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EHP16055 – Update and add to the existing 2013 Scientific Consensus Statement to incorporate the most recent science and to support the 2017 update of the Reef Water Quality Protection Plan

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Disclaimers

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Definitions

Pollutants: Pollution means the introduction by humans, directly or indirectly, of substances or energy into the environment resulting in such deleterious effects as harm to living resources, hazards to human health, hindrance to aquatic activities including fishing, impairment of quality for use of water and reduction of amenities (GESAMP 2001). This document refers to suspended (fine) sediments, nutrients (nitrogen, phosphorus) and pesticides as 'pollutants'. Within this report we explicitly mean enhanced concentrations of or exposures to these pollutants, which are derived from (directly or indirectly) human activities in the Great Barrier Reef ecosystem or adjoining systems (e.g. river catchments). Suspended sediments and nutrients naturally occur in the environment; all living things in ecosystems of the Great Barrier Reef require nutrients, and many have evolved to live in or on sediment. The natural concentrations of these materials in Great Barrier Reef waters and inflowing rivers can vary, at least episodically, over considerable ranges. The majority of pesticides do not naturally occur in the environment.

Source Catchment pollutant loads: Unless otherwise specified, the modelling results presented in this document are based on the most recent Report Card 2015 baseline modelling predictions, which represent pollutant delivery to the Great Barrier Reef for the 2012-2013 baseline period. This is used as a point of reference to assess progress towards load reduction targets. The model includes hydrology data from 1986 to 2014 (28-year record) and static land use data over the model run period, which were based on the latest available Queensland Land Use Mapping Program (QLUMP) data in each natural resources management region (McCloskey et al. 2017).

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1. Introduction

The aim of this project is to develop basin-specific water quality targets for the 35 basins, as defined by the Australian Water Resource Council (Bureau of Meteorology 2017), discharging into waters of the Great Barrier Reef (GBR) (Figure 1). The primary pollutants of concern for GBR water quality are suspended sediments, in particular the fine fraction sediment (<16 μm), particulate nitrogen (PN), particulate phosphorus (PP), dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus) and pesticides. These are the pollutants addressed in Reef Water Quality Protection Plan 2013 (Queensland and Australian governments 2013). The main land uses (shown in Figure 1) contributing pollutant loads are rangeland grazing for sediment and particulate nutrients and sugarcane for dissolved inorganic nutrients and photosystem II inhibiting herbicides (Bartley et al. 2017). Contributions from other land uses, including urban areas, are relatively minor in comparison to agriculture but can be important at local scales.

1.1 Existing pollutant load reduction targets

The existing GBR pollutant water quality targets are included below.

Reef Water Quality Protection Plan 2013 targets (by 2018)

Reef Water Quality Protection Plan 2013 sets targets designed to work towards the overarching goal of ensuring that 'by 2020 the quality of water entering the lagoon from broadscale land use has no detrimental impact on the health and resilience on the GBR'. The Reef Water Quality Protection Plan 2013 targets (based on a comparison with the 2009 baseline) to be achieved by 2018 include:

- at least a 50% reduction in anthropogenic end-of-catchment DIN loads in priority areas
- at least a 20% reduction in anthropogenic end-of-catchment loads of sediment and particulate nutrients in priority areas
- at least a 60% reduction in end-of-catchment pesticide loads in priority areas. The pesticides referred to are the photosystem II inhibiting herbicides hexazinone, ametryn, atrazine, diuron and tebuthiuron.

The priority areas are referred to in Reef Water Quality Protection Plan 2013 Appendix 1.

Reef 2050 Long-Term Sustainability Plan targets (by 2025)

The Reef 2050 Long-Term Sustainability Plan (Commonwealth of Australia 2015) builds on the Reef Water Quality Protection Plan 2013 targets; the extended Reef 2050 Long-Term Sustainability Plan targets are in italics:

- at least a 50% reduction in anthropogenic end-of-catchment DIN loads in priority areas, *on the way to achieving up to an 80% reduction in nitrogen in priority areas by 2025*
- at least a 20% reduction in anthropogenic end-of-catchment loads of sediment in priority areas, *on the way to achieving up to a 50% reduction in priority areas by 2025*
- at least a 20% reduction in anthropogenic end-of-catchment loads of particulate nutrients in priority areas
- at least a 60% reduction in end-of-catchment pesticide loads in priority areas.

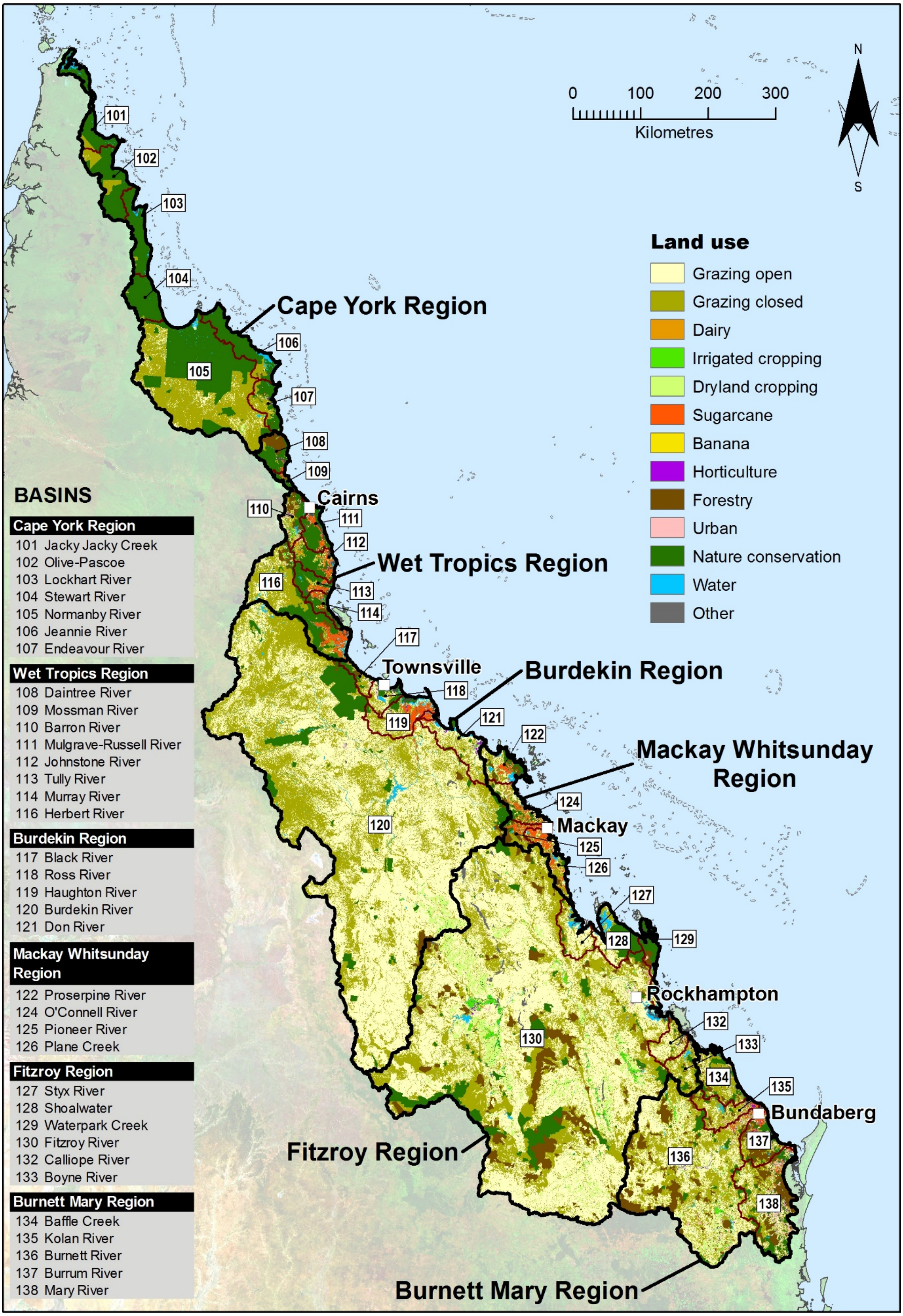


Figure 1. Boundaries of the 35 basins (as defined by the Australian Water Resources Council) and land use in the Great Barrier Reef catchment. Map provided by Queensland Government Department of Natural Resources and Mines.

1.2 Defining basin-specific and ecologically relevant targets

The Water Quality Guidelines for the GBR Marine Park (GBRMPA 2010) are the primary guidelines defined to support and maintain GBR ecosystem health and were used to conceptually link GBR water quality with pollutant load reductions at a regional scale (e.g. Kroon 2012). Since then, both regional and basin-specific targets have been developed for pollutant load reductions that will ensure the GBR guidelines are met (e.g. Brodie et al. 2012, Brodie and Lewis 2014, Brodie et al. 2014, Brodie et al. 2015a, Brodie et al. 2015b, Brodie et al. 2016, Wooldridge et al. 2015). The targets presented here, referred to as 'ecologically relevant targets' (ERTs), are necessary to achieve the overall long-term Reef Water Quality Protection Plan goal *'to ensure that by 2020 the quality of water entering the reef from broadscale land use has no detrimental effect on the reef's health and resilience'* (Queensland and Australian governments 2013, pp 16). It is recognised that the GBR Water Quality Guidelines (GBRMPA 2010) are mostly specific to coral, and consideration of other factors of ecosystem health needs to be incorporated in the future.

In establishing these targets, it is important to recognise that the GBR Water Quality Guidelines (GBRMPA 2010) for nutrients and sediments were established to *maintain* ecosystem health and are defined by concentrations that are known to place stress on an ecosystem and cause a detrimental impact on system health. Given that in many locations the nearshore and inshore areas of the GBR are already quite degraded, meeting the guidelines is unlikely to allow for significant *restoration* of ecosystem health, but rather may *promote* system recovery. Therefore, restoration of ecosystems is likely to ultimately require lower guideline values in some locations. Hence, we recommend that the guidelines be reviewed by the Great Barrier Reef Marine Park Authority in the near future to be regionally specific.

Basin-specific ERTs have been established in supporting studies for the Tully, Wet Tropics, Burdekin, Fitzroy and Burnett Mary Water Quality Improvement Plans (WQIPs), but these were not derived using a consistent approach, and basin-specific targets were not derived for the Mackay Whitsunday region or for every basin in other regions. In summary:

- **Cape York:** Based on basin-specific targets established for the Cape York WQIP (Cape York NRM and South Cape York Catchments 2016). The date for achieving the targets is 2022 in all catchments, except for the Normanby which is 2037.
- **Wet Tropics:** Established for the Tully (Kroon 2008, Brodie et al. 2012) and subsequently for all basins (Brodie et al. 2014; Wooldridge et al. 2015).
- **Burdekin:** Established for the Burdekin (Brodie et al. 2012 and revised in Brodie et al. 2015a) and subsequently for the Haughton Basin (Brodie et al. 2015a), and completed for all basins with reference to the Reef Water Quality Protection Plan targets. Note that the targets are established across basins in the Lower Burdekin to account for the entire sugarcane area.
- **Mackay Whitsunday:** Not derived.
- **Fitzroy:** Established in Brodie et al. (2015b) in the Fitzroy Basin and completed for all basins with reference to the Reef Water Quality Protection Plan targets.
- **Burnett Mary:** Established in Brodie and Lewis (2014) for all basins.

Brodie and Waterhouse (2016) completed a review and update of these existing basin-specific targets as part of a larger project to assess the total costs and water quality benefits of different policy scenarios for all industries and GBR regions to achieve the water quality targets as set out in the Reef 2050 Long-Term Sustainability Plan (Alluvium 2016).

This project defines basin-specific water quality targets for the 35 basins of the full GBR region using the eReefs hydrodynamic, sediment transport and biogeochemical model and monitoring data. Where possible, targets have been set based on an ecological outcome in the GBR. The ecological end points may be a water quality condition based on GBR Water Quality Guidelines or, where possible, a specific ecological outcome such as a parameter linked to light requirements for seagrass.

This report is presented in two major parts to reflect the different approaches used for the pollutants: Part 1—Sediments and nutrients and Part 2—Pesticides.

2. Sediments and nutrients—methods

2.1 Load reduction scenarios

Six input scenarios for river pollutant loads were run using the eReefs hydrodynamic, sediment transport and biogeochemical model (see Table 1). The scenarios were defined by the DEHP and endorsed by the Reef Water Quality Protection Plan Independent Science Panel. The eReefs model (4 km) has been run from 2011 to 2014 using sediment and nutrient loads from two Source Catchment model outputs: one based on 2012-2013 catchment management practices (baseline, or 'scenario B') and one based on presumed pre-development catchment condition (pre-development, or 'scenario P'). The differences in input loads between the two scenarios are the calculated anthropogenic loads.

In addition, four intermediate scenarios were run based on incremental reductions applied to estimated anthropogenic daily loads as follows:

- Scenario 1: A theoretical load reduction increment applied to the anthropogenic component of 20% for sediments and 50% for nutrients (from 2009 baseline), which is equivalent to the original 2018 Reef Water Quality Protection Plan targets (Queensland and Australian governments 2013)
- Scenario 2: A theoretical load reduction increment applied to the anthropogenic component of 30% for sediments and 60% for nutrients (from 2009 baseline)
- Scenario 3: A theoretical load reduction increment applied to the anthropogenic component of 40% for sediments and 70% for nutrients (from 2009 baseline)
- Scenario 4: A theoretical load reduction increment applied to the anthropogenic component of 50% for sediments and 80% for nutrients (from 2009 baseline), which is equivalent to the 2025 Reef 2050 Long Term Sustainability Plan targets (Commonwealth of Australia 2015).

The modelled scenarios include load reductions already achieved since 2009, which are 11% for sediments and 16% for nutrients. Levels of additional reduction are given in Table 1. An example of the calculation is presented in Figure 2.

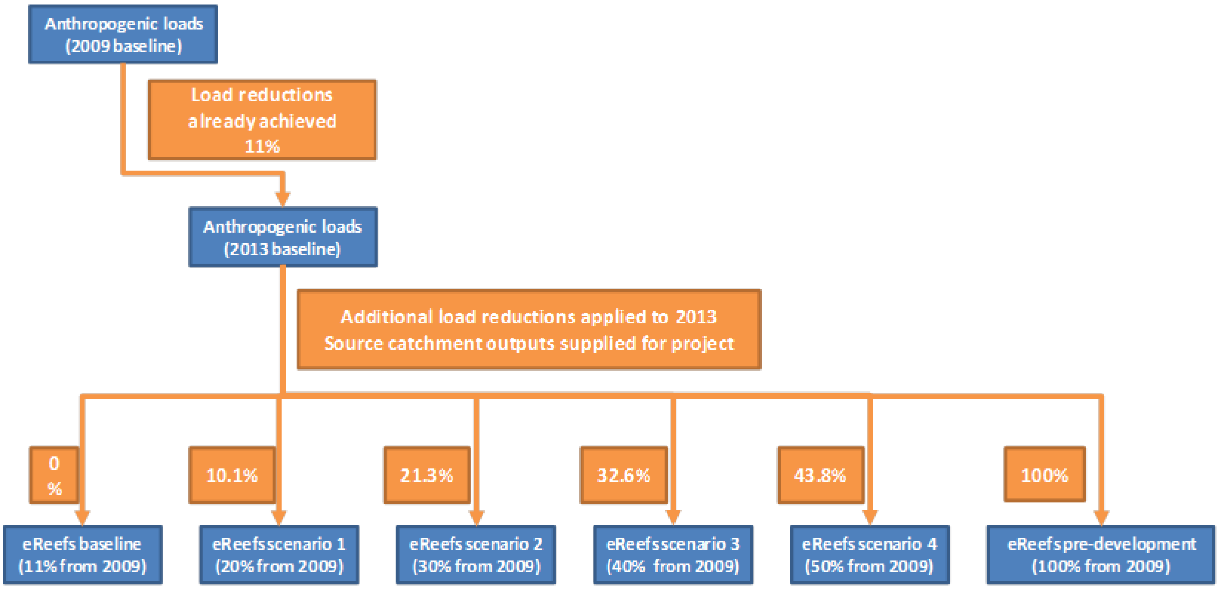


Figure 2. Example of the approach used for calculating the anthropogenic sediment load reductions for the scenarios and accounting for progress of load reductions to date.

Table 1. The adjusted load reduction scenarios assessed for target setting based on anthropogenic load reductions.

Scenario	Sediments			Nutrients		
	Scenario anthropogenic load reduction (%)	Progress to date (%)	% of additional anthropogenic sediment loads modelled	Scenario anthropogenic load reduction (%)	Progress to date (%)	% of additional anthropogenic nutrient loads modelled
Baseline	0		0	0		0
Scenario 1	20		10.1	50		40.5
Scenario 2	30		21.3	60		52.4
Scenario 3	40	11	32.6	70	16	64.3
Scenario 4	50		43.8	80		76.2
Pre-development	100		100	100		100

2.2 Defining ecological end points / criteria

To ensure that the pollutant water quality targets are ecologically relevant, we reviewed the literature on the primary ecological responses of corals and seagrass to elevated fine suspended sediments ('fine sediment') and nutrient concentrations. This information was used to inform the selection of final criteria for analysis of model outputs.

Nutrients

Excess nutrient pollutant export from the rivers in the GBR has been associated with several ecosystem impacts (Brodie et al. 2011). These include reef degradation and overall reduced coral biodiversity between Townsville and Cooktown, with a reduction in species richness of 40 species compared with the expected value in this region (DeVantier et al. 2006); enhanced vulnerability of reef corals to thermal bleaching stress (Wooldridge 2016); increased presence of macroalgae on reefs, which can affect coral diversity and/or larval coral recruitment (De'ath and Fabricius 2010); and reef damage from coral-eating crown-of-thorns starfish (CoTS) (*Acanthaster planci*) outbreaks (Fabricius et al. 2010).

