the mud above this resuspension depth and maintain high turbidity over coral reefs until all that mud has been advected away or deposited in deeper waters. This sedimentation occurs during the wet season, which is also when juvenile corals have just settled on the substratum, and these juveniles are particularly susceptible to sedimentation (Fabricius *et al*. 2003).

During such events, that lasted ten days during our study, the high SSC values (0.5 kg m^{-3} in surface waters and 2 kg m^{-3} at 10 m depth) shut off all sunlight at a few metres depth. Such sedimentation has detrimental effects on the ecological integrity and diversity of inshore coral reefs. The implication is that GBR coral reef ecosystems effectively extend into adjacent watersheds, and their conservation in Marine Protected Areas will fail without a decrease of soil erosion in the adjoining river catchment coupled with the creation of terrestrial protected areas to act as buffer zones (Richmond *et al.* 2007).

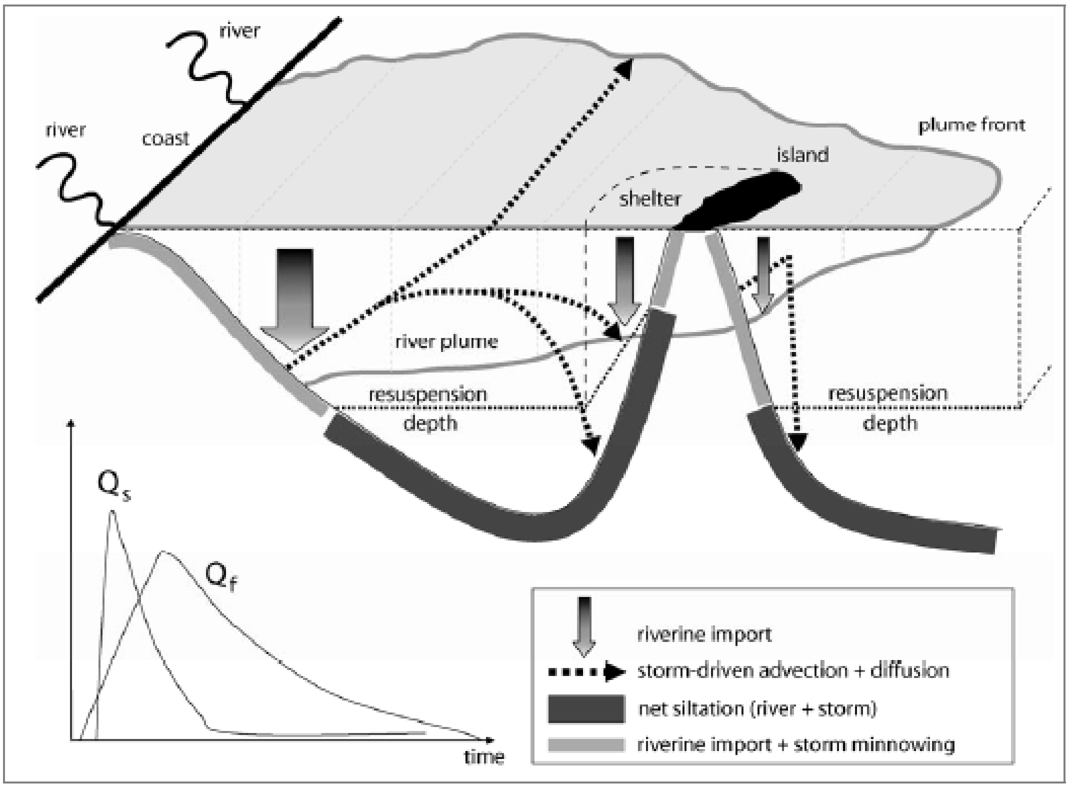

Figure 11: Sketch of the dynamics of river and fine sediment in the transient river plume, highlighting mud deposition during the first flush Qs of eroded soil from the catchment during the rise in the river flood Qf during calm weather, the spread of river plumes, the resuspension and minnowing of that mud during storms and its spread in a wide area of the inner shelf, the preferential settling of that sediment below the resuspended depth, and the accumulation of sediment higher up in the water column in the shelter zone in the lee of islands and reefs.

By comparing the results of this study at a scale of twenty kilometres as sketched in Figure 11, with that of Wolanski *et al*. (2003a) of the fate of mud in small embayments at scales of a few hundreds of metres, the processes are similar in both systems and the impact on coral reefs is similar. In both systems the riverine mud is initially distributed inshore by river plumes and then re-distributed over the whole coral reef ecosystem by waves and currents. During that redistribution process some of that sediment is flushed out. The key question for coral survival is the net sediment budget, i.e. whether the yearly loss of sediment by oceanographic processes exceeds the yearly gain of sediment by river inflow (Richmond *et al*. 2007). The larger size of the GBR thus is not the savior of its coral reefs on the inner shelf.

The fate of mud on the GBR inner shelf at scale of twenty kilometres appears to be also similar to that of the fate of mud in mangrove swamps at a scale of a few meters to tens of meters (Furukawa *et al.* 1997). In mangrove swamps the mud is trapped in shelter zones behind trees while in the GBR the mud is trapped in shelter zones behind islands and reefs (Figure 11).

In mangrove swamps the freshly deposited sediment is reworked and redistributed by bioturbation while in the GBR is reworked and redistributed by waves. The ultimate result, i.e. the spread of the mud over the whole ecosystem, is the same in both systems.

While the mud may ultimately be minnowed out, this flushing occurs at time scales much longer than the flood event, therefore harming the coral for long periods after the flood has subsided. Such events can be lethal to some juvenile corals. The conservation of coral reefs on the inner shelf of the Great Barrier Reef is not possible without proper catchment management.

Output: Floodplain sedimentation dynamics in Dry Tropics catchments; study preparations (UNSW@ADFA)

The key tasks for this objective are:

- Identify catchment choke points in the FRC and quantify the rate and temporal patterns of sediment and contaminant storage in these zones using field data and GIS modelling.
- Determine the relationship between sediment storage in these sinks with recent changes in landuse history or management practices.
- Compare field measurements of floodplain sedimentation and storage with those predicted by catchment scale sediment transport models such as SedNet.

In an attempt to better understand the dynamics of sediment transport and delivery in Queensland's coastal catchments, an analysis of catchment choke points or major within-valley constrictions commenced in the Fitzroy River catchment, where valley width reduces dramatically relative to the upstream reaches. In some of these bottlenecks, channel pattern upstream and downstream of the bottleneck is notably different, with a propensity for change from multi-channel anabranching to single meandering.

The field work program commenced in the latter half of 2006 involving a drilling and detailed surveying program of one representative choke point on the Nogoa River subcatchment (Figure 12). The location of survey transects and drill holes are marked. The analysis of theses data for sedimentological, radionuclide and chronological data will form the focus of future research.

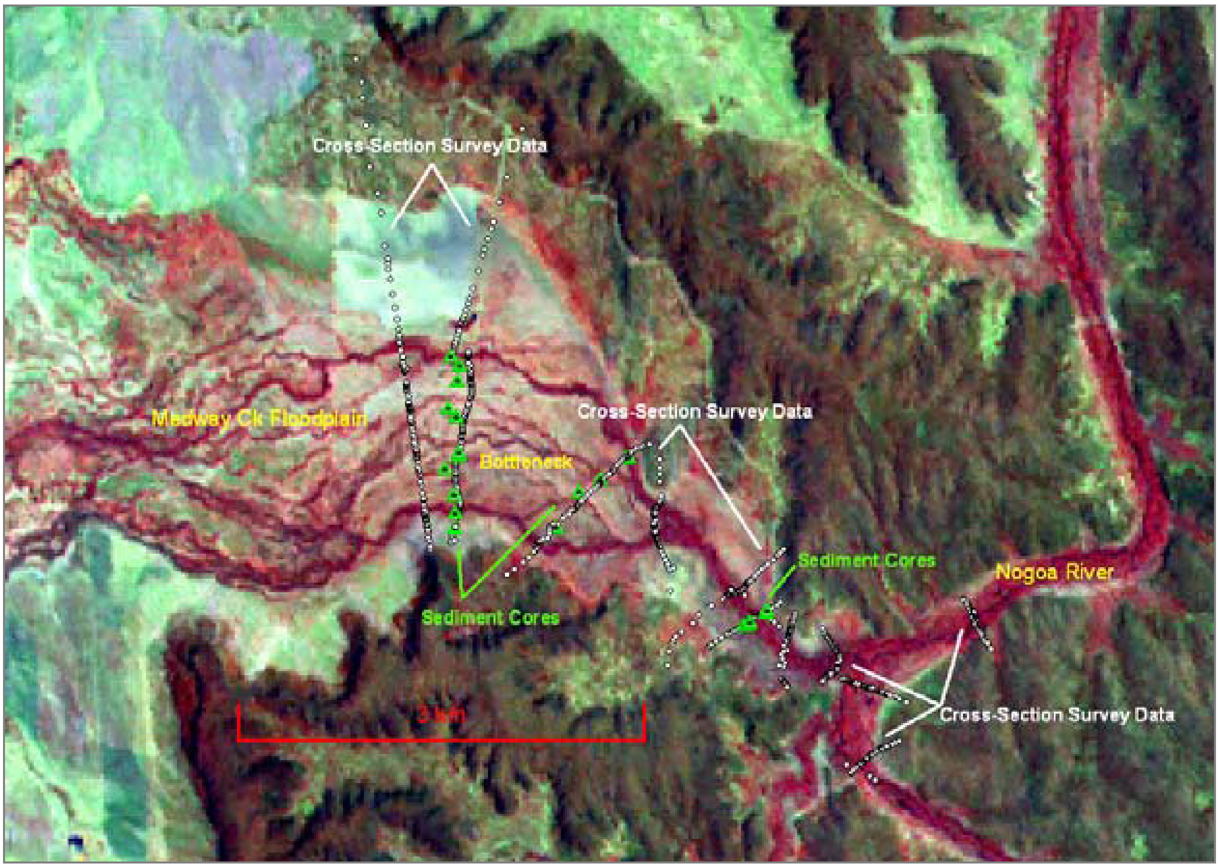

Figure 12: Satellite image of a representative choke point on Medway Creek, a major tributary of the Nagoa River in the Fitzroy Basin. Shown are the locations of survey transects and the location of shallow drill cores.

Project 3.7.3 Freshwater Indicators and Thresholds of Concern

Project Leader and Host Organisation: Professors R. Pearson and A. Arthington, JCU and GU (with CSIRO)

The goal of this project is to develop conceptual biophysical models based on previous work to identify, (i) appropriate indicators of waterway health; and (ii) probable thresholds of concern, in terms of contaminant concentrations, ecological processes and biodiversity in freshwater environments. The indicators will be tested in waterways in the Wet and the Dry tropics, so that they can be implemented in fully functional monitoring systems, for example, as part of the Reef Water Quality Report Card. The work will build on the *Catchment to Reef* Joint CRC Program, which has concentrated on sampling protocols and design, and has generated improved understanding of the requirements of an indicator system. This project will fully develop that indicator system, and provide methods for monitoring for a range of user groups.

Key Objectives:

- Conduct field, laboratory and desk-top research to develop physical, chemical and ecological indicators of freshwater ecosystem health in the Wet and Dry Tropics as part of an integrated reporting product that meets end-user needs and objectives;

- Identify thresholds of potential concern relating to land use, water quality, riparian condition, habitat and food web structure in freshwater ecosystems of the Wet and Dry Tropics;
- Develop an interactive Web database documenting the distribution and ecological requirements of freshwater biota in the Wet and Dry Tropics, to assist river health assessments and inform a range of end users;
- Train new researchers via PhD programs that will be integral to the identification and testing of efficient and effective freshwater condition indicators in the Wet and Dry tropics; and
- Provide monitoring methods, manuals and guidelines of relevance to a range of skills and end users.

Summary of Outputs for Project 3.7.3

The outputs for Year 1 of this project are integrated with the completion of a number of tasks that were initiated through the *Catchment to Reef* Joint CRC Program. Accordingly, an overview of those products that are specifically relevant to the objectives of this MTSRF project is provided below.

