# 2013 Scientific Consensus Statement

## Chapter 2
Resilience of Great Barrier Reef marine ecosystems and drivers of change

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## Executive summary

This chapter focuses on the temporal dynamics, spatial extent and cumulative impacts of current and future drivers of change on Great Barrier Reef water quality, and subsequent impacts on marine ecosystems in the Great Barrier Reef Marine Park. These include the acute influences of large flood events driven by extreme weather, salinity stress, tropical cyclones, thermal stress, crown-of-thorns starfish outbreaks and other anthropogenic drivers such as coastal development activities. To date, impacts on the Great Barrier Reef from these drivers have been documented but the potential for additive and synergistic effects will be more severe than indicated from studies of individual stressors (Veron *et al.,* 2009).

Since the previous consensus statement (Brodie *et al.,* 2008) there have been consecutive extreme wet seasons with 2010-2011 being the start of a La Niña phase that caused the largest floods on record in multiple rivers of the Great Barrier Reef catchment. Seven cyclones affected north Queensland between 2009 and 2012, collectively impacting a significant area of the Great Barrier Reef. Large-scale and in some cases severe flooding resulted from Brisbane to Cairns, as well as physical damage to coral reefs and seagrasses (Thompson *et al.,* 2011, McKenzie *et al.,* 2012). Extreme rainfall and flood events dominated the 2012-2013 Queensland summer under a climate system that is warmer and moister, demonstrating that climate change is already affecting Australia (Climate Commission 2013a,b). Conversely, thermal stress events have been relatively minor since 2008, a likely consequence of the active monsoon trough and associated cloud cover. A new outbreak of crown-of-thorns starfish appears to have started on reefs in the northern Great Barrier Reef in 2012 and is expected to move south, presenting a medium-term driver of change for coral reefs. Ongoing and future coastal developments also represent a pressure on Great Barrier Reef ecosystems, as does increasing shipping traffic in the Marine Park.

The recent downward trend in coral cover on the Great Barrier Reef (De'ath *et al.,* 2012) highlights some critical questions of concern: will the system be resilient enough to sustain ecosystem functions, populations of keystone species and biodiversity into the future under continued global, regional and local pressures? The approximately 50 per cent decline in coral cover on monitored mid-shelf and outer-shelf reefs over the past three decades suggests that impacts on the system will exceed the capacity for recovery if this trend continues. Another key question is whether the recent cluster of severe cyclones and wet seasons on the Great Barrier Reef will leave time for recovery, and whether more severe disturbances combined with deteriorating conditions will become the norm, leading to further ecosystem-wide decline. Knowledge of critical periods required for recovery or transition to alternate states, particularly for coastal habitats, is critical to manage drivers and activities influencing the Great Barrier Reef.

To answer these questions we provide an introduction to ecosystem resilience and vulnerability in the Great Barrier Reef, and then review the literature on past, present and future disturbances on the Great Barrier Reef. We then present an overview of which disturbance types represent system perturbations with limited influence on resilience *per se* and which disturbances represent threats to resilience. Lastly, we discuss how predicted environmental scenarios for the coming decades represent risks to the Great Barrier Reef ecosystem and the implications for ecosystem resilience.

## Introduction

In this chapter, drivers of change are defined as natural or human-induced factors that directly or indirectly elicit a change in the ecosystem (based on Millennium Ecosystem Assessment 2005). Understanding drivers of change helps to: (1) identify causes and mechanisms of change (Biggs *et al.,* 2011, Fereira *et al.,* 2011), (2) anticipate and predict future condition, and (3) understand the context of past change. Drivers operate at multiple scales, from global to regional to local, and the drivers of change that are the focus of this review are extreme weather events that drive the delivery of terrestrial pollutants into the Great Barrier Reef, such as severe rainfall and cyclone-associated rainfall, as well as those that directly impact on Great Barrier Reef ecosystems, such as cyclones, thermal anomalies and crown-of-thorns starfish outbreaks. These, along with coastal development and shipping, have been identified as significant issues for the Great Barrier Reef ecosystem (GBRMPA 2009b).

How these drivers interact to impact on Great Barrier Reef ecosystems is not well understood but emerging evidence shows that multiple stressors can have additive as well as synergistic impacts on coral reefs and seagrass meadows (Negri *et al.,* 2011, Fabricius *et al.,* 2011, Collier *et al.,* 2011). Of concern is the fact that projected climate change is expected to change the magnitude and frequency of extreme events and drive further water quality declines. The impacts of poor water quality on coral reefs and seagrasses beds can manifest as either acute, short-term changes associated with high-nutrient, high-sediment, low salinity flood plumes, or more chronic impacts associated with changes in long-term water quality conditions (Devlin *et al.,* 2012a). Chronic exposure to increased concentrations of nutrients and turbidity can affect the recovery potential and resilience of some species (Fabricius *et al.,* 2011, see Chapter 1).

The frequency and intensity of these multiple drivers vary through annual and decadal periods, and are expected to be a continued source of variation and impacts into the future. While inherently stochastic, many of these disturbances have co-occurred in recent years with resultant declines in the condition of Great Barrier Reef ecosystems, such as coral reefs and seagrass meadows (De'ath *et al.,* 2012, McKenzie *et al.,* 2012). The return time of acute disturbances has an influence on the ability of biological communities to recover and reorganise, and on their resilience to further disturbance. Of equal importance are chronic stressors such as degraded water quality, increased sea temperatures and ocean acidification, which can directly and indirectly affect ecosystem responses to acute disturbances and reduce reef resilience.

More extreme events have occurred over the last decade in line with projections associated with climate change, leading to frequent severe cyclones and large scale flooding (e.g. 2011 and 2013; Climate Commission 2013a,b). The extreme weather events experienced in 2012-2013 are consistent with the type of events scientists expect to see more often in a warming climate (Climate Commission 2013b). Great Barrier Reef ecosystems are showing declining trends in condition due to the cumulative pressures of these episodic events and the likelihood that drivers of change will become more extreme in the future has significant implications for water quality and Great Barrier Reef ecosystems. A reduction in pollutant loads from catchments is essential to halt and reverse further declines of Great Barrier Reef ecosystems at a time of a rapidly warming climate and progressive ocean acidification (see Chapter 1).

Large-scale mortality events associated with recent flooding have been documented for coral reefs (Berkelmans 2009, Berkelmans *et al.,* 2012) and seagrass meadows (McKenzie *et al.,* 2010, McKenzie *et al.,* 2012). The recent extreme weather events have also shown that acute stress can result in increased mortality of marine animals that depend on seagrass meadows, such as dugongs and turtles in the Great Barrier Reef (McKenzie *et al.,* 2012). These acute events often exacerbate the impacts of chronic disturbances leading to sudden and sometimes catastrophic and compounding impacts in the environment, as seen with dugong losses following extreme flooding in 2011 (see Chapter 3). Chronic press-type disturbances like degraded water quality, have been shown to reduce both resistance to other stressors, such as warmer waters, and recovery potential.

In combination, the severe cyclones and flooding events that have occurred since 2008 have affected more than half of the Great Barrier Reef. The extreme weather events of 2010-2011 are a demonstration of how multiple stresses can impact on Great Barrier Reef habitats to produce significant ecological responses. Events in recent years provide insight into how future projections of more climate extremes, that is more intense cyclones, rainfall and runoff events, are likely to affect the Great Barrier Reef (Trenberth 2012); the weight of evidence now supports some attribution of these extreme events to a warming climate (Climate Commission 2013b). Addressing chronic pressures in the system, such as poor water quality, will be a key strategy for enhancing ecosystem resilience to future change.

## Synthesis process

This chapter represents the contribution of multiple authors, and is the culmination of many hours of discussion and effort. Many scientists participated in a one-day expert workshop to discuss the scope of the chapter and the current state of knowledge, and provided essential guidance in planning this chapter. Initially the chapter was to focus on episodic events and their implications for management. Discussions at the expert workshop clearly identified that this would not adequately consider the cumulative or synergistic effects of different drivers of change, and the fact that chronically poor water quality can undermine ecosystem resilience, including the ability of habitats to recover from episodic disturbances. The chapter was refocused accordingly, and now explicitly considers a larger number of future drivers of change and how they influence Great Barrier Reef water quality and the implications for the resilience of the Great Barrier Reef ecosystem.

The authors who contributed to writing this chapter conducted a comprehensive literature review, accessing the latest scientific information available in peer-reviewed journals, research reports and government reports. Authors also considered and utilised emerging results that were unpublished at the time of writing but are now published or 'in press'. The aim was to provide a thorough review of episodic events and drivers of water quality change since the last consensus statement in 2008, and implications for ecosystem resilience and management. This chapter is intended to complement (rather than duplicate) other chapters in the Scientific Consensus Statement, in particular, Chapters 1 and 4.

As well as the authors who co-wrote the chapter, a number of scientists reviewed the draft product, providing constructive input to improve the content and focus of the chapter. These include Len McKenzie (James Cook University), Britta Schaffelke (Australian Institute of Marine Science), Angus Thompson (Australian Institute of Marine Science), Julieanne Blake (Queensland Department of Environment and Heritage Protection) and Mike Ronan (Queensland Department of Environment and Heritage Protection). Our sincerest thanks go to all these contributors.

## Previous Consensus Statement findings

The previous scientific consensus statement concluded that "*climate change and major land use change will have confounding influences on Great Barrier Reef health*" (Brodie *et al.,* 2008). Primarily these findings focused on the complex synergies between the impacts of stress related to poor water quality and climate change (e.g. thermal bleaching and ocean acidification). A key finding was that poor water quality slowed recovery following episodic events like cyclones, crown-of-thorns starfish outbreaks and coral bleaching. Post-disturbance, corals can face high competition for space from macroalgae at sites with poor water quality conditions driving low recruitment and juvenile survivorship. Conversely, corals can recover faster in good water quality conditions, highlighting the strength of the link between water quality and reef resilience. The 2008 consensus statement described this link mostly from the perspective of the role of land use practices in exacerbating declining water quality with the possibility of increased frequency of disturbance.

The state of knowledge in 2008 about episodic events and the future influence of climate change predicted that the frequency of extreme weather events would increase (Elmhirst *et al.,* 2009). Extreme weather was expected to include more intense (but not more frequent) cyclones as well as more frequent droughts alternating with more frequent severe flooding. Increases in the variability of rainfall patterns and the intensity of droughts and floods would make land management problematic in some catchments. Droughts lead to reduced vegetation cover, making soils more prone to erosion, mobilisation and transport into coastal waters during floods. Hence the risk of soil erosion and loss was predicted to increase in 2009 as the frequency and/or severity of extreme weather events increased. The crown-of-thorns starfish outbreak risk was also predicted to increase as higher nutrient delivery after drought-breaking floods has been associated with the initiation of primary outbreaks of crown-of-thorns starfish in the Wet Tropics. The predicted increase in the intensity of tropical cyclones was expected to lead to extensive reef damage at regional scales. Cyclones of category three or higher have been documented to cause significant physical damage to reefs, breaking branching corals and dislodging large massive corals (Fabricius *et al.,* 2008). This report continues the consideration of the link between water quality and reef resilience but also reviews the additional stress of the increasing severity and frequency of extreme weather events like tropical cyclones and thermal stress.