The health and ecology of coral reefs are sensitive to DIN enrichment. A threshold value of chlorophyll *a* (Chl-*a*) less than 0.45 $\mu g L^{-1}$ has been identified as an important trigger value for the maintenance of a healthy reef status and has been adopted as the marine trigger value in the GBR Water Quality Guidelines (GBRMPA 2010), with a higher wet season value of 0.63 μgL^{-1}.

For all of these nutrient effects, the nitrogen must be in an immediately or potentially bioavailable form; for example, while nitrate is immediately bioavailable, bacterial action can transform organic nitrogen to nitrate (known as mineralisation), making it bioavailable. DIN (nitrate and ammonium) derived from agricultural fertiliser losses is immediately bioavailable. The PN derived from soil erosion in grazing lands and natural areas to the river mouths is likely to become bioavailable through mineralisation within the lagoon waters or in the sediment.

The effects of increased nutrient loads to GBR coastal aquatic and marine ecosystems that were considered in this assessment are summarised below.

1. Crown-of-thorns starfish (text derived from Scientific Consensus Statement 2017 Chapter 1 – Schaffelke et al. 2017)

CoTS are one of the major causes of coral mortality in the GBR system (De'ath et al. 2012). River nutrients can influence CoTS outbreak dynamics (Schaffelke et al. 2017) when large discharges (>10 km^3) from the Wet Tropics and the Burdekin rivers occur in the region between Hinchinbrook and Lizard islands while phytoplankton-feeding CoTS larvae are present in the water column (Brodie et al. 2005, Brodie et al. 2017, Fabricius et al. 2010).

The CoTS spawning period is mainly from November to February (Babcock et al. 2016) and Chl-*a* concentrations are most relevant in this period. Further development of a CoTS outbreak, however, requires sufficient live coral cover to sustain adult populations. A wave of outbreaks is initiated when these favourable conditions are reinforced by favourable hydrodynamic conditions in the area between Cairns and Lizard Island (Hock et al. 2014, Wooldridge and Brodie 2015). After waves are initiated in the Cairns to Lizard Island area (as they were in 1962, 1978, 1993 and 2009), outbreaks progress southward (mainly on mid-shelf reefs) over a period of about 12 years to the areas approximately offshore from Mackay. It is generally assumed (Brodie 1992) that numbers of outbreaks have increased in the period since pre-development, and that the frequency of CoTS waves has increased greatly from frequencies possibly as low as every 50–80 years to about every 15 years over the last 60 years (Fabricius et al. 2010).

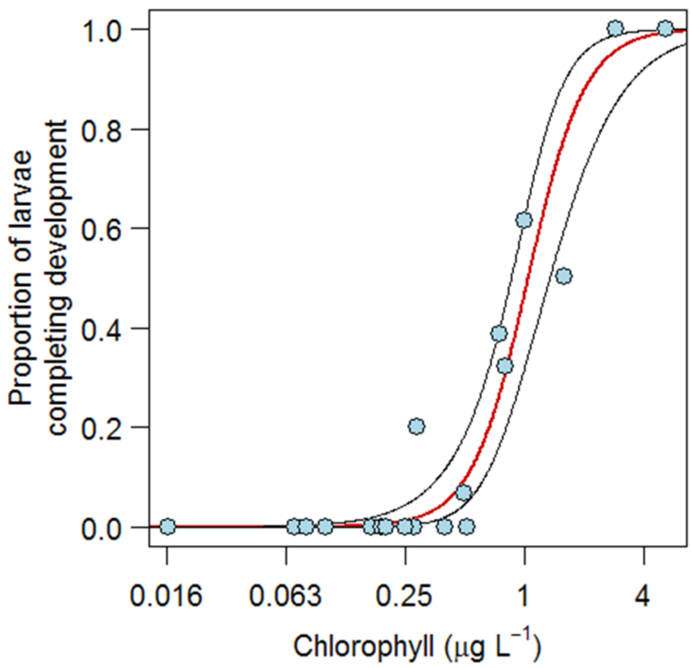


Figure 3. Predictions of the probability of survival of CoTS larvae in response to increasing Chl-*a* concentrations. Reproduced from Fabricius et al. (2010).

The Chl-*a* concentrations at which the probability of larval survivorship change rapidly are not single point but on a continuum, as shown in Figure 3. Thus, the probability of survival increases from almost zero at Chl-*a* 0.25 μgL^{-1}, to 40% at 1 μgL^{-1} to a predicted 100% at 2 μgL^{-1}. However, further studies since the results in Fabricius et al. (2010) show that the most favourable concentration for larval survival is estimated to be at 1 μgL^{-1} (compared to 0.1 and 10 μgL^{-1}) in Pratchett et al. (2017) and at 1 μgL^{-1} compared to much lower and higher concentrations in Wolfe et al. (2015). At higher Chl-*a* concentrations (above 1 μgL^{-1}), larvae develop more slowly (Pratchett et al. 2017, Wolfe et al. 2015), and below Chl-*a* 0.2 μgL^{-1} or at low phytoplankton biomass larvae generally also grow slowly and do not easily reach a competent (able to recruit to the reef) stage (Pratchett et al. 2017, Fabricius et al. 2010, Wolfe et al. 2015, Uthicke et al. 2015).

Chosen threshold values for a quantitative increase in larval survivorship, such as Chl-*a* 0.8 μgL^{-1} (Wooldridge and Brodie 2015) or 1.0 μgL^{-1} (Wolfe et al. 2015) are both acceptable options to use in the model. As can be seen in Figure 3, and is now better known from new research (Brodie et al. 2017), enhancement of survivorship of CoTS larvae starts at Chl-*a* concentrations of 0.4 μgL^{-1} and increases in effect to about a concentration of 1 μgL^{-1}. Therefore, various criteria can be used depending on the degree of enhancement chosen. In considering the inclusion of the relationship between Chl-*a* and CoTS for the current analysis, a conservative (precautionary) end point of Chl-*a* 0.6 μgL^{-1} was chosen (this is also equivalent to the GBR Water Quality Guideline value for wet season Chl-*a* of 0.63 μgL^{-1}).

2. Macroalgae versus coral diversity

As a direct effect, enhanced nutrient availability (especially of nitrogen) can promote the growth of fleshy macroalgae at locations with sufficient light (Schaffelke et al. 2005). Macroalgae are more abundant on reefs in waters with higher concentrations of water column Chl-*a* (above 0.45 μgL^{-1}), which is responsive to nutrient availability (top panel of Figure 4; De'ath and Fabricius 2008). High macroalgal biomass has a number of adverse effects on corals through: space competition (McCook 2001); altering the corals' microenvironment which effects coral metabolism (Hauri et al. 2010); reducing coral settlement (Birrell et al. 2008) and increasing the susceptibility to coral disease (Morrow et al. 2012).

The end point of Chl-*a* 0.45 μgL^{-1} was chosen for this criterion, which is the annual GBR Water Quality Guideline value for Chl-*a*.

3. Increased coral bleaching susceptibility

DIN availability is important in the functioning of the coral–algae symbiosis, and elevated DIN concentrations can cause changes that disrupt the ability of the coral host to maintain an optimal population of algal symbionts (Wooldridge 2016). Together with increased temperature, elevated DIN concentrations and changes in N:P ratios can increase the susceptibility of corals to bleaching (Wooldridge 2016, Wooldridge et al. 2017, Vega Thurber et al. 2014, Wiedenmann et al. 2013, D'Angelo and Wiedenmann 2014, Rosset et al. 2017).

Fabricius et al. (2013a) propose a conceptual framework that synthesises the apparently inconsistent result of recent studies that suggest either greater or reduced thermal tolerance in response to changes in nutrient status. The framework illustrates two important points: (i) nutrients and light can be either stress or beneficial factors, with optimum responses at species-specific tolerance levels and detrimental effects if rates are much higher or lower, (ii) shifts in the trophic status of the environment (from oligotrophic to eutrophic) do not easily translate into shifts in the trophic status of reef corals (from starved to well-fed), because the food preferences and trophic plasticity vary greatly between species. The review (Fabricius et al. 2013a) concludes that in more eutrophic environments, as found on parts of the inshore GBR south of Cooktown, exposure to additional nutrients is predominantly a stress factor for most coral species, and that improvement of water quality would improve the tolerance of inshore corals to thermal stress. The responses of early life history stages of the common inshore coral *Acropora tenuis* to a combination of excess inorganic and organic nutrients and elevated temperatures indicate that recruitment and recovery potential of this species may be limited at GBR inshore reefs (Humanes et al. 2016).

In this case, the effect (more zooxanthellae due to DIN enrichment) leads to higher bleaching sensitivity at the same temperature rise point (Wooldridge 2016, Wooldridge et al. 2017, Gustafsson et al. 2014). The Chl-*a* threshold used in the Wooldridge models is 0.5 $\mu g\ L^{-1}$ (similar to the annual GBR Water Quality Guideline value for Chl-*a*) but this will also be a continuous variable, as increased concentrations of DIN will lead to larger effects (but perhaps not linearly). This relationship was not used in the final analysis of targets, for reasons described later in this document.

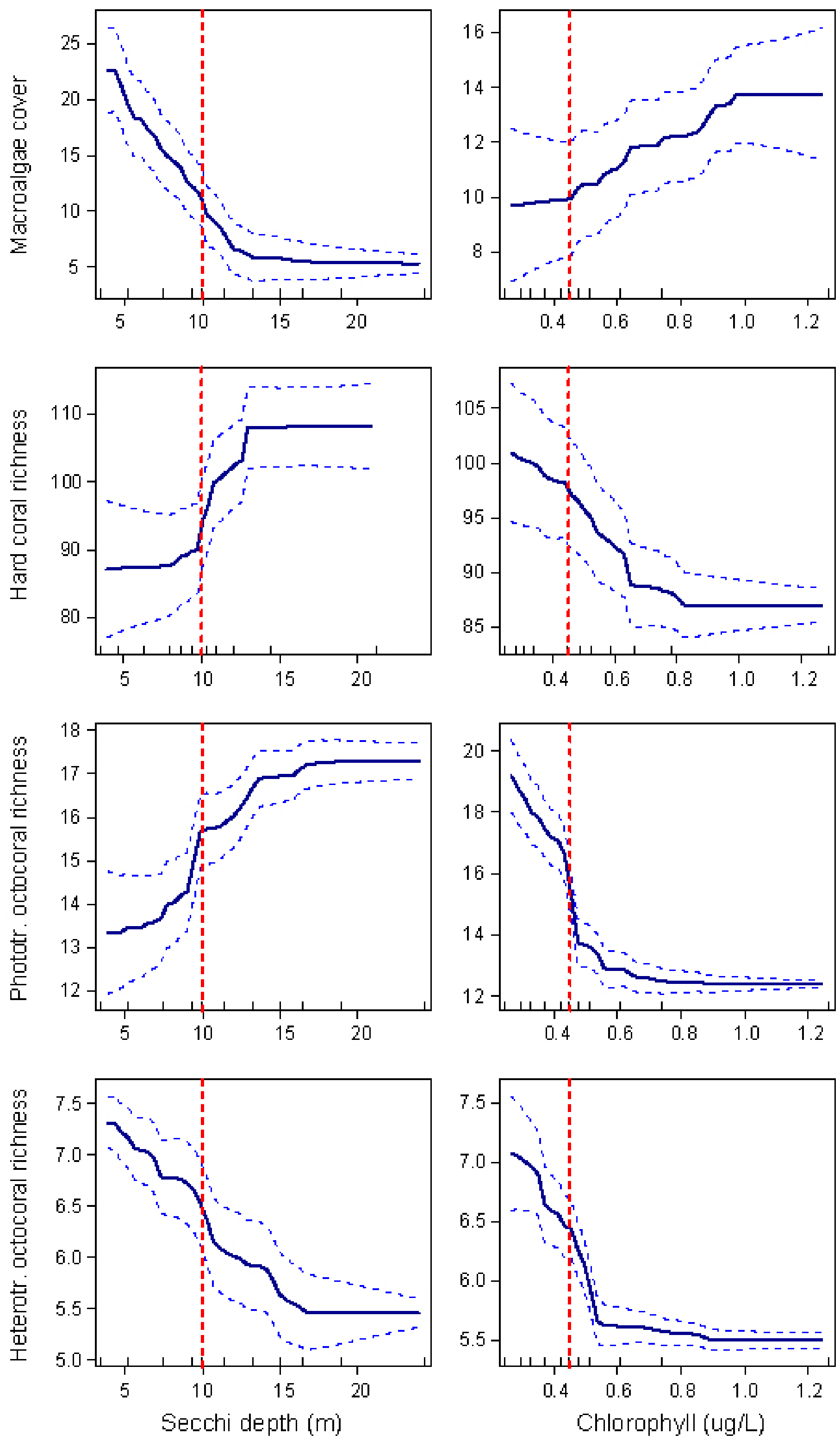


Figure 4. Partial effects of Secchi depth and chlorophyll concentration on the four measures of ecosystem status. Relative distances across and along were included in this model, but not shown here. The red dashed line indicates values found in coastal waters of Cape York. The plots suggest substantial improvement in Reef status (higher biodiversity of hard corals and phototrophic octocorals, lower macroalgal cover) at water clarity of 5−15 m Secchi depth and Chl-*a* concentrations of 0.3–0.6 µgL^{-1}. Source: Reproduced from De'ath and Fabricius (2008).

Several other effects of nutrient enrichment have been documented and are summarised below. These effects are not able to be accounted for in the assessment at this time due to the difficulty in quantifying the relationships between nutrient enrichment and effect.

- **Bioerosion of corals** (both live and dead) occurs via a large range of organisms, but two of the main types are microborers, often algae and sponges, and macroborers, often worms and bivalves (Hutchings et al. 2005). The growth of both of these types of borers can be increased by nutrient enrichment; for example, algal borers grow with increased dissolved inorganic nutrient availability, and filter-feeding sponges, worms and bivalves grow with increased phytoplankton biomass. Increased bioerosion by these organisms can interact with reduced calcification due to ocean acidification to additively reduce reef net calcification (DeCarlo et al. 2015).
- **Coral disease** is a significant contributor to coral cover declines on the GBR (Osborne et al. 2011) and is predicted to worsen with global pressures of increasing temperature and ocean acidification (Maynard et al. 2015, O'Brien et al. 2016). While coral disease is considered a general stress response of corals, it has been positively correlated to sedimentation and elevated concentrations of nutrients and organic matter (Harvell et al. 2007, Haapkylä et al. 2011, Vega Thurber et al. 2014, Thompson et al. 2014, Pollock et al. 2014, Pollock et al. 2016).
- **Production of phytoplankton due to inputs of river-derived nutrients reduces water clarity** and, hence, light availability for benthic plant communities, for example, seagrass and coral (Collier et al. 2016a, Petus et al. 2014). In inner shelf waters, the reduction of in situ light penetration due to resuspended sediment is usually a more dominant effect, but in deeper waters (>15 m) where resuspension does not normally occur, the light reduction due to phytoplankton may be an important factor, for example, for deepwater seagrass communities (see below).
- **Epiphytes** growing on the leaves of seagrasses and macroalgae growing in seagrass meadows increase their productivity and biomass turnover with increasing nutrient loads (Cebrian et al. 2013). When they increase to bloom proportions, epiphytes and macroalgae have been known to cause seagrass die-off at various locations throughout the world (Cambridge et al. 1986, Cabaço et al. 2013). Epiphytes are highly variable in the GBR (see Scientific Consensus Statement 2017 Chapter 1 – Schaffelke et al. 2017), but there is not yet any documented evidence of lasting effects on seagrass condition, which may be due to a number of reasons, including complex biological interactions (e.g. grazing) and rapid seagrass growth (Cebrian et al. 2013, Unsworth et al. 2015). However, the potential for epiphyte and macroalgal blooms from nutrient enrichment and their impact on seagrass condition warrant further investigation.

A summary of the criteria in terms of time periods, spatial extent and thresholds as used in the modelling is presented in Table 2.

Table 2. Summary of analysis criteria for DIN reduction from rivers.

Criteria	Relevant time period	Spatial extent	Threshold	Reference
CoTS	Nov–Feb (spawning period)	Initiation zone (Lizard Island to Cairns)	Chl-*a* <0.6 μgL^{-1},	Fabricius et al. (2010)
Bleaching	Nov–Apr (summer of 2013-2014)	Reefs identified in GBRMPA features map	Chl-*a* <0.5 μgL^{-1}	Wooldridge (2009, 2016)
Macroalgae / Coral diversity	All years, all waters	Reefs (Model Run 1) All waters (Model Run 2)	Chl-*a* <0.45 μgL^{-1}	De'ath and Fabricius (2010), GBRMPA (2010)

Suspended sediment

The effects of increased sediment loads to GBR marine ecosystems that were considered in this assessment are summarised below.

1. Light reduction for seagrass

Light is presently regarded as the primary limiting factor of seagrass production in the GBR (Collier and Waycott 2009), and reductions in light availability have been directly linked to seagrass loss (Collier et al. 2012a, Collier et al. 2012b). Light penetration in coastal waters is strongly regulated by the resuspension of fine sediments, which may occur year-round (Fabricius et al. 2013b, Fabricius et al. 2014, Fabricius et al. 2016, Logan et al. 2013, Logan et al. 2014).

