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Paddock to Reef Integrated Monitoring, Modelling and Reporting Program

PROGRAM DESIGN 2018–2022

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Cover image: view south towards the Russell River National Park and the junction of the Russell and Mulgrave Rivers over flooded sugar fields (February 2015).

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AIMS	Australian Institute of Marine Science
APSIM	Agricultural Production Systems sIMulator
ASRIS	Australian Soil Resource Information System
BGC	eReefs coupled hydrodynamic, sediment and biogeochemical model
BMP	Best management practice
BoM	Bureau of Meteorology
CAG	(Paddock to Reef Program) Coordination and Advisory Group
CDOM	Coloured dissolved organic matter
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAF	Queensland government Department of Agriculture and Fisheries
DARTS	DAta Recording Tool for Science (see Glossary)
DES	Queensland government Department of Environment and Science
DIN	Dissolved inorganic nitrogen
DNRME	Queensland government Department of Natural Resources, Mines and Energy
DoEE	Australian government Department of Environment and Energy
DOP	Dissolved Organic Phosphorus
DON	Dissolved Organic Nitrogen
DPSIR	Driver, Pressure, State, Impact, Response
EMC	Event mean concentration
ERA	Environmentally Relevant Activity
FRP	Filterable reactive phosphorus
GBR	Great Barrier Reef
GBRMPA	Great Barrier Reef Marine Park Authority
GBRF	Great Barrier Reef Foundation
GHHP	Gladstone Healthy Harbour Partnership
GIS	Geographic Information System
GRASP	GRASs Production model
GRTS	Generalised Random Tessellation Stratification
PSII-HEq	Photosystem II – Herbicide Equivalent
IMOS	Integrated Marine Observing System
ISP	(Reef Plan) Independent Science Panel
JCU	James Cook University
LGAQ	Local Government Association of Queensland
LiDAR	Light Detection and Ranging
LTMP	Long Term Monitoring Program
MCL	Maintain current load
msPAF	multi-substance Potentially Affected Fraction
MWHR2RP	Mackay Whitsunday Healthy Rivers to Reef Partnership
ND	Not determined
NESP	National Environmental Science Program
NPD	Normalised Patch Density
NRM	Natural Resource Management
OGBR	Office of the Great Barrier Reef
P2R	Paddock to Reef (Integrated Monitoring, Modelling and Reporting Program)
PSCI	Patch Size Connectivity Index
PN	Particulate Nitrogen
PP	Particulate Phosphorus

QAO	Queensland Audit Office
QA/QC	Quality Assurance/ Quality Control
QLUMP	Queensland Land Use Mapping Program
QPWS	Queensland Parks and Wildlife Service
QSpatial	Queensland Spatial Catalogue
QUT	Queensland University of Technology
RDI	Research Development and Innovation
RIMReP	Reef 2050 Integrated Monitoring and Reporting Program
RUSLE	Revised Universal Soil Loss Equation
RUSMIG	Reef Urban Stormwater Management Improvement Group
SALI	Soil and Land Information database
SILO	Scientific Information for Land Owners
SKIP	Science Knowledge and Information Provision (see Glossary)
SLATS	Statewide Landcover and Trees Study
SSIMR	Spatial and Scientific Information Management for Reef (see Glossary)
SRA	Sugar Research Australia
STP	Sewage Treatment Plant
TWG	Technical Working Group
UQ	(The) University of Queensland
WEV	Wetland Environmental Values
WFAT-M	Wetland Field Assessment Tool for Monitoring
WQIP	Water Quality Improvement Plan
WWF	World Wide Fund (for Nature)
WWTP	Wastewater Treatment Plant

Glossary

'ABCD' management practices: ABCD management practice frameworks were first developed in 2008 to represent different levels or standards of management practice within different industries for different water quality parameters (i.e. sediment, nutrients and pesticides). The terminology commonly used to describe the management practices in the frameworks were A = innovative practices; B = best management practice; C = minimum standard practices; D = superseded practices. The 2013 Paddock to Reef program Water Quality Risk Frameworks replaced the ABCD frameworks with an equivalent risk to water quality: A = Lowest risk; B = Moderate-Low risk; C = Moderate risk; D = High risk. These have been further refined with the 2018 update to the frameworks (see section 4.1).

APSIM: The *Agricultural Production Systems sIMulator (APSIM)* model is an advanced simulation crop model that contains a suite of modules which enable the simulation of plant, animal, soil, climate and management interactions. It is used for modelling the efficacy of management practices in sugarcane in the Paddock to Reef program.

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

Beale Ratio: A method for calculating pollutant load estimations. On days on which samples are taken, the daily load is calculated as the product of concentration and flow, and the mean of these loads is also calculated. The mean daily load is then adjusted by multiplying it by a flow ratio, which is derived by dividing the average flow for the year as a whole by the average flow for the days on which chemical samples were taken. A bias correction factor is included in the calculation, to compensate for the effects of correlation between discharge and load. The adjusted mean daily load is multiplied by 365 to obtain the annual load.

Best Management Practice (BMP): Best management practices articulate a reasonable best practice level which can be expected to result in a moderate-low water quality risk.

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.

Coastal ecosystems: Coastal freshwater wetlands and estuarine systems connect the land and sea and have the potential to influence the health and resilience of the Great Barrier Reef. This includes the Great Barrier Reef catchment and 10% of the marine waters seawards of the coastline (GBRMPA, 2012).

DARTS: The DAta Recording Tool for Science (DARTS) within the SSMIR data management environment (see below) provides a platform for monitoring data from the Paddock to Reef program to be uploaded, stored and managed. Metadata is stored for all datasets.

EMC: The Event Mean Concentration is the pollutant concentration derived when dividing total pollutant load by total flow.

eagle.io: A cloud-based data acquisition, storage and visualisation platform. The Great Barrier Reef Catchment Loads Monitoring Program uses eagle.io to monitor and control the operational status of all its automated monitoring station. See Appendix 2 for further detail.

eReefs: The eReefs research project is a collaboration between the Great Barrier Reef Foundation, CSIRO, the Australian Institute of Marine Science, Bureau of Meteorology and Queensland Government. The eReefs system models a wide range of marine variables covering physical properties (temperature, current, light penetration) as well as biogeochemical parameters (such as the concentration of nutrients, sediments, plankton and chlorophyll-a). Three-dimensional model outputs are generated for the entire Great Barrier Reef lagoon (from South East Queensland to Torres Strait) at various resolutions (1km and 4km) on a daily basis. It provides information on physical processes, sediment transport, biogeochemistry and ocean colour.

GRASP: The GRASs Production model (GRASP) is used to derive changes in ground cover (C-factor) to represent reductions in loads for different grazing management practices in the RUSLE model (see below).

HowLeaky: *HowLeaky* is water balance and water quality simulation software environment incorporating the *PERFECT* water balance model, developed to assess the impacts of different land uses, soil types, management practices and climates on hydrology and water quality.

Human Dimensions: In the sense that human behaviour will impact on water quality outcomes, human dimensions include social, cultural, institutional and economic factors: from the aspirations and capacities of landholders, industries and communities, to their stewardship practices, and broader governance of the Reef.

HYDSTRA Database: The electronic data management system established by the Queensland Government for managing river flow and surface water data.

P2R Projector: The Paddock to Reef Project Selector ('P2R Projector Tool') is an online application based on Paddock to Reef program paddock and catchment modelling outputs. It is a spatially and project-specific prioritisation tool created to support groups who are working with farmers on improving their water quality. See Appendix 2 for further detail.

Management unit: There are 47 management units in the Great Barrier Reef catchment, which incorporate the 35 basins that drain directly to the Great Barrier Reef and additional internal catchments or management units within the Burdekin and Fitzroy basins.

msPAF: The multi-substance Potentially Affected Fraction (msPAF) 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) 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).

NRM region: There are six natural resource management (NRM) 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.

Nutrients: Nutrients are the natural chemical elements and compounds that plants and animals need to grow. Carbon, hydrogen and oxygen are abundant nutrients in nature, but nitrogen and phosphorus are not always so freely available, and therefore affect plant growth. Nitrogen and phosphorus are transported in run-off as tiny particles (particulates) and dissolved in water. The dissolved nutrients are immediately available for biological uptake, and particulate nutrients may also become biologically available.

Other pollutants: Includes contaminants such as antifouling paints, coal particles, metals and metalloids, marine debris/microplastics, personal care products, petroleum hydrocarbons and pharmaceuticals. In addition, contaminants such as nanomaterials, perfluorooctane sulfonate and perfluorooctanoic acid may be present, but no monitoring information is available for the Great Barrier Reef lagoon.

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.

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

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 until 2050. 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.

RUSLE: The *Revised Universal Soil Loss Equation (RUSLE)* is used to describe soil erosion processes. The equation is used to predict the long-term average annual soil loss. The equation includes the rainfall erosivity factor, the soil erodibility factor, the topographic factors and the land management factors.

2017 Scientific Consensus Statement: The *2017 Scientific Consensus Statement: Land use impacts on Great Barrier Reef water quality and ecosystem condition* is a foundational document which provides the scientific understanding underpinning the Reef 2050 Water Quality Improvement Plan 2017-2022. It was collated by a multidisciplinary group of scientists, with oversight from the Independent Science Panel. The 2017 Scientific Consensus Statement provides an update to the last statement published in 2013.

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 (<16 µm) sediment moving furthest into the marine environment, leading to increased turbidity and reduced light, and therefore posing the greatest risk.

SKIP: The *Science Knowledge and Information Provision (SKIP)* is a structured data repository within the SSMIR platform (see below), with enhanced metadata capabilities. Its primary purpose is to capture, collaborate and preserve scientific data for specific locations for the Paddock to Reef program through a structure of project sites, libraries and folders. It is based on the Microsoft SharePoint 2010 platform.

Social Factors: Social factors measure the human dimensions that influence the capacity, motivations and barriers to landholder engagement in stewardship and agricultural management practice adoption that improve water quality outcomes.

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.

SPOT Satellite Imagery: A high resolution satellite imagery product available since 1986. The SPOT satellite Earth Observation System generates products at a range of pixel sizes, between 2.5m and 20m.

SSIMR: The *Spatial and Scientific Information Management for Reef (SSMIR)* data management environment provides a centralised environment for the management of Paddock to Reef program data, incorporating procedures, protocols and infrastructure appropriate for the storage, management, access and delivery of information and data needed for, and produced by, projects. DARTS and SKIP (see definitions here) are data management tools within SSMIR.

Stewardship: Local environmental stewardship is the actions taken by individuals, groups or networks, with various motivations and levels of capacity, to protect, care for or responsibly use the environment in pursuit of environmental, economic and/or social outcomes in diverse social-ecological contexts (derived from Bennett et al., 2018).

Water Quality Risk Frameworks: The Paddock to Reef program Water Quality Risk Frameworks identify the management practices with greatest potential influence on off-farm water quality, and articulate a reasonable best practice level which can be expected to result in a moderate-low water quality risk.

Wet season water types (for the Marine Monitoring Program): The wet season water types used by the Marine Monitoring Program are produced using MODIS true colour imagery reclassified to six distinct colour classes defined by their colour properties. The wet season water types are regrouped into three water types (primary, secondary and tertiary) characterised by different concentrations of optically active components (suspended sediment, colour dissolved organic matter and chlorophyll-a), which control the colour of the water and influence the light attenuation, and different pollutant concentrations:

- Primary water type (colour classes 1–4): Corresponds to the brownish to brownish-green turbid water masses. These waters have high nutrient and phytoplankton concentrations but are also enriched in sediment and dissolved organic matter and have reduced light levels. They are typical for nearshore areas or inshore regions of flood river plumes.
- Secondary water type (colour class 5): Corresponds to the greenish to greenish-blue water masses and are typical of coastal waters dominated by algae, but also with some dissolved matter and some fine sediment present. Relatively high nutrient availability and increased light levels due to sedimentation favour an increased coastal productivity in this water type. This water type is typical for the coastal waters or the mid-region of river plumes.
- Tertiary water type (colour class 6): Transitional, greenish-blue water mass with slightly above ambient turbidity and nutrient concentrations. This water type is typical for areas towards the open sea or offshore regions of flood river plumes.

Wetlands (definitions from the Queensland Wetlands Program): Areas of permanent or periodic/intermittent inundation, with water that is static or flowing fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed 6m. To be a wetland, the area must have one or more of the following attributes:

- At least periodically, the land supports plants or animals that are adapted to and dependent on living in wet conditions for at least part of their life cycle.
- The substratum is predominantly undrained soils that are saturated, flooded or ponded long enough to develop anaerobic conditions in the upper layers.
- The substratum is not soil and is saturated with water, or covered by water at some time.

Wetland systems (Queensland Wetlands Program definition) include:

- *Riverine wetlands* are all wetlands and deep water habitats within a channel. The channels are naturally or artificially created, periodically or continuously contain moving water or connect two bodies of standing water.
- *Palustrine wetlands* are primarily vegetated non-channel environments of less than 8ha. They include billabongs, swamps, bogs, springs, soaks etc. and have more than 30% emergent vegetation.
- *Estuarine wetlands* are those with oceanic water sometimes diluted with freshwater run-off from the land.
- *Lacustrine wetlands* are large, open, water-dominated systems (e.g. lakes) larger than 8ha. This definition also applies to modified systems (e.g. dams), which are similar to lacustrine systems (e.g. deep, standing or slow-moving waters).

Wetland*Info*: Wetland*Info* is a first-stop-shop for wetland information in Queensland providing a range of tools and resources to assist with the sustainable management of wetlands.

Executive summary

The Great Barrier Reef is renowned internationally for its ecological importance and beauty. However, it is under increasing threat from a range of pressures including the combined impact of land run-off associated with past and ongoing catchment development and management activities, coastal development activities, extreme weather events and climate change impacts such as the recent extensive coral bleaching events.

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. The long-term (2050) outcome for the plan is that '*Good water quality sustains the outstanding universal value of the Great Barrier Reef, builds resilience, improves ecosystem health and benefits communities'*. The Reef 2050 WQIP defines objectives to contribute to ecosystem health and social and ecosystem resilience and benefits, and sets targets for improved water quality, land and catchment management and community engagement.

The Reef 2050 WQIP needs to be supported by a robust monitoring and evaluation program. The Paddock to Reef Integrated Monitoring, Modelling and Reporting program (Paddock to Reef program) was established in 2009, and will continue to provide the principal framework for evaluating and reporting progress towards Reef 2050 WQIP targets through the Great Barrier Reef Report Card. The program is a collaboration involving Queensland and Australian government agencies, industry bodies, regional Natural Resource Management bodies, landholders and research organisations. It is jointly funded by the Australian and Queensland governments, and has continued to improve in terms of scope, methodology and application over the 10-year period of implementation.

A key consideration for the Paddock to Reef program is the ability to reflect changes in water quality at the end-of-catchment in the context of a variable climate, and to assess this against targets set over relatively short time frames. This is particularly true for large dry tropical catchments such as the Burdekin River, which has high inter- and intra- annual flow variability, and where considerable time lags exist before water quality improvements may be detected at the end-of-catchment via direct monitoring. A model framework supported by monitored data that links management action in catchments to water quality and ecological responses to receiving waters is required to report progress in the timeframes of the Reef 2050 WQIP targets and is a fundamental underpinning to the Paddock to Reef program. Modelling scenarios can also assist in separating climate and management influences.

The design framework for the Paddock to Reef program (Section 1.2.2) is built on these concepts. It provides a comprehensive approach to integrating monitoring and modelling information on management practices, catchment indicators, catchment loads and the health of the Great Barrier Reef across a range of scales. It integrates the best available information for multiple lines of evidence, recognising and addressing the issue that data confidence varies across the indicators and regions.

This document outlines the updated five-year design of the Paddock to Reef program from 2018 to 2022. It is informed by a program review which considered whole of program issues such as data management, scoring, reporting and communication (Section 1.3.2) including recommendations for program improvement (Section 6). The scope and methods of the program areas were also considered, building on individual external reviews. The review has resulted in an integrated monitoring and modelling program design that optimises the use of available resources and capacity. The revised scope of the program aligns with the expanded scope of the Reef 2050 WQIP and is complementary to and supportive of the Reef 2050 Long-Term Sustainability Plan (Reef 2050 Plan), regional water quality improvement plans and the associated monitoring and reporting programs i.e. the Reef 2050 Integrated Monitoring and Reporting Program (RIMReP) and Regional Report Cards. As the RIMReP becomes operational, the Paddock to Reef program will be nested within RIMReP to report on catchment-based activities and, along with the Regional Report Cards, deliver the Catchment and Estuaries theme within the broader RIMReP design.

The Paddock to Reef program delivers a range of products and outputs to support adaptive management and implementation of the Reef 2050 Plan and Reef 2050 WQIP. Section 3 describes these outputs and identifies how the program supports reporting of progress towards the Reef 2050 WQIP targets, objectives and long-term outcome. Key products include the annual Great Barrier Reef Report Card and supporting technical reports, and a range of tools to support prioritisation and decision-making. Some examples include: the 'P2R Projector Tool' which is a prioritisation tool to support the selection of projects to improve water quality for the sugarcane, banana and grains industries (the capacity to include grazing data is being developed in this phase of the Paddock to Reef program); and eagle.io which is a web-based platform utilised by the Catchment Loads Monitoring Program to report catchment monitoring data in real time to program partners via a secure login. A catchment modelling dashboard is also being developed for visualisation of modelling outputs including maps and graphs based on user defined queries (e.g. parameter, timeframe). The Paddock to Reef program reporting elements, measures and scope are summarised in Section 4. There are 13 inter-related program areas under five themes which are integrated through a common assessment and reporting framework.

The Paddock to Reef program actively applies the principle of continuous improvement and maintains a high standard of protocols for quality assurance and scientific review (Section 4). The 2018-2022 design incorporates several improvements, most of which have been progressed in the last two years. These are summarised in the description of each program area (Section 3). Highlights include:

- The update of the agricultural management practice adoption Water Quality Risk Frameworks for each of the key agricultural industries to better align terminology and incorporate additional practices. In addition, the spatial baselines that show current levels of adoption for each class of management have been updated with more lines of evidence, and larger and more representative datasets. This builds greater confidence in the land management practice adoption reporting.
- More detailed modelling of sugarcane, bananas and grains management practice, soil and climate scenarios (e.g. sugarcane management scenarios increased from 4 to 156 to represent more combinations of management to better reflect how management occurs).
- Expansion of the coverage of the catchment water quality monitoring sites from 14 basins to 20 basins, and 25 sites to 43 sites sampled on a regular basis, with a further 19 sites to be sampled for pesticides in 2017-2018 and 2018-2019.
- Incorporation of improved inputs to the catchment pollutant load models including seasonal ground cover, improved soils layer, extended modelling climate period and hydrology recalibration, finer resolution topographic data, and expanded water quality monitoring data sets.
- A desktop and field gully-mapping program is continuing to improve the spatial representation of gullies in the catchment models. As updated gully maps become available they are incorporated into the models – areas included to date are the Normanby, Burdekin and Fitzroy catchments, and Burnett and Herbert will be completed in 2018.
- Increased calibration of the ground cover method, which is based on approximately 3,600 field sites (previously approximately 1,800 field sites), and improved estimations of highly bare areas to better predict erosion from gullies, scalds, tracks, cattle pads, etc.
- Reporting of a 50m riparian vegetation buffer (previously 100m) which aligns with the buffer widths used for identifying Category R vegetation (i.e. high value regrowth in riparian areas) of the *Vegetation Management Act 1999*. This is achieved through the use of higher resolution imagery.
- Separation of wetland hydrological modification in defining changes in wetland extent.
- Development and implementation of the wetland condition and pressures monitoring program.
- Expansion of the spatial/temporal sampling of the Marine Monitoring Program in four focus areas and introduction of marine water quality sampling in Cape York.
- Incorporation of eReefs marine modelling outputs into marine condition reporting products.

Recommendations for future improvements to the Paddock to Reef program are included in Section 6. Many of these improvements are related to the incorporation of new input data, adoption of higher resolution products (e.g. ground cover monitoring), improvements to the ease of access to the data (across all program areas) and proposed expansion in geographic coverage of the programs (e.g. in the Marine Monitoring Program).

This design document for the Paddock to Reef program provides an overview of the background and objectives of the program (Section 1), an overview of the program delivery arrangements (Section 2), a description of the program outputs including reporting and communication (Section 3), an overview of each program area (Section 4), data management and quality assurance protocols (Section 4), issues of confidence and uncertainty (Section 5), and recommendations to support continuous improvement (Section 6). Further detail of the design is provided in supporting technical documents and online resources, identified in the text. It represents a strong foundation for monitoring, interpreting and reporting on water quality status and trends and related ecosystem health in the Great Barrier Reef, and the pressures and drivers of water quality condition from the Great Barrier Reef catchment. The program design also develops and improves the evidence base that provides the foundation for learning and improvement to support adaptive management for actions within the Reef 2050 Plan and Reef 2050 WQIP.

1. Introduction and background

1.1 The Paddock to Reef Integrated Monitoring, Modelling and Reporting Program

The Great Barrier Reef is an extensive coral reef system (Figure 1) which also contains high value areas of seagrass and mangroves, and a range of iconic megafauna including whales, dugongs, turtles, sharks, dolphins and large fish. The cumulative effects of multiple pressures have substantially reduced the health and resilience of this unique system (Waterhouse et al., 2017a). This includes the combined impact of land run-off associated with past and ongoing catchment development, coastal development activities, extreme weather events and the impacts of a changing climate such as the recent extensive coral bleaching events. Additionally, Great Barrier Reef coastal ecosystems have been highly modified and continue to be exposed to a range of catchment development pressures.

Further to these wide scale chronic pressures, recent, more localised disturbance events have resulted in severe and extensive impacts to a number of Great Barrier Reef ecosystems—including prolonged periods of extreme elevated sea surface temperatures, multiple severe tropical cyclones and the progression of the fourth wave of crown-of-thorns starfish population outbreaks. Climate change is likely to continue to be the strongest driver of ecological change for the Great Barrier Reef in the future with increased frequency in coral bleaching events and more severe cyclones (GBRMPA, 2014a). Reducing the chronic pressures on Great Barrier Reef ecosystems, through improvements in water quality and land and catchment management, is critical to improve the health and build resilience of Great Barrier Reef ecosystems to strengthen the Reef's ability to withstand and recover from extreme events (Waterhouse et al., 2017a).

As illustrated in Figure 2, management of these issues is addressed through a range of policy, planning, monitoring and reporting initiatives. In 2015, the Australian and Queensland governments released the Reef 2050 Long-Term Sustainability Plan (Reef 2050 Plan) (Commonwealth of Australia, 2015). The Reef 2050 Plan identifies seven themes (ecosystem health, biodiversity, heritage, water quality, community benefits, economic benefits and governance) for managing the Great Barrier Reef World Heritage Area. The Reef 2050 Water Quality Improvement Plan 2017-2022 (Reef 2050 WQIP) (Queensland and Australian government, 2018) delivers the water quality theme within the Reef 2050 Plan. The plan is a joint commitment of the Australian and Queensland governments and identifies actions that will help minimise the risk to the Great Barrier Reef from a decline in the quality of water entering the Great Barrier Reef from adjacent catchments. It builds on three previous iterations of the Reef Water Quality Protection Plan (2003, 2009 and 2013). The long-term (2050) outcome for the plan is that '*Good water quality sustains the outstanding universal value of the Great Barrier Reef, builds resilience, improves ecosystem health and benefits communities*'.

In response to the broader scope of the Reef 2050 Plan, findings of the Great Barrier Reef Water Science Taskforce (GBRWST, 2016), stakeholder consultation, and the findings of the 2017 Scientific Consensus Statement, the Reef 2050 WQIP builds on previous water quality plans by:

- Including all sources of land-based water pollution: agriculture, industry, urban and public lands, while recognising that the majority of land-based water pollution still arises from agricultural activities.
- Incorporating the human dimensions of change. These include social, cultural, institutional and economic factors: from the aspirations and capacities of landholders, industries and communities, to their stewardship practices, and the broader governance of the Great Barrier Reef.
- Incorporating ecosystem objectives for biodiversity and improving the condition of wetland coastal ecosystems.
- Setting separate targets for reducing water pollution from each catchment, to enable better prioritisation of where action needs to be taken.

The name of the water quality plan has changed from the Reef Water Quality Protection Plan to the Reef 2050 Water Quality Improvement Plan 2017-2022 to better demonstrate its alignment with the Reef 2050 Plan.

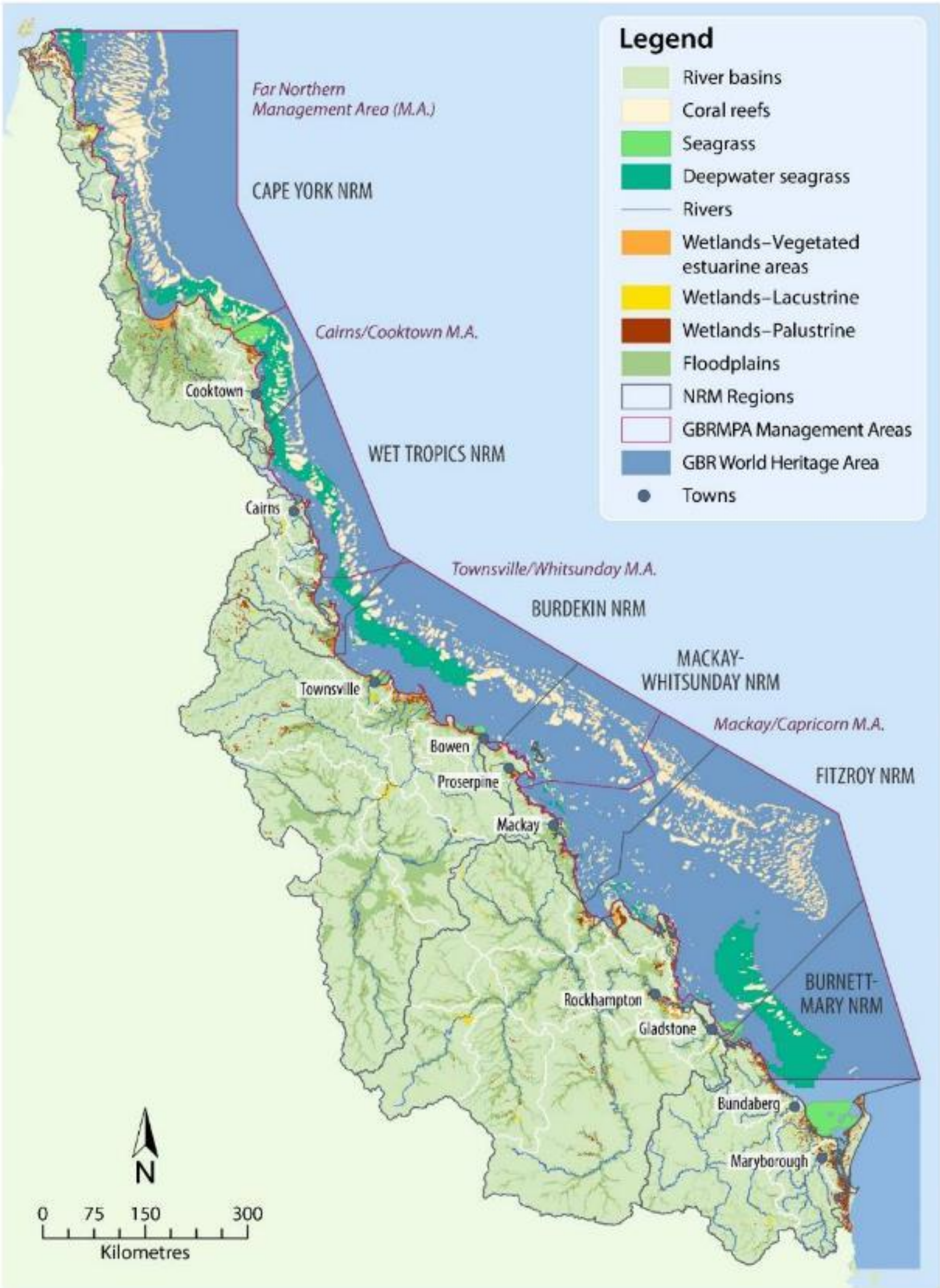

Figure 1. Map showing the Great Barrier Reef Management Areas, coastal aquatic and marine habitats, catchment boundaries, NRM regions and marine NRM boundaries. Map prepared by D. Tracey, TropWATER James Cook University.

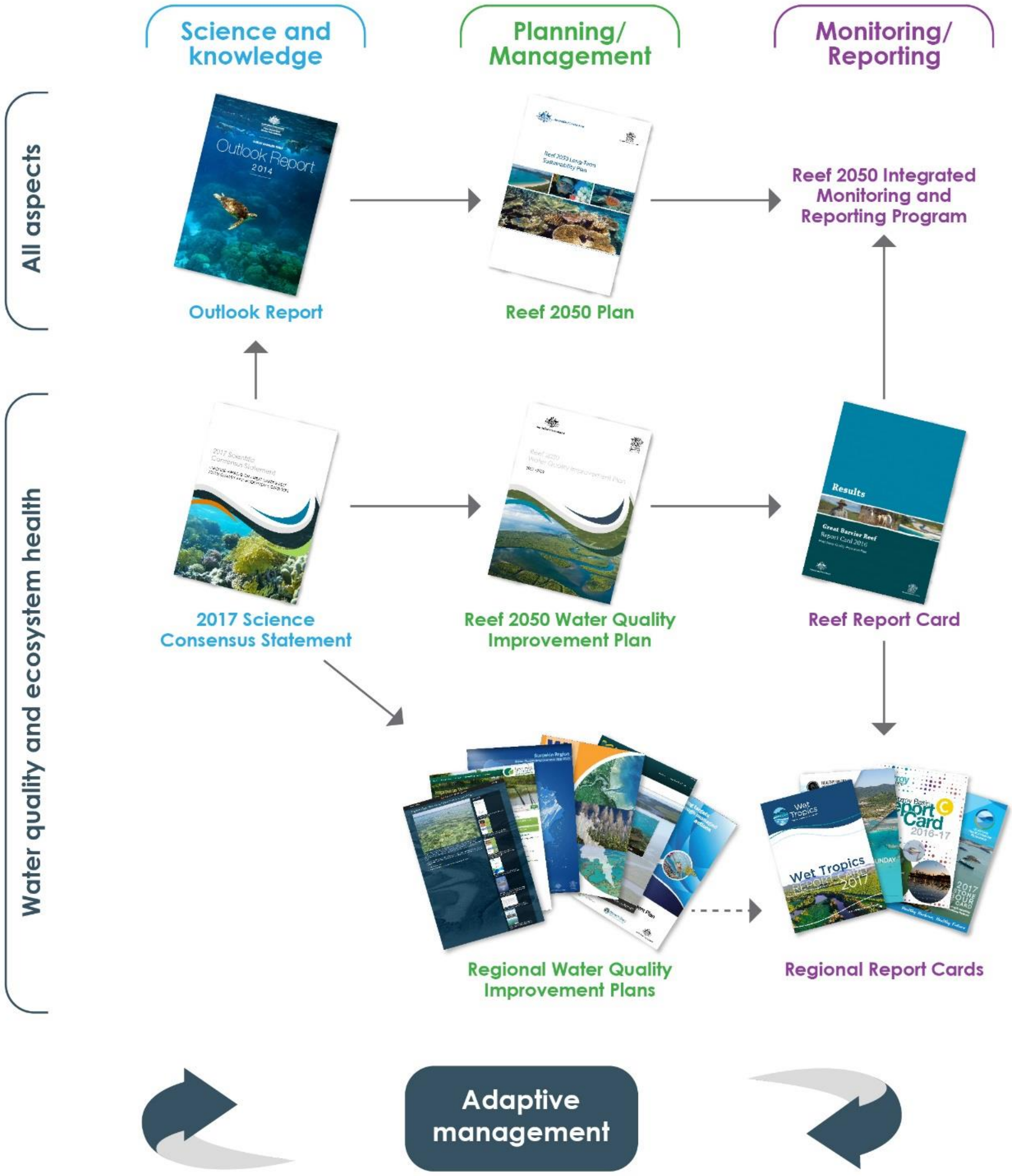

Figure 2. Illustration of the scope of the Reef 2050 Water Quality Improvement Plan in the context of related Great Barrier Reef programs at Great Barrier Reef and regional scales.

The Reef 2050 WQIP defines objectives to contribute to ecosystem health and social and ecosystem resilience and benefits, and sets targets for improved water quality, land and catchment management and community engagement (Figure 3). Of critical importance for the health of the Great Barrier Reef is the definition of catchment-specific end of catchment load targets for fine sediment, dissolved inorganic nitrogen and particulate nutrients, and ecosystem protection targets for pesticides. These load reduction targets are defined to maintain ecosystem health and as such are considered to be ecologically relevant.

Table 1 shows water quality targets for each catchment with the relative spatial management priority for water quality improvement (as defined by Brodie et al., 2017). The plan also identifies work areas and actions required to improve the quality of water entering the Great Barrier Reef.

As illustrated in Figure 4, the Reef 2050 WQIP requires a robust monitoring and evaluation program, to evaluate the efficiency and effectiveness of implementation and report on progress towards the long-term outcome, objectives and targets (the 'Evaluating performance' work area, B4). The Paddock to Reef Integrated Monitoring, Modelling and Reporting program (Paddock to Reef program) established in 2009 (and reviewed in 2013), contributes to the immediate outcome of 'Enabling delivery' and will continue to provide the principle framework for evaluating and reporting progress towards Reef 2050 WQIP targets. The program is jointly funded by the Australian and Queensland governments, and has continued to improve in terms of scope, methodology and application over the 10-year period of its implementation. This design is for the third phase of the Paddock to Reef program, 2018 to 2022.

A new monitoring and evaluation program, the Reef 2050 Integrated Monitoring and Reporting Program (RIMReP), is currently being designed to track progress towards the targets and objectives of the broader Reef 2050 Plan. The program will span the Great Barrier Reef World Heritage Area and adjacent catchments, incorporating the seven themes outlined in the Reef 2050 Plan: biodiversity, ecosystem health, water quality, community benefits, heritage, economic benefits and governance. It will encompass all aspects of the Great Barrier Reef environment, including natural and physical attributes, heritage values, and social, economic and cultural aspects. The program will provide the coordination, alignment and integration of existing monitoring, modelling and reporting programs (such as the Paddock to Reef program) to capitalise on existing program investment, provide value for money, improve efficiency and avoid duplication of effort.

The RIMReP is being designed with advice from Expert Theme Groups: Coral Reefs, Seagrass, Marine Physico-Chemical Environment, Islands, Megafauna (which has several subgroups: dugong, turtles, seabirds and shorebirds, great whales, coastal dolphins, drones, Indigenous monitoring, citizen science), Human Dimensions, Indigenous Heritage, Fisheries and Catchment and Estuaries. As the program becomes operational, the Paddock to Reef program will be nested within RIMReP to report on catchment-based activities and, along with the regional waterway health report cards, deliver the Catchment and Estuaries theme within the broader RIMReP design. The marine components of the Paddock to Reef program, currently delivered by the Marine Monitoring Program largely focus on the coastal and inner shelf areas of the Great Barrier Reef. The updated design for this component of the Paddock to Reef program will be delivered via the new RIMReP Program Design.

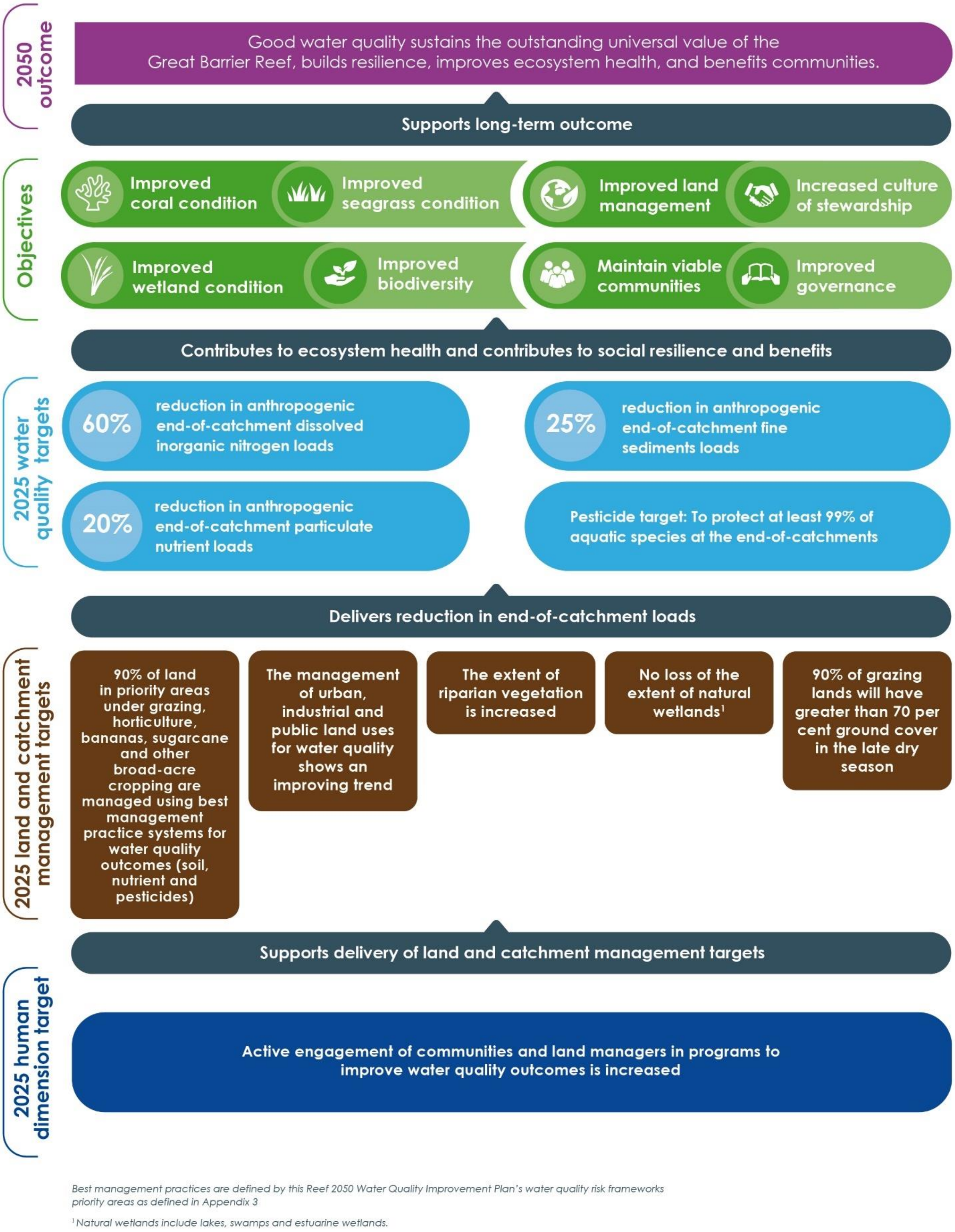

Figure 3. Reef 2050 Water Quality Improvement Plan outcomes, objectives and targets. Source: Reef 2050 WQIP.

Table 1. End-of-catchment anthropogenic water quality targets for the Reef catchments by 2025 and relative priorities for water quality improvement (t= tonnes; MCL = maintain current load; ND= not determined). Reproduced from the Reef 2050 WQIP.