Since 2008, several large Great Barrier Reef river basins have experienced the largest annual discharges on record, and some have experienced unusually large discharges in consecutive years. The impacts caused by these extreme events are reviewed in this chapter and new assessments are made of the drivers of change likely to be key influences on ecosystem condition of the Great Barrier Reef in the years ahead. The previous consensus statement emphasised the links between land use practices, water quality and coral resilience; the capacity to resist impacts and recover after a disturbance. Management actions that protect reefs from high nutrient, sediment and pesticide concentrations were described as essential in the 2008 statement. We continue that discussion and re-emphasise that recommendations and actions taken to improve water quality and minimise the effects of poor water quality are critical to supporting and maintaining the resilience of Great Barrier Reef habitats in an era of climate change.

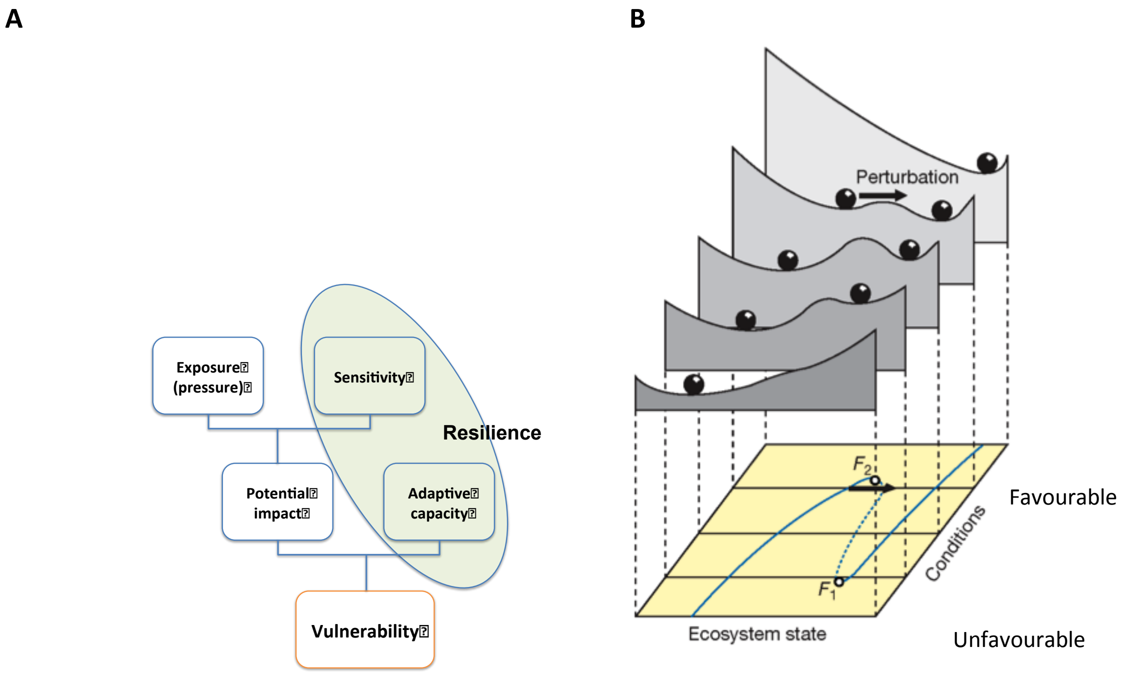
# Scientific consensus 2013

## Resilience, vulnerability and cumulative effects

The ecological definition of resilience is the ability of a system to absorb shocks and recover from disturbances while retaining its function (Holling 1973, Nyström *et al.,* 2000, Scheffer *et al.,* 2001, Folke *et al.,* 2004). Functionally, resilience is the result of population growth rates, the repair of structures and habitats, the competition of desired over less desired functional groups (e.g. corals over macroalgae), and the rate and direction of the reassembly of communities (Bellwood *et al.,* 2004, Nyström *et al.,* 2008). In the ecological definition, sensitivity or stress resistance is part of resilience (Nyström *et al.,* 2008). The greater the resilience, the better the system will be able to recover from disturbance events and maintain ecosystem functions and goods and services in the long term. From a management perspective, actions to support ecosystem resilience provide insurance in the face of increasing disturbance frequency. Ecological resilience theory provides a framework for identifying critical thresholds and tipping points (Mumby *et al.,* 2007), and thus aids in identifying management actions likely to be most effective in reducing ecosystem vulnerability to future drivers of change (Anthony and Maynard 2011, Anthony *et al.,* 2011).

Vulnerability is broadly defined as the degree to which a system or species is exposed to and able to cope with adverse disturbances (IPCC 2007). Vulnerability is the result of exposure, sensitivity, and adaptive capacity (Schroter *et al.,* 2004, Füssel and Klein 2006). As adaptive capacity is functionally synonymous with recovery potential, resilience is a subset of vulnerability (Figure 1a; Marshall *et al.,* 2013). For example, an ecosystem that is heavily impacted by a series of severe perturbations may have low vulnerability if it is resilient. Conversely, a system with low resilience facing similar or less severe disturbances will be highly vulnerable (Figure 1b).

**Figure 1.** Conceptual representations of resilience and vulnerability: (A) Conceptual model of vulnerability used by the Intergovernmental Panel on Climate Change (IPCC) and United Nations Framework Convention on Climate Change (UNFCCC), where resilience is captured by sensitivity and adaptive capacity (Schroter *et al.,* 2004, Fussel and Klein 2006). (B) Illustrates how the combination of pulse-type (perturbation) and press-type (condition) pressures can influence the dynamics of the systems (Scheffer *et a*l., 2003).



The resilience of the Great Barrier Reef is challenged by a suite of stressors acting separately or in combination both temporally and spatially. A key regional or local-scale driver of resilience on the Great Barrier Reef is water quality, specifically nutrients, turbidity and sedimentation (Fabricius 2011). The role of reduced water quality, in particular high nutrients, in lowering resilience on coral reefs has previously been questioned based on the assumption that loss of herbivores, e.g. through overfishing, is required to trigger a phase shift (Hughes *et al.,* 2007). There are now several lines of evidence on the Great Barrier Reef however, demonstrating that high turbidity as an acute stressor has a negative impact on herbivore abundance (Wolanski *et al*., 2003, Cheal *et al.,* 2010). Reduced water quality is therefore likely to lower reef resilience through three mechanisms: (1) bottom-up enhancement of macroalgal growth (Schaffelke 1999), (2) negative impacts on coral physiology (Fabricius *et al*., 2013), and (3) loss of top-down control of macroalgal abundance through loss or displacement of herbivores.

Multiple stressors often influence reef ecosystems simultaneously. For example low salinity, high nutrients and the presence of other pollutants such as pesticides are all experienced during flood events and can impact on coral reef health (Goreau 1964, Kerswell and Jones 2003, van Woesik *et al.,* 1995, Fabricius *et al.,* 2005, 2010). Stress-resistance of communities, however, depends on the sensitivity of the resident species and further on the combined effect of the above mentioned stressors (Coles and Jokiel 1978, Faxneld *et al.,* 2010). This can lead to medium and long term impacts like reduced densities of juvenile corals (Thompson *et al.,* 2011), subsequent changes in community composition (Thompson *et al.,* 2011, Smith *et al.,* 2005), decreased species richness and shifts to communities that are dominated by more resilient coral species and macroalgae (Hughes *et al.,* 2011, DeVantier *et al.,* 2006). Other long term ecological impacts can be seen in the proliferation of crown-of-thorns starfish in areas that are regularly influenced by anthropogenic nutrient loads (Fabricius 2010, Brodie *et al.,* 2005, see section on *What is the extent of impacts of episodic events across the Great Barrier Reef*?).

Climate change is a package of acute (pulse) and chronic (press-type) stressors, including ocean acidification, an insidious driver of change that will steadily erode coral resilience (Anthony *et al.,* 2011, Anthony and Marshall 2012). While thermal anomalies are climate change driven acute events that lead to coral mortality or sub-lethal stress (Berkelmans *et al.,* 2004, Wooldridge *et al*., 2005), elevated mean sea temperatures also suppress coral growth rate (De'ath *et al.,* 2009), which is a key resilience indicator (McClanahan *et al*., 2012). The synergistic impacts of multiple disturbances have been documented in French Polynesia, where reefs experienced one tropical cyclone and four thermal bleaching events between 1991 and 2006. Large declines in coral cover from approximately 51 per cent to approximately 22 per cent after the cyclone were followed by a phase-shift to algal dominance; however, this did not persist. Instead, coral community composition changed, returning to pre-disturbance coral cover within a decade (Adjeroud *et al.,* 2009). This demonstrates the resilience of coral reefs to recover after extreme events, at least in terms of coral cover, however with the loss of coral diversity and community complexity.

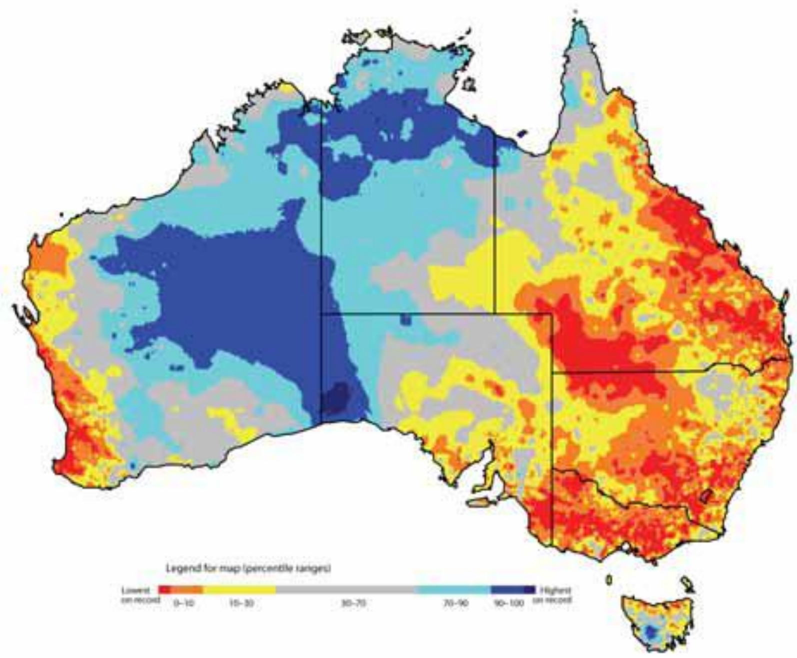
Great Barrier Reef ecosystems are increasingly threatened by multiple disturbances, and a critical challenge is to find management actions that promote recovery and maintain ecosystem resilience. The cumulative impacts of extreme events, such as floods, tropical cyclones, crown-of-thorns starfish outbreaks and thermal stress act to exacerbate the chronic impacts of poor water quality, which remains a major driver of change. Ultimately, extreme events will be difficult to manage directly and together with chronic poor water quality can erode the ability of ecosystems to cope with or recover from future disturbances and change. Improving water quality entering the Great Barrier Reef from the catchment however can be managed and will be a critical resilience strategy in the face of increasing intensity of extreme events and ocean acidification.