Seagrass meadows of the GBR undergo seasonal changes in growth, with the peak growing season typically during spring when benthic light availability is highest and there is a low risk of extreme water temperatures, resulting in maximum abundance (i.e. distribution and density) in late spring and early summer (Chartrand et al. 2016, McKenzie 1994, Rasheed et al. 2014). This is also a time for formation of carbohydrate reserves (Collier et al. 2016b), and many species are flowering (McKenzie et al. 2016, Rasheed 2004). Conversely, abundance declines in the wet season from early summer and reaches the lowest in winter. Seagrass can also undergo acute and chronic changes in abundance caused by extreme events: floods, water temperature and disturbance from cyclones (e.g. Birch and Birch 1984, Coles et al. 2015, McKenzie et al. 2016, Petus et al. 2014, Rasheed and Unsworth 2011).

The impact of degraded water quality on seagrass meadow abundance will vary depending on the timing relative to the seasonal cycles mentioned above. The peak seagrass growing season is sensitive to degraded water quality because the increase in abundance, formation of reserves and seed banks produced through sexual reproduction. For example, the 2010-2011 wet season began earlier than average in October, and this appeared to hamper growing season recovery from previous wet season losses, which led to the lowest abundances ever observed throughout the GBR (McKenzie et al. 2016, Rasheed et al. 2014). However, severely degraded water quality during the wet season can also drive rapid seagrass loss, and place seagrass beds in a poor state ahead of the following growing season (McKenzie et al. 2016). For example, substantial seagrass loss occurred in the Burdekin region between 2008 and 2009 when there were very large riverine flows in January and February and high frequency of exposure to turbid primary water (Petus et al. 2014, McKenzie et al. 2016, Collier et al. 2012b). The relative sensitivity and resilience has not yet been quantitatively assessed in relation to these cycles.

The criteria considered for fine sediment are summarised in Table 3. In this analysis, the impacts of sediment discharge from all rivers able to be modelled by eReefs at the present time (21) were considered for the downstream footprint (see section 2.4 for a definition of ‘river footprint’) over water of <10 m (the resuspension zone), a delivery period of December to March (the river discharge period), a period of the complete year for chronic effects and an analysis end point variable as the minimum bottom (benthic) light, which is equivalent to 6 mol photon m^{-2} d^{-1}.

The effect of increased fine sediment loads on the light requirements of coral was not analysed as it was for seagrass, because the mismatch of the model resolution (4 km) was considered too coarse to resolve the fine-scale distribution of coral by area and depth. This missing effect is very important for the Fitzroy, where using just a seagrass end point gives a target of no reduction in fine sediment as there is no significant seagrass in Keppel Bay (i.e. the larger Keppel Bay). However, there is coral in Keppel Bay affected by sediment discharged from the Fitzroy River (see Wenger et al. 2016), and a local target is needed. In other places such as Cleveland Bay, both seagrass and coral cohabit, and load reductions needed for seagrass light requirements may also cover coral requirements to some extent, although this needs further examination.

Table 3. Summary of analysis criteria for reduction of suspended sediment from rivers. Acute refers to unfavourable condition over a shorter period. While the acute and chronic limits are the same, the acute ensures that the conditions are favourable in the summer growing season.

Criteria	Relevant time period	Depth	Threshold	Reference
Seagrass health (acute)	Dec–Mar	<10 m	Running monthly mean >6 mol photon m^{-2} d^{-1}	Collier et al. (2012a, 2012b), Collier et al. (2016a, 2016b), Chartrand et al. (2016)
Seagrass health (chronic)	Full modelling period	<10 m	Running monthly mean >6 mol photon m^{-2} d^{-1}	Collier et al. (2012a, 2012b), Collier et al. (2016a, 2016b), Chartrand et al. (2016)

In the final analysis, only the chronic case from Table 3 was used to set targets. The interaction of chronic and acute stress could be explored further in the future.

2. Other effects

Several other effects of elevated suspended sediment concentrations are documented, but the thresholds are more difficult to quantify. These are summarised below, but were not able to be accounted for in the assessment at this time.

- **Sedimentation on corals.** High concentrations of suspended sediment can cause direct biological effects (e.g. interfering with filter feeding), alter the light quantity and quality and smother the corals' surface with a fine layer of sediment (Flores et al. 2012, Jones et al. 2015). Most importantly, light reduction, elevated suspended sediments and sediment deposition negatively affect the reproductive cycle and early life histories of corals (Jones et al. 2015). Two of the newly recognised mechanisms for the negative effects of suspended sediments are the entanglement and entrapment of coral sperm by sediment particles (Ricardo et al. 2015) and ballasting of the buoyant egg–sperm bundles (Ricardo et al. 2016a), both reducing fertilisation success of corals. Conversely, developing embryos and larvae tolerate exposure to suspended sediments through mechanisms to remove particles (Ricardo et al. 2016b). The subsequent coral life history stage, successful larval settlement, is again reduced by a thin layer of fine, terrigenous settlement (Perez et al. 2014), supporting the conclusions of other similar research (Jones et al. 2015).
- **Sedimentation in turf algae and herbivore feeding.** Increased benthic terrigenous sediment loads, within the epilithic algal matrix (EAM) found on coral reefs, can suppress fish herbivory and detritivory on coral reefs (Bellwood and Fulton 2008, Goatley and Bellwood 2012, Gordon et al. 2016). In doing so, sediments may drive a change in the state of the EAM from palatable, short, productive algal turfs to unpalatable, long sediment-laden algal turfs. These changes may reduce the resilience of coral reefs to other stressors (Goatley et al. 2016). Finer sediments have greater effects on the suppression of herbivory (Tebbett et al. 2017a, Tebbett et al. 2017b).
- **Fine suspended sediment adverse effects on coral reef fish.** Coral reef–associated damselfish respond to suspended sediment, and their larval development, foraging success and habitat use are adversely affected at concentrations that have been observed at GBR inshore reefs (Johansen and Jones 2013, Wenger et al. 2011, Wenger et al. 2013, Wenger et al. 2014, Wenger et al. 2015, Wenger and McCormick 2013).

2.3 Summary of final criteria

The specific ecological outcomes included in the modelling were:

- **Improved coral diversity versus macroalgae.** Reducing DIN loads leads to an increase in coral diversity and a reduction in macroalgae abundance, where average Chl-*a* concentration in the water column does not exceed the GBR Water Quality Guideline value for Open Coastal waters.
  - ***Criteria 1:*** *Chl-*a *<0.45 µgL^{-1}, all years, all waters within river footprints.*
- **Reduced coral bleaching.** Reducing nutrient (DIN) loads leads to a decrease in bleaching sensitivity of corals, where average Chl-*a* concentration in the water column does not exceed the threshold value identified by Wooldridge (2016) and Wooldridge et al. (2017).
  - ***Criteria 2:*** *Chl-*a *<0.5 µgL^{-1}, one summer (2014 summer), all reefs within the river footprints.*
- **Reduced CoTS populations.** Reducing nutrient loads (probably DIN, but consideration of PN and PP as well) leads to a decrease in the frequency of CoTS outbreaks. The water quality indicator used here is Chl-*a* concentration (as a proxy for phytoplankton biomass) above which CoTS larvae have a greatly increased chance of survivorship to the settlement stage.
  - ***Criteria 3:*** *Chl-*a *<0.6 µgL^{-1}, November to March each year, CoTS initiation zone, all waters within the river footprints.*
- **Improved seagrass 'health'.** Reducing suspended sediment loads leads to reduced resuspension throughout the year and improved light availability (Fabricius et al. 2014, Fabricius et al. 2016, Wooldridge 2017) in shallow areas (<10 m), which is a key driver of seagrass abundance.
  - ***Criteria 4:*** *Light 6 mol photon m^{-2} d^{-1} for seagrass, all years, <10 m, all waters within river footprints – the 'chronic' case.*

However, for the final targets we did not use the CoTS and bleaching scenarios—they have been considered in this project but not used for setting final targets. The CoTS scenarios were not used because the time period of the modelling (four years) was found to be inadequate to capture the inter-annual variation expected in the 'initiation zone' during the approximately 17-year period of major episodes of CoTS outbreaks erupting from the area between Cairns and Lizard Island. In addition, issues with the basin total flows driving underestimates of river footprints (see section Caveats and limitations below) appeared to be serious for the rivers influencing CoTS initiation in the years modelled. The bleaching scenarios were not used because there is still uncertainty about the level of nutrient enrichment and the bleaching response. In addition, the bleaching scenario is likely to be constrained by the time period of the analysis, in that it was only conducted in one summer within a single below average flow year (2014).

2.4 Modelling approach

River footprints

The eReefs biogeochemical model is coupled to a near-real time fully baroclinic hydrodynamic model forced by historical data from the atmosphere and oceanic boundary that produces skilful assessments of circulation (at 4 km resolution) for a very large marine domain, inclusive of the entire continental shelf and proximate Coral Sea, from Papua New Guinea to the New South Wales border (Herzfeld 2015, Baird et al. 2016). The coupled models received freshwater flows with associated sediment and nutrient loads from 17 of the 35 major basins in the GBR catchment: Normanby, Daintree, Barron, Mulgrave-Russell, Johnstone, Tully, Herbert, Haughton, Burdekin, Don, O'Connell, Pioneer, Fitzroy, Boyne, Calliope, Burnett and Mary. Nutrient and sediment loads from the Normanby Basin were miscalculated in the eReefs model, leading to reduced confidence in the results for this region (eReefs simulations undertaken after June 2016, but not part of this report, do not present such limitation, and all flow and river tracer calculation are correct). Major rivers in other regions are adequately represented; however, smaller coastal creeks and rivers that have potential important influences in the inshore areas are missing. The model is configured to receive inputs from the remaining 18 GBR basins but, at the time of this analysis suitable flow and loads data were not available from these rivers.

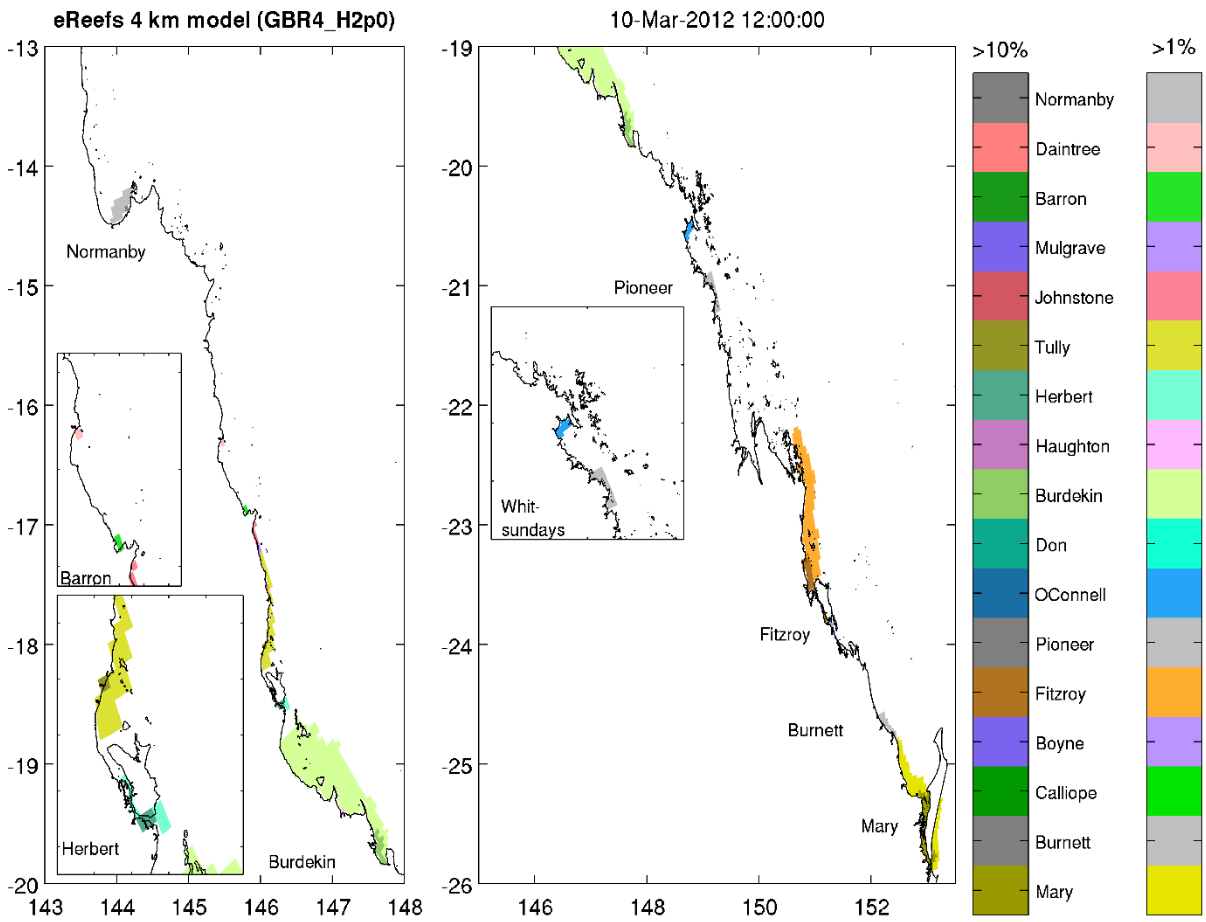


Figure 5. River footprints for 10 March 2012 calculated using the release of a passive tracer in river flows. For each river, two scenarios are depicted by different hues. The darker represents locations where greater than 10% of the water is from a particular river, while the lighter hue represents inputs between 10% and 1%. Where no river exceeds 1%, the ocean appears white. If water at a particular location contains multiple river waters, only the higher concentration plume is shown. For this analysis, we define the footprint as areas by the lesser contour (>1% of freshwater content).

To calculate the basin-specific load reductions, each basin is represented by the footprint of the major river of the basin. Each footprint is modelled with the eReefs biogeochemical model using the gauged river discharge. The hydrodynamic movement of the pollutants that are transported in the river discharge is modelled to determine the concentrations and spatial extent of the pollutants as they mix with the receiving oceanic water. The nominal footprint of each river at a particular point in time is determined by the surface locations where the volume of freshwater from a particular river exceeds that from all other rivers and is greater than 1% of the seawater volume (i.e. salinity depressed by

~0.35 psu). For locations where no river exceeds 1% of the seawater volume, there is no river footprint, and the water is said to be 'oceanic'.

It should be noted that the concentrations of the pollutants in the footprint have been modelled using the aggregated load of the whole basin. The reason the aggregated load of the whole basin is used is because (i) the smaller creeks and rivers in the basin that discharge their own load directly to the coast cannot (at this stage) be resolved with the eReef hydrodynamic model, and (ii) the ocean hydrodynamic conditions are fairly consistent at the basin scale at which the model runs (16 km^2). Using this approach means that concentrations in the footprint are likely to be overestimated close to the river mouth, and the spatial extent of the footprint is underestimated for some basins. This is because the aggregated load of the whole basin is diluted by the discharge volume of a single river, which is measured at the most downstream gauging station located some distance upstream of the mouth of the river at the tidal zone. The proportion of the basin represented by the gauged discharge used in the modelling is reported in Table 4 (basins with low representivity, <60%, are shaded in grey). However, the overestimated concentrations are likely to dissipate quickly and become inconsequential to the load reduction calculations as the freshwater mixes with the much larger volume of the receiving ocean. For those basins with low representivity (Table 4), expectedly there will be greater uncertainty in the estimates in the concentrations and spatial extent of the river footprint, and therefore greater uncertainty in the load reduction estimates.

Table 4. Basin area covered by gauges compared to total basin area used in the model. The basins where less than 60% of the basin is gauged are highlighted in grey. The major basins (rivers) in the GBR catchment included in the version of the model used for this report are in bold font. *Gauges used which are not in the basin area. Source: Waterhouse et al. (2017c).

NRM region	Basin	Australian Waters Resource Council no.	Basin area (km^2)	Relevant gauges	Percentage of basin covered by key gauges
Cape York	Jacky Jacky	101	2,963	Pascoe River at Garraway Creek*	0
	Olive Pascoe	102	4,180	Pascoe River at Garraway Creek	31
	Lockhart	103	2,883	Pascoe River at Garraway Creek*	0
	Stewart	104	2,743	Stewart River at Telegraph Road	17
	Normanby	**105**	**24,399**	**Normanby River at Kalpowar Crossing**	**53**
	Jeannie	106	3,638	Endeavour River at Flaggy*	0
	Endeavour	107	2,182	Endeavour River at Flaggy	15
Wet Tropics	**Daintree**	**108**	**2,107**	**Daintree River at Bairds**	**43**
	Mossman	109	473	Mossman River at Mossman	22
	Barron	**110**	**2,188**	**Barron River at Myola**	**89**
	Mulgrave-Russell	**111**	**1,983**	**Mulgrave River at Peets Bridge + Russell River at Bucklands**	**42**
	Johnstone	**112**	**2,325**	**South Johnstone River at Upstream Central Mill + North Johnstone at Tung Oil**	**57**
	Tully	**113**	**1,683**	**Tully River at Euramo**	**86**
	Murray	114	1,107	Murray River at Upper Murray	14
	Herbert	**116**	**9,844**	**Herbert River at Ingham**	**87**
Burdekin	Black	117	1,057	Black River at Bruce Highway	24
	Ross	118	1,707	Bohle River at Hervey Range Road	8
	Haughton	**119**	**4,051**	**Haughton River at Powerline**	**44**
	Burdekin	**120**	**130,120**	**Burdekin River at Clare**	**100**

NRM region	Basin	Australian Waters Resource Council no.	Basin area (km²)	Relevant gauges	Percentage of basin covered by key gauges
	Don	**121**	**3,736**	**Don River at Reeves**	**27**
Mackay Whitsunday	Proserpine	122	2,494	O'Connell River at Staffords Crossing*	0
	O'Connell	**124**	**2,387**	**O'Connell River at Staffords Crossing**	**14**
	Pioneer	**125**	**1,572**	**Pioneer River at Dumbleton Weir T/W**	**95**
	Plane	126	2,539	Sandy Creek at Homebush	13
Fitzroy	Styx	127	3,013	Waterpark Creek at Byfield*	0
	Shoalwater	128	3,601	Waterpark Creek at Byfield*	0
	Waterpark	129	1,836	Waterpark Creek at Byfield	12
	Fitzroy	**130**	**142,552**	**Fitzroy River at The Gap**	**95**
	Calliope	**132**	**2,241**	**Calliope River at Castlehope**	**57**
	Boyne	**133**	**2,496**	**Calliope River at Castlehope***	**0**
Burnett Mary	Baffle	134	4,085	Baffle Creek at Mimdale	34
	Kolan	135	2,901	Kolan River at Springfield	19
	Burnett	**136**	**33,207**	**Burnett River at Figtree Creek**	**92**
	Burrum	137	3,362	Gregory River at Leesons	19
	Mary	**138**	**9,466**	**Mary River at Home Park**	**72**

The footprint of each river, which varies over time with river flow and ocean circulation, is calculated each day (Figure 5). As the river flows are identical for each load reduction scenario, the river footprints for each scenario are also identical.