Output: Report on the status and trends of water quality and ecosystem health of fresh waters in the Wet Tropics (JCU, GU)

See: Connolly, N., Butler, B., Pearson, R. and Arthington, A. (2007) *Status and trends of water quality and ecosystem health of fresh waters in the Wet Tropics.*

This document aims to review the nature of the waterways, their environs and the factors influencing them, and that they influence, in the Wet Tropics bioregion (incorporating the Wet Tropics World Heritage Area) as a preliminary to investigating the status and trends of aquatic ecosystem health. The review of the current understanding is near completion; the quantitative status and trends section is yet to be completed.

With regard to assessing status and trends, it is important, (i) to clarify the processes that influence past, current and future water quality, (ii) to outline the influence of water quality on species and communities of microbes, plants and animals, (iii) the converse – to describe the influence of organisms themselves on water quality; and (iv) to be clear that the traditional view of water quality (i.e. materials dissolved and suspended in the water column) is blinkered as it ignores other facets of waterway heath, including assessment of sediment constituents (e.g. they often supply copious nutrients that are not available in the water column), and habitat quality (flow, temperature and light environments, plant abundance, weeds, riparian quality, etc). Without a holistic appraisal of all these factors, many of which are routinely missed in water quality assessments, entirely false interpretations of conditions (status and trends) may be made. This (draft) document provides an outline of these issues that must underpin the development of concepts and reports on status and trends in ecosystems health, and provides a preliminary status and trends overview.

The report indicates that there is a distinct contrast between the upland forest streams in the Wet Tropics World Heritage Area, in which water quality is relatively pristine, and the streams and wetlands of the tablelands and lowland floodplains which in many cases are severely affected by agriculture, infrastructure, urbanisation, and industry (Figure 13). For example, riverine lagoons and channelised waterways in the Herbert floodplain show strong negative influences of inputs of organic matter and nutrients, as well as poor quality of the riparian systems. Together these factors have caused or enhanced weed invasion, hypoxia and depleted fauna. Some of the fast flowing streams of the Russell-Mulgrave system have suffered similar impacts, although hypoxia is not a problem because of the turbulent water.

In Babinda Creek, for example, much of the natural riparian vegetation is missing, and is replaced by weeds, which offer little shade to the stream and little in the way of normal organic input. On the other hand, nearby Behana Creek (a tributary of the Mulgrave River), also flowing through a sugarcane growing area, has intact riparian zone, mostly good water quality, and a rich fauna (despite the fact that much of its flow is diverted to supply Cairns city). The status of waterways is, therefore, mixed. A complete inventory is not possible, but it will be feasible to document a range of examples such as these, potentially providing benchmarks against which to assess future change.

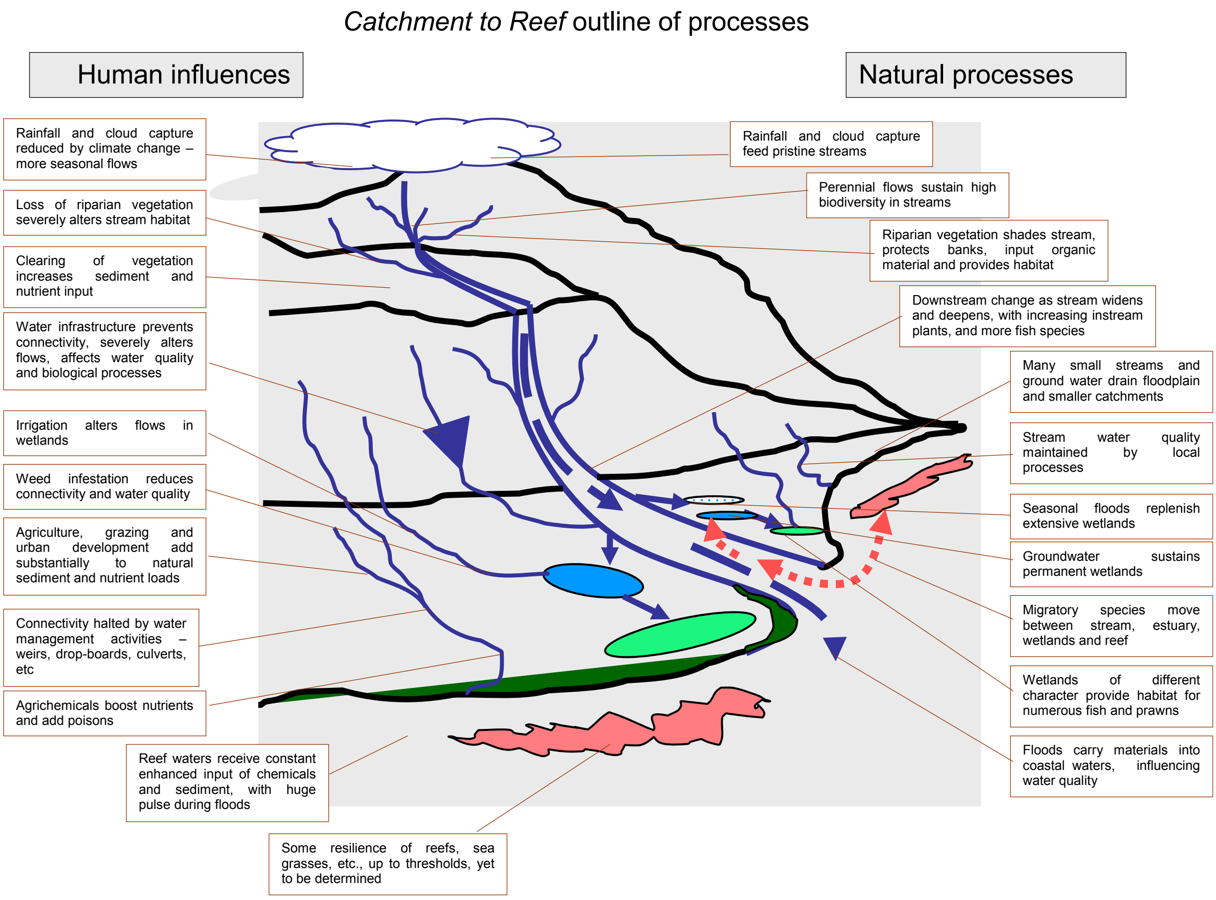

Figure 13: Outline of catchment to reef processes.

Explicit assessment of trends requires two or more assessments of status at any place, and as suggested above, these are mostly unavailable. The Reef Plan implicitly indicated that there has been a downward trend in ecosystem health in its mission to ‘halt and reverse the decline’ in water quality in GBR catchments. Long-term data sets of export from rivers of nutrients support the notion of a ‘decline’, although these sort of end-of-river data do not directly relate to health in the streams themselves. Data on the biota of most systems will be anecdotal because even where detailed sampling has been undertaken, it usually has not been repeated. In addition, changes and ‘trends’ do occur naturally and need documenting to pride a benchmark for human-induced trends.

There is no doubt that trends habitat extent and quality have been downwards across many catchments in the Wet Tropics. While upland forest streams are quite well protected, and have suffered least, lowland systems have suffered decline in extent (up to 75% loss of wetlands in some catchments), in the vegetation cover of their catchments and in their riparian cover. Meanwhile they now receive run-off and through-flow from agriculture, with elevated levels of sediment, nutrients and organic material, as well as pesticides and other chemicals. Further, they have been invaded by noxious riparian and aquatic weeds. It is not surprising, then, that some streams and lagoons support only a fraction of what would be a normal biota, and that fish kills occur all too often (although fish kills can happen as a result of natural processes too). What is surprising is that some systems still sustain a diverse fauna – for example, the Mulgrave River has a diverse fish fauna, including several endemic elements. Clearly the fauna can be quite resilient – and it can bounce back after devastation by very poor conditions, as has been demonstrated in the Burdekin floodplain following weed removal: the diversity of fish species jumped from two to sixteen in only a few months.

Such recovery from disturbance is a healthy trend, but it does depend on there being suitable refuge areas to sustain species through the times of greatest disturbance.

Further assessment of status and trend information for waterways of the Wet Tropics will be an ongoing need for managers and requires long term monitoring efforts in addition to supporting modelling tools to predict the influence of various management actions on river waterway health.

Output: Report on Catchment to Reef River Health for Wet Tropics rivers in the GBR catchments (JCU, GU)

See: Arthington, A. and Pearson, R. G. (eds.) (2007) *Biological Indicators of Ecosystem Health in Wet Tropics Streams*. James Cook University, Townsville (247pp.)

The *Catchment to Reef* program aimed to develop appropriate monitoring methods for water quality and ecosystem health in aquatic ecosystems in the Wet Tropics and GBR World Heritage Areas. The three-year program was seen as an essential step towards minimising the downstream effects of agriculture and improving the ecosystem health of the GBR lagoon and its feeder catchments. Its goal was to provide a sound scientific basis for the development of monitoring tools, protocols and guidelines appropriate to the Wet Tropics. The research plan addressed this goal via seven tasks that encompassed the concept of a continuum of processes from catchment source to sea. The individual tasks represented themes that were closely interlinked and overlapped operationally, derived from and extending Rainforest CRC and CRC Reef research. This report presents the results of the research undertaken in *Catchment to Reef Task 3 – River Health Assessment Tools*.

The research was designed to explore the concept of river health and to represent it as an integrated suite of protocols and techniques for biological river health assessment in Wet Tropics streams. The ultimate goal was the adoption of the methodology by relevant agencies and persons responsible for or interested in ecosystem health monitoring. This report represents the technical output of this research. A manual detailing protocols and techniques for river health assessment in Wet Tropics waterways, based on this research, will be produced through the MTSRF program.

The study sought to investigate the chain of influence from land-use to stream ecosystem response, via the response of individual ecosystem components, to understand how these influences operate and to underpin the development of monitoring tools and guidelines appropriate to the streams of the Wet Tropics (and eventually to other GBR and tropical catchments). It compiles accumulated knowledge of the ecology of Wet Tropics streams. The study fills a gap in the understanding of these streams and provides empirical relationships that will enable utilisation of existing broad-scale datasets to provide a wider geographic context for the findings of the study and allow greater generalisation of the results. It is also the first coordinated investigation of Wet Tropics streams where a variety of ecosystem components (geomorphology, water quality, aquatic and riparian vegetation, invertebrates and fish) have been surveyed simultaneously at a large number of sites to describe natural gradients and to determine the effects of land-use and related stressors. The results provide a much needed benchmark description of the aquatic biota and environmental characteristics of these systems. The study also provides strong evidence of cause-and-effect relationships between natural biophysical variables and stressor variables representing land-use patterns and effects in tropical catchments.

The report comprises six chapters:

1. Introduction: The Catchment to Reef Program and Stream Health Monitoring

This chapter provides an introduction to the study and outlines the concept of stream ecosystem health and describes the study design. The study area is the Wet Tropics World Heritage Area, with case studies in the Russell-Mulgrave catchment (Figure 14).

