Australian Government

Queensland Government

Methods

Reef Water Quality Report Card 2017 and 2018

Reef 2050 Water Quality Improvement Plan

#31897 | 0619

AGRICULTURAL LAND MANAGEMENT PRACTICE ADOPTION METHODS

This report summarises the development of revised management practice benchmarks for the Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP) and how progress toward the plan's 2025 land management target for adoption of best practice is assessed.

The target for adoption of agricultural best management practice is as follows (Australian and Queensland governments, 2018):

- 90% of land in priority areas under grazing, horticulture, bananas, sugarcane and other broadacre cropping are managed using best management practice systems for water quality outcomes (soil, nutrient and pesticides).

Each year significant investment is directed towards the adoption of best practice farm management systems with the aim to achieve the Reef 2050 WQIP's outcome and targets and improve the quality of the water flowing into the Great Barrier Reef.

The effectiveness of these investments are monitored and reported on by the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program (Paddock to Reef program).

The Stewardship – Agricultural management practice adoption program is a component of the Paddock to Reef program. It measures progress towards the Reef 2050 WQIP target for the adoption of agricultural best management practices and provides data to the Catchment pollutant delivery – Catchment loads modelling program component of the Paddock to Reef program so the impact of investment on water quality can be estimated.

Water quality risk frameworks

Best management practices for water quality outcomes are defined in Paddock to Reef program water quality risk frameworks for each major agricultural industry. These frameworks identify the farm management practices with the greatest potential to influence off-farm water quality and to articulate a reasonable best practice level which can be expected to result in a moderate-low risk to off-farm water quality.

For grazing systems, the water quality risk frameworks describe practices impacting upon land condition, soil erosion (pasture – hillslope, streambank and gully) and water quality. For sugarcane, horticulture, bananas and grains, the framework details management practices and systems for managing nutrients, pesticides and soils. Gathering this information across the landscape helps to prioritise areas which need greater support to improve landholders' management practices.

Practices in the water quality risk frameworks are described in terms of their relative water quality risk, which range from lowest to high. The 'best practice' and 'minimum standard' levels are typically the levels targeted by Reef 2050 WQIP investments. These levels generally align with the "Above Industry Standard" and "Industry Standard" levels described in industry BMP programs.

Industry-led BMP programs provide whole-of-business approaches to identifying potential farm management improvements across many areas, for example; land management, energy efficiency, animal welfare, biosecurity, and occupational health and safety. Whilst the industry programs include practices relevant to water quality risk and stewardship, this is not their only focus. The water quality risk frameworks employed by the Paddock to Reef program describe only the farm practices that influence off-farm water quality.

Table 1. Water Quality Risk Frameworks for the Reef 2050 Water Quality Improvement Plan and alignment with the 'ABCD' terminology and industry best management practice (BMP) programs (generalised).

Terminology	Practice standard			
Water Quality Risk Framework	Lowest risk, commercial feasibility may be unproven	Moderate-low risk	Moderate risk	High risk
	Innovative	Best practice	Minimum Standard	Superseded
ABCD	A	B	C	D
Industry BMP programs (generalised)	Above industry standard (Typically aligns with moderate-low risk but in some instances aligns with lowest risk state.)	Above industry standard (Typically aligns with moderate-low risk but in some instances aligns with lowest risk state.)	Industry standard	Below industry standard

Importantly:

- The suites of practices relevant to each pollutant are described in the water quality risk frameworks. Not all of the practices in the production system are described - only those practices with the greatest potential to influence off-farm water quality risk (i.e. through reducing the movement of sediments, nutrients or pesticides off-farm).
- The majority of these practices also present productivity and/or profitability enhancements.
- Not all practices are equal. The frameworks allocate a percentage weighting to each practice depending upon its relative potential influence on off-farm water quality.

Reef 2050 Water Quality Improvement Plan adoption benchmarks

Farm management practice adoption estimates were reviewed during 2016 and 2017 to establish realistic management practice adoption benchmarks in each sector, and also to align with updated water quality risk frameworks. The benchmark is regarded as a point-in-time assessment, nominally set as the 30 June 2016. Progress toward the Reef 2050 WQIP target is measured from the commencement of the 2016-2017 year.

Paddock to Reef program management practice and management system benchmarks have been developed for each agricultural industry sector, and in each major river basin within each region. Annual progress towards the Reef 2050 WQIP target for adoption is measured from these benchmarks. There are varying levels of uncertainty or confidence in these benchmarks for many reasons (see Table 2).

Table 2. Summary of data sources and uncertainty around management system benchmarks developed for the Reef 2050 WQIP.

Industry	Primary data sources	Confidence in benchmarks	Sources of uncertainty
Grazing	• Grazier 1:1 surveys 2013-16 • Previous reporting to Paddock to Reef program • Grazing BMP* (aggregated, anonymous).	Moderate – low	Relatively small proportion of the overall large population is represented in the datasets. Inability to describe land condition (as a consequence of management) across the landscape.
Horticulture	• Hort360 BMP • Industry experts.	Moderate	Very good industry representation, however lack of alternative lines of evidence for cross checking.
Bananas	• Previous reporting to Paddock to Reef program • Industry experts • Industry surveys • Research, Development and Extension projects.	Moderate –low	No discrete fit-for-purpose datasets available for some key practices, heavy reliance on sometimes divergent expert experience.
Sugarcane	• Previous reporting to Paddock to Reef program • Compliance reporting (reef protection legislation) • Smartcane BMP (anonymous, aggregated) • Industry surveys • Soil analyses trends • Industry experts • Confidential commercial data.	Moderate – High	Several different large and representative datasets providing evidence for most practices in most catchments. However, benchmarks for some practices are based on expert opinion (as no data sources exist).

Broad-acre cropping (Grains)	• Previous reporting to Paddock to Reef program • Industry experts • Grains BMP (anonymous, aggregated).	Moderate	No discrete fit-for-purpose datasets available for some practices. Expert experience sometimes divergent on some practices.

*BMP = best managemen practice

Assessing progress towards the Reef 2050 Water Quality Improvement Plan target

As described above, the agricultural management practice adoption benchmarks were updated for each of the management practices, for each agricultural industry, each region and each river basin. These are reviewed and revised every five years, whereas annual changes from the benchmark are based on management practice data reported each year. Delivery organisations involved in Reef 2050 WQIP investment programs collect spatial and management practice adoption data throughout the year and deliver it to a central repository to generate the dataset of improved adoption. For the purpose of describing industry status and progress towards the practice adoption target, best management practice is defined as the summed area managed under lowest and moderate-low risk (or 'A and B' practice) levels in each catchment.

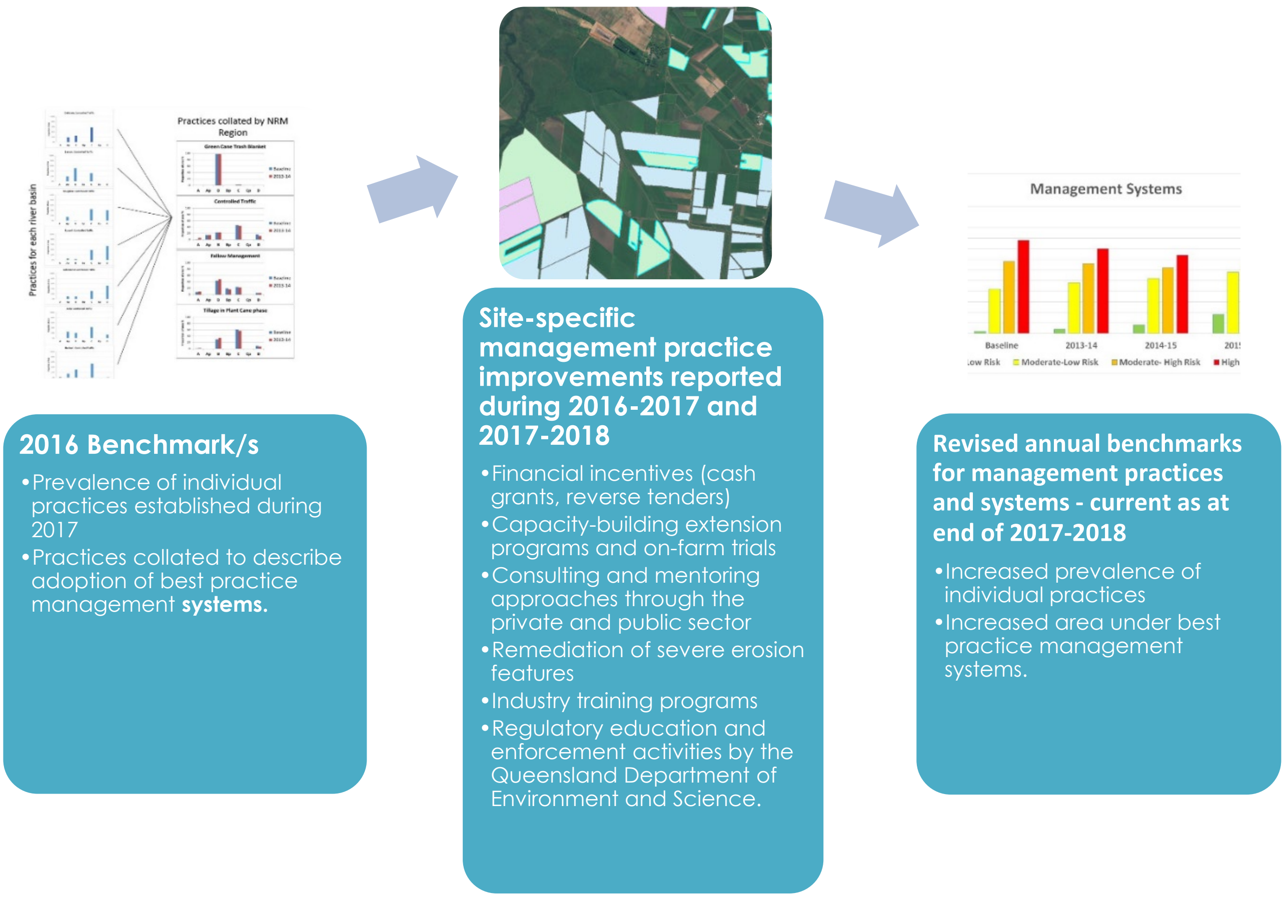

Figure 1. The process for monitoring benchmarks and management practice improvements.

Evidence of management practice change

Progress of adoption of improved practices and best management practice systems is monitored over time. Organisations that receive funding from Reef 2050 WQIP programs for the purpose of increasing the adoption of best management practice, are required to report the impacts of their programs and projects as per the relevant industry water quality risk framework. The 'interventions' reported and assessed through these programs and projects (Table 3) for the Reef Water Quality Report Card 2017 and 2018 include:

- Financial incentives (direct grants and tenders)
- Capacity-building extension programs and on-farm trials
- Consulting and mentoring approaches through the private and public sector
- Remediation of severe erosion features
- Industry training programs
- Regulatory education and enforcement activities by the Queensland Department of Environment and Science (DES).

Organisations must provide accurate spatial data and farm management attributes according to a schema provided by the Paddock to Reef program. The management practice attributes include a 'before the intervention' assessment, and an 'after the intervention' assessment, that identifies which practice/s have changed as a result of the intervention. In this way, an adoption profile is created and maintained for specific land parcels. These data are subject to strict privacy limitations (according to the *Information Privacy Act 2009*) and are not provided to anyone for any purpose other than modelling estimated water quality improvements. Access to these data is restricted and possible only by a team of four officers in the Queensland Department of Agriculture and Fisheries (DAF).

The limitations with this approach are:

- Management change is identified where and when it is reported to have occurred. This relies on delivery organisations sensibly and appropriately reporting on their activities and the impacts of those activities. The Paddock to Reef program describes and reports on the impacts of change for which there is reasonable and sensible justification. It is important to note however that in most cases it is not possible for the Paddock to Reef program to verify that reported improvements have occurred and/or the true extent to which they have occurred. This has resulted in instances of *overstatement* of adoption in previous years.
- Management improvements that occur without the intervention of third party delivery organisations are rarely detected as there are no industry-wide mechanisms for capturing or reporting management practice change. There is likely to be a degree of *underestimation* of improvements for this reason. The five-year benchmarks endeavour to capture management state on this broader scale but the intervening periods are reliant on reported changes.
- Any regression of practices (i.e. adopting practices that increase water quality risk) is difficult to detect as these are unlikely to be reported. However, the approach can appropriately reflect regression if necessary. For this reason, it is possible that the degree of adoption at a catchment scale may be *overstated*.

<table>
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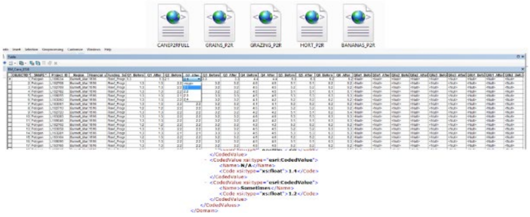
<td colspan="2"></td>
<td>Delivery organisations provide annual evidence of impact to the Paddock to Reef program, in the form of GIS data and detailed management practice data (as coded responses to questions based on the water quality risk frameworks).</td>
</tr>
<tr>
<td colspan="2"></td>
<td>A sugarcane farm is reported at the lowest risk management state for nitrogen fertiliser use in 2015-2016.</td>
<td rowspan="2">The data is reviewed on a site-by-site basis to provide assurance that reporting towards adoption targets and modelled pollutant load reductions is sensible. This review includes:

identifying data handling errors
checking that the nature of the intervention aligns with the reported impact
checking that the degree of impact (farm management change) is sensible and realistic, including checking that the reported impacts correspond with other independent lines of evidence available to the Paddock to Reef program
checking that individual sites and impacts on those sites have not previously been reported to the Paddock to Reef program and included in estimates of progress towards Reef Water Quality Protection Plan targets.
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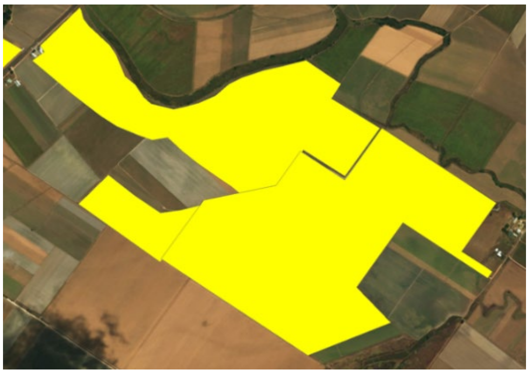
<td colspan="2"></td>
<td>The same sugarcane farm is reported at the highest risk management state for nitrogen fertiliser in 2016-2017.
Identifying spatial and temporal conflicts is essential to ensure that impacts are sensible and not captured more than once.</td>
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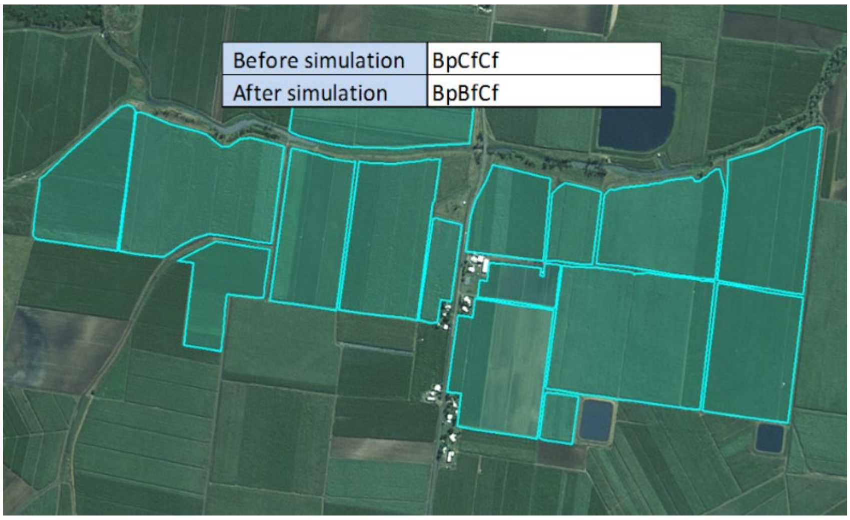
<td colspan="3">
</td>
<td>For every site (usually a paddock or farm) the management regime and how it is has changed is aligned to modelling simulations which best represent that management (as ‘before’ and ‘after’ simulations). The example (left) codifies the trash management, machinery traffic and tillage regime, nutrient rates and timing, and weed management on a sugarcane farm.
Data provided annually to Paddock to Reef catchment modelling constitutes layers that describe change in this way for many hundreds of individual sites.</td>
</tr>
</table>

The management practice and management system benchmarks for each catchment and natural resource management region are adjusted annually to reflect the areas validated in the above steps.
Reef Water Quality Report Cards contain data aggregated up to represent estimates of area under management systems, at the scale of natural resource management regions.

Figure 2. The broad process for evaluating impacts reported by organisations through the Reef 2050 WQIP.

A summary of the projects and programs that reported on-ground impact for the 2016-2017 and 2017-2018 years is presented in Table 3. The total spatial extent reported to the Paddock to Reef program is sometimes different to the spatial extent utilised by the Paddock to Reef program in modelling for average annual pollutant load reductions. This can be for several reasons:

- Different projects operating in the same catchment can have some overlaps and this is to be expected. However the impacts can only be described in the Reef Water Quality Report Card once.

- Insufficient evidence for the Paddock to Reef program to include reported impacts in the Reef Water Quality Report Card results.

- Some of the reported management practice improvements may be too small to be reflected as management system improvements in the modelling of average annual pollutant load reductions.

Table 3. Program and project investments reviewed for Reef Water Quality Report Card 2017 and 2018.

Natural resource management region	River Basin	Commodity	Program	Total reported spatial extent of *practice change* reviewed for Reef Water Quality Report Card 2017 and 2018 (ha or km of stream)		Corrected spatial extent utilised in determining progress toward Reef 2050 WQIP targets for adoption and water quality	
				2016-2017	2017-2018	2016-2017	2017-2018
Burnett Mary	Mary	Grazing	Aus. Government Reef Trust III – Reef Alliance	-	510ha	-	510ha
				-	5km		5km
	Baffle	Grazing	Aus. Government Reef Trust III – Project Pioneer	3,091ha	-	3,091ha	-
	Burnett	Grazing	Qld Government Department of Natural Resources and Mines (DNRME) Sustainable Agriculture Project	696ha	-	665ha	-
			Aus. Government National Landcare Program (NLP) - Better Catchments	-	719ha	-	719ha
			Qld Government DNRME Queensland Regional Natural Resource Management (QNRM) Program	-	172ha	23[1]ha	171ha
			Aus. Government Reef Trust III – Reef Alliance	-	1,353ha	-	1,320ha
				-	3km	-	3km
			Aus. Government Reef Trust III – Project Pioneer	7,042ha	-	7,042ha	-
		Grains	Aus. Government NLP – Better Catchments	-	1,555ha	-	306ha
		Sugarcane	Aus. Government Reef Trust III – Reef Alliance	-	229ha	-	229ha
	Burrum	Sugarcane	Aus. Government Reef Trust III – Reef Alliance	163ha	65ha	163ha	65ha
Fitzroy	Calliope	Grazing	Qld Department of Agriculture and Fisheries (DAF) Extension	-	273ha	-	273ha

[1] This change is the result of a project undertaken on a property in the Dawson catchment, of which 23ha fell into the Burnett catchment boundary.

Natural resource management region	River Basin	Commodity	Program	Total reported spatial extent of *practice change* reviewed for Reef Water Quality Report Card 2017 and 2018 (ha or km of stream)		Corrected spatial extent utilised in determining progress toward Reef 2050 WQIP targets for adoption and water quality	
				2016-2017	**2017-2018**	**2016-2017**	**2017-2018**
	Comet	Grazing	Qld Government DNRME QNRM Program	1,417ha	-	1,411ha	-
			Qld Government DAF Extension	-	282ha	-	282ha
	Dawson	Grazing	Qld Government Reef Trust I – Saving our Soils	-	10ha	-	10ha
			Aus. Government Reef Trust II – Gully Remediation	-	4,258ha	-	4,255ha
			Aus. Government Reef Trust III – Project Pioneer	-	55ha	-	-
			Qld Government DNRME QNRM Program	3,581ha	-	3,581ha	-
				8km	-	8km	-
			Qld Government DAF Extension	-	34,730ha	-	34,730ha
	Isaac	Grazing	Qld Government DAF Extension	107,296ha	4,666ha	107,296ha	4,666ha
			Qld Government Reef Trust I – Saving our Soils	-	4,362ha	-	3,446ha
			Aus. Government Reef Trust II – Gully Remediation	451ha	1,567ha	451ha	1,121ha
				7km	-	7km	-
			Qld Government DNRME QNRM Program	-	2,671ha	-	2,685[2]ha
				4km	5km	4km	5km
	Fitzroy	Grazing	Qld Government DNRME QNRM Program	338ha	3ha	338ha	3ha
			Aus. Government System Repair	693ha	-	676ha	-
				2km	-	2km	-
			Qld Government Reef Trust I – Saving our Soils	-	18,033ha	-	14,188ha

[2] This figure is larger than the total reported spatial figure due to projects undertaken on properties in Mackay Whitsunday region overlapping the Fitzroy region (Isaac River catchment) boundaries.

Natural resource management region	River Basin	Commodity	Program	Total reported spatial extent of *practice change* reviewed for Reef Water Quality Report Card 2017 and 2018 (ha or km of stream)		Corrected spatial extent utilised in determining progress toward Reef 2050 WQIP targets for adoption and water quality	
				2016-2017	**2017-2018**	**2016-2017**	**2017-2018**
			Aus. Government Reef Trust II – Gully Remediation	156ha	586ha	156ha	535ha
	Mackenzie	Grazing	Qld Government DAF Extension	2,952ha	25,091ha	2,952ha	25,090ha
			Qld Government Reef Trust I – Saving our Soils	-	11,519ha	-	10,608ha
				-	2km	-	2km
			Aus. Government Reef Trust II – Gully Remediation	-	161ha	-	45ha
	Nogoa	Grazing	Qld Government DAF Extension	-	70ha	-	70ha
			Qld Government DNRME QNRM Program	1,771ha	-	1,771ha	-
				1km	-	1km	-
			Aus. Government Reef Trust II – Gully Remediation	603ha	1,615ha	603ha	1,615ha
	Styx	Grazing	Qld Government Reef Trust I – Saving our Soils	-	4,153ha	-	3,671ha
Mackay Whitsundays	O'Connell	Sugarcane	Qld Government DAF Extension	15ha	-	15ha	-
			Aus. Government Reef Trust III – Reef Alliance	-	2,243ha	-	2,243ha
		Grazing	Qld Government DAF Extension	806ha	-	806ha	-
			Aus. Government Reef Trust III – Reef Alliance	1,486ha	-	1,486ha	-
			Qld Government DNRME QNRM Program	17ha	1,090ha	17ha	1,090[3]ha
				24km	5km	24km	5km
	Pioneer	Grazing	Qld Government DAF Extension	7,214ha	-	7,211ha	-
			Qld Government DNRME QNRM Program	19ha	24ha	19ha	24ha

[3] This figure is larger than the total reported spatial figure due to projects undertaken on properties in Mackay Whitsunday region overlapping the Fitzroy region (Isaac River catchment) boundaries.