We recognise that the river footprints used in the target-setting methodology are different from those used in the Risk Assessment in Scientific Consensus Statement 2017 (Waterhouse et al. 2017a), where river flows were adjusted to full basin flows for several input layers, and the marine zones represent an average extent, defined using a combination of the eReefs model outputs and the assessment of wet season water type frequency (annual average from 2002 to 2016).

Modelling scenarios

The modelling period used was 1 January 2011 – 31 December 2013. For each river footprint, the task is to determine which load reduction scenario is required to meet the criteria. Figure 6 quantitatively represents, within a basin's footprint, the minimum load reduction scenario (Table 1) required to meet the water quality criteria (e.g. Chl-*a* <0.45 μgL^{-1}) within a 16 km^2 grid cell.

The properties of every grid cell (at midday each day) are analysed and the following process undertaken:

- Select a single model grid cell where the target applies (i.e. <10 m for bottom light targets).
- Determine the river of greatest influence (or ocean if none) at this location.
- Identify the minimum load reduction scenario (starting from the baseline) meeting the target, and assign one count to this river-scenario combination.
- Repeat the process, and complete the tally for all grid cells on all days.

The following is an example of this process. If a 16 km^2 grid cell has, at midday, 8% Burdekin water, 1% Don water, and all other rivers are negligible, and the estimated surface Chl-*a* concentrations for the six scenarios (B, 1, 2, 3, 4 and P) are 0.71, 0.65, 0.48, 0.44, 0.43 and 0.42 μgL^{-1} respectively, then the grid cell (at this time point) is considered to be within the Burdekin footprint, and to meet the Chl-*a* criterion of 0.45 μgL^{-1}, a minimum load reduction of 40% is required (i.e. Scenario 3 produces a Chl-*a* concentration of 0.44 μgL^{-1}). Subsequently, one count is added to the Scenario 3 column in the Burdekin River panel. For the next grid cell or time, perhaps the Don water has the greatest influence, and a minimum load reduction of Scenario 1 is required, in which case one count is added to the Scenario 1 column in the Don River panel, and so on. Eventually, when the tally is complete, the height of the column represents the number of instances that a particular scenario met the target within that river footprint over the duration of the analysis.

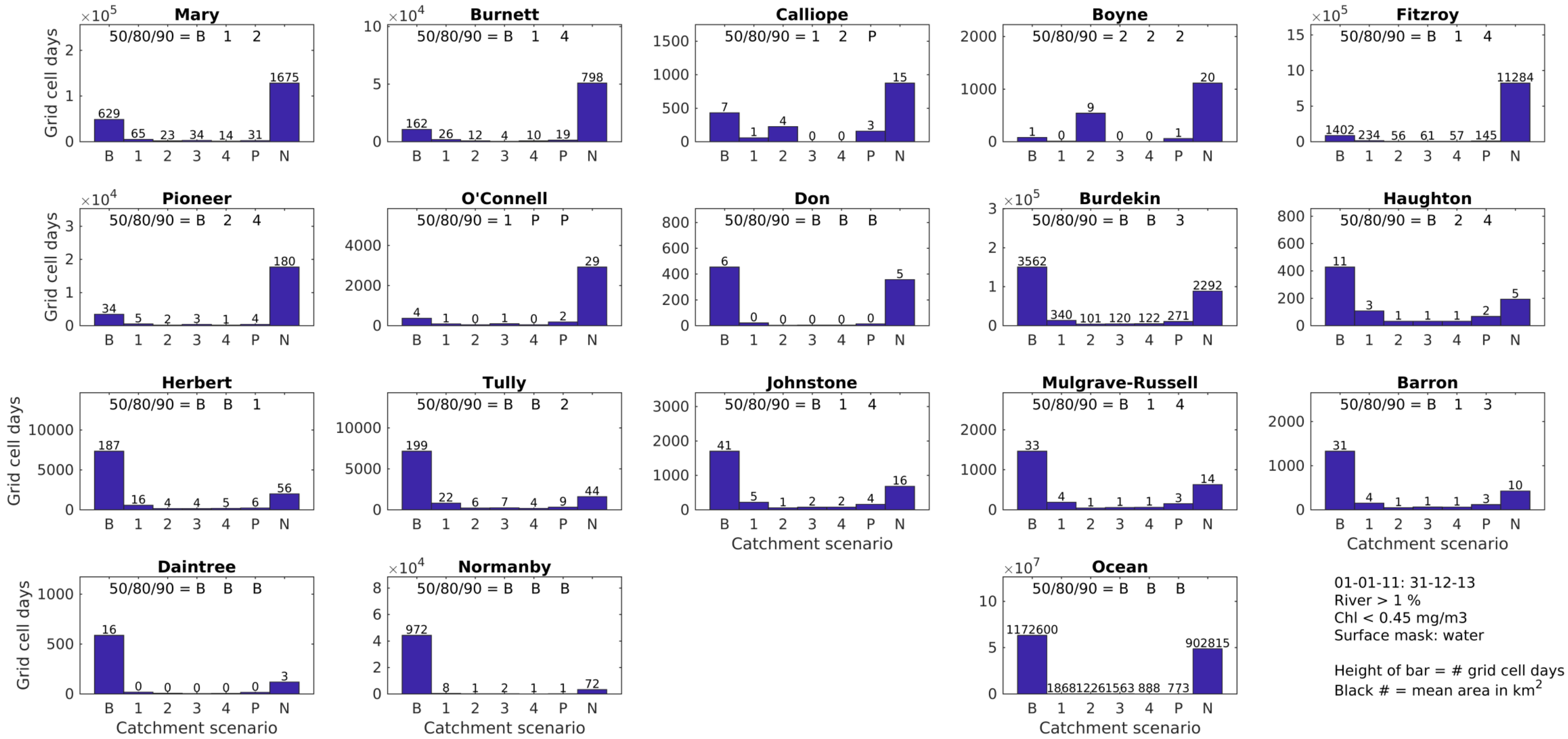


Figure 6. Individual river basin load calculations for an ecological target. Panels for each river show the number of 16 km^2 grid cells that meet the target for each scenario (blue bars), the average area of the footprint meeting the target for duration of analysis (black text above bars), and the minimum load reduction scenario required to meet the target for 50%, 80% and 90% of the time (black text at top of graph). The bottom right text lists the analysis period, the freshwater plume edge, the criteria and the spatial extent (Surface mask).

In addition to the B, 1, 2, 3, 4 and P scenarios, there is an 'N' scenario. A grid cell count (a point in time and location) is assigned to this scenario when the criteria are not met with any of the other modelled scenarios, including the pre-development scenario (P). As criteria are not based on extensive long-term observational records, it is to be expected that over the duration of the analysis, occasionally the criteria will not be met, even in the pre-development scenario. If the N scenario dominates the histogram (e.g. the Fitzroy River in Figure 6), it suggests that the target has been set too low because the ecological outcome sought did not even occur in the pre-development times within the footprint of that river or that the differences between the pre-development and current load estimates are of low accuracy.

Similarly, the targets are not designed to be met every single day of the analysis period. Thus, a management decision must specify what per cent of the time the target must be met. To assist, three options were considered: 50th, 80th and 90th percentiles (labelled within each panel as 50, 80 and 90). For each of those percentiles, the minimum load reduction scenario required to meet this level of target achievement can be identified.

Finally, once a scenario has been completed for a particular criterion and river, the corresponding reduction in river load over the analysis period can be determined. Load reductions for each basin are then calculated from the annual mean of the 1986-2014 catchment model time period.

The heights of the histogram columns represent the number of 16 km^2 grid cells within a particular basin's footprint that met the target over the duration of the analysis. For example, over the three-year model period (1 January 2011 – 31 December 2013), there were approximately 300,000 cell counts for the Burdekin River footprint. To give this perspective, the black number above each column (Figure 6) represents the daily averaged footprint (km^2) of the river that meets the criteria for that scenario. The sum of these areas for all scenarios (i.e. the sum of the black values above the columns in Figure 6) represents the daily average footprint (km^2) of the river between 1 January 2011 and 31 December 2013. It must be noted though, that the counts are only conducted on days when a footprint is present, so there are no cell counts when there is no flood plume. Thus, using the Burdekin River example, the daily average footprint was estimated to be 6,808 km^2.

Caveats and limitations

1. The eReefs model also assessed the footprints of basins outside the GBR catchments area to determine if they had any influence on the GBR World Heritage Area (GBRWHA). This included the Logan, Brisbane, Pine and Caboolture rivers in South East Queensland and the Fly River in Papua New Guinea. The modelled results (not shown here) found that the footprints of these rivers do not extend into the GBRWHA.
2. We assume the river with the greatest influence on a particular grid cell at a particular time is solely responsible for the water quality at that time. This will generally be true of sediments. In some cases nutrients can spread in the plume of one river, but influence the water quality at a later time when another river has a greater influence. This is most clearly seen in the Wet Tropics rivers, with a number of rivers in close proximity, and for small rivers near large rivers, such as the Calliope and Fitzroy plumes. As the final load reduction calculations are averaged over seasons, any river misattribution errors are likely to cancel out.
3. In the histogram (Figure 6), cells assigned to scenario 'N' are not included in calculating which scenario is required to meet the percentage target. For basins with a large proportion of the daily average footprint assigned to the 'N' scenario, the load reduction required will be artificially reduced. The option of including 'N' in the percentage of time the target must be met was not chosen as it introduces the possibility of requiring a load reduction target greater than the anthropogenic load.

4. All scenarios modelled suspended sediment and nutrient reductions simultaneously, whereas the Source Catchment loads are shown for just DIN or suspended sediment. For some variables, such as Chl-*a*, it may be safe to assume that DIN loads drive Chl-*a* within the river footprint. But for other variables, such as bottom light, it may be a combination of fine sediment and DIN. Thus, caution should be exercised when using a single figure to determine reductions in loads. Coupled results need to be disentangled to determine the most important factor driving the marine response (sediments or nutrients). Generally in this study, for DIN, we ignored the fine sediment 'matching' target and for fine sediment ignored the 'matching' DIN target, but the secondary influence was considered on a case-by-case basis.
5. It is assumed that the Source Catchments pre-development load estimates are the best available and are not questioned through this process.
6. Application of the eReefs 4 km (16 km^2 cell area) output results in large spatial interpolations of data in some locations, particularly where there are narrow channels such as Hinchinbrook Channel. This coarse grid size is particularly limiting along the coastline, where shallow waters and resuspension events can dominate conditions and where intertidal seagrass beds are often located. In fact, with a 4 km resolution, many of the shallow regions with seagrass appear either as land, or as grid cells too deep for seagrass. This limitation is likely to result in underestimates in the calculation of potential exposure of seagrass to sediment and DIN. This is also relevant to coral reefs, although there are comparably smaller areas of reefs in these nearshore coastal waters.
7. The bias in Chl-*a* of the model is -0.07 μgL^{-1}. This means that the model gives results which uniformly are 0.07 μgL^{-1} too low. This results in a conservative output for the targets.

Notwithstanding these uncertainties and the fact that multiple ecological targets may lead to multiple water quality targets, the eReefs scenarios provided additional inputs to the total body of evidence from which the final load calculations were derived.

3. Sediments and nutrients: results

3.1 Modelling outputs for each criterion: nutrients

Table 5 shows the results for DIN from each of the three criteria runs to illustrate the differences, even though only one criterion is selected for the final assessment. There is some agreement between the Chl-*a* 0.45 μgL^{-1} macroalgae criterion and the Chl-*a* 0.5 μgL^{-1} bleaching criterion. The CoTS criterion (a factor only in the wet season) is complicated by the fact that these were below average river discharge years. Many of the rivers show no footprint or 'NF' for the CoTS scenario, primarily because the plumes for these areas do not influence the nominal CoTS initiation zone, but also many of the footprints are likely to be underestimated by the limitations of river discharge in the model (described above and listed in Table 5). This is likely to be the case for the rivers between the Daintree and the Burdekin where there is evidence in other years of river plumes influencing the CoTS initiation zone, even within the modelled years (Álvarez-Romero et al. 2013, Brinkman et al. 2014, Devlin et al. 2015, Wooldridge and Brodie 2015, Brodie et al. 2017). In our uncertainty analysis, we have noted those rivers where the footprint is likely to be underestimated due to the limitations with flow data (Table 4) or other input data (such as end-of-catchment load estimates).

The macroalgae criterion (Chl-*a* 0.45 μgL^{-1}) shown in Table 6 has been selected as the scenario for target setting as it is considered to be the most representative scenario for DIN reductions in the GBR. It is also the most conservative scenario in most cases. Further analysis could use all three criteria for a potentially more accurate result, but this was outside the scope of the current work.

Note that the model outputs below are based on a reduction in dissolved nitrogen, that is, both dissolved organic nitrogen (DON) and DIN. Nevertheless, as scenarios are based on anthropogenic loads which are comparatively small for DON, we have assumed that the reduction is mostly applied to DIN. Knowledge of management options to reduce DON is limited at this time.

Table 5. Model outputs (as percentage reductions of the anthropogenic load) for the criteria run for the eReefs scenarios for DIN.

Basin	Macroalgae criteria Chl-*a* <0.45 μgL^{-1} (1 Jan 2011 – 31 Dec 2013) (scenario result)	DIN from bleaching (scenario result)	DIN target from CoTS (average of 3 years of results) (scenario result)
Normanby	0 (B)	0 (B)	0 (B)
Daintree	0 (B)	0 (B)	0 (B)
Barron	64.3 (3)	0 (B)	0 (B)
Mulgrave-Russell	76.2 (4)	76.2 (4)	0 (B)
Johnstone	76.2 (4)	76.2 (4)	0 (B)
Tully	52.4 (2)	64.3 (3)	NF
Herbert	40.5 (1)	52.4 (2)	NF
Haughton	76.2 (4)	NF	NF
Burdekin	64.3 (3)	52.4 (2)	N
Don	B	>76.2 (P)	NF
O'Connell	P	N	NF
Pioneer	76.2 (4)	52.4 (2)	NF
Fitzroy	76.2 (4[1])	52.4 (2)	NF
Boyne	52.4 (2[1])	P	NF
Calliope	P[1]	P	NF
Burnett	76.2 (4)	>76.2 (P)	NF
Mary	52.4 (2)	40.5 (1)	NF

Notes:
Scenario results: P = pre-development; B = 0; 1 = 40.5; 2 = 52.4; 3 = 64.3; 4 = 76.2; N = target not met;
NF = no footprint over coral
[1] Small anthropogenic load, so minimal action needed.

Table 6. Model outputs (as percentage reductions of the anthropogenic load) for the criteria run for the eReefs scenarios for DIN based on the macroalgae criterion. The pre-development results are adjusted to the maximum target reduction.

Basin	Macroalgae criteria Chl-*a* <0.45 μgL^{-1} (1 Jan 2011 – 31 Dec 2013) (scenario result)	Adjusted DIN target just from macroalgae	Comment
Normanby	0 (B)	0	Ignore the results; error in specification of loads in the eReefs model for northward facing rivers (Normanby only) was identified after the scenarios were completed. Future simulations do not have this problem.
Daintree	0 (B)	0	Adopt model output.
Barron	64.3 (3)	64.3	Adopt model output.
Mulgrave-Russell	76.2 (4)	76.2	Adopt model output.
Johnstone	76.2 (4)	76.2	Adopt model output.
Tully	52.4 (2)	52.4	Adopt model output.
Herbert	40.5 (1)	76.2	Adjusted to be equivalent to adjacent basins. The load estimation from Report Card 2015 used in eReefs scenario was an underestimate compared to Report Card 2015 revised anthropogenic DIN loads where there is greater confidence. The 4 km grid resolution also constrains the ability to model discharge from the Herbert River into Hinchinbrook Channel.
Haughton	76.2 (4)	76.2	Adopt model output.
Burdekin	64.3 (3)	64.3	Adopt model output.
Don	0 (B)	0	Adopt model output.
O'Connell	P	>76.2	Adjust to maximum target reduction.
Pioneer	76.2 (4)	76.2	Adopt model output.
Fitzroy	76.2 (4[1])	0	The load estimation from Report Card 2015 was used in eReefs scenario and is considered to be an overestimate compared to Report Card 2016 revised loads where there is greater confidence and relatively minor anthropogenic DIN loads. However, our confidence in the estimates of the anthropogenic DIN loads from the Fitzroy Basin is low.
Boyne	52.4 (2[1])	0	Adjusted to reflect small anthropogenic load; minimal action needed.
Calliope	P[1]	0	Adjusted to reflect small anthropogenic load; minimal action needed.
Burnett	76.2 (4)	76.2	Adopt model output.
Mary	52.4 (2)	52.4	Adopt model output.