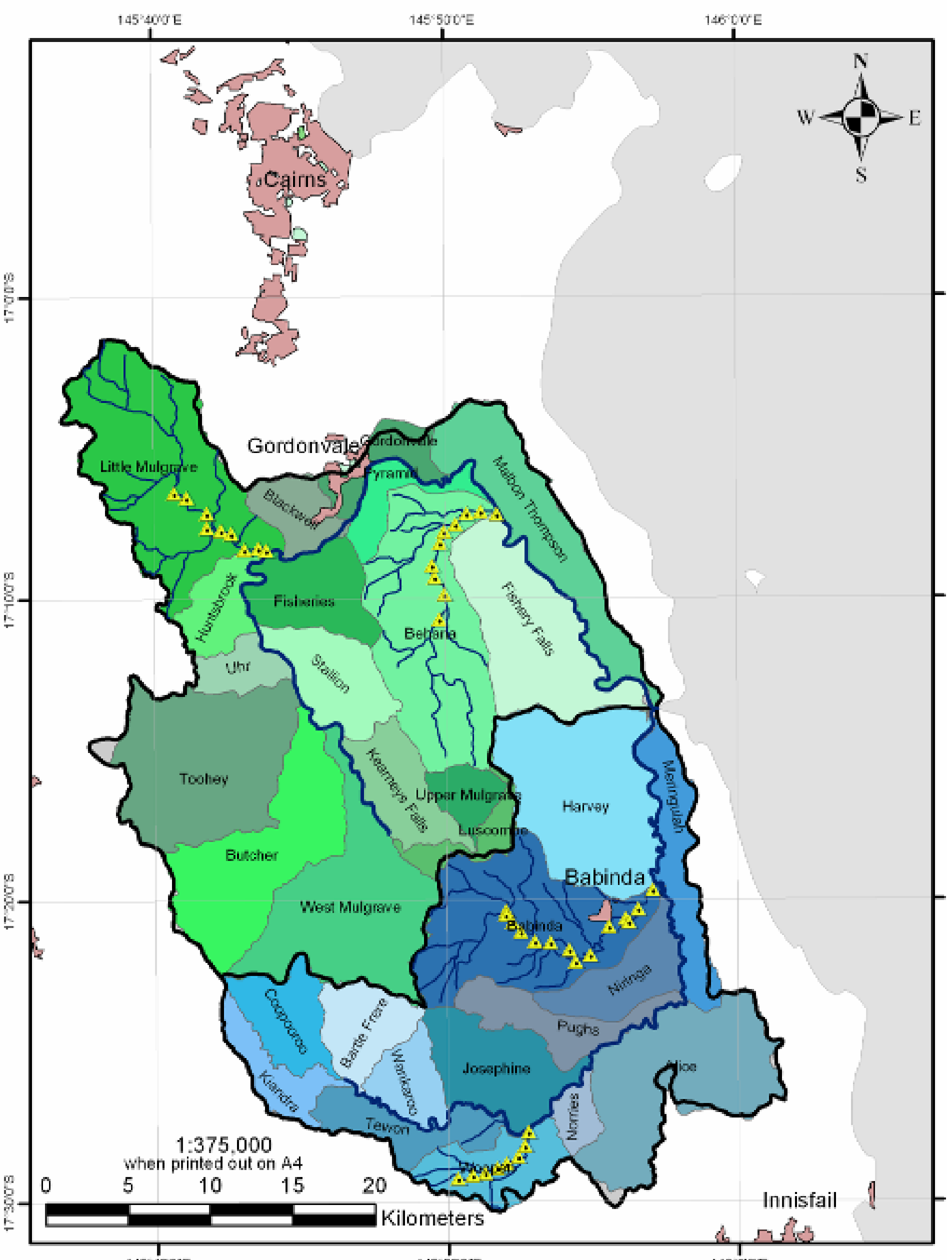

Figure 14: Russell-Mulgrave sub-catchments.
Study sites are indicated by yellow triangles.

2. *Hydrology, geomorphology and water quality in four Wet Tropics streams with contrasting land-use management*

The purpose of this component of the study was to provide a background physico-chemical description of the Russell-Mulgrave catchment and four case study streams (Little Mulgrave River and Behana Creek in the Mulgrave River catchment, and Babinda Creek and Woopen Creek in the Russell River catchment – Figure 13) and provide an assessment of the types and extent of physico-chemical disturbances, to support the analyses of biotic distributions described in subsequent chapters. This report, therefore, provides a detailed description of the study streams but is only preliminary in that it only touches on some of the physico-chemical processes that are operating in these systems.

The descriptions provided in the report offer a sound basis for comparing biological attributes among streams. They clearly demonstrate downstream gradients in several characteristics of the study streams, including stream power, substrata type, temperature, conductivity and nutrient concentrations. These gradients were consistent with the hydrogeomorphology of the streams and the influence of agriculture on them. Contrasts between streams, in particular, indicated strong land-use influences. How these relate to the biota of the streams is dealt with in the following chapters. But it seems very likely that the detailed approach to stream descriptions will be vital in disentangling potential influences on the ecological integrity of the streams. This approach would clearly benefit any future health assessment of streams in the region and elsewhere.

3. *Aquatic macrophytes as indicators of catchment land-use management and water quality in Wet Tropics streams*

This component presents an assessment of the use of aquatic macrophytes as indicators of catchment land use and riparian disturbance in the Wet Tropics region of North Queensland. Macrophyte assemblages are described in terms of assemblage composition (species presence-absence and abundance) and assemblage metrics (univariate summary statistics of assemblage attributes). The influence of hydraulic habitat on macrophyte assemblage patterns observed over catchment land-use and riparian disturbance gradients is also investigated. The study sites are those identified in Chapter 2.

The study concluded that the key macrophyte assemblages identified in the Wet Tropics region have limited applicability as direct indicators of catchment land use (over the land-use gradient surveyed). While each assemblage type was associated with different land-use categories, all assemblage types were arrayed over a gradient of riparian canopy cover and riparian condition. Riparian canopy cover and condition scores were negatively correlated with the proportions of anthropogenic land uses. This suggests that riparian restoration itself would restore aquatic macrophyte assemblages in disturbed streams such as Babinda and Woopen Creeks to a 'pre-disturbance' state. Thus, in terms of the metrics presented here, riparian restoration alone would be expected to have significant benefits for aquatic macrophyte assemblages in the Wet Tropics region, independent of any land-use impacts. Consequently, it is evident that a riparian condition assessment would provide an adequate indication of the state of aquatic macrophyte assemblages in Wet Tropics, based on the range of metrics presented. Hydraulic habitat was also an important determinant of macrophyte assemblage structure.

Three assemblage metrics have promise as indicators of riparian disturbance in the Wet Tropics region. However, their utility as indicators of catchment land use *per se* appears limited. These metrics were therefore either poor descriptors of assemblage structure, or were not strongly influenced by catchment land use or water quality. Simultaneous autoregressive models for all metrics included riparian condition as a significant predictor, with water quality and land-use descriptors poor predictors. The results suggest that maintenance or restoration of riparian zones would be the most successful approach to maintain aquatic macrophyte assemblages in Wet Tropics streams in a relatively intact state.

4. Macroinvertebrates as indicators of ecosystem health in Wet Tropics streams

This component was undertaken to describe the patterns of macroinvertebrate distributions in selected lowland streams of the Wet Tropics and to obtain baseline data that could be used to develop predictive models of macroinvertebrate composition. It aimed to associate the response of macroinvertebrate assemblages to the physico-chemical environment and anthropogenic disturbance in these streams, and to determine methodologies for surveying macroinvertebrates to monitor these impacts. How the macroinvertebrate assemblages were affected by variations in riparian vegetation and land-use practices was determined by contrasting sites that differed in a variety of bio-physical characteristics.

The results showed clear patterns of macroinvertebrate distributions in the streams surveyed because of the strong gradient in substratum particle sizes along each stream and differences in particle sizes between streams. The macroinvertebrate assemblages were useful in classifying the streams into upper, middle and lower reaches and demonstrated a consistent longitudinal gradient of assemblage structure. The consistency of these patterns enabled comparisons between streams using analysis of covariance and this proved to be a robust approach in detecting differences between streams. Many samples were taken across gradients – an approach that proved to be very successful, and were demonstrated to be of high utility in developing monitoring protocols. However, testing of indices and sample size demonstrated that to detect differences there was a trade-off in the amount of detail and effort applied at the site scale and the number of sites used in comparisons. Understanding this trade-off is valuable in that effort can be concentrated to suit individual constraints. Nevertheless, site selection will be critical to avoid confounding effects and will depend on prior knowledge of the macroinvertebrate distributions or require a pilot study.

Results describing the impacts of the loss of riparian vegetation and coarse particulate organic matter provide further evidence of the importance of riparian vegetation. However, the conclusions are tentative because the results have not been replicated in the catchments, and there is a need for similar surveys to be carried out in different catchments to generalise the conclusions. Moreover, further surveys should encompass other types and degrees of impact to test our approach across different levels of disturbance. Nonetheless, the results showing that riparian vegetation is a key determinant in maintaining instream diversity is encouraging, as this is the most common remediation currently being applied in these streams and the results confirm that maintaining and rehabilitating riparian vegetation is a beneficial activity.

The efficacy of different monitoring indices was demonstrated, with species richness being the most promising index, although identification at a higher taxonomic level (i.e. family) was still more effective than using the commonly adopted 'Stream Invertebrate Grade Number – Average Level' (SIGNAL) index. This highlights the need to test indices under the situations in which they are to be applied, and to ensure that appropriate measures are being used to answer the management questions.

5. Freshwater fish as indicators of ecosystem health in Wet Tropics streams

This component evaluated the extent to which present day agricultural practices and other anthropogenic stresses have an impact on stream fish in four sub-catchments of the Russell-Mulgrave river basin. The study involved a paired catchment comparison, with two streams sampled in both the Russell and Mulgrave catchments. The aim was to investigate the effects, if any, of contrasting land use and management practices in the two catchments, using both a comparative and referential approach to this question.

The relationships uncovered in this study, using analyses of factors affecting observed versus expected fish assemblage structure, all point to the value of using fish as indicators of stream degradation resulting from catchment land use and riparian degradation. Fish assemblages in Wet Tropics streams were particularly responsive to the effects of degraded riparian systems on stream habitat structure, especially aspects of habitat (e.g. velocity) related to the presence and abundance of aquatic macrophytes, including alien species such as para grass and Singapore Daisy. The presence and abundance of alien fish species were also correlated with altered habitat conditions, and were most prevalent and abundant in catchments with a high proportion of land use devoted to sugar cane production and urbanisation.

The study demonstrated that modifications to the riparian zone of Wet Tropics streams can have major implications for the maintenance of their ecological health. Of particular concern in the Wet Tropics region is that introduced ponded pasture grasses such as para grass and other alien weeds are encouraged by the altered light environment and favourable temperature and water regimes. The riparian zone also helps to stabilise bank-associated structures such as undercuts whilst simultaneously providing complexity to the aquatic habitat in the form of root masses, woody debris and leaf litter. In addition, the fruits of riparian trees and the insects that feed in and on riparian foliage are important to aquatic food webs, particularly in the Wet Tropics region. Clearly, the riparian zone is very important in maintaining the health of these stream ecosystems.

The next steps in advancing towards a routine monitoring program for stream ecosystem health in the Wet Tropics should be to explore the use of various methods and tools designed to evaluate the condition of riparian vegetation systems. This investigation should evaluate the utility of a range of condition metrics, and progress towards the development of rapid assessment methods based on remote sensing techniques, ground-truthed against actual riparian condition. Following this, it is suggested that relationships between remotely sensed and ground measures of riparian condition and fish assemblage structure be further explored in a wider range of tropical catchments. Linked to this, further work is recommended on the factors and processes that underpin the observed effects of riparian degradation and aquatic macrophyte proliferation on stream fish assemblages, including effects on alien species. These process studies should include examination of food web structure and how riparian degradation may alter sources of carbon and food web dynamics, and the effects of riparian modification on fish habitat structure, movement requirements and life history processes.

A final research theme should be to establish thresholds of ecological response to land-use stress, such that the degree of modification of riparian vegetation, and other factors, that endanger stream health can be identified before the stream ecosystem reaches a critical level of deterioration. The development of quantitative stressor-response relationships should be the major advance in the next phase of stream ecosystem health assessment in the Wet Tropics and other northern river systems.

6. Summary and Synthesis: Integrated protocols for monitoring the ecosystem health of Australian Wet Tropics streams

This chapter summarises the findings of the individual chapters of the River Health component of the *Catchment to Reef* program, compares their approaches and outcomes, and evaluates their utility for a river health monitoring program. It presents a suite of indicators suitable for assessment of stream ecosystem health, based on the research findings.

A monitoring manual will be produced as part of the MTSRF program. It will deal with monitoring as a 'question-driven' activity, rather than as a data-amassing exercise, and will include methods for appropriate analysis and interpretation to meet particular needs. By 'question-driven' we mean that it is important to be clear *why* monitoring is being undertaken (e.g. is it for decadal, annual or monthly reporting of condition; is it to examine riverine and catchment condition; is it to determine quantities of contaminants being delivered to the GBR, etc.). This consideration then drives other questions: *what*, *how*, *when* and *how often* to sample and *who* to plan, administer and undertake the exercise (including sampling, sample analysis, data analysis and interpretation) are all crucial issues that will be addressed in the manual.

As indicated above, depending on the questions being addressed, and subject to an appropriate study design (multiple sites vs. appropriate models) and methods, the suite of recommended variables to describe/measure in streams of the Wet Tropics is:

- Flow regime of the stream;
- Physical condition of the stream sites including: current velocity; bank stability; channel form; width; depth; sediment characteristics, including particle size and amount of detritus;
- Major water quality characteristics, including maximum and minium values (measure through repeated 24-hr cycles) of temperature, conductivity, ph, dissolved oxygen, clarity, suspended solids, hardness, nitrate, phosphate;
- Riparian condition (vegetation structure, weediness, canopy cover);
- Aquatic macrophyte cover;
- Species richness of aquatic macrophytes;
- Proportion of aquatic macrophyte species that are alien;
- Species richness of invertebrates ('species' here meaning taxa at highest level of resolution possible);
- Family richness of invertebrates;
- Fish species richness and assemblage composition;
- Number and proportion of alien fish species; and
- Proportion of fish abundance due to alien species.