Natural resource management region	River Basin	Commodity	Program	Total reported spatial extent of *practice change* reviewed for Reef Water Quality Report Card 2017 and 2018 (ha or km of stream)		Corrected spatial extent utilised in determining progress toward Reef 2050 WQIP targets for adoption and water quality	
				2016-2017	**2017-2018**	**2016-2017**	**2017-2018**
				10km	-	10km	-
		Sugarcane	Aus. Government Reef Trust III – Reef Alliance	-	1,874ha	-	1,874ha
	Plane Creek	Sugarcane	Qld Government DAF Extension	12ha	-	12ha	-
			Aus. Government Reef Trust III – Reef Alliance	-	6,380ha	-	6,380ha
		Grazing	Qld Government DAF Extension	2,250ha	-	2,246ha	-
			Qld Government DNRME QNRM Program	20ha	326ha	20ha	326ha
				1km	1km	1km	1km
	Proserpine	Grazing	Qld Government DNRME QNRM Program	11ha	740ha	11ha	740ha
				-	2km	-	2km
			Aus. Government Reef Trust III – Reef Alliance	466ha	-	466ha	-
Burdekin	Bowen	Grazing	Qld Government DAF Extension	22,270ha	1,195ha	22,270ha	1,195ha
			Aus. Government Reef Trust III – Gully Remediation	59ha	-	59ha	-
			Aus. Government Reef Trust III – Reef Alliance	2,597ha	3,544ha	2,597ha	3,544ha
			Qld Government DNRME QNRM Program	12ha	-	12ha	-
	Don	Horticulture	Qld Government DAF Extension	-	79ha	-	79ha
		Grazing	Aus. Government Reef Trust III – Project Pioneer	171ha	-	171ha	-
			Aus. Government Reef Trust III – Reef Alliance	28,772ha	3,680ha	28,772ha	3,638ha
			Aus. Government Greening Australia Sediment Project	-	262ha	-	262ha
			Qld Government DAF Extension	-	9,049ha	-	8,977ha
	Haughton	Horticulture	Qld Government DAF Extension	-	44ha	-	44ha

Natural resource management region	River Basin	Commodity	Program	Total reported spatial extent of *practice change* reviewed for Reef Water Quality Report Card 2017 and 2018 (ha or km of stream)		Corrected spatial extent utilised in determining progress toward Reef 2050 WQIP targets for adoption and water quality	
				2016-2017	2017-2018	2016-2017	2017-2018
		Grazing	Aus. Government Reef Trust III – Project Pioneer	12,894ha	-	12,801ha	-
			Aus. Government Reef Trust III – Reef Alliance	8,691ha	24,704ha	8,691ha	24,649ha
				19km	11km	14km	11km
		Sugarcane	Aus. Government Reef Trust II – Reverse Tender	-	866ha	-	866ha
			Aus. Government Reef Trust III – Reef Alliance	-	2,096ha	-	2,096ha
			Qld Government DES RP161 Program	3,668ha	5,560ha	3,668ha	5,560ha
	Lower Burdekin	Grazing	Aus. Government Reef Trust III – Reef Alliance	8,204ha	13,468ha	7,161ha	13,468ha
				10km	20km	10km	20km
			Aus. Government Reef Trust III – Gully Remediation	5ha	-	5ha	-
			Aus. Government Reef Trust III – Project Pioneer	32,159ha	-	32,159ha	-
			Qld Government (NESP 3.1.7) Innovative Gully Remediation Strathalbyn	-	58ha	-	58ha
			Qld Government DAF Extension	54,320ha	-	54,302ha	-
		Sugarcane	Aus. Government Reef Trust II – Reverse Tender	-	1,451ha	-	1,451ha
			Aus. Government Reef Trust III – Reef Alliance	-	3,341ha	-	3,341ha
			Qld Government RP161	2,285ha	2,854ha	2,285ha	2,854ha
	Suttor	Grazing	Aus. Government Reef Trust III – Project Pioneer	132,999ha	-	107,023ha	-
			Qld Government DAF Extension	511,100ha	79,544ha	509,702ha	79,395ha
	Upper Burdekin	Grazing	Aus. Government Reef Trust I – Saving our Soils	4,292ha	8,459ha	4,292ha	7,870ha
			Aus. Government Reef Trust III – Project Pioneer	71,063ha	-	62,602ha	-

Natural resource management region	River Basin	Commodity	Program	Total reported spatial extent of *practice change* reviewed for Reef Water Quality Report Card 2017 and 2018 (ha or km of stream)		Corrected spatial extent utilised in determining progress toward Reef 2050 WQIP targets for adoption and water quality	
				2016-2017	2017-2018	2016-2017	2017-2018
			Aus. Government Reef Trust III – Reef Alliance	51,946ha	75,318ha	29,074ha	70,968ha
				82km	45km	82km	11km
			Qld Government DAF Extension	2,293ha	50,386ha	2,293ha	37,450ha
Wet Tropics	Johnstone	Sugarcane	Qld Government DAF Extension	-	59ha	-	59ha
			Qld Government DES RP163 Protecting our Chemicals (Sugar Research Australia - SRA)	2,693ha	-	2,693ha	-
			Qld Government DES Reef compliance program	-	62ha	-	62ha
			Aus. Government Reef Trust IV – Reverse Tenders	-	3,317ha	-	3,317ha
		Bananas	Aus. Government Reef Trust III – Reef Alliance	200ha	-	200ha	-
	Barron	Bananas	Aus. Government Reef Trust III – Reef Alliance	48ha	-	48ha	-
		Sugarcane	Qld Government DAF Extension	-	898ha	-	898ha
			Qld Government DES – RP163 Protecting our Chemicals (SRA)		428ha	-	428ha
		Horticulture	Qld Government DAF Extension	-	24ha	-	24ha
		Grains	Aus. Government Reef Trust III – Reef Alliance	-	35ha	-	-
	Tully	Bananas	Aus. Government Reef Trust III – Reef Alliance	-	28ha	-	28ha
		Sugarcane	Qld Government DES – RP163 Protecting our Chemicals (SRA)	-	1,950ha		1,950ha
			Qld Government DES – TF11.9 Cane to Creek (Sugar Research Australia)	-	30ha		30ha
			Aus. Government Reef Trust IV – Reverse Tenders	-	77ha	-	77ha
		Sugarcane	Qld Government DAF Extension	1,890ha	-	1,890ha	-

Natural resource management region	River Basin	Commodity	Program	Total reported spatial extent of *practice change* reviewed for Reef Water Quality Report Card 2017 and 2018 (ha or km of stream)		Corrected spatial extent utilised in determining progress toward Reef 2050 WQIP targets for adoption and water quality	
				2016-2017	2017-2018	2016-2017	2017-2018
	Mulgrave-Russell		Qld Government DES – RP163 Protecting our Chemicals (SRA)	-	3,639ha	-	3,63 ha
			Qld Government DES – TF11.9 Cane to Creek (SRA)	-	3,624ha	-	3,624ha
			Aus. Government Reef Trust IV – Reverse Tenders	-	674ha	-	674ha
		Bananas	Aus. Government Reef Trust III – Reef Alliance	-	42ha	-	42ha
		Sugarcane	Aus. Government Reef Trust IV – Reverse Tenders	-	906ha	-	906ha
	Murray	Sugarcane	Qld Government DES – RP163 Protecting our Chemicals (SRA)	-	627ha		627ha
			Aus. Government Reef Trust IV – Reverse Tenders	-	310ha	-	310ha
	Herbert	Sugarcane	Qld Government DES Reef compliance program	-	409ha	-	409ha
		Grazing	Aus. Government Reef Trust III – Reef Alliance	-	4ha	-	4ha
Cape York	Normanby	Bananas	Aus. Government Reef Trust III – Reef Alliance	444ha	-	444ha	-
		Grazing	Aus. Government Reef Trust II – Gully Prevention & Remediation (Kings Plains Project)	41,472ha	-	41,468ha	-
			Aus. Government Reef Trust III – Reef Alliance	-	14,951ha	-	14,951ha
			Qld Government DES - On Ground Works – Springvale	-	59,256ha	-	59,256ha
	Endeavour	Grazing	Aus. Government Reef Trust II – Gully Prevention & Remediation (Kings Plains Project)	2,767ha	-	2,767ha	-

Describing progress

Management practices that are at the moderate-low risk (B) and lowest risk (A) levels are considered as 'best management practices'. These are summed in describing the proportion of total area in a catchment that is managed under best practice, and practices are combined according to their weightings to describe 'best management practice systems'. Colour coding based on five categories (Table 4) is also used to indicate progress toward the 90% adoption target.

Table 4. Colour-coded scoring system used to indicate progress.

Adoption progress – scoring system		
0–22%	E – Red	Very poor
23–45%	D – Orange	Poor
46–67%	C – Yellow	Moderate
68–89%	B – Light green	Good
90–100 %	A – Dark green	Very good

Qualitative confidence rankings

A multi-criteria analysis has been used to qualitatively score the confidence in each indicator used in the Reef Water Quality Report Card from low to high. The approach combined expert opinion and direct measures of error for program components where available.

References

Australian and Queensland governments 2018, Reef 2050 Water Quality Improvement Plan 2017-2022, <https://www.reefplan.qld.gov.au/about/>.

Further reading

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Glossary

Adoption: In this context adoption is the process of changing how something is done on farms. Adopting a new farm management practice usually requires the acquisition of new knowledge and skills, and often new or different farm equipment and infrastructure. The extent to which a specific practice is adopted (adoption rate) is described as a percentage of the overall population or area. For example, 98% of the sugarcane growing area in the Johnstone River catchment retains harvested crop residues on the soil surface.

Benchmark: A value set at a reference point in time. In this context benchmarks are describing farm practice adoption rates at specific points in time. For example, the 2016 benchmark for low-risk usage regime of residual herbicides in sugarcane in the Burdekin River catchment is 67% of the sugarcane growing area.

Best management practice systems: Farms are managed using many different management practices. There is a "best practice" level for each of these practices. The farm management **system** is a complex blend of all of these practices. Achieving a best management practice system means that all, or the majority of the constituent practices, are occurring at the best practice level. In the context of the Reef 2050 WQIP, the management systems described are best practice for off-farm water quality.

Industry best management practice program: In Queensland, each major agricultural industry sector leads a voluntary program that assists landholders to benchmark their current practices against an industry-developed set of standards. These standards are available for all aspects of farm business management, including the many of elements that are relevant when considering risks to off-farm water quality. Industry BMP programs operating in Great Barrier Reef catchments during 2016-2017 and 2017-2018 included:

- Sugarcane: Smartcane BMP (Queensland Cane Growers Organisation)
- Bananas: Banana BMP Guide (Australian Banana Growers Council)
- Beef cattle grazing: Grazing BMP (AgForce Queensland)
- Grains: Grains BMP (AgForce Queensland)
- Horticulture: Hort360 (Growcom)

Stewardship: Stewardship is the responsibility of carefully managing something. In the context of the Reef 2050 WQIP, it involves implementing or supporting farm practices that reduce sediment, nutrients, and pesticide pollution.

GROUND COVER MONITORING METHODS

This report summarises the data and methods used for reporting progress towards the Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP) 2025 land and catchment management target for ground cover.

The target for ground cover is as follows (Australian and Queensland governments, 2018):

- 90% of grazing lands will have greater than 70% ground cover in the late dry season.

"The ground cover target focusses on late dry season ground cover levels across grazing lands, recognising that water quality risk is generally highest at the onset of the wet season. The target incorporates an area-based component (i.e. 90% of grazing lands will have achieved the ground cover target), while providing for natural variability in ground cover levels. Research supports a ground cover target of 70% to minimise erosion."(Reef 2050 WQIP)

Background

Why measure ground cover?

Ground cover is defined as the vegetation (living and dead) and biological crusts and rocks that are in contact with the soil surface and is a key indicator of catchment condition. Ground cover is a key component of many soil processes, including infiltration, run-off and surface erosion. In the Great Barrier Reef catchments, low ground cover can lead to soil erosion which contributes to increased sediment loads reaching the Great Barrier Reef lagoon and loss of productivity for grazing enterprises.

It is particularly important to maintain ground cover during dry periods, or periods of unreliable rainfall, to minimise loss of water, soil and nutrients when rainfall eventually occurs. This practice will also maximise the pasture growth response to rainfall. Implementing appropriate and sustainable land management practices, particularly careful management of grazing pressure, can help to maintain or improve ground cover, reducing erosion and improving the stability and resilience of the grazing system.

Factors that influence ground cover

Ground cover levels are the result of complex interactions between landscape function (soil type, topography and vegetation dynamics), climate and land management. Some areas maintain naturally higher levels of ground cover due to factors such as high soil fertility and consistently high annual rainfall. The impacts of grazing land management practices on ground cover levels in these areas can be minimal due to the resilience of the land in responding to pressures. In areas where rainfall is less reliable and soils are less fertile, ground cover levels can vary greatly and the influence of grazing land management practices on ground cover levels and on the species composition of the ground cover can be more pronounced.

A number of initiatives aimed at improving grazing land management in Great Barrier Reef regions are in place or are planned. They include programs which are improving management of ground cover levels appropriate to the regional conditions, such as:

- the industry-led Grazing Best Management Practice program
- infrastructure projects such as fencing key areas and better distribution of watering points for stock
- trials of different grazing strategies
- a range of extension and education activities including development of online, interactive and reporting tools for accessing and viewing ground cover information.

Reporting ground cover levels for the Reef 2050 Water Quality Improvement Plan

Progress towards the 2025 land and catchment management ground cover target is assessed by the Ground cover monitoring program and is based on the measurement of late dry season ground cover using Landsat satellite imagery for historical measurements, and Sentinel-2 imagery when available in more recent years (post-2015). All imagery has been processed to produce fractional ground cover estimates, using field data for calibration. While a range of factors influence ground cover levels, reporting is focused only on information that describes regional ground-cover levels in the current and historical context. Rainfall data is provided for context only, as it is the primary driver of ground cover levels at a regional scale.

A range of products have been developed by the Queensland Ground Cover Monitoring Program that account for the influence of climate, land management and soil type. These products are more appropriate for monitoring local-scale variability and differences in ground cover levels, but are of limited use for the regional-scale reporting required here. Access to some of these products is via the interactive online tool VegMachine and the online reporting tool, FORAGE. Products that prove useful for describing ground cover levels at the regional scale will help to revise future ecologically-relevant and regionally-focused targets, and will be incorporated into future reporting.

Methods

The following is a brief overview of the data and methods used for reporting regional ground cover in the Great Barrier Reef Report Card 2017-2018. For further detail about data processing, refer to the ground cover technical report (DES, 2019).

Ground cover data

Reporting is based on the measurement of late dry season ground cover using Landsat satellite imagery for historical measurements, and Sentinel-2 imagery when available in more recent years (post-2015). All imagery has been processed to produce fractional ground cover estimates, using field data for calibration.

Ground cover satellite imagery and fractional ground cover

Measurement of ground cover for reporting is based on data derived following the method described in Trevithick et al. (2014). The underlying fractional ground cover data will be updated using a machine learning (support vector regression) algorithm, still in development. This is a new method using additional field data to train and calibrate a machine learning approach (support vector machines). The newer method produces results very similar to the previous method, allowing for comparison of results with earlier report cards, but with much greater information on the known accuracy of the product and some improvements in areas of known error such as scalded locations.

The fractional ground cover method measures the proportion of green cover, non-green cover and bare ground using reflectance information from late dry season from several sources of satellite imagery. These include the longer-term dataset of Landsat imagery (1987 to present; several versions) with a spatial resolution of approximately 30m and an acquisition frequency of 16 days, and the European Space Agency's Sentinel-2A and Sentinel-2B satellites (mid-2015 to present) with a higher spatial resolution of 10m and a more frequent acquisition of every five days. Fractional cover data produced between the two sources is statistically comparable. The switch to using Sentinel-2 data is expected to improve ground cover estimates, particularly in areas that are cloud affected.

It is important to note that the fractional cover data measures all cover as viewed from above by the satellite, including the trees and shrubs as well as the ground cover and bare ground. It is then further corrected to effectively remove the influence of trees and shrubs, providing individual estimates of the level of green ground cover, non-green ground cover and bare ground at ground level (Figure 1). This method works in areas of tree cover up to 60% persistent green (i.e. woody vegetation) cover, at which point the canopy becomes too dense to reliably achieve an estimate of the ground. This means that fractional ground cover can be reported for the majority (>90%) of the grazing lands of the Great Barrier Reef catchment areas. As a final step, the green and the non-green ground cover fractions are summed to produce a total ground cover estimate (erosion and run-off are influenced by all ground cover). This estimate of total ground cover is what is used for reporting and is hereafter referred to simply as 'ground cover'.

The current fractional ground cover product was developed using approximately 1,800 field observations across a range of ground cover, tree cover and shrub cover levels, within a range of environments. This product is used in the 2017-2018 reporting period. A newer fractional ground cover algorithm has been developed using machine learning techiques and calibrated using over 4,000 field observations. This new product will be used for the remaining reporting years and while it is believed to be more accurate, it will not effect overall results at a catchment scale. The current fractional ground cover product has been assessed using linear regression to have a an accuracy of 17% RMSE (Figure 2).

Late dry season ground cover

Late dry season ground cover is defined using seasonal composites of images for spring (September–November) (for the period 1987 to present). It is estimated using a seasonal composite of fractional ground cover data images (Landsat prior to 2015 and Sentinel-2 post-2015) acquired throughout the season (requiring at least three observations per pixel). The data is then corrected for tree cover to produce a seasonal ground cover dataset for all areas with up to 60% tree canopy cover. This approach has the advantage of removing errors and outliers in the data (e.g. due to cloud or cloud shadow artefacts), and providing the most spatially comprehensive coverage as there is generally very little missing data due to cloud, cloud shadow or satellite sensor issues. For areas where there is still missing data, further infilling can be undertaken using what are referred to as seasonal ground cover 'patches'. These are pixel values generated in areas where less than three valid observations were made in a season. This process is only undertaken for the Landsat imagery, as the more frequent Sentinel-2 data typically has very little missing data once composited.

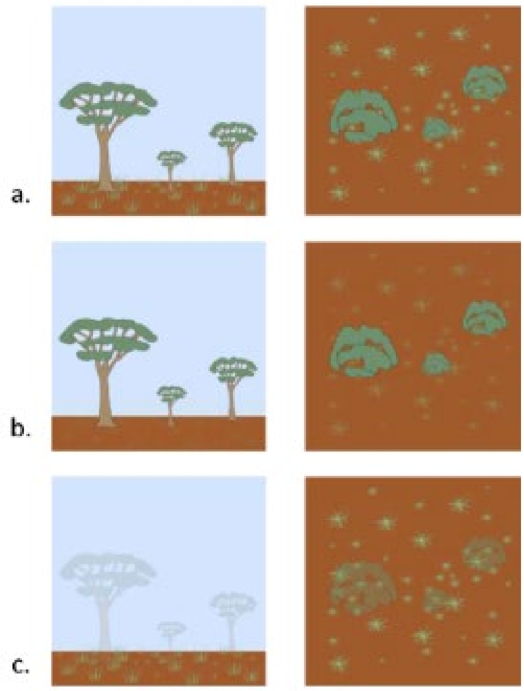


Figure 1. Schematic representation of the correction of the fractional cover data to estimate the fractional ground cover (Trevithick et al., 2014), used for reporting. (a) Fractional cover measures all vegetation cover including trees, shrubs and ground cover, as well as bare ground. The ground cover and bare ground are partially obscured by the trees and shrubs. (b) Next, a time-series approach is used to estimate the percentage of 'persistent' cover in the tree and shrub layers. (c) Finally, a correction factor is applied, based on field data, to effectively remove the 'persistent' cover in the tree and shrub layers, thus providing an estimate of the green cover, non-green cover and bare ground, all at the ground level – the fractional ground cover.

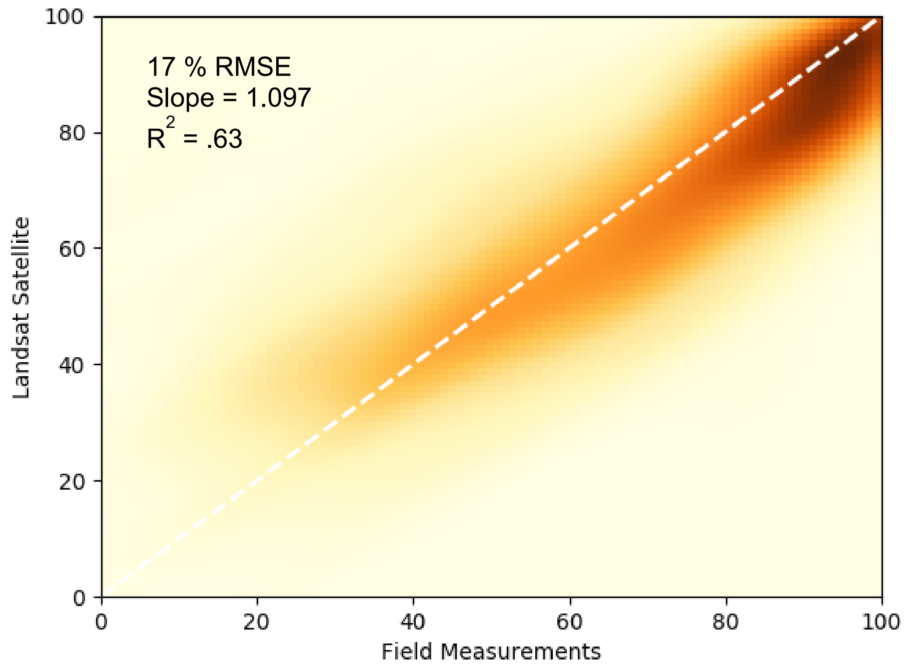


Figure 2. Comparison of field measurements of fractional cover with Landsat derived fractional ground cover for 2,047 sites across Australia. The linear regression shows a RMSE of 17%, within the specified guidelines for Reef reporting.

Reporting regions and grazing lands

Reporting is based on the six natural resource management regions of the Great Barrier Reef region:

- Cape York region
- Wet Tropics region
- Burdekin region
- Mackay Whitsunday region
- Fitzroy region
- Burnett Mary region.

Grazing lands in the reporting regions were spatially-defined based on the most recent land use data provided by the Queensland Land Use Mapping Program (DSITIA, 2012). The most recent version of the mapping for Burdekin and Wet Tropics is 2016, while Cape York, the Wet Tropics and Burnett Mary are current to 2013, 2015 and 2017 respectively.

A *reporting region* is defined as that part of an NRM region which is grazing land and has less than 60% persistent green (i.e. woody vegetation) cover.

Reporting ground cover

This report provides a regional overview of late dry season ground cover levels in the Great Barrier Reef catchments based on analysis of seasonal (spring) total ground cover data. The statistics are calculated for each pixel (i.e. 30m x 30m area) and then summarised (i.e. averaged) for each of the 35 catchments.

Statistics reported for each region include:

- mean late dry season ground cover
- mean long term late dry season ground cover (1987 to reporting season)
- the percentage of the region's reporting area with late dry season ground cover greater than 70% in the reporting year
- the percentage of the region's reporting area with mean late dry season ground cover greater than 70% for the Landsat historical record (1987 to the reporting year).

Graphs show the distribution of ground cover for each region across the range of ground cover levels. Maps of ground cover percentages are provided for the entire Great Barrier Reef region, and for each reporting region, as a visual representation of the statistics listed above. A map comparing ground cover decile rankings for the reporting year with long-term mean levels is also produced.

It is important to note that averaging ground cover across whole regions can mask localised areas of lower cover, particularly in large catchments with a strong rainfall gradient (e.g. the Burdekin and Fitzroy). The mean ground cover reported is therefore indicative of general levels of ground cover within the reporting region. For additional level of reporting, the reporting regions are further divided into catchments (and sub-catchments for larger catchments) in the ground cover technical report (DES, 2019).

Rainfall data

Rainfall data is provided for current and historical context as rainfall is the primary driver of ground cover levels at the regional scale. In general, high rainfall in the preceding seasons results in higher ground cover levels and low rainfall in preceding seasons results in lower ground cover levels. Rainfall data is obtained from SILO as a 5km grid. For each reporting region. The mean annual rainfall is then calculated from September to August for each year from 1986, to align the mean annual rainfall with the late dry season reporting period.

Scoring system

A standardised scoring system is used for each of the key indicators in the reef report card. The scoring system is used to assess and communicate the status of the indicator against the Reef 2050 WQIP 2025 targets.

Ground cover target

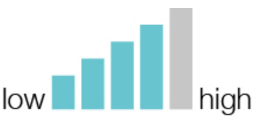
- 90% of grazing lands will have greater than 70 per cent ground cover in the late dry season.

Table 1: The colour-coded ground cover scoring system

Status	Criteria	Grade and colour code
Very poor ground cover	Less than 60% of grazing lands meet the optimal cover level	E - Red
Poor ground cover	Between 60-69% of grazing lands meet the optimal cover level	D - Orange
Moderate ground cover	Between 70-79% of grazing lands meet the optimal cover level	C - Yellow
Good ground cover	Between 80-89% of grazing lands meet the optimal cover level	B - Light Green
Very good ground cover – Target met	More than 90% of grazing lands meet the optimal cover level	A - Dark Green

Optimal cover level for 2018 is > 70 % ground cover.

Qualitative confidence ranking



A multi-criteria analysis is used to qualitatively score the confidence in each indicator used in the Reef report card from low to high. The approach combined the use of expert opinion and direct measures of error for program components where available. Ground cover has received a four-bar confidence ranking.

Groundcover

Maturity of methodology (weighting 0.5)	Validation	Representativeness	Directness	Measured error
New or experimental methodology	Remote sensed data with no or limited ground truthing	1:1,000,000	Measurement of data that have conceptual relationship to reported indicator	Error not measured or >25% error
Peer reviewed method	Remote sensed data with regular ground truthing (not comprehensive)	1:100,000	Measurement of data that have a quantifiable relationship to reported indicators	10-25% error
Established methodology in published paper	Remote sensed data with comprehensive validation program supporting (statistical error measured)	1:10,000	Direct measurement of reported indicator with error	Less than 10% error
3 x0.5 = 1.5	3	3	2	2

Bolded cells indicate assessment ranking

Total score = 11.5, equates to **four bars**.

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RIPARIAN VEGETATION EXTENT MONITORING RESULTS

This report summarises the data and methods used for reporting progress towards the Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP) 2025 catchment management target for riparian vegetation extent.

The target is as follows (Australian and Queensland governments, 2018):

- The extent of riparian vegetation is increased.

Riparian woody vegetation and ground cover are the vegetation adjacent to waterways, which can help reduce pollutant flow to the waterways and stabilise the streambank (Lyons et al., 2000). For the current era, riparian woody vegetation areas include riparian forest (trees > 5m height with dense foliage cover (Specht, 1970); riparian woodlands (trees >5m in height with sparse foliage cover (Specht, 1970) and shrublands (shrubs < 8m in height) (Specht, 1970). Riparian areas that are non-woody and have very low ground cover levels may be areas of concern for soil and nutrient loss to the stream (Lyons et al., 2000). Maintaining and enhancing riparian woody vegetation and ground cover in riparian areas is, therefore, important to minimise impacts on water quality in Great Barrier Reef (GBR) catchments.

Monitoring of riparian vegetation extent is based on analysis of satellite imagery to map woody vegetation and ground cover in riparian areas. The program also leverages monitoring of woody vegetation from the Statewide Landcover and Trees Study (SLATS) (DES, 2018), and monitoring of ground cover as part of Queensland Ground Cover Monitoring Program.

For the Reef Water Quality Protection Plan 2013, the riparian area was defined as any area within 100m of a (mapped) stream or riverine wetland. The riparian extent monitoring provided historical and current data and information about riparian vegetation extent and cover in the GBR catchments. Previous results include mapping of the original (pre-clearing) and current (2001, 2005, 2009, 2013) extent of riparian vegetation based on Landsat satellite imagery, which has a spatial resolution of approximately 30m. The spatial resolution of Landsat has some limitations and uncertainty for reporting on riparian vegetation, and riparian woody vegetation in particular, as these areas are often very narrow (i.e. < 30m) and fragmented as a result of historical clearing.

The 2017 and historical extent results will be presented as part of the Reef Water Quality Report Card 2017 and 2018.

For the Reef 2050 WQIP, the riparian area has been revised to be any area within 50m of a (mapped) stream or wetland, to better align reporting with areas identified as Category R vegetation (i.e. high value regrowth in riparian areas) for the purposes of the *Vegetation Management Act 1999.* The riparian woody vegetation extent has also been revised to a spatial resolution of 10m (using Sentinel data) which is more appropriate for riparian areas. It is important to note that this change in spatial resolution will mean that there will be scale differences with current and previous reporting.

Methods

Riparian vegetation is measured using Sentinel-2 Multi-Spectral Instrument (MSI) satellite imagery, while clearing changes in riparian areas are assessed using data derived from Landsat satellite imagery. The Department of Environment and Science's Remote Sensing Centre has an extensive archive of Landsat 5, 7 and 8 data acquired since 1984, and Sentinel-2 data acquired since 2015. The Landsat datasets have been pre-processed to standardised surface reflectance to enable comparison over time (Flood et al., 2013). Landsat data have been used by various riparian studies, as reviewed in Goetz (2006). Landsat data have a moderate spatial resolution, with a pixel size of 30m. The return interval of each Landsat satellite is 16 days, however the intervals are phased resulting in coverage every eight days or better. Sentinel-2 data have a finer spatial resolution than Landsat, with pixel sizes of 10-20m, depending on the band. Since the launch of Sentinel-2B in 2017, Sentinel-2 imagery is available every five days. Sentinel-2 data has been pre-processed to standardised surface reflectance, with an algorithm applied to reduce the difference between Sentinel-2 and Landsat reflectance values, in order to provide comparable measurements over time (Flood, 2017).

Monitoring and reporting of riparian vegetation extent (and cover) is made up of three key components:

1. Defining and mapping riparian areas
2. Mapping riparian woody vegetation extent and measuring changes to this extent over time.
3. Estimating riparian ground cover and analysing how it changes over time within riparian areas.

Defining and mapping riparian areas

Riparian areas range from small headwater creeks to major rivers. Many studies have shown the benefits of using GIS and remote sensing to analyse vegetation within a range of specified distances to a stream (Goetz, 2006, Yang, 2007, Apan et al., 2002). For the purposes of meeting the range of objectives for this component of the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program (Paddock to Reef program), riparian areas will be defined by a 50m buffer zone applied to a combination of topographic drainage line data and riverine wetlands, as mapped by the Queensland Wetlands Program. The same drainage data will be used as is used for defining Category R areas for the *Vegetation Management Act 1999* to ensure consistency. As this is a new dataset, results in this report will not be directly comparable with previous reports.