Notes: Scenario results: P = Pre-development; B = 0; 1 = 40.5; 2 = 52.4; 3 = 64.3; 4 = 76.2; N = target not met; NF = no footprint over coral. [1] Small anthropogenic load, so minimal action needed.

3.1 Modelling outputs for each criteria: sediment

Table 7 shows the results for fine sediment targets using the criterion ***Light 6 mol photon m^{-2} d^{-1}for seagrass (Collier et al. 2012a, Collier et al. 2012b, Collier et al. 2016a, Collier et al. 2016b) – chronic case, all years, waters in river influence <10 m.***

Important notes and limitations for this scenario include:

1. The limitations with the 4 km grid noted above are particularly relevant for seagrass where coastal seagrasses are located close to the coast.
2. There is a large proportion of 'N' (does not meet the criterion) results. This could have possibly been reduced by adding another threshold for deeper water seagrass species.
3. The model tracks river sediments, which may exclude the effects of nutrient-driven turbidity. The main contributor to low light in <10 m is resuspension of sediment, rather than phytoplankton, but this is not necessarily the case in Wet Tropics and needs further investigation.
4. All scenarios have equal amounts of coloured dissolved organic matter.

Table 7. Model outputs (as percentage reductions of the anthropogenic load) for the light criterion run for the eReefs scenarios for fine sediment. The pre-development results are adjusted to the maximum target reduction.

Basin	6 mol photon m^{-2} d^{-1}, 10 m deep, seagrass chronic criteria (1 Jan 2011 – 31 Dec 2013)	Adjusted fine sediment targets from seagrass criteria	Comment
Normanby	0 (B)	0	Ignore the results; error in specification of loads in the eReefs model for northward facing rivers (Normanby only) was identified after the scenarios were completed. Future simulations do not have this problem.
Daintree	0 (B)	0	Adopt model output.
Barron	0 (B)	0	Adopt model output.
Mulgrave-Russell	10.1 (1)	10.1	Adopt model output.
Johnstone	P	>43.8	Adjust to maximum target reduction.
Tully	21.3 (2)	21.3	Adopt model output.
Herbert	32.6 (3)	32.6	Adopt model output. Note the 4 km grid resolution also constrains the ability to model discharge from the Herbert River into Hinchinbrook Channel; high uncertainty in results.
Haughton	0 (B)	0	Adopt model output.
Burdekin	32.6 (3)	32.6	Adopt model output.
Don	32.6 (3)	32.6	Adopt model output.
O'Connell	P	>43.8	Adjust to maximum target reduction.
Pioneer	21.3 (2)	21.3	Adopt model output.
Fitzroy	32.6 (3)	32.6	Adopt model output.
Boyne	P	>43.8	Adjust to maximum target reduction.
Calliope	32.6 (3)	32.6	Adopt model output.
Burnett	21.3 (2)	21.3	Adopt model output.
Mary	21.3 (2)	21.3	Adopt model output.

Notes: Scenario results: P = Pre-development; B = 0; 1 = 10.1; 2 = 21.3; 3 = 32.6; 4 = >43.8.

3.2 End-of-basin water quality targets

Approach

For the definition of targets for basins that are not included in the model outputs, the existing WQIP basin-specific targets were used, or targets were defined by proportionality with adjacent rivers if there were similar areas of land use.

As PN and PP loads are tightly correlated with fine sediment loads, and management of erosion reduces all three, we have chosen to have the same percentage targets of PP and PN as for fine sediment. However, we do know that the nutrient content of soils varies across soil types and localities in the GBR catchment (Garzon-Garcia et al. 2017), which may have implications for targets in some locations. At present, the load reductions in tonnes for PN and PP have been calculated from the percentage load reductions of fine sediment as the best available approach.

After some discussion of the likely errors and uncertainties (listed above) in the modelling process, it was agreed by the Reef Water Quality Protection Plan Independent Science Panel to *round down the results to the nearest 10% for all parameters*.

Ross and Black basins targets

Note that for the Ross and Black River basins no eReefs modelling was available; targets were not set by other methods in the Burdekin WQIP; and we have limited alternative methods available at this time to be able to set ecologically relevant targets (ERTs) for these basins. A load reduction target has only been set for the Ross Basin based on comparison with similar basins. It was determined that the modelled DIN anthropogenic load characteristics of the Ross Basin (180 tonnes/yr) is most similar to the Barron Basin (152 tonnes/yr), with a large proportion of the DIN load being derived from urban land uses, primarily sewage treatment plant (STP) contributions, in both locations. The DIN contribution from the Townsville STP is estimated to contribute 70% of the anthropogenic DIN load from the Ross Basin, with a load estimate of 123 tonnes per year (derived from McCloskey et al. 2017). This is in comparison to STP contributions in other basins, where the next highest STP contribution is from the Fitzroy Basin, estimated to be 62 tonnes per year. In addition, the Marine Likelihood of Exposure Indexes for DIN in the recent GBR risk assessment completed for Scientific Consensus Statement 2017 (Waterhouse et al. 2017a) were comparable between the Barron (0.1) and Ross (0.13) basins. It is therefore recommended that a DIN pollutant load reduction target comparable to the Barron Basin is adopted for the Ross Basin, that is, 60%.

Further studies will be needed to determine fine sediment and particulate nutrient targets for the Ross Basin and all targets for the Black Basin. This is denoted in the following tables by 'ND', meaning not determined. The Reef Water Quality Protection Plan 2013 targets should never be applied to individual basins, as they were not determined at a basin scale. It is clear that water quality targets need to be established for these basins, and the target load reductions are highly unlikely to be zero (as for some northern Cape York basins). Studying the locally developed pollutant transport model for these basins (led by Townsville City Council) revealed similar results between the current model version and the (GBR-wide) Source Catchments model, but improving input data may help improve the pollutant load assessments for these basins in the future.

Cape York region fine sediment targets

For the Cape York basins (Jacky Jacky, Olive Pascoe, Lockhart, Stewart, Normanby, Jeannie and Endeavour), the eReefs model was either not available or not working adequately in 2016. The listed targets in this report were adapted from the WQIP targets (Cape York NRM and South Cape York Catchments 2016). However, the WQIP targets were not based on a receiving water model, and hence are not ecologically relevant for marine waters. Thus, they were derived from the WQIP and adjusted after further consideration of the current Source Catchment modelling results.

The process for setting the WQIP targets involved using the 'degree of disturbance' scores determined as part of the definition of environmental values for the region, for each basin. The Draft environmental values and water quality objectives for eastern Cape York waters (DEHP 2017) are based on the 2022 (short term) WQIP targets for the flood event water quality guidelines. These are presented as a percentage improvement from current water quality. The WQIP identified that improvements in water quality were required in 'modified waters'. These were mainly in the Normanby and Endeavour systems and adjacent estuarine/coastal waters.

In summary, the WQIP noted that:

> *For rivers that are slightly or moderately disturbed such as the upper Normanby river tributaries, targets have been set for reductions in suspended sediment concentrations and particulate nutrients. The targets are for a 10th percentile reduction in suspended sediments and particulate nutrients during the wet season and a 25% reduction of flood event concentrations. At the lower Normanby (end-of-catchment) targets are set for a short term (7 year) 10% reduction in event sediment and particulate nutrient concentrations. The end-of-catchment targets are lower due to the large fraction of sediment that settles out within the catchment. Targets have also been set to reduce nutrient concentrations in the Laura River across all season.*
>
> (Cape York NRM and South Cape York Catchments, 2016 p. 35)

Since the WQIP was released, improvements to the Source Catchments modelled estimates have changed our understanding of anthropogenic and total fine sediment loads. The recent model version presents the anthropogenic load as a greater proportion of the total load, therefore, the reduction targets (as per cent of anthropogenic load) are lower percentage than the WQIP reduction targets.

Confidence ratings

Confidence ratings for the targets were derived using a set of criteria for DIN and fine sediment. The ratings are assessed as either High, Moderate, Moderate-low or Low confidence, as shown in Table 8.

The criteria for DIN are:

Where there is limited anthropogenic load, and land use and catchment characteristics are known	**High**
Where eReefs is used, the result is comparable with the relevant WQIP or analogy to the adjacent basin is valid, and land use and catchment characteristics are known	**Moderate**
Where eReefs is used, no WQIP result is available, but analogy to adjacent basin is valid, and land use and catchment characteristics are known	**Moderate-low**
Where eReefs is not used, the result is comparable with the relevant WQIP or analogy to the adjacent basin is valid, and land use and catchment characteristics are known	**Moderate-low**
Where eReefs is not used, no WQIP result is available, there is limited confidence in analogy with other basins, and land use and catchment characteristics are known	**Low**

The criteria for fine sediment and particulate nutrients are similar:

Where there is limited anthropogenic load, and land use and catchment characteristics are known	**High**
Where eReefs is used, the result is comparable with the relevant WQIP or analogy to the adjacent basin is valid (except in Wet Tropics, where there is low confidence in WQIP suspended sediment targets), and land use and catchment characteristics are known	**Moderate**
Where eReefs is used, no WQIP result is available, but analogy to adjacent basin is valid, and land use and catchment characteristics are known	**Moderate-low**
Where eReefs is not used, the result is comparable with the relevant WQIP or analogy to the adjacent basin is valid, and land use and catchment characteristics are known	**Moderate-low**
Where eReefs is not used, no WQIP result is available, there is limited confidence in analogy with other basins, and land use and catchment characteristics are known	**Low**

Table 8. End-of-catchment anthropogenic water quality targets recommended for fine sediment, DIN, PP and PN for the 35 GBR basins by 2025. Results in red are included in the eReefs modelling scenarios. Note that targets identified as being greater than the maximum targets in Tables 6 and 7 are further adjusted to be equal to the maximum target here.

Basin	Fine sediment reduction %	DIN reduction %	PP reduction %	PN reduction %	Justification	Confidence in DIN targets**	Confidence in fine sediment, PP and PN targets **
Jacky Jacky	0	0	0	0	WQIP	High	Moderate-low
Olive Pascoe	0	0	0	0	WQIP	High	Moderate-low
Lockhart	2[1]	0	2	2	WQIP	High	Moderate-low
Stewart	6[1]	0	6	6	WQIP	High	Moderate-low
Normanby*	10[1]	0	10	10	WQIP	High	Moderate
Jeannie	6[1]	0	6	6	WQIP	High	Moderate-Low
Endeavour	10[1]	0	10	10	WQIP	High	Moderate-low
Daintree*	0	0	0	0	eReefs output	Moderate	Moderate
Mossman	0	50[2]	0	0	DIN from WQIP; sediment, PP and PN analogy with Daintree	Moderate-low	Moderate-low
Barron*	0	60	0	0	eReefs output	Moderate	Moderate
Mulgrave-Russell*	10	70	10	10	eReefs output	Moderate	Moderate
Johnstone*	40	70	40	40	eReefs output	Moderate	Moderate
Tully*	20	50	20	20	eReefs output	Moderate	Moderate
Murray	20	50	20	20	Analogy with Tully	Moderate-low	Moderate-low

Basin	Fine sediment reductio n %	DIN reductio n %	PP reductio n %	PN reductio n %	Justification	Confidence in DIN targets**	Confidence in fine sediment, PP and PN targets **
Herbert*	30	70	30	30	eReefs not used for the Herbert due to the modelling issues for the Hinchinbrook Channel and dated load inputs; used WQIP	Moderate-low	Moderate-low
Black	ND	ND	ND	ND	Insufficient data	ND	ND
Ross	ND	60	ND	ND	Analogy with Barron (see above)	Low	ND
Haughton*	0	70	0	0	eReefs output	Moderate	High
Burdekin*	30	60	30	30	eReefs output but limited by knowledge of anthropogenic DIN sources in grazing lands	Moderate-low	Moderate
Don*	30	0	30	30	eReefs output	Moderate	Moderate
Proserpine	0	70	0	0	Analogy to adjacent basins for DIN; for fine sediment, dam trapping significantly reduces outputs	Low	Moderate-low
O'Connell*	40	70	40	40	eReefs output	Moderate-low	Moderate
Pioneer*	20	70	20	20	eReefs output	Moderate-low	Moderate-low
Plane	0	70	0	0	Analogy to adjacent basins	Moderate-low	High
Styx	0	0	0	0	Analogy to adjacent basins	High	High
Shoalwater	0	0	0	0	Analogy to adjacent basins	High	High
Waterpark	0	0	0	0	Analogy to adjacent basins	High	High
Fitzroy*	30	0	30	30	eReefs output but limited by knowledge of anthropogenic DIN sources in grazing and cropping lands	Low	Moderate
Calliope*	30	0	30	30	eReefs output	High	Moderate-low
Boyne*	40	0	40	40	eReefs output	High	Moderate-low
Baffle	20[3]	50[3]	20	20	Analogy to adjacent basins for sediment, WQIP for DIN	Moderate-low	Moderate-low
Kolan	20[3]	50[3]	20	20	Analogy to adjacent basins for sediment, WQIP for DIN	Moderate-low	Moderate-low
Burnett*	20	70	20	20	eReefs output	Moderate	Moderate
Burrum	20[3]	50[3]	20	20	Analogy to adjacent basins for sediment, WQIP for DIN	Moderate-low	Moderate-low
Mary*	20	50	20	20	eReefs output	Moderate	Moderate

Notes:

Where loads are 0% this means that there should be no increase in the current total loads as a minimum requirement (i.e. ‘maintain current loads’).

All targets are rounded downwards to the appropriate multiple of 10%, that is, 76 is rounded to 70 due to the uncertainty in the estimates explained above.

All PP and PN targets are identical to the % reduction targets for fine sediment.

ND = Not determined at this stage, hence no ERTs set.

Additional sources: [1] Cape York WQIP (Cape York NRM and South Cape York Catchments 2016). Note these targets do not always follow the nearest 10% rule for rounding; [2] Wet Tropics WQIP (Terrain NRM 2015); [3] Burnett Mary WQIP (Burnett Mary Regional Group 2015).

* Included in eReefs model output.

**Confidence ratings based on criteria described above.

4. Comparison of targets with those in the WQIPs

Table 9 presents a comparison of the targets already defined at a basin scale and those proposed in this project. The pesticide targets are presented in section 7. In most instances, the proposed targets are comparable to or lower than the existing targets except in a few instances, including:

- fine sediment, PN and PP: Don, Calliope, Boyne
- DIN: Barron, Ross, Don, Proserpine, O’Connell, Pioneer, Kolan

Table 9. Comparison of the proposed basin pollutant water quality targets (shaded in blue) and those included in the regional WQIPs.

NRM region	Basin	Fine sediment % reduction		DIN % reduction		PN % reduction		PP % reduction	
		Proposed	WQIP	Proposed	WQIP	Proposed	WQIP	Proposed	WQIP
Cape York[3]	Jacky Jacky	0	0	0	0	0	0	0	0
	Olive Pascoe	0	0	0	0	0	0	0	0
	Lockhart	2	6	0	0	2	6	2	6
	Stewart	6	6	0	0	6	6	6	6
	Normanby	10	30*	0	0	10	30*	10	30*
	Jeannie	6	6	0	0	6	6	6	6
	Endeavour	10	10	0	0	10	10	10	10
Wet Tropics	Daintree	0	50	0	50	0	50	0	50
	Mossman	0	50	50	50	0	50	0	50
	Barron	0	50	60	50	0	50	0	50
	Mulgrave-Russell	10	50	70	70	10	50	10	50
	Johnstone	40	50	70	80	40	50	40	50
	Tully	20	50	50	80	20	50	20	50
	Murray	20	50	50	80	20	50	20	50
	Herbert	30	50	70	80	30	50	30	50
Burdekin	Black	ND	20*	ND	50*	ND	20*	ND	20*
	Ross	ND	20*	60	50*	ND	20*	ND	20*
	Haughton	0	20*	70	80[1]	0	20*	0	20*
	Burdekin	30	50	60		30	52	30	52
	Don	30	20*	0	50*	30	20*	30	20*
Mackay Whits.	Proserpine	0	ND	70	ND	0	ND	0	ND
	O’Connell	40	ND	70	ND	40	ND	40	ND
	Pioneer	20	ND	70	ND	20	ND	20	ND
	Plane	0	ND	70	ND	0	ND	0	ND
Fit	Styx	0	20*	0	0*	0	20*	0	20*

NRM region	Basin	Fine sediment % reduction		DIN % reduction		PN % reduction		PP % reduction	
		Proposed	WQIP	Proposed	WQIP	Proposed	WQIP	Proposed	WQIP
	Shoalwater	0	20*	0	0*	0	20*	0	20*
	Waterpark	0	20*	0	0*	0	20*	0	20*
	Fitzroy	30	50	0	0*	30	50	30	50
	Calliope	30	20*	0	0*	30	20*	30	20*
	Boyne	40	20*	0	0*	40	20*	40	20*
Burnett Mary	Baffle	20	50	50	50	20	50[2]	20	50[2]
	Kolan	20	50	50	50	20	50[2]	20	50[2]
	Burnett	20	50	70	50	20	50[2]	20	50[2]
	Burrum	20	50	50	50	20	50[2]	20	50[2]
	Mary	20	50	50	50	20	50[2]	20	50[2]

Notes: *Targets were not in WQIPs and were defined in Brodie and Waterhouse (2016). ND = not determined

[1] Lower Burdekin – 80% DIN from sugarcane areas in ALL of Lower Burdekin including parts of the Burdekin, Haughton and Don Basins.

[2] Note that the PN and PP ERTs were adjusted for Burnett Mary from WQIP from 20% to 50% to align with TSS target.

[3] All Cape York basin-specific targets are for 2022, except for Normanby which is 30% by 2037 (equivalent to an ERT), but has not been calculated using the same method as other ERTs.