These same variables will form the basis of monitoring programs of rivers and wetlands of different character, although the study designs will need to be modified to incorporate flow regime characteristics, and physical-chemical gradients in slow-flowing, intermittent and non-linear systems, such as floodplain lagoons.

This synthesis is preliminary and focuses on streams in the central Wet Tropics (Russell-Mulgrave catchments). Testing of the conclusions is planned elsewhere in the Wet Tropics, across other GBR catchments and in other habitats (highly seasonal systems, lowland wetlands) as part of the MTSRF research program, which will also develop reporting mechanisms that will be readily accessible to all stakeholders. The MTSRF program builds on, extends and will conclude the *Catchment to Reef* research reported here.

Output: Catchment to Reef Water Quality Report, Chapter 1 – Water quality monitoring in tropical Queensland: Context and issues (JCU)

See: Brodie, J., Butler, B., Pearson, R., Bainbridge, Z. and Lewis, S. (2008) Water quality monitoring in tropical Queensland: Context and issues. In: Pearson, R. G. (ed.). *Final Report – Tasks 1 and 2, Catchment to Reef Joint Research Program.* Cooperative Research Centre for Tropical Rainforest Ecology and Management (Rainforest CRC) and Cooperative Research Centre for the Great Barrier Reef World Heritage Area (Reef CRC).

Output: Refinement of conceptual biophysical models for Wet Tropics waterways, and improved understanding of connectivity and hydro-ecological function in coastal catchments.

A joint workshop involving participants of MTSRF Project 3.7.3 and Project 3.7.4 was held to elucidate conceptual biophysical models for Wet Tropics waterways (streams, rivers, floodplain wetlands). The workshop successfully developed understanding of major processes operating in Wet Tropics waters, providing a conceptual base for development of indicators and identification of thresholds of potential concern. Further detail of the outcomes of the workshop is included in the overview of Project 3.7.4.

Project 3.7.4 Wetlands and Floodplains: Connectivity and Hydro-ecological Function

Project Leader and Host Organisation: Dr Jim Wallace, CSIRO

Floodplains and wetlands are important physical and biological links in the aquatic continuum, providing unique and essential habitat and connectivity for specialist and wide ranging fauna. Yet very little is known about the hydrological dynamics of these systems, and about the dynamics of the physical and biological connectivity through them. These systems provide access and vital habitat for iconic species such as Barramundi, but they are typically badly managed, highly impacted and, in the case of freshwater wetlands, severely depleted (~75% of such wetlands in GBR catchments having been lost to agricultural and other development). Proper management will depend on understanding the biophysical relationships and connectivities in these systems. This project will develop a core floodplain hydrological model to quantify two important aspects of hydro-ecological functioning: (i) sources, sinks and transport of sediments and nutrients across floodplains; and (ii) connectivity of wetland systems within floodplains. In parallel, conceptual models of the ecological dynamics of these systems and how these interact with the hydrological processes will be developed. Ecological work to test the models of ecological processes and dynamics and links to estuarine systems will depend on the level of co-investment in the project.

Key objectives:

- Quantify how the flood regime affects the main sinks and sources of sediment and nutrients and their transport across floodplains.
- Develop a model to predict how the hydrological response and connectivity of tropical floodplains are affected by land use, land and water management and climate.
- Develop models that link ecological structure (e.g. biodiversity, community patterns) and processes to the core floodplain hydrology model to quantify the consequences of changes in water body connectivity between freshwater and saline waterways for biodiversity, biological connectivity and proper ecological function.

Summary of Outputs for Project 3.7.4

Output: Synthesis of hydro-ecological modelling opportunities in coastal catchments: connectivity and hydro-ecological function (CSIRO, JCU, GU)

See: Wallace, J., Arthington, A. and Pearson, R. (2007) Hydro-ecological modelling in coastal catchments: Connectivity and hydro-ecological function. Unpublished Report on a Workshop hed at the CSIRO Davies Laboratory, Townsville, 19-20 April 2007. Report to the Marine and Tropical Sciences Research Facility (MTSRF) (45pp.) (http://www.rrrc.org.au/publications/downloads/Project-373--374-Hydroecology-Workshop-Report.pdf)

This report summarises the presentations, discussion and recommendations made at a Hydro-ecological modelling Workshop held as part of the MTSRF Water Quality Program. The main aim of the Workshop was to initiate the development of an integrated package of conceptual and quantitative models, supported by field-based research, to predict the key hydro-ecological functions in Wet Tropics rivers, wetlands and floodplains. Particular attention was given to connectivity issues that need to be understood and managed at a range of spatial scales.

The Workshop was held under the auspices of two MTSRF projects; Project 3.7.3 which is designed to develop conceptual biophysical models to identify: (i) appropriate indicators of waterway ecosystem health, and (ii) probable thresholds of concern and their effects on biodiversity and ecological processes. In parallel, and closely linked with this project, is Project 3.7.4, that focuses on the development of a core floodplain hydrological model to quantify two important aspects of hydro-ecological functioning: (i) sources, sinks and transport of sediments and nutrients across floodplains; and (ii) connectivity of wetland systems within floodplains. The twin development of conceptual models of the ecological dynamics of these systems and how they interact with the hydrological processes is strategically designed to improve our capability to predict the impacts of changes in land use, land and water management and climate on the flow and water quality regimes and ecological dynamics in the wetlands and floodplains of catchments adjacent to the Great Barrier Reef.

The Workshop involved thirty leading hydrological and ecological experts and was held on 19-20 April 2007 at the CSIRO Davies laboratory. During the first day a series of thirteen hydrological and ecological presentations relevant to tropical floodplains were made. The second day focussed on the development of disciplinary and integrated hydrological and ecological models using a breakout group approach. The hydrological presentations highlighted recent studies of floodplain hydrology using contrasting static and hydro-dynamic approaches. The former combined state of the art remote sensing techniques with peak river-flow data to identify inundated areas in the Murray-Darling basin. The hydro-dynamic floodplain modeling showed how inundation extent, material transport and wetland connectivity could be simulated dynamically during individual flood events. The differences between the flow and water quality regimes in the Wet and Dry Tropics were also highlighted along with the potential role of wetlands to filter sediment and nutrients. The connection of the floodplain system to the marine environment was made via two presentations, one on estuarine bio-geochemistry and the other on freshwater-marine water quality interactions.

Links with the ecological domain were made by a scene setting paper on water and ecosystem health, which was followed and illustrated by recent studies in the Wet Tropics. These two papers demonstrated the complexity of ecological interactions in tropical waterways, but also how statistically rigorous approaches could help the monitoring programs of natural resources managers. The interaction of the hydrological regimes with freshwater ecosystems was elaborated by looking at the influence of various characteristics of a river's flow regime on habitat structure, fish diversity, fish migration, reproduction and recruitment processes, and other ecological processes (migration, spawning) associated with lateral and longitudinal patterns of connectivity. New PhD research on the influence of flow seasonality on the recruitment ecology of riverine fishes from lowland Wet Tropics rivers was also presented. This project will identify the location of recruitment under the influence of seasonal (wet and dry) flow regimes and document shifts in habitat use and migratory patterns. Fish migration was also addressed in the context of man-made structures, where conceptual models of fish passage were used to aid their design. The final paper described a software tool, the 'ecological response modeling framework' (ERM) for compiling the existing knowledge of ecological responses to time series of habitat drivers such as flow, water quality, and physical habitat drivers such as woody debris or substrate. Ecological response models, such as habitat suitability and rule based models are also captured in the ERM framework as is a measure of the confidence of each model component.

Much of the discussion on the second day revolved around the Marine Catchment Basin concept proposed by Gehrke and Sheaves (2006); see Figure 15. This links the 6 key domains of the upper and lower catchment with the open ocean waters. Land, wetland and river interactions are represented in the upper catchment, floodplain and estuary and these connect with the marine environment via the freshwater plume that mixes with the deeper ocean waters. Lateral interactions occur in each domain, but with differing hydrological and ecological characteristics. Longitudinal interactions between the domains mix waters of different chemistry and acts as a conduit for materials as well as freshwater and marine biota. The Marine Catchment Basin concept was used as a construct for discussion and led to an initial 'typology' of the hydrological and ecological regime in each of the model domains. It was recognised that details of the Marine Catchment Basin concept would be different in Wet and Dry tropical systems and that hydrological and ecological sub-models would need to be specified for each domain and system. Candidate hydrological and ecological models for each domain were proposed along with suggestions on how the goals of the two MTSRF Projects could be both clarified and better integrated.

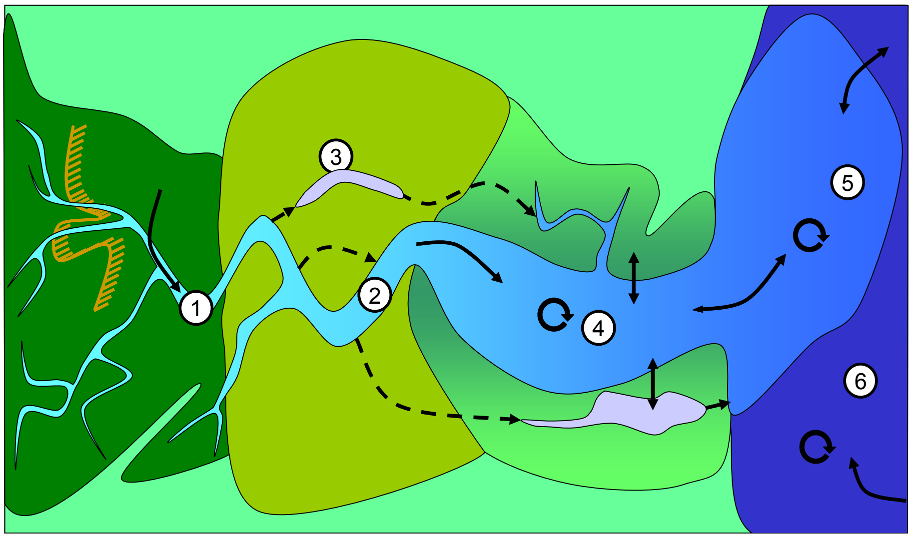

Figure 15: The Marine Catchment Basin concept showing the major sub-components of the catchment, floodplain, estuary and marine continuum. (1) River reaches upstream of the lowland floodplain; (2) Lowland river reaches adjacent to; (3) Well-developed floodplain with freshwater wetlands; (4) Estuarine reaches with salt-tolerant riparian vegetation and brackish wetlands; (5) River plume extending seaward; and (6) Coastal waters outside the river plume. Arrows indicate direction of major material transport within numbered zones. Circular arrows show major zones of material recycling. Modified from Gehrke and Sheaves (2006) who adapted the original concept of Caddy (2000).

Workshop participants made twelve primary recommendations centred on the use and modification of the Marine Catchment Basin concept as an overarching framework to build and link component hydrological and ecological models. Within this framework the number and type of models to be developed should be clarified. Separate models would be required for the hydro-ecological links during the dry (ambient flow) season and the wet (flood flow) season. Natural and modified flow regimes need to be modelled and the role of groundwater needs to be better understood. Comparative approaches to floodplain inundation modelling should be considered, especially where this might provide a means of extrapolating inundation modelling to a range of other catchments along the GBR coast. There was a recommendation to include measurement and modelling of carbon and detritus in the floodplain hydro-dynamic model and wetland filtering model. This would open up links to food web analysis and ecological models as well as providing a vital link with estuarine models. The capacity to deal with estuarine connectivity should be further explored, for example, by linking the proposed floodplain hydro-dynamic model to an estuarine eco-hydrology model. Linking with the UNESCO Ecohydrology program would help to develop this aspect of the projects. Further recommendations referred to the need to liaise closely with MTSRF marine water quality projects to ensure maximum synergy of data and models that run from the upper catchment, via river channel, floodplain and estuary and out into the marine environment. Finally, further field trips to Tully to refine experimental designs were recommended along with presentation of the projects to local stakeholders and NRM managers.