Management priority					
	Very high		Moderate		Minimal
	High		Low		Not assessed

Region	Catchment/ Basin	Area (ha)	Targets								Pesticide target to protect min 99% of aquatic species at end-of-catchment
			Dissolved inorganic nitrogen		Fine sediment		Particulate phosphorus		Particulate nitrogen		
			tonnes	% reduction	kilo-tonnes	% reduction	tonnes	% reduction	tonnes	% reduction	
Cape York	Jacky Jacky Creek	296,330	**MCL**	MCL	**MCL**	MCL	**MCL**	MCL	**MCL**	MCL	
	Olive Pascoe River	417,950	**MCL**	MCL	**MCL**	MCL	**MCL**	MCL	**MCL**	MCL	
	Lockhart River	288,330	**MCL**	MCL	**1**	2	**2**	2	**5**	2	
	Stewart River	274,280	**MCL**	MCL	**2**	6	**2**	6	**7**	6	
	Normanby River	2,439,490	**MCL**	MCL	**15**	10	**5**	10	**15**	10	
	Jeannie River	363,750	**MCL**	MCL	**2**	6	**2**	6	**9**	6	
	Endeavour River	218,240	**MCL**	MCL	**3**	10	**3**	10	**11**	10	
Wet Tropics	Daintree River	210,670	**MCL**	MCL	**MCL**	MCL	**MCL**	MCL	**MCL**	MCL	
	Mossman River	47,240	**52**	50	**MCL**	MCL	**MCL**	MCL	**MCL**	MCL	
	Barron River	218,880	**52**	60	**MCL**	MCL	**MCL**	MCL	**MCL**	MCL	
	Mulgrave-Russell River	194,400	**300**	70	**16**	10	**19**	10	**53**	10	
	Johnstone River	232,390	**350**	70	**100**	40	**250**	40	**490**	40	
	Tully River	168,350	**190**	50	**17**	20	**23**	20	**68**	20	
	Murray River	110,840	**120**	50	**8**	20	**11**	20	**32**	20	
	Herbert River	984,590	**620**	70	**99**	30	**57**	30	**200**	30	
Burdekin	Black River	105,970	**ND**	ND	**ND**	ND	**ND**	ND	**ND**	ND	
	Ross River	170,820	**74**	60	**ND**	ND	**ND**	ND	**ND**	ND	
	Haughton River	405,080	**640**	70	**MCL**	MCL	**MCL**	MCL	**MCL**	MCL	
	Burdekin River	10,310,940	**100**	60	**840**	30	**440**	30	**720**	30	
	Don River	373,620	**MCL**	MCL	**55**	30	**43**	30	**75**	30	
Mackay/ Whitsunday	Proserpine River	249,440	**110**	70	**MCL**	MCL	**MCL**	MCL	**MCL**	MCL	
	O'Connell River	238,760	**130**	70	**96**	40	**120**	40	**250**	40	
	Pioneer River	157,360	**140**	70	**35**	20	**23**	20	**61**	20	
	Plane Creek	253,870	**260**	70	**MCL**	MCL	**MCL**	MCL	**MCL**	MCL	
Fitzroy	Styx River	301,340	**MCL**	MCL	**MCL**	MCL	**MCL**	MCL	**MCL**	MCL	
	Shoalwater Creek	360,180	**MCL**	MCL	**MCL**	MCL	**MCL**	MCL	**MCL**	MCL	
	Waterpark Creek	183,650	**MCL**	MCL	**MCL**	MCL	**MCL**	MCL	**MCL**	MCL	
	Fitzroy River	14,254,470	**MCL**	MCL	**390**	30	**380**	30	**640**	30	
	Calliope River	224,060	**MCL**	MCL	**15**	30	**54**	30	**107**	30	
	Boyne River	249,630	**MCL**	MCL	**6**	40	**5**	40	**9**	40	
Burnett Mary	Baffle Creek	408,470	**16**	50	**11**	20	**15**	20	**33**	20	
	Kolan River	290,450	34	50	**6**	20	**5**	20	**14**	20	
	Burnett River	3,319,540	**150**	70	**85**	20	**29**	20	**68**	20	
	Burrum River	337,170	**93**	50	**3**	20	**3**	20	**8**	20	
	Mary River	946,580	**180**	50	**130**	20	**160**	20	**470**	20	

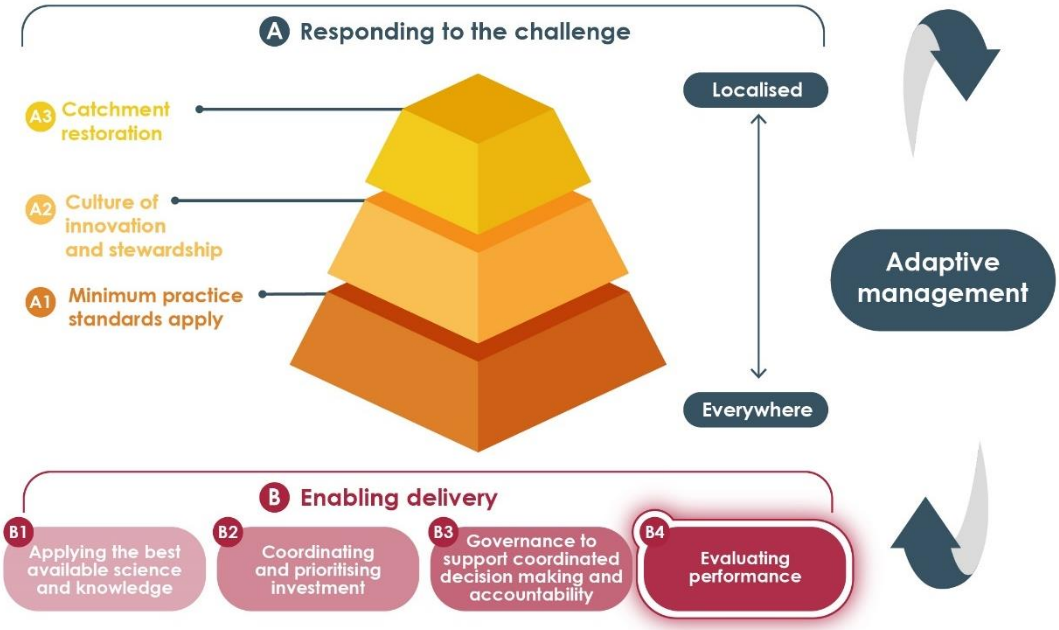

Figure 4. Visual summary of the Reef 2050 Water Quality Improvement Plan work areas. Source: Reef 2050 WQIP.

At a regional scale, implementation of the Reef 2050 WQIP is guided by regional Water Quality Improvement Plans (WQIPs). These regional plans were either updated or developed between 2014 and 2016 and define management strategies to support improved water quality outcomes for each of the six Natural Resource Management (NRM) regions which cover the Great Barrier Reef catchments. The Queensland and Australian governments support the regional waterway health report card partnerships in the Great Barrier Reef catchment as part of the Reef 2050 Plan (identified as a specific action). The partnerships bring together all levels of government, industry, research bodies, agriculture and community to develop a shared vision for their waterways and provide an annual report card on their health that can help inform continuous improvement in waterway health. Partnerships are in place for Gladstone Harbour, Mackay Whitsunday, Fitzroy Basin, Wet Tropics and the Dry Tropics (Townsville) area. The links between these partnerships and the regional WQIPs is being strengthened over time.

Further information on regional reporting is presented in Section 3.3.2.

The objectives of the Paddock to Reef program are to:

1. Monitor, interpret and report on water quality status and trends and related ecosystem health in the Great Barrier Reef, and the pressures and drivers of water quality condition from the Great Barrier Reef catchment.
2. Report on the progress towards Reef 2050 Water Quality Improvement Plan targets, objectives and long-term outcome through the delivery of the Great Barrier Reef Report Card.
3. Develop and improve the evidence base that provides the foundation for learning and improvement to support adaptive management for actions within the Reef 2050 Water Quality Improvement Plan.
4. Provide knowledge and insights to enable partners to evaluate, prioritise and continuously improve the efficiency and effectiveness of Reef 2050 Water Quality Improvement Plan delivery and implementation at Great Barrier Reef-wide, regional and catchment scales.
5. Provide the primary mechanism for evaluation of the water quality theme of the Reef 2050 Plan and in conjunction with the regional report cards, the Catchment and Estuaries theme of the Reef Integrated Monitoring and Reporting Program.

Broadscale improvements in water quality due to the adoption of new management practices may take years or decades to achieve. Bridging the gap between management action and water quality and ecosystem impacts can be achieved by modelling the delivery of pollutants generated in paddocks, transported downstream by rivers, to estuaries and ultimately to Great Barrier Reef coral reefs and seagrass meadows. In some conditions, pollutant delivery can extend to mid-shelf and even offshore areas.

A key consideration for the Paddock to Reef program is the ability to reflect changes in water quality at the end-of-catchment in the context of a variable climate, and to assess this against targets set over relatively short time frames. This is particularly true for large dry tropical catchments such as the Burdekin River, which has high inter- and intra- annual flow variability, and where considerable time lags exist before water quality improvements may be detected at the end-of-catchment via direct monitoring. Marine sediment resuspension from cyclones and tidal surges also complicates responses. Due to these lag times and 'noisy' water quality signals associated with inter-annual flow variability, it can take many years to capture the flow and pollutant concentration variability at a site (e.g. Melland et al., 2018). It is estimated that at least a 25-year flow period is suitable for measuring changes in run-off (Chiew and McMahon, 1993), and up to 50 years is needed for pollutant loads (Darnell et al., 2012). These response time frames are outside the current target time frames for the Reef 2050 WQIP, or previous plans. A model framework supported by monitored data that links management action in catchments to water quality and ecological responses to receiving waters is required to report progress in the time frames of the Reef 2050 WQIP targets and is a fundamental underpinning to the Paddock to Reef program. Modelling scenarios can also assist in separating climate and management influences.

The design framework for the Paddock to Reef program is built on these concepts. It provides a comprehensive approach to integrating monitoring and modelling information on management practices, catchment indicators, catchment loads and the health of the Great Barrier Reef across a range of scales. It integrates the best available information for multiple lines of evidence, recognising and addressing the issue that data confidence varies across the indicators and regions.

The RIMReP has adopted a modified Drivers-Pressures-State-Impact-Response (DPSIR) model. This organising framework, agreed to at an intergovernmental level, was applied in the Great Barrier Reef Outlook Report 2014 (GBRMPA, 2014a) and the Great Barrier Reef Strategic Assessment Report (GBRMPA, 2014b). To ensure direct alignment with the overarching RIMReP framework and principles, the Paddock to Reef program is also expressed within this framework. The DPSIR framework for the Paddock to Reef program is shown in Figure 5.

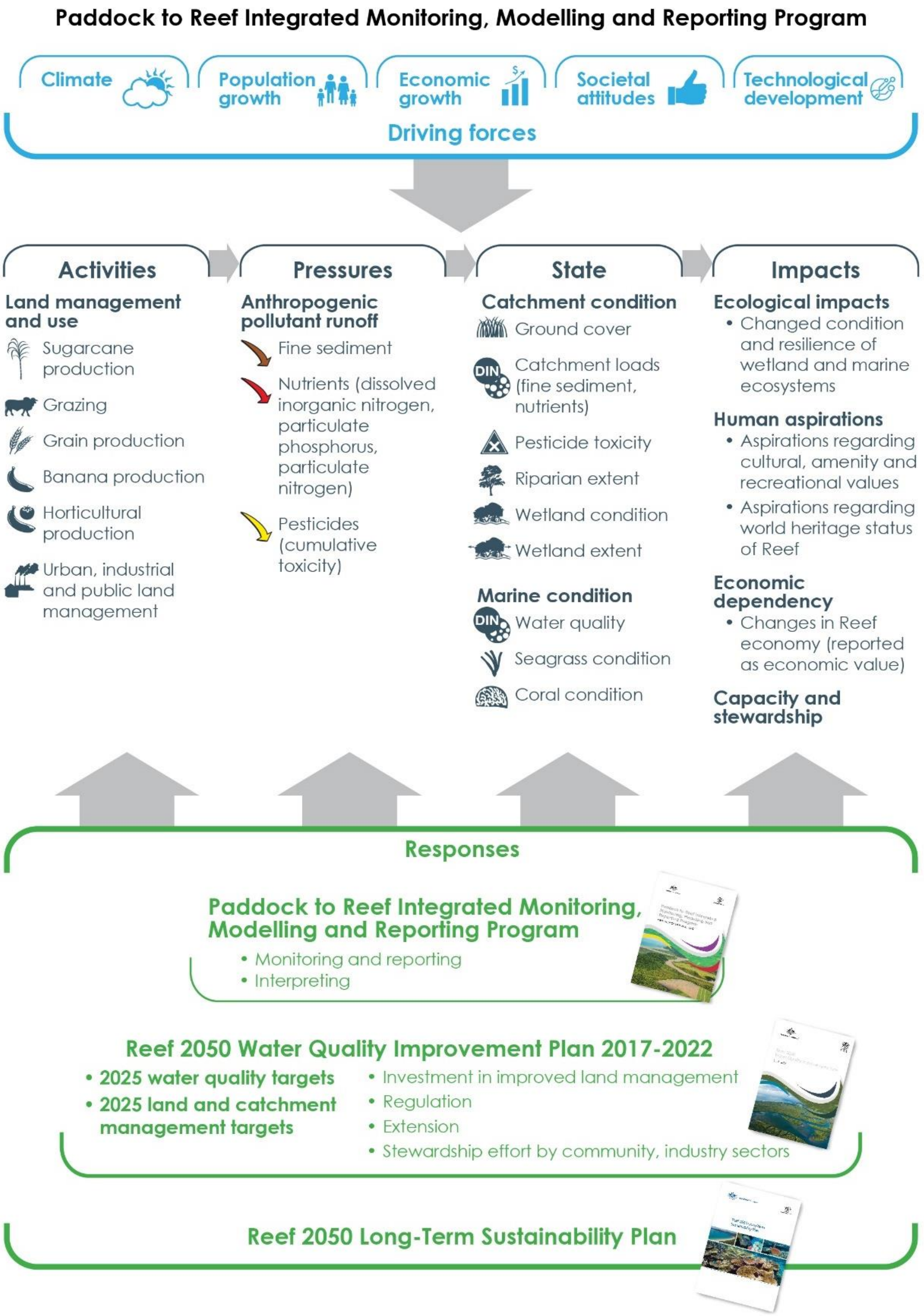

Figure 5. Drivers-Pressures-State-Impact-Response 'DPSIR' framework for the Paddock to Reef program. The Paddock to Reef program framework feeds directly into the Reef Integrated Monitoring and Reporting Program (RIMReP) to provide evaluation of the Reef 2050 Plan. This framework aligns with the DPSIR framework adopted by RIMReP.

1.2 Paddock to Reef program overview

1.2.1 Scope

The Great Barrier Reef coastal and marine ecosystems receive run-off from 35 catchments which drain 424,000km^2 of coastal Queensland (Figure 6). The Great Barrier Reef catchments are largely dominated by summer rainfall and river discharge which delivers large volumes of sediments, nutrients and pesticides to the Great Barrier Reef coastal and marine receiving waters. Compared to pre-development conditions, it is estimated that the annual mean fine sediment loads to the Great Barrier Reef lagoon have increased approximately 5-fold for the entire Great Barrier Reef catchment, ranging between 3- and 8-fold depending on the region (Bartley et al., 2017). The nutrient load has also increased considerably, for example, the annual mean dissolved inorganic nitrogen (DIN) load is also estimated to have experienced a Great Barrier Reef-wide 2.0-fold increase from pre-development conditions (ranging between 1.2 and 6.0, with the exception of Cape York) (Bartley et al., 2017). Pesticides are not natural and monitoring data shows that pesticides have been detected across the Great Barrier Reef and its catchments, even though some are in very small quantities.

Grazing is the dominant agricultural land use occupying approximately 73% of the Great Barrier Reef catchments, with large areas in the Burdekin and Fitzroy catchments. Sugarcane (1.3% of the Great Barrier Reef catchment area) and horticulture crops (0.2%) are more prevalent in coastal areas. Grain crops and irrigated cropping are prevalent in the inland areas of the Fitzroy region and cover approximately 2.8% (grains 2.4%; cropping 0.42%) of the Great Barrier Reef catchment area. Small urban centres are located along the coast with major centres in Cairns, Townsville, Mackay, Rockhampton and Bundaberg (total urban 0.58% of the Great Barrier Reef catchment area). Reef-based tourism, as well as commercial and recreational fisheries, are an important part of the regional economy.

While it is intended that the Paddock to Reef program addresses the full geographic scope of the Great Barrier Reef catchments and the receiving waters of the Great Barrier Reef, there are limitations in the ability to monitor and report across the whole geographic extent due to accessibility and resourcing. These limitations are overcome to some extent by the integrated monitoring and modelling approach adopted by the Paddock to Reef program, where modelling can be used to infill spatial gaps in the monitoring, and monitoring can be used to improve the models. This is explained further in the context of the framework, described in Section 1.2.2 below. This approach can be used to support specific locations where there is more limited monitoring, such as marine areas of the Cape York, Fitzroy and Burnett Mary regions. There is also recognition that water quality influences extend into mid-shelf of the Great Barrier Reef and, in large events, outer-shelf areas which is presently not included in the scope of the Marine Monitoring Program within the Paddock to Reef program. Amendments to the spatial scope of the Marine Monitoring Program are being addressed through the RIMReP development process to consider these priority gaps.

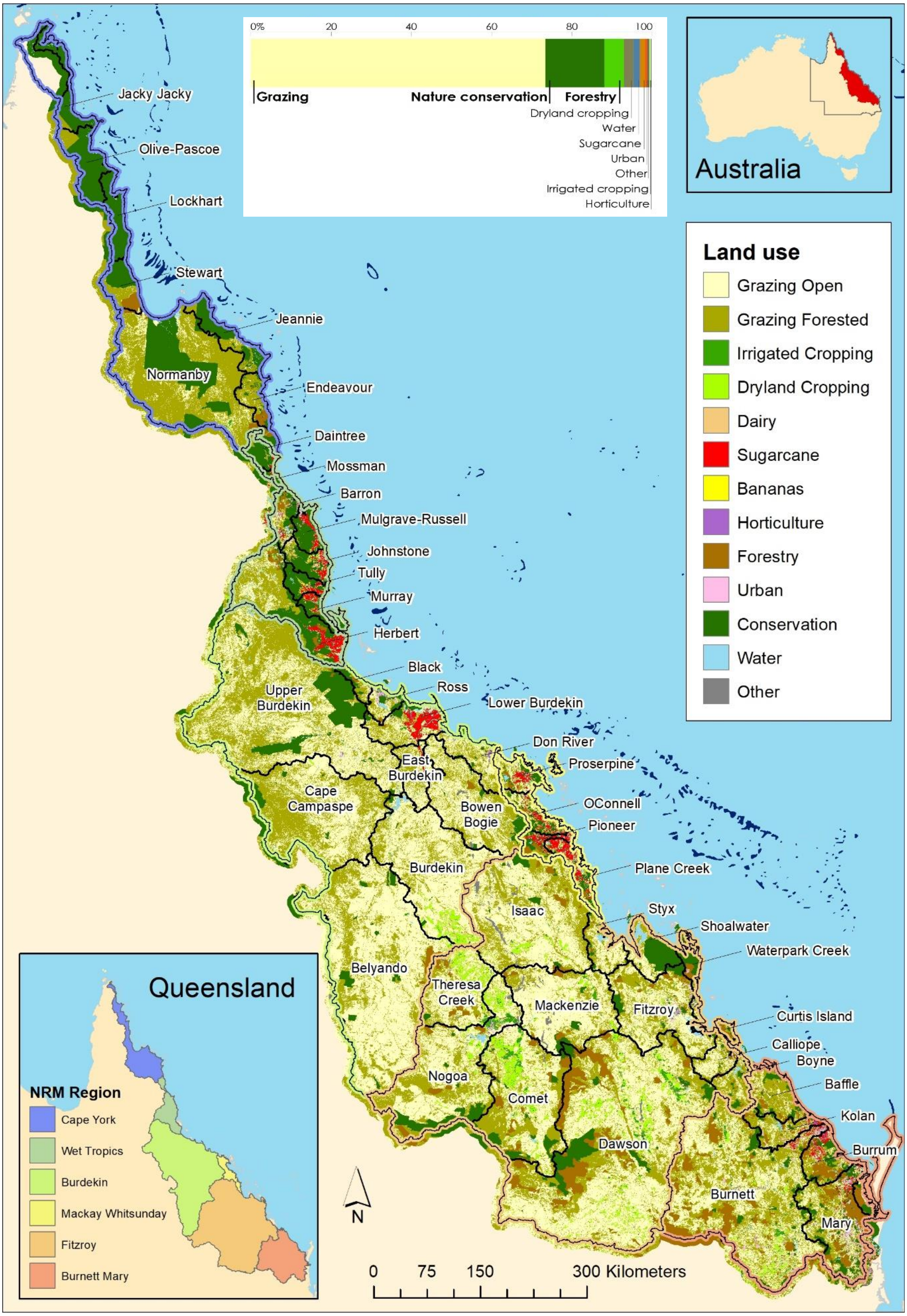

Figure 6. Map of the geographic scope of the Paddock to Reef program, showing the six Regional Natural Resource Management Regions, 35 major catchments and the Great Barrier Reef World Heritage Area boundary. Inset (top centre) shows the percentage of area of each land use in the Great Barrier Reef catchment.

1.2.2 Paddock to Reef program framework

The framework for the Paddock to Reef program is illustrated in Figure 7. The program uses multiple lines of evidence to report against the Reef 2050 WQIP targets and support program evaluation. It adopts a combined monitoring and modelling approach across a range of attributes, and at a range of scales across the Great Barrier Reef catchments including paddock, sub-catchment, catchment, regional and Great Barrier Reef-wide. In line with the Reef 2050 WQIP overarching framework of targets, objectives and the long-term outcome (Figure 3), the program evaluates management practice adoption, management practice effectiveness (in terms of water quality benefits and economic outcomes), catchment condition, pollutant run-off and marine condition.

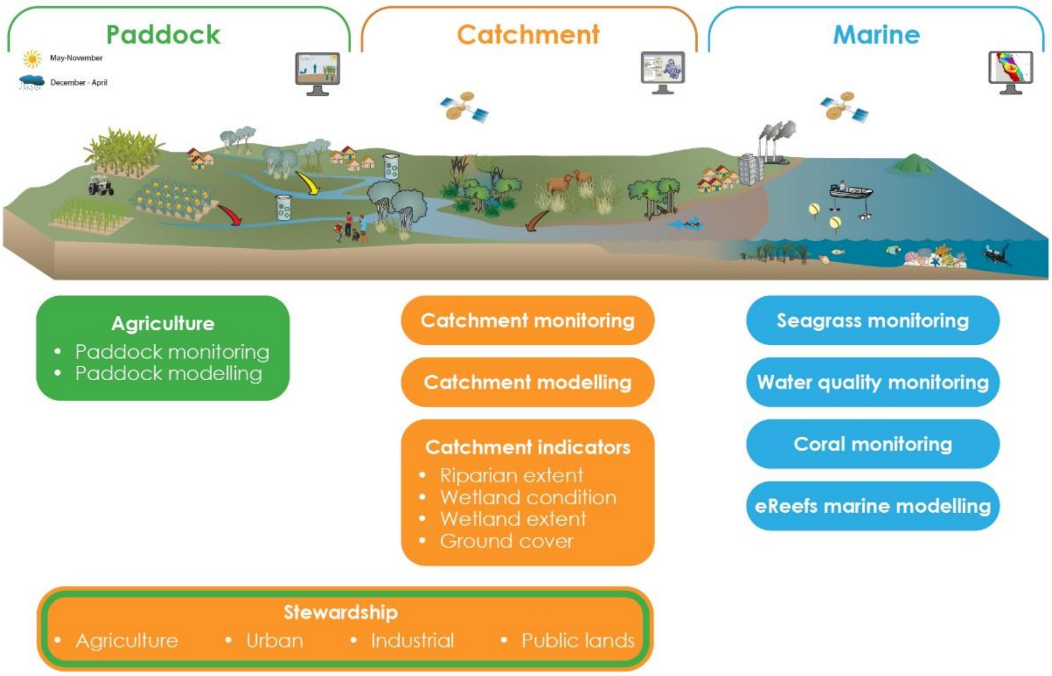

Figure 7. Graphical representation of the program areas within the Paddock to Reef program, 2018-2022.

The program areas are inter-linked (as shown in Figure 8) and integrated through a common assessment and reporting framework, the Great Barrier Reef Report Card. The program areas are outlined below with the main program themes and described in more detail in Section 4.

Stewardship

- Agricultural management practice adoption
- Social factors influencing agricultural management practice adoption (*phased implementation*)
- Non-agricultural land use management practice adoption (*phased implementation*)

Management practice effectiveness and paddock pollutant delivery (agricultural land uses)

- Economic benefits of agricultural management practices (*phased implementation*)
- Paddock monitoring of water quality benefits
- Paddock modelling of practice effectiveness (water quality)

Catchment pollutant delivery

- Catchment loads monitoring
- Catchment loads modelling

Catchment condition

- Ground cover monitoring
- Riparian vegetation extent monitoring
- Wetland extent monitoring
- Wetland condition and pressure monitoring

Marine condition

- Marine monitoring
- Marine modelling *(phased implementation)*

As noted above, the scope of the Paddock to Reef program has expanded to align with the scope of the Reef 2050 WQIP. Environmental stewardship for both agricultural and non-agricultural (industry and urban) sectors can be demonstrated through investment in technology or practices that meet or exceed standards that will ensure that harm to the environment is minimised or avoided or that the health of the 'receiving environment' is enhanced. In the context of the Paddock to Reef program, the term 'stewardship' is defined as follows:

Local environmental stewardship is the actions taken by individuals, groups or networks, with various motivations and levels of capacity, to protect, care for or responsibly use the environment in pursuit of environmental, economic and/or social outcomes in diverse social-ecological contexts (derived from Bennett et al., 2018).

The *Agricultural management practice adoption* program area (Section 4.1.1) collects information about the current adoption of land management practices. Introducing additional questions related to social factors influencing agricultural management practice adoption will improve understanding of what motivates different individuals and entities to conduct their business in a way that achieves improved environmental outcomes (demonstrates environmental stewardship). This is detailed in Section 4.1.2.

With the *Non-agricultural industry management practice adoption* frameworks under development, there is scope to introduce the collection of similar human dimension factors related to innovation and stewardship. To date, assessment and reporting on the management practice effectiveness or 'stewardship' of non-agricultural sectors in Great Barrier Reef catchments has been developed and driven by the regional report card partnerships. Stewardship of the urban, heavy industry, and ports sectors has been reported by the Gladstone Healthy Harbour Partnership (GHHP), and the Mackay Whitsunday Healthy Rivers to Reef Partnership (MWHR2R) has also reported on aquaculture and tourism. This is further explained in Section 4.5.

The Reef 2050 WQIP also includes specific implementation actions for catchment restoration which are integrated within the program areas above. For example, gully and streambank management practice adoption are built into the grazing Water Quality Risk Framework and have guidance tools such as the Reef Trust Phase IV Gully and Streambank Toolbox. Management practice frameworks will be established for other relevant water quality catchment restoration activities such as wetland rehabilitation and treatment systems (potentially in agricultural, urban and public lands), building on existing knowledge and drawing on new research results as they become available. Water quality improvements from catchment restoration activities are currently incorporated into the Paddock to Reef program where spatial management practice adoption data and site-specific efficacy data are provided. Refinements to this process including efforts to streamline and improve data provided will be progressed during this phase of the Paddock to Reef program.

Recognising the importance of communities, industries and land managers in influencing water quality outcomes, the Reef 2050 WQIP includes specific consideration of the 'human dimensions' of achieving water quality improvements. These include social, cultural, institutional and economic factors and are addressed in the Stewardship theme: from the aspirations and capacities of landholders, industries and communities, to their stewardship practices, and, broader governance of the Great Barrier Reef.

The design of the Paddock to Reef program to support evaluation of the human dimensions target will be further refined in the future, as the indicators relevant to Great Barrier Reef water quality are identified and a baseline is developed. It will be integrated with the existing program areas, and link directly with the Human Dimensions component of RIMReP.

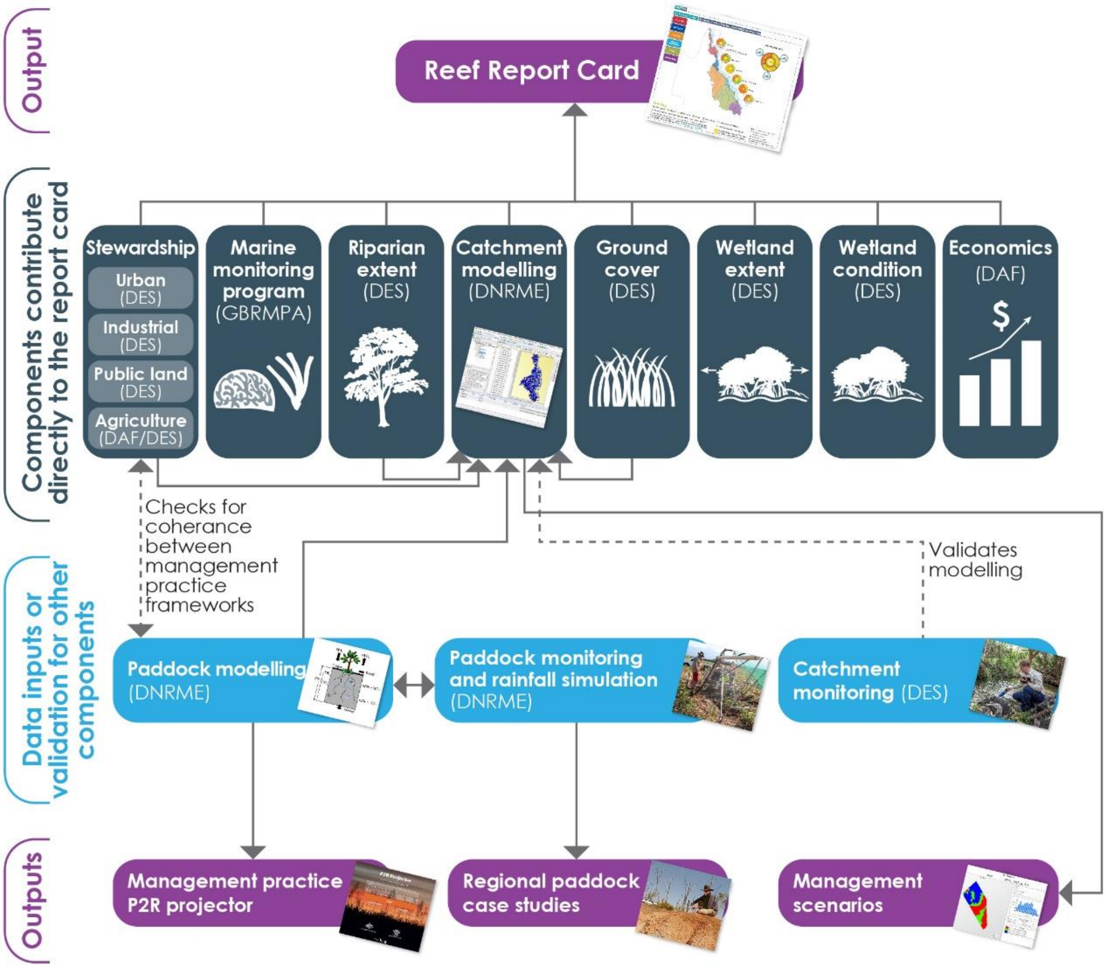

Figure 8. Paddock to Reef program areas and major outputs (lead organisations in brackets).

1.3 The 2018-2022 Program Design

1.3.1 Purpose

This Paddock to Reef Integrated Monitoring, Modelling and Reporting (Paddock to Reef) Program Design 2018-2022 sets out the objectives, program delivery arrangements, program outputs, design elements and implementation processes for the Paddock to Reef program from 2018 to 2022. It builds upon the original program design developed in 2009 and reviewed in 2013 and is a key element of the implementation plan for the Reef 2050 WQIP.

The updated design ensures that the Paddock to Reef program is able to deliver the following needs:

- Maintain and enhance a high quality program to monitor, interpret and report on water quality status and trends and related ecosystem health in the Great Barrier Reef, and the pressures and drivers of water quality condition from the Great Barrier Reef catchment.
- Report on the progress towards Reef 2050 WQIP targets, objectives and long-term outcome through the delivery of the Great Barrier Reef Report Card.

- Develop and improve the evidence base that provides the foundation for learning and improvement to support adaptive management for actions within the Reef 2050 WQIP.
- Provide knowledge and insights to enable partners to evaluate, prioritise and continuously improve the efficiency and effectiveness of Reef 2050 WQIP delivery and implementation at Great Barrier Reef-wide, regional and catchment scales.
- Coordinate and integrate monitoring, evaluation and reporting at a range of scales from the paddock to the reef using information on land management practice change, land condition, water quality and Reef ecosystem health.
- Meet the needs and outputs of the Reef 2050 Plan and associated monitoring, evaluation and reporting through RIMReP.
- Support the implementation of regional water quality management and reporting by contributing to the needs and outputs of the regional report cards.
- Build on existing knowledge generated since the commencement of the Reef Water Quality Protection Plan in 2003 and use new research, development and innovation, monitoring and reporting programs to ensure efficiencies are maximised.
- Incorporate the most recent scientific knowledge, including the findings of the 2017 Scientific Consensus Statement: Land use impacts on Great Barrier Reef water quality and ecosystem condition (herein referred to as the 2017 Scientific Consensus Statement; Waterhouse et al., 2017a) and previous independent reviews from sub-program areas.
- Review science, monitoring and modelling to ensure that the modelling scenarios are credible, methods are fit for purpose and the results are able to detect changes with time from land management practice change, key drivers and pressures.
- Document, maintain and periodically review methods for monitoring, modelling and reporting to ensure that the design is fit for purpose, and document design changes and implications of those changes.
- Coordinate the security, maintenance, long-term custodianship, use and sharing of data and information from a range of partners and have consistent quality control and interpretation processes.
- Provide accountability and transparency through the development of clearly defined annual implementation plans.

1.3.2 Process for review and development of the 2018-2022 Program Design

The 2018 review of the Paddock to Reef program was led by the Office of the Great Barrier Reef (OGBR), located in the Department of Environment and Science (DES) and C_2O Consulting. It built on the review and improvement processes adopted for each program area, which all incorporate strong elements of independent review, the findings of the 2017 Scientific Consensus Statement and the updated Reef 2050 WQIP. Technical integration with RIMReP and the regional report cards was also a key consideration.

The overarching process for the development of the program design for 2018-2022 is shown in Figure 9. The outcomes of a program-wide technical and stakeholder workshop, intensive input from the leaders of each program area, and advice from the Coordination and Advisory Group and the Independent Science Panel assisted in the development of the design. The final document was reviewed by the Independent Science Panel, an independent reviewer and the joint government Executive Steering Committee for final approval. For further information please contact the OGBR.

In 2014-2015, the Queensland Audit Office (QAO) completed an audit to determine whether the adverse impact of broadscale land use on the quality of water entering the Great Barrier Reef was declining (Queensland Audit Office, 2015). It focused on the efficacy of the activities undertaken or funded by Queensland Government agencies, the effectiveness of monitoring of these activities and the reliability of public reporting of outcomes, particularly the reporting on the achievement of the Reef Water Quality

Protection Plan. Specific issues related to the scope of catchment monitoring, the verification processes for management practice change data, improving accuracy of the catchment modelling and reporting data confidence. These issues have now been addressed and are incorporated as improvements to the program design. The improvements are highlighted within each program area (Section 4) and a complete response is reported in the Follow-up of Management water quality in the Great Barrier Reef catchments (Report 16: 2017-2018) (Queensland Audit Office, 2018).

The most significant changes that were made to the design as a result of the review are associated with scope of activities (both to align with the expanded scope of the Reef 2050 WQIP and to harness new knowledge such as the eReefs marine modelling), adjustment of program delivery arrangements to reflect the newly developed role of RIMReP and the regional report cards, formal incorporation of incremental improvements made in each program area, implementation of consistent data management approaches across all program areas, and addition of program outputs including the development of more accessible tools to support a more adaptive approach to implementation of the Reef 2050 WQIP.

The design provides a solid framework to incorporate the outcomes of the range of water quality investments that are likely to be implemented over the next five years. New major initiatives such as the Major Integrated Projects are already directly linked to the Paddock to Reef program monitoring, evaluation and reporting requirements. Processes are in place to ensure that adequate protocols and standards are provided to new delivery partners, such as the Great Barrier Reef Foundation (GBRF), to ensure delivery (and feedback) of relevant data through the common Paddock to Reef program framework.

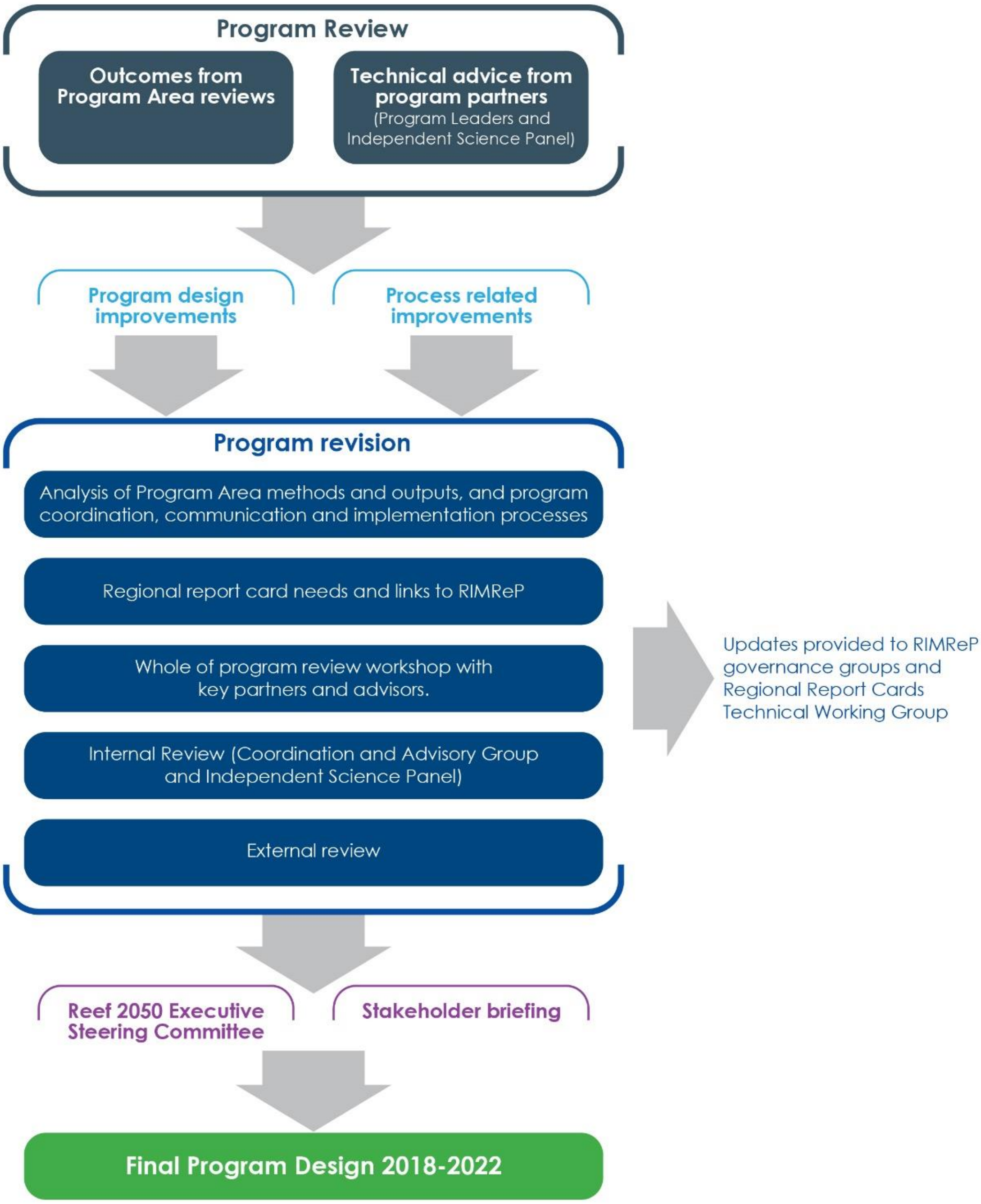

Figure 9. Illustration of the process to develop the Paddock to Reef program design for 2018-2022.

2. Program delivery

The 2018 review of the Paddock to Reef program identified that the existing governance and coordination structures were generally working well, but that the scope needed to be expanded to address the additional scope included in the Reef 2050 WQIP. While no major changes to the main structure of the delivery arrangements are proposed for implementation in 2018-2022, some roles and responsibilities have been modified. The establishment of RIMReP to support the Reef 2050 Plan and introduction of the regional report cards since the last design period, are reflected in the updated governance arrangements.