5. Calculating load reductions as tonnes

The calculated load reductions (tonnes) for each basin were based on the proposed targets for DIN, fine sediment, PN and PP. This was completed using the Source Catchments 2015 model run of anthropogenic baseline load estimates for each basin, and calculating the percentage load reduction to estimate the target anthropogenic load for each parameter.

Table 10. Calculated DIN anthropogenic (anth.) load reductions (annual average loads in tonnes per year) required to meet the proposed DIN end-of-catchment load reductions by 2025. Calculated from the 2012-2013 anthropogenic baseline Report Card 2015 Source Catchment model outputs (see McCloskey et al. 2017).

NRM region	Basin	DIN total baseline load (2012-2013) (t/yr)	DIN anth. baseline load (2012-2013) (t/yr)	Proposed anth. DIN target reduction (%)	DIN load reduction* (from anth. baseline) (t)	DIN target anth. load (t/yr) by 2025	DIN target total load (t/yr) by 2025
Cape York	Jacky Jacky	67	0	0	0	0	67
	Olive Pascoe	98	1	0	0	1	98
	Lockhart	49	0	0	0	0	49
	Stewart	30	0	0	0	0	30
	Normanby	105	9	0	0	9	105
	Jeannie	35	0	0	0	0	35
	Endeavour	40	1	0	0	1	40
	REGIONAL TOTAL	423	11	0	0	11	423
Wet Tropics	Daintree	478	135	0	0	135	478
	Mossman	160	104	50	52	52	107
	Barron	152	87	60	52	35	100

NRM region	Basin	DIN total baseline load (2012-2013) (t/yr)	DIN anth. baseline load (2012-2013) (t/yr)	Proposed anth. DIN target reduction (%)	DIN load reduction* (from anth. baseline) (t)	DIN target anth. load (t/yr) by 2025	DIN target total load (t/yr) by 2025
	Mulgrave-Russell	934	423	70	296	127	638
	Johnstone	1,059	499	70	349	150	709
	Tully	777	384	50	192	192	585
	Murray	414	232	50	116	116	298
	Herbert	1,522	886	70	620	266	902
	REGIONAL TOTAL	5,496	2,750	61	1,678	1,072	3,818
Burdekin	Black	97	21	-	-	21	97
	Ross	180	123	60	74	49	106
	Haughton	1,016	914	70	639	274	377
	Burdekin	1,104	171	60	103	69	1,001
	Don	177	68	0	-	68	177
	REGIONAL TOTAL	2,574	1,297	63	816	480	1,758
Mackay Whitsunday	Proserpine	310	157	70	110	47	200
	O'Connell	325	186	70	130	56	194
	Pioneer	256	193	70	135	58	121
	Plane	464	366	70	256	110	208
	REGIONAL TOTAL	1,355	902	70	631	270	723
Fitzroy	Styx	91	10	0	0	10	91
	Shoalwater	100	5	0	0	5	100
	Waterpark	65	4	0	0	4	65
	Fitzroy	799	159	0	0	159	799
	Calliope	47	6	0	0	6	47
	Boyne	37	3	0	0	3	37
	REGIONAL TOTAL	1,140	186	0	0	186	1,140
Burnett Mary	Baffle	58	32	50	16	16	42
	Kolan	78	68	50	34	34	45
	Burnett	246	207	70	145	62	101
	Burrum	199	186	50	93	93	106
	Mary	459	361	50	181	181	278
	REGIONAL TOTAL	1,040	854	55	468	385	571
TOTAL	**GBR TOTAL**	**12,028**	**5,999**	**60**	**3,594**	**2,405**	**8,434**

* Note the target reduction is for the period until 2025. This is an aggregate target for this period, not an additional amount every year.

Table 11. Calculated fine sediment anthropogenic (anth.) load reductions (annual average loads in kilotonnes per year) required to meet the proposed fine sediment end-of-catchment load reductions by 2025. Calculated from the 2012-2013 anthropogenic baseline Report Card 2015 Source Catchment model outputs (see McCloskey et al. 2017).

NRM region	Basin	Fine sediment total baseline load (2012-2013) (kt/yr)	Fine sediment anth. baseline (2012-2013) (kt/yr)	Proposed anth. fine sediment target reduction (%)	Fine sediment load reduction* (from anth. baseline) (kt)	Fine sediment target anth. load (kt/yr) by 2025	Fine sediment target total load (kt/yr) by 2025
Cape York	Jacky Jacky	52	43	0	0	43	52
	Olive Pascoe	72	54	0	0	54	72
	Lockhart	67	54	2	1	53	66
	Stewart	49	41	6	2	38	47
	Normanby	186	151	10	15	136	171
	Jeannie	42	31	6	2	29	40
	Endeavour	59	27	10	3	25	56
	REGIONAL TOTAL	526	400	6	23	377	503
Wet Tropics	Daintree	103	28	0	0	28	103
	Mossman	17	6	0	0	6	17
	Barron	55	32	0	0	32	55
	Mulgrave-Russell	253	156	10	16	141	238
	Johnstone	379	260	40	104	156	275
	Tully	157	83	20	17	66	140
	Murray	74	39	20	8	31	66
	Herbert	478	331	30	99	232	379
	REGIONAL TOTAL	1,516	936	26	243	692	1,273
Burdekin	Black	62	34	ND	0	34	62
	Ross	62	49	ND	0	49	62
	Haughton	183	157	0	0	157	183
	Burdekin	3,260	2,786	30	836	1,950	2,425
	Don	213	183	30	55	128	158
	REGIONAL TOTAL	3,781	3,209	28	891	2,319	2,890
Mackay Whitsunday	Proserpine	131	75	0	0	75	131
	O'Connell	314	241	40	96	145	217
	Pioneer	227	173	20	35	139	192
	Plane	146	99	0	0	99	146
	REGIONAL TOTAL	818	589	22	131	458	687
Fitzroy	Styx	104	94	0	0	94	104
	Shoalwater	67	59	0	0	59	67
	Waterpark	65	57	0	0	57	65
	Fitzroy	1,507	1,292	30	388	904	1,119
	Calliope	57	50	30	15	35	42
	Boyne	24	16	40	6	9	18
	REGIONAL TOTAL	1,824	1,568	26	409	1,159	1,415
Burnett Mary	Baffle	75	53	20	11	42	65
	Kolan	40	30	20	6	24	34
	Burnett	548	426	20	85	341	463
	Burrum	26	17	20	3	14	22
	Mary	770	666	20	133	533	637
	REGIONAL TOTAL	1,459	1,192	20	238	954	1,221

NRM region	Basin	Fine sediment total baseline load (2012-2013) (kt/yr)	Fine sediment anth. baseline (2012-2013) (kt/yr)	Proposed anth. fine sediment target reduction (%)	Fine sediment load reduction* (from anth. baseline) (kt)	Fine sediment target anth. load (kt/yr) by 2025	Fine sediment target total load (kt/yr) by 2025
TOTAL	**GBR TOTAL**	**9,925**	**7,894**	**25**	**1,935**	**5,958**	**7,990**

* Note the target reduction is for the period until 2025. This is an aggregate target for this period, not an additional amount every year.

Table 12. Calculated PN anthropogenic (anth.) load reductions (annual average loads in tonnes per year) required to meet the proposed PN end-of-catchment load reductions by 2025. Calculated from the 2012-2013 anthropogenic baseline Report Card 2015 Source Catchment model outputs (see McCloskey et al. 2017).

NRM region	Basin	PN total baseline load (2012-2013) (t/yr)	PN anth. baseline load (2012-2013) (t/yr)	Proposed PN anth. target reduction (%)	PN load reduction * (from anth. baseline) (t)	PN target anth. load (t/yr) by 2025	PN target total load (t/yr) by 2025
Cape York	Jacky Jacky	269	217	0	0	217	269
	Olive Pascoe	451	343	0	0	343	451
	Lockhart	315	258	2	5	253	310
	Stewart	153	120	6	7	113	145
	Normanby	253	153	10	15	138	238
	Jeannie	204	147	6	9	138	196
	Endeavour	251	111	10	11	100	240
	REGIONAL TOTAL	1,896	1,349	4	48	1,302	1,848
Wet Tropics	Daintree	579	59	0	0	59	579
	Mossman	101	22	0	0	22	101
	Barron	201	88	0	0	88	201
	Mulgrave-Russell	1,227	525	10	53	473	1,174
	Johnstone	1,986	1,217	40	487	730	1,500
	Tully	875	340	20	68	272	807
	Murray	400	160	20	32	128	368
	Herbert	1,327	697	30	209	488	1,118
	REGIONAL TOTAL	6,696	3,109	27	848	2,261	5,848
Burdekin	Black	143	54	ND	0	54	143
	Ross	98	83	ND	0	83	98
	Haughton	223	187	0	0	187	223
	Burdekin	2,887	2,407	30	722	1,685	2,165
	Don	305	250	30	75	175	230
	REGIONAL TOTAL	3,657	2,982	27	797	2,184	2,859
Mackay Whitsunday	Proserpine	387	226	0	0	226	387
	O'Connell	845	624	40	250	375	595
	Pioneer	450	305	20	61	244	389
	Plane	468	305	0	0	305	468
	REGIONAL TOTAL	2,150	1,460	21	311	1,150	1,839
Fitzroy	Styx	829	704	0	0	704	829
	Shoalwater	646	548	0	0	548	646
	Waterpark	1,268	1,122	0	0	1,122	1,268
	Fitzroy	3,066	2,130	30	639	1,491	2,427
	Calliope	439	358	30	107	250	332
	Boyne	113	23	40	9	14	104
	REGIONAL TOTAL	6,361	4,885	15	756	4,129	5,605
Burnett Mary	Baffle	268	164	20	33	131	235
	Kolan	101	68	20	14	54	87
	Burnett	667	341	20	68	273	599
	Burrum	58	38	20	8	30	51
	Mary	2,899	2,347	20	469	1,878	2,430

NRM region	Basin	PN total baseline load (2012-2013) (t/yr)	PN anth. baseline load (2012-2013) (t/yr)	Proposed PN anth. target reduction (%)	PN load reduction * (from anth. baseline) (t)	PN target anth. load (t/yr) by 2025	PN target total load (t/yr) by 2025
	REGIONAL TOTAL	3,993	2,957	20	591	2,366	3,402
TOTAL	**GBR TOTAL**	**24,753**	**16,742**	**20**	**3,351**	**13,391**	**21,402**

* Note the target reduction is for the period until 2025. This is an aggregate target for this period, not an additional amount every year.

Table 13. Calculated PP anthropogenic (anth.) load reductions (annual average loads in tonnes per year) required to meet the proposed PP end-of-catchment load reductions by 2025. Calculated from the 2012-2013 anthropogenic baseline Report Card 2015 Source Catchment model outputs (see McCloskey et al. 2017).

NRM region	Basin	PP total baseline load (2012-2013) (t/yr)	PP anth. baseline load (2012-2013) (t/yr)	Proposed PP anth. target reduction (%)	PP load reduction* (from anth. baseline) (t)	PP target anth. load (t/yr) by 2025	PP target total load (t/yr) by 2025
Cape York	Jacky Jacky	44	37	0	0	37	44
	Olive Pascoe	75	59	0	0	59	75
	Lockhart	95	80	2	2	78	93
	Stewart	45	38	6	2	36	43
	Normanby	78	53	10	5	48	72
	Jeannie	41	30	6	2	28	39
	Endeavour	77	30	10	3	27	74
	REGIONAL TOTAL	454	327	4	14	313	440
Wet Tropics	Daintree	83	17	0	0	17	83
	Mossman	17	7	0	0	7	17
	Barron	45	27	0	0	27	45
	Mulgrave-Russell	276	187	10	19	168	257
	Johnstone	756	616	40	246	369	510
	Tully	181	117	20	23	93	158
	Murray	84	55	20	11	44	73
	Herbert	291	191	30	57	133	234
	REGIONAL TOTAL	1,733	1,215	29	357	859	1,376
Burdekin	Black	77	23	ND	0	23	77
	Ross	50	42	ND	0	42	50
	Haughton	141	118	0	0	118	141
	Burdekin	1,797	1,479	30	444	1,035	1,354
	Don	174	142	30	43	99	131
	REGIONAL TOTAL	2,239	1,805	27	486	1,318	1,753
Mackay Whitsunday	Proserpine	164	88	0	0	88	164
	O'Connell	416	304	40	122	182	294
	Pioneer	184	116	20	23	93	161
	Plane	228	144	0	0	144	228
	REGIONAL TOTAL	992	653	22	145	508	847
Fitzroy	Styx	428	364	0	0	364	428
	Shoalwater	308	262	0	0	262	308
	Waterpark	517	457	0	0	457	517

NRM region	Basin	PP total baseline load (2012-2013) (t/yr)	PP anth. baseline load (2012-2013) (t/yr)	Proposed PP anth. target reduction (%)	PP load reduction* (from anth. baseline) (t)	PP target anth. load (t/yr) by 2025	PP target total load (t/yr) by 2025
	Fitzroy	1,822	1,250	30	375	875	1,447
	Calliope	221	180	30	54	126	167
	Boyne	60	12	40	5	7	55
	REGIONAL TOTAL	3,357	2,525	17	434	2,091	2,923
Burnett Mary	Baffle	125	77	20	15	62	110
	Kolan	37	25	20	5	20	32
	Burnett	268	146	20	29	117	238
	Burrum	25	17	20	3	13	22
	Mary	972	789	20	158	632	814
	REGIONAL TOTAL	1,426	1,054	20	211	843	1,216
TOTAL	**GBR TOTAL**	**10,201**	**7,579**	**22**	**1,646**	**5,932**	**8,555**

* Note the target reduction is for the period until 2025. This is an aggregate target for this period, not an additional amount every year.

6. Regional and Great Barrier Reef–wide targets

Regional and GBR-wide targets were estimated by converting basin targets from per cent reductions into tonnes reductions, then adding the load reductions required for the basins in each region or the GBR total to generate a total reduction required in tonnes. This was then expressed as a percentage of the anthropogenic baseline (i.e. the 2012-2013 anthropogenic baseline Report Card 2015 Source Catchment model outputs) for the region or the total GBR (Table 14). These are also summarised as per cent load reductions in Table 15, but have not been rounded as the basin-scale targets have been, as they are derived from the sum of the basin results for basin-scale outcomes and not defined specifically for regional outcomes.

Table 14. Calculated load reductions required to meet the proposed end-of-catchment load reductions by 2025. Calculated from the 2012-2013 anthropogenic baseline Report Card 2015 Source Catchment model outputs. Reductions are expressed as *anthropogenic* load reductions, but target loads are shown as anthropogenic and total loads. Note that these figures have not been rounded to illustrate the steps in the calculation of the regional and total GBR targets.

NRM region	Fine sediment					DIN					PN					PP				
	Anth. baseline (kt/yr)	Proposed anth. target reduction (%)	Load reduction by 2025 (kt)	Target anth. load (kt/yr)	Target total load (kt/yr)	Anth. baseline (t/yr)	Proposed anth. target reduction (%)	Load reduction by 2025 (t)	Target anth. load (t/yr)	Target total load (t/yr)	Anth. baseline (t/yr)	Proposed anth. target reduction (%)	Load reduction by 2025 (t)	Target anth. load (t/yr)	Target total load (t/yr)	Anth. baseline (t/yr)	Proposed anth. target reduction (%)	Load reduction by 2025 (t)	Target anth. load (t/yr)	Target total load (t/yr)
Cape York	400	6	23	377	503	11	0	0	11	423	1,349	4	48	1,302	1,848	327	4	14	313	440
Wet Tropics	936	26	243	692	1,273	2,750	61	1,678	1,072	3,818	3,109	27	848	2,261	5,848	1,215	29	357	859	1,376
Burdekin	3,209	28	891	2,319	2,890	1,297	63	816	480	1,758	2,982	27	797	2,184	2,859	1,805	27	486	1,318	1,753
Mackay Whitsunday	589	22	131	458	687	902	70	631	270	723	1,460	21	311	1,150	1,839	653	22	145	508	847
Fitzroy	1,568	26	409	1,159	1,415	186	0	0	186	1,140	4,885	15	756	4,129	5,605	2,525	17	434	2,091	2,923
Burnett Mary	1,192	20	238	954	1,221	854	55	468	385	571	2,957	20	591	2,366	3,402	1,054	20	211	843	1,216
GBR total	7,894	25	1,935	5,958	7,990	5,999	60	3,594	2,405	8,434	16,742	20	3,351	13,391	21,402	7,579	22	1,646	5,932	8,555

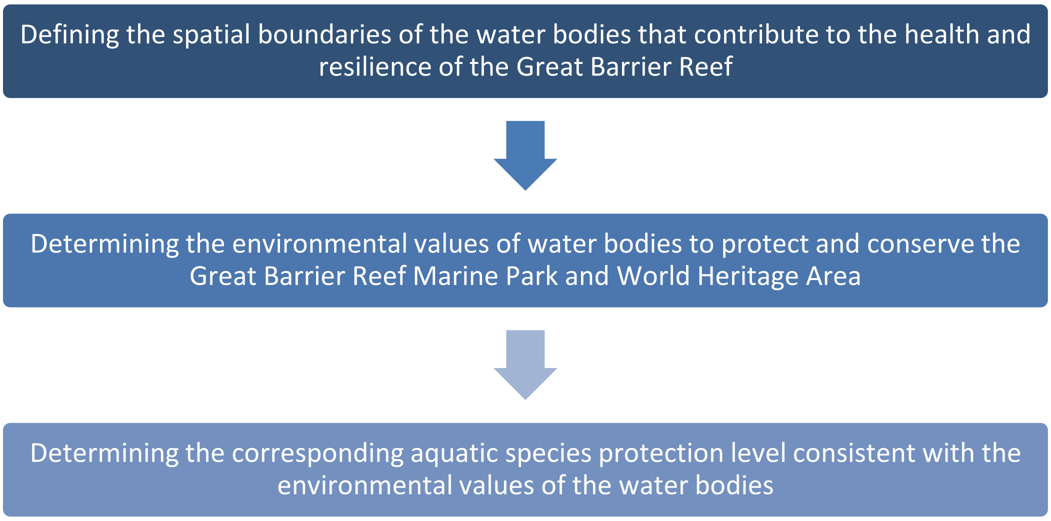
Table 15. Percentage load reductions (annual average loads) required to meet the proposed end-of-catchment load reductions by 2025. Calculated from the anthropogenic baseline from Report Card 2016 loads.