Project 3.7.5 Socio-economic Constraints to and Incentives for the Adoption of Land Use and Management Options for Water Quality

Project Leader and Host Organisation: Dr Peter Roebeling, CSIRO

This project evaluates the socio-economic constraints to and risks associated with the adoption of land use and management options for water quality improvement at the private and social level, to identify and assess instruments that are most cost-effective in promoting the adoption of these ‘best’ land use and management options by community embedded agents in rural and urban areas in North Queensland’s catchments.

Key Objectives:

- Assess the cost-effectiveness of land use and management options for water quality improvement, including agricultural as well as non-agricultural diffuse and point sources;
- Identify agent profiles, aspirations and attitudes, characterising (private) agent specific constraints to and risks associated with the adoption of land use and management options for water quality improvement;
- Identify community (including institutional) structures and networks, characterising (social) community specific constraints to and risks associated with the adoption of land use and management options for water quality improvement; and
- Identify and assess instruments that are most effective in promoting the adoption of ‘best’ land use and management options by community embedded agents.

Summary of Outputs for Project 3.7.5

Output: Final report on the assessment of the long-term effectiveness of best management practices (BMPs) for water quality for the most important production systems in the Wet Tropics (CSIRO).

See: Roebeling, P. C., Webster, A. J., Biggs, J. and Thorburn, P. (2007) Financial-economic analysis of current best management practices for sugarcane, horticulture, grazing and forestry industries in the Tully-Murray catchment. Report to the Marine and Tropical Sciences Research Facility. Reef and Rainforest Research Centre Limited, Cairns (59pp.) (http://www.rrrc.org.au/publications/downloads/375-CSIRO-Roebeling-_2007_-Tully-CCI-BMP-Analysis.pdf)

This report was prepared for the Cardwell Shire Floodplain Program coordinated by the Far North Queensland Natural Resource Management board (FNQ NRM Ltd) under the Water Quality Improvement Program (WQIP) for the Tully-Murray catchment, supported by funding from the MTSRF program. The study analyses the cost-effectiveness of most promising best management practices (BMPs) for water quality improvement in sugarcane, horticulture, grazing and forestry production in the Tully- Murray catchment. More specifically, the objectives of this study are to:

- Determine the (plot level) financial-economic consequences of BMP implementation in sugarcane, horticulture, grazing and forestry production.
- Determine the effectiveness of these BMPs in reducing fine suspended sediment, dissolved inorganic nitrogen and persistent herbicide delivery.
- Assess the impact of climate change and population growth on BMP cost effectiveness and attainment of water quality targets

The approach developed by Roebeling *et al.* (2005) is therefore applied and extended this uses production system simulation models (APSIM, LUCTOR and PASTOR) and a hydrological model (SedNet/ANNEX) in combination with sound cost-benefit analysis, while the impact of population growth on attainment of water quality targets is assessed using a classic urban economic model with environmental amenities (see Roebeling *et al.* 2007).

Scenarios for BMP are based on the compilation of practices identified in Roebeling and Webster (2007), and include tillage management, fallow management, nitrogen application rate, nitrogen application method and herbicide application rate in the case of sugarcane production, interrow management and fertiliser application rate in the case of (banana) horticulture production, stocking rate and nitrogen application rate in the case of grazing production, and finally interrow management in the case of forestry production.

- In sugarcane production, moving towards a zero tillage system as well as moving towards a legume (rather than a bare) fallow are attractive from a financial-economic perspective, while only zero tillage leads to a reduction in water pollutant (fine suspended sediment – FSS) delivery. Matching nitrogen application rates to crop requirements is attractive from a financial-economic as well as a water pollutant (dissolved inorganic nitrogen – DIN) delivery perspective, while split (rather than single) application of nitrogen leads to minor changes in profitability and water pollutant delivery. Reduced herbicide application comes at a small cost while leading to a considerable reduction in pollutant delivery.
- In (banana) horticulture production, maintenance of grassed (rather than bare) interrows leads to a small reduction in profitability though does lead to a considerable reduction in water pollutant (FSS) delivery. Matching fertilizer application rates to crop requirements rates lead to a decrease in water pollutant (DIN) delivery and gross margins, unless efficiency gains can be made through re-composition of fertilizer application ratios.
- In grazing production, matching stocking rates to pasture carrying capacity leads to a small reduction in water pollutant (FSS) delivery as well as an increase in profitability. Matching nitrogen application rates to pasture requirements is attractive from a financial-economic perspective and leads to small reductions in water pollutant (DIN) delivery.
- In (hard timber) forestry production, maintenance of grassed (rather than bare) interrows leads to a small reduction in water pollutant (FSS) delivery and profitability.

Consequently, options for cost-effective water quality improvement are largest in sugarcane production (tillage management, nitrogen application rate and herbicide application rate) and (banana) horticulture production (interrow management in banana), while options for cost-effective water quality improvement in grazing and forestry production are limited (Table 1).

Climate change and population growth are shown to potentially impact on the attainment of water quality targets. While climate change does not seem to affect, for an example of the sugarcane industry, BMP cost-effectiveness, it may lead to a significant increase in levels of water pollutant (DIN) delivery under some climate change projections for 2070. In case water pollution from residential land uses exceeds water pollution from the land uses it replaces, it can be expected that water pollution increases with population size and that the potential for water quality improvement through BMP adoption in agriculture is reduced due to population growth.

A number of caveats to this study must be mentioned. First, this BMP cost effectiveness assessment is a plot-level study and, consequently, does not include costs associated with BMP implementation at the farm and community level. Second, not all of the used production system simulation models are equally suited for BMP cost-effectiveness assessment – APSIM resulted to be best suited as it contains the most sophisticated routines for the calculation of C-factors and DIN concentrations while it also allows for the assessment of the largest range of current and future BMP. Third, persistent herbicide (HER) delivery calculations are fairly simplistic as there is no hydrological model available that accurately describes the relationship between plot level persistent herbicide concentrations and persistent herbicide delivery. Finally, it must be noted that the figures in this document are generated for the Tully-Murray catchment and, consequently, care should be taken when transferring these figures to other catchments.

Table 1: Cost-effectiveness of best management practices for water quality improvement in sugarcane, horticulture, grazing and forestry production systems.

Production system	Management practice	Gross margin	FSS delivery	DIN delivery	HER delivery
Sugarcane	Tillage management	(+)	++	0	0
	Fallow management	+	0	–	0
	Nitrogen application rate ~ requirements	+	(0)	++	0
	Nitrogen application method	(0)	0	(+)	0
	Herbicide application rate	(–)	0	0	++
Horticulture	Interrow management	(–)	++	0	0
	Fertilizer application rate ~ requirements	–	(0)	+	0
Grazing	Stocking rate ~ carrying capacity	+	(+)	(0)	0
	Nitrogen application rate ~ requirements	+	(0)	(+)	0
Forestry	Interrow management	(–)	(+)	0	0

Project 3.7.7 Conceptual and Statistical Framework for the Water Quality Component of the Integrated Report Card

Project Leader and Host Organisation: Dr Andy Steven, CSIRO

A key deliverable of the MTSRF program is the development of an Integrated Report Card Framework (IRCF) for reporting on condition and trends in catchment and marine health of the GBR and Torres Strait regions. The key management driver of this, and a number of other MTSRF projects concerned with indicator development, is the requirement for state and federal government authorities and other stakeholders to provide robust assessments of the present 'state' or 'health' of regional ecosystems in the Great Barrier Reef (GBR) catchments and adjacent marine waters. An integrated report card format, that encompasses both biophysical and socio-economic factors, is an appropriate framework through which to deliver these assessments and meet a variety of reporting requirements. It is now well recognised that a 'report card' format for environmental reporting is very effective for community and stakeholder communication and engagement, and can be a key driver in galvanising community and political commitment and action.

Although a report card needs to be understandable by all levels of the community, it also needs to be underpinned by sound, quality-assured science. In this regard this project was establish to develop approaches to address the statistical issues that arise from amalgamation or integration of sets of discrete indicators into a final score or assessment of the state of the system. In brief, the two main issues are, (1) selecting, measuring and interpreting specific indicators that vary both in space and time; and (2) integrating a range of indicators in such a way as to provide a succinct but robust overview of the state of the system. Although there is considerable research and knowledge of the use of indicators to inform the management of ecological, social and economic systems, methods on how to best to integrate multiple disparate indicators remain poorly developed.

Key Objectives:

- Focus on statistical approaches aimed at ensuring that estimates of individual indicators are as robust as possible; and
- Present methods that can be used to report on the overall state of the system by integrating estimates of individual indicators.

It was agreed at the outset, that this project was to focus on developing methods for a water quality report card. This was driven largely by the requirements of *Reef Water Quality Protection Plan* (RWQPP) and led to strong partner engagement with the Reef Water Quality Partnership.

Summary of Outputs for Project 3.7.5

Output: Report on existing approaches to environmental condition reporting relevant to water quality reporting for the Great Barrier Reef (CSIRO).

See: Browne, M., Kuhnert, P., Peterson, E., Bartley, R., Steven, A. and Harch, B. (2007) Review of existing approaches used to develop integrated report card frameworks and their relevance to catchments draining to the Great Barrier Reef. Report to the Marine and Tropical Sciences Research Facility. Reef and Rainforest Research Centre Limited, Cairns (72pp.) (http://www.rrrc.org.au/publications/downloads/Revised-Project-377-Final-Report-250607.pdf)

This report provides a review of relevant report card approaches from national and international report card programs, raises awareness as to some of the issues and requirements for developing a report card for the GBR region, and provides some principles and an approach on how to proceed with developing a report card for the GBR region.

While there is no formal definition of a report card, in this document an integrated reporting framework (IRCF) is defined as '*a scientifically valid approach for the integration and presentation of operational monitoring data in an accessible format for adaptive ecosystem management'*. This definition captures the challenge of designing a report card to represent ecological condition that aims to statistically summarise a diverse range of data sources from a complex environment into a simplified form that remains scientifically valid. This definition also reflects the role that integrated report frameworks play within an adaptive management framework which involves ongoing monitoring and assessment. It also highlights the challenge of ensuring that the integrated components not only represent tools that managers can use, but are transparent to the scientific community and other stakeholders that require the detail underlying the report card grade. This places emphasis on the science behind the grade itself and its development. From our review of the literature a general framework for report card development is presented. The following points are made in relation to the general principles resulting from our review, as well as the implications for the development of a Great Barrier Reef (GBR) Integrated Report Card Framework (IRCF):

1. *Define the scope and objectives of the program, and establish what resources are available*

The scope of the IRCF must suit the available resources and time-frame. The goals and scope of the IRCF should be established as quickly as possible in order to guide subsequent stages. An overly ambitious or poorly defined scope will make it difficult to implement subsequent development stages. Existing data sets/monitoring programs may not be ideal given the requirements of the IRCF. Goals and scope of the IRCF may have to be revisited if they are to be constrained by available data.

Implications for the GBR IRCF

It is clear from the case studies presented in this report, with the exception of the millennium assessment, that no other studies have attempted to bring together environmental condition reporting across an area as large as the GBR and Torres Strait (~ 767 000 km2) with such a diversity of habitats, and drivers / issues to be considered. Furthermore issues of data paucity, particularly in the Cape York catchments will be an issue. We believe, however, that the right policy and institutional drivers are in place to move the development phase forward for addressing water quality issues in the GBR. The Reef Water Quality Protection Plan (RWQPP) and the recent formation of the Reef Water Quality Partnership — as is a collective representation of end-users - are important for providing the articulation of the objectives, issues, scope, resolution and style of reporting that will be required. This is important for specifying the science required for the development of the framework for water quality related issues. For biodiversity and conservation issues both terrestrially, and in the marine environment, these needs are not as well defined. Some IRCF reviewed in this report have strong socio-economic (human use / governance) components, while others ignore these entirely in favour of validated measures of environmental and ecological integrity. This is a decision-point to be resolved early in the GBR IRCF development. If the focus of the IRCF is ecological, it is worth considering avoiding socio-economic reporting (at least in the early years) to avoid distracting from the primary goal. Reporting on management actions is a separate matter, and may be considered in another program.