Mapping riparian woody vegetation extent

The extent of riparian woody vegetation is mapped using Sentinel-2 satellite imagery. The imagery has been cross-calibrated to enable transition between Sentinel-2 and the previously used Landsat imagery (see historical assessments below)(Flood, 2017).

An index of woody vegetation, know as Foliage Projective Cover, calibrated using a database of over 2,000 quantitative field observations of woody vegetation cover, is applied to the Sentinel-2 satellite imagery to predict areas of woody vegetation cover within the riparian area. An Foliage Projective Cover threshold of 11% is selected to distinguish areas of woody vegetation. This may include areas of vegetation with low height but dense cover, such as heathlands.

The extent of riparian woody vegetation will be revised and updated in 2021-2022 to report on net change in extent between 2017-2018 and 2021-2022.

Measuring changes to riparian extent over time

Historical and recent losses of riparian vegetation are analysed using woody vegetation clearing data from the SLATS and 'pre-development' forest data. Due to the historical time-series required for this component of the reporting, these analyses rely on the use of SLATS Landsat-based data, which has an archive extending to the mid-1980s (for Landsat's 5, 7 and 8). Some scale/resolution differences may reduce the precision and accuracy of some of the reporting statistics derived from this component, particularly when comparing losses mapped by SLATS using Landsat imagery with current woody vegetation extent mapped using Sentinel-2 imagery.

The pre-clearing woody vegetation areas are defined as areas assessed as woody (forests, woodlands and tall shrublands) before European settlement. These data are derived from pre-clearing Regional Ecosystem mapping (Accad et al., 2001). The recent losses relate only to anthropogenic clearing, and do not include vegetation loss from natural events such as cyclones and drought stress, which typically have a faster recovery time than regrowth after clearing. This distinction is determined through the SLATS classification process.

Riparian woody vegetation loss in extent is reported for three time periods for the Great Barrier Reef catchments:

1. Pre-clearing baseline to 2016-2017, to provide an approximate estimate of the extent of modification to riparian woody vegetation in each of the regions
2. From 1988 to 2016-2017, for historical woody vegetation clearing summaries
3. From 2001 to 2005, 2005 to 2009, 2009 to 2013 and 2013 to 2017 for recent woody vegetation clearing trends.

Estimating riparian ground cover

For riparian areas with up to 11% Foliage Projective Cover, ground cover is estimated and reported for the current reporting year. Ground cover monitoring is included to recognise the importance of having some level of vegetation cover in riparian areas to help minimise erosion, particularly where woody vegetation is not present to stabilise the soil. Ground cover reporting in riparian areas is based on Sentinel-2 seasonal fractional cover data derived using the method described by Flood (2017). The Sentinel-2 fractional cover product is not specifically a ground cover product, and does contain woody vegetation. However, as its use is restricted to non-forested areas it is suitable for the purposes of assessing ground cover. Ground cover levels will be the late dry season for the reporting year of interest.

Assessing progress towards the target

The Reef 2050 WQIP 2025 target that "the extent of riparian vegetation is increased", will be reported in 2019 for data from 2017 and in 2021 for data from 2020. Specifically, the extent of riparian woody vegetation in 2017 will be compared to the extent in 2020 with progress measured by the net change between those two dates. A positive change in extent will indicate progress. A negative change would indicate that no progress has been made.

Additional reporting on progress towards the target will be derived from analysis of the ground cover levels in riparian areas. Reporting the ground cover levels will help to report on the maintenance of ground cover in the riparian areas over time, providing some indication of the management of those areas in terms of grazing or other pressures such as cropping.

Qualitative confidence ranking

Confidence

A multi-criteria analysis was used to qualitatively score the confidence in each indicator used in the report card from low to high. The approach combined the use of expert opinion and direct measures of error for program components where available. Riparian vegetation extent received a three bar confidence ranking.

Riparian extent

Maturity of methodology (weighting 0.5)	Validation	Representativeness	Directness	Measured error
New or experimental methodology	Remote sensed data with no or limited ground truthing	1:1,000,000	Measurement of data that have conceptual relationship to reported indicator	Error not measured or >25% error
Peer reviewed method	Remote sensed data with regular ground truthing (not comprehensive)	1:100,000	Measurement of data that have a quantifiable relationship to reported indicators	10-25% error
Established methodology in published paper	Remote sensed data with comprehensive validation program supporting (statistical error measured)	1:10,000	Direct measurement of reported indicator with error	Less than 10% error
2 x 0.5 = 1	2	2	2	2

Bolded cells indicate assessment ranking

Total score = 9, equates to **Three bars**.

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WETLAND EXTENT MONITORING METHODS

This report summarises the data and methods used for reporting progress towards the Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP) 2025 catchment management targets.

The target for wetland extent is as follows (Australian and Queensland governments, 2018):

- No loss of the extent of natural wetlands (lakes, swamps and estuarine wetlands).

Catchment management targets aim to prevent further loss of wetland extent. Healthy wetlands can assist with filtering pollutants from the water in some situations, and provide important habitat for many animals and plants.

The extent of wetlands and changes in extent are reported every four years (2001, 2005, 2009, 2013, 2017 and will be repeated in 2021). Comparisons of current extent with pre-clearing extent are also made.

Regional ecosystem mapping and wetlands mapping

The regional ecosystem mapping is derived by delineating the pre-clearing regional ecosystems from stereo aerial photography in conjunction with other information sources including geology and soils mapping, historical survey records and field survey. Remnant vegetation cover is determined from the extent of clearing (2001, 2005, 2009, 2013 and 2017) from satellite imagery (Landsat Thematic Mapper and SPOT) which has been processed and supplied by SLATS (Neldner et al. 2019). For most of Queensland the mapping is validated to a scale of 1:100,000 which includes over 8,000 wetland ground-truthing sites, however coastal areas may be compiled at 1:50,000 scale and specific targeted areas such as those covered by a detailed Property Map of Assessable Vegetation (PMAV) may be compiled at 1:25,000 scale.

The wetlands mapping methodology is a multi-step process. The maximum extent of water bodies is derived by analysis of a selection of satellite images commencing in 1991 through to 2017. This imagery is then combined with topographic and wetland regional ecosystem data to map wetland extent (also includes drainage and springs datasets). The maximum extent is derived from these various datasets and changes in wetland inundation due to wetting and drying cycles are included as additional attributes on the mapping and not reflected as changes in wetland extent.

The extent of wetlands is summarised by catchment into three types of wetland systems (EPA, 2005):

1. Palustrine (vegetated freshwater swamp) systems are wetlands with more than 30% emergent vegetation cover, or less than eight hectares.

2. Lacustrine (lake) systems are wetlands that are over eight hectares with less than 30% emergent vegetation cover (but excluding riverine channels and associated fringing vegetation). Areas of open water less than eight hectares are classified as lacustrine if the water is over 2m deep.

3. Estuarine (mangroves and salt flats) wetlands occur in coastal areas that are tidally inundated and dominated by mangrove or salt flat (saltmarsh and salt pan) communities.

Riverine and marine wetlands (including estuarine channels and coastal waters) are not included in the analysis.

Wetlands are assigned a local hydrology modifier to distinguish natural wetlands (those where no local hydrological modification is observed), from hydrologically modified wetlands such as a constructed bund or levee in a swamp. The extent of both natural (unmodified) and modified wetlands is reported on for each wetland system, however the reporting does not include artificial or highly modified wetlands.

The wetland mapping is dependent on the regional ecosystem mapping program as a major input. Mapping of regional ecosystems and their remnant extent is updated every two years. For this to occur:

1. Satellite imagery (Landsat Thematic Mapper and SPOT) has to be processed and supplied by the Statewide Landcover and Trees Study (SLATS) (DES, 2018).
2. Change detection determined from an analysis of the differences between 2013 to 2017 Landsat Thematic Mapper and SPOT has to be processed and supplied by SLATS.

There is usually a one-year turnaround time from the date of satellite image capture and the supply of processed imagery and change detection to the Queensland Herbarium for use in the regional ecosystems mapping update.

Updates to wetland extent also rely on waterbody mapping supplied by SLATS, targeted field validation and property scale assessment data.

A combination of automated and manual interpretation of imagery is used to delineate change in wetland extent due to clearing of vegetation, destruction of water bodies from draining or earthworks, or the creation of new water bodies through dam or weir construction. Changes in wetland extent due to seasonal wetting and drying are not recorded as wetland loss or gain.

Improvements in wetland delineation are back-cast over the 2001, 2005, 2009, 2013 datasets and revised extent figures for these periods is also provided.

Assessing progress towards the target

The wetlands mapping will be used to report on the current extent of wetlands (2017 and again in 2021), and the change in wetland extent between 2001, 2005, 2009, 2013, 2017 and 2021. The change in extent is reported as a percentage of the current data to enable comparison between catchments of different sizes. Results are reported at the Great Barrier Reef-wide, regional, catchment and major sub-catchment scales.

Scoring

	Very good	No loss (0%) of wetlands
	Good	<0.10% loss of wetlands
	Moderate	0.11-0.50% loss of wetlands
	Poor	0.51-3.00% loss of wetlands
	Very Poor	Greater than 3.00% loss of wetlands
	No data	

Qualitative confidence ranking

Confidence

A multi-criteria analysis was used to qualitatively score the confidence in each indicator used in the report card from low to high. The approach combined the use of expert opinion and direct measures of error for program components where available. Wetland extent received a four bar confidence ranking.

Glossary

Natural wetlands: Wetlands where structures or activities that modify the local hydrology cannot be observed from satellite imagery or aerial photography.

Modified wetlands: Pre-existing wetlands that have visible modifying structures such as bunds or drains but are considered to retain many of their functional and ecological attributes.

Highly modified wetlands: Pre-existing wetlands that have visible modifying structures such that they have significantly altered functional and ecological attributes - not reported on.

Artificial wetlands: Artificially constructed wetlands, in areas where no wetland existed prior to the commencement of construction - not reported on.

Wetland extent: Refers to the aerial extent of wetland.

Baseline extent: Refers to wetland extent at the start of a reporting period.

Pre-clearing: Refers to aerial extent of wetland prior to settlement, clearing and development .

Historical loss: Estimated difference between pre-clearing wetland extent and current wetland extent. As wetland mapping does not have a pre-clearing baseline, historical loss is estimated from an analysis of Regional Ecosystem mapping.

Reporting periods: Wetland mapping is updated on a four-yearly cycle. Each update incorporates improvements in mapping and produces new wetland extents (as at the end of the calendar year) every four years starting with 2001, (this report is based on 2001, 2005, 2009, 2013 and 2017 extents). Changes in wetland extent are calculated by comparing each four-yearly extent with the preceding extent to produce the following reportable periods:

- January 1 2002 - December 31 2005, referred to as (2001-2005)
- January 1 2006 - December 31 2009, referred to as (2005-2009)
- January 1 2010 -December 31 2013, referred to as (2009-2013)
- January 1 2014 - December 31 2017, referred to as (2013-2017).

Palustrine wetlands: Predominantly freshwater wetlands with more than 30% emergent vegetation cover, or less than eight hectares (vegetated freshwater swamp).

Lacustrine wetlands: Wetlands that are over eight hectares with less than 30% emergent vegetation cover (excluding riverine channels and associated fringing vegetation). Areas of open water less than eight hectares are classified as lacustrine if the water is over 2m deep.

Estuarine wetlands: Wetlands that occur in coastal areas, are periodically tidally inundated and dominated by mangrove or salt flat (saltmarsh and salt pan) communities. This type does not include coastal waters and estuaries.

Coastal waters and estuarine channels: Areas of oceanic water that is at least occasionally diluted with freshwater run-off from the land, and not dominated by mangrove or salt flat (saltmarsh and salt pan) communities – not reported on.

PMAV: Property Map of Assessable Vegetation under the *Vegetation Management Act 1999.*

SLATS: Statewide Landcover and Trees Study.

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WETLAND CONDITION MONITORING METHODS

This report describes analysis methods used to produce the Reef Water Quality Report Card 2017 and 2018 wetland condition results. Within the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program the Wetland condition monitoring program aims to monitor progress towards the Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP), improved wetland condition objective.

The program design is described in the Great Barrier Reef (GBR) catchments wetland monitoring pilot study: assessment methods and monitoring design (Tilden et al., 2015) and the proposed program analysis methods are set out in detail in The Great Barrier Reef catchments wetland monitoring program: analysis methods (Tilden and Vandergragt, 2017).

Methods

The analysis methods document referred to above (Tilden and Vandergragt, 2017) identified a number of activities to be carried out in 2017 and 2018. The aims were to:

- assess wetland condition and change in wetland condition in GBR freshwater floodplain wetlands
- examine sources of variance in data gathered with the program's wetland assessment tool.

Baseline data for pressure on wetland values and the state of wetland values were reported in 2016. The 2017 and 2018 analyses (covered by this report card) focussed on:

- Testing for change in wetland condition (pressure on environmental values and state of environmental values) between 2016 and 2018.
- Testing against precision criteria set in the program design phase to see if the assessment method yields sufficient power to detect change between two times with a sample of 40 wetlands. The criteria were a detectable difference of one point on the wetland assessment tool's 13-point scoring scale[1] with a <5% chance of Type 1 error (false detection of change) and a less than 20% chance of Type II error (failing to detect a change), which equates to a power of 80%.
- Examining interoperator variability as a source of variance in assessment data with a view to improving the precision of the instrument.

The test of interoperator variability is the first of a number of planned investigations to identify and quantify sources of uncertainty in the program's wetland data. Also of interest is the degree to which natural variability adds uncertainty that would mask changes or trends in wetland condition. The program's wetland assessment tool was designed to assess anthropogenic impacts while being unresponsive to natural variability. Sufficient data has not been collected as yet to test for natural variability. Activities are planned to research the effects of rainfall, climate zone (tropical versus subtropical) and wetland habitat type on wetland assessment scores, to see if natural variability has been factored out to an acceptable degree.

[1] On this scoring scale, 1 is the most pristine wetland condition (pressure or state), while 13 represents the most disturbed condition (pressure or state).

Progress with monitoring design

Table 1 shows the GBR wetland condition monitoring program sample design – an augmented serially alternating design comprising one panel[2] of 20 wetlands assessed every year and four panels of 20 assessed in alternate years following a pattern that repeats every eight years. The total sample size is 100 wetlands, comprising a spatially balanced random sample of wetlands selected using the GRTS[3] method. The sub-population sampled for the GBR-wide monitoring program is natural freshwater floodplain wetlands in high density assemblages.

By the end of 2018, 63 wetlands had been assessed at least once and 39 had been assessed twice, allowing us to test for change between the 2016 baseline and 2018, and also to establish whether precision criteria set in the design phase had been met.

Table 1. Panel design for the Great Barrier Reef catchments wetland monitoring program.

Panel	Year									
	2016	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**
1	20	20	20	20	20	20	20	20	20	20
2	20		20						20	
3		20		20						20
4					20		20			
5						20		20		
Year total	40	40	40	40	40	40	40	40	40	40
Total sample	**40**	**60**	**60**	**60**	**80**	**100**	**100**	**100**	**100**	**100**

The discrepancy in the numbers of wetlands proposed to be assessed by the end of 2018 and those actually assessed had two sources. First, after the initial GRTS draw, an extra wetland from the Mackay Whitsunday region was added to the sample. This extra wetland was drawn from the original GRTS random sample following standard procedures. It was needed because the original sample of 40 wetlands (panels 1 and 2), designed to proportionally represent the whole GBR catchment by region, yielded only one wetland for Mackay Whitsunday due to the relatively small number of freshwater floodplain wetlands in that region. Second, two wetlands dropped out of the original panel 1 sample and were replaced from the GRTS random sample with two new ones from within the regions of the dropouts (Burdekin Dry Tropics and Mackay Whitsunday).

Data collection

Wetland assessment data was collected in two ways:

- desk top analysis based on imagery and spatial data using a range of data sets for 15 indicators primarily related to the pressure index
- field-based data collection methods for ten indicators primarily related to state.

[2] A panel is a group of wetlands with the same schedule of repeat assessments across years.
[3] Generalised Randomised Tessellation Stratified sampling

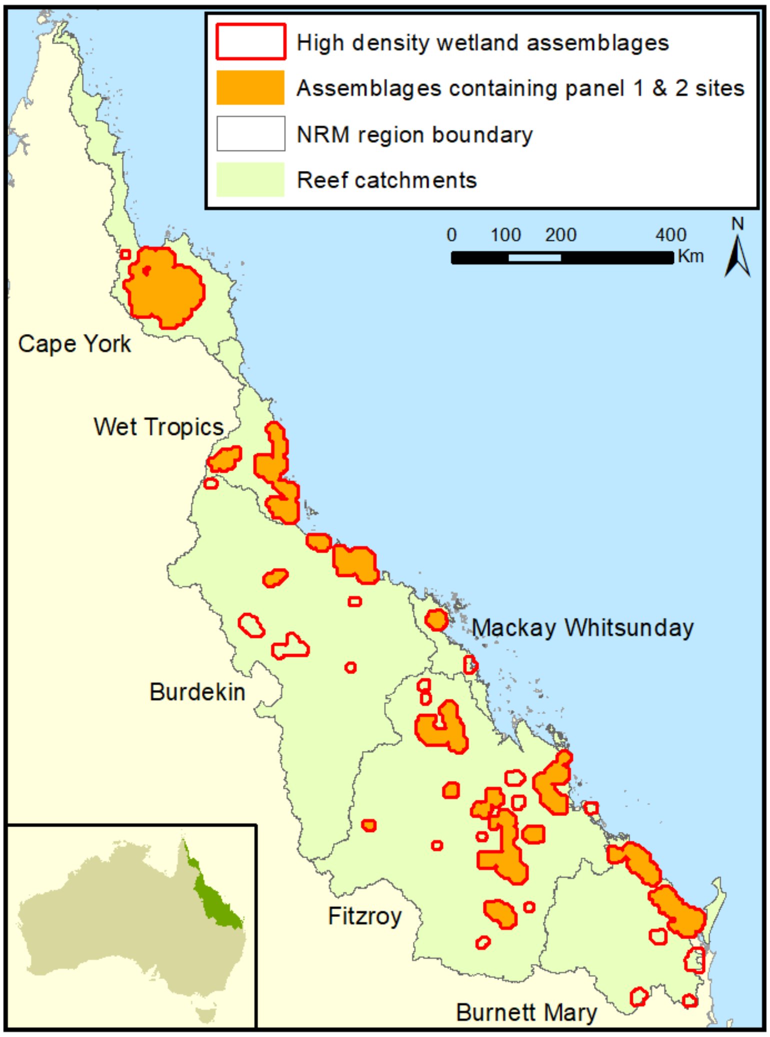

Figure 1. High density wetland assemblages containing panel 1 and panel 2 wetlands assessed in 2016 and 2018.

Calculating summary statistics

For each wetland, the assessment tool produces overall scores for **pressure** on wetland environmental values and the **state** of wetland environmental values (condition) plus scores on four wetland environmental value (WEV) sub-indices for both pressure and state. The WEV sub-indices are:

- biotic integrity: the biological health and diversity of the wetland's ecosystems
- local physical integrity: the wetland's natural physical state and integrity
- local hydrology: the wetland's natural hydrological cycle
- connectivity: the natural interaction of the wetland with other ecosystems including other wetlands.

The status and change assessment for 2018 focussed on the 39 freshwater floodplain wetlands in the GBR catchments that had been assessed at least twice. Descriptive parametric and non-parametric statistics, were calculated. Mean and variance of scores for overall wetland pressure and state were used to characterise the level of anthropogenic disturbance to GBR natural freshwater floodplain wetlands in 2018, along with the mean and variance per WEV for pressure and state. Norman (2010) summarises work supporting the use of parametric statistics on aggregated ordinal data.

Scoring scales for individual wetland and GBR-wide assessments

Generating the GBR scale wetland condition Pressure and State scores is a five step process. It starts with indicator scoring at the individual wetland scale then steps through to calculating wetland scale WEV scores and overall Pressure and State grades. GBR-wide grades for the four WEVs (*biotic integrity*, *local physical integrity*, *local hydrology* and *connectivity for pressure and state respectively) and the overall* GBR-wide State and Pressure report card grading are then calculated. These steps, score classes and cut-off values are summarised in 2 to 5.

Table 2. Scores per indicator: Individual indicators (pressure and state) are assessed on ordinal scales with scores generally ranging from one to five.

Condition	**Very low pressure/Very good state**	**Low pressure/ Good state**	**Moderate pressure/ Moderate state**	**High pressure/ Poor state**	**Very high pressure/ Very poor state**
Indicator scores (individual wetlands)	1	2	3	4	5

Table 3. Scores per WEV: The indicator scores are aggregated and converted into sub-index numeric scores for each of the four WEVs per wetland : *biotic integrity*, *local physical integrity*, *local hydrology* and *connectivity for both pressure and state respectively*.

WEV sub-index cutoff values	≤1.53	>1.53 to ≤2.33	>2.33 to ≤3.13	>3.1 to ≤3.93	>3.93

Table 4. Overall wetland pressure and state scores: The four WEV pressure scores and the four WEV state scores are then aggregated to generate an overall numeric pressure and state (OP and OS) score per wetland corresponding to a 13 point grading scale as shown below.

Aggregated overall pressure and state cut-off values	≤1.27	>1.27 to ≤1.53	>1.53 to ≤1.8	>1.8 to ≤2.07	>2.07 to ≤2.33	>2.33 to ≤2.6	>2.6 to ≤2.87	>2.87 to ≤3.13	>3.13 to ≤3.4	>3.4 to ≤3.67	>3.67 to ≤3.93	>3.93 to ≤4.2	>4.2
Pressure and state score classes (grades)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**

Table 5. GBR wide scores: At the GBR-wide scale individual WEV pressure and states scores and overall pressure and state scores are calculated by averaging the numeric values obtained from the individual wetlands. The GBR-wide pressure and state scores are then converted to the report card grades as shown below.

GBR scale WEV Sub-index Pressure and State report card grading

WEV subindex cutoffs (1–5 scale)	<1.5	≥1.5 to <2.5	≥2.5 to <3.5	≥3.5 to <4.5	≥4.5
Report Card grade	A	B	C	D	E

GBR scale State and Pressure report card grading

Index cutoffs (1–13 scale)	<2.5	≥2.5 to <5.5	≥5.5 to <8.5	≥8.5 to <11.5	≥11.5
Report Card grade	A	B	C	D	E

Baseline backcasting

Due to minor upgrades of the wetland assessment tool, the 2016 baseline statistics used to make comparisons in the Reef Water Quality Report Card 2017 and 2018 vary slightly from those used in Reef Water Quality Report Card 2016.

In particular, when the 2016 results were first reported, one indicator of pressure on ‘local physical integrity’ (modelled sediment supply) was non-discriminating. All wetlands had a score of one for this indicator, leading to an aggregated WEV2 grade of ‘A’. Following a methods change, this indicator now discriminates across the range of wetland disturbance.

All 2018 comparisons between summary statistics for 2016 and 2018 use the 2016 backcast results for index and sub-index scores (pressure and state).

Assessments of change between 2016 and 2018

Tests for change between 2016 and 2018 analysed aggregated wetland assessment scores.

Paired-sample t-tests were used to test for any statistically significant differences in overall pressure and state scores and sub-index pressure and state scores between the 2016 and 2018 survey periods ($p \leq 0.05$). All assessments of change use the 2016 back-cast results. Test results are for the $n = 39$ wetlands that were surveyed in both 2016 and 2018.

All paired-sample t-tests were two-tailed and were performed using the ‘t.test’ function from the ‘stats’ package in R (R Core Team, 2018).

Analysis by land use type

The aims of this analysis are to:

- determine if, in 2018, there were any significant differences in pressure or in state scores between wetlands surrounded by conservation land uses and those surrounded by other land use categories
- determine if land use intensity (LUI) in the wetland and the surrounding area affects change in scores between 2016 and 2018.

All analysis used data from the $n = 39$ wetlands surveyed in both 2016 and 2018. Data were aggregated pressure and state scores (i.e. scores between one and 13 for the overall pressure and state of wetlands; scores between one to five for the individual pressure and state WEVs).

To test for differences in condition between wetlands within conservation land uses and wetlands surrounded by all other land uses, Mann-Whitney U tests were performed on 2018 data only. This test uses sample distributions instead of measures of central tendency to test for difference in populations. The null hypothesis is that ‘there is no difference between score distributions attributable to land use type’.

To test the significance of changes in average scores by land use category between 2016 and 2018, we used paired-sample t-tests (two-tailed, $p \leq 0.05$, $N = 16$ for wetlands surrounded by conservation land use and $N = 22$ for wetlands surrounded by all other land uses). For each land use category comparisons between 2016 and 2018 were made at the overall pressure or state score level, as well for individual WEV pressure or state scores.

Non-response bias

The previous reef wetland condition report (2016) established that there was a non-response bias in the program’s wetland assessment data related to the intensity of land use surrounding wetlands. Managers of wetlands surrounded by high intensity land uses such as cropping and manufacturing were less likely to agree to monitoring than managers of wetlands surrounded by conservation land uses with intermediate acceptance rates for wetlands surrounded by land use of intermediate intensity.

Because a slightly different cohort of wetlands was assessed for the change analyses reported here, a new set of weights was calculated and applied to correct for the non-response bias. Using the method of Johnson (2008), weights were calculated by dividing the expected proportions of wetlands in each land use intensity class (high, moderate and low) by the observed proportions.

All aggregated scores for the pressure on wetland values and the state of wetland values were adjusted using the resulting weights and summary statistics were recalculated.

Both unadjusted and adjusted results are given in the 2018 wetland condition results report.

Power to detect change

As described earlier, paired-sample t-tests were used to test for changes in wetland pressure and state scores (both overall and per WEV) between 2016 and 2018.

The 'power.t.test' function from the 'stats' package in R (R Core Team, 2018) was used to to determine the minimum change in score that could be detected in these paired-sample t-tests, with a power of 0.80 and a significance level of $p = 0.05$, based on a sample size of $N = 39$ and the standard deviations of differences in scores recorded between 2016 and 2018.

Repeatability testing

Forty-one wetlands, comprising panels 1and 3 of the program sampling design, were assessed in 2017. In a repeatability study 11 of these wetlands were assessed twice. The two assessments were carried out on the same day to reduce other sources of extraneous variance among the repeat assessments. The assessment teams, each comprising two members, worked independently. The teams had similar levels of experience with the wetland assessment tool.

Data from the 11 repeat-assessment wetlands were examined using various descriptive and statistical techniques to gauge the contributions of individual indicators to interoperator variability in the wetland assessment tool. The aim is to minimise this source of variability.