## Increased incidence of extreme events since 2008

Extreme weather events experienced in Australia during 2010 and 2011 were associated with a La Niña phase of the El Niño–Southern Oscillation (ENSO). El Niño–Southern Oscillation is a major source of inter-annual climate variability in northeast Australia with La Niña producing cooler wet conditions and El Niño producing hot dry conditions (Lough and Hobday 2011). It is often quantified using the southern oscillation index (SOI), which is an indication of the phase and intensity of El Niño–Southern Oscillation, calculated using the pressure difference between Tahiti and Darwin. During typical El Niño events (negative southern oscillation index), the summer monsoon circulation is weaker than normal and is associated with more frequent south-easterly winds. Cloud cover is reduced, increasing radiation and elevating sea surface temperatures (SST), with considerably lower rainfall and river flows than in La Niña years. During typical La Niña events (positive southern oscillation index), the summer monsoon circulation is stronger than normal with more frequent north-westerly winds and with cloud cover, rainfall and river flows all higher than average. El Niño–Southern Oscillation drives the strength of the summer monsoon circulation, thus tropical cyclone formation and intensity are both typically greater during La Niña years. Overall, the level of disturbance is greater during La Niña events when the more vigorous summer monsoon circulation and heightened tropical cyclone activity causes enhanced rainfall and river flow (Lough and Hobday 2011).

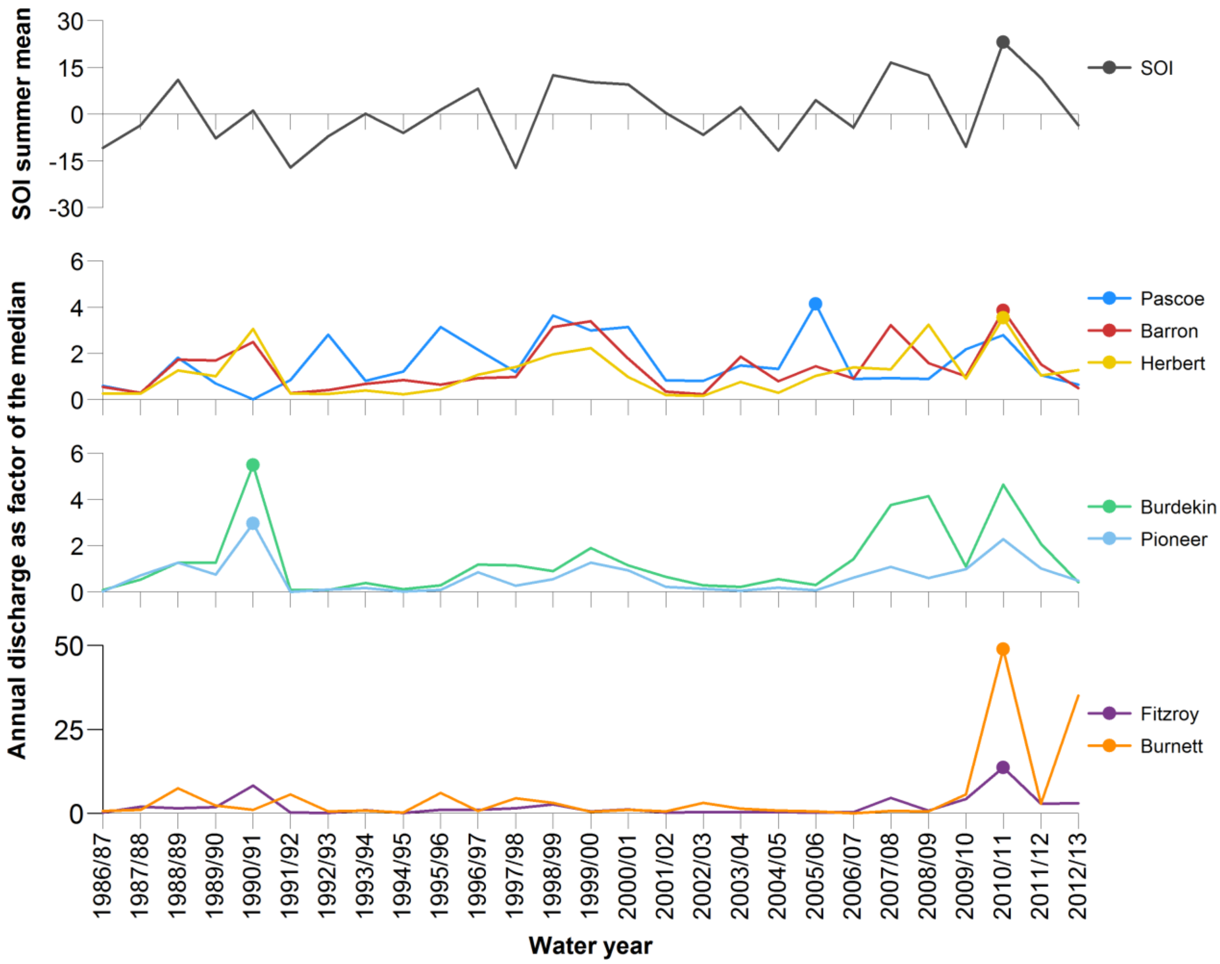
From the early 1990s through to mid-2000s the Great Barrier Reef catchment experienced a number of strong El Niño-related events, (negative southern oscillation index), especially in the central and southern sections. The culmination of over a decade of below average rainfall led to a drought that has been compared with the worst drought ever recorded in Australia (DNRW 2007). Many of the Great Barrier Reef catchments had rainfall less than the 10$^{th}$ percentile for the period 2001–2007 (Figure 2). These drought conditions lead to reduced groundcover across large areas. Drought-breaking rains resulted in increased loads of sediment and nutrients being exported from the catchment. The implications of these extreme weather patterns historically is documented in the sediment signature of coral cores taken from the Great Barrier Reef (McCulloch *et al.,* 2003).

**Figure 2.** Rainfall from April 2001 to January 2007 relative to historical long term records of average rainfall (DNRM 2007).



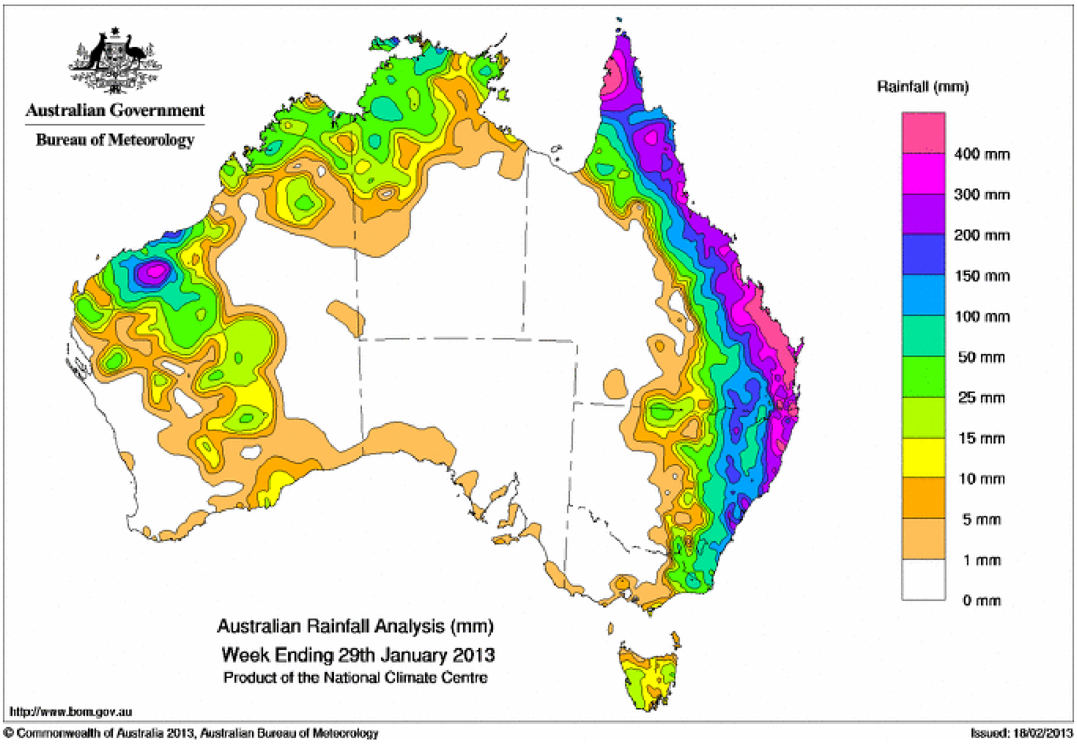

A very strong La Niña began in mid-2010, and December 2010 had the highest monthly southern oscillation index value since 1973. This resulted in the 2010-2011 wet season having extreme rainfall, both intense and prolonged, and the largest floods on record in multiple Great Barrier Reef river basins. In 2010-2011, the Burnett and Fitzroy Rivers had the largest flood events since records began (1971 and 1964, respectively) with annual discharges 49 times and 14 times the 25-year medians (1987-2011), respectively (Figure 3). The magnitude of annual discharge for 2010-2011 tended to be larger in southern and central river basins than in northern river basins. In the Pioneer and Burdekin Rivers, the 2010-2011 floods were 2.3 and 4.6 times the median, respectively. In the Herbert and Barron Rivers the 2010-2011 floods were the largest flows on record at 3.5 and 4.0 times the 25-year median values, respectively (Figure 3).

**Figure 3.** Annual time-series of the summer mean southern oscillation index (SOI), and river discharge as a factor (multiple) of the median annual discharge since 1986, to enable comparisons between seven river gauges with long term records draining into the northern, central and southern Great Barrier Reef lagoon. Annual discharge equal to the median value at each site has a value of one. Filled circles show the maximum value in each time-series. Note the difference in scale on the bottom plot. The 2012-2013 discharges are for the six-month period October to March. Data source: monthly flows http://watermonitoring.derm.qld.gov.au; monthly southern oscillation index http://www.bom.gov.au




In January 2013, extreme rainfall again fell over the east coast of Queensland due to former Tropical Cyclone Oswald (Figure 4; BoM 2013). Although it didn't cause major physical damage to Great Barrier Reef ecosystems, former Tropical Cyclone Oswald caused record daily rainfall at Rockhampton (more than 400 millimetres) and in the Burnett catchment (Gayndah 282 millimetres; Mt Perry 345 millimetres; Mundabbera 315 millimetres; Monto 185 millimetres; and Bundaberg), while Gladstone set records for its highest four-day rainfall (820 millimetres).The river height record was broken at Bundaberg (9.53 metres for the Burnett River), although the limited duration and spatial extent of this system meant that annual river discharges in most basins were smaller than in 2010-2011 (Figure 3). The extreme rainfall and flooding experienced in 2012-2013 occurred in a climate system that contains vastly more heat compared with 50 years ago (Trenberth 2012) and has been influenced by the shifting climate (Climate Commission 2013a). Although determining the nature of that influence is more complex for rainfall than for temperature-related extreme events, observations by scientists worldwide affirm the basic physics that heavy rainfall becomes more likely as the climate warms (Climate Commission 2013a,b).

**Figure 4.** Rainfall from 23-29 January 2013 showing the extreme wet conditions in Queensland and the Great Barrier Reef catchment (Source: www.bom.gov.au/jsp/awap/rain).