2.1 Governance and coordination

The Paddock to Reef program is a collaborative program involving approximately 20 organisations and more than 100 individuals. Sound governance and coordination arrangements are critical to the success of such a complex and interdisciplinary program. The governance and coordination arrangements for this phase of the Paddock to Reef program are shown in Figure 10 and involve:

- The *Reef 2050 Executive Steering Committee* provides implementation direction and comprises senior officers of the principal Australian and Queensland government agencies involved in the Reef 2050 Plan.
- The *Reef 2050 Advisory Committee* provides strategic advice on the implementation of Reef 2050 actions, stakeholder priorities, and highlights any emerging cross-sectoral issues that need to be addressed.
- The *Reef Independent Science Panel (ISP)* provides independent science-based and technical advice on Great Barrier Reef water quality science needs including water quality monitoring and reporting programs.
- The *Coordination Advisory Group (CAG)* provides review and technical advice for all aspects of the program including implementation, continuous review and improvement and reporting. This group includes representation from each program area (replacing the previously separate Program Leaders group) as well as several experts with technical expertise in the major elements of the Paddock to Reef program. It is also responsive to issues arising from the ISP and Reef 2050 Executive Steering Committee.
- As an aligned activity, the *Regional Report Card Technical Working Group (TWG)* provides review and advice for aspects of freshwater, estuarine and marine (inshore/offshore) condition as well as community stewardship reporting for the Wet Tropics, Mackay Whitsunday and recently established Dry Tropics regional report cards. The Fitzroy and Gladstone regional report cards maintain independent science panels and would benefit from closer alignment with the TWG to ensure effective and efficient science delivery. The CAG and TWG function to deliver the Catchment and Estuary theme under RIMReP.

  The ISP provides independent scientific review of both the Paddock to Reef and regional report card programs of Mackay Whitsunday, Wet Tropics and Dry Tropics. Close links are maintained between the Paddock to Reef program and other relevant research, development and innovation and extension programs and forums. Further details on these links are described in Section 3.3.

The OGBR is responsible for oversight and delivery of the Paddock to Reef program and production of the Great Barrier Reef Report Card within the context of Reef 2050 WQIP. Working closely with the Australian Government Reef Branch within the Department of Environment and Energy (DoEE), the OGBR also provides policy, science, and communication coordination and direction for the program. The Great Barrier Reef Marine Park Authority (GBRMPA) and the Queensland Departments of Natural Resources, Mines and Energy (DNRM), Agriculture and Fisheries (DAF) and other areas of the Department Environment and Science lead key components of the program.

The Paddock to Reef program is directly supported by the *Paddock to Reef Cross Regional Coordinator* who ensures coordinated delivery between the program areas and across NRM regions. This role has an emphasis on cross-program synthesis outputs, coordination of regional synthesis/communication events and supports development of tools that facilitate data access.

Each program area is led by a *Program Leader* who ensures coordinated delivery of their program area.

Delivery partners include the lead organisations for each program area, including DES, DAF, DNRM, GBRMPA and GBRF. In addition, all of the regional NRM bodies within the Great Barrier Reef catchments are involved (directly contracted) in the delivery of the Paddock to Reef program. Their role involves collection and integration of regional data and information on land management practices, including the collection of fertiliser and pesticide usage data. They also disseminate information, results and products derived from the Paddock to Reef program to regional stakeholders including extension staff, industry partners and landholders. The role of the regional waterway health partnerships is also likely to increase over time with the expanded scope of the Paddock to Reef program, and the increasingly strong linkages between the regional report cards, RIMReP and the Paddock to Reef program.

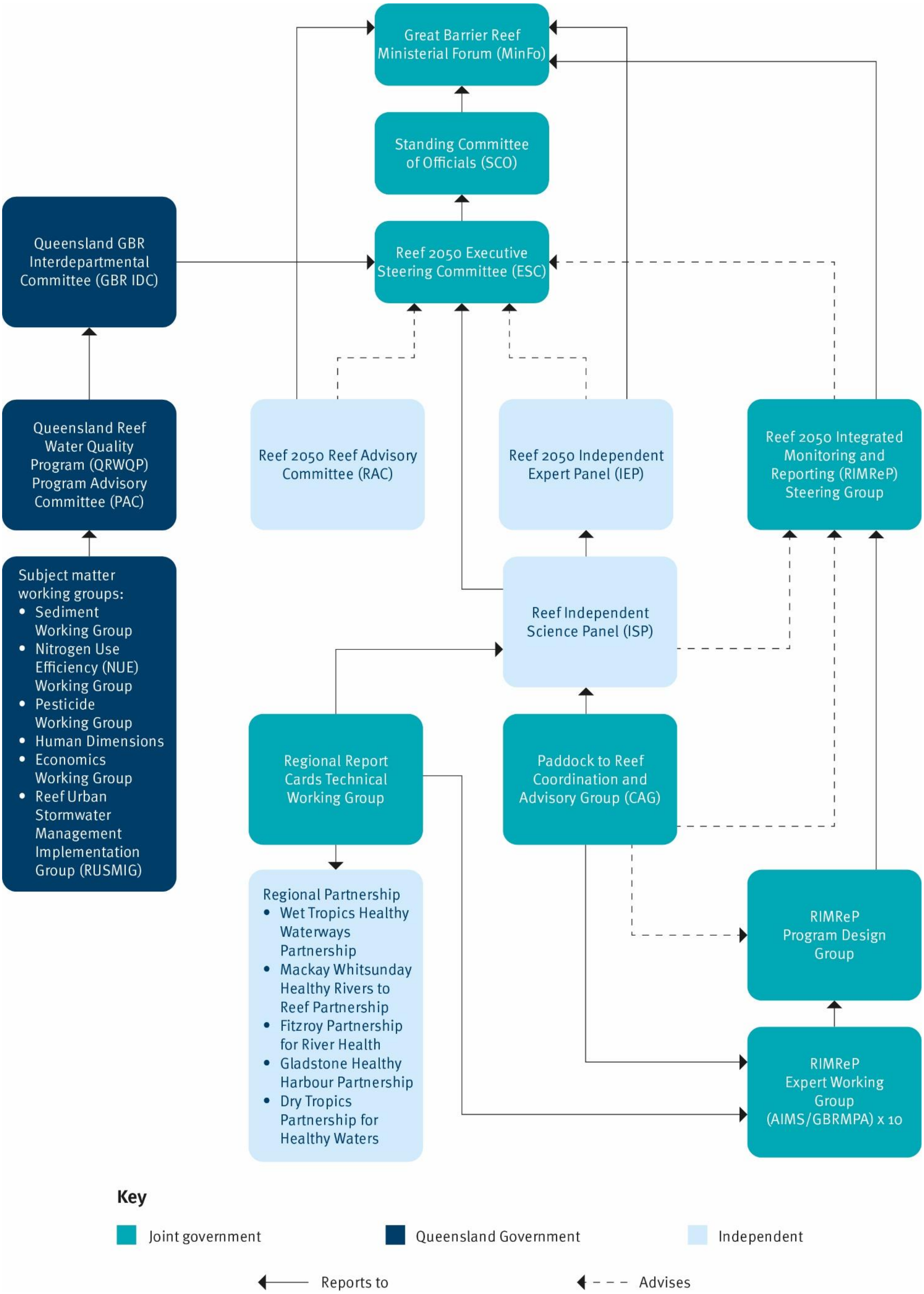

Figure 10. Governance and coordination arrangements for the Paddock to Reef program, 2018-2022.

2.2 Resourcing

The Paddock to Reef program is funded by the Australian and Queensland governments, with the catchment components primarily administered by the Queensland Government and the Great Barrier Reef Marine Park Authority (GBRMPA) responsible for the Marine Monitoring Program.

The Queensland and Australian governments also provide resourcing to the five regional report card partnerships.

2.3 Scientific review and quality control

The Paddock to Reef program maintains a high standard of scientific rigour through the employment of a high standard of requirements for peer review, the maintenance of quality assurance and quality control procedures (discussed further in Section 5), and a principle commitment to continuous improvement based on the best available science (see also Section 6). All documentation associated with the program design for each program area, and all report card products are reviewed by the ISP. The technical reports are reviewed within lead organisations and externally peer reviewed.

Each program area is externally reviewed within each phase and design elements are updated in response to these reviews. The main review processes undertaken in the previous phase of the Paddock to Reef program (2013 to 2018), and scheduled reviews for this phase are summarised in Appendix 1.

The Paddock to Reef program is underpinned by a comprehensive data management system (Section 5.1). The Spatial and Scientific Information Management for Reef (SSIMR) data management environments, DARTS (DAta Recording Tool for Science) and SKIP (Science Knowledge and Information Provision) are designed to maintain and support an environment to archive, manage, access and share data and information used and/or generated by the Paddock to Reef program areas. Data management for each program area is also described in Section 4.

3. Program outputs – supporting adaptive management

The Paddock to Reef program has a philosophy of adaptive management and action learning which requires the provision of direct feedback to target audiences with an emphasis on two-way communication. This will help to ensure program results are understood and drive the adoption of improved management practices.

3.1 Evaluating and adapting actions in the Reef 2050 WQIP

Understanding the progress made against Reef 2050 WQIP targets through the Paddock to Reef program informs assessment of the success of current investments and provides modelled information to target future investments. To support the effectiveness and efficiency of water quality programs, project design and governance needs to be analysed with knowledge consolidated to guide program and project decision-making and delivery. To facilitate this process, the Queensland Government has developed an evaluation framework for the Queensland Reef Water Quality Program to inform the mix of mechanisms used to deliver the Reef 2050 WQIP outcomes, objectives and targets. This framework will involve annual program evaluations designed to enable adaptive management.

Each of these evaluations draw heavily on the outputs of the Paddock to Reef program, particularly in regard to predicting and assessing the impact of the joint investment. The balance between estimation of total progress towards targets arising from all investments through the annual Great Barrier Reef Report Card and the use of the Paddock to Reef program outputs to evaluate different investment approaches, enhance program and project design, and adaptive management of investments, will need to be carefully managed given the finite resources available.

The joint governance arrangements and various Great Barrier Reef committees are evaluated through regular reviews and self-evaluations. In addition, funding has been allocated to evaluate different governance mechanisms to provide lessons for enhanced program delivery. These evaluation processes will ensure that water quality programs are continuously improved based on lessons learnt.

There are several activities that the Paddock to Reef program will adopt to improve the feedback loops between the monitoring and modelling results, and Great Barrier Reef water quality management decisions. These include:

- Preparation of annual investment report from the management practice adoption team on the adoption outcomes from major investment programs included in the Paddock to Reef program. This will also be complemented by project-specific feedback. The intent of the reporting is to describe the scope of funding and predicted nature of the water quality (and ultimately, economic) benefits supported by interpretation of the data.
- Continued support to the Regional Coordinators for the Paddock to Reef program to provide feedback on regional implementation, across the suite of project delivery providers. These opportunities are part of the evaluation for the investment programs and the Paddock to Reef program can contribute data, information and insights to future program design.
- Implementation of a strategic program of scenario modelling in the catchment (Source Catchments) and marine (eReefs) modelling platforms to inform management prioritisation. The catchment modelling scenarios can predict 'what if' scenarios for different levels of management practice adoption. The marine modelling can then be used to estimate the marine water quality response to these catchment management scenarios.

In addition to these annual processes, the Paddock to Reef program has a prominent role in generating, interpreting and preparing information for designing the next phase of management under the Reef 2050 WQIP. Over the next five years, this will include contribution to the following exercises for review of the Reef 2050 WQIP in 2022:

- Analysis of the costs of meeting the Reef 2050 WQIP targets. This will use knowledge of the rates of management practice adoption (across all industries), outputs of the management practice catchment modelling scenarios, and economic monitoring and modelling outputs.
- Update of the relative risk assessment of degraded water quality on Great Barrier Reef coastal and marine ecosystems and prioritisation of basins for management. This will draw on the rates of management practice adoption (across all industries), monitored and modelled end of catchment pollutant load and species protection estimates, outputs of the management practice catchment modelling scenarios, economic monitoring and modelling outputs, and catchment and marine condition indicators.
- Revision of the Reef 2050 WQIP targets across all program areas.
- Update of the 2017 Scientific Consensus Statement, using all aspects of the Paddock to Reef program outputs.

Broader communication of the information and data from the Paddock to Reef program is also essential for influencing change and decision-making. The proposed communication approaches are described below.

3.2 Communication of information and data

Clear and transparent communication regarding the health of the Great Barrier Reef and the effectiveness of management initiatives is vital for decision-makers, the community and stakeholders. The aim is to increase the level of ownership in addressing water quality issues in the Great Barrier Reef and increase the trust in the results of monitoring and modelling programs. The Paddock to Reef program can support regional stakeholders in making management decisions by providing data and knowledge in a format that is easy to understand and that can be extended to landholders and the community.

In the agricultural industries, the regional NRM bodies, industry groups and government extension teams are the primary vehicles for extending information to landholders and the community. In the urban setting, local governments play a key role in influencing the adoption of improved management practices within the community. In industrial areas, industry partners can deliver key messages to the broader community and key stakeholders. The regional waterway health partnerships have an important role in facilitating communication and engagement for improving water quality and ecosystem health in urban and industrial areas.

As part of the review of the Paddock to Reef program, consultation with regional stakeholders has identified a number of specific communication needs and mechanisms for extending the results (Gongora et al., 2017). The target audiences for the Paddock to Reef program are:

- Technical advisors to landholders, such as DAF, regional NRM and industry extension officers, industry organisations, commercial agronomic advisors and suppliers
- Program managers, people managing programs aimed at improving landholder's practices such as regional NRM groups, Reef Alliance and commercial agronomic advisors
- Industry groups, for example, CANEGROWERS, AgForce, Queensland Ports Association, Queensland Resources Council
- Queensland and Australian government agencies, local government, and other investors
- Organisations within the Reef 2050 WQIP governance arrangements

- Ministers, senior managers and policy officers involved in implementation of Reef 2050 WQIP and Reef 2050 Plan
- Landholders with monitoring sites
- Paddock to Reef program implementers
- Scientists and researchers
- Conservation organisations, such as WWF and Australian Marine Conservation Society
- Traditional owner groups in the Great Barrier Reef
- The wider community

With these audiences in mind, there are three main types of information that provide a useful mechanism for applying the results of the program:

1. Practical information that is useful for extension and relevant to landholders. Examples include the results of farm or paddock trials and the results from studies that include economic and profitability assessments. Showcasing examples of landholders that have implemented improvements is an effective method of communicating this type of information. Highlighting the private and public benefits of the practices discussed is key. This type of information is relevant to extension officers, industry advisors and landholders.
2. The results of monitoring programs and projects that describe the current state of assets at sub-catchment, catchment and marine scales. In the Paddock to Reef program, this comprises the catchment monitoring, wetland condition and marine monitoring programs. This information is relevant for all regional stakeholders, e.g. program managers, extension staff, industry advisors and in some cases, landholders. Information from monitoring projects that engage landholders (e.g. Project NEMO, Project 25 or Sandy Creek monitoring) carry the most credibility for industry and landholders. This information is best presented by industry advisors, with the scientists addressing the technical aspects.
3. Information that assesses progress towards the Reef 2050 WQIP targets, objectives and long-term outcome. While all regional stakeholders have some interest in this information, it is of most interest to those delivering programs and managing government funding.

There is general agreement that in many cases, the best people to deliver messages to landholders are technical advisors, extension staff and other landholders. In some cases, direct communication between scientists and landholders may also be suitable. Further effort is required to improve communication products and training to support these roles in this next phase of the Paddock to Reef program.

The key messages for communicating Paddock to Reef program results will necessarily vary between the audiences. However, there are several overarching key messages that need to be conveyed to all audiences to provide context for the results. In particular, key messages relating to the conceptual understanding of measuring water quality improvement using monitoring and modelling tools, which cannot be detected in the present day using monitoring methods, are important to communicate, for example:

- Climatic factors (rainfall and river discharge) have an important influence on pollutant load delivery that results in highly variable yearly monitoring results. This challenges our capacity to detect the overall improvements in water quality attributed to improved land and catchment management in relatively short time frames (as described in Section 1.2). Applying long-term average climate conditions in the models assists in teasing out the management and climate signals in the results, and therefore, the improvements in water quality solely attributed to improved land and catchment management can be estimated.

- Natural time lags exist between changes on land and changes in water quality. The Source Catchment models provide predictions of the future benefits of improving land and catchment management in the present day.
- Time lags also exist between improved water quality and detecting the ecosystems' response, depending on the recovery timeframes and existence of other disturbances such as elevated temperatures.

These are complicated concepts that need to be communicated effectively in conveying the challenges in interpreting change and trends in water quality parameters used for reporting.

Other key messages are associated with:

- articulating the conceptual understanding between management practices and water quality outcomes;
- the water quality benefits of improved management practices;
- the contribution of each land use to pollutants discharged annually;
- current understanding of the ecological risk of different pollutants on coastal and marine ecosystems;
- the role water quality plays in the ability of Great Barrier Reef ecosystems to recover from large disturbance events such as extensive coral bleaching and cyclones; and
- more broadly, the role of the Paddock to Reef program in assessing progress towards the Reef 2050 WQIP targets, objectives and long-term outcome including the need for the combined monitoring and modelling approach.

Some of the tools for communicating results include:

- report cards;
- videos;
- conceptual models and infographics;
- simple key messages;
- fit for purpose presentations to a range of audiences, e.g. farmer shed meetings;
- farm demonstration and field days;
- case studies and fact sheets;
- online portals for data access and visualisation (e.g. eagle.io for monitoring data, modelling dashboard for catchment modelling results); and
- technical reports, conference papers and journal articles.

Delivery mechanisms include:

- websites;
- oral presentations, e.g. regional roadshows, conferences, workshops, shed meetings;
- social media, including Facebook, YouTube, Instagram;
- paid media – digital, press and broadcast advertising;
- industry, stakeholder and scientific publications;
- public and industry events and meetings; and
- news media.

The key messages and tools for communicating data and information relating to the Paddock to Reef program will be documented and implemented as part of the overall Reef 2050 WQIP Communication Strategy and Reef 2050 Science Communication Implementation Plan.

3.3 Paddock to Reef program reporting framework

3.3.1 Reporting products

A tiered approach to reporting is adopted, with increasing level of detail across the tiers (as illustrated in Figure 11. The first tier is the Great Barrier Reef Report Card which tracks the progress toward the Reef 2050

WQIP targets and reports on wetland and the inshore marine condition. It includes key findings, summary results and key contextual information. Tier 1 is published through the Reef 2050 WQIP website as html and via an interactive map.

Assessment of progress towards the Reef 2050 WQIP targets and objectives in the Great Barrier Reef Report Cards is based on a scoring system designed specifically for the Paddock to Reef program. A five-point scoring system is adopted for each key indicator and reported as A - Very good, B - Good, C - Moderate, D – Poor or E – Very poor). For example, in the Management Practice Adoption program area, scores are provided for each industry and for soil, nutrient and pesticide management practices for the achievement of the target that 90% of sugarcane lands are managed using best management systems in priority areas. The progress is assessed by the proportion of area where low and moderate-low water quality risk practices are adopted. The scores are based on the proportion of progress towards the target, with A = achievement of the target (90-100% adoption of low and moderate-low water quality risk practices), B = 68-89% adoption, C = 46-67% adoption, D = 23-45% adoption and E = 0-22% adoption.

The A, B, C, D, E grades make it easier to track progress towards the targets. The targets are considered ambitious. Therefore, progress that is equal to or exceeds the target is considered A - Very good (dark green), whereas poor progress towards the target is considered to E – Very poor (red). A full description of the approach to the scoring is prepared for each Great Barrier Reef Report Card (for example, the Scoring System for the Great Barrier Reef Report Card 2016). The approach to confidence scoring is described in Section 5.3.

The second tier reports provide detailed results, contextual information, a summary of the methods and confidence scoring. This information is published through the Reef 2050 WQIP website (www.reefplan.qld.gov.au).

The third tier reports are required for individual program areas in the Paddock to Reef program. These reports include detailed documentation of the methods including any relevant decision rules and assumptions. They are available as PDF reports on relevant agency websites and linked from the Reef 2050 WQIP website or hosted directly e.g. catchment monitoring and modelling. The primary audience for these reports are scientists, collaborators and technical reviewers.

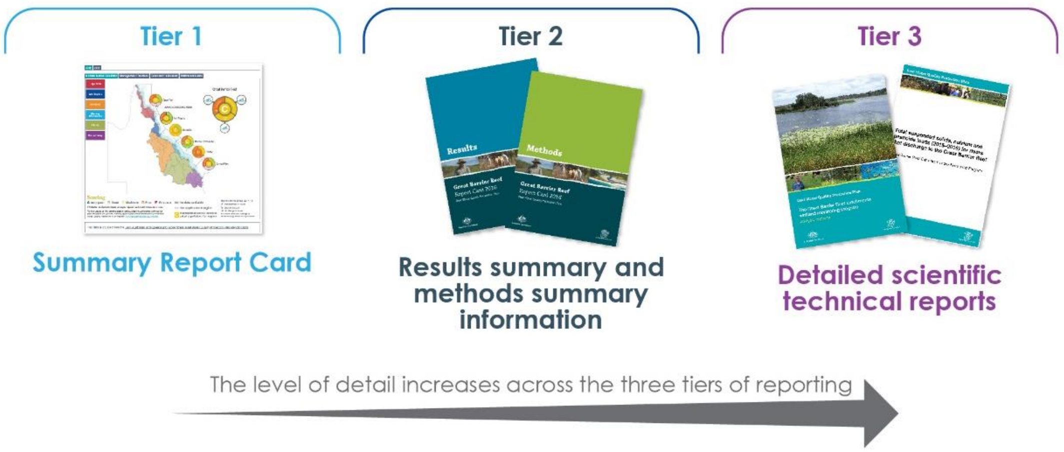

Figure 11. The tiered approach to reporting adopted for the Paddock to Reef program, with increasing level of detail across the tiers.

Additional reporting platforms are also used by individual programs to improve the availability and visualisation of their data. A brief description of the most prominent reporting tools for the Paddock to Reef program is provided in Appendix 2. Some examples include: 1) the 'P2R Projector Tool' which is a prioritisation tool to support the selection of projects to improve water quality for the sugarcane, banana and grains industries (the capacity to include grazing data is being developed in this phase of the Paddock to

Reef program); and 2) eagle.io which is a web-based platform utilised by the Catchment Loads Monitoring Program to report catchment monitoring data in real time to program partners via a secure login. A catchment modelling dashboard is also being developed for visualisation of modelling outputs including maps and graphs based on user defined queries (e.g. parameter, time frame).

The Queensland Government Water Tracking and Electronic Reporting System (WaTERS) is also being improved to report point source release monitoring and tracking data online.

The current characteristics of reporting for each program area in the Paddock to Reef program are summarised in Table 2. A more detailed description of the data accessibility and access tools identified in the table is provided in Appendix 2.

In addition to reporting progress towards a greater scope of targets and objectives, reporting products in this phase of the Paddock to Reef program will include additional context for the results, including pressures such as climatic influences. This recognises that the condition of catchment, coastal and marine ecosystems is influenced by factors other than water quality. While these influences have been factored into reporting in the past, explicit reporting will assist in data interpretation at the report card level. The pressures will be reported as a time series and will also highlight the occurrence of episodic large events in terms of magnitude, duration and frequency. Reporting years will be classified relative to a long-term record and characterised according to the prevailing conditions. This will also assist in assessing the water quality impacts of changes in land management practices with the need to identify trends over time.

Table 2. Characteristics of reporting for each Program Area in the Paddock to Reef program. Note: Tier 1 and 2 = Great Barrier Reef Report Card, Tier 3 = Technical reports. The tools are described in Appendix 2. Note that the Reef 2050 WQIP Objectives for Improved land management, Increased culture of stewardship and Maintain viable communities, and Improved biodiversity are linked to the Land and catchment management, the Human dimensions targets and the Long-term outcome respectively. Improved governance is reported as part of the Reef 2050 Human Dimensions theme of RIMReP. GBR = Great Barrier Reef.

Program area *Section for details* Description	**Relevant outcome, target and/or objective for reporting**	**Indicator**	**Reporting** *Frequency* Characteristics	**Scale**	**Data accessibility and application tools**	**Primary communication tools**
Stewardship						
Agricultural management practice adoption (Stewardship) *Section 4.1.1* Develops rigorous estimates of management practice adoption and annual management practice change for the major agricultural industries of the GBR catchments—sugarcane, grazing, horticulture, grains and bananas	90% of land in priority areas under grazing, horticulture, bananas, sugarcane and other broad-acre cropping are managed using best management practice systems for water quality outcomes (soil, nutrient and pesticides) Active engagement of communities and land managers in programs to improve water quality outcomes is increased	Current adoption of agricultural management practices (proportional area under best management practice)	*Annual reporting* Tier 1 and 2 – Management practices that are at the Moderate-Low risk (B) and Low risk levels (A) are taken to be 'best management practices'. Summed to describe the proportion of area managed under best practice, and practices are combined according to their weightings to describe 'best management practice systems'. Interactive report card enables users to drill down to see scores for sub-indicators e.g. soil, nutrients and pesticides for sugarcane – and then into practices e.g. nitrogen surplus, placement and timing (under nutrients). Tier 3 Technical Reports in development.	GBR-wide Regional 35 basins and down to 47 sub catchments where relevant (+ finer scale for internal programs/investors/delivery agents)	'P2R Projector Tool' for predicting water quality benefits from proposed projects in sugarcane, bananas and grains Spatial data wrangler tool (for internal use) - a geospatial tool for management and review of spatial agricultural management practice data	Development of a Standardised Investment Report proposed (in development) Targeted presentations to investors and delivery agencies Presentations at shed meetings and field days, regional forums Peer reviewed journal articles and conference papers
Agricultural management practice adoption (Social factors influencing management practice adoption) *Section 4.1.2* Improves current understanding of the social factors that influence management practice adoption in agricultural industries	Active engagement of communities and land managers in programs to improve water quality outcomes is increased	Indicators of the social factors influencing agricultural management practice adoption in development	The baseline dataset will be established in 2018 Approach to be finalised in 2019	To be determined	In development	In development

Program area *Section for details* Description	Relevant outcome, target and/or objective for reporting	Indicator	Reporting *Frequency* Characteristics	Scale	Data accessibility and application tools	Primary communication tools
Non-agricultural land use stewardship *Section 4.2* Develops and implements assessment and reporting frameworks for the management of urban, industrial and public land uses to assess improvements in water quality	The management of urban, industrial and public land uses for water quality shows an improving trend Active engagement of communities and land managers in programs to improve water quality outcomes is increased	Current adoption of non-agricultural management practices	Reporting to be determined. Approach to be finalised in 2019	To be determined	In development	In development
Management practice effectiveness and paddock pollutant delivery (agricultural land uses)						
Economic benefits of agricultural management practices *Section 4.3* Provides a systematic set of comparative cost-benefit economic data for assessing the economic implications of changing agricultural land management practices	90% of land in priority areas under grazing, horticulture, bananas, sugarcane and other broad-acre cropping are managed using best management practice systems for water quality outcomes (soil, nutrient and pesticides) Active engagement of communities and land managers in programs to improve water quality outcomes is increased	Indicators of the economic benefits of agricultural management practices in development	Not reported in Great Barrier Reef Report Card Reporting to be determined	Modelling information presented by industry	In development	Case studies for specific sites Technical reports Presentations at shed meetings and field days, regional forums Peer reviewed journal articles and conference papers
Paddock monitoring of water quality benefits *Section 4.4* Provides on-ground evidence of, and on-ground demonstration of, the effectiveness of	60% reduction in anthropogenic end-of-catchment dissolved inorganic nitrogen loads 20% reduction in anthropogenic end-	Water quality outcomes of a suite of management practices	Not reported in Great Barrier Reef Report Card Annual summary reports Tier 3 - Technical reports, Qld Government Library online	Paddock monitoring information presented by industry	P2R Projector Tool	Case studies for specific sites Technical reports Presentations at shed meetings and field days, regional forums

Program area *Section for details* Description	Relevant outcome, target and/or objective for reporting	Indicator	Reporting *Frequency* Characteristics	Scale	Data accessibility and application tools	Primary communication tools
management practices for managing sediment, nutrients and pesticides in the key agricultural industries	of-catchment particulate nutrient loads 25% reduction in anthropogenic end-of-catchment fine sediment loads Pesticides: To protect at least 99% of aquatic species at end-of-catchments					Peer reviewed journal articles and conference papers
Paddock modelling of water quality benefits (water quality outcomes) *Section 4.5* Models a suite of farm management scenarios that represent the management practice combinations that existed at the baseline and subsequent improvements to these practices across soils and climate zones for the sugarcane, grazing, banana and grains industries. These outputs are used for management practice scenarios in the catchment model		Generation coefficients and loads for key water quality parameters from different management practice scenarios	Not reported in Great Barrier Reef Report Card Tier 3 - Technical reports, Qld Government Library online	Modelling information presented by industry	P2R Projector Tool	Case studies Technical reports Presentations at shed meetings and field days, regional forums Peer reviewed journal articles and conference papers
Catchment pollutant delivery						
Catchment loads monitoring *Section 4.6* Monitors the concentrations of total suspended solids (TSS), nutrients (nitrogen and phosphorus analytes) and pesticides for multiple sites within 20 priority basins that discharge to the GBR	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-	Monitored end of catchment and sub-catchment water quality concentrations and load estimates, and percent species protected from pesticide impacts	*Annual reporting* *Nutrients, sediments and pesticides* Not reported in Great Barrier Reef Report Card Tier 3 Annual Technical Reports Annual results summaries	Regional: 20 priority basins and up to 47 sub catchments where relevant (+ finer scale for internal programs/investors/delivery agents)	Near-real time reporting for selected sites via customisable dashboards for different audiences (via eagle.io approx. 22 sites with 10 new nitrate sensors) Online loads calculation tool (ReLo)	Annual results summary and technical reports eagle.io for real time data management and web based data reporting Presentations at shed meetings, field days, regional forums

Program area *Section for details* Description	**Relevant outcome, target and/or objective for reporting**	**Indicator**	**Reporting** *Frequency* Characteristics	**Scale**	**Data accessibility and application tools**	**Primary communication tools**
Provides the primary monitoring data set used to validate and calibrate Source Catchments water quality models	of-catchment fine sediment loads					Pesticide guideline exceedance reports Peer reviewed journal articles and conference papers
	Pesticides: To protect at least 99% of aquatic species at end-of-catchments	msPAF risk metric for pesticides detected in catchments. Only those pesticides for which a species sensitivity distribution has been developed (see King et al., 2017a, b) can be included in the msPAF risk metric Only concentration information will be reported for all other pesticides not included in the msPAF metric	*Annual reporting* Tier 1- For the 2018/2019 Great Barrier Reef Report Card only (to be released in 2019), the catchment monitoring program will report the pesticide *pesticide risk baseline* using the 2015-18 monitoring data Tier 3 - msPAF risk metric	35 basin scale but only for high priority basins with pesticide risk	In development	Annual results summary and technical reports eagle.io for real time data management and web based data reporting Presentations at shed meetings and field days Presentations at regional forums Peer reviewed journal articles and conference papers
Catchment loads modelling *Section 4.7* Estimates average annual loads of key pollutants (sediment, nutrients and pesticides) for each of the 35 catchments draining to the GBR. It reports on the anthropogenic baseline load and the change in loads for each subsequent year due to adoption of improved		Modelled estimates of the annual average end of catchment nutrient and sediment loads and percent species protected from pesticide impacts	*Annual reporting* Tier 1 – Estimation of the reduction in the modelled pollutant load for the current year from the average annual modelled anthropogenic baseline (total load less the pre-development load) Tier 1, Tier 2 - Annual – show tonnage and percentage reductions Present long-term progress to date cumulatively over time – plus annual progress (new scoring) Tier 3 – Annual Technical Reports	GBR-wide Regional 35 basin scale (can go to sub-catchments e.g. spatial hotspot maps for management purposes but not target reporting as targets not at this scale)	Modelling Dashboard - model visualisation and hotspot spatial mapping (for automated reporting) Customisable dashboards e.g. for policy / technical / delivery audiences	Annual technical report Modelling Dashboard - model visualisation and hotspot spatial mapping (for push reporting) Presentations at regional forums Peer reviewed journal articles and conference papers

Program area *Section for details* Description	Relevant outcome, target and/or objective for reporting	Indicator	Reporting *Frequency* Characteristics	Scale	Data accessibility and application tools	Primary communication tools
land management practices						
Catchment condition						
Ground cover monitoring *Section 4.8* Provides annual mapping and reporting of ground cover levels in grazing lands. The data is also an important input to the water quality models	90% of grazing lands will have greater than 70% ground cover in the late dry season	Ground cover extent	*Annual reporting* Tier 1 - Regional overview of late-dry-season ground-cover levels in the GBR region 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 regions Tier 2 – shows range of statistics e.g. • Progress to target • Long-term mean ground cover levels (%) • Current year mean ground cover (%) • Area less than 70% cover (long-term %) • Area with less than 70% cover for current year • Cover decile rankings • Contextual information e.g. mean annual rainfall (Oct-Sept to align with late-dry season reporting) Method in development to represent trends	GBR-wide Regional 35 basins and 47 management units (property x land types possible via tools)	VegMachine, FORAGE, development of grazing components in P2R Projector Tool, online dynamic reporting	Presentations at regional forums Peer reviewed journal articles and conference papers
Riparian vegetation extent monitoring *Section 4.9* Maps and reports on riparian vegetation extent and cover every four years. The data is also an important input to the water quality models	The extent of riparian vegetation is increased	Riparian vegetation extent	*Data updated every four years, but still report every year (with explanation)* Tier 1 - Data derived from Landsat satellite imagery is used to estimate net change in extent of riparian forest and riparian ground cover. Tier 2 – Statistics reported include: • the extent of riparian forest and the estimated area remaining of the pre-European extent of riparian forest • the amount of forest loss in recent history and up to reporting year of interest • the patch size and connectivity of the remaining riparian forests	GBR-wide Regional 35 basins and 47 management units	Data provided through Open Data portals (e.g. QSpatial and TERN)	Presentations at regional forums Peer reviewed journal articles and conference papers

Program area *Section for details* Description	**Relevant outcome, target and/or objective for reporting**	**Indicator**	**Reporting** *Frequency* Characteristics	**Scale**	**Data accessibility and application tools**	**Primary communication tools**
			the level of ground cover in non-forested riparian areas			
Wetland extent monitoring *Section 4.10* Maps and reports on the historic (pre-clearing) and current extent of natural and hydrologically modified wetlands and change in natural and hydrologically modified wetland extent every four years.	No loss of the extent of natural wetlands (lakes, swamps and estuarine wetlands)	Wetland extent	*Data updated every four years, but still report every year (with explanation)* Tier 1 – Reports current extent of natural wetlands (lacustrine, palustrine, estuarine (mangrove and saltmarsh) (2017 and 2021), and the change in natural wetland extent between 2001, 2005, 2009, 2013, 2017 and 2021. The change in natural extent is reported as a percentage of the current data to enable comparison between catchments of different sizes Tier 2 – Presents basin-scale results for natural (unmodified) and total (unmodified and modified) wetland areas in terms of: • extent for each reporting year • total losses between each reporting period • comparison between current and pre-clear natural wetland extent	GBR-wide Regional 35 basins (47 management units)	All wetland extent program outputs available on Wetland*Info* website: • Mapping • Wetland extent and change statistics • Report Spatial data available for download from QSpatial	Wetland Info Presentations at regional forums Peer reviewed journal articles and conference papers
Wetland condition and pressures monitoring *Section 4.11* Monitors and reports on the condition of, and pressures on natural freshwater wetlands (palustrine and lacustrine)	Objective: Improved wetland condition	Wetland condition and pressures	*Data updated every two years, but still report every year (with explanation)* Tier 1 – Presents the results of wetland Pressure and State indicators Tier 2 – Reporting of scores for individual Pressure and State indicators is being considered to further assist in directing management responses Tier 3 - Technical Report detailing program methods	GBR-wide Regional reporting being scoped	In development	Presentations at regional forums Peer reviewed technical reports, journal articles and conference papers Fact sheets
Marine condition						
Marine Monitoring Program *Section 4.12* Assesses trends in ecosystem health and resilience indicators for	Objective: Improved coral condition Objective: Improved seagrass condition	Coral condition Seagrass condition	*Annual reporting* Tier 1 – Presents the results of the marine water quality metric from eReefs, coral and seagrass indicators as a combined metric The long-term trends in coral cover change and	GBR-wide Regional Sub regional Site specific	Site specific coral data online – pilot; possibly seagrass	Annual technical reports Presentations at regional forums Wet season newsletters

Program area *Section for details* Description	**Relevant outcome, target and/or objective for reporting**	**Indicator**	**Reporting** *Frequency* Characteristics	**Scale**	**Data accessibility and application tools**	**Primary communication tools**
the GBR in relation to water quality and its linkages to end-of-catchment loads. There are three in situ monitoring sub-components—water quality (including pesticides), seagrass and coral. The reporting framework integrates data from the three sub-components to evaluate the long-term outcome of the Reef 2050 WQIP	Long-term outcome: Good water quality sustains the outstanding universal value of the GBR, builds resilience, improves ecosystem health and benefits communities	Inshore water quality condition	seagrass abundance are shown. Trends in water quality will be shown in the future Additional information on pressures including river discharge, cyclones and coral bleaching events are presented for context Tier 2 – More detailed reporting of regional and subregional results of coral and seagrass indicators, site specific water quality for sediments, nutrients and pesticides and river-derived pollutant exposure Tier 3 – Annual Technical Reports	Water quality conducted in Cape York, Wet Tropics, Burdekin, Mackay Whitsunday NRM regions Expansion into Fitzroy and Burnett Mary NRM regions proposed (subject to funding)		Peer reviewed journal articles and conference papers
Marine Modelling Program *Section 4.13* Operates in collaboration with the Marine Monitoring Program to predict, assess and report trends in GBR water quality (indicators of sediment and nutrients) using the eReefs marine modelling platform	Long-term outcome: Good water quality sustains the outstanding universal value of the GBR, builds resilience, improves ecosystem health and benefits communities	Inshore water quality condition	*Annual reporting* Tier 1 – Presents the results of the marine water quality metric Tier 2- More detailed reporting of the marine water quality metric results (in development) Tier 3 - Contribution to Marine Monitoring Program Annual Technical Report (in development)	GBR-wide Regional Sub regional Location specific	eAtlas visualisation of eReefs outputs	Contribution to Marine Monitoring Program Annual Technical Reports Presentations at seminars Newsletters Peer reviewed journal articles and conference papers
		GBR-wide water quality	In development	GBR-wide	eAtlas visualisation of eReefs outputs	In development
		Pressures and drivers including rainfall, river discharge, temperature, land use	*Annual reporting* Tier 1 – Add contextual climate information and trends e.g. rainfall and temperature. Approach to be finalised in 2019	GBR-wide Regional	In development	In development

3.3.2 Links to Regional Report Cards and RIMReP

The Great Barrier Reef Report Card is complemented by regional waterway health report cards that provide information relevant to local communities and local decision-makers on the health of their waterways. The report cards are produced by the regional waterway health partnerships. The partnerships will also continue to evolve their report cards to ensure they meet the needs of the local community. For example, some partnerships will work with Indigenous ranger programs to build cultural monitoring and reporting capacity. There is a focus on building linkages between the report card results and management responses through a series of framework revisions and workshops. An urban management practice adoption framework is being developed which incorporates stewardship and an urban waste component. The Mackay Whitsunday and Wet Tropics regional report cards are currently reporting on marine debris and are looking to develop indicators which help define the local problem, identify sources of litter and pathways for debris reduction.

The regional report cards build on information produced by the Paddock to Reef program, incorporating other locally relevant information to provide regional scale integrated reporting on the condition of:

- Freshwater (water quality, fish and habitat and hydrology)
- Estuarine (water quality, fish and habitat and hydrology)
- Inshore (water quality, seagrass, coral and fish)
- Offshore (water quality, coral and fish)
- Community stewardship (social, economic and cultural)
- Other social, economic and cultural indicators

As described in Section 1.1, the scope of RIMReP includes a wide range of interest areas, designed to support monitoring and evaluation of the Reef 2050 Plan. As the program becomes operational, the Paddock to Reef program will be nested within RIMReP to report on catchment-based activities along with the regional waterway health report cards. In a similar way, the regional report cards as they evolve will improve their 'nesting' within the Paddock to Reef program.

The marine components of the Paddock to Reef program, currently delivered by the Marine Monitoring Program, largely focus on water quality, coral reef and seagrass ecosystems in the coastal and inner shelf areas of the Great Barrier Reef. The scope of RIMReP in the marine environment will be broader than this, also encompassing fisheries, islands, megafauna (including dugong, turtles, seabirds and shorebirds, great whales and coastal dolphins), Indigenous monitoring and citizen science and broader social and cultural factors. Given the high degree of linkage between the Paddock to Reef program, regional report cards and RIMReP, and the opportunities for collaboration and delivery efficiencies between the programs, it is essential to establish and maintain a clear understanding and agreement of the data dependencies between the programs. The current linkages are shown in Table 3 which can be progressively updated as details are determined and improvements are achieved.