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Glossary

Aggregated wetland assessment scores: The wetland assessment method uses scores at three levels – *indicators* are aggregated into four *sub-indices* based on wetland environmental values (WEVs). The WEV sub-indices are aggregated into two *indices*, overall pressure and overall state. The aggregation methods average the scores of indictors to derive sub-index scores, which are in turn averaged to derive index scores.

Augmented serially alternating design: A monitoring design consisting of a number of panels of sites (wetlands), where one panel is assessed every year (the augmented section of the design) and the remaining panels are assessed in different years on a regular and repeating schedule.

Baseline: A baseline is the initial collection of data used for comparison with subsequently acquired data. In the case of the wetland condition monitoring component of the Reef Report, baseline data for the 2018 wetland results reported here were collected in 2015 and 2016 and reported in the Reef Water Quality Report Card 2016.

DPSIR framework: A causal framework for describing the interaction between society and the environment. Driver, Presssure, State, Impact, Response.

Interoperator variability: Interoperator variability is the amount of variability between the results obtained by two or more observers examining the same material.

Natural wetlands: Natural wetlands are areas that existed as wetlands before European settlement and that still meet the definition of wetlands (whether modified or not) in current state-wide wetland mapping.

Non-response bias: A non-response bias occurs when randomly selected subjects (wetland managers) choose not to be involved in a study (wetland assessment), not at random, but in ways that are meaningful to the phenomenon under study.

Panel: A panel is a group of wetlands with the same schedule of repeat assessments across years.

Power (to detect an change): In statistical testing, Power = $(1 - \beta)$, where β is the probability of making a Type II error, that is failing to detect an effect.

Pressure: Under the DPSIR framework, pressure refers to human activities directly affecting the environment.

Repeatability: The closeness of agreement between results of successive measurements of the same subject (wetland) carried out under the same conditions of measurement. See interoperator variability.

Spatially balanced random sample: A random sample whose sample sites are more or less evenly dispersed over the extent of the population being studied.

State: Under the DPSIR framework, characteristics, at a particular time, of ecosystem processes and the organisms and habitats that define, support and/or adversely affect ecosystem environmental values.

Wetland condition: Under the Great Barrier Reef Wetland Condition Monitoring Program, wetland condition refers to the pressure on wetlands' natural environmental values and the state of those values under a Driver, Pressure, State, Impact, Response (DPSIR) conceptual framework.

Wetland environmental values: Wetland environmental values are individual physical and biological characteristics associated with a particular wetland that provide its ecological, social and economic benefits and are sometimes referred to as ecosystem services. The Wetland Condition Monitoring Program assesses wetland environmental values (WEVs), defined as:

- biotic integrity – the biological health and diversity of the wetland's ecosystems
- local physical integrity – the wetland's natural physical state and integrity
- local hydrology – the wetland's natural hydrological cycle
- connectivity – the natural interaction of the wetland with other ecosystems including other wetlands.

CATCHMENT LOADS MONITORING METHODS

This report summarises the methods undertaken by the Catchment pollutant delivery – Catchment loads monitoring program that reports the catchment loads monitoring results required for the delivery of the Reef Water Quality Report Card 2017 and 2018. The Catchment loads monitoring program provides data to the Catchment loads modelling program to validate progress towards achieving the Reef 2050 Water Quality Improvement Plan, 2025 water quality targets.

The targets for water quality that will contribute to ecosystem health and social resilience and benefits are as follows (Australian and Queensland governments, 2018):

- 60% reduction in anthropogenic end-of-catchment dissolved inorganic nitrogen loads.
- 20% reduction in anthropogenic end-of-catchment particulate nutrient loads.
- 25% reduction in anthropogenic end-of-catchment fine sediments loads.
- Pesticide target: To protect at least 99% of aquatic species at the ends-of-catchments.

Monitoring sites

Catchment water quality is currently measured at more than 43 sites across 20 major catchments that discharge to the Great Barrier Reef lagoon (Figure 1) as part of an ongoing, long-term monitoring program. Water quality monitoring site numbers and locations vary slightly from year to year, due to various logistical, climatic and operational reasons, the current monitoring site numbers can be found on the Reef Plan website.

During the 2016-2017 monitoring year, a total of 34 sites were monitored. Twenty end-of-catchment sites and 14 sub-catchment sites across 17 major catchments were monitored for total suspended solids and nutrients. Pesticides were monitored at a sub-set of 17 end-of-catchment sites and two sub-catchment sites across 14 major catchments (pesticides were not monitored in the Olive Pascoe, Normanby and Barron catchments).

During the 2017–2018 monitoring year, a total of 57 sites were monitored across 30 major catchments, consisting of 22 end-of-catchment sites and 18 sub-catchment sites for total suspended solids and nutrients. Pesticides were monitored at a sub-set of 32 end-of-catchment sites and three nested sub-catchment sites (pesticides were not monitored in the Cape York region).

Monitoring sites are classified as either end-of-catchment or sub-catchment sites. The end-of-catchment monitoring sites are located at the lowest point in a river or creek, where the discharge can be accurately measured, typically where gauging stations have been established and are being maintained by the Queensland Department of Natural Resources, Mines and Energy. Sub-catchment sites are located at the lowest point in a sub-catchment (tributary), mainly at existing gauging stations. Water quality samples collected at each monitoring site provide data related to land management activities in the catchment area upstream of the site. Both site types provide field data that are used to calibrate and validate catchment models.

Monitoring currently captures an estimated 92% of the total suspended solid load and 88% of the dissolved inorganic nitrogen load discharged to the Great Barrier Reef lagoon and pesticides are monitored in all priority locations.

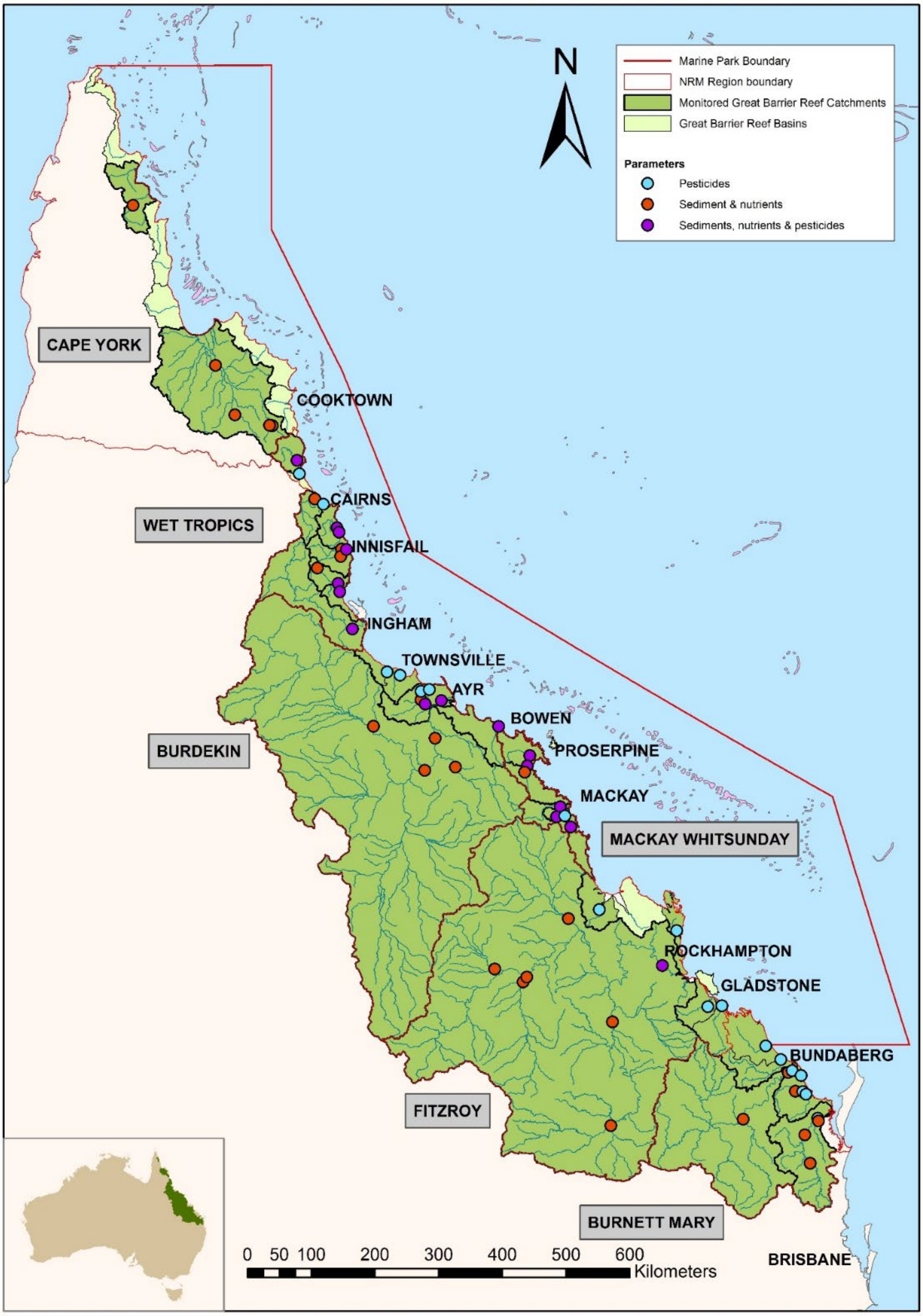

Figure 1. Map showing the location of catchment monitoring sites in the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program.

Rainfall data

Rainfall totals and rainfall decile data are currently obtained from the Bureau of Meteorology National Climate Centre. These data are synthesised using geographic information system tools to display total annual rainfall and annual rainfall deciles for Queensland during the period from 1 July to 30 June of each year (2016-2017 and 2017-2018). The total annual rainfall and annual rainfall deciles provide contextual information regarding the state of the climate during the reported monitoring year and is described in detail within the annual technical report.

Water quality sampling

Water samples are collected, stored, transported and quality assured and quality controlled in accordance with the Environmental Protection (Water) Policy Monitoring and Sampling Manual 2018 (www.ehp.qld.gov.au/water/monitoring/sampling-manual). Water quality samples are collected using two methods: manual grab sampling and automatic grab sampling using refrigerated pump samplers. Intensive sampling (daily or every few hours) is conducted during high flow events and monthly sampling is conducted during low or base-flow (ambient) conditions. For pesticides, intensive sampling (daily or every few hours) is similarly conducted during high flow events and weekly to monthly sampling is conducted during low or base-flow (ambient) conditions over the wet season. For the purpose of sampling pesticides, the standardised wet season (i.e. for assessing the main pesticide exposure period) commences with the first runoff event and continues for 182 days (6 months).

Where possible, total suspended solids, nutrients and pesticide samples were collected concurrently. Manual grab samples collected during low flow conditions, where sites are tidally influenced, were taken on the outgoing, low tide. Automatic grab samplers installed in tidal sites were activated during rainfall run-off events based on discharge measured with Horizontal Acoustic Doppler Current Profilers and conductivity and turbidity readings recorded *in situ*.

River discharge data

The volume of water flowing in the rivers is calculated using one of four methods, depending on the location and data availability:

- measured discharge from existing gauging station and extracted from Hydstra - the surface water database of the Department of Natural Resources, Mines and Energy (DNRME);
- 'time and flow factored' measured discharge from existing DNRME gauging station;
- modelled flows generated in the Source Catchments modelling platform using the Sacramento rainfall run-off model, where the Parameter Estimation Tool (PEST) was coupled with Source for the calibration process; or
- a combination of modelled flow and flow measured by Horizontal Acoustic Doppler Current Profiler.

The selected method for each site is reported annually in the technical report or ArcGIS dashboard.

Water quality sample analysis

The Science Division Chemistry Centre (Dutton Park, Queensland) analyses water samples for total suspended solids and nutrients (Table 1). The Queensland Health Forensic and Scientific Services Organics Laboratory (Coopers Plains, Queensland) analyses water samples for pesticides (Table 2). Both laboratories are accredited by the National Association of Testing Authorities for the analyses conducted.

Table 1. Summary information for each reported analyte in the catchment monitoring program.

Reported Pollutants	Abbreviation	Measured Analytes
Sediment (Total suspended solids)	TSS	Total suspended solids
Total nitrogen	TN	Total nitrogen as N
Particulate nitrogen	PN	Total nitrogen (suspended) as N
Dissolved organic nitrogen	DON	Organic nitrogen (dissolved) as N
Ammonium nitrogen as N	NH_4-N	Ammonium nitrogen as N
Oxidised nitrogen as N	NO_x-N	Oxidised nitrogen as N
Dissolved inorganic nitrogen	DIN	Ammonium nitrogen as N + Oxidised nitrogen as N
Total phosphorus	TP	Total phosphorus as P
Particulate phosphorus	PP	Total phosphorus (suspended) as P
Dissolved organic phosphorus	DOP	Organic phosphorus (dissolved) as P
Dissolved inorganic phosphorus	DIP	Phosphate phosphorus as P

Pesticide monitoring and reporting differs from nutrients and suspended solids due to the large range of pesticides used in agriculture and the variation in their use from one year to the next. For this reason, water samples are analysed for a general suite of pesticides. However, not all pesticides that are detected are reported each year. Other detected and non-detected pesticides will be reported via the pesticide exceedance dashboard. A sub-set of pesticides, referred to as the *reference pesticides*, are used to measure and model the progress towards the pesticide water quality target[1]. The reference pesticides (Table 2) have been selected based on the frequency of their detection in catchments, the availability of ecotoxicity data for individual pesticides, and their capacity to be modelled in Source Catchment models. The reference pesticides include herbicides and insecticides used in a range of agricultural land uses, including sugarcane, grazing, cropping and horticulture.

1 Note: The pesticide target encompasses all pesticides in GBR water bodies. All possible measures are taken to include as many pesticides in the metric to measure progress towards the target; however, measuring and modelling progress is reliant on other data (e.g. ecotoxicity and application data) not just concentration information, which is not available for all pesticides detected in catchments. For this reason, not all pesticides are included in the metric to measure progress towards the target. The number and types of pesticides included in the metric will expand over time as new data is collected.

Table 2. Pesticides included in pesticide risk metric. Not all of the listed pesticides were necessarily detected in collected water samples.

Reference pesticide	Pesticide type	Mode of Action
Chlorpyrifos	Insecticide	Acetylcholine esterase (AChE) inhibitor
Fipronil	Insecticide	Gamma-aminobutyric acid (GABA) gated chloride channel blocker
Imidacloprid	Insecticide	Nicotinic receptor agonist
Haloxyfop	Herbicide	Acetyl-coenzyme A carboxylase (ACCase) inhibitor
Imazapic	Herbicide	Acetolactate synthase (ALS) inhibitor
Metsulfuron-methyl	Herbicide	
Pendimethalin	Herbicide	Microtubule synthesis inhibitor
Metolachlor	Herbicide	Acetolactate synthase (ALS) inhibitor
Reference pesticide	**Pesticide type**	**Mode of Action**
Ametryn	Herbicide	PSII inhibitor
Atrazine	Herbicide	
Terbuthylazine	Herbicide	
Tebuthiuron	Herbicide	
Simazine	Herbicide	
Diuron	Herbicide	
Terbutryn	Herbicide	
Hexazinone	Herbicide	
Metribuzin	Herbicide	
2,4-D	Herbicide	Auxin mimic (Phenoxy-carboxylic acid auxins)
MCPA	Herbicide	
Fluroxypyr	Herbicide	Auxin mimic (Pyridine-carboxylic acid auxins)
Triclopyr	Herbicide	
Isoxaflutole	Herbicide	4-hydroxyphenylpyruvate dioxygenase (4-HPPD) inhibitor

Calculating nutrient and sediment loads

The suitability of the generated water quality monitoring data for use in load calculations was assessed using a sample representivity rating. The annual rating of sampling representivity was assessed against two criteria:

1. the number of samples collected in the top five per cent of annual monitored flow
2. the ratio between the highest flow rate at which a water sample was collected and the maximum flow rate recorded.

The representivity was determined for each monitoring year by assigning a score using the system presented in Table 3.

Table 2. Scores assigned to total suspended solids and nutrients data to determine their representivity.

Number of samples in top 5 per cent of flow	Score	Ratio of highest flow sampled to maximum flow recorded	Score
0 – 9	1	0.00 – 0.19	1
10 – 19	2	0.20 – 0.39	2
20 – 29	3	0.40 – 0.59	3
30 – 39	4	0.60 – 0.79	4
>40	5	>0.80	5

The rating of sample representivity for each analyte was the sum of the scores for the two criteria. Sample representivity for each analyte was rated as 'excellent' when the total score was greater than or equal to eight, 'good' when the total score was six or seven, 'moderate' for total scores of four or five or 'indicative' when the score was less than four. Furthermore, hydrographs were visually assessed to verify the representivity rating.

For nutrients and sediment, the concentration and flow data are used to determine the total load of each pollutant that is transported past the monitoring site in each catchment and sub-catchment. Annual and daily loads are calculated for total suspended solids and the nutrient analytes listed in Table 1, for the catchments and sub-catchments listed in Table 4, using the Loads Tool component of the software Water Quality Analyser 2.1.2.6 (eWater 2012). The total suspended solids and nutrient loads were calculated using concentrations reported in milligrams per litre (mg L^{-1}).

One of two methods was used to calculate loads: the average load (linear interpolation of concentration) or the Beale ratio. Average load (linear interpolation of concentration) is the most accurate and reliable method, provided events are adequately sampled, with a representivity rating of excellent. For complex events or events with a representivity rating of good, moderate and indicative, the Beale ratio is one of the recommended methods (Joo et al. 2012).

Calculating the Pesticide Risk Metric

The Pesticide Risk Metric estimates the percentage of species protected (reciprocal of percentage of species affected) by mixtures of pesticides detected during a standardised wet season of 182 days. The wet season was determined to be the only period of time when there was a significant risk of pesticide run-off. This metric, calculated from the monitored concentration data for the 22 reference pesticides, was used to estimate the percentage of species protected in each monitored catchment, which is also used to validate the Source Catchment modelled estimates of progress, from the Pesticide Risk Baseline[2], towards the end of catchment target. Note that modelled estimates of progress towards the pesticide target will be reported in future years.

In order to express the concentration data for all 22 reference pesticides as a single number that represents the overall risk to aquatic ecosystems, it was necessary to convert all the

2 The Pesticide Risk Baseline was generated using a suite of models that can predict the pesticide mixture toxicity from monitored sites to the whole catchment, region and GBR scales. The Baseline was developed using Catchment loads monitoring program data collected from monitoring sites across Queensland from 2015 to 2018. The model build, compared the monitored pesticide trends to spatial, climate and landuse characteristics at those sites. The Pesticide Risk Baseline then used the relationships developed to predict the current estimate of percent species protected from mixtures of 22 reference pesticides observed in major catchments discharging to the GBR (Warne et al. 2019).

pesticide concentration data into a term that represented the toxicity of the mixture of pesticides in each water sample. This was achieved using the multi-substance potentially affected fraction (ms-PAF) approach (Traas et al. 2002).

The 22 reference pesticides have multiple different modes of action (Table 2). The toxicity of pesticides with different modes of action was calculated using the independent action model of joint action (Plackett and Hewlett 1952) within the multiple-substance-potentially affected fraction (ms-PAF) method. Further details on how the pesticide risk metric calculations were made are provided in Warne et al. (2019). The pesticide mixture toxicity was calculated for all samples collected over the wet season. Where there was more than one sample per day a daily mean concentration was calculated.

The mixture toxicity data (i.e. ms-PAF values) for all water samples collected over the wet season were then summarised as a single value. In order to do this, it was necessary to estimate the daily average ms-PAF for days that weren't monitored during the wet season using a multiple imputation technique (Rubin 1996; Donders et al. 2006; Patrician 2002). This involved fitting a statistical distribution to the observed data for the wet season for the site. This distribution was then used to impute values to fill in the missing days in the 182-day period. The resultant 182 days of data were then divided by 182 to obtain the Pesticide Risk Metric and ranked into five risk categories (Table 4). These categories are consistent with the ecological condition categories used in the Australian and New Zealand Water Quality Guidelines for Fresh and Marine Waters.

Calculating the contribution of pesticide sub-categories

The Pesticide Risk Metric method was used to obtain Pesticide Risk Metric values for four groups of pesticides - total pesticides, insecticides, PSII herbicides and non-PSII herbicides.

Table 4. Risk categories used to assess pesticide risk

Pesticide Risk Metric value		Risk Category	Ecological Condition (ANZWQG)
% species affected	% species protected		
≤1%	≥99%	Very low	High Ecological Value
>1 to <5%	>95 to <99%	Low	Slightly to Moderately Disturbed
5 to <10%	>90 to 95%	Moderate	Highly Disturbed
10 to <20%	>80 to 90%	High	
≥20%	≤80%	Very high	

Assessing progress towards the targets

The water quality targets for sediment and nutrients are based on annual average end of catchment load reductions and the pesticide target is based on the percent of species being protected - the progress of which is assessed through the Source Catchments model. This model is validated by the results of the catchment monitoring.

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PESTICIDE RISK BASELINE METHODS

This report summarises the methods used to estimate the pesticide risk baseline in the 35 major catchments and six natural resource management regions of the Great Barrier Reef. The pesticide risk baseline is required to assess progress towards meeting the Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP) 2025 water quality target for pesticides. Note that progress made towards meeting the pesticide target through improved land management practices will be reported in the Reef Water Quality Report Card 2019 to be released in 2020.

The water quality target for pesticides has changed from a loads-based target to a risk-based target that is:

- to protect at least 99% of aquatic species at the end-of-catchments (Australian Government and Queensland Government, 2018)

As a result of the change in the pesticide target and the methodology used to measure progress to the target, the results in the Reef Water Quality Report Card 2017 and 2018 will not be comparable with previous report cards[1].

Overview of the methods

We set a new baseline for pesticides based on monitoring data collected from 2015 – 2018. Progress to meeting the new pesticide target will be modelled and reported in future report cards from this baseline. The method to calculate the pesticide risk baseline is a newly developed method and as such, a detailed explanation of its development and validation is provided in the Pesticide Risk Baseline Tier 3 Report (Warne et al. in prep). A summary of the methods used to generate the pesticide risk baselines reported in the Pesticide Risk Basline Results report and the Reef Water Quality Report Card 2017 and 2018 is stated below.

The method to calculate the pesticide risk baselines for all GBR catchments and natural resource management regions relies on a combination of monitoring data with modelling to calculate a 'per cent of species protected' to all areas including those that are not routinely monitored. The 22 pesticides[2] that were included in the calculation of the Pesticide Risk Baseline (Warne et al. in prep) are herbicides and insecticides presented in Table 1– no fungicides were included. To assess which pesticides were having the greatest contribution to the total pesticide risk, the 22 pesticides were divided into three groups; (i) photosystem II (PSII) inhibiting herbicides, (ii) other herbicides (i.e. non-PSII herbicides), and (iii) insecticides.

The Catchment loads monitoring program (e.g. Huggins et al., 2017) collects monitoring data on pesticides for a portion of catchments (i.e. the monitored portion of a catchment that is upstream of the monitoring site), regions and the total Great Barrier Reef catchment area; i.e. 38 out of ~970 waterways that discharge to the Great Barrer Reef. As such, predictive relationships were required to estimate the pesticide risk for the whole of (major) catchment, region and Great Barrier Reef scales. The monitoring data are a reflection of the

[1] The previous pesticide target was a load reduction target (similar to the nutrient and sediment targets). Measuring progress towards that target involved modelling the annual loads of five photosystem II inhibiting herbicides discharging to the Great Barrier Reef.

[2] The 22 pesticides were selected based on how frequently they were detected in the monitored catchments, the availability of ecotoxicity data, and the ability to be modelled in Source Catchment models. For details refer to Warne et al. in prep).

concentrations and types of pesticides that result from the catchment-specific land and hydrological conditions upstream of the monitoring site. Using the relationships between the land-use, spatial and hydrological variables in a catchment and the pesticide monitoring data, we can predict what the pesticide risk would be for areas that aren't monitored, based on their specific land and hydrological conditions.

Table 1. The 22 pesticides that were included in the pesticide risk baseline. Pesticides are grouped according to their type; (PSII) indicates photosystem II inhibiting herbicides, (OH) indicates 'other' herbicides (i.e. non-PSII herbicides), and (I) indicates insecticides.

2,4-D (OH)	Ametryn (PSII)	Atrazine (PSII)
Chlorpyrifos (I)	Diuron (PSII)	Fipronil (I)
Fluroxypyr (OH)	Haloxyfop (OH)	Hexazinone (PSII)
Imazapic (OH)	Imidacloprid (I)	Isoxaflutole (OH)
MCPA (OH)	Metribuzin (PSII)	Metolachlor (OH)
Metsulfuron-methyl (OH)	Pendimethalin (OH)	Prometryn (PSII)
Simazine (PSII)	Tebuthiuron (PSII)	Terbuthyalzine (PSII)
Triclopyr (OH)		

The process of deriving the pesticide risk baseline for the whole-of-catchment, region and Great Barrier Reef scales, involves a number of key steps. The main types of data, the steps involved and the order in which the steps were conducted are presented in Figure 1. In summary:

1. aqueous pesticide concentration data was collected by the Great Barrier Reef Catchment loads monitoring program for 38 catchments or sub-catchments (Step 1, Figure 1).

2. the measured risk of pesticide mixtures (termed the pesticide risk from here on) to aquatic species at each monitoring site was then determined from the concentration data using the pesticide risk metric (Step 2, Figure 1). The risk is expressed as the average per cent of species affected during the wet season of 182 days for each of the monitored catchments (Step 3, Figure 1).

3. land-use and site-specific spatial and hydrological variables were calculated or collected for each catchment (Step 4, Figure 1)

4. the pesticide risk and catchment variables for all the monitored catchments were regressed against each other to develop predictive pesticide risk and catchment variable relationships (Step 5, Figure 1)

5. the pesticide risk and catchment variable relationships were used to predict the pesticide risk for each catchment (Step 6, Figure 1). The validity of relationships was tested by comparing the predicted pesticide risk with the pesticide risk measured at catchments not used to derive the relationships

6. the same land-use and site-specific spatial and hydrological variables were calculated for the 35 major catchments (Step 7, Figure 1), and the relationships were scaled-up and used (Step 8, Figure 1) to predict the pesticide risk for 35 major catchments (Step 9, Figure 1)

7. the same land-use and site-specific spatial and hydrological variables were then calculated for the natural resource management regions and the Great Barrier Reef catchment area and the relationships used (Step 10, Figure 1) to predict the pesticide risk for the six natural resource management regions and the Great Barrier Reef (Step 11, Figure 1)

8. the pesticide risk values, expressed as per cent of species affected, were converted to the per cent of species protected (per cent species protected = 100 minus per cent affected) and these form the pesticide risk baseline

9. this process was undertaken for 'total pesticides', i.e. all 22 pesticides together. Steps 2-6 were then repeated for the three pesticide groups; i.e. PSII herbicides, other herbicides and insecticides.