## How does extreme weather affect Great Barrier Reef catchments and pollutant loads?

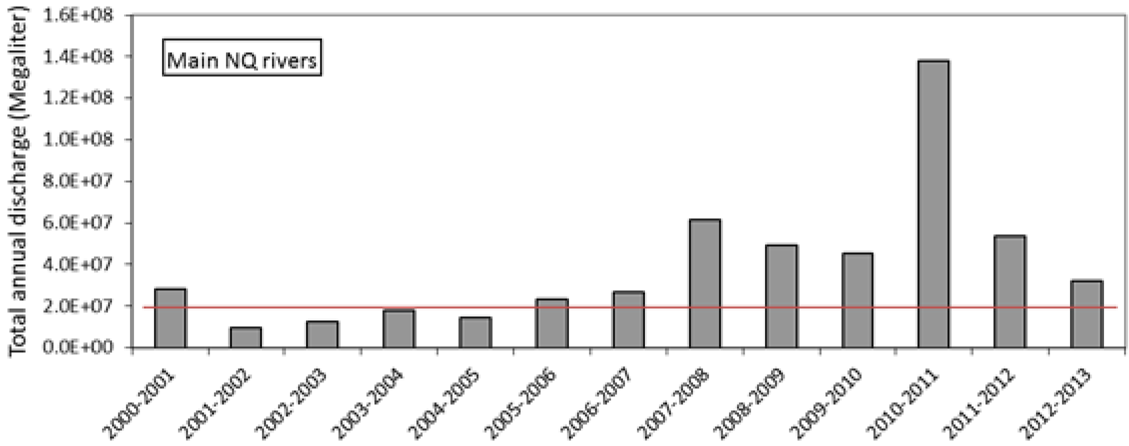
The exposure of Great Barrier Reef ecosystems to large flood events, and hence the resilience required to recover from those events, is spatially variable depending on:

(1) their *proximity* to the coast
(2) the *magnitude* of a given flood, particularly relative to the long-term flood variability to which ecosystems may be adapted
(3) the *pollutant load* delivered (water quality in flood events).

The flood magnitude is also an indicator of the area of the Great Barrier Reef lagoon directly impacted by flood waters (see section on *What is the extent of impacts of episodic events across the Great Barrier Reef*?). Extreme weather events, such as intense rainfall and tropical cyclones have the potential to increase flood magnitude and pollutant load, as well as the frequency with which significant floods occur. This will have implications for the exposure of inshore ecosystems to flood waters and subsequent ecological impacts.

The proximity of marine ecosystems – seagrass and coral reefs – to river discharges has a north-south gradient, with ecosystems in the far north and Wet Tropics being closer to the coast, and therefore experiencing greater exposure to flood waters, than ecosystems in the central and southern Great Barrier Reef. Total river discharges to the Great Barrier Reef lagoon have been above the median since 2007-2008, with significant flows in 2010-2011 (Figure 5).

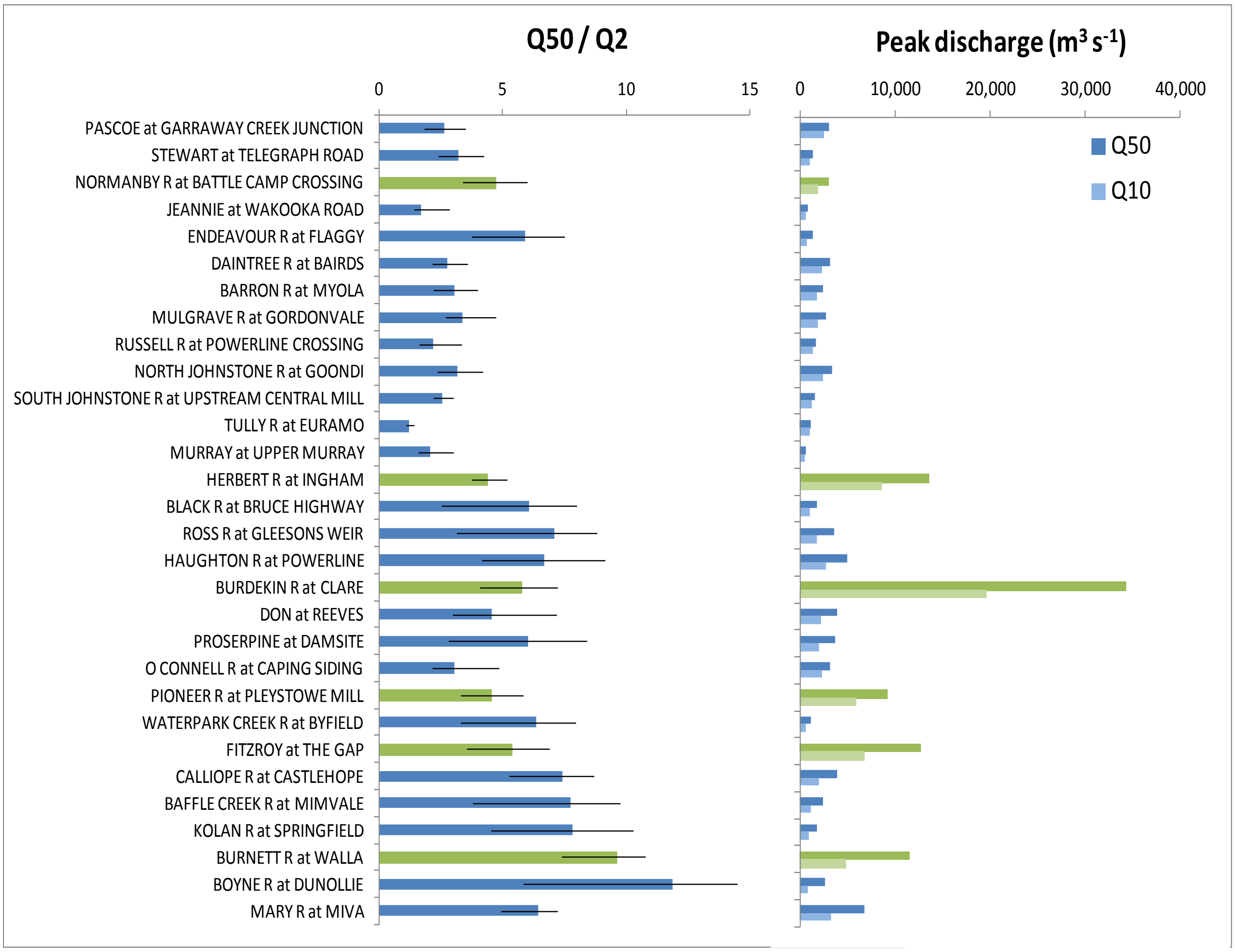
**Figure 5.** Total discharge from main Great Barrier Reef rivers showing above median flow since 2007-2008 (Data source: http://watermonitoring.derm.qld.gov.au)




The ecological significance of flood events in recent years is driven by flood magnitude relative to the median annual discharge. In terms of the regional significance of recent flood events, the relative magnitude has a latitudinal gradient, with the largest floods occurring in central and southern rivers (Figure 3). This analysis includes the top five rivers in terms of peak absolute instantaneous flood discharge, which are the Burdekin, Herbert, Fitzroy, Burnett and Pioneer (Figure 6).

The north-south gradient in recent flood magnitudes is consistent with a general increase in long-term flood variability from north to south (Figure 6). The Wet Tropics rivers tend to experience more regular flood events (smaller magnitude but higher frequency) and conversely, rivers in the Dry Tropics – Burnett-Mary, Fitzroy and Burdekin regions – typically have small discharges in many years interspersed by relatively larger flood events (Figure 6).

**Figure 6.** Left: Flood variability at selected Great Barrier Reef river gauges, represented by the ratio of the peak discharge of the flood with 50 year recurrence interval relative to peak discharge of the flood with two-year recurrence interval (Rustomji *et al.,* 2009). Error bars show 90 per cent confidence interval based on bootstrap resampling. Right: Peak flood discharges. Rivers stations plotted in green have the largest peak discharge in each natural resource management region.




Due to catchment activities, pollutant loads of the Wet Tropics river basins are the largest source of dissolved inorganic nitrogen to the Great Barrier Reef, while the Burdekin and Fitzroy river basins are the largest source of total suspended solids (see Chapter 4).

In summary, recent large flood events in the Great Barrier Reef catchment, particularly in 2010-2011, are highly significant against the long term records. An increase in flood magnitude is consistent with expectations based on global warming science (Climate Commission 2013b). The spatial patterns of these recent floods are consistent with long-term flood variability in the central and southern Great Barrier Reef basins, and this spatial trend is an indication of the locations where future events are likely to be more extreme.

## What is the extent of impacts of episodic events across the Great Barrier Reef?

The spatial and temporal extent of flood plumes in the Great Barrier Reef has been tracked using remote sensing combined with traditional surface sampling to determine pollutant concentrations (Devlin and Schaffelke 2009, Devlin *et al.,* 2012a,b, Schroeder *et al.,* 2012, Alvarez-Romero *et al.,* 2013). Concentrations of dissolved and particulate material in flood plumes have been shown to be two to 100 times higher than under non-flood conditions (Schaffelke *et al.,* 2012, Furnas *et al.,* 2011, Bainbridge *et al.,* 2012), and can remain elevated for many weeks and over distances of ten to hundreds of kilometres. Several water quality pollutants show strong, persistent concentration gradients from inshore to offshore and, less pronounced, from north to south (De'ath and Fabricius 2008).

Coral proxies have provided evidence of increased sediment export to the Great Barrier Reef lagoon from the Burdekin River (McCulloch *et al.,* 2003, Lewis *et al.,* 2007) while nitrogen isotopes in the (insoluble) organic component of the coral skeleton have been used to quantify increases in nutrient loads from the Pioneer River (Marion 2007, Jupiter *et al.,* 2007, 2008). Modelling studies have linked this pollutant discharge to reef ecosystem exposure to determine possible ecological effects (Devlin *et al.,* 2003, Wolanski and De'ath 2005, Wooldridge *et al.,* 2006, Alvarez-Romero *et al*., 2013). In the future, linking end-of-catchment pollutant loads with marine ecosystem impacts in near real-time will be possible through receiving water models to be developed by eReefs[1].

A semi-quantitative assessment of the exposure of Great Barrier Reef coral reefs and seagrasses to total suspended solids and dissolved inorganic nitrogen (see Chapter 3) identified the area of potential risk using a range of different techniques (Alvarez-Romero *et al.,* 2013, Devlin *et al.,* 2012a, Schroeder *et al.,* 2012). The composition of plume waters provides information on the gradient of risk through the duration of the plume (Devlin *et al.,* 2012a), with the gradient identified by the variable surface exposure to total suspended solids, dissolved inorganic nitrogen and coloured dissolved organic matter (measured by a salinity proxy) (Table 1). The variability of the results demonstrates the dispersal patterns and area of influence as the plume moves along the coast and extends offshore. The primary (nearshore) plumes are the most turbid component with high total suspended solids, and are typically constrained along the narrow coastal zone and therefore cover the smallest area in the inshore Great Barrier Reef. In contrast, the full extent of a flood plume is the maximum spatial coverage of primary, secondary (characterised by elevated chlorophyll *a*, a proxy indicator for dissolved inorganic nitrogen; Furnas *et al.,* 2005) and tertiary (characterised by elevated coloured dissolved organic matter) waters and covers the greatest area of the Great Barrier Reef lagoon, often reaching mid-shelf reefs. Estimating plume extent based on specific remote sensing parameters can provide variable estimates of plume extent due to the remote sensing attribute being utilised to map the plume. Ultimately, the exact area of exposure does not need to be quantified but the location and frequency of exposure is critical for identifying ecosystems most at risk from flood events, and which pollutants of concern are most likely to be present in the plume.