	Percentage reduction from the 2013 anthropogenic baseline load							
NRM region	**Fine sediment**	**Fine sediment rounded***	**DIN**	**DIN rounded***	**PN**	**PN rounded***	**PP**	**PP rounded***
Cape York	6	**5**	0	**0**	4	**5**	4	**5**
Wet Tropics	26	**25**	61	**60**	27	**25**	29	**30**
Burdekin	28	**30**	63	**60**	27	**25**	27	**25**
Mackay Whitsunday	22	**20**	70	**70**	21	**20**	22	**20**
Fitzroy	26	**25**	0	**0**	15	**15**	17	**20**
Burnett Mary	20	**20**	55	**55**	20	**20**	20	**20**
GBR-wide	25	**25**	60	**60**	20	**20**	22	**20**

*All NRM region targets are rounded to the nearest 5%.

7. Setting the pesticide targets

The revised pesticide targets for the draft Reef 2050 Water Quality Improvement Plan 2017-2022 have been developed to ensure consistency with the long-term goal[1] of Reef Water Quality Protection Plan 2013 (Queensland and Australian governments 2013), the *Environmental Protection (Water) Policy 2009* and the National Water Quality Management Strategy (ANZECC and ARMCANZ 1994). Thus, the process for setting the pesticide targets involved:



7.1 Spatial boundaries of the water bodies that contribute to the health and resilience of the Great Barrier Reef

The pesticide targets should be applied to the area within the spatial boundary that includes all water bodies contributing to the health and resilience of the GBR. This spatial boundary should also encompass the boundaries of the GBR Marine Park and the GBRWHA. The boundary of the GBR Marine Park is recorded in GBRMPA (2003). The boundaries of the GBRWHA extend from the low water mark of the mainland and take in all islands and internal waters of Queensland.

The GBR Marine Park Authority is responsible for the management of the GBR Marine Park (GBRMPA 2003) and identifies six NRM regions that are involved in the management of water quality for the Great Barrier Reef:

1. Burnett Mary
2. Fitzroy
3. Mackay Whitsunday
4. Burdekin
5. Wet Tropics
6. Cape York

[1] The long-term management goal of Reef Water Quality Protection Plan 2013 is to 'ensure that by 2020 the quality of water entering the reef from broadscale land use has no detrimental impact on the health and resilience of the Great Barrier Reef' (Queensland and Australian governments 2013).

Both the Australian and Queensland governments recognise that the GBR receives run-off from catchments within these six NRM regions and that the water quality discharged from these catchments must be managed to achieve the long-term goals of Reef Water Quality Protection Plan 2013 (Queensland and Australian governments 2013).

The GBR Water Quality Guidelines (GBRMPA 2010) also define spatial boundaries across the continental shelf and identify five distinct water bodies for water quality management:

1. enclosed coastal
2. open coastal
3. mid-shelf
4. offshore
5. the Coral Sea.

The locations of the boundaries for each of the water bodies (2–5) are defined in GBRMPA (2010). Enclosed coastal water bodies (i.e. water body 1) delineate the most landward boundary across the continental shelf, and this definition was adopted from the Queensland Water Quality Guidelines (DEHP 2009). Therefore, enclosed coastal water bodies provide a point of commonalty between Queensland and Australian government water quality guidelines with respect to the GBRWHA. The enclosed coastal water bodies are defined within DEHP (2009, p. 132), as follows:

> **Enclosed coastal/lower estuarine waters:** lie at or near the mouth of an estuary channel, and are frequently subject to some degree of residual mixing with inflowing fresh water. As such, they fall within the broad definition of an estuary. They include shallow coastal waters in straits or enclosed bays adjacent to the mouth of inflowing streams or estuaries. They also include the most downstream reach of the main channel of the estuary, which exchanges with coastal waters on every tide.

The most upstream point in a catchment of an enclosed coastal water body is defined as (DEHP 2009, p. 132):

> **Upstream limit of enclosed coastal/lower estuary:** The upper limit of the enclosed coastal water type is the lower limit of the middle estuary … [middle estuary is defined in section B.2.3.4 of DEHP 2009]. This is typically a short distance upstream of the mouth of the main estuary channel.

Thus, the spatial extent of the water bodies that contribute to the health and resilience of the GBR, and where the pesticide targets will be applied, are defined here as the boundaries of the identified six NRM regions from Burnett Mary to Cape York and the five water bodies defined within GBRMPA (2010), with the landward boundary being the upstream point in the catchment of the enclosed water body (as defined above). Examples of this point in catchments are presented in Figure 7. This area encompasses the spatial boundaries of the GBR Marine Park (outlined in GBRMPA 2003) and the GBRWHA.

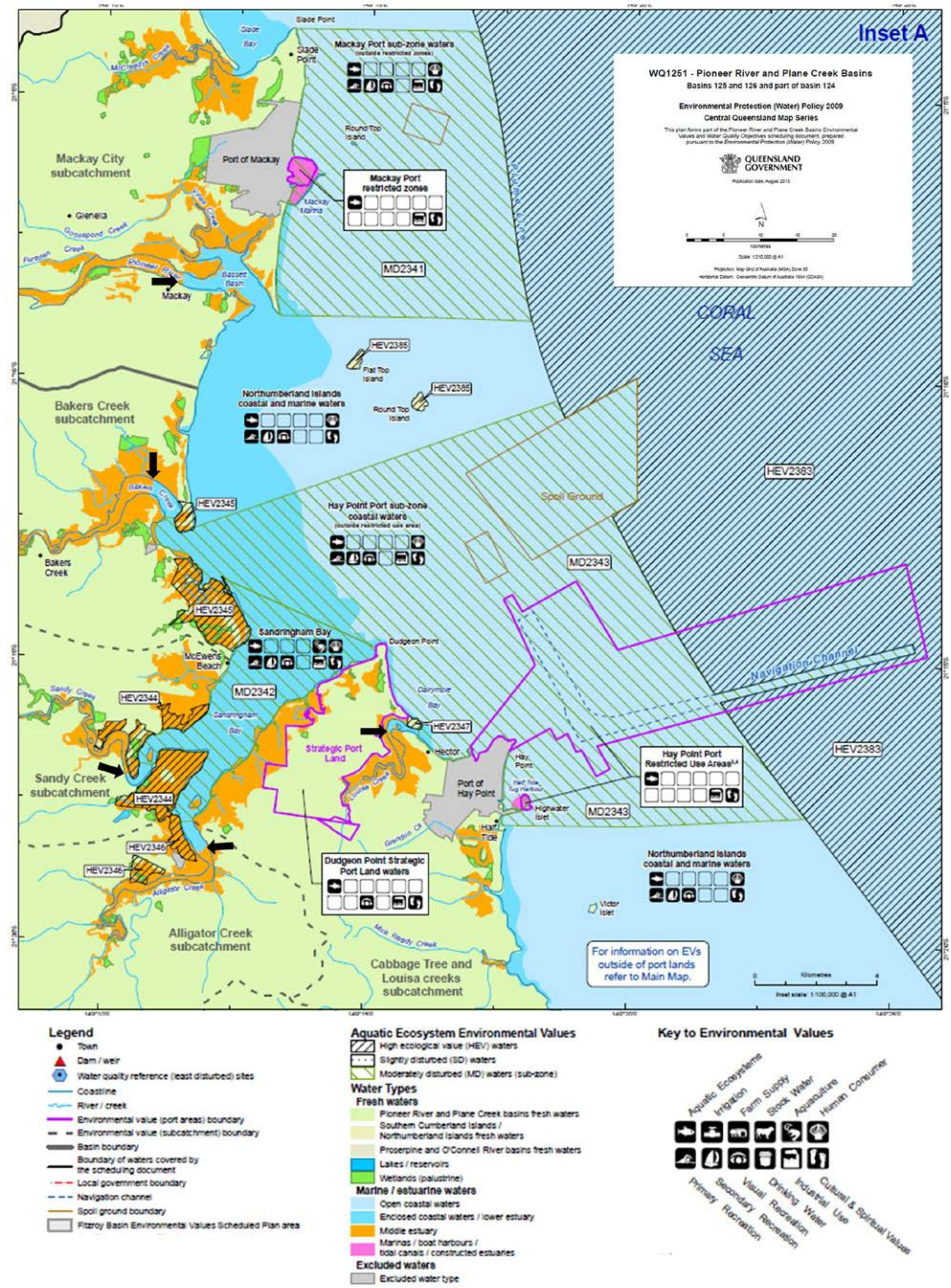


Figure 7. Map of water types (as defined by DEHP 2009) in the Pioneer River and Plane basins. Black arrows indicate the most upstream point in the catchment of the enclosed water body. This map has been adapted from the Central Queensland Map Series, WQ1251 – Pioneer River and Plane Creek, Environmental Protection (Water) Policy 2009.

7.2 Environmental values of water bodies to protect and conserve the status of the Great Barrier Reef Marine Park and World Heritage Area

The pesticide targets are defined by the water quality management goals for the GBR. In accordance with the National Water Quality Management Strategy (ANZECC and ARMCANZ 1994), the management goals for water quality within a water body are dependent on the environmental values assigned to that water body. Australian national, state and local water quality guidelines provide a framework for recognising and protecting water quality for a range of existing environmental values (ANZECC and ARMCANZ 2000, DEHP 2009, GBRMPA 2010). Environmental values are defined by the National Water Quality Guidelines (ANZECC and ARMCANZ 2000):

> Environmental values are particular values or uses of the environment that are important for a healthy ecosystem or for public benefit, welfare, safety or health and which require protection from the effects of pollution, waste discharges and deposits.

Marine waters within the GBR Marine Park come under the jurisdiction of the GBR Marine Park Authority and, therefore, the environmental values of those water bodies are defined by the Water Quality Guidelines for the GBR Marine Park (GBRMPA 2010). As a general rule, water bodies need to be managed to protect the most sensitive environmental value. Although the environmental values of the GBR include aquatic ecosystems, primary industries, recreation and aesthetics, and cultural and spiritual values, the ecosystem protection guideline values dominate because aquatic ecosystems are the most sensitive environmental value requiring the highest level of protection (GBRMPA 2010).

Coastal waters that are outside of the GBR Marine Park zone fall within the purview of the Queensland *Environmental Protection (Water) Policy 2009*, and most also fall within the GBRWHA. To avoid conflict between the Queensland and Australian governments for those coastal waters that overlap both jurisdictions, the Queensland Water Quality Guidelines (DEHP 2009, section 2.3.4) provides the following clarification:

> Because there are no Queensland guidelines for pesticides, the GBR Marine Park water quality guidelines for pesticides will be adopted in all waters of the Marine Park, including the Enclosed Coastal zone.

Thus to determine the ecosystem protection level assigned for pesticides for waters of the GBR, the GBR Water Quality Guidelines (GBRMPA 2010) are to be adopted.

7.3 Aquatic species protection level

The GBR Water Quality Guidelines (GBRMPA 2010) provide the following definitions with respect to the protection of aquatic ecosystem values of the GBR, including all waters of the GBRWHA:

i. The two levels of condition are high ecological value, and slightly disturbed [recognised in the Australian National Water Quality Management Strategy].
ii. The management intent for waters with high ecological value aquatic ecosystems is to maintain the natural values of the ecosystems, including biotic, physical form, riparian vegetation, flow and physicochemical water quality attributes.
iii. For slightly disturbed aquatic ecosystems, the management intent is to maintain their current values and improve their slightly disturbed attributes back towards their natural values.
iv. Influence areas of river discharges from the GBR catchments (Maughan et al. 2008) have been assigned an aquatic ecosystem condition of slightly to moderately disturbed.
v. For high ecological value water bodies, a guideline concentration that is protective of 99% of species is ideal. Regardless of the current condition of the waters (high ecological value, slightly

to moderately disturbed or highly disturbed), aquatic ecosystem protection is the highest environmental value currently applied to the entire GBRWHA.

vi. The trigger values are chosen to be applied in the GBR Marine Park case regardless of the current condition of the ecosystems, or indeed regardless of the flow of water. Even in ecologically highly disturbed trawl grounds, reaching effect levels of pesticides and biocides on the species being trawled would be unacceptable. Therefore, trigger values for these parameters as derived in these guidelines apply to all of the five water bodies at the derived concentration protective of 99% of species. Our aim will be that for any water in the marine park, the concentrations are below the guideline trigger values although it is acknowledged that, for some of the time, for some of the waterways, they are currently likely to be exceeded during seasonal events.

Thus, to protect all the environmental values of the GBR, the Reef Water Quality Protection Plan 2017 pesticide target will be set, in agreement with the high ecological value protection levels defined in ANZECC and ARMCANZ (2000), to achieve concentrations of all pesticides in water bodies of the GBR that will be protective of at least 99% of species, where the toxic impacts of all pesticides in the water body are considered collectively. The same pesticide target applies across all five water bodies as described by GBRMPA (2010) for all catchments within the six NRM regions from the Burnett Mary to Cape York. The landward boundary of the pesticide target, for catchments discharging water to the GBR, is set near the mouth of the estuary channel at the upper limit of the enclosed coastal/lower estuary water body (as defined by DEHP 2009). In short, the pesticide target for the draft Reef 2050 Water Quality Improvement Plan 2017-2022 is:

To protect at least 99% of aquatic species at the end of catchments.

The methodology for measuring and reporting progress towards achieving the new pesticide target is in development by the Queensland Department of Science, Information Technology and Innovation.

8. Discussion

8.1 Expected outcomes of meeting the draft Reef 2050 Water Quality Improvement Plan 2017-2022 targets

What is success?

The management of terrestrial pollutant discharge to the GBR implicitly assumes that the continuing decline of species and ecosystems arising from increased loads of nutrients and sediments and concentrations of pesticides would be reversed if these pollutants were reduced, and system restoration may be achieved. Such restoration has been observed after, for example, nutrient management in Tampa, Florida when seagrass meadows were restored to near their pre-pollution condition (Greening et al. 2014). In the GBR case, the restoration possibilities are complicated by the reality of multiple stressors, particularly those associated with climate change such as increasing sea surface temperatures and wide scale bleaching in both 2016 (Hughes et al. 2017a) and 2017 (Hughes et al. 2017b). At the GBR-wide scale, water quality management alone, even if very successful, will not be adequate to reverse the decline in coral cover on the GBR unless significant action is taken nationally and globally to address climate change (Hughes et al. 2017b). However, local-scale efforts for water quality improvement remain a high management priority for GBR ecosystem health outcomes in critical parts of the GBR and will provide a significant degree of resilience for these sections. CoTS outbreaks reduce the resilience of GBR reefs (Vercelloni et al. 2017), and effective reduction in CoTS numbers through nutrient management is still a worthwhile objective for the mid-shelf reefs between Lizard Island and Townsville.

Ecologically relevant sediment and nutrient load reduction targets have been set for the 35 basins of the GBR catchment (Table 19). These targets consider ecological end points in the GBR (e.g. Brodie et al. 2016), and determine a sufficient load reduction such that the ecological end points are achieved. Hence these targets, if achieved, should lead (all other stressors being ignored) to a reversal of the decline in GBR ecosystem condition and the possibility of restoration as discussed above.

In respect to nutrient-enriched conditions, there are well-documented cases of eutrophied marine systems dominated by algae where reductions in nutrient loading have not returned the systems to their original ecological status (Duarte et al. 2009, Lotze et al. 2011, McCrackin et al. 2017), or where recovery has been partial at best (Elliot et al. 2016, Borja et al. 2010, Gross and Hagy 2017). This may be attributed to the range of other factors in the system that have also dramatically changed during the period of increased nutrient loading, such as human population increases, freshwater run-off changes, global temperature increases and fish stock losses. Alternatively, the management regime that enabled the nutrient loading reductions may have weakened or been repealed in the case of legal solutions (Gross and Hagy 2017). Complex responses (Carstensen et al. 2011) of phytoplankton to N loading and reductions in N loadings have also occurred contrary to the expected effect. In Moreton Bay, N reductions have not reduced algal growth as the system is possibly P-limited (Wulff et al. 2011), although increased growth of one species has been observed (nitrogen-fixing *Lyngbya majuscula*).

Some of these factors are also present in the GBR and may well interfere with attempts to return the GBR to a more desirable condition through pollutant load reductions alone.

In coral reef systems, the issues of reversibility, time lags and phase change have been the subject of much recent research (Bruno et al. 2009, Elmhirst et al. 2009, Hughes et al. 2010, Mumby et al. 2007, Norström et al. 2009). However, further research is required on ecosystem responses to changing water quality responses, particularly in combination with other stressors such as climate change, to quantify the likely time lags of the response of the GBR ecosystems and the nature and trajectory of the response.