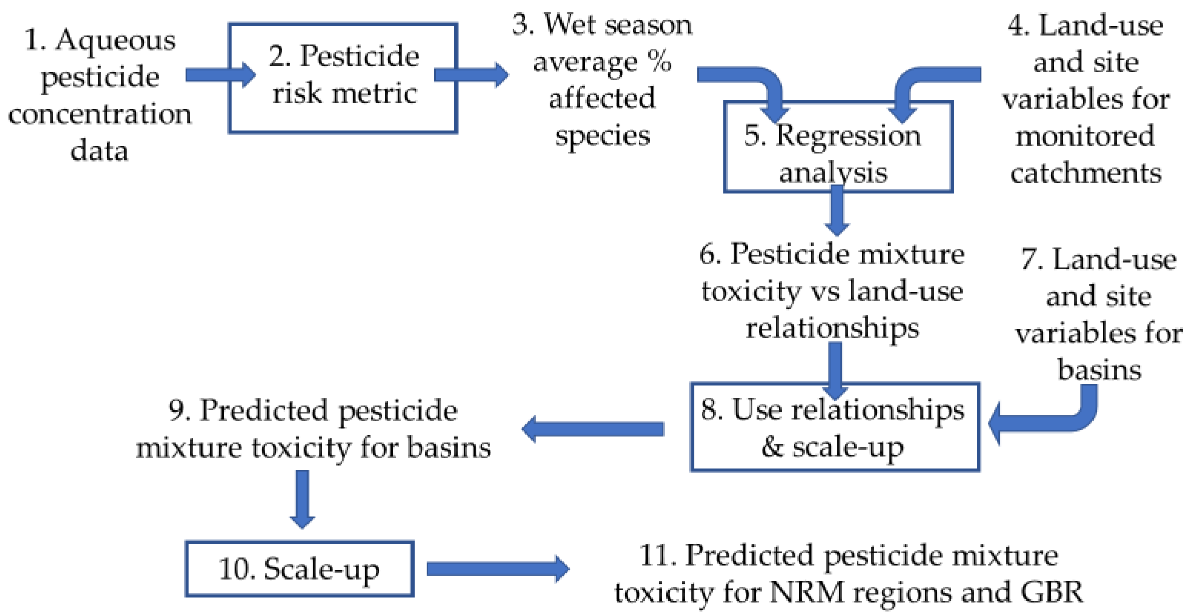


Figure 1. Schematic of the process of calculating the pesticide risk baseline at three different spatial scales: whole of catchment, region and Great Barrier Reef scales.

Constraints and assumptions in the pesticide risk baseline

In order to be transparent, the assumptions and constraints that were made in developing the pesticide risk baseline are presented below. The available information strongly indicates that the vast majority of the assumptions are valid and for the others the assumptions are reasonable. The assumptions of the project were:

- the measured pesticide concentrations collected through grab sampling are representative of the vertical and horizontal variation of pesticide concentrations in the water of the monitored catchments
- the quality assurance and quality control procedures implemented by the Catchment loads monitoring program are appropriate

- the measured pesticide concentrations are the dissolved and bioavailable concentration or a reasonable surrogate of the bioavailable concentration
- the sampling design (when monitoring is triggered, the frequency and duration of sampling) provides pesticide concentrations that are representative of the wet season
- the hydrological explanatory variables used in the relationships to predict pesticide risk, which are site specific, are representative of the catchment
- that land use will determine the pesticides detected in the monitored waterways, their concentation and combined toxicity
- the use of the independent action model, as described in the section pesticide risk metric, to estimate mixture toxicity is appropriate for the 22 selected pesticides
- the 68 unique combinations of site and year for which there are pesticide concentration data available are sufficient to develop high quality relationships to predict pesticide risk
- the dominance of pesticide data from 2017-2018 does not bias the pesticide risk baseline.

The constraints of the project were:

- pesticide data for the three most recent years (2015-2016, 2016-2017 and 2017-2018) were used in order to reflect current conditions but this meant that many sites only had one year of pesticide concentration data (see Table 2)
- there is no pesticide monitoring data available for any waterways in the Cape York region to use in developing or validating the relationships to predict pesticide risk (Table 2)
- the predictive relationships were independently derived for PSII herbicides, other herbicides, insecticides and total pesticides. Therefore the sum of the predicted pesticide risk values for PSII herbicides, other herbicides and insecticides will not necessarily equal the predicted total pesticide risk values. Therefore the predictive relationships for PSII herbicides, other herbicides and insecticides were only used to estimate the relative contribution of these groups of pesticides to the pesticide risk
- the data used was the best available at the time
- in order to protect freshwater, estuarine and marine organisms, ecotoxicity data for fresh and marine species were combined
- a risk based method (multiple-substance potentially affected fraction method) was used to be consistent with the Reef 2050 WQIP pesticide target and the Australian and New Zealand Guidelines for Fresh and Marine Water Quality for toxicants <www.waterquality.gov.au/anz-guidelines/guideline-values/default/water-quality-toxicants>.

Pesticide concentration data

Aquatic pesticide concentration data for 2015-2016, 2016-2017 and 2017-2018 were obtained from the Catchment loads monitoring program. This program monitors 35 waterways, including catchments and sub-catchments, for the 22 pesticides listed in Table 1. Not all sites were sampled for pesticides for all three years (Table 2). All pesticide analyses were conducted by the Queensland Health Forensic and Scientific Services Organics Laboratory (Coopers Plains, Queensland), which is accredited for these analyses by the National Association of Testing Authorities. Pesticides were extracted from the water samples using solid phase extraction and then identified and quantified using liquid chromatography-mass spectrometry. The quality assurance and quality control procedures implemented by the Catchment loads monitoring program to determine the accuracy of pesticide concentrations (Huggins et al., 2017) were adopted.

Table 2. The waterways monitored for pesticides and used to derive the Pesticide Risk Baseline and the years for which pesticide data were available (indicated by an X). S-C indicates a site at a sub-catchment. No waterways in the Cape York region were monitored for pesticides.

Waterway	NRM Region	2015 – 2016	2016 – 2017	2017 – 2018
Baffle Creek	Burnett Mary	-	-	X
Barratta Creek	Burdekin	X	X	X
Barron River	Wet Tropics	-	-	X
Black River	Burdekin	-	-	X
Boyne River	Fitzroy	-	-	X
Burdekin River	Burdekin	X	X	X
Burnett River at Ben Anderson Barrage (S-C)	Burnett Mary	X	X	-
Burnett River at Quay St. Bridge	Burnett Mary	-	-	X
Burrum River	Burnett Mary	-	-	X
Calliope River	Fitzroy	-	-	X
Comet River (S-C)	Fitzroy	X	X	X
East Barratta Creek	Burdekin	-	-	X
Elliot River	Burnett Mary	-	-	X
Fitzroy River	Fitzroy	X	X	X
Gregory River	Burnett Mary	-	-	X
Haughton River at Powerline (S-C)	Burdekin	X	X	-
Haughton River at Giru weir	Burdekin	-	-	X
Herbert River	Wet Tropics	X	X	X
Johnstone River	Wet Tropics	X	X	X
Kolan River	Burnett Mary	-	-	X
Mary River at Homepark (S-C)	Burnett Mary	X	X	-
Mary River at Churchill St.	Burnett Mary	-	-	X
Mossman River	Wet Tropics	-	-	X
Mulgrave River (S-C)	Wet Tropics	X	X	X
North Johnstone River (S-C)	Wet Tropics	X	X	X

O'Connell River at Staffords Crossing (S-C)	Mackay Whitsunday	-		X
O'Connell at Caravan Park	Mackay Whitsunday	X	X	X
Pioneer River	Mackay Whitsunday	X	X	X
Proserpine River	Mackay Whitsunday	-		X
Russell River (S-C)	Wet Tropics	X	X	X
Sandy Creek	Mackay Whitsunday	X	X	X
Styx River	Fitzroy	-	-	X
Tinana Creek (S-C)	Burnett Mary	-	X	X
Tully River	Wet Tropics	X	X	X
Waterpark Creek	Fitzroy	-	-	X

Pesticide risk metric

The pesticide risk metric is a combination of three published methods (Figure 2). These are:

i. the **multiple-substance potentially affected fraction (ms-PAF)** method (Traas et al., 2002), which was used to convert the pesticide concentration data to per cent of aquatic species affected

ii. the **independent action model** of joint action (Bliss, 1939, Plackett and Hewlett, 1952), which was used to combine the per cent of species affected by multiple pesticides into one value representing the risk of the mixture of pesticides.

iii. and a **multiple Imputation method** (Donders et al., 2006), was used to estimate the pesticide risk for days without pesticide monitoring data and to determine the average per cent of species affected over the wet season.

The metric calculates the risk posed by mixtures of 22 selected pesticides and expresses it as the per cent of species affected for each water sample and then finally as the average per cent of species that should be affected during the wet season (a standardised 182 day period). Exposure was estimated during the wet season as this is when the majority of the rain falls and pesticides are transported to waterways and aquatic organisms are exposed. To determine the pesticide risk baseline and to report against the target, the per cent of species affected is converted to the per cent of species protected (i.e. per cent species protected = 100 minus per cent species affected).

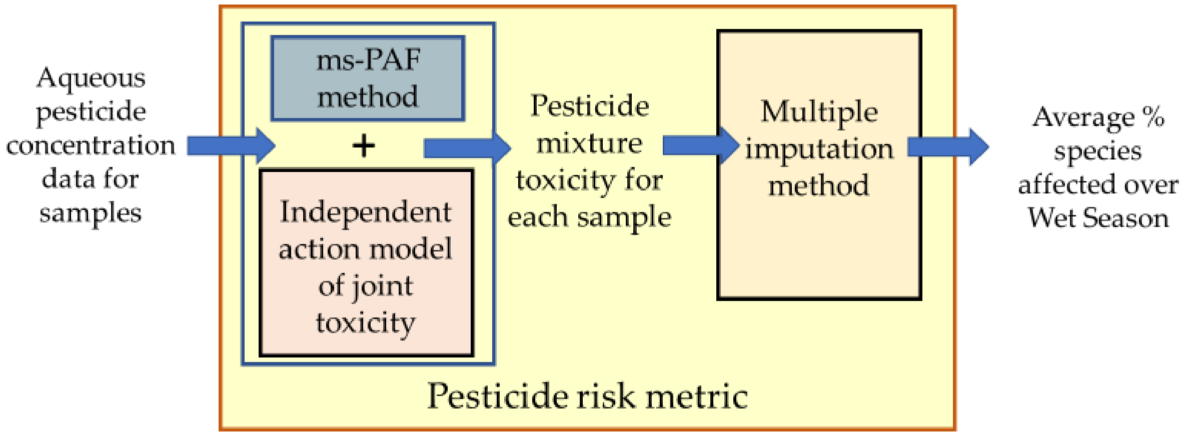


Figure 2. Schematic of the components of the pesticide risk metric that is used to estimate the pesticide risk of individual samples and all samples combined from a monitored catchment.

The multiple-substance potentially affected fraction (ms-PAF) method was selected because it can estimate the toxicity of mixtures of chemicals and express this as the per cent of species affected or protected, which is consistant with the Australian and New Zealand Guidelines for Fresh and Marine Water Quality.

The pesticide reduction target (Australian and Queensland governments, 2018) applies at the mouth of catchments that discharge to the Great Barrier Reef and as such it needs to protect estuarine and marine species. Toxicity data for both fresh and marine species were therefore combined to estimate the pesticide risk, expressed as the per cent of species that should be affected when exposed to the selected pesticides. The per cent of species affected by an individual pesticide is estimated from its species sensitivity distribution, which is a representation of the varying sensitivities of aquatic species to the toxicity of a pesticide (Traas et al., 2002). The process uses statistical probability to estimate the per cent of species in an ecosystem likely to be affected by a given concentration of a pesticide. The toxicity data used to generate the species sensitivity distributions were obtained from a series of proposed default guideline values[3] (King et al., 2017) that have been generated as part of the current revision of the Australian and New Zealand Guidelines for Fresh and Marine Water Quality <www.waterquality.gov.au/anz-guidelines/>. The species sensitivity distributions were generated using the nationally endorsed method for deriving species sensitivity distributions and default guideline values (Warne et al., 2018).

The independent action model was selected as the most appropriate model for determining the toxicity of mixtures of the selected pesticides (for details refer to Warne et al., in prep) as it provided closer estimates of the per cent of species affected compared to water quality guideline values for individual pesticides. In addition it permits the contribution of individual pesticides to the pesticide risk to be determined.

The pesticide risk metric calculates the per cent of species affected for each water sample. But for reporting in the Reef Water Quality Report Card 2017 and 2018 a single number is required to express the pesticide risk and it was determined that the baseline would be based on the average per cent of species protected over the wet season. There is not pesticide monitoring data at any site for each day of the wet season. Therefore, a multiple imputation method was adopted as it is a well-accepted method for dealing with missing data (Rubin,

[3] Default guideline values is the new term for the limits set in the Australian and New Zealand Guidelines for Fresh and Marine Water Quality. This term replaced the term trigger values.

1996, Patrician, 2002; Donders et al., 2006,) that is widely used in the fields of statistics, epidemiology and social and political sciences. Multiple imputation methods fit a distribution to the existing data and then use re-sampling techniques to calculate estimates for the days missing data. Then the average per cent of species affected during the wet season was calculated for the pesticide data for each site and year (Table 2).

The pesticide risk was calculated for all 22 selected pesticides – termed the total pesticide risk. The pesticide risk was also separately calculated for the PSII herbicicdes, for other herbicides and for insecticides.

Developing relationships to predict pesticide risk at the whole of catchment, region and Great Barrier Reef scales

Relationships were developed between pesticide risk and land-use, spatial and hydrological variables. The pesticide risk data for this was generated as described in the section pesticide risk metric. The land-use, spatial and hydrological variables used to develop the relationships and how they were obtained is stated below. Relationships were developed separately for all pesticides, PSII herbicides, other herbicides and insecticides.

Land-use and site-specific spatial and hydrological variables

All the variables used to develop the relationships are presented in Table 3.

Spatial Variables

Latitude and longitude of the monitoring sites were obtained as well as the adopted middle thread distance, monitored surface area of each catchment expressed as a percentage of the all catchments that discharge to the Great Barrier Reef, and the natural resource management region in which each site was located.

Upstream catchment boundaries (shapefiles) were generated using topographical maps, watercourses, 1m contours and imagery from the SIR Geoportal then checked against local knowledge supplied by clients or subject matter experts. Shapefiles for the 35 major catchments were supplied by the Soil and Land Resources Unit within the Queensland Department of Environment and Science. These were the same as those developed for the Great Barrier Reef Source Catchment model (Australian and Queensland governments, 2019).

The natural resources management region boundary shapefiles were sourced from QSpatial <http://qldspatial.information.qld.gov.au/> and are consistent with those used in the Reef 2050 WQIP.

The surface area of each natural resource management region was extracted using the calculate geometry tool in ArcGIS Pro <www.esri.com/en-us/arcgis/products/arcgis-pro>, then summed to provide an area for all six natural resource management regions. The size of each monitored catchment relative to that the entire Great Barrier Reef catchment area was then determined by dividing each monitored catchment surface area by the summed area of all six natural resource management regions. This provided the explanatory variable relative monitored catchment size (m^2) for each of the sample sites.

Adopted middle thread distance is the length of a waterway, in kilometres, measured along the middle of the deepest section of a watercourse from the sample site to the river mouth. The adopted middle thread distance was included in the development of the pesticide risk versus land-use relationships to see if distance of the site from the river mouth affected pesticide risk. Most adopted middle thread distance data was extracted from the Queensland Department of Natural Resources, Mines and Energy Stream Gauging Station Index 2014 <https://water-monitoring.information.qld.gov.au>. Adopted middle thread distance was calculated by hand for sites that had no entry in the Gauging Station Index using a combination of ArcGIS Pro and Google Earth.

Land use variables

Land use types were grouped into thirteen categories that align with those used in the Great Barrier Reef Source Catchment model (i.e., bananas, conservation, dryland cropping, forestry, forested grazing, open grazing, horticulture, irrigated crops, sugarcane, urban, water, wetlands and other). Land-use was expressed as a per cent of total monitored catchment surface area.

The most recent Queensland Land Use Mapping Program dataset was extracted from QSpatial <www.qld.gov.au/environment/land/management/mapping/statewide-monitoring/qlump>.

Hydrological variables

Hydrological variables were included to capture the influence of precipitation, soil moisture and run-off on pesticide risk values. These included: average rainfall; maximum rainfall; total rainfall; average soil moisture; total soil moisture; maximum soil moisture; maximum and average relative run-off expressed as a percentage of the long-term average run-off; and maximum and average rainfall expressed as a percentage of the long-term average rainfall. These data were obtained from the Bureau of Meteorology (Frost et al., 2018).

Table 3. The spatial, land-use and hydrological variables used to derive the relationships to predict pesticide risk.

Spatial variables	Land-use variables (% of total monitored catchment surface area)	Hydrological variables
Natural resource management region	Banana	Average rainfall
Major catchment	Conservation	Average % rainfall
Catchment	Dryland Cropping	Maximum rainfall
Latitude	Forestry	Maximum % rainfall
Longitude	Grazing Forested	Total rainfall
AMTD[1]	Grazing Open	Average soil moisture
Monitored catchment surface area	Horticulture	Total soil moisture
	Irrigated Cropping	Maximum soil moisture
	Sugar	Average % runoff
	Urban	Maximum % runoff
	Water	
	Wetland	
	Other	

[1] Adopted middle thread distance

Statistical methods

There were 68 sets of pesticide risk, land-use, spatial and hydrological data for unique site and year combinations. These data were randomly allocated, on a 80:20 basis, to a training set and a validation set. The data in the training set were used to derive the relationships. The data in validation set were used to test how accurately the best relationships were able to predict the pesticide risk at other sites/year combinations.

Forward and backward step-wise regression was used to develop relationships between pesticide risk and land-use, spatial and hydrological variables from the training set.

Determining the best relationships

The best relationship for each of the following: all pesticides; PSII herbicides; other herbicides; and insecticides was determined based on the following:

- how well the statistical assumptions of regression analysis were met (indicated by the diagnostic figures)
- the quality of the fit of the relationships to the pesticide risk data in the training set (indicated by the adjusted coefficient of determination (R^2) values)
- how well the values predicted by the relationships agreed with the measured values for the sites in the validation set
- whether the predicted total pesticide risk values for whole-of-catchment, region and Great Barrier Reef scales were reasonable given the land-use and measured pesticide mixture toxicity values of the monitored catchments.

The variables used in the best relationships for each group of pesticides are presented in Table 4. The selected relationships were able to explain between 68% and 79% of the variation in pesticide risk values for all pesticides, PSII herbicides, other herbicides and insecticides.

Table 4. The predictive variables used to generate the pesticide risk baseline (total pesticides) and the contribution of the grouped pesticide types (PSII herbicides, other herbcides and insecticides) to the pesticide risk (per cent species affected).

Pesticide group	Predictive variables
Total pesticides (pesticide risk baseline)	Per cent dryland cropping, sugar cane, conservation, horticulture and urban
PSII herbicides	Adopted Middle Thread Distance and per cent conservation, horticulture, irrigated cropping and sugar cane
Other herbicides	Per cent urban, conservation, horticulture, dryland cropping and sugar cane
Insecticides	Average rainfall and per cent forestry, water, grazing forested, horticulture and sugar cane

Using the relationships to predict pesticide risk for whole-of-catchment, region and the Great Barrier Reef scales

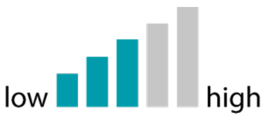
The relationships developed above between pesticide risk and land-use, spatial and hydrological variables were for monitored catchments. Appropriate land-use and site-specific spatial and hydrological variable values for the major catchments, regions and the Great Barrier Reef catchment area were then substituted into the best pesticide risk relationships to predict the pesticide risk at the whole-of-catchment, region and Great Barrier Reef scales.

For more detail on all aspects of the methods used to derive the pesticide risk baseline refer to the pesticide risk baseline Tier 3 Report (Warne et al., in prep).

Qualitative confidence rankings Pesticide Risk Baseline

A multi-criteria analysis was used to qualitatively score the confidence in each indicator used in the Reef Water Quality Report Card 2017 and 2018 from low to high. The approach combined expert opinion and direct measures of error for program components where available.

The methods used to calculate the pesticide risk baseline for measuring progress towards the pesticide target received a three-bar confidence ranking. The rationale for this confidence ranking is provided below.



Rationale for the Confidence Ranking

Maturity of methods

A score of one was awarded because not all individual methods used have been reviewed, the combination of methods used have not been reviewed, and the relationships used to predict pesticide risk have not been reviewed.

Validation

A score of two was awarded because the land use, spatial and hydrologic variables for predicting the pesticide risk (per cent of species affected), the pesticide monitoring (concentration) data, and the relationships used to predict pesticide risk were validated, but there is no validation of the per cent of species protected at the end of catchments.

Representativeness

A score of three was awarded because in 28 of the 35 basins that discharge to the Great Barrier Reef at least one catchment was monitored for pesticides. The seven basins without any pesticide monitoring are in Cape York, which should have a very low risk from pesticides (based on land use statistics).

Directness

A score of two was awarded because the assessment uses a mix of quantified assessments (i.e. catchment monitoring data, laboratory-based ecotoxicology data, remotely sensed land-use and spatial data, and modelled hydrological data) however, the per cent of species protected at the end of catchments is not directly measured.

Measurement error

A score of one was awarded because the error in the multiple data sources used and the multiple steps in the methodology is not able to be quantified at this point in time.

GLOSSARY

Adopted middle thread distance (AMTD): The distance between a monitoring site and the mouth of the waterway measured along the deepest part of the channel.

Australian and New Zealand Guidelines for Fresh and Marine Water Quality: The numerical and descriptive limits for pollutants and physico-chemical properties of water that are used in Australian and New Zealand to manage the quality of water for various purposes.

Bioavailable concentration: The concentration of a pollutant that is available (i.e., can be absorbed or cause harmful effects) to organisms. The bioavailable concentration is usually less than the total concentration or even the dissolved concentration. Bioavailability of a chemical is controlled by a variety of factors.

Catchment: The natural drainage area upstream of a point that is generally on the coast. It generally refers to the 'hydrological' boundary. There may be multiple catchments in a basin. Great Barrier Reef catchments are any terrestrial areas that drain into the Great Barrier Reef World Heritage Area.

Herbicides: A type of pesticide (see below) that specifically kill or inhibit plants. Herbicides usually inhibit a specific biochemical pathway that only occurs in plants and thus are far more toxic to plants than other organisms.

Insecticides: A type of pesticide (see below) that specifically kill or inhibit insects. Insecticides usually inhibit a specific biochemical pathway that only occurs in insects and thus are far more toxic to insects than other organisms. Insects are closely related to arthropods (e.g. crabs, prawns, lobsters) and these types of organisms are also affected by insecticides.

Independent action: A model for predicting the toxicity of mixtures of pollutants that do not interact but exert their toxicity in different ways (i.e. they have different modes of action).

Multi-substance Potentially Affected Fraction (msPAF): A method allows for the estimation of the effect of multiple pollutants on an ecosystem (originally described by Traas et al., 2002). Species sensitivity distributions form the basis of the method, similar to what is used to generate the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC and ARMCANZ, 2000; ANZG, 2019) for ecosystem protection. The msPAF risk metric estimates the fraction of species affected by the temporal exposure to mixtures of pesticides during the principal exposure period (i.e. the wet season).

Major catchment: There are 35 major catchments that drain into the Great Barrier Reef. A major catchment (basin) can be made up of a single or multiple river catchments (e.g. North and South Johnstone river catchments belong to one major catchment, the Johnstone catchment). Major catchments are primarily used here when discussing the relative delivery of a pollutant to the marine system.

Monitored catchment: The catchment area upstream of the monitoring site. Generally does not include the whole of catchment as the monitoring site is situated upstream of the mouth of the catchment.

Multiple imputation method: A statistical method used to estimate values from datasets that are missing. It does this based on the distribution of the data that is present.

Natural Resource Management (NRM) region: There are six natural resource management regions covering the Great Barrier Reef catchments. Each region groups and represents catchments with similar climate and bioregional setting, with boundaries extending into the adjacent marine area. The regions are Cape York, Wet Tropics, Burdekin, Mackay Whitsunday, Fitzroy and Burnett Mary.

Other herbicides: In this report this term refers to all herbicides included in the Pesticide Risk Baseline project that were not PSII herbicides.

Per cent land use: The surface area of land used for a particular purpose (e.g. conservation, forested grazing, horticulture) expressed as a per cent of the surface area of a catchment, region or the entire Great Barrier Reef catchment area.

Pesticides: Pesticides, including herbicides, insecticides and fungicides, are used for protecting agriculture against pest organisms (e.g. weeds and insects). Pesticides have been detected in sediments and waters of rivers, creeks, wetlands, estuaries, and the inshore parts of the Great Barrier Reef lagoon. The types and concentrations of pesticides in the fresh, estuarine and marine ecosystems vary between catchments and regions, reflecting the main land-use in each area.

Pesticide risk: The risk posed by mixtures of pesticides and expressed as the per cent of species likely to be adversely affected (i.e. per cent affected species). The pesticide risk was calculated for all 22 selected pesticides (the total pesticide risk), for the PSII herbicides, other herbicides and insecticides.

Pesticide risk baseline: The estimate of the per cent of species that were protected at the mouth of catchments that discharge to the Great Barrier Reef between 2015 and 2018. The per cent of species protected is calculated as 100 per cent minus the per cent of species affected.

Pesticide risk metric: This is the method used to calculate the toxicity of mixtures of the 22 selected pesticides that occur in waterways during the wet season (see glossary). The pesticide risk metric is a combination of a number of different methods: the multi-substance potentially affected fraction method, the independent action model and a multiple imputation method.

Photosystem II inhibiting herbicides (PSII herbicides): PSII herbicides bind to and block a specific binding site that is part of the photosystem II component of photosynthesis. Examples of PSII herbicides include atrazine, diuron, simazine and tebuthiuron.

Quality assurance and quality control: Processes used to ensure all aspects of a project are accurate and reliable and that the results and conclusions can therefore be trusted.

Reef 2050 Long-Term Sustainability Plan: The Reef 2050 Long-Term Sustainability Plan, or Reef 2050 Plan, is a joint commitment of the Australian and Queensland governments (released in March 2015) and is the overarching framework for protecting and managing the Great Barrier Reef. It defines actions, targets, objectives and outcomes to drive and guide the short, medium and long-term management of the Great Barrier Reef. The Reef 2050 Water Quality Improvement Plan (see below) aligns with and is nested within the Reef 2050 Plan.

Reef 2050 Water Quality Improvement Plan: The Reef 2050 Water Quality Improvement Plan 2017-2022 (Reef 2050 WQIP) is a joint commitment of the Australian and Queensland governments that seeks to improve the quality of water flowing from the catchments adjacent to the Great Barrier Reef. It defines actions, targets, objectives and a long-term outcome to drive and guide management of activities influencing water quality in the Great Barrier Reef.