Table 3. Data dependencies of the Paddock to Reef program, regional report cards and RIMReP for program reporting. TBD = To be determined; n/a = not applicable. P2R = Paddock to Reef program; MMP = Marine Monitoring Program, BoM = Bureau of Meteorology, LTMP = Long Term Monitoring Program.

Indicator	**Paddock to Reef program data**		**Regional report cards**					**RIMReP**	**Principles for complementary report cards**
	Metric	**Provider:**	**Wet Tropics**	**Dry Tropics**	**Mackay Whitsunday**	**Fitzroy**	**Gladstone**		
Agriculture management practice adoption data and assessment		**DAF lead**						Use P2R data	Regional Report Cards and RIMReP use P2R data
Sugarcane	Basin level reporting of management practice adoption	DAF lead and multiple providers	✓ Basin level reporting of % change in A+B uptake. Aggregated progress to targets	TBD	✓ Basin level reporting of % change in A+B uptake. Aggregated progress to targets	n/a	n/a		
Grazing	Basin level reporting of management practice adoption	DAF lead and multiple providers	✓	TBD	✓ Basin level reporting of % change in A+B uptake	Doesn't report on management adoption for agriculture	Doesn't report on management adoption for agriculture		
Horticulture	Basin level reporting of management practice adoption	DAF/Growcom	✓	TBD	✓ Don basin reporting of % change in A+B uptake (limited industry in other Mackay Whitsunday basins so not reported)	Doesn't report on management adoption for agriculture	n/a		
Bananas	Basin level reporting of management practice adoption	DAF/Australian Banana Growers Council	✓	n/a	n/a	n/a	n/a		
Grains	Basin level reporting of management practice adoption	DAF lead and multiple providers	n/a	n/a	n/a	Doesn't report on management adoption for agriculture	n/a		

Indicator	Paddock to Reef program data		Regional report cards					RIMReP	Principles for complementary report cards
	Metric	Provider:	Wet Tropics	Dry Tropics	Mackay Whitsunday	Fitzroy	Gladstone		
Social factors influencing management practice adoption	Project specific data	OGBR / and multiple providers						Human Dimensions program in development	
Urban management practice adoption and effectiveness and stewardship	TBD	**OGBR coordination**	✓	✓	✓	✓ Drinking water quality (raw and treated, also suitability of water for irrigation based on salinity)	✓	Human Dimensions program in development	P2R and RIMReP and regional report cards use same data
Industrial and public lands	TBD	**OGBR coordination**					✓		P2R and RIMReP and regional report cards use same data
Catchment monitoring	Basin scale annual loads TSS, dissolved and particulate nutrients, pesticides as msPAF	**DES lead**	✓ Concentration data (nutrients and sediments reported as annual concentration compared to guideline and pesticides as msPAF)	TBD	✓ Concentration data (nutrients and sediments reported as annual concentration compared to guideline and pesticides as msPAF)	✓ Concentration data (salinity and sulfate, nutrients, turbidity, metals and toxicants) Ecology (where available but limited at this stage)	n/a		Regional report cards and RIMReP use P2R data
Catchment modelling	Progress towards end of catchment load reduction targets	**DNRME lead**	n/a	n/a	n/a	n/a	n/a		Regional report cards and RIMReP use P2R data
Riverine and estuarine health		**DES lead**	✓ Water quality, habitat and hydrology, fish, groundwater water quality	TBD	✓ Water quality, habitat and hydrology, fish	✓ Water quality, macroinvertebrates, barramundi recruitment	✓ Connectivity		RIMReP and regional report cards use same data

Indicator	Paddock to Reef program data		Regional report cards					RIMReP	Principles for complementary report cards
	Metric	**Provider:**	**Wet Tropics**	**Dry Tropics**	**Mackay Whitsunday**	**Fitzroy**	**Gladstone**		
Catchment indicators:	**DES lead**	**DES lead**							Regional report cards and RIMReP use P2R data
Ground cover	Basin scale annual change	DES lead	n/a	TBD	n/a	✓ (used but not in grades – context only)	n/a		
Wetland extent	Basin scale approx. four yearly changes	DES lead	✓ % loss since pre-development	TBD	✓ % loss since pre-development	Not reported	n/a		
Riparian extent	Basin scale approx. four yearly changes	DES lead	✓ % loss since pre-development	TBD	✓ % loss since pre-development	n/a	n/a		
Wetland condition	GBR-wide condition and pressures assessment	DES lead	n/a	n/a	n/a	n/a	n/a		P2R regional scale monitoring and reporting would enable use in regional report cards
Marine		**GBRMPA lead**							
Seagrass	Seagrass health – GBR-wide, regional, sub regions, site specific	JCU	✓	TBD	✓	✓ Will be included if data available in time for Fitzroy reporting date	✓	TBC	Regional report cards and P2R use RIMReP data
Coral	Coral health – GBR-wide, regional, sub regions, site specific	AIMS	✓	TBD	✓	✓ If data available in time for Fitzroy reporting	✓	TBC	
Water quality *Site specific water quality condition –* • *Inner shelf* • *Mid-shelf* • *Outer shelf*	Inner shelf only - regional, sub regions	AIMS, JCU	✓ MMP ✓ BoM /Port ✓ LTMP	TBD	✓ MMP ✓ BoM / Port ✓ LTMP	Not reported	Not used, conducted through the Port Curtis Integrated Monitoring Program	TBC	
Event monitoring	Exposure to river discharge	JCU	n/a	TBD	n/a	n/a	n/a		

Indicator	Paddock to Reef program data		Regional report cards					RIMReP	Principles for complementary report cards
	Metric	Provider:	Wet Tropics	Dry Tropics	Mackay Whitsunday	Fitzroy	Gladstone		
Marine water quality modelling	GBR-wide water quality condition	eReefs	✓ MMP	TBD	✓ MMP	n/a	n/a		
Other RIMReP components Eg. megafauna, heritage, fish	TBD in RIMReP design process	TBD in RIMReP design process						TBD in RIMReP design process	TBD in RIMReP design process

4. Program design

This section of the design provides an overview of each of the program areas in the Paddock to Reef program in terms of: description, objectives, delivery partners, methods, approach to assessing progress towards the targets or objectives, and applications of the information. The characteristics of data management, reporting and areas for improvement are summarised across the Paddock to Reef program in subsequent sections.

Stewardship

4.1 Agricultural land management practice adoption

4.1.1 Stewardship

This program area 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.

The adoption of improved management practices is reported using industry specific management practice frameworks (Water Quality Risk Frameworks). For sugarcane, horticulture, bananas and grains, practices are ranked from lowest risk (which may in some instances be innovative or commercially unproven) to high risk (superseded practices that have the highest water quality risk). They are ranked from very low soil erosion and water quality risk to moderate-to-high soil erosion and water quality risk for grazing (see Table 4).

For Reef 2050 WQIP, new management system benchmarks in all industries have been set at 2016-2017 as the benchmark year from which to show improvements.

ASSOCIATED REEF 2050 WQIP TARGET:

2025 land and catchment management target

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

Information provided by the Agricultural Land Management Practice Adoption program area forms the basis for modelling water quality improvements resulting from investments in improved farm management practices.

Objectives:

- Review and report on progress toward achieving the Reef 2050 WQIP management practice adoption target and develop rigorous estimates of the management system status and change to inform modelling assessments of the progress towards Reef 2050 WQIP water quality targets.
- Provide feedback to program investors regarding the relative impacts of programs and projects aimed at improving farm management practices in the Great Barrier Reef catchments.

Delivery partners:

Department of Agriculture and Fisheries (DAF) (lead), Queensland and Australian government program investors, delivery organisations (e.g. regional NRM bodies, industry partners).

Methods:

Detailed methods for the Management Practice Adoption Program Area are updated annually, and are available as technical reports for download on the Paddock to Reef program website (www.reefplan.qld.gov.au/measuring-success).

The main data sources, inputs and outputs of the management practice adoption component are shown in Figure 12.

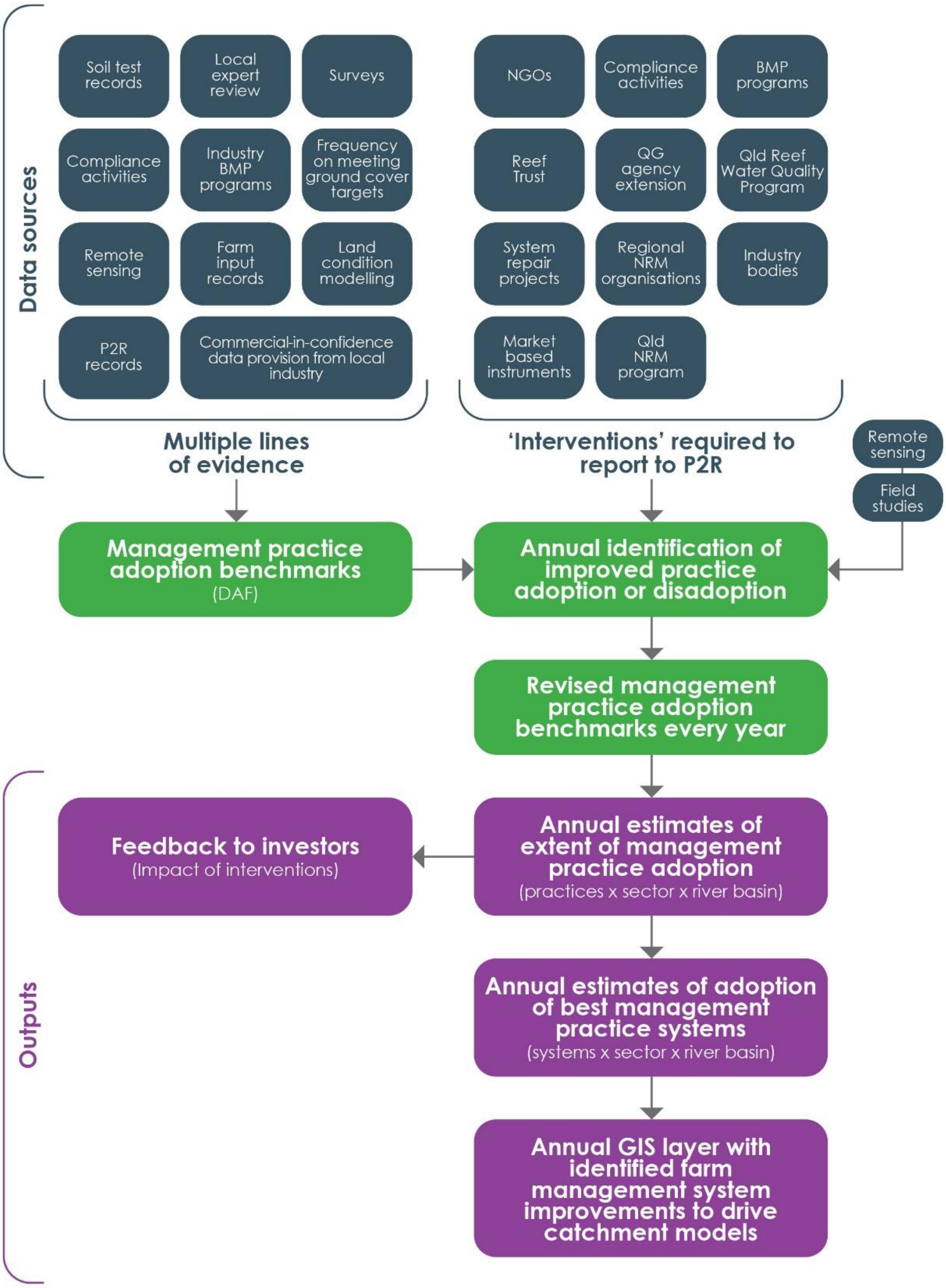

Figure 12. Main data sources, inputs and outputs of the management practice adoption program area.

Water quality risk frameworks

In the context of the management practice adoption target, 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 management practices with greatest potential influence on off-farm water quality and articulate a reasonable best practice level which can be expected to result in a moderate-low water quality risk.

For grazing systems, the water quality risk framework describes 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.

The 'best practice' level is typically the level targeted by Reef 2050 WQIP investments. These practices are described in terms of their relative water quality risk, which range from Low to High.

Table 4. Water quality risk frameworks for the Reef 2050 Water Quality Improvement Plan and alignment with the ABCD terminology and industry best management programs (generalised).

Terminology	Practice standard			
ABCD	A	B	C	D
Water quality risk framework	Lowest risk, commercial feasibility may be unproven	Moderate-low risk	Moderate risk	High risk
	Innovative	Best practice	Minimum Standard	Superseded
Industry BMP (generalised)	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 frameworks. Not all of the practices in the production system are described, only those practices that pose the greatest potential water quality risk, through movement of sediments, nutrients or pesticides off-farm, are described.
- 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.

WQIP adoption benchmarks

The prevalence of all of the practices described in industry water quality risk frameworks was reviewed to establish a realistic baseline of management practice adoption for the 2016-17 year; the commencement of the Reef 2050 WQIP. These adoption benchmarks, where possible, were developed for each of the sub-catchments relevant for each agricultural industry. Annual progress towards the WQIP target for adoption is measured from these benchmarks.

Adoption benchmarks are developed and maintained for each constituent practice. At the farm scale, these management practices combine to form a management system. For reporting and modelling purposes, the mix of management practices is analysed to develop management system risk ratings (from low to high) that reflect the water quality risk posed by the mix of practices on a farm. The weighting applied to each practice in the water quality risk frameworks is used to develop a water quality risk score for a management system (see for example, 2016 Great Barrier Reef Report Card Methods).

Monitoring change and annual revision of adoption benchmarks

Progress of adoption of improved practices and best management practice systems is monitored over time. Organisations receiving 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 work as per the relevant industry water quality risk framework. The ‘interventions’ reported to date include:

- Financial incentives (cash grants and reverse 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; and
- Regulatory education and enforcement activities by the 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 intervention’ assessment, and an ‘after 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 and are not provided to anyone for any purpose other than modelling estimated water quality improvements.

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 evidence.
- Management improvements that occur without the intervention of third party delivery organisations are not detected as there are no industry-wide mechanisms for capturing or reporting management practice change. There is likely to be a degree of *understatement* of improvements for this reason. The five-year benchmarks endeavour to capture management state on this broader scale but the intervening periods are reliant of reported changes.
- Any regression of practices (i.e. adopting practices with greater 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 some improvements may be *overstated*.

Steps taken by the Paddock to Reef program to ensure impacts are sensible include:

- Matching the nature of the intervention and effort with the degree of change reported;
- Analysis of ground cover trends over time for reported grazing land parcels;
- Land condition modelling over time for reported grazing land parcels;
- Estimates of pasture utilisation rates for specific grazing sites;
- Confirming presence of stream and gullies;
- Obtaining site-specific data on the estimated erosion rates from gullies in remediation projects;
- Remote sensing of some management attributes including crop type and sequence, crop row spacing and fallow management; and
- Analysis of some crop inputs and identifying inconsistencies with other lines of evidence.

Individual follow up assessments will continue to be encouraged through investment programs in this phase to ensure that reported practices have been fully implemented and are maintained. For example, investors can add contractual obligations in agreements with delivery organisations to evaluate impact to a satisfactory standard.

Catchment restoration, rehabilitation and repair is considered particularly important for accelerating progress towards the water quality targets. It is recognised that best management practices alone will not meet the water quality targets, and that landscape rehabilitation in strategic locations with specific design criteria, is expected to contribute to better outcomes for water quality and overall Great Barrier Reef coastal and marine ecosystem health.

The Reef 2050 WQIP outlines a range of catchment restoration activities focusing on riparian vegetation, streambanks, gullies and wetlands and builds on work previously undertaken (Reef 2050 WQIP, Implementation Table A3). Where these practices are an integral part of agricultural land management, they are already included in the water quality risk frameworks, for example, gully and streambank management in grazing lands. However, the frameworks for larger scale catchment restoration actions and wetland rehabilitation and treatment system interventions need to be developed, building on existing resources (e.g. Reef Trust Phase IV Gully and Streambank Toolbox, Wetland Rehabilitation Guidelines, Wetland Grazing Guidelines, Treatment System Toolbox and the Wetland Farm Management System Handbook).

For catchment restoration projects that are already underway, individual project outputs are incorporated into the catchment models. A number of treatment systems are being trialled (e.g. as part of the Queensland Reef Water Quality Program Major Integrated Projects 2016-2020 and the Great Barrier Reef Innovation Fund 2016-2020) as a mechanism for improving water quality in the Great Barrier Reef catchments. While conceptually these treatment systems show promise in some locations, as with natural wetland systems, careful consideration needs to be made with respect to catchment hydrology, residence time, rainfall patterns and other factors (Eberhard et al., 2017). Further testing of treatment systems within the catchments of the Great Barrier Reef is needed.

The monitoring and evaluation approach for catchment restoration actions will be resolved in this phase of the Paddock to Reef program.

Data management: Management practice adoption data is recorded and archived in an ESRI file geodatabase. An annual snapshot of the management practice adoption data is uploaded to SKIP.

Assessing progress towards the target

As described above, the management practice adoption benchmarks were updated for each of the critical practices, for each agricultural industry, each region and each river basin in 2016-17. These are reviewed and revised every five years and annual change is based on reported data 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 current 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 Low and Moderate-Low risk (or 'A and B' practice) levels.

The catchment rehabilitation and treatment systems outcomes would support the assessment of progress towards the land and catchment management targets and water quality targets. Contribution to these targets supports progress towards the Reef 2050 WQIP objectives about ecosystem condition.

Program improvements

In response to the QAO and the Great Barrier Reef Water Science Taskforce (GBRWST, 2016), several major improvements have been implemented in this program area in the last two years:

- The water quality risk frameworks for each of the key agricultural industries have been updated to reflect improved knowledge (refine and/or include new practices) and better align terminology.
- The management practice adoption benchmarks that estimate prevalence of farm management practices and systems have been updated with more lines of evidence, and larger more representative datasets. This further improves confidence in the land management practice adoption reporting.
- Remote sensing tools are being incorporated into the review of reported investments.
- A 'spatial wrangling tool' has been developed to assist with the routine processing of large GIS datasets. The tool rapidly identifies conflicts in spatial extent and aligned management attributes for

data provided by different organisations, and across years. It produces a merged spatial layer with codified management systems for each polygon as a key input for the catchment modelling task.

- The paddock scale modelling data is now accessible in a tool to assist in project prioritisation and selection (P2R Projector Tool; see Appendix 2).
- Extensive review and analysis of data to provide the most realistic assessments of reported farm management status and improvements.
- Use of the metrics and products developed for reporting on the ground cover target (see section 3.8) are utilised at farm scale and considered in the adoption benchmarks, and routinely utilised in assessing areas of reported management improvement.

The program will continue to deliver improved datasets through increased sample sizes, further validation and standardised approaches to assessing ground cover and land condition in grazing, and considering input use efficiency metrics in cropping. The frameworks will also be expanded to incorporate greater scope of catchment restoration management actions as required. Additional improvements are also proposed and included in Section 6.1, Table 18.

Applications of the information:

- Provides data for reporting progress towards the Reef 2050 WQIP targets of '90% of land in priority areas under grazing, horticulture, bananas, sugarcane and other broad-acre cropping are managed using best management practice systems for water quality outcomes (soil, nutrient and pesticides), and 'Active engagement of communities and land managers in programs to improve water quality outcomes is increased' in the Great Barrier Reef Report Card.
- Provides primary input data to some regional report cards.
- Reports to the Queensland and Australian governments on impacts of investment.
- Provides feedback to delivery organisations, including guidance to prioritise investment for projects that deliver outcomes, assessment of what has been reported to a satisfactory standard, and assessment of projects that have achieved real impact. The P2R Projector Tool also utilises the management practice adoption data for guiding project selection.
- Water quality risk frameworks inform the model parameters and simulations conducted by the paddock modelling.
- Annual management practice change GIS layers are the direct input into the catchment modelling of water quality improvements.
- Monitoring and reporting of catchment remediation and treatment projects will assist in informing management options for improving water quality from the Great Barrier Reef catchments. The information for wetland treatment projects will be incorporated into a treatment system toolbox on Wetland*Info* in 2018. This will provide easy access to the data and information and will assist in communication.

4.1.2 Social factors influencing management practice adoption

This component of the Agricultural Management Practice Adoption program area will progress our understanding of the social factors that influence agricultural management practice adoption in agricultural industries. It will inform the progress of agricultural communities (and further expanding to non-agricultural industries) towards the Reef 2050 WQIP 2025 human dimensions target.

The program area also contributes to the Reef 2050 WQIP objectives of supporting industries and communities to build a culture of innovation and stewardship and developing a quantitative measure of a range of human dimension factors related to innovation and stewardship.

ASSOCIATED REEF 2050 WQIP TARGET:

Informs the 2025 land and catchment management target

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

2025 human dimensions target

Active engagement of communities and land managers in programs to improve water quality outcomes is increased

Objectives:

- Define and measure a set of indicators associated with social factors that influence adoption, and other key human dimensions factors of relevance among agricultural landholders. These indicators will be used to provide a Human Dimensions baseline measure for the Reef 2050 WQIP and will later inform ongoing monitoring of these indicators.
- Inform the design of water quality investment programs by improved evaluation of the drivers of management practice adoption by landholders.
- Align with the regional report cards to incorporate indicators of social factors that influence adoption.

Delivery partners:

OGBR (lead), Queensland and Australian government program investors, delivery organisations e.g. CSIRO and James Cook University (JCU), will deliver the baseline; and other regional data providers will be involved once implementation is underway.

Methods:

A phased approach is being adopted to implement this new program area, which is anticipated to be fully operational by March 2019.

Framework and design

The first phase of this program area focuses on defining suitable indicators (incorporating *indicators of agricultural practice change for landholders*) to enable the social influences on agricultural land managers' actions to be assessed. These new indicators will support assessment of '*why landholders are engaging and making particular management decisions*'. Specifically, this new program area will identify the behavioural change factors that are believed to encourage landholders to adopt improved management practices for water quality outcomes.

The indicators of agricultural practice change for landholders are shown in Table 5. The indicators are grouped into six themes, with examples of questions or measures. These are likely to be practice-specific and incorporated into the process for assessing management practice adoption described above.

Table 5. Indicators of agricultural practice change for landholders.

Indicator theme	Description	Example question/measure
Attitudes (towards the practice)	How attractive, beneficial and/or risky the practice is (compared to current practice).	• To what extent do you believe that reducing the amount of nitrogen fertiliser you apply to your crop, will lead to better outcomes for your farm? • To what extent do you believe that reducing the amount of nitrogen fertiliser you apply to your crop, is a risky thing to do?
Perceived behavioural control	How easy or difficult it is to perform the practice (self-efficacy/capability), and whether it is within one's control (perceived control).	• If you wanted to, how easy would it be for you to reduce the amount of nitrogen fertiliser you apply to your crops? • Whether or not you reduce the amount of nitrogen fertiliser is a decision that is completely up to you.
Motivation	How motivated one is to perform the practice, and whether this is for intrinsic or extrinsic reasons.	• Compared to other issues you face in running your business, how important to you is reducing the amount of nitrogen fertiliser that you apply to your crop? • Can you tell me why it is important to you to reduce the amount of nitrogen fertiliser you apply to your crops? Because: a) of the possibility of improved productivity (extrinsic); b) it seems to be the right thing to do to be seen as a good farm manager (extrinsic), or; c) of the possibility of contributing to something worthwhile (intrinsic).
Behaviours (past and future)	Whether the practice (or precursor practices) has been used in the past, and whether there is a stated intention to trial or use certain practices in the future, in a particular situation, at a particular time.	• In the past month, have you taken any action to reduce the amount of nitrogen fertiliser you apply to your crops? • Do you intend to reduce the amount of nitrogen fertiliser you apply, the next time you fertilise your crop?
Group norms	Whether other land managers/ farmers in the community (with whom one has strong ties) approve of, and perform the practice themselves.	• How likely do you think it is that growers in your region have reduced the amount of nitrogen fertiliser they apply to their crops? • How many growers in your local area would think that reducing the amount of nitrogen applied to their crops is a good thing to do?
Trust	Level of trust in information sources and advice networks related to improved practices.	• How much do you trust the advice you receive from industry experts about how much nitrogen fertiliser should be used?

The existing Paddock to Reef program process for management practice adoption data (see Section 4.1.1) will be used to collect the *Indicators of agricultural practice change*. It is expected that 5-6 additional questions will be incorporated into the standard Paddock to Reef program practice change questionnaire, which would start building a clearer picture of the drivers of practice change. Additional indicators are being developed to assess the cultural influences and anecdotal evidence of a culture of stewardship and collection methods for these are yet to be developed, however it is not likely to be through the Paddock to Reef program.

The OGBR is liaising with RIMReP's Human Dimensions working group to both consult on the indicators but also to create pathways for data flow once RIMReP is operational.

The Human Dimensions baseline dataset (required to fulfil Action 7.3 outlined in the Reef 2050 WQIP) is being developed in 2018, building on from existing monitoring and evaluation datasets (e.g. Cane Changer, Griffith University Mackay Study - RP161 study, Major Integrated Projects etc.). Methods will be developed to measure the indicators, to assess changes over time, compare the effectiveness of different types of landholder support, inform decision-making about how projects are delivered to landholders and adaptively manage projects for continuous improvement.

The indicators will be provided to all practice change projects to report on yearly from late 2018, allowing for ongoing monitoring. It will be extended to other land uses during this phase of the Paddock to Reef program.

Data management: Data will ultimately be stored in SSIMR.

Assessing progress towards the target

The approach to assessing progress towards the Human Dimensions targets is still in development.

Applications of the information:

- Provides data for reporting progress towards the Reef 2050 WQIP target of 'Active engagement of communities and land managers in programs to improve water quality outcomes is increased' in the Great Barrier Reef Report Card.
- The baseline dataset and ongoing annual monitoring will provide data to assist in interpretation of the results for interpreting progress towards the management practice adoption target '90% of land in priority areas under grazing, horticulture, bananas, sugarcane and other broad-acre cropping are managed using best management practice systems for water quality outcomes (soil, nutrient and pesticides)', and enable an assessment of areas for improvement (which may inform program design and delivery). Within individual projects, this may be the approaches to engagement with growers, project decision-making, etc.

4.2 Non-agricultural land use management practice adoption and effectiveness (*phased implementation*)

While the main sources of water pollution from Great Barrier Reef catchments continue to be from agriculture, the Reef 2050 WQIP recognises that urban and industrial land uses can create concentrated pollution that has important local impacts. The increased presence of waste plastics, including micro-plastics, is an emerging pollution threat to the Great Barrier Reef, and can come from urban areas in some cases.

Urban development is regulated. Water quality requirements (minimum standards) for urban land uses are set through the Queensland *Planning Act 2016* and the *State Planning Policy 2017*. The majority of compliance and development assessment for urban development is the responsibility of local governments. The Queensland Government invests into capacity building for local government and industry to implement effective compliance and development assessment programs. Sewage treatment plants (STPs), are included in the urban components of this program area.

Industrial land uses (environmentally relevant activities) are regulated under the *Environmental Protection Act 1994*. Examples of environmentally relevant activities include aquaculture, abattoirs and some extractive and petroleum activities.

ASSOCIATED REEF 2050 WQIP TARGET:

2025 land and catchment management targets

The management of urban, industrial and public land uses for water quality shows an improving trend

2025 human dimensions target

Active engagement of communities and land managers in programs to improve water quality outcomes is increased

Improved management of public lands is important for decreasing diffuse sourced water pollution and fostering a sense of collaborative effort across Australian, state and local government agencies. In particular, unsealed roads and road construction activities can be a significant source of sediment in some areas.

The Reef 2050 WQIP includes an action to incorporate water quality risk management practice frameworks for urban and industrial land uses into the Paddock to Reef program.

Objectives:

- Develop an urban water quality management practice adoption framework that captures where current practices sit against an ABCD risk framework that includes meeting minimum standards (e.g. compliance with legislative requirements), best practice, innovative management approaches, and additional stewardship actions that address urban pressures impacting on water quality.
- Incorporate into the urban water quality management practice adoption framework causal links between management actions and water quality outcomes by linking with existing water quality monitoring data.
- Develop separate management practice adoption frameworks to assess and communicate compliance, best practice, innovation and stewardship measures in industrial sectors.
- Update the Public Lands Strategy to ensure that the land management strategies that apply to Queensland's public lands in Great Barrier Reef catchments (including roads, National Parks, Defence lands and State forests) meet standards that effectively avoid or mitigate sediment, nutrient and pesticide run-off into waterways from the various land uses.

Delivery partners and key stakeholders:

This program area is being coordinated by the OGBR in DES in partnership with several stakeholder partners. These include:

- Reef Urban Stormwater Management Improvement Group (RUSMIG)
- Regional report card partnerships and Technical Working Group (TWGs) for Wet Tropics, Mackay Whitsunday and Dry Tropics and Gladstone Independent Science Panel
- Queensland Water Sewerage and Water Environmental Advisory Panel and Technical Reference Group
- Local Government Association of Queensland (LGAQ)
- Australian Government.

Industrial partners will be identified at a later stage.

Methods:

The management of non-agricultural land uses for improved water quality outcomes is an addition to the Reef 2050 WQIP and the monitoring and evaluation framework, methods and delivery arrangements are still being developed.

Presently, reporting on the management practice effectiveness or 'stewardship' of non-agricultural sectors is inconsistent across the established regional report cards in Queensland. Fitzroy Partnership for River Health and the Wet Tropics Healthy Waterways Partnership do not assess sector performance against a framework; although case studies of good environmental stewardship are included in their report card content. The Gladstone Healthy Harbour Partnership and Mackay-Whitsunday Healthy Rivers to Reef Partnership use stewardship assessment frameworks for relevant non-agricultural sectors.

Assessment of stewardship under these frameworks relies on publicly available information and self-reporting by agencies and/or industry representative bodies, supplemented with compliance data from government agencies.

The current scope of work is to deliver updated non-agricultural frameworks for the regional report cards. The new Dry Tropics Partnership for Waterway Health will pilot the updated urban water quality management practice adoption framework.

There is scope to include a set of human dimensions indicators to support assessment of what factors are influencing the uptake of innovative management practices that exceed best practice in urban and industrial sectors.

A phased approach for the development and implementation of these new frameworks for the Paddock to Reef program is being adopted, as described below.

Framework and design

Urban

A new urban water quality management practice adoption framework is being delivered for the regional report cards that will determine a measure of environmental stewardship for water managers in the urban environment and to identify and drive suitable management actions to deliver improved water quality outcomes in urban land uses.

There is a sizeable body of work that has already been done in Queensland to define best practice urban water management that is available to inform the current update. Most of this work relates to defining water quality management practices related to diffuse pollution sources (e.g. roads and infrastructure construction projects, major residential developments and stormwater management in mature residential or industrial areas) from lowest risk (A) to highest risk (D). Separate framework elements need to be developed for Diffuse Source activities -Private Sector Development, Public Sector Development/Construction, Established Urban - and one for Point Source activities suitable for both local government and private operators. The frameworks will identify the management practices with the greatest potential to improve water quality and articulate a reasonable best practice level which can be expected to result in a lower water quality risk.

There is increasing focus on marine debris and the impact of micro-plastics in the marine environment. The responsibility of urban centres for managing these pollutants is to be included in this framework with causal links between management effectiveness and a gross pollutant metric (to tie in with regional report card marine debris monitoring). The development of ABCD practices related to urban stormwater and litter management (e.g. avoidance/reduction, capture) will be incorporated into the urban frameworks where relevant. Catchment restoration actions within non-agricultural land uses will also be considered in this phase of the Paddock to Reef program.

Industrial

Separate assessment frameworks will need to be developed for industrial activities in this phase of the Paddock to Reef program. This will include environmentally relevant activities such as aquaculture and heavy industry. Where possible, the program will draw on the work already conducted by the regional report cards described above.

Public lands

The review and update of the Public Lands Strategy will ensure that the land management practices associated with the various land uses on public lands meet current objectives and management principles for improving water quality entering the Great Barrier Reef. Public land includes a range of different land tenures that are vested in either - Commonwealth, State or local government.

Data management: Data management arrangements are still in development.

Assessing progress towards the target

Reporting progress towards the target that 'The management of urban, industrial and public land uses for water quality shows an improving trend' will be defined following development of the management assessment frameworks described above.

Applications of the information:

- Provides data for reporting progress towards the Reef 2050 WQIP target that 'The management of urban, industrial and public land uses for water quality shows an improving trend' in the Great Barrier Reef Report Card.
- The data can also be used to assist in urban planning and management prioritisation.
- Provision of information to the wider community on the pollutant generation characteristics from other land uses is critical for progressing management practice improvement and engagement.
- Regional report card partnerships will undertake local reporting of agreed sectors where applicable.

Management practice effectiveness and paddock scale pollutant delivery (agricultural land uses)

4.3 Economic benefits of agricultural management practices *(phased implementation)*

The economic monitoring and modelling program will be designed to provide a systematic set of comparative cost-benefit economic data as it relates to the priority catchments, agricultural industries and practices. An economic assessment component was incorporated into the original Paddock to Reef program design in 2009. This included work by DAF and CSIRO to assess the cost-effectiveness of management practices in sugarcane and grazing in several areas, but primarily in the Wet Tropics, Burdekin and Mackay Whitsunday regions. This work was resourced through the Paddock to Reef program in the first two years, and was subsequently resourced through related research initiatives including the Australian Government Reef Rescue Water Quality Research and Development Program (Star et al., 2013; van Grieken et al., 2015) and DAF (Poggio et al., 2014).

There is increasing interest from programs to optimise their investment by facilitating adoption of the most cost-effective management options. A number of studies have been completed in recent years to support these decisions including at the regional scale to support the development of WQIPs (e.g. Park et al., 2015; Star et al., 2015) and most recently, a Great Barrier Reef wide assessment of the cost of meeting the Reef 2050 Plan water quality targets (Alluvium, 2016) and prioritisation based on marine water quality risk and the cost-effectiveness of pollutant load reductions (Star et al., 2017). Economic modelling is therefore a critical component of program evaluation and has been reinstated formally as part of the Paddock to Reef program in this design. The scope of work within the current resources requires further development and prioritisation.

ASSOCIATED REEF 2050 WQIP TARGET:

Informs the 2025 land and catchment management target

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

2025 human dimensions target

Active engagement of communities and land managers in programs to improve water quality outcomes is increased

Objectives:

- Determine the economic implications of changing land management from modelling various management practice scenarios.
- Provide economic information to program managers, extension officers and agricultural technical advisors to assist in the facilitation of accelerated adoption of improved management practices.
- Inform investment prioritisation assessments for agricultural industries in the Great Barrier Reef catchments, including data to inform analysis of the costs of meeting the Reef 2050 WQIP water quality targets.

Delivery partners:

DAF (lead), DES and DNRME paddock modellers

Methods:

The methods for this program area are still being developed and will be established in 2018-2019, building on previous work. The methods for assessing the cost-effectiveness of agricultural management practices range between industries and past work is captured in specific project reports. Synthesis of this work for sugarcane is provided in Harvey et al. (2016) and for grazing in Moravek et al. (2016).

Framework and design

It is recognised that the economic monitoring and modelling program needs to meet several objectives to support Reef 2050 WQIP evaluation. These are illustrated in Figure 13 and described below.

- **Order 1: Farm level profitability**. Identify and validate management practice solutions using actual biophysical and financial data. Provides input data, parameters and validation of higher order modelling. Value adds to extension information, supports increased adoption rates and improves confidence in best management practices.
- **Order 2: Project impact.** Determines economic impact of projects and cost-effectiveness. Assists in program prioritisation, insights into what has worked well or needs improvement and understanding of impediments/influencers of adoption.

- **Order 3: Broader Economic Impact.** Determines broader economic and value-added impact of programs. Supports government reporting, community reporting, policy development and impact assessment.

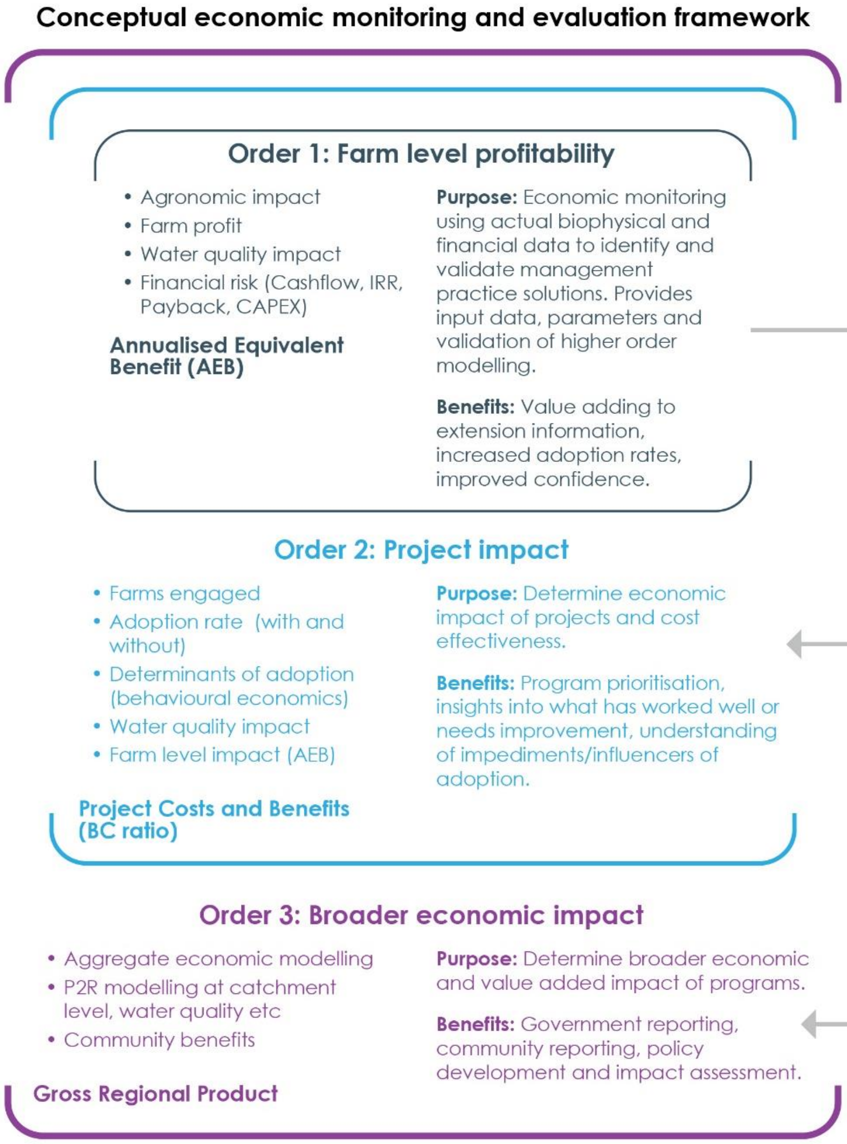

Figure 13. Proposed conceptual economic monitoring and evaluation framework to be recognised within the Paddock to Reef program.

The theoretical framework for the economic modelling component showing data inputs and outputs is shown in Figure 14. Input data is derived from the paddock modelling outputs (APSIM, GRASP and HowLeaky; see Section 4.5 below). It is likely that the yield and production monitoring data to support the economic modelling would be collected as part of the paddock monitoring activities described in Section 4.4 in addition to results from other experimental sites where possible. There may be some opportunity to capture data and information on transition costs and risks at the same time which is helpful for assessing the factors influencing practice change.