2. *Understand the system, drawing together and documenting all relevant theoretical and empirical knowledge, as well as expert opinion*

Conceptual frameworks and conceptual models play an important role here. Establishing the relationships between drivers, stressors and ecological impact is facilitated by explicit conceptual models of specific biophysical dynamics. An IRCF should encompass both the human and biophysical system, and provide clear direction in terms of management actions. Adherence to an appropriate and well-supported conceptual framework will assist here. An entire-system approach is particularly important, and the relationships between anthropogenic stressors, pollutant vectors, environmental conditions and ecological responses should be made explicit.

Implications for the GBR IRCF

A conceptual framework establishing the types of indicators to be reported and their degree of connectedness and causality need to be agreed. Possible models include the traditional pressurestate-response approach as used in SoE reporting, the pressure-vector-condition currently being developed by the Queensland Government for its Stream and Estuary Assessment Program (SEAP), the Millennium Ecosystem framework that focuses on the linkages between ecosystem services and human wellbeing.

Establishing causality between pressure-vector-response indicators – particularly for ecological and socio-economic issues has generally been poorly addressed by most report cards to date. We believe, however, that the main research challenge for the MTSRF Report card should be the development of a coherent longitudinal integration of various habitats and their indicators, from the top of the catchment through flood plains and estuaries and onto the inner and outer reef. Working groups of experts need to be set up and tasked with documenting the key dynamics and relationships of the biological, chemical and physical properties of the system early in the IRCF design process. These conceptual models guide and justify the subsequent processes of indicator selection, regionalisation and indicator integration.

3. *Establish a measurement framework that will address the constructs defined in Phase 1 in terms of the systems identified in Phase 2. This will include the definition of spatial reporting units (that should be scaleable), and the choice of indicators and their benchmarks.*

Implications for the GBR IRCF

A multi-scale regionalisation needs to be developed that will ultimately be a pragmatic compromise between the reporting units already determined through administrative arrangements, and the use of biophysical data of landscape attributes to determine a regionalisation capable of meeting a hierarchy of reporting needs. Consideration of hydrological dynamics and stream connectivity will be important for determining the areas of human use that impact a given aquatic location and can form the basis for a multi-scale spatial classification.

This will be a major component of ongoing research and will need to consider the following:

- Latitudinal climate and landscape variation;
- Definition and delineation of habitats;
- Scales of variability (spatial and temporal) that occur within a patterned hierarchy of habitat and bioregion;
- Identifying regions of minimal human disturbance that can be used to define appropriate benchmark reference conditions and thresholds-of-concern; and
- Establishing human disturbance gradients would that can be used for validation of indicators, reference conditions, and regionalisation schemes.

Possible approaches to regionalisation may include:

- The use of landscape attributes or biological attributes singly or in combination;
- Clustering frameworks, with independent reference criteria for each cluster that may also be compared to model-based approaches. The influence of non-anthropogenic factors on indicators may be modelled and accounted for explicitly;
- Remote sensing methods will also be a great use in defining bioregions and mapping habitat extent; and

- The use of expert opinion to help guide the selection of attributes and the identification of regional boundaries, especially for the reporting regions will be beneficial; a number of methods have been developed in Queensland already for applying expert opinion that can be readily adopted.

It is often possible to refer to national or international guidelines to determine reference levels for physical indicators (e.g. pertaining to water quality). Other indicators (biotic indicators in particular) will demand a process of reference level determination that is strongly related to the regionalisation scheme. All indicators will demand evaluation with respect to criteria described in this document, such as specificity, responsiveness and economy. The Queensland Water Quality Guidelines provide a framework for determining these objectives but the current values set for wet and dry tropical regions are based on very sparse data.

4. *Establish an integration and reporting framework that will integrate and present the data generated in Phase 3 in a valid manner.*

The organisation of the IRCF should be hierarchical, reporting at multiple levels of detail with regards to spatial, temporal and indicator specificity. This appears the ideal approach to accomplish the parallel goals of providing both transparency and methodological rigour.

The choice of how to integrate multiple indices can range from simple methods of averaging, or reporting the percent of sites and / or times an indicator meets a specified objective, through to more complex methods where individual indicators may be weighted, normalised to a common metric or interpolated over spatial or temporal reporting units. One of the major shortcomings of most of the methods reviewed is that they have no or very crude representations of uncertainty. This issue will be evaluated as part of future work undertaken in the project.

Recommendations about the strengths and limitations of each approach and the scope of works required for development and implementation is discussed more fully in subsequent reports. Internet presentation is recommended to maximise accessibility to the public. The use of active and interactive PDF technologies is of particular value.

Output: Report on recommended conceptual and statistical framework for the development of a water quality Integrated Report Card for the Great Barrier Reef (CSIRO).

See: Kuhnert, P., Bartley, R., Peterson, E., Browne, M., Harch, B., Steven, A., Gibbs, M., Henderson, A. and Brando, V. (2007) Conceptual and statistical framework for a water quality component of an integrated report card for the Great Barrier Reef catchments. Report to the Marine and Tropical Sciences Research Facility. Reef and Rainforest Research Centre Limited, Cairns (124pp.) (http://www.rrrc.org.au/publications/downloads/377-CSIRO-Kuhnert-2007-IRC-Final-Report.pdf)

This report presents a conceptual and statistical framework for the development of an Integrated Report Card (IRC) for the Great Barrier Reef (GBR) region in North Queensland, Australia. Integrated catchment management groups, as well as State and Federal Government bodies, now have an obligation to report on condition and trend in their catchments and marine waters as part of the response to the Reef Water Quality Protection Plan. In this context there is a need for a consistent approach to reporting on catchment and water quality condition at each of these levels.

To facilitate the development of an IRC for the GBR region, this project was undertaken with the broad objective of developing a scientifically robust framework to support the production of report card(s) that integrate biophysical and socio-economic data from indicators that represent the pressures, vectors and responses in tropical aquatic landscapes of the GBR and Torres Strait Regions. The water quality theme was selected as the area of focus for the development of a pilot framework in 2006/2007.

This project developed the following:

1. *A description of the various phases required for indicator development and the associated statistical monitoring design approaches for data collection.*

   This report outlines fifteen guidelines that should be used to evaluate each indicator before it is finally accepted in a report card for the GBR region. Broadly, the criteria encompass conceptual relevance, feasibility of implementation, response variability and interpretation and utility.

2. *A list of mature indicators for the GBR catchment, freshwater and marine regions, as well as (limited) available information on thresholds of concern, potential data sets and indicators requiring development.*

   In consultation with MTSRF research scientists, a total of 53 mature indicators were identified from an original 82 potential indicators that are suitable for use within a GBR water quality report card. It is envisaged that this initial list of 53 mature indicators will be reduced further as more results from the 'domain' research programs become available over the next four years. The next stage is now for the 'domain' research groups within the MTSRF program to evaluate each of the mature indicators according to the fifteen guidelines presented in Section 3.1 of the report. This step will need to be done in conjunction with all of the organisations responsible for monitoring catchment, freshwater and marine condition and trend in the GBR catchments, and in some cases this may require specific pilot programs to be set up to rigorously test the indicator of interest. The outcome of this process will be a final list of indicators that is suitable for use in a GBR report card.

3. *Approaches for indicator assessment, integration and visualisation.*

   This report highlights that the process of indicator evaluation, assessment, and integration requires an understanding of the natural variability, measurement error and co-variability of each indicator with respect to 'reference condition'. For an indicator to be useful, it should have a reasonably high responsiveness to human disturbance, must be shown to be a suitable predictor of the ecological resource of interest, and the level of natural variability and measurement error associated with the indicator must be relatively minimal. To facilitate the visualisation of a large number of potential indicators, the GBR water quality 'data wheel' has been put forward as the preferred visualisation approach for the GBR report card. After evaluating a range of options in previous MTSRF reports (see Browne *et al.* 2007), the data wheel approach is recommend for a number of reasons including, (i) it is flexible and new indicators, or indicator groups (e.g. socio-economic indicators) can be added at any stage; (ii) this type of visualisation option removes the need for different visualisation approaches for the scientific technical reports versus community report cards as different layers of the data wheel can be removed to reduce the complexity of visualisation where required; (iii) variations in the colour scheme can be used to demonstrate uncertainty in the data sets and potentially highlight where more data are needed for certain indicators; and (iv) this approach promotes consistency between the catchment, freshwater and marine approaches, rather than having different visualisation options as done for other report cards.

4. *A discussion of preferred statistical approaches that enable appropriate spatially focused reporting against targets or threshold of concern.*

   Spatial partitioning is the process of subdividing a geographical space into one or more homogeneous sub-regions based on data that reflects differences in environmental and/or biological characteristics. It represents a critical component of any environmental monitoring program because it helps to ensure that an indicator's response to anthropogenic impacts will be interpreted correctly. *It is important to note that throughout this report 'spatial partitioning' refers to appropriate spatially focused reporting against targets or threshold of concern not the actual reporting zones.* In this report we present two statistically and ecologically valid methodologies that can be used for freshwater and marine spatial partitioning. The spatial framework for the freshwater spatial partitioning successfully accommodates hydrologic connectivity and nested catchments, which are a unique characteristic of stream networks. A range of cluster analysis techniques, distance metrics, and methods for determining cluster structure were explored. Choice of the number of clusters was determined using two quantitative techniques: the average silhouette width and the Gap statistic for each clustering solution examined. A fuzzy cluster analysis was also constructed to investigate the likely group membership at the edges of the clusters identified. This allowed us to inspect the boundaries of each cluster visually and to determine where uncertainties in classification arise.

5. *Demonstration of the conceptual and statistical framework for a water quality component of an integrated report card using the Tully-Murray freshwater and marine regions of the GBR.*

   The Tully-Murray catchment and marine zone were chosen as a pilot region to showcase methods for spatial partitioning, indicator assessment, and indicator integration for use in an integrated reporting framework. Two indicator assessment methods were demonstrated for the freshwater and marine environments. In the first, thresholds of concern were used to test for compliance at each of the sites and a proportion of the region that met the threshold was provided. The second approach was based on a statistical technique known as 'bootstrapping', which was used to examine the variability around the indicator within a spatially relevant neighbourhood. More importantly, an estimate of the bootstrap confidence interval was produced for the value recorded at the site and compliance was assessed accordingly. There are a number of ways of integrating assessments to form an overall evaluation of ecosystem health in terms of the proportion of sites that have exceeded a threshold. Some of the methods described here included averaging within regions, a weighted average within regions, and averaging across regions were demonstrated in the report using data from the Tully/Murray catchment and marine zone.

   Arising from this research general recommendations are made for the further development of an Integrated Report Card for the GBR region. It is emphasised that the development of such a report card will take several years and will require the strong engagement and coordination of the various science, operational and end user stakeholder groups.

Recommendation 1: Indicator development and incorporation into an IRC: Dedicated working groups within each of the IRC disciplinary classes (catchment, freshwater and marine) need to be set up to facilitate the further development and finalisation of the indicators to be used in the report card. The working groups will need to consist of the research scientists testing the indicators, the government bodies undertaking the routine monitoring, as well the statisticians that will be involved in the final analysis and integration of the data. Where appropriate regional body stakeholders may also be involved to provide community feedback on indicator development.

The outcome of the working group process will hopefully lead to a final list of indicators that are suitable for use in an IRC for the GBR, as well as match the reporting requirements of each of the agencies involved. It is important to note that while we are suggesting at least three working groups, it is vital that the different components (catchment, freshwater and marine) remain connected and continue to focus on the linkages at the catchment to reef scale. The connectivity between the groups could be facilitated via the Reef Partnership.

Recommendation 2: Set up pilot monitoring programs: As follow-on to Recommendation 1, there is the need to set up pilot monitoring programs to assist with indicator testing and selection. This will be crucial for developing the thresholds of concern that are expected to be very different between wet and dry catchments (and associated marine monitoring zones) and between upland and estuarine conditions. The pilot programs may build on existing monitoring programs (e.g. AIMS Long term Marine Monitoring Program, or QNRW's Stream and Estuary Assessment Program), however, the programs may need to be refocused to address specific indicators. It is acknowledged that monitoring across the entire GBR is not necessarily practical, therefore a preliminary spatial partitioning exercise, similar to the one conducted in this report for the Tully catchment, would be useful for the entire GBR region so that areas with different biophysical conditions can be identified and targeted for sampling and establishing targets and/or thresholds of concern. The pilot programs could also be set up along side other research programs such as CSIRO's National Research Flagship on Water for a Healthy Country so that existing research can help inform the indicator development and testing.