Regression: A statistical method of determining if there is a relationship between one or more variables and then mathematically describing the relationship.

Relationship: This means that two or more variables affect another variable. For example, in a positive relationship increasing one variable will lead to the other variable increasing, while in a negative relationship increasing one variable will lead to the other decreasing.

Sensitive: The sensitivity of an organism is how susceptible it is to the harmful effects of pollutants (e.g. pesticides). A sensitive species is one that starts experiencing harmful effects at low concentrations of a pollutant. A non-sensitive (tolerant) species is one that starts experiencing harmful effects at high concentrations of a pollutant. A sensitive species is the opposite of a tolerant species.

Species sensitivity distribution (SSD): A SSD is a relationship between the concentration of a pollutant species that causes harmful effects and the per cent of species that are affected. It is a cumulative frequency distribution of the sensitivity of species to a pollutant. From a SSD the concentration that should protect any selected per cent of species can be calculated. It can also be used to predict the per cent of species that will be affected at any given pollutant concentration.

Source Catchments: The eWater CRC Source Catchments modelling framework simulates sediment, nutrient and pesticide loads entering the Great Barrier Reef lagoon including the pollutant loads at a sub-catchment scale. The framework allows specific customised models to be added as 'plug-ins' to meet a particular modelling objective.

Wet season: A period of 182 days that starts on the first day of the monitoring year (1 July to 30 June) when a rise in river water level and an increase in aqueous pesticide concentrations occurs.

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CATCHMENT LOADS MODELLING METHODS

This report summarises the data and methods used for reporting progress toward the Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP) 2025 water quality targets. The catchment loads modelling program is one line of evidence used to report on progress in the Reef Water Quality Report Card 2017 and 2018.

The targets for water quality that will contribute to ecosystem health and social resilience and benefits are as follows (Australian and Queensland governments, 2018):

- 60% reduction in anthropogenic end-of-catchment dissolved inorganic nitrogen loads.
- 20% reduction in anthropogenic end-of-catchment particulate nutrient loads.
- 25% reduction in anthropogenic end-of-catchment fine sediment loads.
- Pesticide target: To protect at least 99% of aquatic species at the end-of-catchments.

Catchment loads modelling

Quantifying the impact of land management practice change on long-term water quality through monitoring alone is not possible at the whole Great Barrier Reef (GBR) scale. Models are therefore used in conjunction with the monitoring program to predict long-term changes in water quality.

The purpose of the modelling is to report annually on the progress towards the Reef 2050 WQIP, 2025 load reduction targets for total suspended sediment (TSS), dissolved inorganic nitrogen (DIN), particulate phosphorus (PP) and particulate nitrogen (PN).

Modelling progress towards the new pesticide target will be reported from 2020 onwards and will account for the recorded progress made in 2017, 2018 and 2019. In its place, this report card will report the new pesticide risk baseline calculated from monitoring data by the catchment loads monitoring program (Australian and Queensland governments, 2019a). The new pesticide risk baseline, and future modelling, estimates the percent of aquatic species protected from 22 of the most common pesticides (photosystem II (PSII) herbicides, other herbicides and insecticides) detected in catchments and coastal ecosystems of the GBR. This is an expansion from previous modelling that reported only five PSII herbicides. The new approach estimates the cumulative risk of mixtures of the 22 pesticides based on wet season concentrations rather than an annual load, as was reported in previous years.

The Source Catchments modelling framework (eWater, 2010) synthesises management practice change, paddock monitoring and modelling, and catchment monitoring data to estimate end-of-catchment pollutant loads. The catchment models generate pollutant loads for current and improved practices for each individual land-use. Modelling is conducted over a fixed climate period, and enables the changes in water quality due to the implementation of improved management alone to be modelled.

Baseline loads are estimated for the current management practice benchmark (2016).

From the baseline, the reduction in loads resulting from improved management practice adoption are calculated by running the model with the new practice adotion layer for the same 28-year modelling period as the baseline. The difference in load being the load reduction for the that invesmtnet year.

Pollutant loads are summarised in the report card for the 35 basins draining to the GBR lagoon. This catchment-scale water quantity and quality model uses a node link network to represent processes of generation, transportation and transformation of water and constituents within major waterways in a catchment (Figure 1). The model generates estimates of run-off and pollutant loads for each functional unit (FUs - areas within a sub-catchment that have similar behaviour in terms of run-off generation and/or nutrient generation, e.g. land use) within a sub-catchment. Runoff and pollutants are transported from a sub-catchment through the stream network, represented by nodes and links, to the end of the catchment. These components represent the sub-catchment and waterway network.

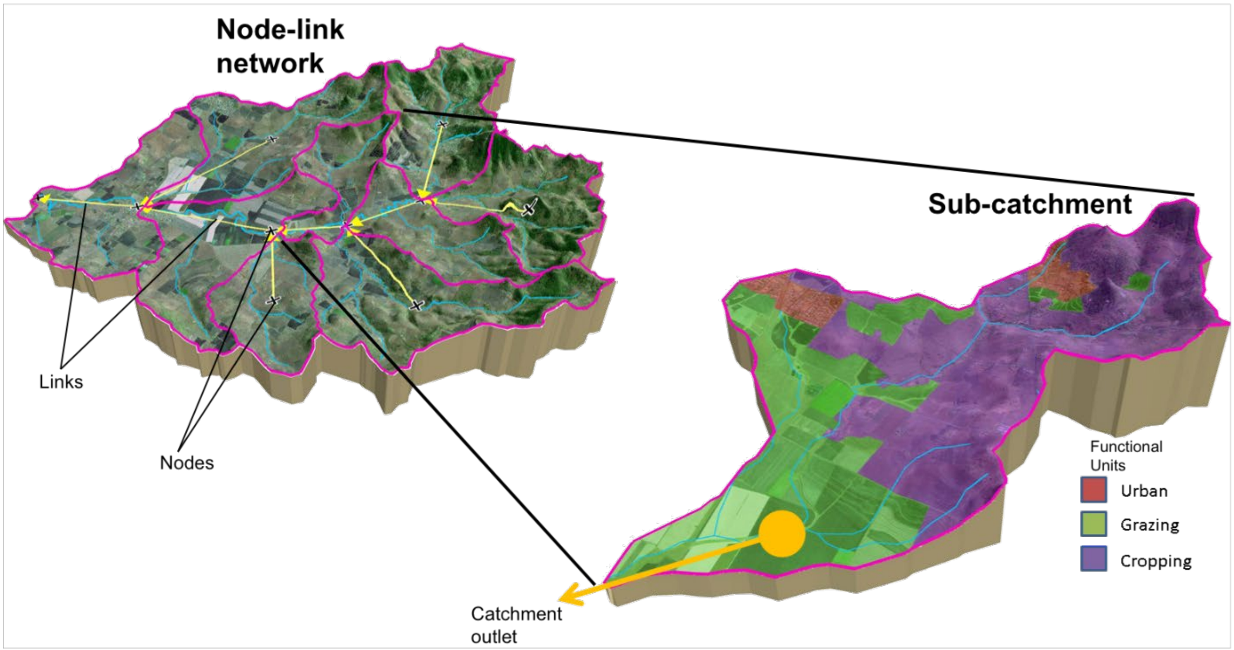


Figure 1. Example of a functional unit (FU) and node-link network generated in Source Catchments (source eWater)

The Source Catchment model runs at a daily time-step which enables the interactions of climate and land management to be reflected in modelled outputs. Aggregated average annual catchment loads are required for the report card. The model runs for a fixed climate period (1986 to 2014), to remove the influence of climate on estimated load reductions. The most current land-use mapping is incorporated when models are periodically updated (details of the mapping data can be found here: www.qld.gov.au/environment/land/management/mapping/statewide-monitoring/qlump/qlump-datasets).

The pollutants modelled were:

- fine sediment (TSS) and coarse sediment
- dissolved and particulate nutrients
- 22 pesticides[1].

[1] *Pesticides are normally modelled each year and the progress to target reported in each report card, however for this year, only the pesticide baselines will be reported (based on monitoring data), i.e. the modelled progress to the*

The Paddock to Reef Integrated Monitoring, Modelling and Reporting Program (Paddock to Reef program) agricultural management practice adoption program area has developed water quality risk frameworks for each agricultural industry. These frameworks articulate best management practice in relation to the Reef 2050 WQIP land and catchment management targets for agricultural management practice adoption. These practices are described in terms of their relative water quality risk, from low to high (A-D). See the Stewardship – Agricultural Management Practice Adoption program methods (Australian and Queensland governments, 2019b) report for more information about the water quality risk frameworks.

To reflect the modelled load reduction for each report card as a result of changes in adoption of improved agricultural management practices, three scenarios[2] are run:

- pre-development load (prior to agricultural development) for the 28-year modelling period. (Note hydrolgoy is maintained as per baseline to enable load changes, due to management alone, to be quantified)
- the baseline load for the 28-year modelling period (i.e. representing the agricultural management practice benchmark 2016
- change load for the 28-year modelling period with the proportion of land managed practice improvement adjusted to reflect the previous years adoption.

The proportion of land managed using defined management practices is the only variable that changes between modelled scenarios. This allows for the relative load reductions attributed to the areas of improved agricultural management practices to be reported. Approximately 10 land-uses are modelled in each region including grazing, sugarcane, cropping and bananas.

Modelled load estimates were calibrated and or validated against field data collected through the Catchment Loads Monitoring program at 43 monitoring sites across 20 catchments that discharge to the GBR lagoon. For further information on the model calibration and validation processes and results, refer to McCloskey et al. 2017A and Waters et al 2014.

The Catchment Loads Modelling program undergoes an external peer review every three to four years. The program was reviewed in 2012, 2015 and 2019. Prior to the release of each report card, modelled load estimates are reviewed both internally and externally.

Management practice change

The Reef 2050 WQIP management practice adoption frameworks describe and categorise farming practices according to recognised water quality improvements at the paddock scale. Improvements in water quality as a result of adopting improved management practices were determined by linking paddock model timeseries outputs to catchment models.

pesticide target will not be reported for the Reef Water Quality Report Card 2017 and 2018. Progress made during these years will be modelled and reported in 2020.

[2] *A scenario describes the major processes in a river system or catchment that are modelled. This includes catchment and sub-catchment definition, rainfall runoff and constituent generation models, data sets and parameters. You can create multiple scenarios to break complex projects into distinct parts or duplicate existing scenarios to conduct what-if experiments without disrupting the original. Any change to the definition of sub-catchments, node-link network, FUs, or the models within FUs, forms a new scenario. Similarly, a different set of inputs or parameters can be used to set up a new scenario, such as a change in land use or a climate change* (eWater Source User Guide 4.1).

Management practice change has been modelled for the sugarcane, grains, horticulture, banana and grazing areas of the GBR catchments. For details on how management practice changes are represented in the modelling, refer to McCloskey et al. 2017A and Waters et al 2014.

Improved management of gullies and streambanks are modelled to reflect activities such as gully restoration, excluding stock via fencing off gullies and streambanks, and installation of off-stream watering points. Spatial data on investments in improved practices are provided by industry and the six natural resource management (NRM) bodies within each region.

Modelling assumptions

- Loads reported for each report card reflect the relative change in modelled average annual loads for the specified model run period (1986 to 2014).
- Land use areas in the model are static over the model run period and are based on the latest available QLUMP data.
- Paddock model runs that are used to populate the catchment models, represent 'typical' management practices for a given management class and do not reflect the actual array of management practices that occur year-to-year across the GBR catchments.
- Paddock model simulations represent the reported management practice adoption water quality risk frameworks as a set suite of pratices.
- Application rates of pesticides and fertilisers that are used to populate the paddock models are derived through consultation with relevant industry groups and regional NRM bodies.
- Management practice adoption areas represented in the model are applied at the spatial scale of the data supplied by the delivery organisations and collated in the Paddock to Reef Agricultural Management Practice Adoption program area.
- The water quality benefits from adopting a management practice change are assigned in the year that on-ground works were implemented, so time lags that may occur in the system are not accounted for.
- It is important to note that these modelled load reductions are based on improved land management adoption data supplied by organisations that receive funding from Reef 2050 WQIP programs. Results are therefore indicative of the likely long-term water quality response due to adoption of improved land management practices for a given scenario, rather than a measured reduction in load.

Linking paddock and catchment models

The publicly available version of the eWater Source Catchments model (www.ewater.org.au) was modified to incorporate hillslope constituent generation from the most appropriate paddock models for cropping, sugarcane and sugarcane areas, and the Revised Universal Soil Loss Equation (RUSLE) for grazing. Gully and streambank erosion and floodplain, channel and reservoir deposition processes added to the model were based on the SedNet/ANNEX approach (Wilkinson et al. 2014). A detailed description can be found in Ellis and Searle (2013) and Ellis (2017). The spatial and temporal representation of gully, streambank and in-stream erosion processes were incorporated to better represent the erosion processes observed in the summer-dominant rainfall areas of northern Australia.

Two approaches were used to represent improved land management practices in the Source Catchments model depending on the land-use of interest. In the first approach, for sugarcane, bananas and cropping, the constituent time-series (e.g. load per day per unit area) for the given land-use was supplied from a paddock model. Unique combinations of climate, soil type and defined management practices within each land use were identified and represented spatially in the paddock model simulations used to inform the catchment models. For cropping (grain cereal crops) and bananas, the HowLeaky model was used (Rattray et al. 2004). For sugarcane modelling, the Agricultural Production Systems sIMulator (APSIM) (Holzworth et al. 2014) was used. For load reduction representation, the defined management practice for a particular land-use segment was altered between scenarios.

In the second approach, the RUSLE model was written into the Source Catchments model to model hillslope soil erosion in grazing lands. The cover term (C-factor) in the model is generated from remotely sensed ground cover satellite imagery seasonally (four scenes per year). The paddock-scale model GRASP (McKeon et al. 1990) was used to provide scaling algorithms for each scenario to account for changes in management in each identified land type; for example, shifting areas from moderate risk to moderate–low risk. These scaling algorithms were applied at the pixel scale to each ground cover satellite image for the modelling period. This is applied according to a spatial representation of areas of defined management practices as provided annually by regional NRM bodies. Calculations were performed pixel by pixel, with results accumulated to a single land-use representation in each sub-catchment. All loads generated for each land use represented within a sub-catchment were then aggregated at the sub-catchment scale and routed through the stream network.

Total load

The **total baseline load** is the load modelled within each GBR catchment using the 2016 management practice benchmark. A pre-development land-use map was also developed and modelled. The model was then run for a 28-year period to establish an average annual load for this period; **the pre-development load**. The **anthropogenic load** was calculated as the total baseline load less the pre-development load.

Load reductions

To reflect investment in improved management practices since 2016, the model was then re-run in each year for the same climate period using the proportions of lowest risk to high risk management practice areas in that year. The relative change in pollutant loads from the anthropogenic baseline after investment reflects the load reduction due to changes in management practices (Figure 2).

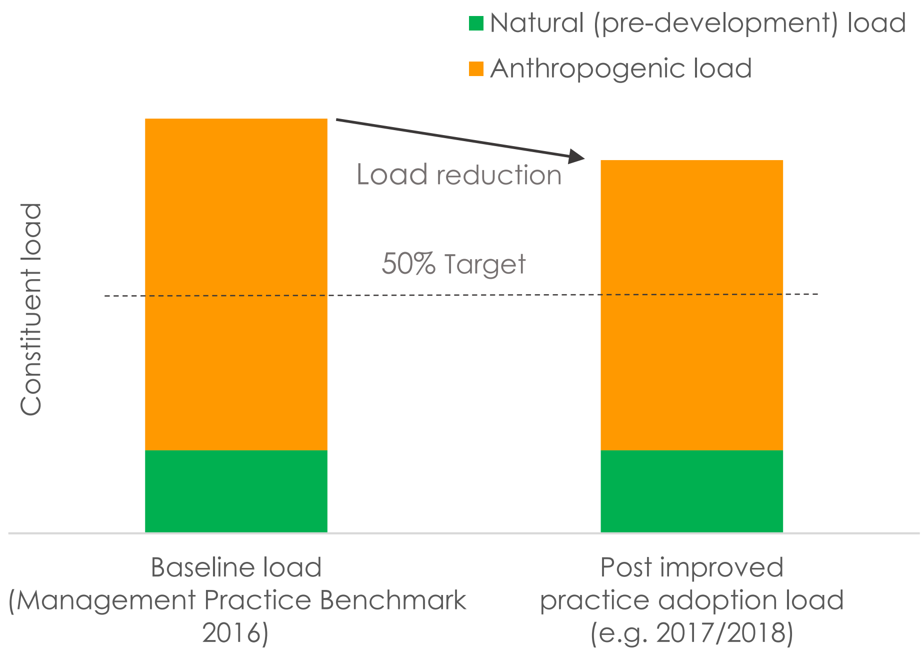


Figure 2. Example of modelled pre-development and anthropogenic pollutant loads, and the load reduction following investment in improved management practices.

Modelling improvements

In response to the independent external review of the program in 2015 by the Queensland Audit Office and the Great Barrier Reef Water Science Taskforce (GBRWST, 2016), improvements have been implemented in this program area in the last two years. These include:

- A desktop and field gully mapping program continues to improve the spatial representation of gully density and geometry in the models. Updated gully maps have been incorporated for selected areas within the Burdekin and Fitzroy regions and all of the Wet Tropics and Burnett Mary regions.
- Annual monitoring/modelling validation workshops are held to compare model performance against monitoring data.
- Updated land-use mapping incorporated for Wet Tropics, Fitzroy and Mackay Whitsunday regions.
- Modifications to the calculation of the cover factor in the hillslope erosion modelling to improve erosion estimates in steep, densely forested catchments.
- Updates to sewage treatment plant contributions.
- Improved alignment between modelled and actual stream location, and steam length and width.
- Updated datasets for riparian vegetation extent, streambank erodibility, floodplain area.
- Research into parameter sensitivity/uncertainty in modelled inputs and outputs is continuing to guide future data collection.

How the information is reported

Progress towards the targets is estimated by determining how much the modelled pollutant load has reduced from the average annual modelled anthropogenic baseline (total load less the pre-development load). This is calculated as a percentage reduction in average annual modelled load.

The average annual percentage reduction in load is calculated as:

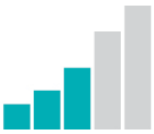
$$\text{Reduction in load (\%)} = \frac{(\text{anthropogenic baseline load} - \text{anthropogenic change}) \times 100}{\text{Anthropogenic baseline load}}$$

where, anthropogenic baseline load = total load less pre-development load

Modelled TSS, DIN, PN and PP at the end of the catchment are reported for the total GBR and for the six regions that make up the GBR catchment.

Qualitative confidence ranking

Confidence



A multi-criteria analysis was used to qualitatively score the confidence in each indicator used in the report card, from low to high. The approach combined expert opinion and direct measures of error for program components where available. Catchment loads modelling received a three-bar confidence ranking.

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Glossary

ANNEX: Annual Network Nutrient Export model is a static model that predicts the average annual loads of phosphorus and nitrogen in each link in a river network.

APSIM: Agricultural Production Systems Simulator

Agricultural Management Practice Adoption program area: A program area of the Paddock to Reef Integrated Monitoring, Modelling and Reporting program which develops rigorous estimates of management practice adoption and annual management practice change for the major agricultural industries of the Great Barrier Reef catchments— sugarcane, grazing, horticulture, grains and bananas.

Sediment: Sediments in water include clay, silt, sand and coarser particulate material, and are referred to 'total suspended solids' (this is how they are measured in the water column) or 'total suspended sediment'. Sediments are characterised by different particle sizes. Not all sediment or particle size fractions present the same risk to the Great Barrier Reef, with **fine** (<20µm) **sediment** moving furthest into the marine environment, leading to increased turbidity and reduced light, and therefore posing the greatest risk.

GRASP: Soil water pasture growth model

HowLeaky: Agricultural system water balance and crop growth model based on PERFECT

USLE: Universal Soil Loss Equation

C-factor: cover management factor (**C**) in the USLE that represents effects of vegetation and other land covers

SedNet: Sediment River Network Model used to determine catchment sediment yields and sediment sources

MARINE MONITORING PROGRAM METHODS

This report summarises the data and methods used for monitoring and reporting within the Marine Condition – Marine Monitoring Program reported in the Reef Water Quality Report Card 2017 and 2018 (Figure 1 - elements other than eReefs marine modelling).

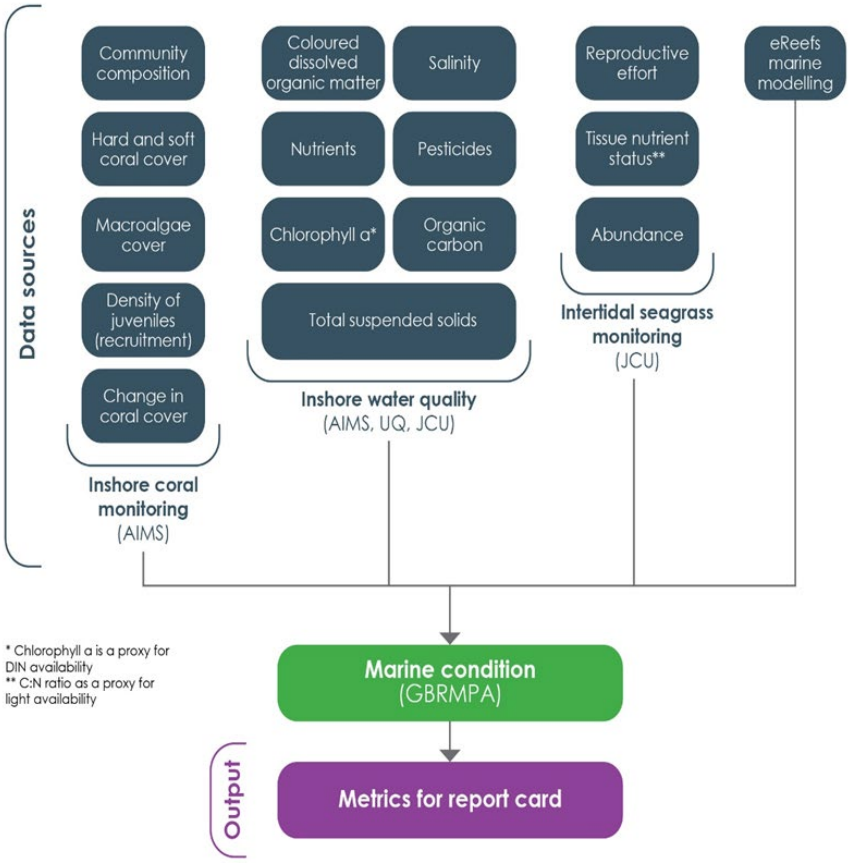

Figure 1. Main data sources, inputs and outputs for the Marine Monitoring Program, which include inshore coral, inshore water quality and inshore seagrass monitoring. The Marine Modelling Program provides the water quality metric based on eReefs model output.

The Marine monitoring program is one line of evidence used to report on progress towards the Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP) (Australian and Queensland governments, 2018) (formerly Reef Water Quality Protection Plan 2013), 2025 water quality outcome and objectives for marine condition. This Tier 2 report is underpinned by detailed annual technical reports (referred to as Tier 3 reports) that undergo independent peer review before being published on the Great Barrier Reef Marine Park Authority's eLibrary website.

The Marine modelling program (the eReefs marine modelling referenced in Figure 1) provides the water quality scores which are combined with coral and seagrass scores to inform the marine condition and metrics for the Reef Water Quality Report Card 2017 and 2018 (Tier 1).

The outcome and objectives from the Reef 2050 WQIP are:

Outcome

- Good water quality sustains the outstanding universal value of the Great Barrier Reef, builds resilience, improves ecosystem health, and benefits communities

Objectives

- Improved coral condition
- Improved seagrass condition

The Marine monitoring program was established in 2005 and assesses trends in ecosystem health and resilience indicators for the inshore Great Barrier Reef in relation to water quality and its linkages to end-of-catchment pollutant delivery. A summary of the indicators and methods used to derive Reef Water Quality Report Card 2017 and 2018 scores are outlined below.

Detailed methods are available in the annual technical reports published on The Great Barrier Reef Marine Park Authority's website <www.gbrmpa.gov.au/our-work/our-programs-and-projects/reef-2050-marine-monitoring-program>.

The inshore Marine monitoring program has three sub-components:

- water quality (Waterhouse et al. 2018, Gruber et al. 2019), including pesticides (Grant et al. 2018, Gallen et al. 2019)
- seagrass condition (McKenzie et al. 2018, McKenzie et al. 2019)
- coral reef condition (Thompson et al. 2018, Thompson et al. 2019).

Since the 2015-2016 water year, the Reef Water Quality Report Card 2017 and 2018 (Tier 1) has been based on averaging the scores for water quality from the eReefs models (Robillot et al. 2018) with scores for coral and seagrass condition from the Marine monitoring program. The Inshore Water Quality component of the Marine monitoring program (Figure 1) provides data on exposure and risk to marine communities from the analysis of flood plumes and pesticide concentrations as well as *in situ* measurements to detect long-term trends at specific locations and in three natural resource management regions.

Inshore water quality, including pesticides

The objectives for the inshore water quality sub-component are listed below (State of Queensland 2018).

1. Monitor, assess and report the three-dimensional extent and duration of flood plumes and link concentrations of suspended sediment and nutrients to end-of-catchment loads, and end-of-catchment pesticide concentrations to marine concentrations.
2. Monitor, assess and report trends in inshore concentrations of sediment, chlorophyll *a*, nutrients and pesticides against the water quality guidelines (Great Barrier Reef Marine Park Authority 2018) and water quality guidelines (Australian and New Zealand governments 2018) for the Great Barrier Reef Marine Park.
3. Monitor, assess and report trends in turbidity and light attenuation for key Great Barrier Reef inshore habitats against established thresholds.

In situ water quality monitoring

Monitoring of year-round in situ water quality parameters in 2016-2017 and 2017-2018 includes the measurement of concentrations of organic carbon, inorganic and organic nutrients (nitrogen and phosphorus), silica, coloured dissolved organic matter, chlorophyll *a*, total suspended solids, turbidity, Secchi depth, salinity and 30 pesticides.

Water quality monitoring is conducted in four of the regions (Figure 2):

- Cape York (four transects added in 2016-2017: off the Pascoe, Normanby-Kennedy, Annan-Endeavour and Stewart Rivers)
- Wet Tropics:
    - Mossman basin
    - Mulgrave-Russell basin
    - Barron-Daintree basin
    - Tully basin
    - Herbert basin
- Burdekin
- Mackay Whitsunday
    - Proserpine/O'Connell basin
    - Pioneer basin
    - Plane basin

The Barron-Daintree sub-region is reported from the collection of data under an independent AIMS program along the long-term Cairns transect where sampling started in 1989.