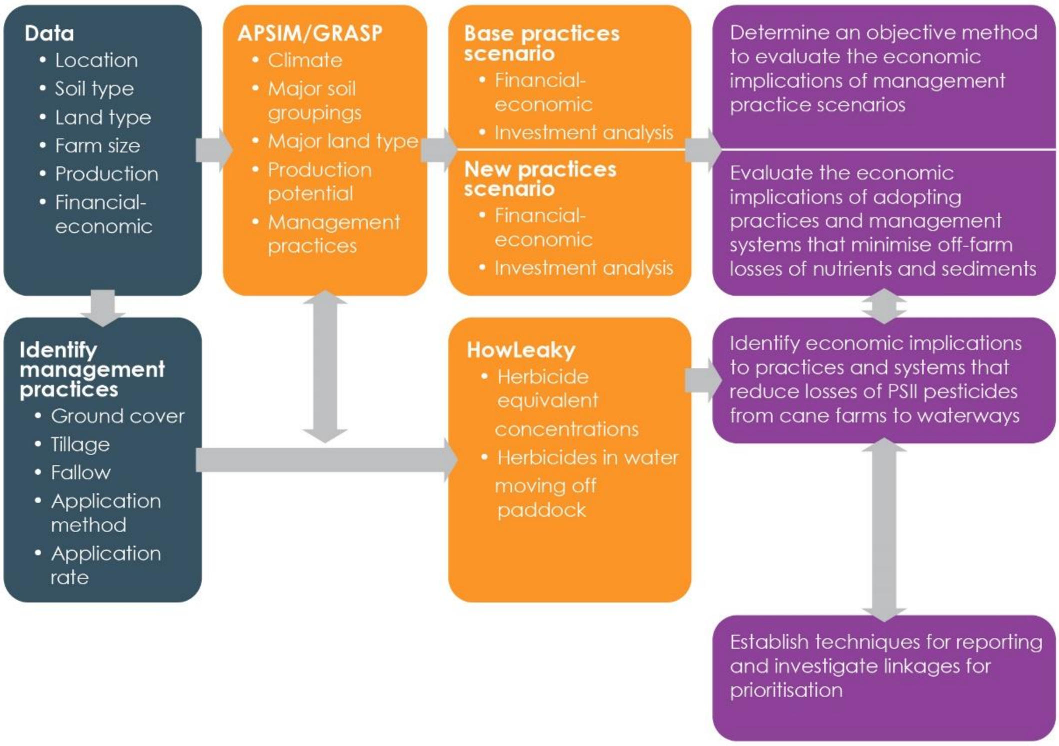

Figure 14. The theoretical framework for economic modelling for sugarcane and grazing in the Great Barrier Reef catchments.

There are a number of tasks required to support the establishment of the agricultural economic monitoring and modelling program:

1. Develop an approach for updating economic modelling to align with the Paddock to Reef program water quality risk ramework for agricultural management practices (described in Section 4.1).
2. Update the water quality risk framework described in Section 4.1 to incorporate farm economic outcomes.
3. Establish techniques for reporting the economic data in the Paddock to Reef program reporting framework.
4. Investigate linkages and opportunities to incorporate economic information into management prioritisation assessments.

Data management: Data management arrangements are still in development.

Assessing progress towards the target

The economic information supports assessment of progress towards the management practice adoption target and human dimension target.

Application of the information:

- The economic data can be used to interpret the status of the Reef 2050 WQIP targets of '90% of land in priority areas under grazing, horticulture, bananas, sugarcane and other broad-acre cropping are managed using best management practice systems for water quality outcomes (soil, nutrient and pesticides)' and 'Active engagement of communities and land managers in programs to improve water quality outcomes is increased'.
- The outputs can inform project selection and management prioritisation. Options for incorporating the data into the P2R Projector Tool (described in Appendix 2) will be investigated in this phase of the Paddock to Reef program.

- The data could be used to inform estimates of the cost of meeting the Reef 2050 WQIP water quality targets.

4.4 Paddock monitoring of water quality benefits

A range of paddock-scale water quality run-off trials are conducted in various regions to provide on-ground evidence of water quality improvements from different land management practices. Paddock monitoring and rainfall simulation field trials provide input to the modelling through measured evidence of the relative effectiveness of on-ground management practices at a practical scale and under local climatic conditions and soil types.

Plot/paddock scale monitoring and rainfall simulation experiments provide opportunities to robustly compare management practices by ensuring the management treatments are the major variable between experimental plots. Rainfall simulation trials can include various process studies, including for example, pesticide half-life trials, mineralisation rate trials for organic additions such as mill mud, etc., as well as run-off generation trials (e.g. measuring pesticide run-off or soil erodibility), as required by the paddock modelling.

Paddock monitoring and rainfall simulation field trials also play an important role in extension through the demonstration of practice effectiveness to target audiences. The program also monitors run-off and water quality from some larger, multi-farm catchments to test practice effectiveness at this larger scale.

Objectives:

- Continue to provide on-ground evidence of, and on-ground demonstration of, the effectiveness of management practices for managing sediment, nutrients and pesticides in the key agricultural industries for improving confidence in the paddock and catchment models, particularly of management effects on water quality and soil erodibility.
- Provide new understanding of water quality processes against priority knowledge gaps.
- Contribute to tools for informing land management change regional investment priorities for water quality improvement.

Delivery partners:

DNRME (lead), DES, Queensland University of Technology (QUT), James Cook University (JCU), other partners contracted as required.

ASSOCIATED REEF 2050 WQIP TARGET:

Informs the 2025 water quality targets

60% reduction in anthropogenic end-of-catchment dissolved inorganic nitrogen loads

25% reduction in anthropogenic end-of-catchment particulate nutrient loads

25% reduction in anthropogenic end-of-catchment fine sediment loads

Pesticides: To protect at least 99% of aquatic species at end-of-catchments

Methods:

Paddock monitoring involves collecting run-off and drainage during actual rainfall events from a uniform portion of a paddock. The paddock monitoring provides direct evidence from real farming systems of the water quality impacts of management practices. These provide a series of ‘anchor points’ of real-world validation for modelling activities across the regions for high priority industries. Paddock monitoring is constrained by its cost and the reliance on natural rainfall events.

Rainfall simulation involves collecting run-off and drainage from a simulated rainfall event from a plot within a paddock. The rainfall simulation monitoring provides a rapid and cost-effective way to generate results across a diversity of land systems and soil types. This allows our understanding of management impacts to be extended across a wider range of environments than would otherwise be possible. By simulating rainfall events, this approach generates data even in dry periods. Rainfall simulation is limited by logistics (people, equipment and seasons), and needs to be calibrated against the paddock monitoring sites.

The activities described in Table 6 are current paddock monitoring activities that will be extended for the first year of this phase (2018-2019) to allow for the completion of the current work program. Paddock monitoring activities for 2019-2022 are being developed for future funding.

Table 6. Summary of paddock monitoring projects to be continued as part of the Paddock to Reef program in 2018-2019.

Project	Delivery Partners	location	Activities	Timeframe
Nutrient loss in run-off and deep drainage from sugarcane in the South Johnstone catchment, Wet Tropics	DNRME	Wet Tropics *Silkwood, South Johnstone*	Run-off plots to assess: • Refined BSES Six-Easy-Steps nitrogen rates based on productivity unit yield potential. • Current Six-Easy-Steps nitrogen rates based on district yield potential. • Enhanced efficiency nitrogen fertiliser.	1 additional wet season, 2017/2018 with time allocated to data analysis and reporting
Groundwater - Surface water contaminant movement investigation	QUT, DNRME and JCU	Wet Tropics *Silkwood, South Johnstone* *Mulgrave*	• Groundwater level monitoring. • Groundwater and surface water sampling. • Water analyses (including stable isotopes of nitrate N and Oxygen). • Sediment sampling (along groundwater flow path). • Sediment analyses (including clay mineralogy). • Column experiments using cores collected from the field site (to investigate processes controlling nitrate attenuation). • Data analysis and reporting (including two publications).	2018/2019 with time allocated for data analysis and reporting
Comparison of best management practices and conventional farming practices in sugarcane and multi-farm monitoring of a sugarcane-dominated catchment; Victoria Plains, Mackay	DNRME	Mackay Whitsunday *Sandy Creek (Plane Creek basin)*	• Six-Easy-Steps (district yield potential) nutrient management versus Six-Easy-Steps (block yield potential) nutrient management. • Controlled release nitrogen fertiliser products versus urea fertiliser. • Use of non-regulated residual herbicides. • Movement of sub-surface applied Imidacloprid through surface run-off. • Design for mill mud investigation.	2018/2019 with time allocated for data analysis and reporting
Grazed landscape contributions to run-off nutrient, sediment, fine sediment and bio-available particulate nutrient loss in the Fitzroy basin	DNRME	Fitzroy	• Characterise and compare run-off properties from the major land uses and management practices at the long-term Brigalow Catchment Study – value adding and back-casting. • Test the assumption that sediment lost from a virgin brigalow forest has the radionuclide signature of surface soil.	2018/2019 with time allocated for data analysis and reporting

Framework and design

The selection of paddock-scale monitoring trials and rainfall simulation is informed by the strategic gaps identified by the paddock and catchment modelling teams, the management practice adoption team and recently published information. Priorities for the 2019-2022 paddock monitoring work program include:

- Priority **industries and regions** as identified by the 2017 Scientific Consensus Statement risk assessment (Waterhouse et al., 2017b). In summary, priority issues for the paddock modelling to be addressed by region are:
  - Wet Tropics, sugarcane: nutrient loss pathways, and efficacy of wetlands and treatment systems;
  - Burdekin, sugarcane: nutrient losses from irrigation run-off versus rainfall run-off, and surface run-off versus deep drainage;
  - Mackay Whitsunday, sugarcane: nutrient loss pathways, and pesticide management;
  - Fitzroy, grazing: fine sediment generation and transport, and bioavailable nutrient sources and processing, pasture response to management; and
  - Burnett Mary, streambank erosion: management options and effectiveness.
- Priority **monitoring treatments for calibrating models** to the soils and management practice in the region as identified in the framework and design section below.
- **Clearly defined and achievable pathway to impact** (e.g. activities that will improve Paddock to Reef program confidence scores).
- **Priority management practices** (i.e. the practices that require further validation for industry acceptance).
- **Priority knowledge gaps** as identified by the 2017 Scientific Consensus Statement and Reef 2050 WQIP Research Development and Innovation Strategy 2018-2022.

Other factors to consider for future paddock monitoring activities include:

- Activities that aren't being addressed via other programs e.g. Sugar Research Australia (SRA) Enhanced Efficiency Fertiliser projects, or trials of wetlands/alluvial gullies in the Major Integrated Projects.
- Activities that have an ability to leverage off existing projects e.g. established paddock monitoring sites such as Victoria Plains.

Table 7 provides a summary of the knowledge gaps and the basins of most relevance to the gap (based on the findings of the management prioritisation in the 2017 Scientific Consensus Statement). Priority locations for paddock monitoring to contribute to filling these knowledge gaps are also identified. This framework provides guidance to paddock monitoring activities in the Paddock to Reef program, and also provides a basis to highlight opportunities for seeking collaboration with research and development and industry partners to improve knowledge in these areas.

Table 7. Priority modelling gaps identified for the paddock monitoring program mapped against the relative management priorities and modelling priorities.

Priority modelling / priority knowledge gap	Basins of relevance to this knowledge gap[1]	Priority locations for paddock monitoring (based on 2019-2022 priorities)
Fine sediments		
Soil erodibility (hillslope, streambank and gully) for soils in grazed landscapes, particularly fine sediment generation and bioavailability of nutrients.	*Grazing lands* Very High: Burdekin High: Fitzroy, Mary, Herbert	Fitzroy, Mary, Herbert (evidence exists for priority catchments in the Burdekin)

Priority modelling / priority knowledge gap	Basins of relevance to this knowledge gap[1]	Priority locations for paddock monitoring (based on 2019-2022 priorities)
The sediment contribution of linear features, cattle pads and tracks in grazing lands.	*Grazing lands* Very High: Burdekin High: Fitzroy, Mary, Herbert Moderate: Johnstone, Burnett	Not location specific; could be trialled in multiple locations
Further refinement of current estimates of peak run-off from hillslopes and improvements to hillslope soil erosion model (e.g. replace RUSLE rainfall factors in grazing).	*Grazing lands with high hillslope erosion contributions* Very High: Burdekin High: Fitzroy, Mary, Herbert Moderate: Johnstone, Burnett	Rainfall simulation - not location specific; could be trialled in multiple locations
Develop and apply advanced surveying and analysis techniques for gully and streambank erosion/deposition.	*Grazing lands with high gully and streambank erosion contributions* Very High: Burdekin High: Fitzroy, Mary Moderate: Johnstone, Burnett	Not location specific; could be trialled in multiple locations
Nutrients		
Full nutrient balance in sugarcane including groundwater and gaseous losses.	*Sugarcane areas* Very High: Herbert, Haughton High: Johnstone, Russell Mulgrave, Tully Moderate: Plane, Murray, Burdekin, Proserpine, O'Connell, Pioneer, Mary	All sugarcane areas but focus in highest nutrient generation areas, e.g. Wet Tropics and Lower Burdekin
Mill mud mineralisation, run-off and deep drainage data including distinction of surface versus incorporated application methods.	*Sugarcane areas* Very High: Herbert, Haughton High: Johnstone, Russell Mulgrave, Tully Moderate: Plane, Murray, Burdekin, Proserpine, O'Connell, Pioneer, Mary	All sugarcane areas but focus in areas of highest application of mill mud, e.g. Mackay Whitsunday basins
Enhanced efficiency fertiliser in sugarcane.	*Sugarcane areas* Very High: Herbert, Haughton High: Johnstone, Russell Mulgrave, Tully Moderate: Plane, Murray, Burdekin, Proserpine, O'Connell, Pioneer, Mary	All sugarcane areas but focus in highest nutrient generation areas, e.g. Wet Tropics and Lower Burdekin and in area with existing monitoring e.g Mackay Whitsunday
DIN run-off and drainage (rain versus irrigation) in Burdekin irrigated sugarcane.	Very High: Lower Burdekin (Haughton)	Lower Burdekin (Haughton)
Improved differentiation of surface and subsurface nutrients to better parametrise the streambank and gully erosion models.	*All land uses but emphasis on grazing lands*	All grazing areas but focus in highest particulate nutrient generation areas, eg. Burdekin, Johnstone
Quantification of DIN generation from grazing lands.	*Grazing lands*	Focus in highest marine risk areas where DIN may be derived from grazing lands (high DIN loads) e.g. Burdekin, Johnstone
DIN in groundwater and re-emergence to streams, and transformation/ losses in the Wet Tropics. Tracer studies to quantify base flow separation volumes for major river systems.	*Wet Tropics sugarcane areas* Very High: Herbert High: Johnstone, Russell Mulgrave, Tully Moderate: Murray	Focus where there is limited knowledge of groundwater interactions, i.e. all except Johnston - Herbert, Russell Mulgrave, Tully
Efficacy of catchment restoration including riparian vegetation and wetland restoration, gully remediation.	*All land use*	All land uses but focus in highest nutrient and sediment generation areas with major restoration efforts, e.g. Wet Tropics and Lower Burdekin
Pesticides		
Properties of more pesticides – e.g. fungicides in bananas, and pesticide mixtures – used where and when.	*Sugarcane and banana areas* Very High: Plane High: Pioneer, Haughton	Industry-specific in highest risk areas, e.g. Tully for bananas, Plane for sugarcane

Priority modelling / priority knowledge gap	Basins of relevance to this knowledge gap[1]	Priority locations for paddock monitoring (based on 2019-2022 priorities)
	Moderate: Tully, O'Connell	
Imidacloprid and other sugarcane grub pesticides in run-off – surface versus sub-surface, and soil half-lives.	*Sugarcane areas* Very High: Plane High: Pioneer, Haughton Moderate: Tully, O'Connell	Focus in highest pesticide generation areas, e.g. Plane, Pioneer, Haughton
Pesticide run-off data in bananas (half-life and run-off extinction coefficients).	*Banana areas* Moderate: Tully	Focus in highest pesticide generation areas in banana areas, e.g. Tully, or opportunistic sites

[1] *As defined in the 2017 Scientific Consensus Statement (see Waterhouse et al., 2017a,b).*

Data management: Technical reports, case studies and journal articles are published at the completion of projects or strategic times throughout the project duration as appropriate. Technical reports (available from Queensland Government Library online), procedures, methods, photographs and other supporting information is captured and managed in SKIP. Site specific information is recorded in DARTS. Case studies are available on the Reef 2050 WQIP website.

Assessing progress towards the target

This data is used to inform and validate the paddock modelling outputs, which in turn inform the catchment modelling of progress towards the water quality targets. Case studies and results of the investigations inform industry and investors.

Program improvements

Recent improvements to this program area include:

- Completion of an audit of the experimental design of each monitoring site has led to stronger relevance of the monitoring results.
- Field and rainfall simulation studies were prioritised to release more resources for data synthesis and interaction with paddock modellers, with additional training for field staff to facilitate closer collaboration with the modelling team.
- An assessment of the value of the monitoring results for extension has assisted in determining communication outputs for the program.
- Improved communication between the paddock monitoring teams and paddock modellers has enhanced coherence and maximised data exchange.

The program will continue to work more closely with the paddock and catchment modelling teams, and the management practice adoption teams to ensure that the experimental design remains relevant and provides useful data for addressing model uncertainties. Opportunities for collaboration with research and development programs will also be sought and formalised. Additional improvements are also proposed and included in Section 6.1, Table 18.

Applications of the information:

Data and information generated through the paddock monitoring and modelling program:

- Directly feeds into the paddock models and informs catchment models that report progress towards the Reef 2050 WQIP Water Quality targets in the Great Barrier Reef Report Card.
- Provides feedback on emerging practices and the water quality signature of practices for informing management practice adoption, and where necessary, adjusting the management practice adoption frameworks.
- Reported via case studies for use by extension officers with landholders.
- Provides demonstration sites for stakeholders and training sites for university students.

4.5 Paddock modelling of practice effectiveness (water quality outcomes)

The paddock scale modelling provides information on water quality in run-off or deep drainage for the sugarcane, grazing, banana and grains industries. It links the management practice adoption data with the catchment model by providing estimates of sediment and nutrient loads and pesticide concentrations for management practice scenarios. A suite of defined farming systems which represent plausible management practice combinations and scenarios are simulated for a large number of combinations of soils and climates.

The catchment model used for reporting progress towards the water quality targets has limited capability for reflecting changes from improved management at the paddock scale. In contrast, paddock soil water balance models are designed specifically to simulate effects of management practices such as crop rotations, intensity of tillage and the application method, rate and timing of herbicides and fertilisers, and grazing pressure and pasture spelling. They are also able to supply daily outputs based on the same rainfall inputs used in the catchment models for many combinations of climate, land use, soil type and management practice. The paddock modelling results are a critical input to the catchment modelling. The effectiveness of individual practices and state of key parameters for the paddock modelling is derived from paddock scale monitoring (historic or within the Paddock to Reef program). In some cases, sub-components of the paddock scale models are derived directly from the monitoring data (e.g. DIN run-off model in sugarcane).

Paddock models can be used to derive 'emergent models' or relationships which can be used in the catchment modelling when other models cannot be used. For example, a simple cover change equation was established from representative GRASP model runs rather than attempting to run GRASP over areas with sparse input soil parameters.

ASSOCIATED REEF 2050 WQIP TARGET:

Informs the 2025 water quality targets

60% reduction in anthropogenic end-of-catchment dissolved inorganic nitrogen loads

25% reduction in anthropogenic end-of-catchment particulate nutrient loads

25% reduction in anthropogenic end-of-catchment fine sediment loads

Pesticides: To protect at least 99% of aquatic species at end-of-catchments

Objectives:

- Model a suite of farm management scenarios that represent the management practice combinations consistent with industry water quality risk frameworks across soils and climate zones.
- Provide sediment and water quality (nutrients and pesticides) modelling for each paddock combination of climate, soil, land use, and land management practice for sugarcane, dryland cropping, horticulture (bananas), and the effects of investments and adoption of land management actions, and input to the Great Barrier Reef Source Catchment model.
- Evaluate effectiveness of management practice systems (i.e. water quality risk frameworks) and components of systems (for example in the sugarcane industry individual practices such as tillage intensity compared with controlled traffic) to inform the prioritisation of on-ground investments (by regional bodies and Australian and Queensland governments) and for economic studies.
- Capture the emergent parameters (e.g. improved soil erodibility in grazing) and relationships from paddock monitoring to improve modelling and understanding of management systems.

Delivery partners:

DNRME (lead), DES

Methods:

Framework and design

The paddock scale modelling provides estimates of the hydrologic balance, including run-off and deep drainage, and the loads and concentrations of particulate and dissolved nitrogen, phosphorus, and pesticides in run-off, across a range of management practice systems or components of systems. Paddock scale model outputs also need to represent the diversity of soils and climates across the Great Barrier Reef catchments.

Three paddock models, Agricultural Production Systems sIMulator (APSIM), GRASP and HowLeaky are used to generate constituent loads in sugarcane, grains, bananas and grazing. The models are based on similar soil water balance, ground cover and run-off sub-models. They are all driven by daily soil water balance sub-models, however, they vary in the level of detail, particularly in terms of representing crops and any extra processes considered (such as pesticide degradation and export). Each model is assigned for use in a particular industry based on its proven ability to deal with management issues specific to that industry. The model approaches currently used for each constituent and land use are summarised in Table 8.

Table 8. Paddock modelling matrix showing the approaches used for each constituent and land use. Note: Source = Source Catchment model or other pre-processors, RUSLE = Revised Universal Soil Loss Equation, BGI = Bare ground index, EMC = Event mean concentration – a single concentration applied to each runoff event in Source Catchments. If modelled by EMC there are no effects of management represented. P2R = Paddock to Reef program.

Constituent	Sugarcane	Grains	Bananas	Grazing
Sediment				RUSLE + Fractional ground cover[1] = baseline
	APSIM with post-processing for slope and soil erodibility (in Source)	HowLeaky time series used directly	HowLeaky time series used directly	GRASP informs cover changes; RUSLE modelled in Source
Nitrogen				
Particulate N	Function of hillslope erosion and soil TN (in Source)	Function of hillslope erosion and soil TN (in Source)	Function of hillslope erosion and soil TN (in Source)	Function of hillslope erosion and soil TN (in Source)
DIN run-off	APSIM time series used directly - empirical function derived from P2R field data	EMC (in Source)	HowLeaky time series used directly – empirical function derived from P2R field data	EMC (in Source)
DIN drainage	APSIM time series used directly	EMC (in Source)	HowLeaky time series used directly – empirical function derived from P2R field data	EMC (in Source)
DON	EMC (in Source)	EMC (in Source)	EMC (in Source)	EMC (in Source)
Phosphorus				
Particulate P	Function of hillslope erosion and soil TP (in Source)	HowLeaky time series used directly	HowLeaky time series used directly	Function of hillslope erosion and soil TP (in Source)

[1] Refer to Section 4.8 for a description.

Constituent	Sugarcane	Grains	Bananas	Grazing
FRP and DOP	HowLeaky functions on APSIM water balance	HowLeaky gives total, split to FRP and DOP in Source	HowLeaky gives total, split to FRP and DOP in Source	EMC (in Source)
Pesticides				
	HowLeaky functions implemented in APSIM	HowLeaky time series used directly	HowLeaky time series used directly	EMC (in Source)

Detailed descriptions and justification of each of the models and how they are applied are in technical reports which include the detailed modelling methodology, assumptions, parameters and results (Shaw and Silburn, 2016; Rattray et al., 2016; Owens et al., 2017). These reports are updated following major changes to the modelling and are available through the DNRME library. Figure 15 illustrates the main data sources, inputs and outputs of the component, and the role of paddock modelling in contributing to catchment modelling is shown in Figure 18, Section 4.7. The required spatial inputs include rainfall from SILO (Scientific Information for Land Owners), soil polygons and attributes from the Australian Soil Resource Information System (ASRIS)/Soil and Land Information (SALI) database, and land use from the Queensland Land Use Mapping Program (QLUMP).

Detailed profiles of management practice levels are provided through the Agricultural Management Practice Adoption program area. These data are processed and merged with paddock modelling by the modellers before they are used by the catchment models. The data is supplied by the regions but only after it is quality checked, collated and transferred by the Agricultural Management Practice Adoption program area.

The paddock monitoring and rainfall simulation components of the program (described above) provide input to test the models through measured evidence of the relative effectiveness of on-ground management practices, and model enhancement. They are also used to parameterise the models with information more specific to a spatial unit and make the results more relevant.

Data management: All paddock modelling input point data and spatial layers, modelled outputs for all scenario runs, assumptions and relevant versions of the software and associated documentation (reports, procedures, methods and other supporting information) are captured and archived in SKIP. Paddock model runs are made available through the P2R Projector Tool (see Appendix 2).

Assessing progress towards the target

This data is used to inform the catchment modelling to assess progress towards the Reef 2050 WQIP Water Quality targets.

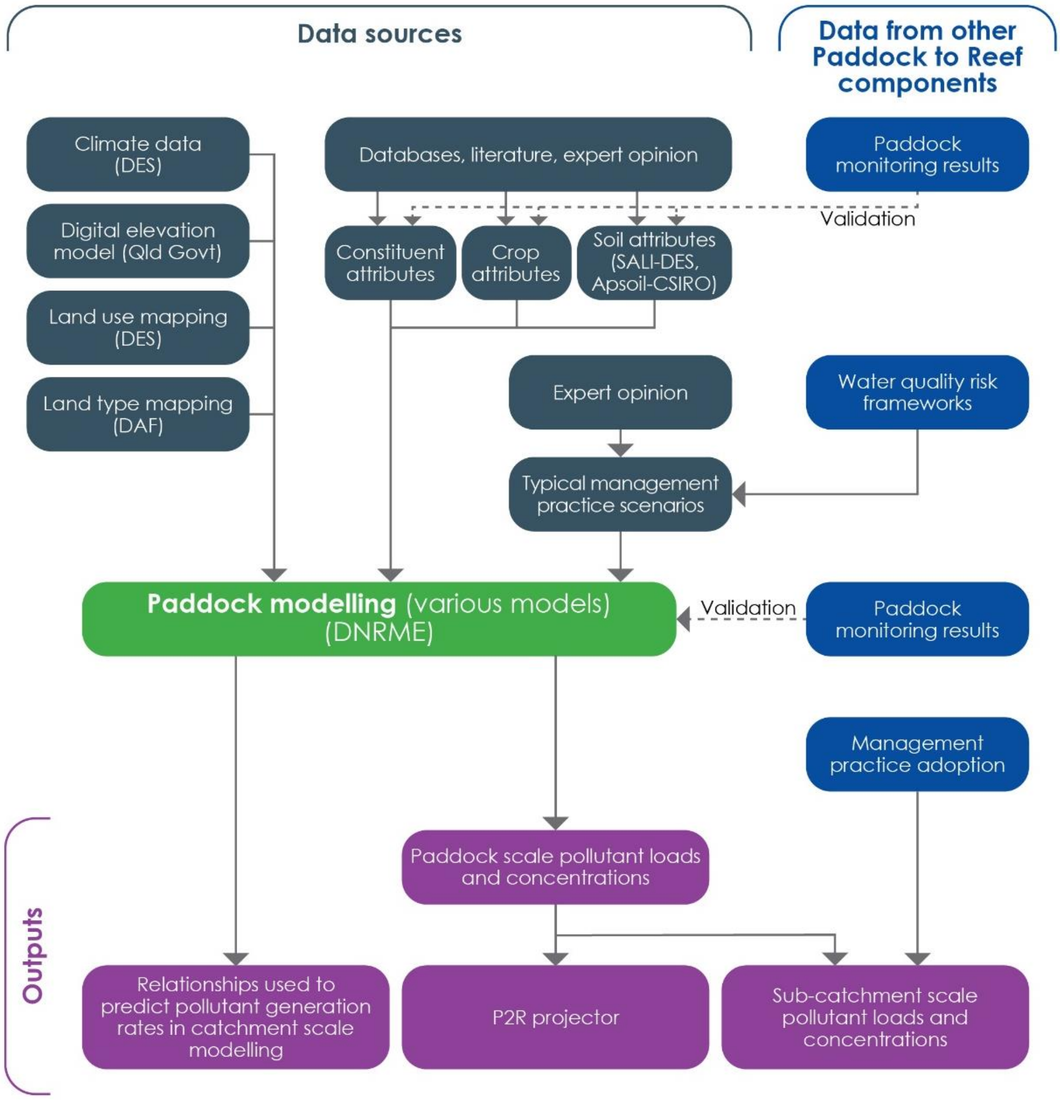

Figure 15. Main data sources, inputs and outputs of the paddock modelling program.

Program improvements

Several major improvements have been implemented in this program area in the last two years:

- More detailed modelling of sugarcane, bananas and grains (e.g. expanded the number of sugarcane management scenarios from 4 to 156).
- Representation of water recycling pits for sugarcane in the lower Burdekin and Burnett Mary regions.
- Automation of summary data and checking of model outputs from batch runs.
- Development of a DIN run-off model for sugarcane and a DIN run-off and drainage model for bananas based on Paddock to Reef program monitoring data.

The program will continue to improve confidence in the model outputs through engagement of regional expertise in reviewing and updating the modelled agricultural management practices, and further expansion in the number and type of model scenarios e.g. including irrigation management for sugarcane in the Mackay Whitsunday and Burnett Mary NRM regions. A number of specific model improvements are also proposed and included in Section 6.1, Table 18.

Applications of the information:

- The paddock modelling outputs are a direct input to the catchment modelling for reporting progress towards the Reef 2050 WQIP Water Quality targets in the Great Barrier Reef Report Card.
- Paddock modelling results are summarised in a range of outputs as per user requirements. Examples include:
    - Mapping of reduction in DIN for a partial management change in nutrients, per hectare, averaged to sub-catchment scale, to allow for quick spatial comparison of relative benefits of investment.
    - Calculated annual outputs, including yields, for DIN trading scheme assessments where inter-year variability is an important consideration.
    - Incorporation of the modelled outputs into the P2R Projector Tool for guiding project selection (see Appendix 2).

Catchment pollutant delivery

4.6 Catchment loads monitoring

The Great Barrier Reef Catchment Loads Monitoring Program is a long-term, large-scale water quality monitoring program conducted along the east coast of Queensland. It monitors the concentrations of total suspended solids (TSS), nutrients (nitrogen and phosphorus analytes) and pesticides for multiple sites within 20 priority basins that discharge to the Great Barrier Reef. From the monitoring data, the program calculates annual and daily loads (mass) of sediment (measured as TSS) and nutrients and the multi substance potential affected fraction (msPAF) risk metric for pesticides.

This program delivers the primary monitoring data set used to validate and calibrate Source Catchments water quality models that measure progress towards the 2025 water quality targets.

The program commenced in 2005 and is now considered a long-term monitoring program for Queensland and Australia. It has been continuously improving to expand the scope of the program; either adding or adjusting the monitoring locations to support improved confidence in the modelling outputs, Reef 2050 WQIP objectives and various regional program deliverables.

ASSOCIATED REEF 2050 WQIP TARGET:

Informs the 2025 water quality targets

60% reduction in anthropogenic end-of-catchment dissolved inorganic nitrogen loads

25% reduction in anthropogenic end-of-catchment particulate nutrient loads

25% reduction in anthropogenic end-of-catchment fine sediment loads

Pesticides: To protect at least 99% of aquatic species at end-of-catchments

Objectives:

- Monitor event and ambient concentrations of sediment (TSS), nutrients (nitrogen and phosphorus analytes) and pesticides in key catchments.
- Calculate sediment and nutrient loads (annual and daily) and the annual pesticide msPAF risk metric.
- Provide concentrations and loads data to calibrate and validate the Source Catchment models that are used to assess progress towards the Reef 2050 WQIP water quality targets.
- Where suitable long-term datasets are available, investigate methods to track long-term trends in water quality entering the Great Barrier Reef lagoon.

Delivery partners:

DES (Water Quality Investigations) (lead), regional collaborators (various, see technical report).

Methods:

Detailed description of the design and methods of the monitoring program is reported annually in technical reports (e.g. Huggins et al., 2017). Figure 16 illustrates the main data sources, inputs and outputs of the catchment monitoring program.

Framework and design

Catchment water quality is currently measured at more than 43 sites across 20 key catchments that discharge to the Great Barrier Reef lagoon (Figure 17). The monitoring sites are located at the lowest point in a river or creek where the discharge can be accurately measured. Water quality samples collected at each monitoring site provide data related to land management activities in the catchment area upstream of the site. It is estimated that the monitoring currently captures approximately 92% of the TSS load and 88% of the dissolved inorganic nitrogen load discharged to the Great Barrier Reef lagoon and pesticides are monitored in all priority locations. The program reports on TSS, multiple nutrient analytes (Table 9) and a large range of pesticides (Table 10).

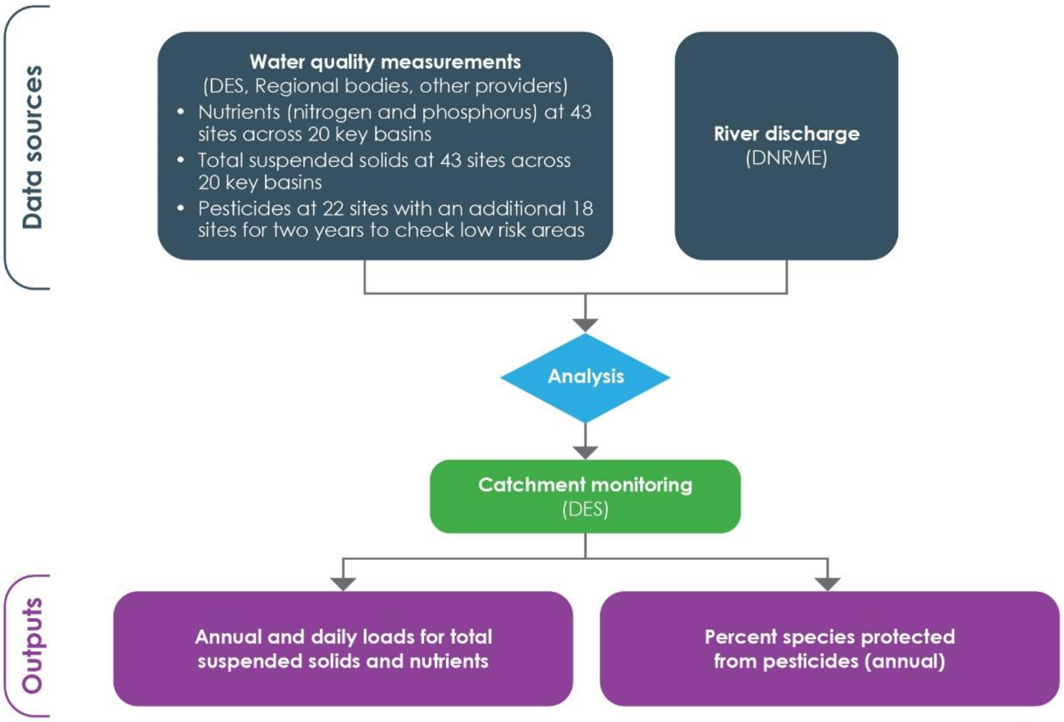

Figure 16. Main data sources, inputs and outputs of the catchment monitoring program area.

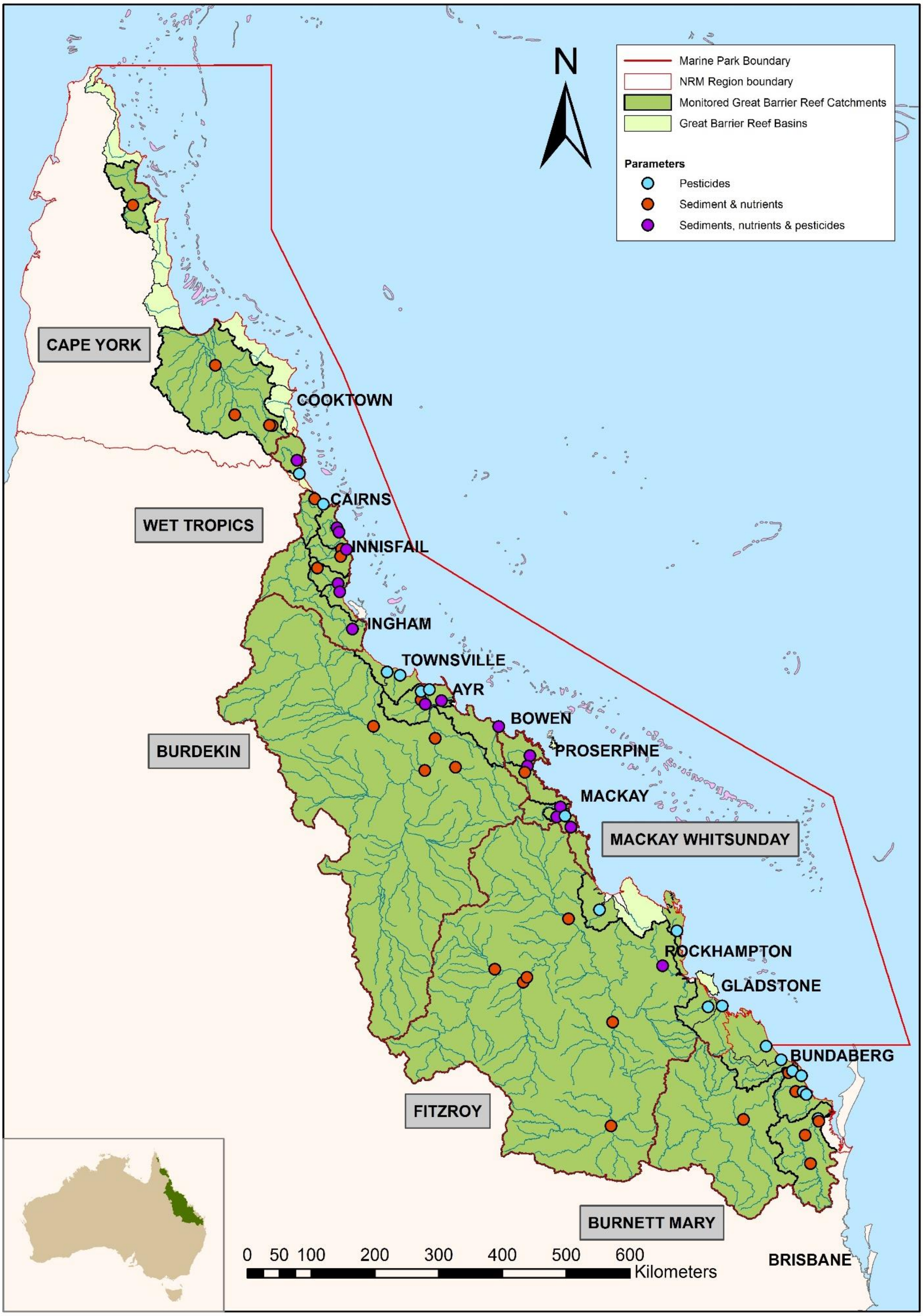

Figure 17. Map and table (Legend) showing the location of catchment monitoring sites in the Paddock to Reef program.

Table 9. 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 their varying use from one year to the next. For this reason, water samples are analysed for a general suite of pesticides and only those that are detected are reported each year. A sub-set of pesticides, referred to as the *reference pesticides*, is used to measure and model the progress towards the targets[2]. The reference pesticides (Table 10) have been selected based on the commonality of their detection in catchments, the availability of ecotoxicity data for individual pesticides, and their capacity to be modelled in Source Catchment models. Defining the list of reference pesticides was necessary to calculate the *pesticide risk baseline*; i.e. the current (2015–2018) per cent of aquatic species protected in each catchment from which progress towards the target is modelled. The reference pesticides include herbicides and insecticides used in a range of agricultural land uses, including sugarcane, grazing, cropping and horticulture.

Table 10. The reference pesticides used to measure the progress towards the pesticide target and to calculate the 2015–2018 pesticide risk baseline, i.e. the current (2015–2018) per cent of species protected in each catchment. The table presents the pesticides according to their mode of action and identifies their current status of inclusion in the monitoring and modelling programs.

Pesticide Groups (Mode of Action)	Reference pesticides	Currently Modelled in Source Catchments	Currently Monitored
Herbicides			
Photosystem II inhibiting herbicides (inhibition of photosynthesis at photosystem II)	Ametryn	Yes	Yes
	Atrazine	Yes	Yes
	Diuron	Yes	Yes
	Hexazinone	Yes	Yes

[2] 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 that 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.

Pesticide Groups (Mode of Action)	Reference pesticides	Currently Modelled in Source Catchments	Currently Monitored
	Prometryn	No – to be included in models	Yes
	Simazine	Yes	Yes
	Tebuthiuron	Yes	Yes
	Terbuthylazine	Yes	Yes
	Metribuzin	Yes	Yes
Synthetic auxins (unregulated plant growth)	2,4-D	Yes	Yes
	Fluroxypyr	Yes	Yes
	MCPA	Yes	Yes
	Triclopyr	No – to be included in models	Yes
Inhibitors of cell division in stems and roots through inhibiting synthesis of branched chain amino acids	Imazapic	Yes	Yes
	Metsulfuron-methyl	Yes	Yes
Inhibitors of fatty acid synthesis (inhibiting Acetyl coenzyme A carboxylase (ACCase))	Haloxyfop	Yes	Yes
Inhibitors of cell division (inhibition of very long chain fatty acid (VLCFA) synthesis)	Metolachlor	Yes	Yes
Inhibitors of pigment synthesis (inhibition of the enzyme 4-HPPD)	Isoxaflutole	Yes	Yes
Inhibitors of microtubule synthesis (inhibit chromosome separation and cell wall formation in plant cell division)	Pendimethalin	Yes	Yes
Insecticides			
Neonicitinoid (Nicotinic acetylcholine receptor (nAChR) agonist)	Imidacloprid	No – to be included in models	Yes
GABA-gated chloride channel antagonist (Disrupts nervous system)	Fipronil	No – to be included in models	Yes
Inhibitors of acetylcholinesterase (AChE) inhibitor (Disrupts nervous system)	Chlorpyrifos	No – to be included in models	Yes

* Fungicides will be the subject of a research project intended to determine whether these are important contaminants in waterways.