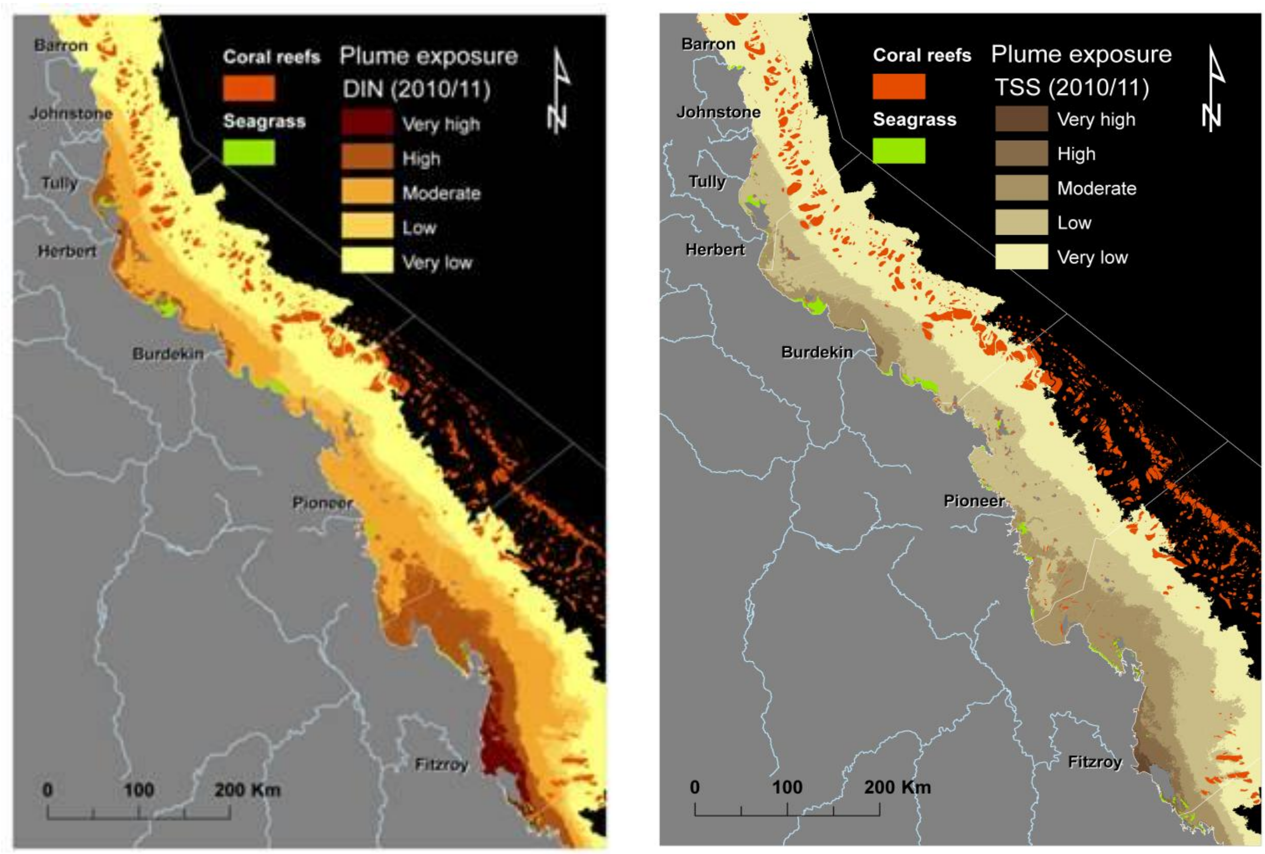
**Table 1.** Maximum area (square kilometres) covered by flood plume waters in 2010-2011 calculated using different mapping techniques: true ocean colour classification (Alvarez-Romero *et al.,* 2013), surface area of high exposure to total suspended solids and dissolved inorganic nitrogen (Devlin *et al.,* 2012a, Alvarez-Romero *et al.,* 2013) and coloured dissolved organic matter elevated levels (Schroeder *et al.,* 2012). Area calculated in true ocean colour includes reefs and seagrass. Area calculated through coloured dissolved organic matter mapping excludes coral reefs. Note this is a maximum value and does not reflect concentration gradients within the extent values.

| Flood plume component | Cape York | Wet Tropics | Dry Tropics (Burdekin) | Mackay Whitsunday | Fitzroy | Total |
|---|---|---|---|---|---|---|
| Primary plume (True ocean colour) | 4142 | 6120 | 10,454 | 7094 | 20,464 | 48,274 |
| Full plume extent – primary, secondary & tertiary (True ocean colour) | 55,474 | 24,877 | 35,771 | 23,940 | 43,911 | 183,973 |
| Surface total suspended solids and dissolved inorganic nitrogen (Ocean colour) | n/a | 23,954 | 32,925 | 41,809 | 63,714 | 122,558 |
| Salinity extent – coloured dissolved organic matter | 4849 | 4593 | 8034 | 4486 | 14,456 | 36,418 |

[1] www.bom.gov.au/environment/eReefs_Infosheet.pdf

Coastal marine ecosystems can experience variable water quality conditions associated with the input of land-based nutrients and sediments (see Chapter 3), reflecting the differences in the dispersal of pollutants and the locations of the habitats. Recent work illustrates this variability in the modelling of pollutant exposure for total suspended solids and dissolved inorganic nitrogen, where the extent of the surface exposure is strongly related to both plume movement and regional load distribution (Alvarez-Romero *et al.,* 2013, Devlin *et al.,* 2012a). The mapping of flood plumes in the 2010-2011 extreme wet season illustrates the degree of pollutant exposure that can be expected under extreme weather conditions in the future (Devlin *et al.,* 2012a). The degree of exposure is an equidistant measure of five classes ranked between zero and one. The exposure value is calculated from the integration of plume frequency, surface pollutant transport and the river loads. This extreme flooding manifested in extensive plumes in Great Barrier Reef coastal and offshore waters (Figure 7).

**Figure 7.** Maps of annual exposure of coral reefs and seagrass to dissolved inorganic nitrogen (DIN) (left) and total suspended solids (TSS) (right) for 2010-2011 wet season reported in Alvarez-Romero *et al.,* 2013. The progression in intensity of colour indicates the degree of exposure. Note that exposure categories reported in recent published work such as Alvarez-Romero *et al.,* 2013 is mapped over five equidistant categories based on total suspended solids or dissolved inorganic nitrogen loads, plume movement and transport models. This work is further developed in Chapter 3 where exposure is grouped into three categories to align with other risk assessment parameters.




The cumulative area of the Great Barrier Reef exposed to total suspended solids and dissolved inorganic nitrogen from the Burdekin, Fitzroy and Wet Tropics rivers is approximately 135,797 square kilometres or 39 per cent of the Great Barrier Reef Marine Park. The largest plume-influenced areas are found adjacent to the Burdekin and Fitzroy rivers, which correlates with the size of these catchments and the magnitude of peak river flow. There are substantial differences in the area of habitat exposed to surface movement of dissolved inorganic nitrogen and total suspended solids, which is determined by the natural distribution of these habitats, as well as by the transport processes associated with each pollutant (Alvarez-Romero *et al.,* 2013, Brodie *et al.,* 2012). A review of Great Barrier Reef areas exposed to total suspended solids and dissolved inorganic nitrogen each wet season found that seagrass meadows are commonly exposed to higher concentrations of total suspended solids and dissolved inorganic nitrogen due to their proximity to river mouths, and most coral reefs have only low exposure to dissolved inorganic nitrogen and particularly total suspended solids (Alvarez-Romero *et al.,* 2013; see Chapter 3).

## How have recent extreme events impacted Great Barrier Reef ecosystems?

Declines in coral cover on the Great Barrier Reef (documented by De'ath *et al.,* 2012) showed a change in average cover from 28 per cent to 14 per cent since 1985. The major drivers of the decline were identified as damage by tropical cyclones (48 per cent of the loss), coral predation by crown-of-thorns starfish (crown-of-thorns starfish; 42 per cent) and coral bleaching (10 per cent). Estimates show that coral cover has the potential to increase by almost three per cent per year when cyclones, crown-of-thorns starfish and bleaching are removed as drivers of change; a clear demonstration of the capacity of reefs to recover. While the study did not consider chronic drivers of coral decline, such as poor water quality and disease, and is therefore likely to be an overestimate of their actual contribution to the documented decline, cyclones, crown-of-thorns starfish and bleaching are still key drivers of change and are likely to increase as a result of more intense extreme events in the future.

The projected increase in intensity of extreme events, such as cyclones and thermal stress events (Climate Commission 2013b) will exacerbate chronic stressors like poor water quality on sensitive Great Barrier Reef ecosystems (coral reefs and seagrasses) (Veron *et al.,* 2009, Waycott *et al.,* 2009, Anthony *et al.,* 2011). For example, the correlation between elevated nutrients and lower coral bleaching thresholds (Wooldridge and Done 2009) has been demonstrated experimentally by Wiedenmann *et al.,* (2012). This study showed that nutrient enrichment – specifically nutrient imbalance – can increase the susceptibility of reef corals to thermal stress and bleaching. Thus addressing chronic stress like poor water quality remains an important management strategy to avoid further declines in reef condition.

Seagrasses also face an array of pressures in the Great Barrier Reef as human populations increase and the potential effects of climate change, such as increased storm activity, come into play (Waycott and McKenzie 2010, Grech and Coles 2010). Little is known about the physiological mechanisms that control seagrass responses to nutrient enrichment. Increased growth is generally expected until limited light availability results in seagrass decline (Touchette 2000). Chronically elevated nutrients have been reported to lower the availability of light to seagrasses due to increased growth of algae and epiphytes on the plants (Burkholder *et al.,* 2007). Chronic and pulsed increases in suspended sediments that increase turbidity can also reduce light and result in reduced productivity and potentially seagrass loss (Waycott and McKenzie 2010). Prior to the extreme events of 2011, seagrass meadows along the Great Barrier Reef were reported to be in a state of decline (McKenzie *et al.,* 2010). Declining plant abundance was noted with limited or absent seed production at many locations. Both are likely to be a consequence of nutrient enrichment (elevated nitrogen) and reduced light availability due to suspended sediments that increase turbidity (McKenzie *et al.,* 2010). These factors have made seagrass populations vulnerable to episodic disturbance in the late 2000s (van Katwijk *et al.,* 2010). In fact, widespread and substantial losses were documented after Tropical Cyclone Yasi and the associated flooding in February 2011 (McKenzie *et al.,* 2012), and habitat recovery will depend on the abundance of seed stock and the period between disturbances.

Flow-on effects to the marine animals that depend on coral reef and seagrass habitats have also been documented. Fish assemblages have been shown to change across water quality gradients (Fabricius *et al.,* 2005) and in response to loss of coral habitat (Halford *et al*., 2004, Yahya *et al*., 2011, Wilson *et al*., 2009). High dugong mortality in Queensland during 2011 was recorded (Meager and Limpus 2012) with 168 reported deaths between January and October 2011, compared to 73 in 2010, 47 in 2009, and 35 in 2008. This is believed to be due mainly to starvation associated with the loss of seagrass meadows (Bell and Ariel 2011). In this same period, approximately 1100 turtles (mostly green turtles) were reported as stranded on the Queensland coast, compared with 624 in the same period in 2010, 715 in 2009, and 645 in 2008 (Meager and Limpus 2012). Any future declines in seagrass meadows are expected to threaten the viability of turtles and dugong, particularly the southern Great Barrier Reef population as survey results from 2011 to 2013 documented a decline from more than 2000 to approximately 600 individuals (Sobtzick et al. 2012).