Techniques used to monitor *in situ* water quality include automated data loggers and collection of water samples in the field for laboratory analysis (Waterhouse *et al.* 2018, Gruber et al. 2019).

More intensive monitoring is conducted in the wet season because the majority of the annual pollutant load to the Great Barrier Reef is delivered then. Specific event sampling is also conducted throughout the wet season in the focus regions (Waterhouse et al. 2018, Gruber et al. 2019). Sampling follows transects extending from rivers chosen according to flow characteristics in a particular year.

Exceedances of individual water quality parameters at specific sites is reported against the Environmental Protection (Water) Policy (EPP) water quality objectives (State of Queensland 2016), as well as for any adjacent commonwealth-only waters (Great Barrier Reef Marine Park Authority 2018), in annual technical reports (Gruber et al. 2019).

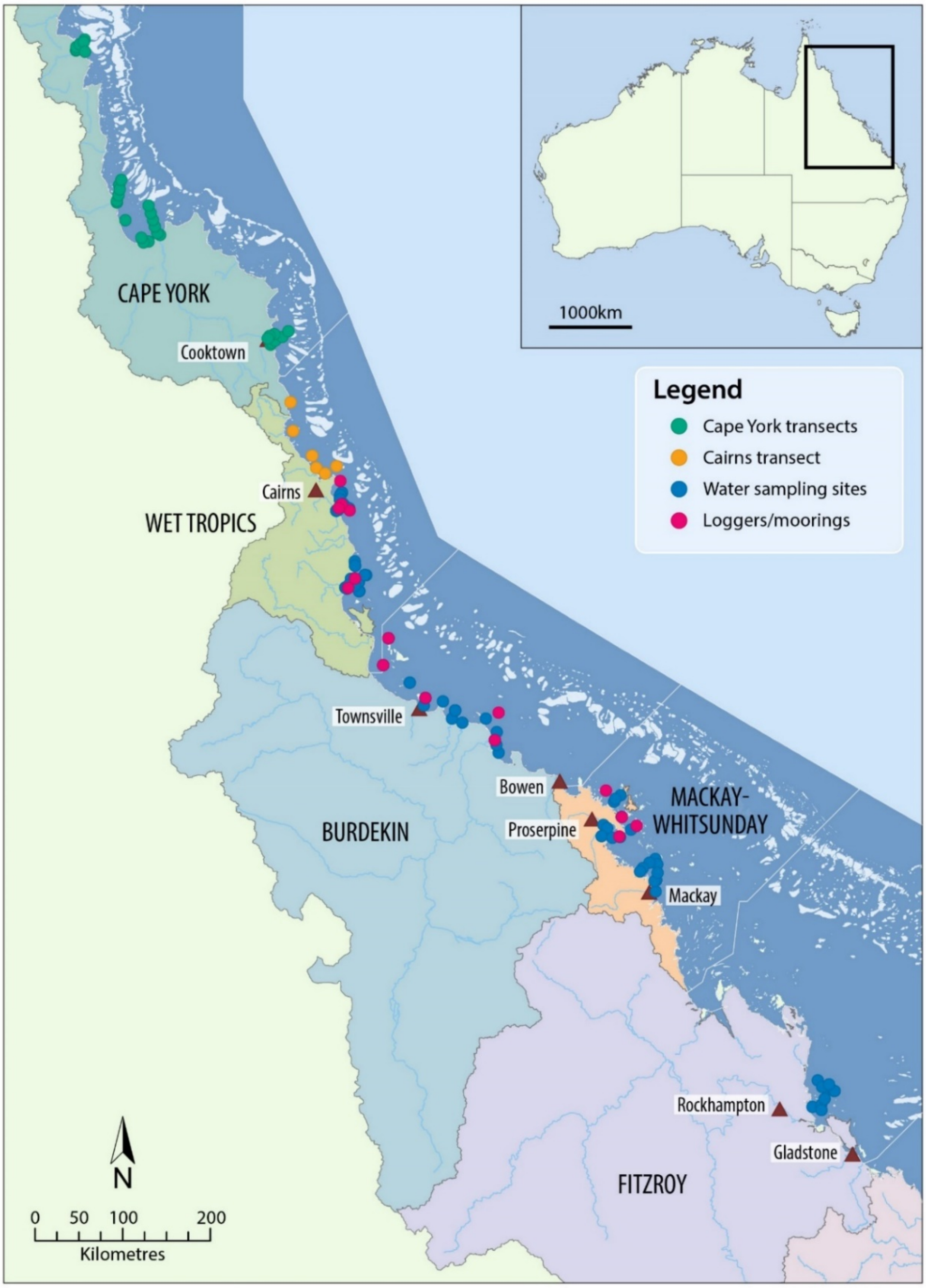

Figure 2. Marine monitoring program water quality monitoring locations and sampling strategy from 2015 onwards. Note: The Cape York transects were added in 2016–2017. Natural Resource Management region boundaries are represented by coloured catchment areas. Source: (Waterhouse et al. 2018, Gruber et al. 2019).

Two versions of a water quality index are prepared as an interpretation tool to visualise trends in the suite of water quality variables measured, and to compare monitored water quality to existing water quality guidelines (Great Barrier Reef Marine Park Authority 2018).

The water quality index uses a set of five key indicators:

- water clarity (total suspended solid concentrations, Secchi depth and turbidity measurements by FLNTUSB instruments, where available)
- chlorophyll *a* concentrations
- particulate nitrogen concentrations
- particulate phosphorus concentrations
- oxidised nitrogen concentrations.

For each monitoring site, these indicators are compared to water quality guidelines (Great Barrier Reef Marine Park Authority 2018), scored based on performance relative to these objectives, and aggregated to give an overall site-specific score. Sites are then aggregated within a region or sub-region to give a regional score.

The water quality index is calculated using two different methods due to changes in the Marine monitoring program design that occurred in 2015, as well as concerns that the index was not responsive to changes in environmental pressures of each year. The changes in design included increased number of sites, increased sampling frequency and a higher sampling frequency during December to April to better represent wet season variability. Thus, statistical comparisons between Marine monitoring program data from 2005-2015 to 2015-onwards must account for these changes. The two versions of the water quality index have different purposes:

1. **Long-term trend**: This version is based on the pre-2015 Marine monitoring program sampling design and uses only the original sites and three sampling dates per year. This sampling design had low temporal and spatial resolution and was aimed at detecting long-term trends in inshore water quality. Key aspects of this version are:
   - annual water quality guideline values are used for comparison with monitoring data
   - only Australian Institute of Marine Science monitoring data are used
   - a four-year running mean is applied to reduce the effect of sampling time on the index
   - the Index is an average of scores for five indicators.

2. **Annual condition:** This version is based on the post-2015 Marine monitoring program sampling design and uses all sites and sampling dates per year. Key aspects of this version are:
   - seasonal water quality guidelines (Great Barrier Reef Marine Park Authority 2018) are used for comparison with monitoring data (i.e. wet season data are compared to a wet season water quality guideline and dry season data are compared to a dry season water quality guideline)
   - both Australian Institute of Marine Science and James Cook University monitoring data are used

- a running mean is not applied
- the index is a hierarchical combination of scores for five indicators.

Further details can be found in Marine monitoring program annual technical reports.

In situ water quality data are not used to generate the water quality metric scores for the Reef Water Quality Report Card 2017 and 2018, but have been included among the data streams used to validate the modelled outputs from the eReefs models.

Satellite remote sensing

At the Great Barrier Reef-wide scale, information is also sourced from satellite remote sensing, which provides the density of observations required to report on such a vast area (Petus et al. 2018, Petus et al. 2019). Remote sensing products including a range of wet-season maps derived from satellite imagery (weekly composites, frequency maps and surface exposure maps) are used to report water quality conditions in the Great Barrier Reef (Waterhouse et al. 2018, Gruber et al. 2019).

Wet season water type maps were produced using MODIS-Aqua (hereafter, MODIS) quasi true colour (hereafter true colour) imagery reclassified to six distinct colour classes defined by their colour properties (Álvarez-Romero et al. 2013) and typical of colour gradients existing across coastal waters, including river plumes, during the wet season (Figure 3). These characteristics vary the impact on the underlying ecological systems.

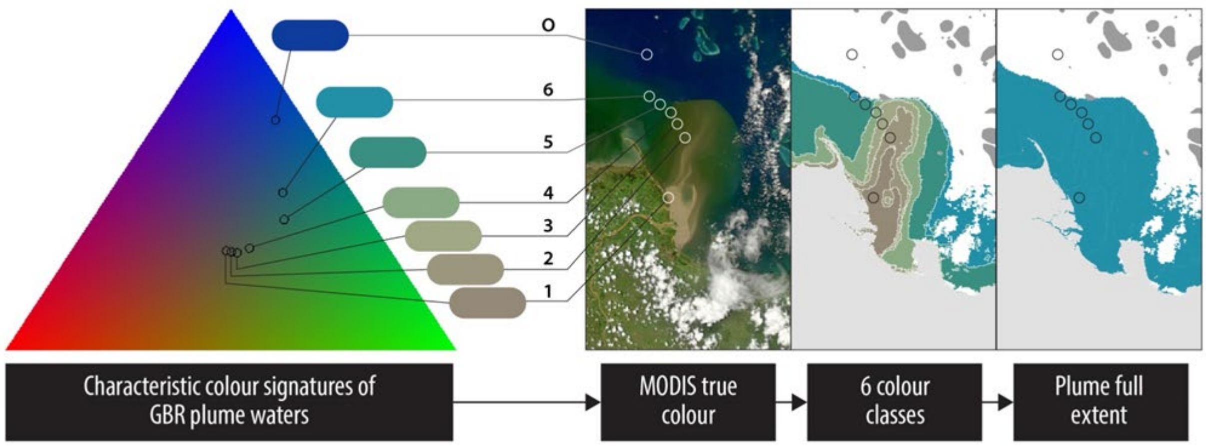

Figure 3. Triangular colour plot showing the characteristic colour signatures of the six wet season water types in the Red-Green-Blue (RGB or true colour) space. The colour of coastal waters depends on concentrations of optically active components (e.g. total suspended solids, colour dissolved organic matter, and chlorophyll *a*), which influence light attenuation (Petus et al. 2018, Petus et al. 2019), as well as different pollutant concentrations. These characteristics vary the impact on the underlying ecological systems.

The six wet season colour classes were further grouped into three wet season water types to assess the broadscale coastal water quality during the wet season, including the composition and spatial variability of river plumes and resuspension processes:

- primary—classes 1 to 4

- secondary—class 5
- tertiary—class 6.

The three water types have the following characteristics:

- **Primary water type:** the brownish to brownish-green turbid waters are typical for inshore regions of Great Barrier Reef river plumes and nearshore marine areas with high concentrations of resuspended sediments found during the wet season. These water bodies in flood waters typically contain high nutrient and phytoplankton concentrations but are also enriched in sediment and dissolved organic matter resulting in reduced light levels. A further break-down into four colour classes is provided for this water type.
- **Secondary water type:** the greenish-to-greenish-blue turbid waters are typical of coastal waters rich in algae (chlorophyll *a*) and also containing dissolved matter and fine sediment. This water body is found in the Great Barrier Reef open coastal waters as well as in the mid-shelf water at times. It has relatively high nutrient availability and light levels favour productivity as suspended sediments are largely settled out (Bainbridge et al. 2012).
- **Tertiary water type:** the greenish-blue waters whilst discernible, have low or no risk of detrimental ecological effects. This water body is typical for areas towards the open sea or offshore regions seaward of river flood plumes and is distinguishable due to the presence of colour dissolved organic matter.

The frequency of the presence of these three wet season water types is assessed on a weekly basis. To evaluate the potential exposure of Great Barrier Reef communities to degraded water quality, the frequency maps are overlaid with coral reef and seagrass meadow distributions to identify which communities are likely exposed to different wet season water quality conditions. The lowest exposure categories are characterised by low exposure frequencies of the primary and secondary water types, and the highest exposure categories are characterised by high exposure frequencies of primary and secondary water types. The exposure information is based on surface water quality conditions, which does not necessarily represent the exposure of benthic communities (Waterhouse et al. 2018; Gruber et al. 2019). The exposure categories have yet to be validated against ecological response data, so they represent relative levels of potential risk.

Pesticides

Pesticides are monitored using two methods (Grant et al. 2018, Gallen et al. 2019):

1. Passive samplers are deployed in both wet and dry seasons and provide time-averaged pesticide concentrations (i.e. the average concentration over the deployment period; typically one or two months) (Booij et al. 2007; Shaw et al. 2009).
2. Grab samples are collected in flood plumes during the wet season, during periods of high freshwater river discharge to provide single 'point in time' concentrations of pesticides in water and capture potential peaks.

Passive samplers are deployed at 11 fixed monitoring sites (Figure 2) and are analysed for a suite of 30 pesticides. Five sites have been continuously monitored between eight and twelve years. A further six sites were introduced more recently (2013 to 2015) to build direct linkages between land-based activities and marine ecosystem health, as well as identify the potential exposure risks in regions of known high pesticide use. These recent sites provide pesticide concentration information in areas where seagrass, coral reef and catchment monitoring activities are also being conducted.

Specific in situ flood plume sampling is also conducted throughout the wet season in the focus regions. In both 2016-2017 and 2017-2018, flood plume monitoring was undertaken along transects extending from the mouths of two rivers in the Wet Tropics region – the Tully and Russell-Mulgrave rivers and from Barratta Creek mouth within the Burdekin focus area during early-season discharge events. In addition, in 2016-2017 grab samples were collected following tropical cyclone Debbie along nearshore transects extending from the Proserpine/O'Connell River catchments and the Pioneer River catchment in the Mackay Whitsunday region, and the Fitzroy River catchment (Waterhouse et al. 2018, Gruber et al. 2019).

Pesticide concentration data are evaluated in two ways:

- **Exceedances:** Individual pesticide concentrations are compared against water quality guidelines that are set for the protection of high ecological value marine ecosystems; i.e. protection of at least 99% of species (Australian and New Zealand governments 2018).
- **Mixtures:** The 2017-2018 year is the first year for reporting using a new method – the multisubstance potentially affected fraction (msPAF) method (Traas et al. 2002, Warne et al. 2018). Measured concentrations of 19 pesticides in Table 1 in a given sample are combined mathematically to predict the per cent of species protected (and conversely that may be affected) by mixtures of the pesticides detected. The remaining 11 pesticides do not have all the available information required to be able to include them in the assessment.

Table 1. Pesticides detected in passive sampler devices that were assessed using the msPAF method for multiple pesticides. Not all of the listed pesticides were necessarily detected in collected water samples.

Name of pesticide	Type	Mode of action
Chlorpyrifos	Insecticide	Acetylcholine esterase (AChE) inhibitor
Imidacloprid	Insecticide	Nicotinic receptor agonist
Haloxyfop	Herbicide	Acetyl-coenzyme A carboxylase (ACCase) inhibitor
Imazapic	Herbicide	Group 1 Acetolactate synthase (ALS) inhibitor
Metsulfuron-methyl	Herbicide	Group 2 Acetolactate synthase (ALS) inhibitor
Pendimethalin	Herbicide	Microtubule synthesis inhibitor
Metolachlor	Herbicide	Acetolactate synthase (ALS) inhibitor
Ametryn	Herbicide	Group 1 PSII inhibitor
Atrazine	Herbicide	
Terbuthylazine	Herbicide	
Tebuthiuron	Herbicide	
Simazine	Herbicide	Group 2 PSII inhibitor
Diuron	Herbicide	Group 3 PSII inhibitor
Terbutryn	Herbicide	
Hexazinone	Herbicide	Group 4 PSII inhibitor
Metribuzin	Herbicide	Group 5 PSII inhibitor
2,4-D	Herbicide	Group 1 auxins (Phenoxy-carboxylic acid auxins)
MCPA	Herbicide	
Fluroxypyr	Herbicide	Group 2 auxins (Pyridine-carboxylic acid auxins)

Water quality guideline values for the protection of high ecological value aquatic ecosystems are set to protect at least 99% of species (i.e. no more than 1% of species affected), the highest protection value possible, in recognition of the marine park and world heritage status of the Great Barrier Reef.

The results of the msPAF analysis are categorised according to the risk categories in Table 2. These categories are consistent with the ecological condition categories used in the Australian and New Zealand Water Quality Guidelines for Fresh and Marine Waters.

Table 2 Risk categories for pesticide mixtures.

Risk categories (% species affected)	Risk categories (% species protected)	Risk category	Risk Level
≤1.0%	≥99%	5	Very low risk
>1 – <5%	>95 – <99%	4	Low risk
5 – <10%	>90 – 95%	3	Moderate risk
10 – <20%	>80 – 90%	2	High risk
≥20.0%	≤80%	1	Very high risk

Marine results are not directly comparable with the end-of-catchment results due to differences in the sampling approach. However, they provide insight into the transport and fate of pesticides, from the end of rivers to marine sites, and the potential risk to marine ecosystems from the mixture of pesticides. The key differences are:

- three of the pesticides, fipronil, isoxaflutole and triclopyr, are not included in the analysis suite for the marine samples (i.e. 19 of the 22 pesticides analysed at the end-of-catchment are analysed for in marine samples). This may mean that the mixture toxicity is underestimated (relative to the catchment monitoring results). However, this is likely to be a minor underestimation as only isoxaflutole is regularly detected at the end-of-catchment (i.e. in Mackay Whitsunday catchments) at concentrations that exceed draft ecosystem protection guidelines for protection of 99% species (0.33 µg/L) and is unlikely to contribute significantly to overall pesticide toxicity in inshore marine waters (Great Barrier Reef Catchment Loads Monitoring Program, pers comm).

- passive samplers are deployed throughout the year providing an ~monthly average concentration of pesticides during both wet and dry seasons. In contrast, end-of-catchment pesticide results are based on high frequency, point in time, grab samples primarily targeting the wet season. Given there is a range of risk reported across the deployments, averages based on passive sampling would likely result in a reduced overall risk.

- the end of catchment pesticide data is converted to a single value representing the time-averaged[1] per cent of species protected during a standardised wet season period (182 days = 6 months). Passive sampler concentrations are converted to a per cent of species protected during each passive sampler deployment.

In the coming years we will explore methods to increase the comparability of the marine and end of catchment pesticide reporting. In the interim, we are reporting the msPAF value of what we know is the minimum protection level achieved during a deployment (i.e. the passive samplers with the highest concentrations and highest msPAF scores at each site).

1 The average is calculated from a multiple imputation approach that uses statistical distributions to infill missing days of data.

Seagrass condition

The objectives for the seagrass condition sub-component are listed below (State of Queensland 2018).

1. Monitor, assess and report the condition and trend of Great Barrier Reef inshore seagrass meadows along identified or expected gradients in water quality in relation to the desired Reef 2050 Long Term Sustainability Plan ecosystem health outcomes.
2. Monitor, assess and report the extent, frequency and intensity of acute and chronic impacts on the condition of Great Barrier Reef inshore seagrass meadows from sediment, nutrients and pesticides.
3. Monitor, assess and report the recovery of Great Barrier Reef inshore seagrass meadows from exposure to flood plumes, sediment, nutrients and pesticides.

Monitoring is conducted in six natural resource management regions, in each major seagrass habitat type where possible (estuarine, coastal intertidal, coastal subtidal, reef intertidal and reef subtidal) (Figure 3). However, monitoring is conducted predominately at intertidal meadows (lower littoral - only exposed to air at the lowest of low tides), with eight locations also including shallow subtidal meadows. The additional Cape York sites (established in 2012), four subtidal sites in the Wet Tropics and Burdekin regions (established in 2008), and two intertidal sites in the Burdekin region (established in 2012) were included in the overall assessments of Great Barrier Reef seagrass ecosystem condition. Additional sites in Cape York (Lloyd Bay), Wet Tropics (Goold Island and Missionary Bay), Burdekin (Shelley Beach), Mackay-Whitsunday (Hydeaway Bay, Pioneer Bay, Tongue Bay, and Newry Bay) and Burnett-Mary (Burrum Heads) monitored by Seagrass-Watch and Queensland Parks and Wildlife Service drop-camera programs, including presence of foundation and other seagrass species, were also included in the Great Barrier Reef Report Card (McKenzie *et al.* 2019).

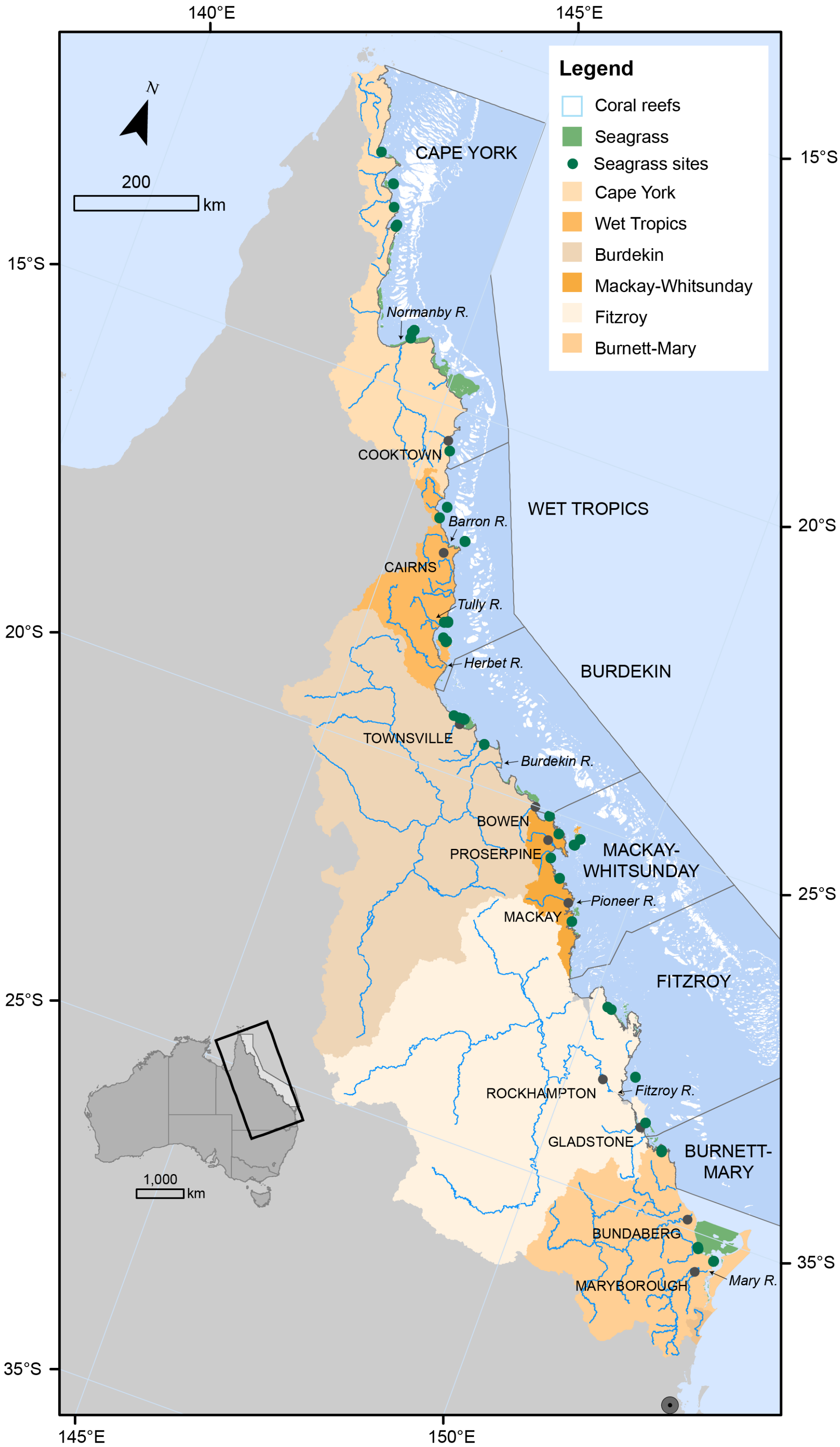

Figure 4. Marine Monitoring Program seagrass monitoring locations (including Queensland Parks and Wildlife Service and Seagrass-Watch). Source: (McKenzie et al. 2019)

Monitoring includes an assessment of three indicators:

- seagrass abundance (per cent cover) is an assessment of the average per cent cover of seagrass per monitoring site in relation to the Seagrass Abundance Guidelines (McKenzie 2009)
- reproductive effort is the ratio of the average number of reproductive structures (spathes, fruits, female and male flowers) of plants on an area basis relative to the long-term average, and provides an indication of the capacity for meadow recovery following disturbances
- tissue nutrient composition as an indicator of nutrient enrichment relative to light available for growth (McKenzie et al. 2019).

Additional indicators of seagrass condition and resilience include species composition, relative meadow extent and density of seeds in the seed bank (McKenzie et al. 2019).

Environmental pressures are also recorded including within-canopy water temperature, within-canopy benthic light, sediment composition as well as macroalgae and epiphyte abundance.

- Within-canopy benthic light is compared to long-term recorded light levels at individual sites as well as daily light thresholds likely to support long-term growth requirements of the species in these habitats (Collier et al. 2016).Within-canopy temperature is discussed in context of the number of days above 35°C. Growth reduction can occur in some species from prolonged warm water exposure (Collier et al. 2011; Collier et al. 2016). 40°C is a critical canopy temperature threshold for photoinhibition and acute temperature stress for seagrass (Campbell et al. 2006).
- Changes in sediment composition can be an indicator of broader environmental changes (such as sediment and organic matter loads and risk of anoxia), and be an early-warning indicator of changing species composition.

Additional data on climate and water quality is obtained from the Bureau of Meteorology and from the Marine monitoring program inshore water quality sub-program (McKenzie et al. 2019).

Coral reef condition

The objectives for the coral reef condition sub-component are listed below below (State of Queensland 2018).

1. Monitor, assess and report the condition and trend of Great Barrier Reef inshore coral reefs along identified or expected gradients in water quality in relation to the desired Reef 2050 Long Term Sustainability Plan ecosystem health outcomes.
2. Monitor, assess and report the extent, frequency and intensity of acute and chronic impacts on the condition of Great Barrier Reef inshore coral reefs from sediment, nutrients and pesticides.
3. Monitor, assess and report the recovery of Great Barrier Reef inshore coral reefs from exposure to flood plumes, sediment, nutrients and pesticides.
4. Monitor, assess and report trends in coral reef resilience indicators: resistant coral species, temperature variability, nutrients, sedimentation, coral diversity, coral disease, macroalgae, crustose coralline algae and coral eating crown-of-thorns starfish.