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. Water samples are collected, stored, transported and quality assured and quality controlled in accordance with the

Catchment Loads Monitoring Program data quality management framework, which is consistent with protocols outlined within the Environmental Protection (Water) Policy 2009 Monitoring and Sampling Manual.

The concentration of nutrients and sediments are analysed by the Science Division Chemistry Centre and pesticides are analysed by the Queensland Health Forensic and Scientific Services Organics Laboratory. 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 DNRME gauging station;
- 'time and flow factored' measured discharge from existing DNRME gauging station;
- modelled flows generated in the Source Catchments modelling platform using the Sacramento rainfall runoff 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.

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 TSS and the nutrient analytes listed in Table 9. The most appropriate load calculation method—either the average load (linear interpolation of concentration) or the Beale ratio—is determined by assessing sample coverage and the representivity rating. Loads are calculated using the Loads Tool component of the software Water Quality Analyser version 2.1.1.6.

Temporal-scaled pesticide concentrations are used to calculate the msPAF risk metric. The msPAF risk metric estimates the fraction of species affected by mixtures of pesticides detected during the wet season (i.e. the principle exposure period). This metric, calculated from the monitoring data, is used to set the 2015–2018 pesticide risk baseline and to validate the Source Catchment model estimates of progress, from the pesticide risk baseline, towards the target. The Source Catchment models also estimate the msPAF risk metric (see Section 4.7).

Data management: Following quality processes, the data and metadata are recorded, stored and managed in DARTS, and the HYDSTRA Database. An online application, eagle.io (described in Appendix 2) is being developed for near real time data management and web-based data reporting. It is anticipated that a live version will be released in July 2020 to all Reef 2050 WQIP partners.

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.

Program improvements

In response to the QAO and the Great Barrier Reef Water Science Taskforce (GBRWST, 2016), several major improvements have been implemented in this program area in the last two years:

- Expansion of the monitoring sites from 14 basins to 20 basins, and increase from 25 sites to 43 sites sampled on a regular basis, with a further 19 sites to be sampled for pesticides in 2017-2018 and 2018-2019. This is in response to the Great Barrier Reef Water Science Taskforce recommendation to improve coverage of the monitoring program (GBRWST, 2016).
- Now monitoring approximately 92% of TSS load and 88% of DIN load discharged to the Reef lagoon and the majority of agricultural pesticide inputs for the msPAF risk metric.
- Development of the web-based load calculation platform "ReLo" for automatic calculation of pollutant loads.

- Improved alignment with the marine monitoring locations to establish 'nested' monitoring transects across the paddock to reef landscape.

Further improvements proposed in this phase of the Paddock to Reef program include incorporation of uncertainty estimates in load calculations and exploration of trend analysis where possible. Additional improvements are proposed in Section 6.1, Table 18.

Applications of the information:

- The monitoring results are used to validate the catchment models and provide a second line of evidence for catchment load reductions and improvements in the percent of species protected from pesticides. This informs reporting of progress towards the Reef 2050 WQIP Water Quality targets in the Great Barrier Reef Report Card.
- The pesticide monitoring data will be used to calculate the 2015-2018 pesticide risk baseline of the percent of species protected in each catchment from pesticide impacts.
- Exceedances of the National pesticide water quality guideline values for ecosystem protection (ANZECC and ARMCANZ, 2000) by monitoring data is reported directly to policy/management groups.
- The data will potentially be used to report trends in catchment loads and the percent of species protected from pesticide impacts.
- The monitoring results are used by the Marine Monitoring Program to provide context for the interpretation of marine water quality information, and as input to the river-derived pollutant loading maps.
- The results are used in some regional report cards for catchment condition reporting.
- The data is provided to eReefs (CSIRO and Bureau of Meteorology [BoM]) to inform hydrology and loads assessments).
- The data is provided on request to research organisations to support research projects (e.g. James Cook University, CSIRO).

4.7 Catchment loads modelling

Given the scale of the Paddock to Reef program and its objectives, it is not possible to measure the impact of land management practice change on water quality through monitoring data alone. Models are therefore used in conjunction with the monitoring program to predict long-term changes in water quality.

The Source Catchments modelling framework allows the synthesis of management practice, paddock monitoring and modelling, and catchment monitoring data to estimate end-of-catchment pollutant loads for the 2017 baseline and changes in loads, relative to the baseline, as a result of improved management practice adoption for each subsequent year. The catchment models generate pollutant loads for current and improved practices for each individual land use. Modelling over a fixed climate period enables the changes in water quality due to the implementation of improved management to be quantified.

ASSOCIATED REEF 2050 WQIP TARGET:

2025 water quality targets

60% reduction in anthropogenic end-of-catchment dissolved inorganic nitrogen loads

25% reduction in anthropogenic end-of-catchment particulate nutrient loads

25% reduction in anthropogenic end-of-catchment fine sediment loads

Pesticides: To protect at least 99% of aquatic species at end-of-catchments

The program reports progress towards the Reef 2050 WQIP 2025 load reduction targets (TSS, DIN, PN, PP) and the species protection target (pesticides) in the Great Barrier Reef Report Card.

Objectives:

Report progress towards the pollutant load reduction targets by:

- Predicting average annual loads for key pollutants for each of the 35 catchments draining to the Great Barrier Reef for the baseline, pre-development and the change in loads for each subsequent year due to adoption of improved management practices.
- Inform regional WQIPs, management prioritisation and investment decisions through the provision of pollutant load estimates for each NRM region, basin and catchments for each primary land use.

Delivery partners:

DNRME (lead), DES loads monitoring team, DNRME/DES catchment and paddock modelling team, DAF practice adoption team, DES remote sensing team, DNRME/DES land resource team.

Methods:

A detailed description of the design and methods of the catchment loads modelling program is reported annually in technical reports (e.g. McCloskey et al., 2017). Figure 18 illustrates the main data sources, inputs and outputs of the Catchment Load Modelling program, highlighting the integrative nature of this program area.

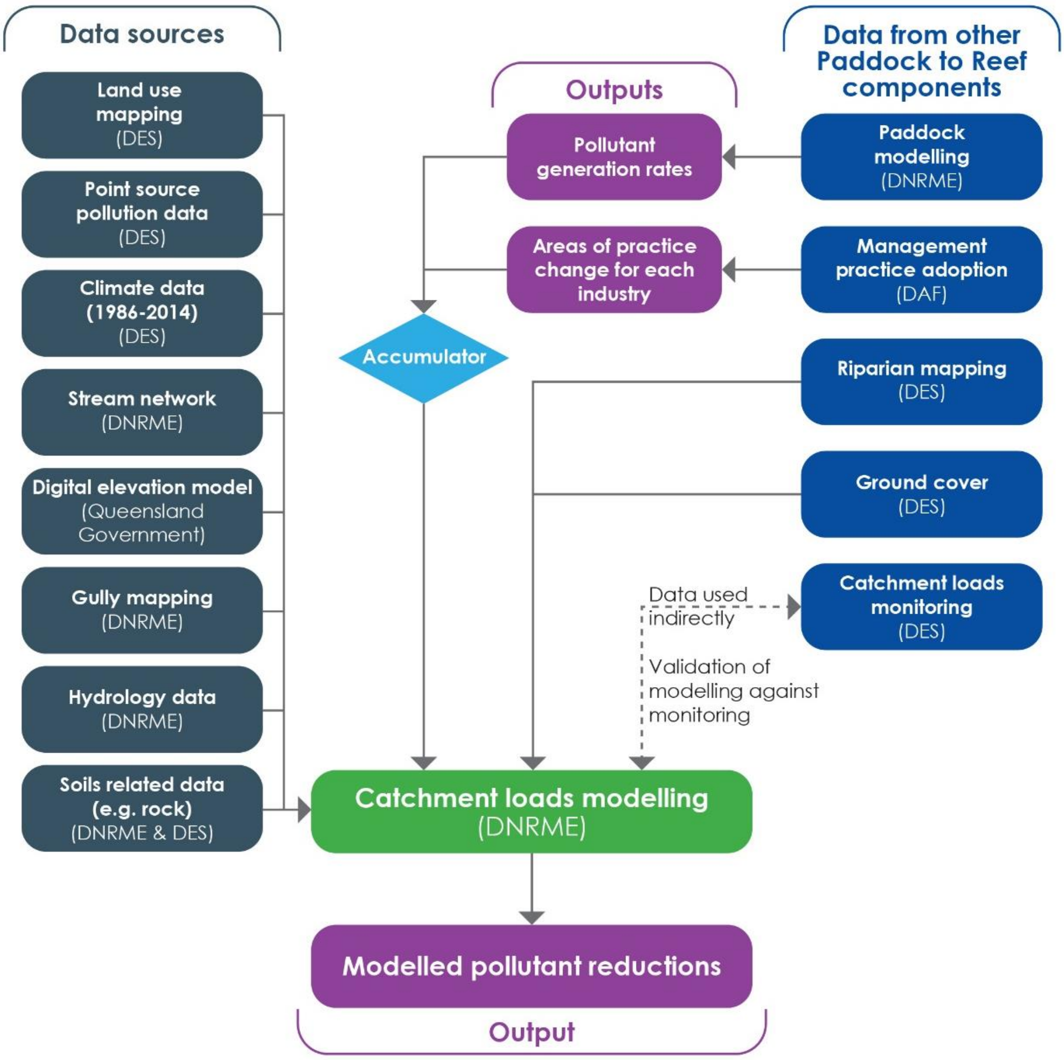

Figure 18. Main data sources, inputs and outputs of the Catchment Modelling program area.

Framework and design

An integrated monitoring and modelling approach is used to report predicted end of catchment loads in the Paddock to Reef program framework. Modelling extrapolates monitoring data through space and time and provides an opportunity to explore the climate and land management interactions and their associated impacts on water quality. The Catchment Loads Monitoring program (Section 4.6) combined with results from research studies and external monitoring data such as water quality improvement projects provides data for Source Catchments model validation. This supports refinement of the pollutant generation and transport process in the model and assists in identifying data gaps and priorities for future monitoring. A detailed description of the validation and calibration processes is provided in Ellis and Searle (2013) and Ellis (2017).

Source Catchments uses a node link network to represent the stream. The model generates run-off and pollutant loads for each functional unit (land use) within a sub-catchment, and run-off and pollutants are transported through the node link stream network to the end of the catchment. Source Catchments runs at a daily time step which enables the interactions of climate and management to be simulated. Daily time-step modelling also enables examination of results at a range of temporal scales. However, average annual catchment load reductions are used for assessing progress against the Reef 2050 WQIP pollutant load reduction targets. The model is run using a fixed climate period from 1986 to 2014 to remove the influence of climate on estimated load reductions from improved management. The latest land use mapping is used to describe the spatial extent of each agricultural land use for the baseline year.

The spatial and temporal representation of gully, streambank and in- stream erosion processes from the SedNet model (Prosser et al., 2001) are incorporated into the Great Barrier Reef Source Catchments model to better represent the dominant erosion processes observed in the summer-dominant rainfall areas of the Great Barrier Reef catchments.

Gully sediment contribution to the stream is calculated as a function of the gully density, gully cross sectional area and likely year of initiation. The estimated gully volume since initiation is converted to an 'eroded' soil mass. This eroded mass is then distributed over the model run period as a function of run-off.

Similarly, for streambank erosion, a mean annual rate of fine streambank erosion (t/yr) is calculated as a function of riparian vegetation extent, streambank erodibility and retreat rate. The mean annual streambank erosion is then distributed as a function of the daily flow. For a full description of the method, refer to Ellis and Searle (2014).

A DNRME gully mapping program is providing updated gully density layers as input layers to the model in the Cape York, Burdekin and Fitzroy NRM regions and other regions are being updated. In addition, the LiDAR (Light Detection and Ranging) 3D mapping acquisition across the Great Barrier Reef catchments (recently commissioned by the Australian Government) will secure detailed mapping of high priority gully and streambanks vulnerable to erosion and fine sediment loss.

As described in the sections above, specific and fit-for-purpose paddock scale models generate the daily pollutant loads for current and improved practices for each individual land use. For sugarcane, bananas and cropping, the constituent time-series (e.g. load per day per unit area) for the given land use is supplied from an output time-series from the paddock models described in Section 4.5. To model hillslope soil erosion in grazing lands, the RUSLE model was written into the Source Catchments model. The cover term (C-factor) in the model is generated from remotely sensed ground cover satellite imagery seasonally (four scenes per year) (see Section 4.8). The paddock scale model GRASP (Section 4.5) is used to provide scaling algorithms for each scenario to account for changes in management practices in each identified land type; for example, shifting areas from moderate risk (C) to moderate–low risk practices (B). These scaling algorithms are 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 provided from the Agricultural Management Practice Adoption program (Section 4.1.1). Calculations are 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 are then aggregated at the sub-catchment scale and routed through the stream network.

For the APSIM sugarcane model simulations, a proportion of the sugarcane DIN load lost to deep drainage through leaching beyond the root zone can now be delivered to the stream in the model via lateral or seepage flow. The proportion is calibrated for the baseline using monitoring results at the closest load monitoring gauging station to improve the alignment of modelled and monitored DIN loads. The loads will vary with the given management practice simulated.

The catchment modelling provides an estimate of the daily run-off and pollutant loads for sediments and nutrients (Table 11) exported to the Great Barrier Reef. The models will also provide metrics of ecosystem exposure to pesticides and improvements in percent of species protected.

Table 11. Constituents included in the catchment model.

Sediment	Nutrients	Pesticides
Fine sediment Coarse sediment	Particulate nitrogen, Dissolved inorganic nitrogen, Dissolved organic nitrogen	Ametryn, Atrazine, Diuron, Hexazinone, Tebuthiuron
	Particulate phosphorus, Dissolved inorganic phosphorus, Dissolved organic phosphorus	In addition, approx. 20 pesticides will be added including herbicides, insecticides and fungicides; these pesticides are to be confirmed

Assessing progress towards the target

The catchment modelling reports progress towards the Reef 2050 WQIP water quality targets as a result of changes to land management practices. To reflect the reported change in adoption of improved management practices (Section 4.1.1), three model scenarios are run:

1. Pre-development scenario, using a pre-development land use map (but other factors such as hydrology remain the same);
2. Baseline scenario, representing land management practices in 2017.
3. Annual scenario. Every year the cumulative investments in practice improvement are represented, with the model re-run for the same climate period to indicate the reductions in long-term annual average loads arising from these investments.

The proportion of land managed under different management practices is the only variable that changes between modelled scenarios. This allows for the relative load reductions attributed to the areas of improved land management to be reported (and removing the climatic influences). The ‘anthropogenic’ load is the difference between the results of scenario (1) and (2). The relative change in the annual pollutant load (scenario 3) from the anthropogenic baseline (scenario 2 – scenario 1) reflects the load reduction due to changes in management practices (Figure 19).

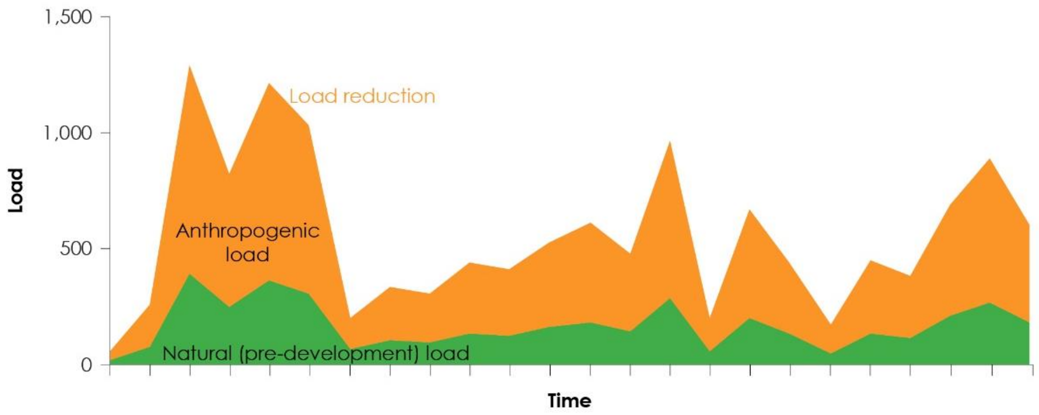

Figure 19. Example of modelled pre-development and anthropogenic pollutant loads, and the load reduction following investment in improved practices.

Key assumptions in estimating pollutant load reductions include:

- Loads reported for each Great Barrier Reef 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 Great Barrier Reef catchments.
- 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 Agricultural Management Practice Adoption program area (Section 4.1.1).
- 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.

All model runs, inputs and outputs are stored in SSIMR (see Section 5.1) annually. A new data visualisation web-based tool is currently being developed with dashboards for modellers, managers and policy agencies.

Program improvements

In response to the independent external review of the program in 2015, and the QAO and the Great Barrier Reef Water Science Taskforce (GBRWST, 2016), several major improvements have been implemented in this program area in the last two years:

- Additional resourcing has been provided for modelling as recommended by the Great Barrier Reef Water Science Taskforce.
- A desktop and field gully mapping program is continuing to improve the spatial representation of gullies in the models. When updated gully maps become available, these have been incorporated (areas included to date are the Normanby, Burdekin and Fitzroy catchments, and Burnett and Herbert will be completed in 2018).
- Annual joint monitoring/modelling validation workshops are held to compare model performance against monitoring data.

- Improvements to modelling operational processes are underway (e.g. reduced modelling run time for the Fitzroy model form 9hrs to 1hr).
- Modelling quality assurance/quality control and sensitivity testing is being conducted through a project with the Australian National University.
- Updated land use mapping has been funded – available mapping will be incorporated in the 2018 update of the models.

Additional improvements to the Paddock to Reef program in recent years include: incorporation of seasonal ground cover, improved soils layer, extended modelling climate period and hydrology recalibration, finer resolution topographic data, and expanded water quality monitoring data sets. The program will continue to deliver model improvements to increase confidence in the model outputs such as incorporation of the 2016-17 management practice adoption baseline dataset in 2018. Additional improvements are also proposed and included in Section 6.1, Table 18.

Applications of the information:

- Provides data for reporting progress towards the Reef 2050 WQIP water targets of '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' and for pesticides 'To protect at least 99% of aquatic species at end-of-catchments' in the Great Barrier Reef Report Card.
- Report on changes to water quality discharging to the Great Barrier Reef lagoon as a result of improved land management practices.
- Modelled outputs and products provided to clients: Regional NRM bodies, OGBR, consultants, Queensland and Australian government, Universities, CSIRO, eReefs, BoM (for example, there were 47 data requests in 2016-2017).
- Modelled outputs are used as direct input data to management prioritisation assessments at the Great Barrier Reef wide scale (e.g. Waterhouse et al., 2017a), regional Water Quality Improvement Plans (e.g. Fitzroy - Star et al., 2016; Burdekin - Waterhouse et al., 2016) and extension prioritisation (e.g. Beutel et al., 2015).
- The modelled pollutant load reductions and scenarios are used to develop estimates of the costs and benefits of management scenarios in the Great Barrier Reef catchments to inform policy and investment prioritisation (e.g. Alluvium et al., 2016; Star et al., 2017; Walshe et al., 2017).

ASSOCIATED REEF 2050 WQIP TARGET:

2025 land and catchment management targets

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

Catchment condition

4.8 Ground cover monitoring

Ground cover is defined as the vegetation (living and dead) and biological crusts and rocks/stones 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.

Objectives:

- Map and report on ground cover levels in grazing lands in the Great Barrier Reef catchment at a range of scales to assess progress towards the Reef 2050 WQIP ground cover target.
- Provide improved data on ground cover to improve water quality model parameterisation.
- Provide data and decision-support tools to help with land management practice improvement and evaluating the effectiveness of practice change programs and on-ground investments aimed at improving ground cover.

Delivery partners:

DES – Remote Sensing Centre (lead). Research and development is undertaken with partners in the Joint Remote Sensing Research Program, DNRME, DAF, CSIRO and the Terrestrial Ecosystem Research Network (TERN).

Methods:

A brief overview of the data and methods used for reporting regional ground cover is provided below. Further detail about data processing is included in the ground cover technical report (DSITI, 2017). Figure 20 shows the main data sources, inputs and outputs for the ground cover monitoring program.

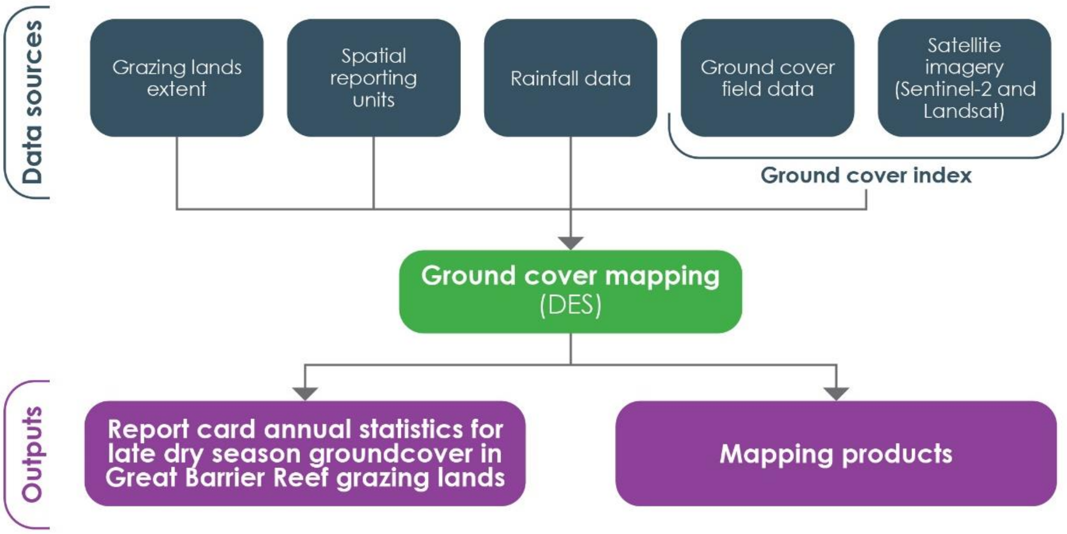

Figure 20. Ground cover monitoring program data inputs and outputs and data processing approach.

Framework and design

Reporting is based on the measurement of late dry season ground cover using Landsat satellite imagery, supplemented with Sentinel 2 satellite imagery when available. 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 2B satellites (mid-2015 to present) with a higher spatial resolution of 10m and more a frequent acquisition of every five days. Fractional cover data produced between the two sources is statistically comparable; the inclusion of 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 21). 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 results in the majority (>90%) of the grazing lands of the Great Barrier Reef catchment areas to being reported. 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 fractional ground cover data has been calibrated using over 3,600 field observations using a range of ground cover, tree cover and shrub cover levels, within a range of environments. This is a considerable increase on the number of sites used for the calibration of the previous fractional cover product (approximately 1,800 sites).

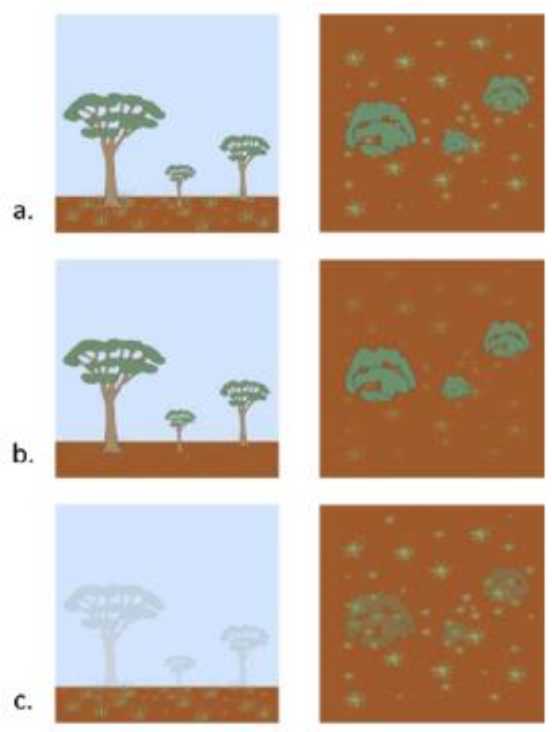

Figure 21. Schematic representation of the correction of the fractional cover data to estimate the fractional ground cover (Trevithick et al., 2014), used for reporting. (a) Fractional cover measures all vegetation cover including trees, shrubs and ground cover, as well as bare ground. The ground cover 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.

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, and all Landsat and Sentinel 2 images acquired throughout the season are assessed (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 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.

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 October to September for each year from 1986, to align the mean annual rainfall with the late-dry-season reporting period.

Assessing progress towards the target

The Reef 2050 WQIP ground cover target specifies that 90% of grazing lands meet the target ground cover level of 70% late season ground cover. This adjustment from the previous target (of 70% ground cover in the late dry season) maintains levels of cover required to minimised erosion and run-off, but also provides an opportunity to factor in the distribution of cover, and to generate statistics at the sub-region or even property scale, while reporting regionally. It also helps address previous reporting issues with averaging and the proportion or distribution factor and also has direct links with management practice targets and issues of total grazing pressure.

The primary metrics that will be used to report on progress towards the target include:

- The area of reporting region meeting 70% ground cover target (this will form the basis of scoring).
- Long term (1987 to reporting year) ground cover statistics and graphs for each reporting region (for continuity with previous report cards).
- Ground cover decile maps for current season – these maps compare the dry season for the reporting year to all dry seasons in preceding years back to 1987.
- Additional reporting at property level (proportion of properties meeting target, and map of properties meeting targets).

It is also important to note that this approach recognises that the ground cover level of 70% may not be relevant at all scales, where rainfall variability, soil type and ground cover composition, along with management, all play important roles in determining rates of run-off and sediment generation. Additionally, some areas in the Great Barrier Reef catchments are naturally low in ground cover. The new target, reporting metrics and decision support tools for the Paddock to Reef program provide a much richer picture of ground cover condition within the reporting regions and capture this variability across the landscape. Further, DES is also investigating the appropriateness of regional targets which are more ecologically-relevant to a particular region.

Data management: Data from this component is stored and maintained in the High Performance Computing facility at the Ecosciences Precinct, Brisbane. This facility provides complete data provenance tracking and reporting and complete data backup service, including the storage of duplicate backups offsite.

Data is also made available as Open Data through a range of delivery mechanisms and formats, for example, the Queensland Government Information Service.

Program improvements

Several improvements have been implemented in this program area in the last two years:

- Improvements to the Fractional Cover method through the development of a new model and calibration which provides quantifiable uncertainty/error. The calibration is based on approximately 3,600 field sites (previously ~1,800 field sites).
- Incorporation of new satellite imagery data (from Sentinel 2A and 2B) to augment Landsat-based monitoring for more complete seasonal composites of ground cover data.
- Improved assessment in highly bare areas which provides potentially better representation of ground cover for gullies, scalds, tracks and cattle pads etc.
- Development of additional options to report by property, by region, and property by land types.

The program will continue to deliver improved datasets through utilisation of higher resolution satellites (Landsat and Sentinel 2). New and enhanced ground cover reporting products are in development including a patchiness metric for improved understanding of the spatial arrangement of cover at a range of scales, and a prototype land condition model. These products may be incorporated into future enhancements to reporting, and will be made available via other mechanisms to help inform Great Barrier Reef water quality programs and policy development. A 'grazing calculator' will also be developed in 2018-2019 to support decision-making at property scale, building on the ground cover and paddock modelling results. Additional improvements are also proposed and included in Section 6.1, Table 18.

Applications of the information:

- Provides data for reporting progress towards the Reef 2050 WQIP target '90% of grazing lands will have greater than 70% ground cover in the late dry season' in the Great Barrier Reef Report Card.
- Provides primary input data to some regional report cards.
- Seasonal cover spatial layers are a primary dataset for the catchment models for estimating pollutant load delivery.
- The data contributes to a range of products produced to support grazing extension (see Appendix 2 for further detail), including the Grazing BMP, and includes:
  - Interactive online tool VegMachine® that uses satellite imagery to summarise ground cover in grazing lands. Users can:
    - Generate comprehensive ground cover monitoring reports
    - Measure land cover change or estimate soil erosion rates
    - View satellite image land cover products
    - Better understand the links between management, climate and cover in grazing land
  - The online reporting tool, FORAGE, which incorporates a number of products such as SILO climate data, satellite imagery and modelled pasture growth, delivering them as PDF property-scale reports, to help decision-making in grazing land and environmental management.

ASSOCIATED REEF 2050 WQIP TARGET:

2025 land and catchment management targets

The extent of riparian vegetation is increased

4.9 Riparian vegetation extent monitoring

Riparian forest and ground cover is the vegetation adjacent to waterways which can help reduce pollutant flow to the waterways and stabilise the streambank. Areas which are non-forested and have very low ground cover levels may be areas of concern for soil and nutrient loss to the stream. Maintaining and enhancing riparian forests and ground cover in riparian areas is, therefore, important to minimise impacts on water quality in Great Barrier Reef catchments.

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

For Reef Plan 2013, the riparian area was defined as any area within 100mof 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 Great Barrier Reef 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 forests and woodlands 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 Great Barrier Reef Report Card 2017 and 2018.

For the Reef 2050 WQIP, the riparian area will be 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 forest extent will also be 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 that will need to be understood and quantified. Further, significant enhancements to SLATS are planned for 2018-2020, and the riparian vegetation extent reporting will also be enhanced as new data becomes available through these planned enhancements. Further details are provided in the Methods section below.

Objectives:

- Map and report the changes in extent of riparian vegetation for Great Barrier Reef catchments every four years at a range of scales to assess progress towards the Reef 2050 WQIP riparian vegetation target.
- Provide data to inform reporting on riparian vegetation targets for regional report cards.
- Provide enhanced data on riparian vegetation extent and cover to improve water quality model parameterisation.
- Inform prioritisation of investment activities such as riparian fencing and bank revegetation and stabilisation, as well as identification of offsets.

Delivery partners:

DES – Remote Sensing Centre. Research and development is undertaken with partners in the Joint Remote Sensing Research Program, DNRME, DAF, CSIRO, and the Terrestrial Ecosystem Research Network (TERN).

Methods:

Framework and design

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

i. Defining and mapping riparian areas.
ii. Mapping riparian forest and woodlands extent and measuring changes to its extent over time within the riparian areas.
iii. Analysing the amount of fragmentation or connectivity of the remaining riparian forest and woodlands at the catchment scale.
iv. Estimating riparian ground cover and analysing how it changes over time within the riparian areas.

Figure 22 shows the main data sources, inputs and outputs for the riparian vegetation extent monitoring program.

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). For the purposes of meeting the range of objectives for this component of the Paddock to Reef program, and to better align reporting with the riparian areas defined by the *Vegetation Management Act 1999*, 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* will be used to ensure consistency.

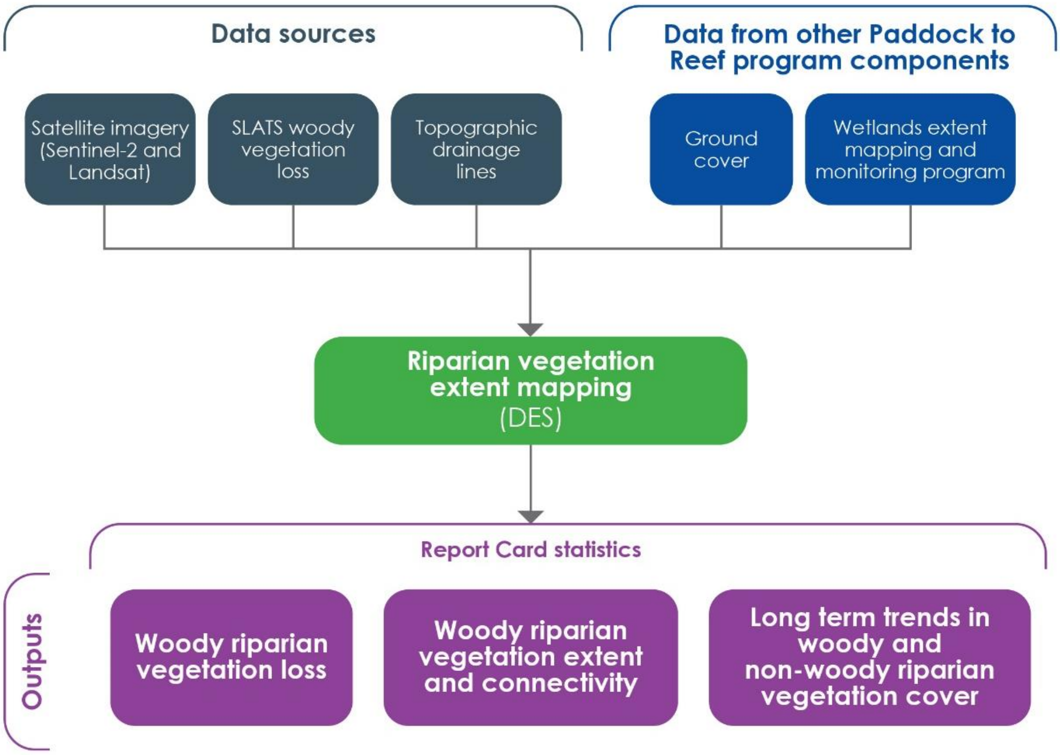

Figure 22. Riparian vegetation extent monitoring program data inputs and outputs and data processing approach.

Mapping the current riparian forest and woodland extent

The extent of riparian forests and woodlands 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).

An index of woody vegetation, 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. Refinements to the initial prediction through manual or automated thresholding and/or time-series analysis and/or manual editing may be required to improve the classification and mapping of the woody vegetation in the riparian areas.

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

Historical and recent riparian vegetation loss

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-1980's (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-development forests are defined as areas assessed as woody (forested) 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 forest and woodlands loss in extent is reported for three time periods for the Great Barrier Reef catchments:

1. Pre-development settlement to 2017-2018, to provide an approximate estimate of the extent of modification to riparian vegetation in each of the regions;
2. From 1988 to 2017-2018, for historical vegetation clearing trends; and
3. From 2001 to 2005, 2005 to 2009, 2009 to 2013 and 2013 to 2017 for recent vegetation clearing trends.

It is important to note that SLATS is planning significant enhancements to its monitoring program between July 2018 and June 2020. This will include the development of a woody extent baseline for the State and the inclusion of the monitoring of woody vegetation regrowth, in addition to its current monitoring of woody vegetation clearing. SLATS is presently also assessing Sentinel 2 imagery, with the potential to replace Landsat for all of its woody vegetation monitoring. SLATS is undertaking trials to understand what impact this would have for reporting woody vegetation extent changes and comparability with past measurements, due to the scale/resolution differences between Landsat and Sentinel 2. It is expected that as data becomes available from the enhanced SLATS, improvements will be made to the riparian monitoring for the Paddock to Reef program to enable accurate reporting of net change in riparian extent on a four-yearly, or possibly more regular basis.

Riparian forest patch size and connectivity

Landscape metrics describe the size and connectivity of forest patches, aiding finer scale analysis of forested riparian areas. These data can help prioritise restoration efforts and measure fragmentation over time. It is expected that as the target is being met, the connectivity of the riparian forests and woodlands should also increase at the catchment scale, improving landscape resilience to erosion and surface run-off processes, and increasing opportunities for biodiversity and carbon sequestration benefits.

The Patch Size and Connectivity Index (PSCI) is developed specifically for riparian forests and woodlands, and takes into account the initial patch size and the distance and size of neighbouring riparian forest patches to provide a more detailed measure of connectivity (expressed as a proportion of an ideal 100% forested scenario). It allows comparisons between catchments, and within the same catchment over time. As vegetation extent is increased, the PSCI value will also increase, indicating that riparian forest patches have become larger and more connected at the landscape scale. Alternatively, as patches either become smaller or the distance between them increases, the PSCI value will decrease (Figure 23). This indicates a loss of connectivity at the landscape scale. A value of 100 would indicate fully connected riparian forests while a value of less than 40 indicates no connectivity.

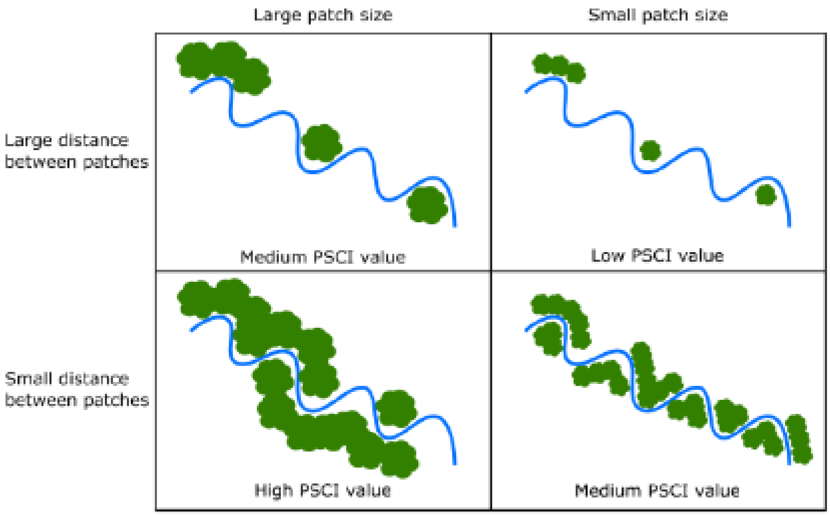

Figure 23. An example of high, medium and low Patch Size and Connectivity Index (PSCI) values. Catchments with large riparian patches have a medium PSCI value if the distance between patches is large or a high PSCI value if distance between patches is small. In contrast, catchments with small riparian forest patches will have a low PSCI value if the distance between patches is large or a medium PSCI value if the distances are small.

A second metric is used to quantify the number of riparian forest and woodland patches per kilometre of stream network. The Normalised Patch Density (NPD) differs from the PSCI as it provides a measure of the linear connectivity of riparian forest and woodland along the stream network. This measure is normalised to account for the different proportion of each catchment's riparian area that is forested.

In contrast to the PSCI, a low NPD value indicates higher linear connectivity while a high NPD value indicates lower linear connectivity (Figure 24). For example, regions such as Cape York have a low number of riparian forest patches, but each patch is very large and the total forested area is also large. This region has a very low NPD value but a high PSCI value. In contrast, the Fitzroy region has a high number of riparian forest patches, yet each patch is small. The Fitzroy region has a high NPD value and a relatively low PSCI value.

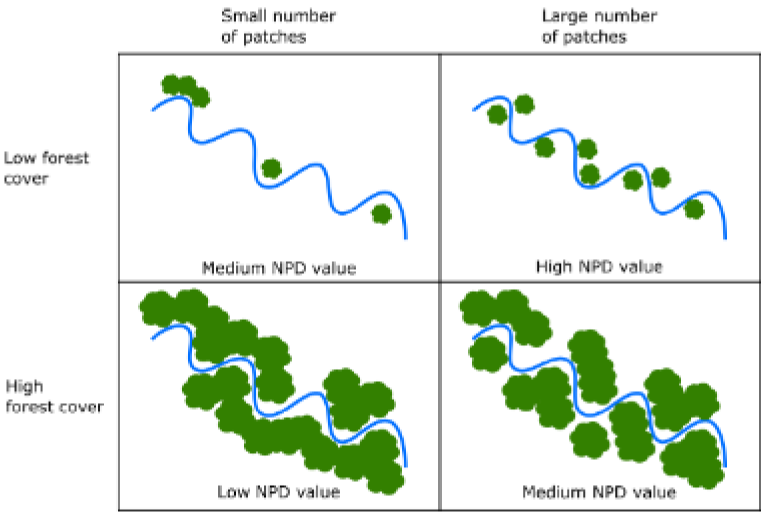

Figure 24. An example of high, medium and low Normalised Patch Density (NPD) values. Catchments with a small number of riparian patches will have a medium NPD value if the overall forested proportion is low or a low NDP value if the overall forested proportion is high. In contrast, a catchment with a large number of patches will have a high NDP value if the overall forested proportion is low or a medium NPD value if the overall forested proportion is high.