Successful examples of management of terrestrial discharges in tropical seagrass/coral reef settings such that ecosystem restoration occurred (see also Kroon et al. 2014) include:

1. Tampa Bay, Florida (Greening et al. 2014) where:

> Following citizen demands for action, reduction in wastewater nutrient loading of approximately 90% in the late 1970s lowered external total nitrogen (TN) loading by more than 50% within three years. Continuing nutrient management actions from public and private sectors were associated with a steadily declining TN load rate despite an increase of more than 1 M people living within the Tampa Bay metropolitan area. Following recovery from an extreme weather event in 1997–1998, water clarity increased significantly and seagrass is expanding at a rate significantly different than before the event. Key elements supporting the nutrient management strategy and concomitant ecosystem recovery in Tampa Bay include: 1) active community involvement, including agreement about quantifiable restoration goals; 2) regulatory and voluntary reduction in nutrient loadings from point, atmospheric, and nonpoint sources; 3) long-term water quality and seagrass extent monitoring; and 4) a commitment from public and private sectors to work together to attain restoration goals.

2. Kāneʻohe Bay, Oahu, Hawaiʻi (e.g. Stimson 2015, Bahr et al. 2015). Sewage discharges into Kāneʻohe Bay, Hawaiʻi increased from the end of the Second World War up to 20 ML/day in 1977 due to increasing population and urbanisation. This chronic discharge into the lagoon introduced high levels of inorganic N and P, and southern lagoon waters became increasingly rich in phytoplankton. Reefs closest to the outfall became overgrown by filter-feeding organisms, such as sponges, tube-worms and barnacles. Reefs in the centre of the bay, further from the outfalls, were overgrown by the indigenous green algae *Dictyosphaeria cavernosa*. After diversion of the outfalls into the ocean in 1978, in-water nutrient levels declined, phyto- and zooplankton populations declined and *D. cavernosa* abundance declined to 25% of previous levels. At the same time, increases in the abundance and distribution of coral species were reported, and the reefs slowly recovered.

What does success mean for the Great Barrier Reef?

Suspended sediment and nutrient load reduction targets and pesticide targets have been recommended for the 35 GBR basins (Table 16). These targets are qualitatively different from previous Reef Water Quality Protection Plan targets (Queensland and Australian governments 2013) in that they attempt to quantitatively estimate load targets that, if met, would ensure an ecological end point in the GBR is achieved. In this way they are more similar to the recent WQIP targets for the Tully (Kroon 2008, Brodie et al. 2012), Wet Tropics (Brodie et al. 2014), Burdekin (Brodie et al. 2012, Brodie et al. 2015a), Fitzroy (Brodie et al. 2015b) and Burnett Mary (Brodie and Lewis 2014) regions which, where possible, were set to reach an offshore ecological end point. Thus, the scientific underpinning of these basin-scale targets is to achieve a restoration outcome for specific GBR ecosystems, and in this particular case, coral and seagrass status.

In essence it is assumed that reductions in suspended sediment, nutrient loading and pesticide risk to the GBR, to the extent of the new targets, will also achieve a significant restoration of coral (cover, diversity and community structure) and seagrass (cover, biomass, spatial extent and community structure). This restoration will then also benefit downstream species that are dependent on good coral or seagrass status, for example dugongs. A complicating factor is, of course, that other stressors besides pollution are also impacting corals and seagrass of the GBR. The most prominent and important of these other stressors is climate change. As climate change impacts (e.g. coral bleaching) accelerate, even highly effective pollution management may not restore coral and seagrass to our projected restoration objectives across large scales (Hughes et al. 2017b). However, more limited objectives for

GBR restoration, compared to the original aims of GBR management, are now under consideration (Hughes et al. 2017b) where water quality management and other local management strategies may still have a very important role to play (Osborne et al. 2017, Norström et al. 2016).

The need for multiple basin targets to be met

For restoration aims to be met (e.g. coral cover restored to some target level in a section of the GBR), it is important to note that multiple basins will need to meet their pollution reduction targets. This is explained in the risk assessment chapter of Scientific Consensus Statement 2017 (Waterhouse et al. 2017a), where the combined risk to ecosystems from all basins in the GBR is analysed. A pertinent example is that for CoTS populations to be reduced in the future, basins from the Daintree in the north to the Burdekin in the south all have to meet DIN targets. The number of basins that require targets to be met together varies with the restoration target and the particular region to which the restoration target applies.

8.2 Moving towards an improved target-setting approach

There is great potential to further improve the eReefs modelling scenario runs to improve our estimates of basin water quality targets. The main improvements that could be made are:

1. Use a longer modelling period for the analysis; for example, seven years is now available rather than the four years available at the commencement of this project.
2. Improve basin water discharge estimates such that the total basin gauged and ungauged flow is used rather than the current method of estimates made from a single gauge site in each basin (Table 4).
3. Include more rivers (basins), particularly the Murray, Proserpine, Plane, Burrum, Baffle, Kolan (all with significant areas of sugarcane and horticulture cultivation).
4. Use a 1 km^2 resolution eReefs model.
5. Run separate scenarios for nutrient reductions and for the sediment reductions.
6. Model a greater range of scenario options, including future scenarios. Construct scenarios for individual basins to investigate the impact of changes in each basin in isolation.
7. Improve the analysis of other end points for DIN, for example CoTS and bleaching response, which were attempted in the current targets setting but not used due to insufficient confidence in the results.

8.3 Synergies and the relationship between the basin targets and management priorities from Scientific Consensus Statement 2017

In parallel to the development of the end-of-catchment pollutant load reduction targets for nutrients and sediment and the pesticide targets in this project, basin-scale management priorities have been identified as part of Scientific Consensus Statement 2017 (Waterhouse et al. 2017b). A comparison of the outputs of the proposed water quality targets and the basin priorities developed in Chapter 5 of Scientific Consensus Statement 2017 (Waterhouse et al. 2017b, see Table 16) shows reasonable alignment between basins, but also some differences due to the different methodologies used and the differing purposes of the two approaches.

Table 16. Relative spatial priorities for water quality improvement in the GBR catchments based on the assessment of pollutant exposure and risk to coastal and marine ecosystems, derived from Chapter 5 of Scientific Consensus Statement 2017 (Waterhouse et al. 2017b). Note that this is a result of the biophysical assessment only, and results for particulate nutrients have been extrapolated from the fine sediment assessment and not considered independently. Social and economic factors determine priorities within basins.

NRM region	Basin	Relative priority			Dominant contributing land use or process for Low to Very High Priority Areas^	
		Sediment and particulate nutrients	DIN	Pesticides	Sediment	DIN
Cape York#	Jacky Jacky Creek	Minimal	Minimal			
	Olive Pascoe River	Minimal	Minimal			
	Lockhart River	Minimal	Minimal			
	Stewart River	Minimal	Minimal			
	Normanby River	Low	Minimal			
	Jeannie River	Minimal	Minimal			
	Endeavour River	Minimal	Minimal			
Wet Tropics	Daintree River	Minimal	Moderate*			Sugarcane
	Mossman River	Minimal	Moderate*			Sugarcane
	Barron River	Minimal	Moderate*			Sugarcane
	Mulgrave-Russell River	Low	High*	Low	Sugarcane	Sugarcane
	Johnstone River	Moderate**	High*	Low	Sugarcane	Sugarcane
	Tully River	Low	High*	Low	Sugarcane	Sugarcane
	Murray River	Low	Moderate*		Sugarcane	Sugarcane
	Herbert River	High**	Very High*	Low	Grazing	Sugarcane
Burdekin	Black River	Minimal	Minimal			
	Ross River	Minimal	Low			STP
	Haughton River	Low	Very High*	Moderate	Grazing	Sugarcane
	Burdekin River	Very High**	Moderate	Low	Grazing	Sugarcane, grazing
	Don River	Low	Low		Grazing	Sugarcane, grazing
Mackay Whitsunday	Proserpine River	Low	Moderate		Grazing, sugarcane	Sugarcane
	O'Connell River	Moderate**	Moderate	Low	Sugarcane	Sugarcane
	Pioneer River	Low	Moderate	Moderate	Streambank sources (various land uses)	Sugarcane
	Plane Creek	Low	High	High	Sugarcane	Sugarcane
Fitzroy	Styx River	Low	Minimal		Grazing	
	Shoalwater Creek	Minimal	Minimal			
	Waterpark Creek	Minimal	Minimal			
	Fitzroy River	High**	Low	Low	Grazing	Grazing
	Calliope River	Minimal	Minimal			
	Boyne River	Minimal	Minimal			
Burnett Mary	Baffle Creek	Minimal	Minimal			
	Kolan River	Minimal	Low			Sugarcane
	Burnett River	Moderate**	Low	Low	Streambank sources	Sugarcane

NRM region	Basin	Relative priority			Dominant contributing land use or process for Low to Very High Priority Areas^	
		Sediment and particulate nutrients	DIN	Pesticides	Sediment	DIN
					(various land uses)	
	Burrum River	Minimal	Low			Sugarcane
	Mary River	High**	Moderate	Low	Streambank sources (various land uses)	Sugarcane

Notes:

High level of uncertainty in these results. Grey shading = not assessed.
^ Determined from Source Catchments load estimates for each land use (derived from McCloskey et al. 2017).
Decision rules: Since we are working with average conditions, a conservative approach was taken: Marine Likelihood of Exposure Index: Very High (red) = >0.9; High (orange) = 0.4–0.9; Moderate (yellow) = 0.15–0.39 and at least 3% load contribution; Low (green) = 0.14–0.03; Minimal (no colour) = <0.02. In addition: **Basins were assessed as highest fine sediment risk to seagrass (see Waterhouse et al. 2017a, Table 18) and therefore are ranked higher than other basins. *Basins were assessed as highest DIN risk for the CoTS influence area (see Waterhouse et al. 2017a, Table 15) and therefore are ranked higher than other basins.

In the determination of the targets, pollutant load reduction targets are expressed as a *per cent reduction* from the 2013 baseline anthropogenic load, so a high percentage reduction may not necessarily mean that the basin is the highest priority in terms of load reductions when considering the tonnage reduction required to meet the target. Basin-scale management priorities in Table 16 were based on a detailed analysis of:

- likelihood of exposure of coral reefs and seagrass to anthropogenic loads
- DIN risk and CoTS (resulted in allocation of a higher priority to the Wet Tropics basins and the Haughton Basin)
- fine sediment risk and seagrass (supported high priority for Burdekin and Fitzroy Basins).

While many of the datasets used in these approaches were the same or similar, there were also differences in the time periods of the assessment, pollutant thresholds and spatial conditions, which is entirely valid given the different objectives.

Comparison of the *tonnage reductions* indicates a good correlation between the highest target reductions and the highest priority basins for each parameter. This comparison also demonstrates that the target reduction required for some basins is even higher than that calculated for a whole region; for example, the DIN reduction required from the Haughton Basin (639 tonnes by 2025) is similar to the total reduction required from all of the Mackay Whitsunday basins combined (631 tonnes by 2025). This can be further illustrated for DIN and fine sediment in Table 17 and Table 18, showing the correlation between the highest priority basins and the ranking of the target load reductions.

This is important for interpretation of the results, as the management prioritisation in Chapter 5 of the Scientific Consensus Statement 2017 (Waterhouse et al. 2017b) and the new targets are both used to inform the preparation of the Reef 2050 Water Quality Improvement Plan.

Table 17. Relative spatial priorities for DIN management in the GBR catchments derived from Chapter 5 of Scientific Consensus Statement 2017 (Waterhouse et al. 2017b), and ranking (from high to low) of the total tonnage reduction required to meet the proposed targets. The regional results (shaded in grey) are included for context. *Basins were assessed as highest DIN risk for CoTS (see Waterhouse et al. 2017a, Table 15) and therefore are ranked higher than other basins.

Basin	Management priority	DIN target reduction (%)	DIN load reduction (tonnes)
GBR TOTAL		60	3,520
Wet Tropics total		60	1,678
Burdekin total		60	816
Haughton	Very High*	70	639
Mackay Whitsunday total		70	631
Herbert	Very High*	70	620
Burnett Mary total		55	468
Johnstone	High*	70	349
Mulgrave-Russell	High*	70	296
Plane	High	70	256
Tully	High*	50	192
Mary	Moderate	50	181
Burnett	Low	70	145
Pioneer	Moderate	70	135
O'Connell	Moderate	70	130
Murray	Moderate*	50	116
Proserpine	Moderate	70	110
Burdekin	Moderate	60	103
Burrum	Low	50	93
Barron	Moderate	60	52
Mossman	Moderate*	50	52
Kolan	Low	50	34
Baffle	Minimal	50	16
Jacky Jacky	Minimal	0	-
Olive Pascoe	Minimal	0	-
Lockhart	Minimal	0	-
Stewart	Minimal	0	-
Normanby	Minimal	0	-
Jeannie	Minimal	0	-
Endeavour	Minimal	0	-
Cape York total		0	0
Daintree	Moderate*	0	-
Black	Minimal	ND	-
Ross	Minimal	60	-
Don	Minimal	0	-
Styx	Minimal	0	-
Shoalwater	Minimal	0	-
Waterpark	Minimal	0	-
Fitzroy	Low	0	-
Calliope	Minimal	0	-
Boyne	Minimal	0	-
Fitzroy total		0	0

Table 18. Relative spatial priorities for sediment management in the GBR catchments derived from Chapter 5 of Scientific Consensus Statement 2017 (Waterhouse et al. 2017b), and ranking (from high to low) of the total tonnage reduction required to meet the proposed targets. The regional results (shaded in grey) are included for context.

Basin	Management priority	Proposed fine sediment target reduction (%)	Fine sediment load reduction (kt)
GBR TOTAL		25	1,935
Burdekin total		30	891
Burdekin	Very High	30	836
Fitzroy total		25	409
Fitzroy	High	30	388
Wet Tropics total		25	243
Burnett Mary total		20	238
Mary River	High	20	133
Mackay Whitsunday total		20	131
Johnstone	Moderate	40	104
Herbert	High	30	99
O'Connell	Moderate	40	96
Burnett	Moderate	20	85
Don	Low	30	55
Pioneer	Low	20	35
Cape York total		5	23
Tully	Low	20	17
Mulgrave-Russell	Low	10	16
Normanby	Low	10	15
Calliope	Minimal	30	15
Baffle	Minimal	20	11
Murray	Low	20	8
Kolan	Minimal	20	6
Boyne	Minimal	40	6
Burrum	Minimal	20	3
Endeavour	Minimal	10	3
Stewart	Minimal	6	2
Jeannie	Minimal	6	2
Lockhart	Minimal	2	1
Jacky Jacky	Minimal	0	0
Olive Pascoe	Minimal	0	0
Daintree	Minimal	0	0
Mossman	Minimal	0	0
Barron	Minimal	0	0
Black River	Minimal	ND	0
Ross River	Minimal	ND	0
Haughton	Low	0	0
Proserpine	Low	0	0
Plane	Low	0	0
Styx	Low	0	0
Shoalwater	Minimal	0	0
Waterpark	Minimal	0	0

ND = not determined.

8.4 Overall conclusions

The final end-of-basin water quality target recommended for fine sediment, DIN, PP and PN for the 35 GBR basins by 2025 are shown in Table 19. To protect all the environmental values of the GBR, the Reef Water Quality Protection Plan 2017 pesticide targets are proposed to be set to protect at least 99% of aquatic species from the effects of all pesticides at the end of the catchment, that is, near the mouth of the estuary channel at the upper limit of the enclosed coastal/lower estuary water body (as defined by DEHP 2009) and covering all five water bodies as described by GBRMPA (2010) for all catchments within the six NRM regions from the Burnett Mary to Cape York.

This project has demonstrated the value of the application of the eReefs modelling platform and load reduction scenarios in establishing basin-specific water quality targets. It has also highlighted the importance of continued development and improvement of these methods and identified opportunities for future work. The development of basin-specific pollutant load reductions and pesticide targets that are ecologically relevant is a major step forward from the 2013 Reef Water Quality Protection Plan targets and provides a strong basis for more targeted management of water quality in the GBR and its catchments.

Table 19. End-of-basin anthropogenic water quality targets recommended for fine sediment, DIN, PP and PN for the 35 GBR basins by 2025.

NRM region	Basin	Fine sediment reduction %	DIN reduction %	PP reduction %	PN reduction %
Cape York*	Jacky Jacky	0	0	0	0
	Olive Pascoe	0	0	0	0
	Lockhart	2	0	2	2
	Stewart	6	0	6	6
	Normanby	10	0	10	10
	Jeannie	6	0	6	6
	Endeavour	10	0	10	10
Wet Tropics	Daintree	0	0	0	0
	Mossman	0	50	0	0
	Barron	0	60	0	0
	Mulgrave-Russell	10	70	10	10
	Johnstone	40	70	40	40
	Tully	20	50	20	20
	Murray	20	50	20	20
	Herbert	30	70	30	30
Burdekin	Black	ND	ND	ND	ND
	Ross	ND	60	ND	ND
	Haughton	0	70	0	0
	Burdekin	30	60	30	30
	Don	30	0	30	30
Mackay Whitsunday	Proserpine	0	70	0	0
	O'Connell	40	70	40	40
	Pioneer	20	70	20	20
	Plane	0	70	0	0
Fitzroy	Styx	0	0	0	0

NRM region	Basin	Fine sediment reduction %	DIN reduction %	PP reduction %	PN reduction %
	Shoalwater	0	0	0	0
	Waterpark	0	0	0	0
	Fitzroy	30	0	30	30
	Calliope	30	0	30	30
	Boyne	40	0	40	40
Burnett Mary	Baffle	20	50	20	20
	Kolan	20	50	20	20
	Burnett	20	70	20	20
	Burrum	20	50	20	20
	Mary	20	50	20	20

Notes:

*Basin targets for the Cape York region were adapted from the Water Quality Improvement Plan targets (Cape York NRM and South Cape York Catchments 2016).

ND = not determined.

Targets are calculated from the Report Card 2015 anthropogenic baseline (2012-2013) modelled loads.

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