Recommendation 3: Data management: There is a need for a central inventory of data sets that are available on the indicators suggested in this report, for the whole of the GBR region. This will include both freshwater and marine systems, as well as the catchment based data (e.g. fertiliser use rates). The freshwater water quality aspect of this is being undertaken by staff at QNRW, and will be crucial for understanding data availability, quality, geographic extent and future needs. Similarly, staff members at GBRMPA and AIMS have access to most of the current marine data. Information such as fertiliser and pesticide application rates in cane systems are available for ~25% of the Queensland cane region (pers. comm. Tim Wrigley), however, funding is required to generate the data into a suitable format. The equivalent should be done for other catchment indicators and agricultural systems such as grazing and horticulture.

Having a list of available data is only the first of a series of data management steps that need to be undertaken. There is an enormous amount of data available in report format for all aspects of the GBR system, however, very little of the data described in these reports are in a suitable format for use in a report card (i.e. in spreadsheet or GIS format). A web based data capture, storage and distribution system that can be used by all parties working on issues to do with GBR water quality (that may be accessed via a Reef Partnership web page for example) would be extremely useful. The data inventory and storage processes will require data sharing agreements allowing data to be shared between organisations. The lack of data sharing agreements was a major impediment to accessing data for use in this report. Sensitivity may be required when attempting to obtain data on land use management practice, and specific agreements need to be made between industry and government on the way in which this data will be used within a report card framework.

Recommendation 4: Using modeled data within a report card framework: Due to the size of the GBR catchments, a number of indicator variables will need to be modelled in some form, rather than directly measured. This may require the use of sediment transportation models, such as SedNet and associated modelling platforms such as E2, as well as approaches such as remote sensing. It is important to communicate this intention with model developers so that more effort can go into improving the accuracy and uncertainty estimates on specific parameters. This will facilitate the use of these types of data within a report card framework.

Recommendation 5: Responsibility for the GBR integrated report card: Within the natural resource management realm of the GBR, there are a large number of different reporting requirements for State, Federal and Regional bodies (e.g. State of Environment and State of Catchment reports). The organisation finally responsible for the GBR IRC needs to be very clear about how the GBR IRC is different (or similar) to other existing reporting frameworks used in the GBR to avoid duplication as well to help form synergies between different government departments.

Recommendation 6: Ownership and leadership of an integrated report card: For the GBR IRC to become a reality requires ownership and leadership by a single organisation. The Reef Water Quality Partnership is the best placed organisation to do this, however, it needs to be equipped with the appropriate resources and it will also need to expand its focus away from just reef 'water quality' to encapsulate other issues in the GBR (e.g. Rainforest, Torres Strait, etc.).

Recommendation 7: Communication strategy: The communication of a final report card product is an enormous task, and a communication strategy should be developed early for the successful transfer of the final report card to the wider community.

Theme 4: Sustainable Use and Management

Program 9: Sustainable Use, Planning and Management of Tropical Rainforest Landscapes

This is a large Program that hosts seven project areas that align directly with research needs for DEW, WTMA, FNQ NRM Ltd, Indigenous groups, industry and other key stakeholders based in the Wet Tropics bioregion and Natural Resource Management region.

Project 4.9.6 Strategic Natural Resource Management and Land Use Planning

Project Leader and Host Organisation: Dr Cathy Robinson, CSIRO

This project will develop a regional/catchment water quality management model that produces cost-effective programs of action suited to the socio-economic context and implemented to meet environmental and water quality targets. Biodiversity values in regional and local area planning incorporating new biodiversity metrics for capturing and valuing different elements of biodiversity will be established, for the protection or enhancement of biodiversity values applied through case studies in local area planning. The key longer term outcomes being targeted include improved planning and institutional arrangements underpinning biodiversity, water quality and wider ecosystem services in the GBR region whilst maintaining viable regional industries and communities; and effective partnerships between researchers, research institutions, resource managers, policy makers, government and non-government agencies that increase the relevance and impact of science in natural resource and regional decision making and governance.

Key Objectives:

- To develop and implement a rigorous cost-effective catchment water quality management model to meet targets for environmental and water quality improvement;
- To define biodiversity values and ecosystem services, based on regional ecosystems, threatened species, threatening process and beneficial processes provided by landholders will be applied through case studies in local area planning; and

- To refine, tailor and apply the concept of market based instruments for implementing ecosystem goods and services specifically for the purpose of using offset schemes for environmental conservation in developing areas.

It is considered that Objective (a) of this study is directly related to water quality threats to the GBR and is therefore reported in this summary; the other objectives are not reported here.

Summary of Outputs for Project 4.9.6

Output: Report presenting the regional / catchment water quality management model (CSIRO).

See: Robinson, C., Taylor, B., McDonald, G., O'Donohue, M., Harman, B., Pearson, L. and Heyenga, S. (2007) *SMART partnerships for integrated water quality outcomes. An overview of the water quality planning systems model and its first phase application in Queensland's Tully-Murray catchment.*

The research outlined in this report aims to inform effective and defensible environmental management strategies for water quality improvement in North Queensland. To achieve this aim, a water quality planning systems model (water quality planning systems model) suited to Great Barrier Reef catchments is outlined which can be used to inform cost-effective programs of action (Management Action Targets) that are suited to the socio-economic context and can be implemented to meet environmental targets (Resource Condition Targets).

The WQ planning systems model builds on existing planning practice and adaptive management frameworks to incorporate broad industry and community perspectives about the benefits of good water quality, the cost of deteriorating water quality and the total (social and economic) costs and benefits of delivering given water quality outcomes from a proposed intervention. This necessitates a range of values and agendas to be considered in the selection of cost-effective delivery modes, intervention responsibilities, prioritisation and location of management interventions, and institutional factors needed to deliver proposed management actions and partnerships.

Collaborative and adaptive planning approaches are used to provide useful frameworks for the water quality planning systems model with a focus on what is described as 'S.M.A.R.T partnership' requirements to design and evaluate cost-effective management interventions to achieve water quality targets in the Reef Catchments. The first phase of S.M.A.R.T partnership applications trialled at the Reef-wide and catchment (Tully-Murray) catchment scales are then described.

Project 4.9.7 Understanding and Enhancing Social Resilience: Science and Management Integration Project

Project Leader and Host Organisation: Professor Helen Ross (UQ), Dr Tim Lynam (CSIRO), Dr Margaret Gooch (JCU)

The project goal is to develop a theoretically defensible and project-appropriate understanding of social resilience that contributes to decision making in relation to water quality change as well as the management interventions to achieve water quality targets at several scales in the GBR catchment area. This understanding will be used to focus the development of indicators of social resilience designed to meet the needs of specific decision makers in specific decision making contexts. The project is addressed at three scales in the GBR region:

- Whole of GBR catchment area (by CSIRO);
- Large catchment (by UQ); and
- The community scale (by JCU).

Two questions guide the project activities designed to achieve this goal:

1. What do decision makers need to know or understand about social resilience at different scales of interest (e.g. GBR, catchment, community)?
2. What investments are most likely to enhance, or detract from, social resilience in relation to water quality change?

Summary of Outputs for Project 4.9.7

Output: Draft conceptual framework – assessment of potential social resilience indicators across spatial scales in the GBR region (CSIRO, JCU, GU)

Whole-of-GBR catchment

The focus of the CSIRO team has been on the following four activities:

- Developing a functional conceptual model of social resilience to guide the research;
- Understanding how end users conceive social resilience and how they would use the concept;
- Assembling case study data sets to inform the development of useful indicators of social resilience at the GBR scale; and
- Clarifying what water quality change means and what are the characteristics of water quality change events.

The conceptual model for this scale has been developed and is being used to guide the research. This conceptual framework for social resilience is based on the use of thresholds of potential concern for social resilience. It is expected that this component of the project will produce thresholds of potential concern for social resilience at the GBR scale.

In addition CSIRO has contributed to the development of an overarching, cross scale conceptual model which all three teams are using (see Figure 1 below).

Social resilience is an exceptionally complex and difficult attribute to define and measure. The project teams have been developing end user acceptable and useful definitions of social resilience that can then be further developed into measurable metrics. It is too early to identify potential management triggers and opportunities. It is, however, likely that the key indicators of social resilience would also suggest where management triggers and opportunities would lie in relation to enhancing social resilience.

End user interviews have been conducted and preliminary analyses carried out of their perceptions of social resilience. This work will be finalised in the next reporting period. The case study data sets have been assembled and are ready for further analysis.

A draft report on water quality change in the GBR has been developed which includes a conceptualisation of water quality change.

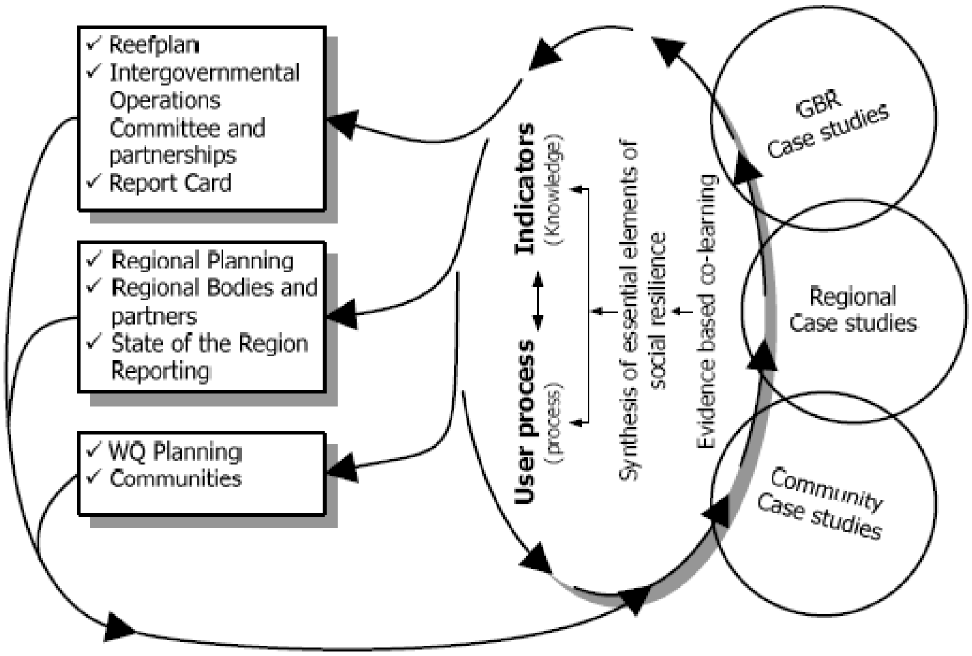

Figure 1: Conceptual framework for the development of indicators of social resilience through a collaborative process with decision makers.

Large catchment scale

The focus of the UQ team has been on the following activities:

- Coordination with the CSIRO and JCU teams over joint project development. This has involved four two-day team workshops to date in Townsville and Brisbane, as well as numerous telephone and email discussions.
- Contributing to the project's conceptual model.
- Developing collaborative relationships with end-users in the FNQNRM / Wet Tropics region, focused on our scale of interest.
- Commencing a literature review on current understanding of 'social ecological systems', 'resilience' and closely related concepts in different disciplinary fields; experience to date in different disciplinary fields re the uses and usefulness of indicators, types of quantitative and qualitative indicators, and classifications of indicators (themes indicated) and actual indicators used in a number of fields with similarities to resilience:
- Development of case studies through consultation with end users and RCCC secretariat (see section on development of case studies below). Note that under our research design, the selection of case studies should not proceed independently of the collaborative process with end users, so remains at 'candidate' stage. (see details in UQ attachment on research design). These case studies are to inform the development of indicators at regional (regional body) scale, to feed into our collaborators' shared planning and management activities (the FNQ NRM regional plan, Aboriginal Cultural and Natural Resource Management Plan, taking account of inputs needed into FNQ 2025 regional growth plan) and the State of the Region report card (with State of the Wet Tropics reporting needs also).
- Commencing liaison with the Reef and State of the Region report card teams, and alignment of our conceptual thinking with theirs.