Monitoring ground cover in riparian areas

For riparian areas with up to approximately 60% tree canopy cover, ground cover is estimated and reported for the current reporting year. Ground cover monitoring is included in this component of the Paddock to Reef program design 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 seasonal data derived using the fractional cover method described above in Section 4.8. 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 forests and woodlands 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 landscape metrics, the PSCI and NPD, as well as reporting of ground cover levels in riparian areas. The landscape metrics may help to identify if progress has been made in increasing landscape connectivity, even if the net change in extent is not significantly increased. 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.

Data management: Data from this component is stored and maintained in the High Performance Computing facility at the Ecosciences Precinct, Brisbane. This facility provides complete data provenance tracking and reporting and a complete data backup service, including the storage of duplicate backups offsite.

Program improvements

Several improvements have been implemented in this program area in the last two years:

- Higher resolution data outputs are generated using new satellites: Landsat + Sentinel 2.
- By adopting higher resolution data, new reporting of the 50m buffer aligns with the buffer widths used for identifying Category R vegetation (i.e. high value regrowth in riparian areas) of the *Vegetation Management Act 1999*.
- Products have been developed to quantify connectivity in riparian vegetation over time.
- Techniques established to enable reporting of ground cover levels in riparian areas up to 60% tree canopy cover.

The program will continue to deliver improved datasets through further utilisation of higher resolution satellites (Landsat and Sentinel 2). Additional improvements are also proposed and included in Section 6.1, Table 18.

Applications of the information:

- Provides data for reporting progress towards the Reef 2050 WQIP target that 'The extent of riparian vegetation is increased' in the Great Barrier Reef Report Card.
- Assessment of the changes in extent of woody and non-woody riparian vegetation in Great Barrier Reef catchments to support monitoring of management practice effectiveness, provide data for water quality model parameterisation, and for informing on-ground investment planning, monitoring and evaluation.
- Provides primary input data to some regional report cards.
- A range of metrics describing riparian vegetation connectivity which may be used for assessment and extrapolation of pressure, function and values for ecological assessment.
- Informing evaluation of policies and initiatives aimed to protect and enhance riparian vegetation for water quality outcomes, biodiversity conservation and management, and offsets, including for carbon sequestration.
- Deriving long-term trends in forest density through time-series analysis of vegetation data produced. These data will help monitor and understand changes in riparian forests and woodlands to help monitor condition and to inform targeting of weed management activities or revegetation works.

4.10 Wetland extent monitoring

This program area assesses the extent of natural wetlands in the Great Barrier Reef catchments and is updated every four years to assess progress towards the Reef 2050 WQIP target of 'no loss of the extent of natural wetlands'. The change in extent of wetlands is based on the Queensland Wetlands Program wetland mapping which draws on remote sensing, topographic mapping and regional ecosystem mapping to identify wetlands based on both water bodies and vegetation. Previous results include mapping of the original (pre-clearing) and current (2001, 2005, 2009, 2013) extent of wetlands. The 2017 and historical extent results will be presented as part of the Great Barrier Reef Report Card 2017 and 2018.

ASSOCIATED REEF 2050 WQIP TARGET:

2025 land and catchment management target

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

Objectives:

- Map and report on the historic (pre-clearing) and current extent of wetlands and change in wetland extent every four years from 2001.
- Map the extent, type and change in extent of natural and hydrologically modified wetlands every four years.

Delivery partners:

DES – Queensland Herbarium (lead), DES – Queensland Wetland Program, DES –SLATS.

Methods:

The methods for assessing wetland extent follow those documented in the regional ecosystem and wetland mapping methods (EPA, 2005; Neldner et al., 2014).

Figure 25 shows the main data sources, inputs and outputs for the wetland extent monitoring program.

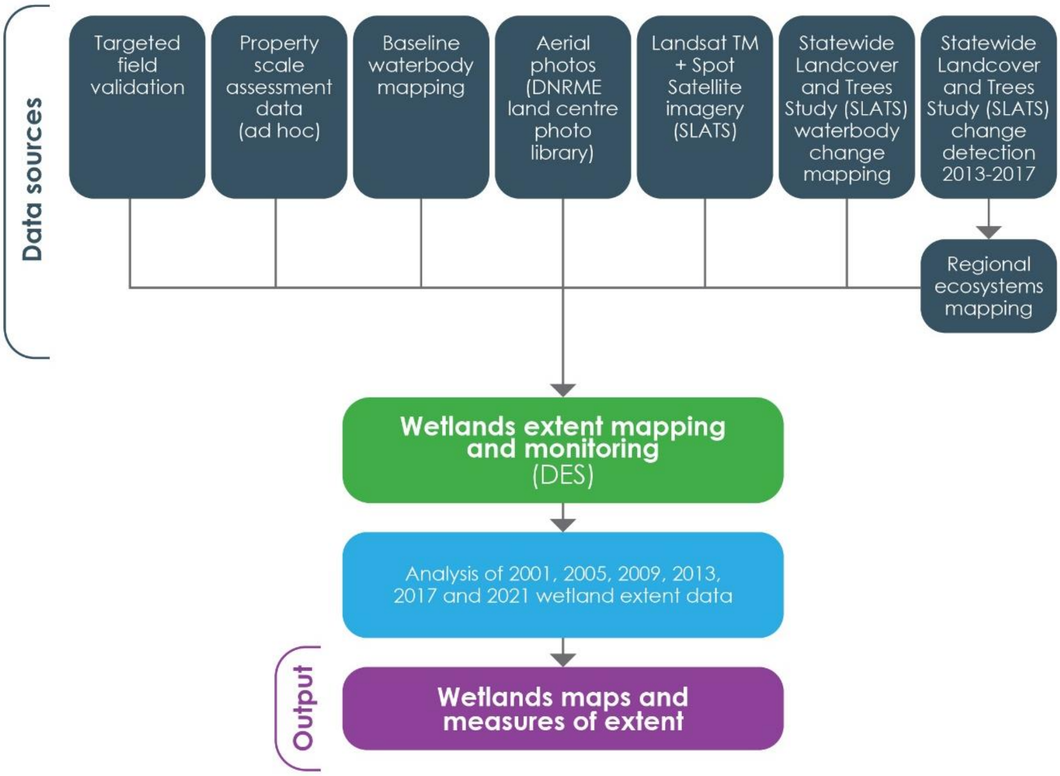

Figure 25. Wetland extent monitoring program data inputs and outputs and data processing approach.

Framework and design

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

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, 2017 and 2021) from satellite imagery (Landsat Thematic Mapper and SPOT) which has been processed and supplied by SLATS. The mapping is validated to a scale of 1:100,000 which includes over 8,000 wetland ground-truthing sites across Queensland.

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 or 2021. 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. This type does not include coastal waters and estuaries which are other components of the estuarine wetland system.

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 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 SLATS (DES).
2. Change detection determined from an analysis of the differences between 2013 to 2017 and 2017 to 2021 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 earth-works, 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.

Data management: Data and metadata are publicly available on WetlandInfo and QSpatial. Relevant data and metadata are stored in SKIP as part of the Paddock to Reef program data archive.

Program improvements:
Several improvements have been implemented in this program area in the last two years:

- Conversion of waterbody data from ArcInfo coverages to ArcMap geodatabase.
- Improvement of the definitions of wetland hydromodifiers and some splitting of hydromodifiers to provide more detail of wetland hydrological modification.
- General improvements in regional ecosystems mapping input data including refinement of estuarine (land zone 1) limits in northern Reef catchments.
- Incorporation of ad hoc and targeted site-specific wetland data.

The program will continue to deliver improved datasets through refinement of the wetland regional ecosystem descriptions to include a wet and a dry phase description where appropriate; better definition of woody fringing vegetation from the waterbody component; and revision of the frequency of inundation attribute through incorporation of ecological knowledge of specific wetland regional ecosystems and incorporation of remotely sensed frequency of inundation data. Additional improvements are also proposed and included in Section 6.1, Table 18.

Assessing progress towards the target
The wetlands mapping will be used to report on the current extent of wetlands (2017 and 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 and catchment scales.

Applications of the information:

- Provides data for reporting progress towards the Reef 2050 WQIP target of ‘No loss of the extent of natural wetlands (lakes, swamps and estuarine wetlands)’ in the Great Barrier Reef Report Card.
- The wetland extent monitoring identifies areas for targeting management to provide greater protection for natural wetlands and informs catchment restoration efforts.

4.11 Wetland condition monitoring

This section describes the assessment, monitoring and reporting of the condition of natural freshwater wetlands (palustrine and lacustrine) and the pressures on them. The importance of wetland ecosystems is recognised in the Reef 2050 Plan within the ecosystem and water quality themes and the Reef 2050 WQIP with the inclusion of an objective to ‘improve wetland condition’. The wetland condition monitoring program tracks whether this objective is being met. The monitoring focuses on natural freshwater floodplain wetlands occurring in especially high-density wetland assemblages. These areas contain more than 60%of the Great Barrier Reef’s natural floodplain wetlands. Natural wetlands are areas that existed as wetlands before European settlement and that still meet the definition of wetlands. The monitored wetlands occur within different major land uses including grazing, cropping, sugarcane, forestry, mining and conservation.

ASSOCIATED REEF 2050 WQIP OBJECTIVE:

Objective:

Improved wetland condition

Objectives:

- Monitor and report on the condition of, and pressures on natural freshwater wetlands in the Great Barrier Reef catchments.
- Provide data demonstrating that the Reef 2050 WQIP objective of an ‘improved wetland condition’ is being met.

Delivery partners:

DES (lead), Regional NRM bodies and catchment organisations, Buubu Gujin Land Trust, Rinyirru (Lakefield) Aboriginal Corporation, and Queensland Herbarium.

Methods:

A detailed description of the program design and methods of the wetland condition monitoring program is provided in a technical report (Tilden et al., 2015) and The Great Barrier catchments wetland condition monitoring program: Analysis methods report (Tilden and Vandergragt, 2017). Figure 26 shows the main data sources, inputs and outputs for the wetland condition monitoring program.

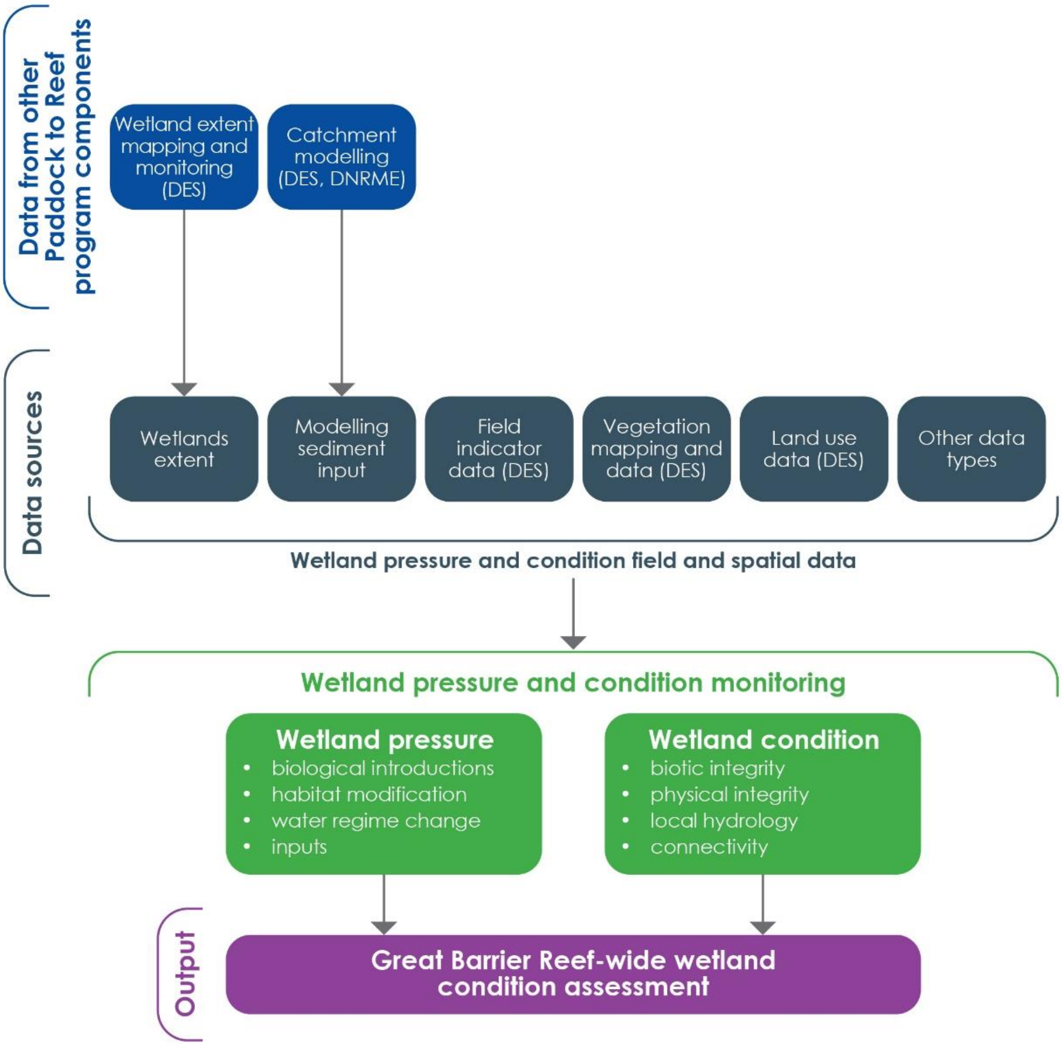

Figure 26. Data inputs and outputs and data processing approach for the wetland condition monitoring program area.

Framework and design

The monitoring program focuses on vegetated swamps (palustrine wetlands) and lakes (lacustrine wetlands) occurring within floodplain systems connected to the Great Barrier Reef lagoon by surface waters. Wetlands from the Normanby catchment to the Mary River catchment are monitored.

Framework and indicators

The Great Barrier Reef wetland monitoring program uses a Driver– Pressure–State–Impact–Response conceptual framework which can be applied at three levels of assessment: landscape-scale studies, rapid wetland-specific assessments, and detailed validating studies and research projects. The program focuses on the Pressure and State elements using rapid wetland-specific assessment methods and will assess impact over time.

The State (condition) index uses four Wetland Environmental Values (WEV):

1. WEV1 Biotic integrity - biological health and diversity of the wetland’s ecosystems.
2. WEV2 Physical integrity - the wetland’s natural physical state and integrity.
3. WEV3 Hydrology - the wetland’s natural hydrological cycle.
4. WEV4 Connectivity - the natural interaction of the wetland with other ecosystems, including other wetlands.

The updated Pressure index uses a range of pressure classes including:

- Input pressures (e.g. changes to chemicals going into the wetland).
- Biological introductions (e.g. pest plants and animals changing the wetland).
- Changes to water regime (e.g. the natural wetland water level being altered by a dam or levy).
- Habitat disturbance and alteration (e.g. changes to native vegetation around the wetland).

In 2014, a pilot study was carried out, both to inform the development of a program for monitoring wetland values in the Reef catchments and to test the Wetland Field Assessment Tool for Monitoring (WFAT–M), developed for the monitoring program (see Tilden et al., 2015). A decision was made to focus on Great Barrier Reef-wide reporting for the current phase of the project (including catchments from the Mary River in the south to the Normanby River in the north); however, the program is designed to allow for rapid scaling up to report by region should additional resources become available (see Tilden et al., 2015).

Sample wetlands are monitored using a rapid assessment method applying both spatial and imagery-based and field-based indicators to determine the pressure on, and the amount of disturbance to, a wetland's environmental values.

Wetlands are assessed by scoring indicators related to 1) the pressure classes including indicators related to land uses, hydrological modification, pests, and habitat disturbance; and 2) condition of environmental values with indicators related to vegetation and fauna, banks and soil disturbance, water regime e.g. water flows into the wetland and connections to other wetlands and natural ecosystems.

Monitoring site location selection and sampling strategy

A spatially balanced random sample of 100 wetlands for Great Barrier Reef-wide monitoring has been selected using the Generalised Random Tessellation Stratification (or 'GRTS') method which samples wetlands in the high-density wetland assemblages. Choosing dense aggregations of wetlands produced a less scattered sample that was more efficient to assess. It also focused on areas where the condition of wetlands was more likely to affect Reef water quality, due to the greater volume of ecological processing by wetlands. Figure 27 shows the aggregations of wetlands that define the sub-population. Approximately 65% of floodplain wetlands and 40% of all Great Barrier Reef catchment freshwater wetlands are encompassed by these areas of dense aggregations.

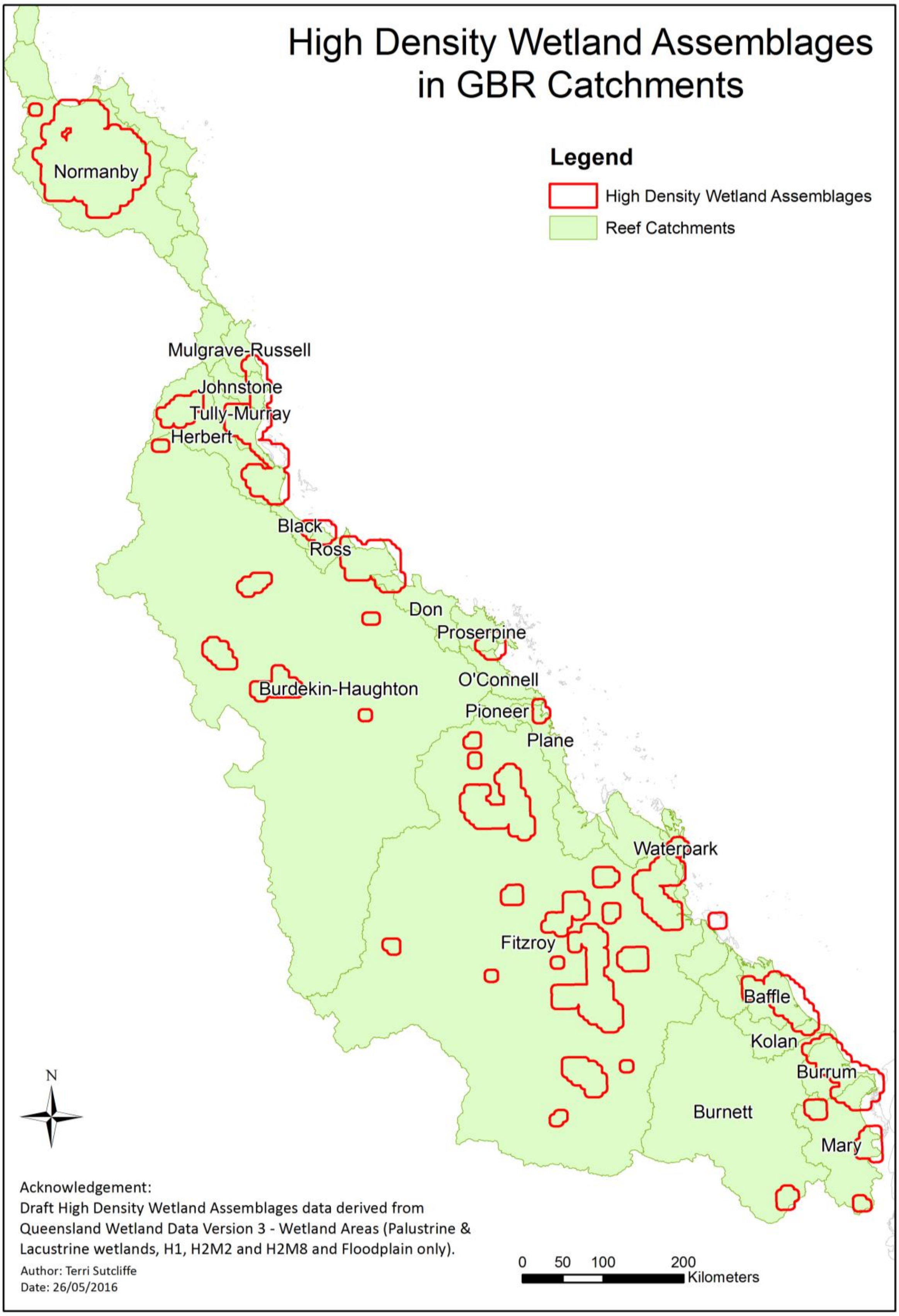

Figure 27. Map showing the high-density wetland assemblages in the Great Barrier Reef catchment used to guide the selection of location of wetland condition and pressures monitoring.

The monitored wetlands occur within different major land uses including grazing, cropping, sugarcane, forestry, mining and conservation. The sampling effort is optimised over time through the application of a flexible alternating panel design, whereby the wetlands are assessed in five panels of 20. The design seeks to optimise detection of both status and trend of wetlands, both at the individual wetland level and, importantly for reporting on progress towards the wetland objective across the defined Great Barrier Reef wetland (sub) population. The chosen panel design increases the number of wetlands sampled over time, thus improving precision of status assessment, while favouring trend detection.

Data management: All data and metadata are archived in SKIP for each wetland condition and pressure reporting period.

Assessing status against the Objective

The baseline status was established for wetland condition at the Great Barrier Reef scale in 2015-2016, with a sample size of 40 wetlands. This was reported in the Great Barrier Reef Report Card 2016.

Data and scoring

The wetland assessment and reporting is a four step process involving 1) desktop assessment of individual wetlands and their buffer areas; 2) field assessment of individual wetlands and their buffer areas; 3) post field processing and completion of QA/QC and 4) post-field calculations of the pressure on the overall wetland and buffer areas and the condition of wetlands. A report is generated for each wetland and whole of Great Barrier Reef catchment statistical analysis is carried out using the 'R SP survey' statistical package which enables reporting on the status of the Reef 2050 WQIP wetland objective that *the condition of natural wetlands will be improved*.

Program improvements

The program was established in 2013 with a pilot program implemented in 2014 and reported for the first time in 2016. The following improvements have been implemented in this program area in the last two years:

- Field data gathering has transitioned to digital methods with automated upload to database.
- The underpinning conceptual modelling has been updated to reflect the findings of the pilot data analysis.
- As a result of a repeatability study and sensitivity analysis, indicators have been improved or deleted, improvements to field methods have been implemented and the pressure index was restructured as a result of the sensitivity analysis.

The program will continue to deliver refinements to the design, including investigation of options for intensification of sampling to enable regional reporting. Additional improvements are also proposed and included in Section 6.1, Table 18.

Applications of the information:

- Provides data for reporting progress towards the Reef 2050 WQIP objective that 'The condition of natural wetlands will be improved'.
- The outputs are designed to inform the development of overarching programs directed towards restoration and best practice management of wetlands, the reduction of pressures and the improvement of wetland condition in the Great Barrier Reef catchments overall.
- Provides ground-truthing and QA/QC for the wetland extent mapping and uses wetland extent mapping and regional ecosystem data as inputs.
- The data will inform the wetland risk assessment contributions to the 2021 Scientific Consensus Statement.

Marine condition

4.12 Marine Monitoring Program

The Marine Monitoring Program (MMP) was established in 2005 and assesses trends in ecosystem health and resilience indicators for the Great Barrier Reef in relation to water quality and its linkages to end-of-catchment loads. There are three monitoring sub-components—water quality (including pesticides), seagrass and coral. Monitoring water quality and the temporal and spatial variation in the status of inshore seagrass and coral reef communities in relation to changes in local water quality is essential in evaluating long-term ecosystem health. The reporting framework integrates data from the three sub-components to evaluate progress towards the long-term effectiveness of the Reef 2050 WQIP long-term outcome that 'good water quality sustains the outstanding universal value of the Great Barrier Reef, builds resilience, improves ecosystem health, and benefits communities'. This outcome is nested under the Reef 2050 Plan water quality outcome that '*Reef water quality sustains the outstanding universal value, builds resilience and improves ecosystem health over each successive decade*'. It is important to note, that detecting improvements in Reef water quality and ecosystem health due to improved management in the short to medium term is confounded by time lags between management implementation and water quality improvement, and by the impacts of episodic events such as cyclones and floods.

The MMP is a foundational element of RIMReP. The design presented here has not yet been revised or expanded to align with the recommendations arising from the RIMReP expert working group review of seagrass, coral and physico-chemical monitoring program design, and will be updated in 2019.

ASSOCIATED REEF 2050 WQIP OBJECTIVES AND OUTCOME:

Objectives:

Improved coral condition

Improved seagrass condition

Long term outcome:

Good water quality sustains the outstanding universal value of the GBR, builds resilience, improves ecosystem health, and benefits communities

Objectives:

- Assess trends in ecosystem health and resilience indicators for the Great Barrier Reef in relation to water quality and its linkages to end-of-catchment loads.
- The objectives for each sub-program are listed below.

Water Quality:

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 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 (GBRMPA, 2010).

Seagrass:

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 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.

Coral:

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 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 crown-of-thorns starfish.

Delivery partners:

GBRMPA (lead) with monitoring conducted by the Australian Institute of Marine Science (AIMS), James Cook University (JCU), Howley Environmental Consulting, the University of Queensland (UQ), Queensland Parks and Wildlife Service (QPWS), Reef Catchments and community volunteers.

Methods:

Detailed methods are available in the annual technical reports published on the Great Barrier Reef Marine Park Authority's website (www.gbrmpa.gov.au). The following section provides a brief summary.

Framework and design

The main data sources, inputs and outputs are shown in *Figure 28*. The three primary sub-programs collect marine condition data at different time intervals to represent seasonal and annual conditions, and to represent the periods of greatest potential stress. A number of techniques are used to represent these conditions on an annual basis.

Inshore water quality

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

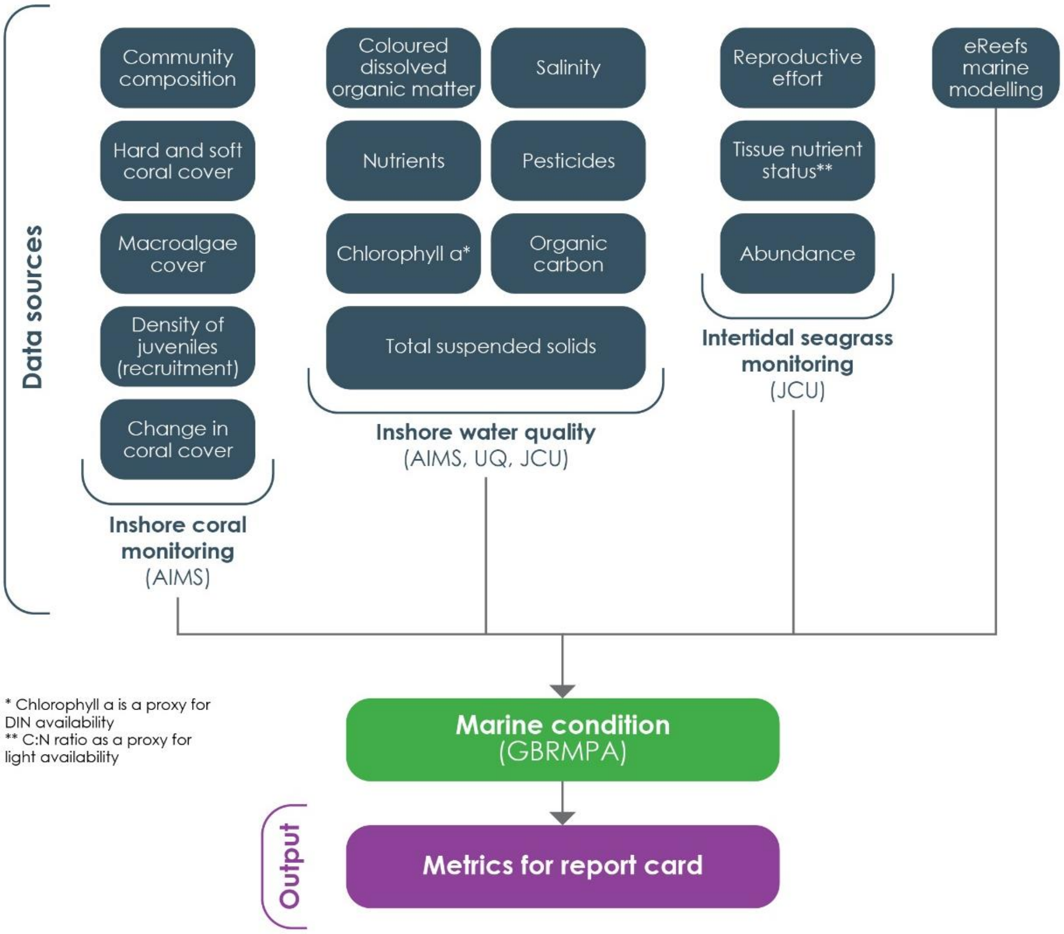

Figure 28. Main data sources, inputs and outputs for the Marine Monitoring Program.

In 2015–2016, the spatial and temporal frequency of site-specific water quality monitoring increased in four focus regions:

- Wet Tropics (Tully basin)
- Wet Tropics (Mulgrave-Russell basin)
- Burdekin
- Mackay Whitsunday (O'Connell basin).

Additional reporting for the Barron-Daintree sub-region of the Wet Tropics is also included due to the continued collection of data along the long-term Cairns transect where sampling started in 1989. In 2016–2017, four transects were added in the Cape York region relevant to the Pascoe, Normanby-Kennedy, Annan-Endeavour and Stewart Rivers (Figure 29).

Techniques used to monitor in situ water quality include automated data loggers and collection of water samples from research vessels for laboratory analysis (Waterhouse et al., 2017c). More intensive monitoring is also conducted in the wet season because the majority of the annual pollutant load to the Great Barrier Reef is delivered by flood events (Waterhouse et al., 2017c). Specific event sampling is also conducted throughout the wet season in the focus regions.

At the Great Barrier Reef-wide scale, information is also sourced from satellite remote sensing, which provides the required density of observations required to undertake a large-scale assimilation. In 2017 water quality condition was underpinned by the eReefs biogeochemical model and data assimilation of chlorophyll-a and Secchi depth in open coastal waters from satellite images (see Section 4.13). This was implemented with the Great Barrier Reef Report Card 2016.

Other 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 monitor water quality conditions in the Great Barrier Reef. Three wet season water types are characterised using remote-sensing imagery to assess the broadscale coastal water quality during the wet season including the composition and spatial variability of river plumes:

- Primary water type - The brownish to brownish-green turbid waters are typical for inshore regions of Great Barrier Reef river plumes or 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.
- 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-water plumes where relatively high nutrient availability and increased light levels due to sedimentation (Bainbridge et al., 2012) favour coastal productivity.
- Tertiary water type - The greenish-blue waters correspond to waters with above ambient water quality concentrations. This water body is typical for areas towards the open sea or offshore regions of river flood plumes.

The frequency of the exposure to these three wet-season water types is assessed on a weekly basis. To evaluate the susceptibility 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 categories have yet to be validated against ecological data, so they represent relative levels of risk. In addition, the exposure information is based on surface water quality conditions, which does not necessarily represent the exposure of benthic communities.

An ocean colour-based model is used to estimate the dispersion of loads of DIN and TSS discharged from the rivers in the Great Barrier Reef catchments, and examine their exposure and influence across the Great Barrier Reef lagoon. The model combines in-situ data, MODIS satellite imagery and modelled annual end-of-catchment loads from all 35 Great Barrier Reef basins. In the model, monitored and modelled end-of-catchment wet-season (November to May) loads provide the mass of constituents delivered to the Great Barrier Reef, in-situ data provides the pollutant mass dispersed within river plumes, and satellite imagery provides the direction and intensity of pollutant mass dispersed throughout the Great Barrier Reef lagoon. The difference between end-of-catchments loads for the current year and for estimated pre-development (using the same river flow) are also mapped.

These outputs are presented in the Tier 2 report for the Great Barrier Reef Report Card and annual technical reports (e.g. Waterhouse et al., 2017c).

Pesticides that have been detected in inshore waters of the Great Barrier Reef include photosystem II (PSII) inhibiting herbicides (e.g. ametryn, atrazine, diuron, hexazinone, simazine and tebuthiuron), knock-down herbicides (e.g. 2,4-D, MCPA), other residual herbicides (e.g. metolachlor and pendimethalin) and insecticides (e.g. imidacloprid and chlorpyrifos). The PSII herbicides diuron, atrazine and hexazinone are the most commonly detected pesticides in inshore waters; they are used to control weeds in the sugarcane, horticulture, grazing and grain-cropping industries. Herbicides, such as the PSII herbicides, detected in Great Barrier Reef ecosystems can have a negative impact on non-target phototrophic species such as phytoplankton, corals and seagrass when discharged into the Great Barrier Reef lagoon (e.g. Magnusson et al., 2008). Insecticides can affect non-target insect and crustacean species in the Great Barrier Reef (Devlin et al., 2015).

Pesticides have been monitored in inshore locations in the Wet Tropics, Burdekin, Mackay Whitsunday and Fitzroy NRM regions using two methods (Grant et al., 2017):

1. Passive samplers are deployed in both wet and dry seasons and provide an integrated assessment of pesticide concentrations over time (Booij et al., 2007; Shaw et al., 2009).
2. Grab samples are collected in flood plumes during the wet season to give an indication of peak pesticide concentrations and dispersal patterns of pesticides from river mouths.

Passive samplers are deployed at 11 fixed monitoring sites to measure time-integrated (monthly) pesticide concentrations sampled from the water column (Booij et al., 2007; Shaw et al., 2009) (Figure 29). 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.

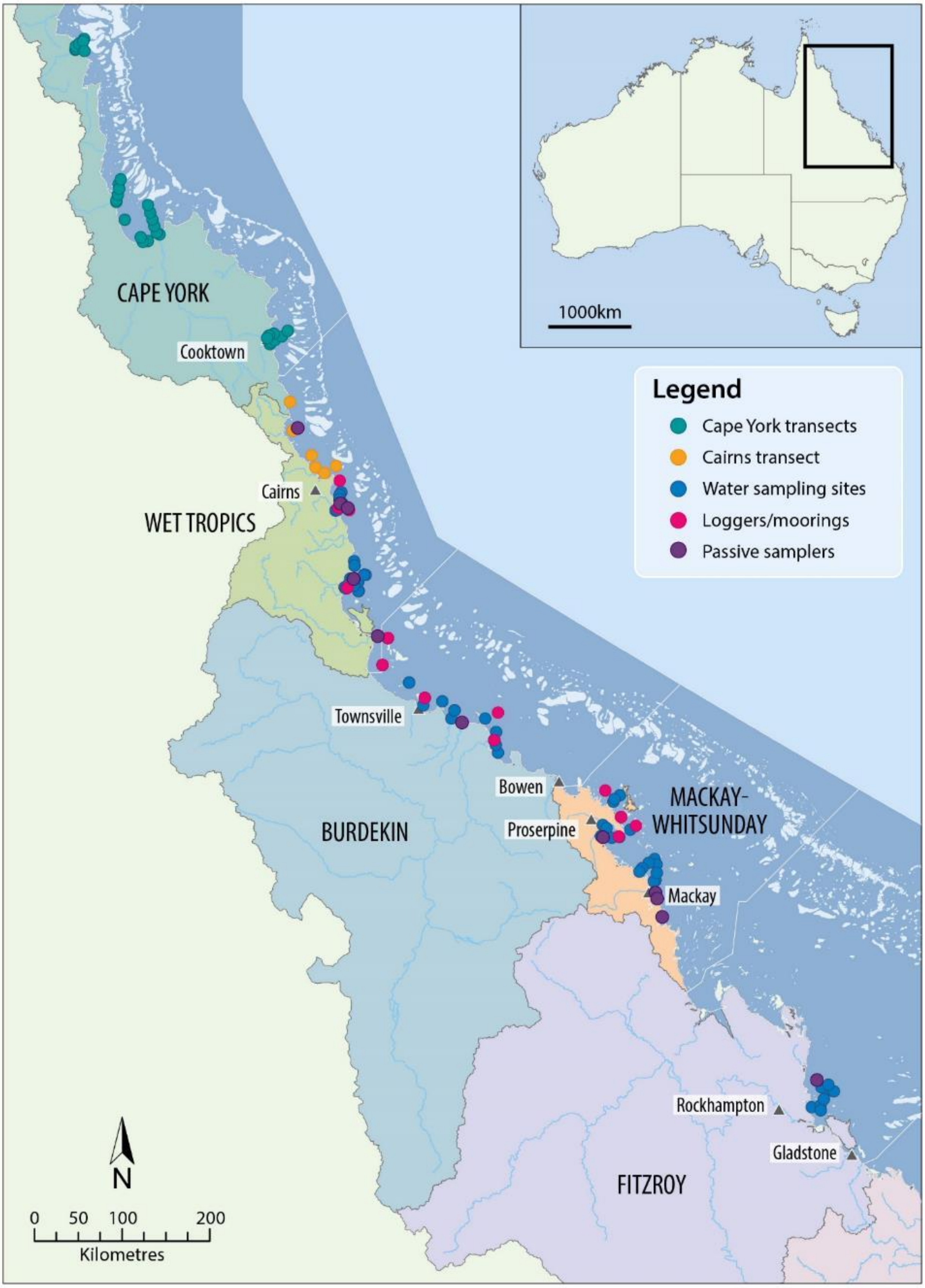

Figure 29. Sampling locations of the MMP water quality monitoring locations and methods sampled from 2015 onwards. Note that the Cape York transects were added in 2016–2017. NRM region boundaries are represented by coloured catchment areas. Source: D. Tracey, TropWATER, James Cook University.

Seagrass condition

Seagrass condition 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. Monitoring is conducted in all of the NRM regions, including each of the major seagrass habitat types where possible (estuarine, coastal, reef, subtidal) (Figure 30).

Monitoring includes an assessment of the seagrass abundance (percent cover) and reproductive effort, which provides an indication of the health of seagrass meadows and their capacity to regenerate following disturbances. Tissue nutrient composition is assessed in the laboratory as an indicator of nutrient enrichment relative to light available for growth (McKenzie et al., 2017, 2018). Additional indicators of seagrass condition and resilience include seagrass species composition, relative meadow extent and density of seeds in the seed bank as an indicator of resilience. Environmental pressures are also recorded including within-canopy water temperature, within-canopy benthic light, sediment composition as well as macroalgae and epiphyte abundance. There is further data on climate and water quality obtained from BoM and from the Marine Monitoring Program inshore water quality sub-program.

Coral reef condition

Coral reef condition monitoring of inshore coral reef communities occurs at reefs adjacent to the Wet Tropics, Burdekin, Mackay Whitsunday and Fitzroy NRM regions (Figure 31). 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 NRM region currently precludes sampling in these locations. Sub-regions are included in the Wet Tropics NRM 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.

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 AIMS – Long Term Monitoring Program (LTMP). These are included in the annual assessment of coral condition, although not all reefs are currently sampled every year.

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 cover of algae that is macroalgae, 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., 2017).

These indicators are formulated around the concept of community resilience:

- coral cover as an indicator of corals' ability to resist the cumulative environmental pressures to which they have been exposed;
- macroalgae cover as an indicator of competition with corals for light and space;
- juvenile coral density as an indicator of the success of early life history stages in the replenishment of coral populations;
- rate at which coral cover increases as an indicator of the recovery potential of coral communities due to growth; and
- community composition as an indicator of selective pressures.

Comprehensive water quality measurements and environmental parameters are also collected at many of the coral reef sites (Thompson et al., 2017).