Coastal (freshwater and marine) wetlands are an important habitat that perform a filtration role for terrestrial waters before they enter the Great Barrier Reef, and are at risk from extreme events combined with sea-level rise. As sea-level rises, storm surges will inundate low lying coastal areas impacting on wetlands that are in integral part of the Queensland coast (Low 2011). Changing rainfall patterns (particularly greater variability of rainfall and more extreme events) are expected to have pronounced effects on wetlands through alterations to hydrological regimes (Erwin 2009, Scavia *et al.,* 2002) and increased flooding duration due to sea-level rises (Day *et al.,* 2004). Consequently, the weight of evidence suggests that the important role that coastal wetlands play in water purification is likely to be compromised, ultimately affecting downstream water quality in the Great Barrier Reef.

## *Flood plume impacts*

Nutrients associated with flood plumes have played a profound role in shaping current coastal processes within the Great Barrier Reef. Until recently a lack of baseline observations of community dynamics had made it difficult to tease apart differences in coral communities that are the result of naturally occurring environmental gradients from those resulting from chronic increases of nutrients, sediments and pesticides (see Chapter 1). The last 10 years of research and monitoring have added further evidence that shows that high levels of nutrients, sediments and turbidity from degraded water quality alters the physiology of inshore corals, impacting on the resilience of inshore coral reef communities and making them more vulnerable to the impacts of climate change (Fabricius 2010). In addition, the frequency of coral diseases has been linked to other stressors such as elevated nutrients (Bruno *et al.,* 2003, Haapkyla *et al.,* 2011) and thermal stress (Selig 2006, Bruno *et al.,* 2007). On Great Barrier Reef inshore reefs the incidence of disease has shown repeated increases following recent major flood events (Thompson *et al.,* 2011).

A major long-term downstream effect of the increased loads of nutrients in flood plumes is postulated to be the triggering of outbreaks of the coral-eating crown-of-thorns starfish (*Acanthaster planci*), which kill significant areas of reef on the Great Barrier Reef (De'ath *et al.,* 2012). The last three outbreaks of crown-of-thorns starfish originated on reefs north of Cairns, the only part of the main reef track regularly influenced by flood waters. Each outbreak was observed three to five years after the largest three floods events on record. It is now thought that the survival and growth of crown-of-thorns starfish larvae is enhanced by increasing concentrations of large phytoplankton that are dependent on the availability of terrestrially-derived nutrients (dissolved inorganic nitrogen and dissolved inorganic phosphorus) Houk *et al.,* (2007) linked the primary driver of outbreaks to a transition zone chlorophyll front. Present day outbreaks can also be influenced by other anthropogenic changes (Brodie *et al.,* 2005, Fabricius 2010), including removal of adult predators (Endean 1982), changes to population structures of predators on larval and juvenile stages (Randall 1972), destruction of larval predators (Chesher 1969) and larval food supply enhancement (Birkeland 1982, Brodie 1992).

Several studies undertaken during the 2010-2011 wet season as part of a the Reef Rescue Marine Monitoring Program measured ecosystem status in the Great Barrier Reef, particularly related to inshore seagrass meadows (McKenzie *et al.,* 2012) and coral reefs (Thompson *et al.,* 2011). Additional studies (e.g. Berkelmans *et al.,* 2012) on the impacts from the 2010-2011 wet season on coral reefs were undertaken in the Keppel Islands (offshore from the Fitzroy River) and showed increased juvenile coral mortality and seagrass impacts, including mortality and decreased areal coverage after the 2011 flood event. However, these impacts were further exacerbated by long periods of exposure to low salinity and high turbidity associated with the flood (McKenzie *et al.,* 2012). Complete seagrass recovery (to more than the 50$^{th}$ percentile abundance and more than 70 per cent distribution foundation species) is expected to take several years, but will depend on habitat condition prior to the impact, the severity of the impact, and whether any future disturbances are experienced. This is also true of corals, where the extreme flooding and associated reduced salinity and turbidity resulted in the loss of coral cover and diversity and subsequent interactions with chronic water quality pressures has potentially retarded recovery (see Chapter 1).

In summary, the management and mitigation of water quality impacts is directly linked to the management of terrestrial derived pollutants. A reduction in nutrient losses from the catchment appears to be essential to halt and reverse further losses in Great Barrier Reef ecosystem performances at a time of rapidly warming climate and progressive ocean acidification. A reduction in catchment-derived pollutants is required to halt and reverse further losses in Great Barrier Reef ecosystem performances at a time of rapidly warming climate and progressive ocean acidification.

### *Tropical cyclones*

In the Great Barrier Reef, acute stresses experienced during cyclones cause physical and physiological damage to corals and seagrass through storm surge, wave action, large discharges of freshwater, and high sediment and nutrient exposure (Fabricius *et al.,* 2008, Brodie and Waterhouse 2011, Woolsey *et al.,* 2012). Given sufficient fetch, sustained gale force winds 17 metres per second and greater can generate waves capable of damaging corals or seagrasses. Since 2008, seven tropical cyclones have produced such winds in the Great Barrier Reef: Tropical Cyclones Ellie and Hamish in 2009, Tropical Cyclones Tasha, Olga and Ului in 2010, and Tropical Cyclones Anthony and Yasi in 2011 (Table 2). All of these storms produced a minimum of nine hours of gale force winds in the Great Barrier Reef with gale force winds affecting a minimum of 1781 square kilometres of coral reef area (approximately nine per cent of total Great Barrier Reef Marine Park reef area). Several notable cyclones (Althea 1971, Winifred 1986, Joy 1990, Celeste 1996, Justin 1997) have affected the Great Barrier Reef since accurate records of cyclones began in 1969. However, none of these exceeded category three while within the Great Barrier Reef until cyclone Ingrid crossed the coast in 2005 (Puotinen 2007).

Tropical Cyclones Hamish and Yasi were the most severe storms to enter the Great Barrier Reef since 1969 in terms of the mean radius to gales (the storm circulation size), the maximum wind speed, and the total reef area affected by gale force and severe cyclone force (33 metres per second and greater) winds. Tropical Cyclones Hamish and Yasi could be characteristic of the predicted intense cyclones that are projected to occur with greater frequency in the coming decades. Intense cyclones are extremely significant drivers of change of habitat condition at large spatial scales. During both Tropical Cyclones Hamish and Yasi, nearly half of the coral reef area in the Great Barrier Reef was exposed to gale force winds with the potential to cause damage. During Tropical Cyclone Yasi, approximately 15 per cent of the reef area in the Great Barrier Reef sustained some coral damage and six per cent was severely damaged resulting in an estimated loss of two per cent of coral cover in the Great Barrier Reef in those 24 hours alone (GBRMPA 2012a). It was also estimated that approximately 98 per cent of the intertidal seagrass area was lost within the affected zone as a consequence of the destructive winds of Tropical Cyclone Yasi, and only a few isolated shoots remained in coastal and reef habitats (McKenzie *et al.,* 2012). Cyclone damage is likely to remain a key driving force of change in the Great Barrier Reef in the future (Osborne *et al.,* 2011, De'ath *et al.,* 2012).

**Table 1.** Tropical storms that produced at least gale force winds since 2009. Storms are written in descending order by total reef area affected by gale force winds (Data source: M. Puotinen). Hpa: hectopascals, m/s: metres per second; +m/s: metres per second and greater.

| Tropical Cyclone Name | Dates | Minimum central pressure (hpa) | Mean central pressure (hpa) | Mean radius to gales in km (size) | Max wind speed (m/s) | Max duration of 17+ m/s gales (hrs) | Max duration of 33+ m/s winds (hrs) | Total reef area in 17+ m/s gales (km2) | Total reef area in 33+ winds (km2) |
|---|---|---|---|---|---|---|---|---|---|
| Hamish | 7-11 March 2009 | 925 | 946 | 240.05 | 62.66 | 31 | 16 | 12,754.90 | 4459.92 |
| Yasi | 2 February 2011 | 930 | 930 | 310.21 | 68.00 | 17 | 8 | 8769.95 | 1170.96 |
| Ului | 20 March 2010 | 964 | 964 | 214.17 | 43.87 | 10 | 3 | 6953.03 | 513.25 |
| Anthony | 30 January 2011 | 984 | 987 | 17.60 | 29.00 | 10 | 0 | 3928.44 | 0.00 |
| Olga | 24 January 2010 | 980 | 991 | 136.86 | 32.11 | 20 | 0 | 2900.05 | 0.00 |
| Tasha | 24 December 2010 | 993 | 995 | 136.86 | 22.48 | 9 | 0 | 1932.85 | 0.00 |
| Ellie | 1 February 2009 | 991 | 991 | 120.38 | 23.75 | 19 | 0 | 1781.13 | 0.00 |

## *Thermal stress*

Periods of higher-than-normal sea surface temperature are stressful to corals and have caused severe and spatially-extensive coral bleaching events in the Great Barrier Reef since the 1980s (Hoegh-Guldberg *et al.,* 2007). The 1998 and 2002 major bleaching events affected reefs throughout the Great Barrier Reef and each event is thought to have caused approximately five per cent coral mortality Great Barrier Reef-wide (Berkelmans *et al.,* 2004). A regional coral bleaching event also occurred in the southern Great Barrier Reef – centred in Keppel Bay – in 2006, and there have been no thermal stress events of note in the Great Barrier Reef since then. National Oceanic and Atmospheric Administration Coral Reef Watch uses remotely sensed data on sea surface temperature to predict the onset and extent of bleaching events and uses degree heating weeks as a measure of accumulated thermal stress. Degree heating weeks thresholds of four and eight degrees Celsius-weeks are indicative that moderate (25 per cent of corals affected) and severe (more than 50 per cent of corals affected) bleaching, respectively, is likely. The four degrees Celsius-weeks threshold was reached between 2008 and 2012 in less than 10 per cent of the reef-containing pixels, and the eight degrees Celsius-weeks threshold was not realised in any reef areas in 2008 or 2012, and was reached in less than two per cent of reef areas from 2009-2011 (Table 3). During this period, no extensive or severe bleaching was documented though local-scale and minor bleaching was noted in some parts of the far northern Great Barrier Reef in 2010-2011, as well as reports of localised bleaching in the Torres Strait[2]. The lack of severe thermal stress events recently obscures the importance of thermal stress as a future driver of change to Great Barrier Reef ecosystems. Bleaching events caused by thermal stress are expected to become both more frequent and more severe as the climate changes (Hoegh-Guldberg *et al.,* 2007).