Community scale

The focus of the JCU team has been on the following activities:

- Contributing to the project's conceptual model (refer to Figure 1 above);
- Developing relationships with community-based end-users in the Wet Tropics and Burdekin Regions; and
- Selecting case study sites to work with communities over the next three years to develop, (a) a shared meaning of key terms such as 'water quality', 'water quality change' and 'social resilience'; (b) an understanding of barriers and opportunities for community level responses to water quality change for meaningful and useful indicators of social resilience at the community scale; (c) long-term mechanisms for sharing and using relevant community-based stewardship indicators; and (d) developing literature and lay reviews to contribute to a collective understanding of social resilience in relation to water quality change.

Output: Report detailing selection and development of case studies across spatial scales (CSIRO, JCU, GU)

Whole-of-GBR catchment

Following discussions with experts, project end users and a review of the literature a set of candidate case studies has been identified and the available data assembled. The case study selection criteria were scale (regional), location in Australia, adequate documentation, and potential for follow-up with an end user involved in the case study. The selected case studies are: the Murray-Darling Basin, Ord Irrigation Scheme, Central Wheatbelt of Western Australia, and Lower Burdekin.

Large catchment scale

Development of a collaborative process with end users has been a focus of the team in order to agree upon a common focus for the project at this scale, and to put research users' knowledge needs to the fore. It is considered that the locations and fine-design of the case studies need to be a shared decision, made on agreed criteria rather than solely a research team choice. Consultation to date, particularly through a workshop on 31 May 2007, favours the Barron catchment for timeliness with the commencement of the Water Quality Improvement Planning process and alignment with JCU's research at community scale, the Johnstone catchment (more typical), or Bloomfield catchments (Aboriginal interest, with a possible invitation subject to ARC exploration of options). There is capacity to conduct two detailed, collaborative, case studies in catchments. The final selection of catchment case studies, from these candidates, requires further discussion.

Community scale

Community scale case studies are being undertaken with communities in the Barron, Douglas and Townsville areas. The Douglas Catchment was chosen as this is the first place where a catchment scale WQIP has been written for the Great Barrier Reef, and is currently being implemented. Thus it provides an ideal opportunity to investigate community level responses to development and implementation of the plan. The Barron Catchment was chosen as a second case study site, as the next WQIP for the FNQ NRM region will be developed and implemented here (the Tully WQIP is almost finished, and there is a lot of research activity in this catchment already). The Barron Catchment was also considered for the number of schools implementing programs with a focus on environmental education (e.g. Reef Guardian Schools and those trialling the FNQ NRM K-12 program). The Barron Catchment is particularly interesting as it contains a variety of different communities including urban, regional and rural and is comprised of diverse individuals and groups of people including traditional owners, tourist operators, rural land holders, 'sea and tree changers', retirees, city residents (Cairns), fishers and others. The Barron Catchment communities will provide an interesting comparison with those in the Douglas, in terms of WQIP planning and implementation process.

The City of Townsville forms the third case study area. This site was chosen as it is the first place where a WQIP for the Great Barrier Reef is being developed for an urban area. This is being coordinated by the Burdekin Dry Tropics NRM and Townsville City Council. The Townsville case will provide an interesting comparison with the Cairns community case studies.

Theme 1: Status of the Ecosystems: Understanding the Condition, Trend and Interdependencies of Environmental Assets of North Queensland

Program 1: Status and Trends of Species and Ecosystems in the Great Barrier Reef

Program 1 will focus on delivering robust indicators of reef health and identifying thresholds of potential concern for the Great Barrier Reef ecosystem. The Program contains two long-term monitoring programs of iconic ecosystems (coral reefs and seagrasses). The reports of condition and response will be linked with research in other MTSRF Programs, notably those for water quality and climate change. The Program will also develop an early warning system for crown of thorns starfish to allow the industry to prepare tactical responses. Support for community-based monitoring (Reef Check) of tourism-intensive sites will be a feature of the Program

Project 1.1.5 Great Barrier Reef Data Synthesis and Development of GBR Component of the Integrated Report Card

Project Leader and Host Organisation: Dr Alan Butler, CSIRO (with AIMS)

This project was established to support the development of an integrated report card for the GBR. Year 1 activities included statistical analysis and synthesis of GBR monitoring data with particular emphasis on threats and risks from water quality.

Summary of Outputs for Project 1.1.5

Output: Report on statistical analysis and synthesis of GBR water quality monitoring data, indicator selection and mapping risk (AIMS).

See: De'ath, G. (2007) *The spatial, temporal and structural component of water quality of the Great Barrier Reef, and indicators of water quality and mapping risk*. Report to the Marine and Tropical Sciences Research Facility. Reef and Rainforest Research Centre Limited, Cairns (71pp.) (http://www.rrrc.org.au/publications/downloads/115-AIMS-Death-2007-WQ-on-GBR.pdf)

This work comprises two components. First, three major data sets from broadscale water quality sampling programs on the GBR are analysed and spatial patterns and temporal change are presented and discussed. Second, the use of these data as potential indicators of water quality is explored. Five potential indicators are calculated and mapped. Problems of estimating risk and relative risk are discussed, an exemplary risk scale is proposed, and risk regions are mapped for the whole of the GBR. Uncertainty levels of risk are estimated and displayed jointly with risk on single maps. These maps and the methods on which they are based represent a useful prototype for future risk mapping programs.

Analyses of Water Quality on the Great Barrier Reef

The three data sets analysed were: (1) lagoon water quality data comprising measures of twelve water quality parameters (1976-2006); (2) long-term chlorophyll monitoring data (1992-2006), and (3) a composite data set on water clarity based on secchi disks.

The principal findings were:

- Spatial-temporal models are poor predictors of water quality parameters. Between 0-40% of the variation in water quality parameters is typically predictable, with chlorophyll and suspended solids being well predicted and derivatives of nitrogen being very poorly predicted.
- Concentrations of all water quality parameters decrease by 50-80% from the coast to a distance 15-20% across the Reef. From 20% across the Reef to the outer Reef they typically decrease by an additional 0-20%. This inner coastal strip should be the focus of future monitoring with fixed sites and automated logging of a few selected parameters; perhaps water clarity and chlorophyll. This cross-shelf pattern of strong decline in the near-shore varies along the coast for many water quality parameters, and is typically much steeper in the central third of the GBR and much flatter in the Far North.
- Synchronised cyclical seasonal variation occurs for most of the water quality parameters. Nutrients typically peak in March-April and are 10-50% lower in August-September. This seasonal variation must be accounted for in sampling programs.
- Despite having collected extensive data on WQ for over thirty years for the twelve water quality parameters and fifteen years for chlorophyll, we cannot make definitive statements about long-term trends in water quality on the GBR. For most of the dissolved water quality parameters the variation is such that further collection of such data should is highly questionable. The temporal trends are poorly estimated due to: (a) high variability of water quality between sampling trips and sampling locations; and (b) low precision and (likely) systematic bias of water quality measures.
- Water clarity is highly predictable spatially (~75%) and is very high compared to the water quality parameters analysed previously. This statistical property, together with its known links to biotic function and ease of measurement, suggest water clarity could be a very useful indicator of water quality, but additional work is needed to assess temporal variation.

Indicators and Mapping Risk

Potential indicators of risk and exemplary risk maps based on values that determine *relative risk* at levels of 'high', 'moderate' and 'low' were developed. It is important to discriminate between *relative risk* and *absolute risk;* the former is relatively easy to predict compared to the latter. Few would argue that increased pollutants leads to increased risk, however specifying a level of exposure that leads to adverse effects is a considerable challenge for a system as complex as the GBR, and is unlikely to be achieved in other than a few restricted instances.

Five potential indicators of relative risk were developed together with measures of risk uncertainty. The measures included both individual and composite measures of water quality, and risk maps based on plausible values that determine high, moderate and low risk regions were generated and interpreted. Of the five indicators; three are derived from the multivariate lagoon water quality data, and of remaining two, one was based on chlorophyll data pooled across lagoon and long-term chlorophyll surveys, and the second was based on water clarity drawn from three data sources. Examples of the risk maps are shown below in Figure 2 (page 114).

This initial exercise in mapping risk shows promise and the work can be further developed in many ways. There are many issues related to validation against field and laboratory experiments, temporal and spatial scales of the effectiveness, cost and ease of implementation, and new technologies, such as automated sensors and remote sensing that can more efficiently gather the data necessary to assess risk. Additional work is proceeding in order to identify indicators that can be used in the field, based on additional empirical analyses. A major focus of the additional work is validation in the sense that biotic measures can be shown to correlate to the indicator values.

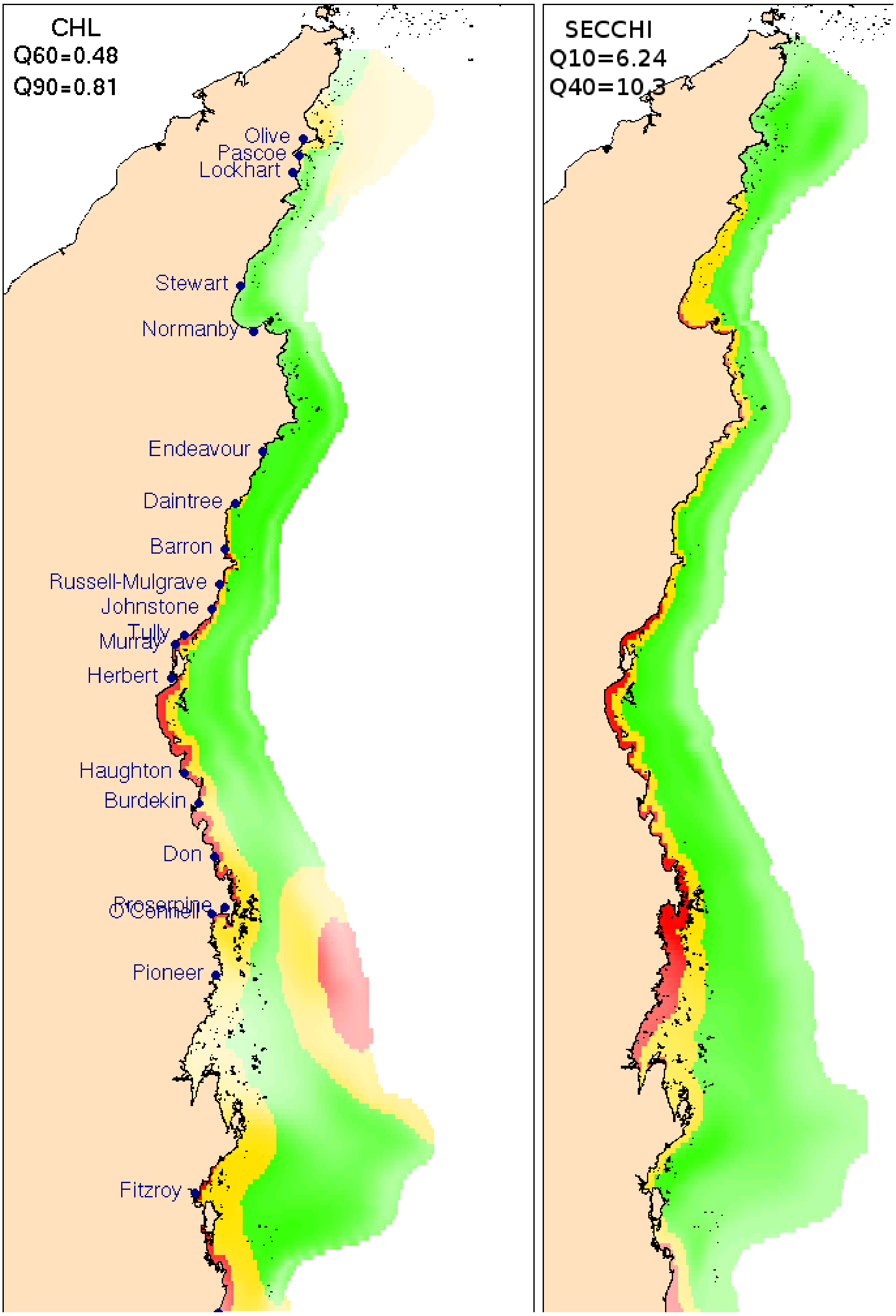

Figure 2: An example of risk maps with associated uncertainty. The left panel show the risk map for chlorophyll, and the right panel the risk for water clarity as measured by secchi disk. The red, orange and green regions indicate high, moderate and low risk regions formed by the 90% and 60th percentile breaks respectively. The strong – pale shades indicate regions of low – high uncertainty of the risk respectively.

Further Information

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