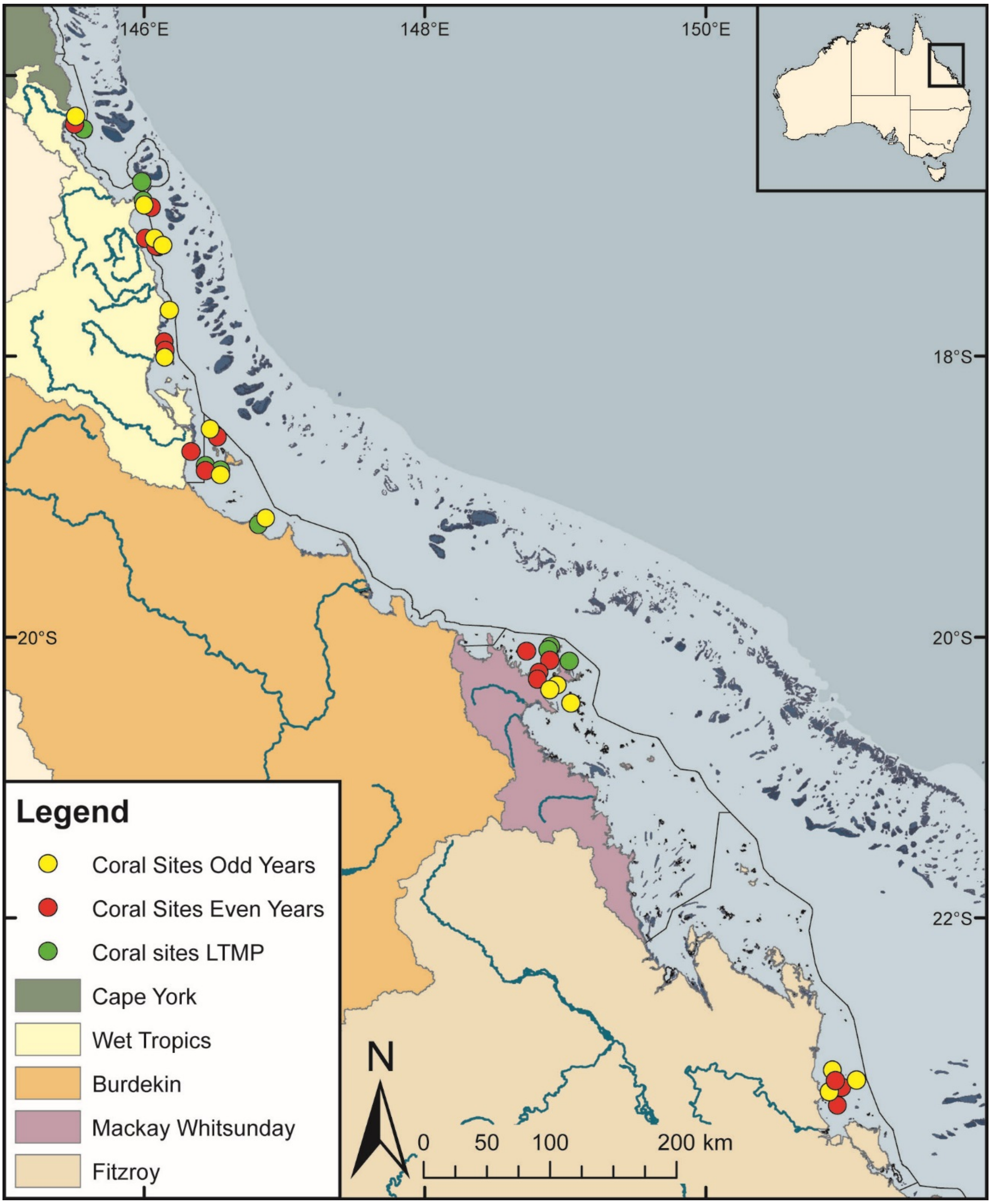

Figure 5. Sampling locations of the Marine monitoring program coral monitoring. Reefs are scheduled to be monitored biannually. Yellow indicates sites scheduled to be monitored in even years, and red dots are scheduled to be monitored in odd years. Green dots indicate sites monitored as part of the long-term monitoring program (LTMP) conducted by Australian Institute of Marine Science. Natural Resource Management region boundaries are represented by coloured catchment areas. Source: (Thompson et al. 2019).

Coral reef condition monitoring of inshore coral reef communities occurs at reefs adjacent to the Wet Tropics, Burdekin, Mackay Whitsunday and Fitzroy natural resource management regions (Figure 4). No reefs are included adjacent to Cape York due to logistic and occupational health and safety issues relating to diving in coastal waters in this region. Limited development of coral reefs in nearshore waters adjacent to the Burnett Mary natural resource management region currently precludes sampling in these locations. Sub-regions are included in the Wet Tropics natural resource management to more closely align reefs with the combined catchments of the Barron and Daintree rivers, the Johnstone and Russell-Mulgrave rivers, and the Herbert and Tully rivers (Thompson et al. 2019).

There are 32 reefs monitored at 2m and 5m depths by the Marine monitoring program, with an additional nine inshore reefs monitored at single depths by the Australian Institute of Marine Science – Long-Term Monitoring Program (LTMP). These are included in the annual assessment of coral condition, although not all reefs are currently sampled every year (Thompson et al. 2019).

Monitoring covers a comprehensive set of community attributes including the assessment of hard and soft coral cover, the number of hard coral juvenile colonies (up to 5cm in diameter), the proportion (per cent) of macroalgae cover, the rate of change in coral cover (as an indication of the recovery potential of the reef following a disturbance) and coral community composition (Thompson et al. 2019).

These indicators are formulated around the concept of community resilience:

- Coral cover is a measure of the abundance of hard and soft corals, and indicates the capacity of coral to persist under the current environmental conditions. Coral cover also represents the availability of brood-stock required for the ongoing supply of future coral generations.

- Coral change is a measure of the observed change in hard coral cover compared to modelled predictions. A healthy and resilient coral reef is expected to show an increase in coral cover during periods free from disturbances and this indicator directly assesses the rate of coral cover increase over the rolling four years of monitoring.

- Juvenile density is a measure of the abundance of hard coral juvenile colonies (up to 5cm in diameter) standardised to space available for coral settlement and indicates the ongoing replacement of corals necessary to recover from disturbances or stress.

- Macroalgal cover is a measure of the proportion of algae cover that is classified as large, fleshy algae. A low score for macroalgae (i.e. poor or very poor) means macroalgal cover is high, which is indicative of poor water quality. Conversely, a high score for macroalgae (i.e. good or very good) means cover is low. High macroalgal cover, once established, reduces the recovery of corals by denying space or producing chemical deterrents that limit coral recruitment and growth.

- Coral community composition scores reflect changes in the relative abundance of coral species from a baseline set at the beginning of the Marine monitoring program. If the composition of communities moves beyond the standard error of their baseline condition toward a community indicative of higher concentrations of nutrients and turbidity, a score of zero is returned. Conversely a score of one is given if the change is toward a community predicted by improved water quality conditions. Comprehensive water quality measurements and environmental parameters are also collected at many of the coral reef sites (Thompson et al. 2019).

Assessing status against the objectives

Improved seagrass condition

Three primary indicators are used to assess and report inshore seagrass condition: abundance, reproductive effort and tissue nutrient status. Trend graphs show the combined score of the indicators over time (colour-graded circles) as well as the indicators contribution to the scores (lines).

Further detail about the selection and scoring of these indicators is documented in annual technical reports (McKenzie et al. 2019).

Improved coral condition

Five indicators are used to assess and report on inshore coral reef condition: coral cover, coral cover change, juvenile coral density, coral community composition and proportional macroalgal cover. Trend graphs show the combined score of the indicators over time (colour-graded circles) as well as the indicators contribution to the scores (lines).

Further detail about the selection and scoring of these indicators is documented in annual technical reports (Thompson et al. 2019).

Synthesis and integration of data and information

The Reef Water Quality Report Card 2017 and 2018 (Tier 1) provides assessment scores for the condition of inshore water quality, seagrass and coral at Great Barrier Reef-wide and regional scales.

Inshore Reef scores are standardised by the area of seagrass and coral reef in the inshore area of each region, while regional scores are unweighted averages. Detailed information is available from annual technical reports on the Marine monitoring program website.

The eReefs marine modelling program provides the water quality metric for the inshore Reef score based on open coastal waters (Robillot et al. 2018; Robillot et al. 2019).

Qualitative confidence rankings

A multi-criteria analysis was used to qualitatively score the confidence in each indicator used in the Reef Water Quality Report Card 2017 and 2018, from low to high. The approach combined expert opinion and direct measures of error for program components where available. Seagrass received a four-bar confidence ranking and coral received a four-bar confidence ranking (Figure 6)..

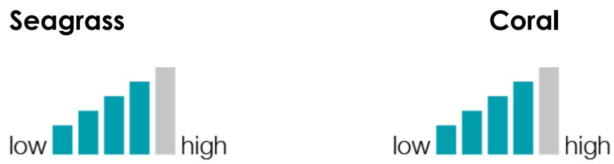

Figure 6. Qualitative confidence rankings for seagrass and coral scores Source: Refer to Appendix 1.

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Appendix A Derivation of confidence ranking

A multi-criteria analysis approach was endorsed by the Independent Science Panel in July 2016 and used to qualitatively score the confidence for each key indicator used in the report card. The approach enables the use of expert opinion and measured data.

A multi criteria analysis identifies the key components that contribute to a problem. These are known as criteria. Each criterion is then scored using a defined set of scoring attributes. The attributes are ranked from those that contribute weakly to the criteria to those that have a strong influence. If the criteria are seen to have different levels of importance for the problem being addressed, they can be weighted accordingly. The strengths of this approach are that it is repeatable, transparent and can include contributions from a range of sources. The weaknesses are that it can be subjective and open to manipulation.

The determination of confidence for the report card used five criteria:

- maturity of methodology (the score is weighted half for this criteria so not to outweigh the importance of the other criteria)
- validation
- representativeness
- directness
- measured error

Seagrass

Maturity of methodology (weighting 0.5)	Validation	Representativeness	Directness	Measured error
New or experimental methodology	Survey with no ground truthing	Less than 10% of population survey data	Measurement of data that have conceptual relationship to reported indicator	Error not measured or >25% error
Peer reviewed method	Survey with ground-truthing (not comprehensive)	**10%-30% of population survey data**	Measurement of data that have a quantifiable relationship to reported indicators	**10-25% error**
Established methodology in published paper	**Survey with extensive on ground validation or directly measured data**	30-50% of population	**Direct measurement of reported indicator with error**	Less than 10% error
3 x0.5 = 1.5	3	2	3	2

Bolded and grey shading in cells indicates assessment ranking. Total score = 11.5, equates to **Four bars**.

Coral

Maturity of methodology (weighting 0.5)	Validation	Representativeness	Directness	Measured error
New or experimental methodology	Survey with no ground truthing	Less than 10% of population survey data	Measurement of data that have conceptual relationship to reported indicator	Error not measured or >25% error
Peer reviewed method	Survey with ground-truthing (not comprehensive)	**10%-30% of population survey data**	Measurement of data that have a quantifiable relationship to reported indicators	**10-25% error**
Established methodology in published paper	**Survey with extensive on ground validation or directly measured data**	30-50% of population	**Direct measurement of reported indicator with error**	Less than 10% error
3 x0.5 = 1.5	3	2	3	2

Bolded and grey shading in cells indicates assessment ranking. Total score = 11.5, equates to **Four bars**.

Glossary

ECO FLNTUSB instrument: Combination fluorometer and scattering meter deployed to measure chlorophyll fluorescence and turbidity

Ecosystem: Dynamic complex of plant, animal and microorganism communities and their non-living environment interacting as a functional unit

Ecosystem health: Ecological processes, biodiversity and function of biological communities is maintained

eReefs: coupled hydrodynamic and biogeochemical models of water quality and ecosystem condition for the Marine Park <https://research.csiro.au/ereefs/models/>

Exposure categories: the proportional exceedance of the guideline values (of sediment and nutrient parameters during the wet season and focuses on total suspended solids, chlorophyll *a*, particulate phosphorus and particulate nitrogen concentrations) multiplied by the likelihood of exposure in each of the water types. Overall exposure scores are categorised into four equally-distributed potential risk categories (I to IV). Exposures risk is termed 'potential' because the risk from surface plumes is not proven in ecosystem response data to confirm the ecological consequences.

Guideline Value: a measurable quantity (e.g. concentration) or condition of an indicator for a specific community value below which (or above which, in the case of stressors) there is considered to be a low risk of unacceptable effects occurring to that community value

Inshore: the enclosed coastal and open coastal water bodies combined. These terms are defined and mapped under schedules in the Environmental Protection (Water) Policy.

Marine Park: Great Barrier Reef Marine Park

MODIS: Moderate Resolution Imaging Spectroradiometer

msPAF: multisubstance-potentially affected fraction

Pollutant: a substance that is present in concentrations that may harm organisms or exceed an environmental quality standard. In this program the term refers primarily to nutrients, sediment and pesticides

Reef 2050 WQIP: Reef 2050 Water Quality Improvement Plan

Reef Plan: Reef Water Quality Protection Plan

Reef 2050 Plan: Reef 2050 Long-Term Sustainability Plan

Secchi depth: A measure of the clarity of water based on the Secchi disk.

Turbidity: A measure of light scattering caused by fine suspended particles, such as clay and silt, detritus, microbes and phytoplankton and zooplankton. Turbidity is affected by a wide range of factors, including natural ones such as wind, waves and currents, as well as anthropogenic ones such as dredging and increased land-based run-off

Water quality index: Metric based on five indicators measured *in situ*

Water quality objective: are long-term goals for water quality management. They are numerical concentration levels or narrative statements of indicators established for receiving waters to support and protect the designated environmental values for those waters. Water quality objectives are not individual point source emission objectives, but the receiving water quality objectives. They are based on scientific criteria or water quality guidelines but may be modified by other inputs (e.g. social, cultural, economic).

Wet season water types: There are three water types: primary, secondary, and tertiary referred to in this report. The term refers to waters that are distinguishable from true color satellite imagery interpretation, and grouped into colour classes according to their optical properties. Primary, secondary and tertiary water types equate to the brownish, greenish and paler greenish-blue waters from the imagery, respectively.

MARINE MODELLING PROGRAM METHODS

The Marine Modelling Program (Waterhouse et al. 2018) directly supports the 2050 outcome of Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP), which is:

"Good water quality sustains the outstanding universal value of the Great Barrier Reef, builds resilience, improves ecosystem health and benefits communities."

The Marine Modelling Program was established in 2016 to:

- Assess trends in ecosystem health for the Great Barrier Reef in relation to water quality and its linkages to end-of-catchment loads by predicting, assessing and reporting trends in inshore water clarity and concentrations of chlorophyll a.
- Predict physical and biogeochemical properties of Reef waters under a range of scenarios to assess the impact of management practices and contribute to the establishment or review of basin-level water quality targets.
- Support regional and whole-of-Great Barrier Reef water quality risk assessments by predicting the impact of rivers on the Great Barrier Reef waters under a range of conditions.

Given the scale of the Great Barrier Reef, it would be impractical to measure and report water quality through the entire domain and at a reasonable frequency using *in situ* monitoring data alone. Satellite imaging can be employed to cover this wide spatial domain but is generally considered to present a lower relative accuracy and is seasonally affected by cloud cover. Therefore, the eReefs deterministic modelling framework is used in conjunction with the *in situ* information collected in the Marine Modelling Program and satellite observations to extrapolate water quality across the entire Great Barrier Reef. The model is used to generate the marine water quality metric which contributes to reporting for the long-term outcome of the Reef 2050 WQIP.

This report describes methods employed to deliver the marine water quality metric for the periods 1 October 2016 to 30 September 2017 (water year 2016-2017) and 1 October 2017 to 30 September 2018 (water year 2017-2018).

Marine modelling methods

Marine models play an integral part in supporting resilience-based management and linking science and observations to policy and decision making. Integrated models spanning physical processes through to water quality and ecosystem response assist regulatory authorities, managers and policy makers in predicting and evaluating the effectiveness of various strategies and actions.

In this context, the marine component of eReefs delivers and operates numerical models capable of simulating and predicting the physical hydrodynamic state, sediment transport, water quality and basal ecology of the Great Barrier Reef lagoon and reef matrix <https://research.csiro.au/ereefs/models/>. Together, these models represent a capability to simulate the transport and fate of waterborne material, of either oceanic or terrestrial origin, and its impact on Reef water quality (Skerratt et al., 2019a).

In 2015-2016, as part of National Environmental Science Programme (NESP) Project 3.2.5, eReefs models were used for the first time to report on chlorophyll *a* (productivity linked to nutrient concentrations) and Secchi depth (proxy for water clarity and presence of fine sediments) across the entire Great Barrier Reef domain (Robillot et al., 2018). These measures underpinned a new water quality metric for the Reef Water QUality report cards. The new metric considers all six natural resource management regions in calculating the Reef-wide score and is based on open coastal waters.

The new metric is underpinned by the eReefs biogeochemical model and integrates true-colour data from satellite images for improved accuracy in what is commonly referred to as data assimilation (Baird et al., 2016). This integration of multiple streams of data to measure and report on water quality differs from the previous metric which relied exclusively on model predictions of water quality variables like chlorophyll and suspended sediments derived from satellite data. The eReefs model has been assessed extensively against *in situ* observations with detailed assessment findings available in Technical assessment of the eReefs biogeochemical simulation [gbr4_H2p0_B3p0_Chyd_Dcrt] against observations (Skerratt et al., 2019b). The approach to the calculation of Reef water quality indices and overall scores was independently peer-reviewed as part of NESP Project 3.2.5.

eReefs coupled hydrodynamic - biogeochemical model

The eReefs coupled hydrodynamic, sediment and biogeochemical modelling system involves the application of a range of physical, chemical and biological process descriptions to quantify the rate of change of physical and biological variables. The process descriptions are generally based either on a fundamental understanding of processes or on actual measurements when a specific process was able to be isolated and studied. The model also requires external inputs, such as observed river flows and pollutant loads. The three components of the model can be characterised as follows:

- The hydrodynamic 3-D model as defined by Herzfeld (2006, 2015)
- The sediment transport model, which adds a multilayer sediment bed to the hydrodynamic model grid and simulates sinking, deposition and resuspension of multiple size classes of suspended sediment (Margvelashvili, 2009, Margvelashvili et al., 2016).
- The biogeochemical model, which simulates optical, nutrient, plankton, benthic organisms (seagrass, macroalgae and coral), detritus, chemical and sediment

dynamics across the whole Great Barrier Reef region, spanning estuarine systems to oligotrophic offshore reefs (Figure 1. Skerratt et al., 2019a).

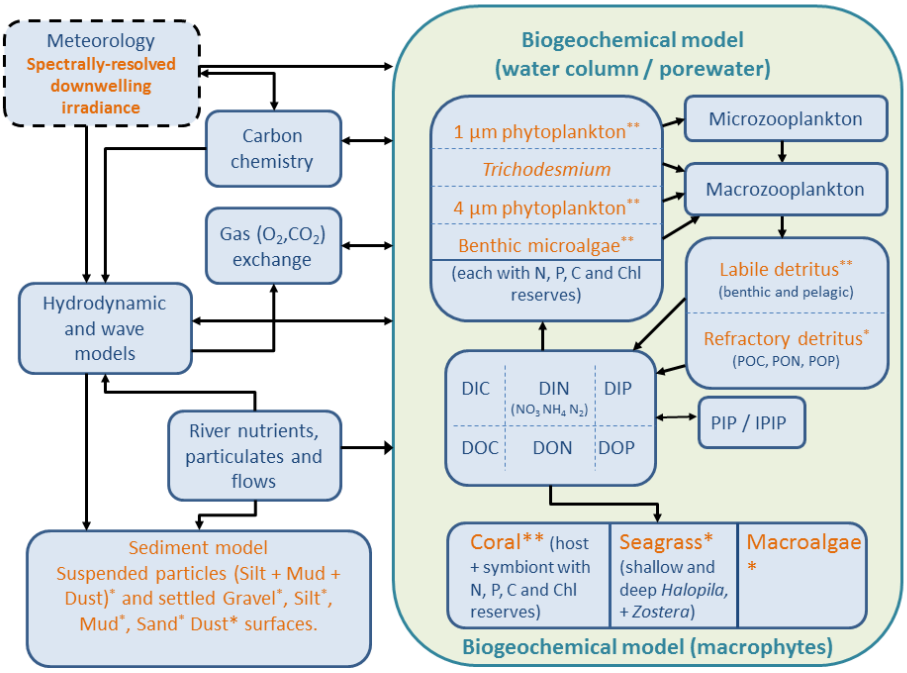

Figure 1. Conceptual framework of the eReefs coupled hydrodynamic-biogeochemical model. Orange variables are optically active (i.e. either scatter or absorb light), influencing the vertical attenuation of light and the bottom light field. The model is forced by rivers along the Reef with nutrient and sediment loads (Baird et al., 2016) using the Source Catchments model. Source: Skerratt et al., 2019a.

Briefly, the biogeochemical model considers four groups of microalgae (small and large phytoplankton, *Trichodesmium* and microphytobenthos), two zooplankton groups, four macrophytes types (seagrass types corresponding to *Zoster sp.*, two *Halophila sp.* types, and macroalgae) and coral communities. Photosynthetic growth is determined by concentrations of dissolved nutrients (nitrogen and phosphorus) and photosynthetically active radiation. Overall, the model contains 23 optically active constituents (Baird et al., 2016). An update to the biogeochemistry model was implemented in 2018 to specifically consider ultrafine sediment particles and their impact on water quality parameters such as water clarity.

The model is currently forced with freshwater inputs from rivers along the Great Barrier Reef. River flows for 17 rivers are obtained from the Queensland Department of Natural Resources, Mines and Energy gauging network. Nutrient concentrations flowing in from the ocean boundaries are obtained from the CSIRO Atlas of Regional Seas (CARS) 2009 climatology (Ridgway et al., 2002).

Pollutant loads originated from the rivers are obtained from the Source Catchments modelling outputs (Ellis and Searle, 2013). To provide daily time series prediction of pollutant loads past July 2014, pollutant generation models are used that estimate daily loads through varying monthly concentrations. These monthly concentration outputs allow the model predictions to be extended by providing daily rainfall run-off model inputs (i.e. the run-off of the day), without the need to update many thousands of farm scale sub-models.

The eReefs model can be run without directly using observations from the marine environment which is referred to as a non-assimilating simulation. Data assimilation provides a single best estimate of the biogeochemical state of the Reef obtained from the combination of both modelling and observations (Baird et al., 2016), and also improves the skill of the model to make predictions (Skerratt et al., 2019a, b). Data assimilation systems can be thought of as using a model to interpolate between observations.

For the Reef, only remote sensing provides the density of observations required to undertake a large-scale data assimilation (see <www.bom.gov.au/marinewaterquality>). For shallow inshore waters, using remote sensing to estimate in-water properties is challenging due to the interactions between chlorophyll *a*, sediments, coloured dissolved organic matter and benthic communities, which all absorb and scatter light in the blue and green wavebands. Instead of using remote sensing to estimate in-water properties, the new water quality metric is based on the optical calculations of the biogeochemical model, which simulates the normalised remote-sensing reflectance. The data assimilation system uses the mismatch between observed and modelled remote-sensing reflectance to constrain the biogeochemical model (Baird et al., 2016).

A 100 member Ensemble Kalman Filter (EnKF) assimilation system is used that is informed by observed ocean colour from both the NASA MODIS Aqua and VIIRS satellites (Jones et al., 2016). When the ocean colour data is ingested, the model shifts a number of optically-active *in situ* quantities, and in particular phytoplankton numbers, in all ensemble members in a manner that is consistent with the statistical properties of the biogeochemical model. The estimate of the biogeochemical state by the assimilation system is the mean of the 100 ensemble members. While the model assimilates ocean colour data from satellite, it is assessed against the *in situ* observations of chlorophyll *a* concentration, from which the skill of the system can be quantified.

Modelling improvements

Following the initial development work under the eReefs Project and NESP 3.2.5 Project, an update to the modelling framework was implemented in 2018 including:

- inclusion of a new fraction of ultrafine sediment particles and modelling of their impact on water quality parameters such as water clarity
- sediment resolution in the upper part of the water column increased from four layers (interfaces at [m]: -0.400 -0.105 -0.025 -0.005 0.000) to 12 layers (interfaces at [m]: -1.000 -0.500 -0.300 -0.200 -0.130 -0.090 -0.060 -0.040 -0.030 -0.020 -0.010 -0.005 0.000).
- inclusion of pollutant loads inputs for all 35 basins (as obtained from Source Catchments modelling outputs) by including an additional 18 river inputs (Boyne, Jackey-Jackey, Olive-Pascoe, Kolan, Plane, Endeavour, Waterpark, Proserpine, Baffle, Jeannie, Styx, Lockhart, Murray, Ross, Burrum, Stewart, Shoalwater, and Mossman)
- sediment types have been partitioned into carbonate and mineral fractions. Optical properties of carbonate minerals (absorption, scattering and backscattering coefficients) introduced from Lucinda Jetty data set
- MODIS and VIIRS data were processed using a regional atmospheric correction algorithm for the period 1 October 2016 to 1 October 2018. Analysis of VIIRS data suggested it was of a higher quality than MODIS, and was given greater weighting in the data assimilation scheme.

The skill of the revised model has been assessed over eight years (see <http://ereefs.info>) and compared to the previous model configuration to confirm it maintained all the properties and skill required to predict water quality.

How the metric is calculated and information reported

As described above, The Great Barrier Reef Report Card marine water quality metric is calculated as follows:

1. Chlorophyll *a* concentration and Secchi depth data are extracted from the assimilated eReefs biogeochemical model at a 4km spatial resolution and daily temporal resolution (midday snapshot) for the entire Reef.
2. The data is partitioned temporally into water years (from 1 October to 30 September of the reporting year), and spatially into zones representing combinations of NRM regions and cross-shelf water bodies (i.e. open coastal, mid-shelf and offshore waters; defined in GBRMPA, 2010). The enclosed coastal water body is excluded due to limitations associated with the 4km model resolution near the coastline.
3. The site-level data (4km x 4km) for each of the three measures are standardised to indices on a continuous scale of zero (very poor) to 100 (very good). This is done by assessing individual values relative to the appropriate water quality guideline value according to a 'modified amplitude indexation routine' (fsMAMP: base 2 logarithm of the ratio of observed value to threshold).
4. Scores for each parameter are aggregated (averaged) temporally over the water year into annual scores and spatially in the open coastal reporting zone. The resulting scores for each of chlorophyll-a and Secchi depth are then averaged to generate a single score for each NRM region.
5. A Reef score is calculated as the weighted (relative areas) average of regional scores.
6. All reported scores are mapped onto a five-point (A–E) colour-coded grading scale (Table 1).

Table 1. Marine water quality metric score to grade scale

Grade	Status	Criteria	Colour
E	Very poor	0–20%	Red
D	Poor	21–40%	Orange
C	Moderate	41–60%	Yellow
B	Good	61–80%	Light green
A	Very good	81–100%	Dark green

Qualitative confidence ranking

Confidence

A multi-criteria analysis was used to qualitatively score the confidence in each indicator used in the report card, from low to high. The approach combined expert opinion and direct measures of error for program components where available. Marine modelling received a three-bar confidence ranking.

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