**Table 2.** Percentage of reef pixels with Degree Heating Weeks (DHW) exceeding four (moderate bleaching threshold) and eight (severe bleaching threshold) degree Celsius-weeks each year since 2008.

| Year | DHW =0 | DHW >0 | DHW ≥4 | DHW ≥8 |
|---|---|---|---|---|
| 2008 | 68.7 | 26.5 | 4.8 | 0.0 |
| 2009 | 54.3 | 37.3 | 7.2 | 1.2 |
| 2010 | 7.3 | 85.5 | 6.0 | 1.2 |
| 2011 | 56.7 | 34.9 | 7.2 | 1.2 |
| 2012 | 56.6 | 43.4 | 0.0 | 0.0 |
| 2013 | 65.1 | 34.9 | 0.0 | 0.0 |

[2] http://www.tsra.gov.au/the-tsra

## *Cumulative impacts*

Great Barrier Reef ecosystems have always been dynamic with periods of recovery and maintenance punctuated by disturbances. Disturbance frequencies have been increasing recently and more of the same is expected in coming decades. It is for this reason that addressing chronic stressors caused by human activities, like degraded water quality, is recommended throughout this chapter. Improving water quality can decrease the sensitivity of corals and seagrasses to episodic disturbances when they occur, and improve recovery post-disturbance (see Wiedenmann *et al.,* 2012). The events of recent years have shown that disturbances can occur in some areas every year for consecutive years and can even occur during the same year in some areas; referred to as 'cumulative impacts'. There is a growing body of work using experimental studies to demonstrate the interactions between multiple stressors on reef organisms and the response of these organisms to drivers, such as thermal stress (e.g. Uthicke *et al.,* 2012, Negri and Hoogenboom 2011, Negri *et al.,* 2011) and tropical cyclones (Tobin *et al.,* 2010).

Analysis of cumulative pressures in the Great Barrier Reef – exposure to freshwater input from floods, cyclones, crown-of-thorns starfish outbreak and thermal stress – between 2001 and 2011 found areas of highest relative exposure are the inshore northern Great Barrier Reef, the inshore and mid-shelf central Great Barrier Reef, and the inshore southern Great Barrier Reef (Figures 8 and 9; Maynard *et al.,* in press). The areas of lowest relative exposure are most of the far northern Great Barrier Reef, some of the inshore Great Barrier Reef between Cooktown and Cairns, parts of the inshore Great Barrier Reef north-east of Bowen, and some of the inshore Great Barrier Reef south-east of Mackay. For reef areas only, the highest relative exposure reefs are in the far northern, offshore and 100 to 200 kilometres north and south of Cooktown, and in parts of the Capricorn Bunkers reefs (Figure 9).

**Figure 8.** Cumulative exposure map for the Great Barrier Reef Marine Park combining freshwater inundation, positive summer sea surface temperature anomalies, and damaging waves from tropical cyclones. Data are scaled from 0 to 1 with 1 being the site with the highest cumulative score, after summing scores for all three disturbances (also scaled from 0 to 1 by anchoring to the maximum value; the highest frequency or probability of the event occurring).

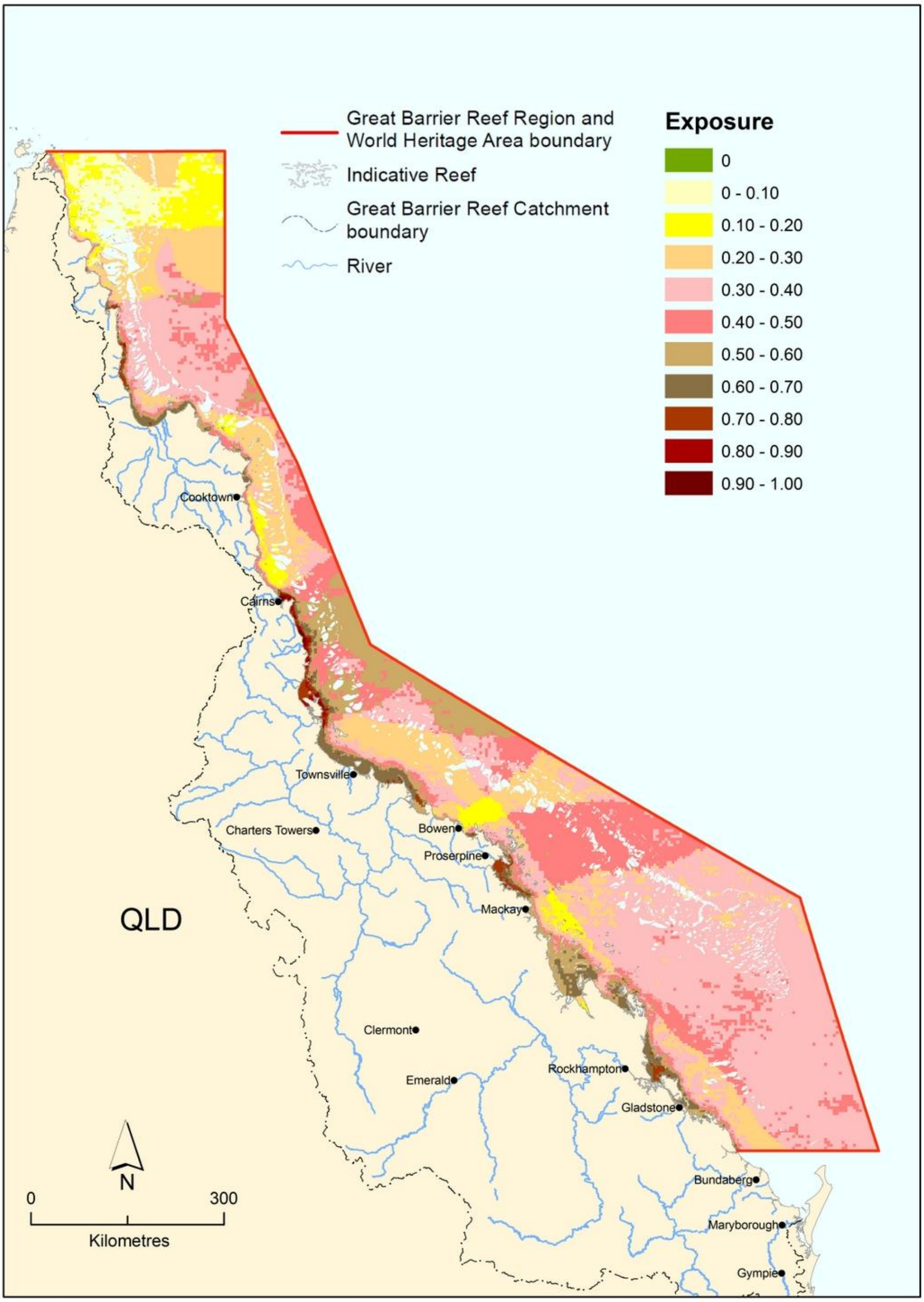
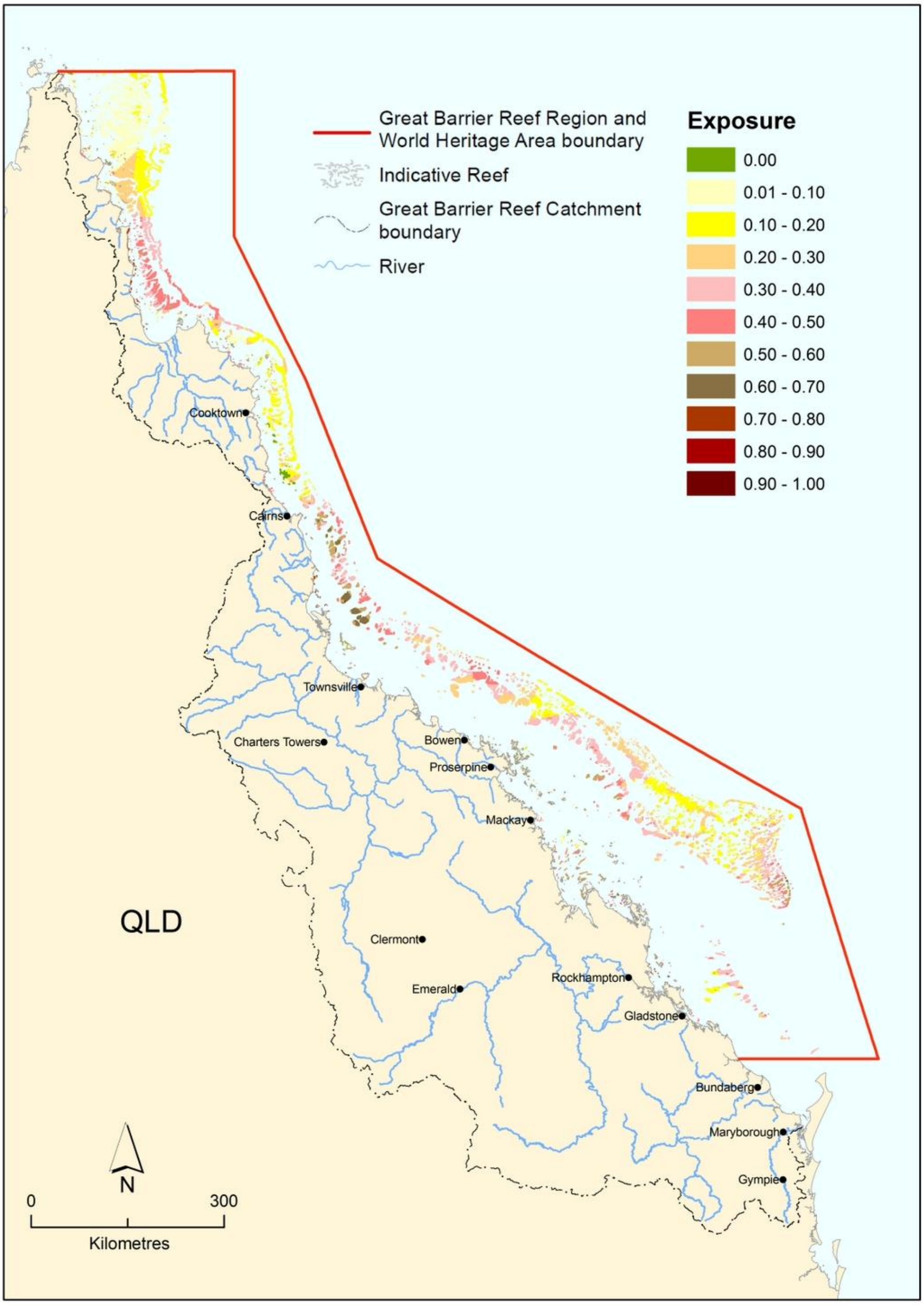


**Figure 9.** Cumulative exposure map for reefs in the Great Barrier Reef Marine Park combining freshwater inundation, thermal stress severe enough to cause bleaching, crown-of-thorns starfish and damaging waves from tropical cyclones. Data are scaled from 0 to 1 with 1 being the site with the highest cumulative score, after summing scores for all four disturbances (also scaled from 0 to 1 by anchoring to the maximum value; the highest frequency or probability of the event occurring).



## How will increasing drivers of change interact with other human pressures on the Great Barrier Reef?

While there has been little change in the last decade in the total area of the Great Barrier Reef catchment used for agricultural, urban and industrial development overall there have been shifts in land use leading to significant development intensification in areas of the coast (e.g. around 50 per cent increase in urban and industry footprint). The intensity of human development along the coast is also about four times that of the Great Barrier Reef catchment more broadly (GBRMPA 2012a). This intensity of development and the legacy of past development and impacts on water quality and ecosystem health have led to declines in inshore habitats and species (e.g. seagrass and saltmarsh habitats, species of sawfish; GBRMPA 2012a,b, McKenzie *et al.,* 2012) and coral communities (De'ath *et al.,* 2012).

The series of severe cyclones in the Great Barrier Reef since 2009 have not been experienced in that magnitude on the Great Barrier Reef for more than 100 years (Yu *et al.,* 2013). There is a legacy of development in places along the coast and in floodplains where the risk from extreme weather and other climate related impacts on both infrastructure and human life is significant (DCC 2010). Development in these areas has resulted in a significant threat of failure or loss of infrastructure, as witnessed following recent flooding and severe cyclones (QFCI 2012). For example, the QNI Refinery began operating in Townsville in 1974 and since 2009 has discharged nutrient-rich water into the Great Barrier Reef on at least three occasions through its emergency provisions. Justification under these provisions was the imminent arrival of cyclones (Tropical Cyclones Hamish and Yasi) and that the holding dam would exceed safe operating capacity with the risk of catastrophic failure. The last discharges in 2011 were reported as 759 megalitres of polluted water, which added an estimated 425 tonnes of nitrogen to inshore Great Barrier Reef waters. This load equates to around 20 per cent of the annual discharge of nutrients from the Burdekin River, released within a few days.

Effective planning is generally the tool used to address cumulative pressures associated with coastal development and industrial nodes. Management of coastal development to address increasing impacts from major weather events is recognised in Queensland's regulatory environment with the development of specific planning guidelines for coastal hazard areas (DEHP 2012). The Council of Australian Governments has recognised flooding and floodplain management as a national issue and national guidelines have been developed (SCPEM 2012, SCARM 2000). Following the extreme flooding in southern Queensland in 2011, the Queensland Flood Commission of Inquiry made a number of recommendations, including requirements for local government planning to minimise the ongoing risks from extreme weather through improved flood risk planning (QFCI 2012). All these actions can help to minimise the impact on water quality from coastal development during and after extreme events. Despite these efforts, development along coastal areas subject to increasing risk from extreme weather events continues to expand. The nature, location and extent of coastal development along the Great Barrier Reef coast can exacerbate the risk to water quality posed by extreme events.

Aside from flooding and the downstream effects on crown-of-thorns starfish outbreak likelihood, tropical cyclones also increase the risks associated with shipping, port and industrial development within and adjacent to the Great Barrier Reef Marine Park. The last two decades has seen an increase in major State Development Areas on the coastal fringe in Gladstone (1993), Townsville (2003), Abbott Point (2008) and Gladstone/Curtis Island (2008). While this allows synergies for infrastructure development, it also concentrates development pressure along the coast and is leading to a significant increase in shipping (GBRMPA 2009b). Shipping through the Great Barrier Reef, including vessels that transit and those that call at a trading port, has been increasing over recent years. In 2002, approximately 3200 vessels called at Great Barrier Reef ports and by 2012 this had increased to 3950, representing an average growth rate of 2.1 per cent over the decade. (Ports Australia 2012). A number of studies have attempted to estimate the likely increase in shipping traffic within the Great Barrier Reef and predict between 3000 and 10,000 Great Barrier Reef port calls by 2020 (GBRMPA 2013, PMG 2012), with the potential to increase the probability of extreme events causing major shipping incidences.

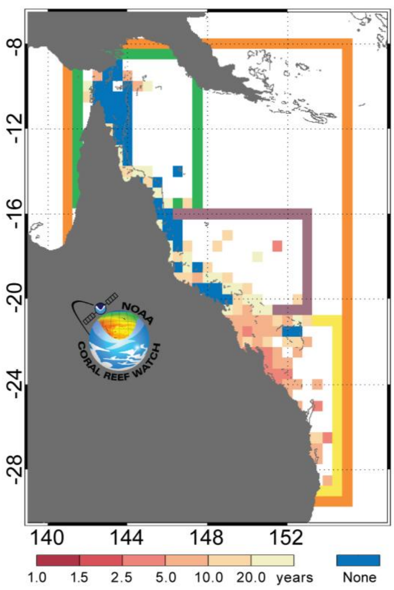
## What is the future for Great Barrier Reef ecosystem resilience?

Overall, the changing climate as observed and predicted within the Great Barrier Reef region will increase the frequency with which coral reefs and seagrass meadows are being disturbed by extreme events such as floods, tropical cyclones and thermal stress. Response to and recovery after these acute events will be exacerbated by chronic poor water quality, which also influences other drivers of ecosystem condition, such as crown-of-thorns starfish outbreaks and disease. The magnitude of impacts and the ability of ecosystems to recover from these events or transition to an alternative state, will depend on

(i) their condition prior to the disturbance
(ii) chronic environmental pressures, such as water quality
(iii) the return period between events compared with recovery time.

On a global scale, business-as-usual carbon emissions are predicted to escalate four key disturbances that will impact coral reefs, seagrass meadows and coastal wetlands: ocean warming (Hoegh-Guldberg *et al.,* 2007, Lough and Hobday 2011), the intensity of tropical cyclones (Knutson *et al.,* 2010), ocean acidification (Sabine *et al.,* 2004, Silverman *et al.,* 2009), and rising sea levels (Lough and Hobday 2011). Ocean warming is predicted to cause an increased frequency and intensity of thermal stress events (Donner *et al.,* 2009). During the past 15 years, several spatially extensive coral bleaching episodes have occurred on the Great Barrier Reef as a consequence of thermal stress (Berkelmans *et al.,* 2004, Oliver and Berkelmans 2009). Based on analysis of satellite data for the period 1985-2009, National Oceanic and Atmospheric Administration Coral Reef Watch has determined the average return period of bleaching-level thermal stress (degree heating weeks of four degrees Celsius-weeks and greater) for reefs in the Great Barrier Reef region (Figure 10). Return times between thermal stress events vary across the region and reveal an increasing trend in disturbance frequency from north to south. This analysis provides longer-term context to the absence of widespread thermal stress in the past five years, affirming that continued attention to thermal stress disturbances is warranted.

**Figure 10.** Return period of bleaching-level thermal stress events (Degree Heating Weeks of at least four degrees Celsius-weeks) for reef-containing pixels for the period 1985-2009. Median interval between thermal stress events is: northern Great Barrier Reef (green outline) – no events; central Great Barrier Reef (purple) – 25.0 years; southern Great Barrier Reef (yellow) – 6.3 years; entire Great Barrier Reef (orange) – 12.5 years. http://coralreefwatch.noaa.gov




The Great Barrier Reef has experienced five severe cyclones (categories four–five on the Saffir-Simpson scale) in the last decade, including three since 2008: Tropical Cyclone Hamish (category five) in 2009, Tropical Cyclone Ului (category four) in 2010 and Tropical Cyclone Yasi (category five) in 2011. It is unclear, however, whether this recent cluster of severe cyclones on the Great Barrier Reef represents a longer-term trend. Since the late 19th century, average rainfall and its variability have significantly increased, with wet and dry extremes becoming more frequent than in earlier centuries. More variable tropical Queensland rainfall (and associated flooding) is likely the consequence of a warming global climate (Lough 2011, Climate Commission 2013b).

Ocean warming, cyclones, acidification, degraded water quality and crown-of-thorns starfish outbreaks can all have lethal as well as sub-lethal effects on the physiological performance of organisms within Great Barrier Reef ecosystems, affecting their resistance to stress. Haapkyla *et al.,* (2011) stated that poor water quality coupled with climate change is increasing the incidence of disease in coral in the Great Barrier Reef. This influence of future climate change on the frequency of extreme events and the consequences for the Great Barrier Reef in terms of risk and recovery will depend on the return period between events. There is an (unquantified) threshold of disturbance event return periods where recovery and resilience is compromised – annual versus sub-decadal versus decadal.

The cumulative impacts from acute stressors, many of them driven by extreme events, are the result of reduced return intervals and the synergistic influence of poor water quality in increasing susceptibility and decreasing ecosystem resilience. Therefore improving water quality, and maintaining critical ecological processes can increase resilience and reduce vulnerability, reducing sensitivity to the disturbances and/or decreasing recovery times for marine ecosystems.

Addressing local scale impacts on tropical marine ecosystems is considered critical for maintaining healthy ecosystems in order to build resilience to future drivers of change, and secure future adaptation options for marine systems (Hoegh-Guldberg *et al.,* 2009, Anthony and Maynard 2011, Wilkinson and Brodie 2011, Bell *et al.,* 2013). Management will need to be coordinated and collaborative across sectors to reduce current stressors of deteriorating water quality, pollution and shipping (Hoegh-Guldberg *et al.,* 2009, Veron *et al.,* 2009, Wilkinson and Brodie 2011). The findings of Wiedenmann *et al.,* (2012) demonstrate how nutrient imbalances increase coral susceptibility to thermal stress and have implications for management as global warming begins to manifest. Ultimately, reef resilience will benefit from considering local nutrient profiles and adjusting agricultural and point source discharge practices in the proximity of coral reefs and seagrass meadows. The findings support the view that management of nutrient enrichment could reduce the effects of thermal stress on coral reefs, and potentially other disturbances.

## Overall conclusions

There is an immediate imperative for management to address water quality issues due to the projected increase in extreme events in the Great Barrier Reef and resultant ecosystem impacts. This review indicates that current and future drivers of poor water quality in the Great Barrier Reef will increase and that subsequent impacts on marine ecosystems and coastal wetlands are likely to increase. A reduction in pollutant loads from catchments is required to halt and reverse further losses in Great Barrier Reef ecosystems at a time of a rapidly warming climate and progressive ocean acidification. Future drivers of episodic flood events, such as more variable rainfall and intense cyclones are projected to increase in frequency, as are drivers that increase the delivery of source pollutants: more intense droughts followed by high rainfall, compromised coastal wetlands and greater coastal development. These increasing drivers will exacerbate other impacts on coral reefs, such as crown-of-thorns starfish outbreaks, disease and shipping incidents. Thermal stress events and ocean acidification, also as a result of climate change, present yet another source of impacts on Great Barrier Reef ecosystems. Collectively, these pressures confirm the immediate imperative for management to continue to address catchment activities that increase pollutant loads in floodwaters, as well as other anthropogenic activities that can be influenced, such as coastal development or activities that are subject to increased risks from extreme events like shipping.

At the scale of the Great Barrier Reef, consideration of the cumulative impacts of multiple drivers of change will need to become a greater focus for management. Recent modelling shows that protection of, and connectivity to, areas expected to have lower exposure to disturbance was important for enhancing the resilience of corals (Baskett *et al.,* 2010) and promoting ecosystem recovery post-disturbance (Cote and Darling 2010). The application of more flexible (both spatial and temporal) management approaches has been identified as critical to allow for climate-related changes in marine environments, with spatially and temporally mobile highly protected (or 'no-take') areas proposed as an option for protecting species as they change their distribution (Hobday 2011).

Some drivers that impact on the Great Barrier Reef however, cannot be directly managed, such as freshwater inputs, thermal stress, ocean acidification and cyclones. Also, crown-of-thorns starfish outbreaks remain a complex problem that requires further investigation to understand the mechanisms behind outbreaks and effective management responses. In these instances, the most effective response is to enhance ecosystem resilience by bolstering the ability of marine communities to resist stress and increase recovery rates, confirming the importance of managing water quality.

If the health and resilience of the Great Barrier Reef is to be maintained, future management will need to look for ways of addressing these cumulative pressures, especially as climate change is predicted to increase extreme events as well as introduce other pressures such as thermal stress and ocean acidification. Water quality is being improved through targeted whole-of-government efforts and significant stakeholder involvement through the implementation of the Reef Water Quality Protection Plan and Reef Rescue initiative. Similar coordinated action is needed to improve the ecological sustainability of coastal developments and their management, especially in light of the predicted increases in both development and extreme events. This is the focus of the Great Barrier Reef Strategic Assessment and will need to remain a focus for the ongoing sustainable management of the Great Barrier Reef World Heritage Area and its catchment.

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