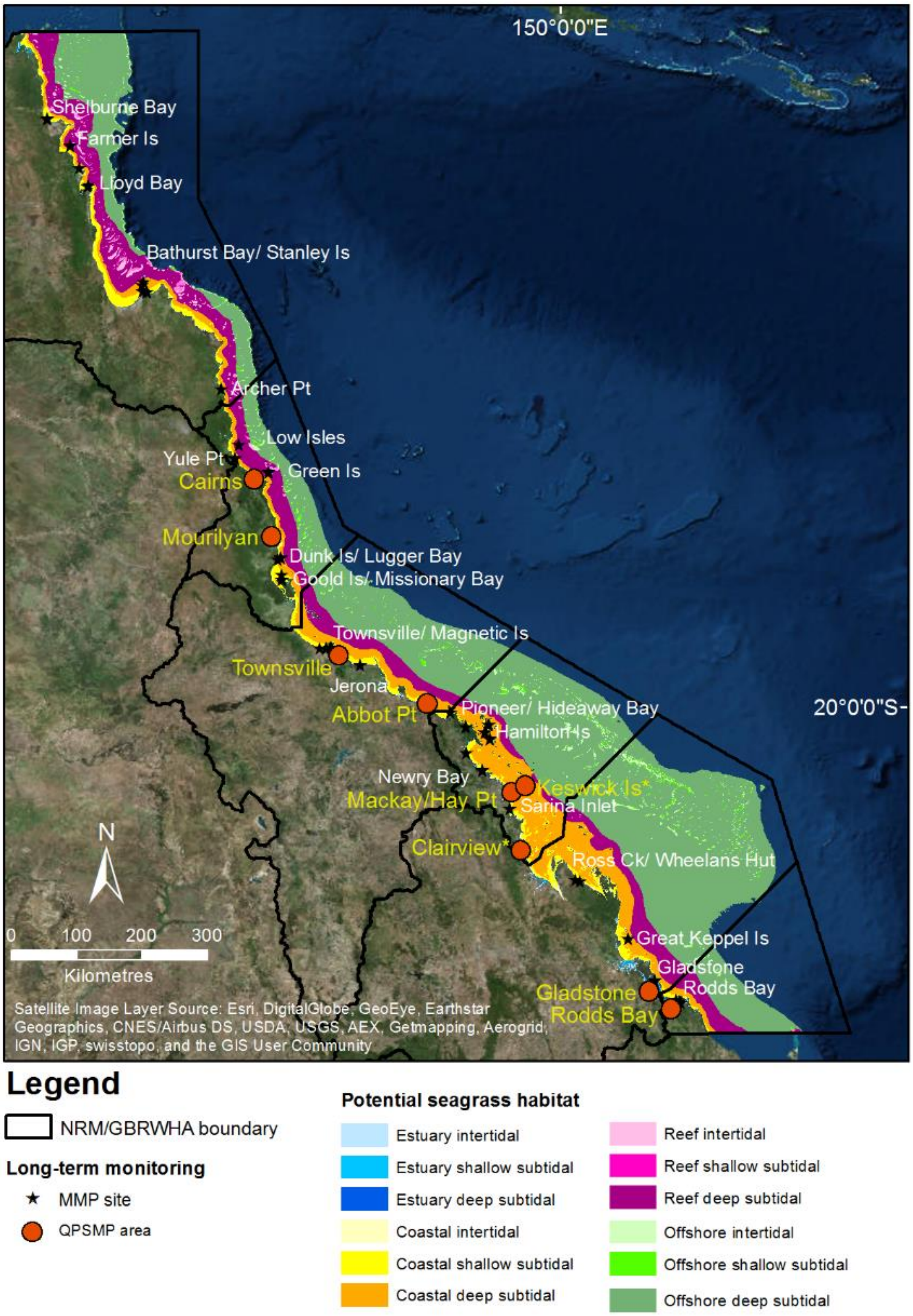

Figure 30. Location of 65 Marine Monitoring Program sites (including QPWS and Seagrass-Watch) and 8 Queensland Ports (QPSMP) monitoring areas overlaid on the 12 water body habitat types identified. Source: Udy et al. (2018).

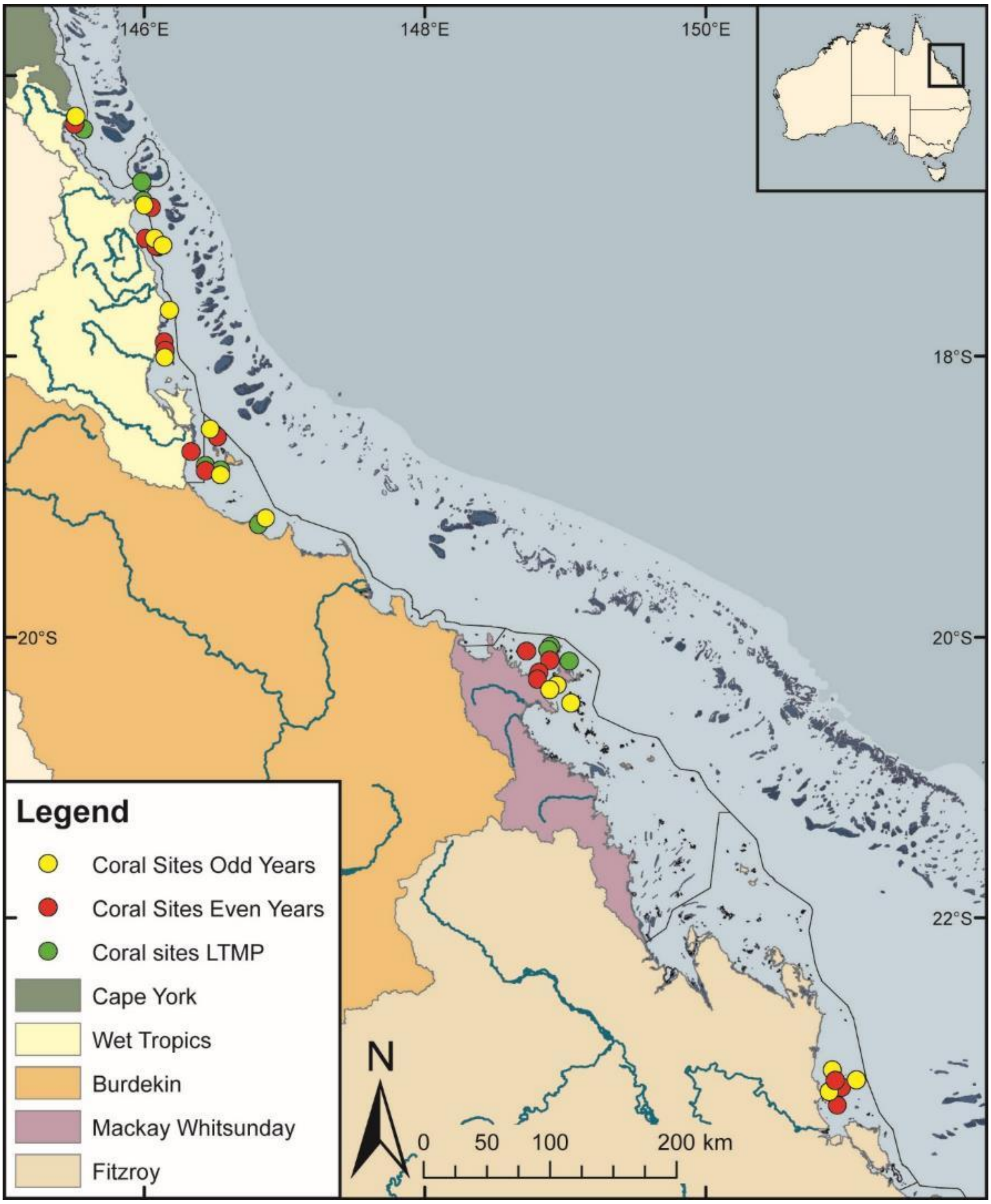

Figure 31. Sampling locations of the Marine Monitoring Program coral monitoring. NRM Region boundaries are represented by coloured catchment areas. Source: Thompson et al. (2017).

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. Further detail about the selection and scoring of these indicators is documented in McKenzie et al. (2018).

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. Further detail about the selection and scoring of these indicators is documented in Thompson et al. (2017).

Inshore water quality *(linked to the 2050 Outcome)*

Water quality condition – productivity/nutrients and water clarity: The metric used to report marine water quality is underpinned by the eReefs model with assimilation of satellite ocean colour data. Further details are provided in the description of the Marine Modelling Program (Section 4.13).

Site specific water quality: A detailed analysis of trends in parameters (turbidity/water clarity, chlorophyll-a and concentrations of particulate nitrogen and phosphorus) relative to the water quality guidelines is conducted annually. Site-specific water quality data are not included in the water quality metric scores, but are used to cross-reference modelled outputs. This is largely because the data are collected at different spatial and temporal scales that are not directly comparable, although the overall trends are generally consistent. Water quality for specific sites is reported against available water quality guidelines (GBRMPA, 2010) in the Tier 2 report for the Great Barrier Reef Report Card.

River-derived pollutant exposure: The wet-season maps derived from satellite imagery are presented in the Tier 2 report for the Great Barrier Reef Report Card and annual technical reports (e.g. Waterhouse et al., 2017c).

Pesticides: To date, an index has been used that determines the ecological risk of mixtures of PSII herbicides[3] weighted by their potencies relative to diuron (PSII-HEq) against five ecological risk categories (Grant et al., 2017). The PSII-HEq concentrations are. An alternative method to assessing pesticide risk will be used in future reports. This new method predicts the proportion of species in an ecosystem that may be adversely affected by exposure to a mixture of pesticides, known as the multi-substance potentially affected fraction, or msPAF (Traas et al., 2002). The recommended level of protection for the Great Barrier Reef is ≥ 99% species protection (GBRMPA, 2010). This approach is an improvement on the PSII HEq approach as it allows the ecological risk of mixtures of all types of pesticides to be estimated not just those with the same toxic mode of action (as with the PSII-HEq index). This will allow the risk of the other herbicides and insecticides that have been detected in the Great Barrier Reef inshore waters to be included in the risk assessment, some of which have been found to exceed marine water quality guidelines. Including this new approach will align the results of the Marine Monitoring Program with the catchment monitoring and modelling programs.

Data management: All of the Marine Monitoring Progam data is stored in the SSIMR data management environments (DARTS and SKIP). Metadata and summaries of annual findings up to 2013 are also discoverable through e-Atlas, and AIMS' logger data can be directly downloaded from an online portal. All monitoring data is available upon request from GBRMPA or the individual institutions. The Marine Monitoring Program annual reports also interpret information from a range of other programs including Seagrass-Watch, AIMS Long Term Monitoring Program, ports data, and Reef Health and Impact Surveys.

Program improvements

Several improvements have been implemented in this program area in the last two to three years, following a major independent review in 2014. They are as follows:

- Alignment of monitoring priorities and sampling locations with the Reef Plan priorities and outcomes of the 2013 risk assessment.
- Spatial/temporal sampling of water quality expanded in four focus areas and Cape York.
- Seagrass monitoring extended to Cape York.
- Seagrass monitoring expanded in subtidal locations with QPWS.
- Related datasets are integrated to the annual reporting (e.g., AIMS LTMP, Seagrass-Watch).
- Reporting metrics have been refined for all sub-programs of the Marine Monitoring Program.
- Incorporation of eReefs modelling outputs.

[3] The PSII herbicides include diuron, hexazinone, atrazine, tebuthiuron, ametryn, prometryn, simazine, terbutryn, flumeturon and two atrazine metabolites.

The program will continue to deliver improvements to the program design which will be considered as part of the RIMReP design process. Examples include consideration of the re-establishment of monitoring in the Fitzroy NRM region and establishment of monitoring in the Burnett Mary NRM region, increased spatial scope of the coral reef and seagrass monitoring, review of the in situ water quality index and seagrass index to assess sensitivity to pressures and drivers, and development of new metrics to represent wet season conditions. Additional improvements are also proposed and included in Section 6.1, Table 18.

Applications of the information:

- Provides data for reporting progress towards the Reef 2050 WQIP outcome that 'Reef water quality supports the outstanding universal value of the Great Barrier Reef, builds resilience, improves ecosystem health, and benefits communities' in the Great Barrier Reef Report Card.
- Site specific data is included in some of the regional report cards. Informs the GBRMPA's management actions.
- Informs Great Barrier Reef Outlook reporting.
- Compiled to produce the annual Marine Results reports.

4.13 Marine Modelling Program

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 affected by cloud cover. Therefore, the eReefs deterministic modelling framework is used in conjunction with the in situ information collected in the Marine Monitoring 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 (described below) which contributes to reporting for the long-term outcome of the Reef 2050 WQIP.

In addition, marine models can assess the impact of individual rivers flowing into the Great Barrier Reef and estimate the extent and properties of flood plumes (contributing to risk assessments). They can also be used to simulate the impact of different management practices on downstream marine water quality (scenarios and target setting).

The eReefs system models a wide range of variables covering physical properties (temperature, current, light penetration) as well as biogeochemical parameters (such as the concentration of nutrients, sediments, plankton and chlorophyll-a). Three-dimensional model outputs are generated for the entire Great Barrier Reef lagoon (from South East Queensland to Torres Strait) at various resolutions (1km and 4km) on a daily basis. eReefs relies on data from wave, atmospheric and global circulation models as inputs, but also on river flow and catchment pollutant load data. Therefore, eReefs can help assess and predict the impact on the marine environment of a range of management practices.

The Marine Modelling Program is a core contributing element of RIMReP. The design presented here has not yet been revised or expanded to align with the recommendations arising from the RIMReP Expert Working Group review on physico-chemical monitoring program design and will be updated in 2019.

ASSOCIATED REEF 2050 WQIP OUTCOME:

Outcome:

Reef water quality supports the outstanding universal value of the GBR, builds resilience, improves ecosystem health, and benefits communities

Objectives:

- 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 and suspended sediments.
- Predict physical and biogeochemical properties of Great Barrier 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.

Delivery partners:

eReefs (Great Barrier Reef Foundation coordination) as a partnership between AIMS, BoM, CSIRO, DES and Great Barrier Reef Foundation, GBRMPA and IMOS.

The Marine Modelling Program relies on a wide array of external inputs including data from a range of wave, atmospheric and ocean circulation models, satellite imagery and in-situ observations.

Methods:

Detailed methods and model validation results are available in eReefs technical reports published on the eReefs website (www.eReefs.org.au) and in project-specific independent technical reports (Logan et al., 2018; Brodie et al., 2017). The following section provides a brief summary.

Framework and design

A revised water quality metric was developed in 2017 as an initial step towards the integration of a broader range of data to measure and report water quality condition. Whereas the previous metric relied exclusively on satellite data, the new metric is underpinned by the eReefs modelling system and integrates satellite images for improved accuracy in what is commonly referred to as a data assimilation process. In situ monitoring data is used to verify model outputs and characterise the model's predictive skill. This initial phase of model and metric development will be followed by further improvements in 2018 and 2019.

Current eReefs coupled hydrodynamic - biogeochemical model

The eReefs coupled hydrodynamic, sediment and biogeochemical (BGC) 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 the process or measurements when the process is isolated. The model also requires as inputs external forcings, 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) and Herzfeld et al. (2015).
- The sediment transport model 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 BGC model 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 32, Baird et al. 2016).

Briefly, the BGC model considers four groups of microalgae (small and large phytoplankton, *Trichodesmium* and microphytobenthos), two zooplankton groups, three macrophytes types (seagrass types corresponding to *Zostera* and *Halophila*, 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).

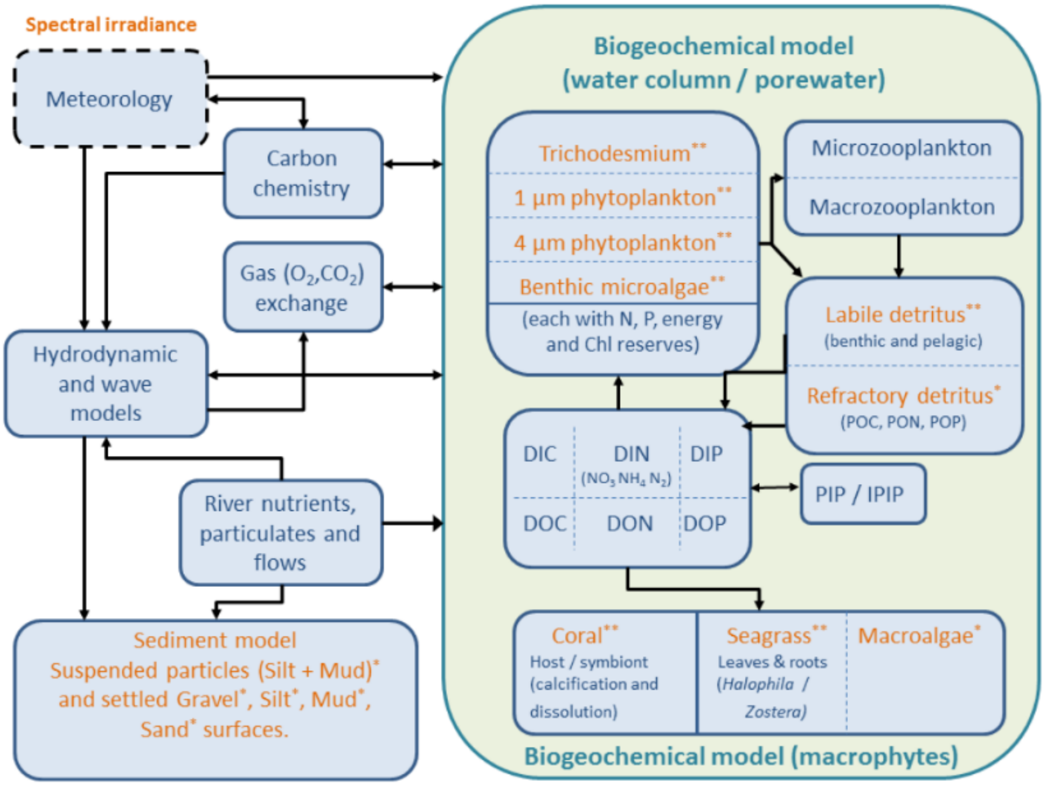

Figure 32. Conceptual framework of the eReefs coupled hydrodynamic-biogeochemical model. The model contains a hydrodynamic, sediment and biogeochemical model. The orange variables are optically active (i.e. either scatter or absorb light), influencing the vertical attenuation of light and the bottom light field. The model is forced by 17 rivers along the Great Barrier Reef with nutrient and sediment loads (Baird et al., 2016) using the Source Catchments model. Source: Baird et al. (2016).

The model is currently forced with freshwater inputs at 17 rivers along the Great Barrier Reef. River flows are obtained from the Queensland Government 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 for the 17 modelled rivers are obtained from the Source Catchments modelling outputs (see Section4.7). 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 Great Barrier Reef obtained from the combination of both modelling and observations, and also improves the skill of the model to make predictions. Data assimilation systems can be thought of as using a model to interpolate between observations. In the case of the eReefs BGC, ocean colour measured by satellite provides the only data set with sufficient temporal (daily) and spatial (1km) resolution for assimilation.

Next phase of development

In a second phase of development, a number of improvements are being implemented to the modelling framework and metric calculation which can be broadly summarised as follows:

- Improving the modelling of TSS concentration and impact on water clarity by better accounting for the fate of very fine sediments and flocs;
- Improving the modelling of the impact of freshwater discharge by implementing high frequency river forecasting models developed in the first phase by the BoM, allowing the prediction freshwater and contaminant inputs from ungauged rivers and therefore expanding the number of river inputs into eReefs;
- Systematically implementing the higher resolution version of the eReefs model to improve predictions in enclosed coastal areas; and
- Reviewing the indicators and relevant guidelines and thresholds underpinning the water quality metric for the Great Barrier Reef Report Card.

Testing and implementation of these improvements will be conducted in 2018 and 2019.

Assessing progress towards the outcome

The Great Barrier Reef Report Card marine water quality metric and associated technical reports allow an assessment of progress towards the overarching Reef 2050 WQIP long-term outcome. The revised water quality metric developed in 2017 is based on the following process:

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 for the entire Great Barrier Reef.
2. The data is partitioned temporally into water years (from 1 October through 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 data for each parameter is then used to calculate a score from 0 (very poor) to 100 (very good) by expressing individual values relative to corresponding thresholds based on the Great Barrier Reef Water Quality Guideline values; GBRMPA, 2010) according to a modified amplitude indexation routine.
4. Scores for each parameter are averaged temporally over the water year 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 Great Barrier Reef score is calculated as the weighted (relative areas) average of regional scores.

Details on the methods for the metric can be found in the Marine Methods for the 2016 Great Barrier Reef Report Card, and information on the National Environmental Science Program (NESP) project which led to the development of the metric can be found on the NESP Tropical Water Quality Hub website.

eReefs consists of many types of data from a range of agencies delivered using a range of services and it has been set up to allow the various data services to be hosted in any location or by any provider. Several eReefs data visualisation portals have been built which can be accessed at http://eReefs.info and http://aims.ereefs.org.au. The metric data can be accessed as part of the Great Barrier Reef Report Card package of information.

Applications of the information:

- Provides data for reporting progress towards the Reef 2050 WQIP outcome that ‘Reef water quality supports the outstanding universal value of the Great Barrier Reef, builds resilience, improves ecosystem health, and benefits communities’ in the Great Barrier Reef Report Card.

- Model outputs, reporting and visualisation products are available publicly and are, or have been used by GBRMPA, regional NRM bodies, Queensland and Australian governments, industry and consultants, universities and research institutions.
- Development of basin-specific ecologically relevant water quality targets for the Great Barrier Reef (Brodie et al., 2017).
- Testing and implementation of an improved water quality index for the 2016 and 2017 and 2018 Great Barrier Reef Report Cards (Logan et al., 2018).
- Scoping study to address poor water quality in the Mackay Whitsunday region (in progress).
- A range of technical reports are publicly available along with peer-review scientific publications dealing with application of the eReefs data in a range of areas including coral bleaching risk assessment and mitigation, impact of ocean acidification at individual reef scale, Reef resilience modelling, light and seagrass modelling, Reef restoration and adaptation feasibility studies and others.

4.14 Summary of Paddock to Reef program indicators

A summary of the measures and indicators in the Paddock to Reef program is provided in Table 12.

Table 12. Summary of the measures and indicators within the Paddock to Reef program, 2018-2022. Note: GBR = Great Barrier Reef.

Program theme	Measure	Scope	Indicators *(frequency)*
Stewardship	Current adoption of agricultural management practices	Sugarcane, grazing, horticulture, bananas, grains	Proportional area of land use that are at the Moderate-Low risk (B) and Low risk levels (A) *Annual*
	Social factors influencing agricultural management practice adoption	Sugarcane, grazing, horticulture, bananas, grains	*In development*
	Current adoption of non-agricultural management practices	Urban areas, industrial land uses, public lands	*In development;* link to regional report cards
Management practice effectiveness and paddock pollutant delivery (agricultural land uses)	Economic benefits of agricultural management practices	Sugarcane, grazing, horticulture, bananas, grains	Cost of changes to management practices *(to be determined)*
	Paddock monitoring of water quality benefits	Sugarcane, grazing, horticulture, bananas, grains	Generation Coefficients (yield) for water quality parameters for different practices on different soil types (TSS, PN, DIN run-off, DIN drainage, DON, PP, FRP, DOP, pesticides) *Experimental periods*
	Paddock modelling of water quality benefits	Sugarcane, grazing, horticulture, bananas, grains	Paddock water quality loads and generation Coefficients (yield) for water quality parameters for different practices on different soil types and different climates (TSS, PN, DIN run-off, DIN drainage, DON, PP, FRP, DOP, pesticides)

Program theme	Measure	Scope	Indicators *(frequency)*
			Annual
Catchment pollutant delivery	End-of-catchment and sub-catchment water quality monitoring	GBR-wide	Loads of TSS, TN, PN, DIN, DON, NH_4-N, NO_x-N, TP, PP, FRP, DOP, pesticides (suite of herbicides, fungicides and insecticides), per cent of aquatic species affected *Year-round and higher frequency event sampling*
	Annual average estimates of end-of-catchment pollutant loads	GBR-wide	Fine sediment, coarse sediment, PN, DIN, DON, PP, DIP, DOP, pesticides (PSII herbicides) *Annual*
Catchment condition	Ground cover extent	GBR-wide	Late-dry-season ground-cover levels in the GBR region based on analysis of seasonal (spring) total ground cover data *Annual*
	Wetland extent	GBR-wide	Extent and net change in extent of natural wetlands (lacustrine, palustrine, estuarine (mangrove and salt flat) and the change in natural wetland extent *Every four years*
	Riparian vegetation extent	GBR-wide	Extent and net change extent of riparian forest and riparian ground cover *Every four years*
	Wetland condition and pressures	GBR-wide	Assessment of biological health (including water quality), physical naturalness, the naturalness of the hydrology, and connectivity to nearby wetlands and native vegetation *Every two years*
Marine condition	Inshore water quality condition	Cape York, Wet Tropics, Burdekin and Mackay Whitsunday NRM regions	Site specific - TSS, turbidity, Chlorpphyll-a, PN, NH_4-N, NO_x-N, DIN, DON, PP, DIP, DOP, DOC, pesticides (PSII herbicides) *Year-round and wet season characteristics*
	GBR-wide water quality	GBR-wide	Modelled - TSS, turbidity, Chlorophyll-a (in development) Remote sensing analysis of wet season water types and river-derived pollutant exposure

Program theme	**Measure**	**Scope**	**Indicators *(frequency)***
			Year-round and higher frequency event sampling
	Seagrass condition	Sites within all NRM regions	Seagrass meadow abundance, reproductive effort and tissue nutrient status *Annual*
	Coral condition	Sites within the Wet Tropics, Burdekin, Mackay Whitsunday and Fitzroy NRM regions	Coral cover, coral cover change, juvenile coral density, coral community composition and proportional macroalgal cover *Annual*
	Pressures and drivers	GBR-wide	Rainfall, river discharge, temperature *Annual and multi-annual trends* Land use *Every five years*

5. Data management, quality assurance, confidence and uncertainty

5.1 Data management

As illustrated in Section 2, the Paddock to Reef program collects, generates and uses significant volumes of plot, paddock, sub-catchment, catchment and marine scaled data in a myriad of data types and formats. The overarching principle of Paddock to Reef program data management is to ensure that all data and information obtained through the Paddock to Reef program are managed appropriately to ensure their long-lasting curation, accessibility, useability and discoverability. All critical monitoring and modelling projects undertaken within the Great Barrier Reef catchments and adjacent marine areas for Reef 2050 WQIP are to be stored and accessed from central environments.

Data management systems

The Spatial and Scientific Information Management for Reef (SSIMR) data management environments, DARTS (DAta Recording Tool for Science) and SKIP (Science Knowledge and Information Provision) are the primary data management and storage systems for the Paddock to Reef program (Figure 33). These systems are designed to maintain and support an environment to archive, manage, access and share data and information used and/or generated by the Paddock to Reef program areas.

The proposed RIMReP data system will need to be able to link to these existing systems.

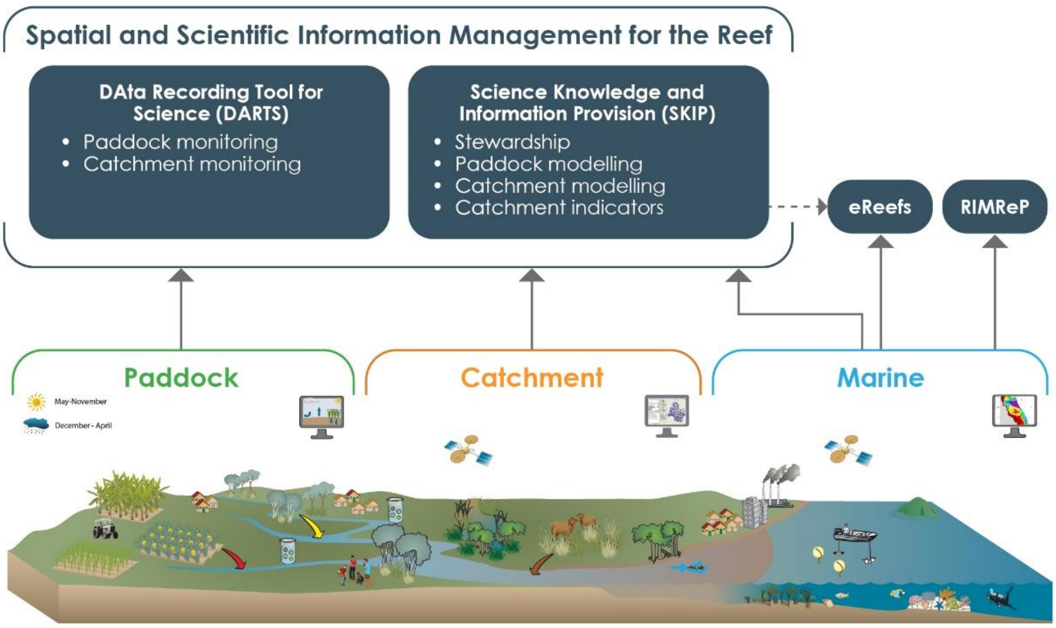

Figure 33. Illustration of the data management system for the Paddock to Reef program, including the Spatial and Scientific Information Management for Reef (SSIMR) data management environment, DARTS (DAta Recording Tool for Science) and SKIP (Science Knowledge and Information Provision).

Specifically, the systems provide:

- A centralised environment for the appropriate management of Paddock to Reef program data and information to ensure their long-lasting curation, accessibility, useability and discoverability;
- Collaboration of data and information between and within all Paddock to Reef program contributing agencies;
- The curation/archive of all data, associated metadata, information and knowledge that has been used and/or generated by Paddock to Reef program processes for evaluating Reef Plan targets for the annual Great Barrier Reef Report Card; and

- An archive package that is aligned with each Great Barrier Reef Report Card, which is approved, signed-off and curated, and therefore becomes a permanent record.

The SSIMR environments are composed of two data management tools, SKIP and DARTS.

1. *SKIP (Science Knowledge and Information Provision)*

SKIP is built on a Microsoft SharePoint 2010 platform and is essentially a structured data repository with enhanced metadata capabilities. The SKIP overarching structure is comprised of:

- project sites;
- libraries (archive libraries per Great Barrier Reef Report Card period, collaboration libraries per Paddock to Reef program area); and
- folders (per Paddock to Reef program area within an archive library and then used to further structure within each program area as needed).

The archive libraries represent the annual Great Barrier Reef Report Card period and all data and information generated for and used by Paddock to Reef program collaborators are uploaded to the appropriate structured folders within. Each archive library therefore represents all data for a reporting period across all components of the Paddock to Reef program.

The collaboration libraries are segmented by program areas and enable collaborators to share interim data and files. These libraries therefore enable a single point of truth for these shared files, ensuring the same and correct version of data is used throughout the program. This area of SKIP is aimed at collaborating and sharing interim datasets.

A project wiki is available for the Paddock to Reef program community to use to collaborate on knowledge related to program deliverables.

Metadata is captured at the project site, folder, file and archive levels of the SKIP structure, allowing both general program information and specific file or file group level information to be stored with the data.

SKIP is currently used to manage the annual data and information from the paddock and catchment modelling, catchment indicators (ground cover index, riparian extent and wetlands extent mapping), management practice adoption, wetland values and pressures and marine components of the Paddock to Reef program.

2. *DARTS (DAta Recording Tool for Science)*

DARTS has been developed as a general-purpose data recording tool for particularly supporting the monitoring components of the Paddock to Reef program. DARTS accommodates a wide range of scientific data, in particular time series information, which is uploaded, stored and managed in DARTS. The DARTS overarching structure is comprised of:

- project (paddock modelling, catchment modelling);
- experiment (region and land-use -based research and monitoring experiments);
- site (represents the monitoring location or area where the experiment is undertaken – e.g. Victoria Plains, gauging station, etc.);
- treatment (e.g. different management practice scenarios undertaken at the site);
- data collection (the datasets – any number of data collections can be stored per treatment and/or site).

Metadata is stored at all levels of the DARTS hierarchy to ensure all levels and data are well described and documented.

The DARTS environment has two components:

- DARTS server – this has a web page front-end used for configuring projects and experiments and a back-end server to manage and store site data. Site version control, check-in/check-out facility, access/permission control, backups, look-up table management, additional metadata template customisation and publishing facility are all controlled from the DARTS server. The server interfaces with the DARTS tool for storage and retrieval of data.
- DARTS tool – this is a data workbench tool installed on each user's desktop and is used for setting up and configuring sites and associated structures for data capture, importing, exporting and reporting. The edited version of a site can be uploaded from the DARTS tool to the server (check-in) for storage and backup and to enable other users to work on the site (check-out).

Currently DARTS is used to manage the data and information from the paddock, catchment and marine monitoring data. DARTS is also in the early stages of being used to manage the data for some of the regional report cards.

The mandatory fields of metadata in both SKIP and DARTS reflect the ANZLIC profile of the ISO 19115 standard. This allows the metadata to be published to metadata catalogues enabling further discoverability. At this stage, the metadata from SKIP and DARTS can be published to the Queensland Spatial Catalogue, QSpatial (http://qldspatial.information.qld.gov.au/catalogue/), if required. Other metadata catalogues and distributed networks could be linked if deemed appropriate.

Presently management practice data is recorded and archived in an ESRI file geodatabase. An annual snapshot of data is uploaded to SKIP.

Datasets and custodians

The lead and supporting organisation for the three elements of the Paddock to Reef data management environment are outlined in Table 13.

Table 13. Summary of datasets, custodians, lead agency, data collection partners and data management tools used for each program area.

Program area	Datasets	Custodians / Lead agency	Data collection partners	Data management tool
Agricultural management practice adoption (Stewardship)	2016-2017 industry benchmarks Annual estimates of management system and management practice change, for each industry and region	DAF	Regional NRM bodies Extension providers and other delivery partners	ESRI spatial geodatabase SSIMR - SKIP (for archival but not for data transfer)
Agricultural management practice adoption (Social factors influencing management practice adoption)	2018 benchmark Annual estimates of the primary factors influencing adoption	OGBR	Regional NRM bodies Extension providers and other delivery partners	To be determined
Non-agricultural land use stewardship	Annual estimates of management system and management practice change, for each industry and region Point source water quality monitoring data	OGBR	Local government and industry partners Regional report card partnerships	To be determined

Program area	Datasets	Custodians / Lead agency	Data collection partners	Data management tool
Economic benefits of agricultural management practices	Cost data for individual management practices in the sugarcane, grazing and banana industries	DAF	To be determined	To be determined
Paddock monitoring of water quality benefits	Treatment scenarios, paddock diary data, raw data from loggers (rainfall, run-off), sampled data (water quality - sediment, nutrients and pesticides, soil characteristics, soil and trash pesticides, plant nutrient content) agronomic data (yield, net return), calculated / derived data (calculated loads, EMC, event summaries, analyses)	DNRME	QUT, JCU	SSIMR - DARTS
Paddock modelling of water quality benefits (water quality outcomes)	Paddock monitoring data, paddock diary inputs, modelling runs, models, outputs	DNRME	DES	SSIMR - SKIP
Catchment loads monitoring	Nutrients, pesticides, TSS concentrations, daily and annual loads calculations, msPAF risk metric for priority sub-catchments and end-of-system sites	DES	Various collaborators	SSIMR - DARTS
Catchment loads modelling	Data inputs, modelling runs, models, outputs, scenarios	DNRME	DES, DAF	SSIMR - SKIP
Ground cover monitoring	Image files, geodatabase files, GIS datasets	DES	DNRME, DAF, CSIRO, TERN	SSIMR - SKIP and DES High Performance Computing facility QSpatial
Riparian vegetation extent monitoring	Image files, geodatabase files, GIS datasets	DES	DNRME, DAF, CSIRO, TERN	SSIMR - SKIP and DES High Performance Computing facility
Wetland extent monitoring	Image files, geodatabase files, GIS datasets	DES		SSIMR - SKIP and WetlandInfo QSpatial

Program area	Datasets	Custodians / Lead agency	Data collection partners	Data management tool
Wetland condition and pressures monitoring	Field and remote imagery-based condition and pressure score data. Scores evidence Indicator specific data e.g. landscape connectivity dataset	DES	Regional NRM bodies and catchment organisations, Buubu Gujin Land Trust, Rinyirru (Lakefield) Aboriginal Corporation, Queensland Herbarium	Scores database ESRI spatial geodatabase SSIMR - SKIP for archiving
Marine Monitoring Program	Data from each sub-component of the Marine Monitoring Program	GBRMPA	AIMS JCU UQ Cape York Water Monitoring Partnership	SSIMR - DARTS and SKIP, plus each provider's own data management system and in some cases, eAtlas (eatlas.org.au)
Marine Modelling Program	Modelled outputs of water quality parameters	eReefs	CSIRO	eReefs Data Visualisation portals http://eReefs.info http://aims.ereefs.org.au

5.2 Quality assurance framework

Quality assurance and quality control (QA/QC) procedures are critical to ensure data confidence and maintain the rigour of the Paddock to Reef program. Table 14 describes the quality assurance framework at the program level. More quality assurance processes are outlined for each program area in the following sections.

Table 14. Quality assurance framework for the Paddock to Reef program.

Quality assurance component	Quality assurance measures in place
Methods	– Report card methods are internally and externally reviewed and published online annually as part of the Great Barrier Reef Report Card production. – Detailed methods and supporting information for each program area are documented by Program Leaders, provided to the OGBR annually, and published in Technical Reports. – The ISP review detailed methods for each program area annually. – Sampling quality controls, training and procedures are primarily the responsibility of each Program Leader.
Data management	– SSIMR implements the data management tools SKIP and DARTS to manage data, metadata and information for paddock and catchment monitoring and modelling programs, the catchment indicator program areas (ground cover, riparian extent, wetlands extent) and marine monitoring. – The agricultural management practice adoption data is captured in a decentralised system (Esri spatial geodatabase) and will use SKIP for archiving data. – New program areas will seek to use SSIMR tools for data storage.

Quality assurance component	Quality assurance measures in place
	– All data used to generate the Great Barrier Reef Report Cards is stored by the OGBR on secure servers. – Release of data and results to non-government stakeholders is limited prior to the formal release of Great Barrier Reef Report Cards by Ministers.
Quality controls	– Quality controls are fit for purpose for each program area and are primarily the responsibility of each Program Leader. The QA/QC procedures and protocols are documented in the technical reports of program areas. – The OGBR checks the Great Barrier Reef Report Card data for any inconsistencies prior to production. – Regional NRM bodies and industry partners review the messages for the Great Barrier Reef Report Card in each region prior to public release. – The CAG and ISP review the detailed results from each program area annually.
Documentation	– The SSIMR data management tools SKIP and DARTS are the primary system for capturing metadata and relevant reports, methods, etc. for the Paddock to Reef program. Other data management and storage systems are identified in Table 13. – The Reef 2050 WQIP website houses or links to all relevant program documentation.
Review and improvement	– The Program Design 2018-2022 was reviewed by the CAG, ISP and externally peer reviewed. – Any changes to the design during program implementation are reviewed by the CAG and ISP as part of an annual review and improvement process. – The methods and approach for each program area undergo peer and independent review as necessary, over the course of the program. – A protocol is in place for recording changes in program design, emphasising changes to reporting and scoring methodology. – Great Barrier Reef Report Card results are reviewed annually by the CAG and ISP. – The Paddock to Reef program research, innovation and development needs to support program improvements are incorporated into the Reef 2050 WQIP Research Innovation and Development Strategy 2018-2022.

5.3 Data confidence and uncertainty

Each of the program areas in the Paddock to Reef program have included measures of confidence in annual reporting which have been presented in the Tier 1 – 3 reports since the 2014 Great Barrier Reef Report Card. The incentive to include confidence measures arose from a recommendation from the QAO in 2014 to report confidence alongside report card scores. As a commitment to continuous improvement, the Paddock to Reef program accepted the QAO's recommendation and, through the CAG, developed a semi-quantitative approach for measuring and reporting confidence.

A summary of the guiding principles and definitions of confidence used in the Paddock to Reef program, and a brief overview of the semi-quantitative approach that has been used to date, is provided below.

5.3.1 Principles

Improving data confidence and reducing uncertainty in measurements and modelling has been a key principle of the Paddock to Reef program since its inception. As described in Section 2, each program area maintains a periodic independent review process, and implements improvements in the program design and methods based on the review recommendations. This process ensures that issues of data confidence and uncertainty are constantly considered and addressed.

Confidence that the Paddock to Reef program outputs are contributing to the objectives (of the whole Paddock to Reef program and of the individual program areas) is assessed through assessment of uncertainty (precision and accuracy of measurements) and consideration of natural variability (representivity) in the results. In this instance, uncertainty refers to the state of knowledge relating to the results produced by the program (the outputs). A low level of uncertainty associated with the program's outputs indicates a high level of confidence that the output is contributing to the objectives of the program. High confidence does not eliminate the presence of uncertainty; each time an observation is made or a score calculated there is the potential that error may be introduced. Even if this potential error is miniscule, it can propagate through further calculations, extrapolation of results, changes in scale, and many other processes. It is important to measure and report this uncertainty. Heterogeneity in measurements are also caused by natural variability, particularly in environmental data, which needs to be captured sufficiently to ensure the outputs are a true representation of what the program reports on.

Confidence as reported by the Paddock to Reef program is the belief of people that the results can be trusted. Confidence, as measured here, encompasses the state of knowledge (uncertainty and variability) of the program's outputs as they link to the program objectives by considering conceptual models, valid use of scientifically robust methods, precision and accuracy and representivity.

Confidence can be improved through reducing uncertainty and increasing representivity. It is very rare (if not impossible) to know everything about a program area; there will always be some degree of knowledge uncertainty. An understanding of potential sources of uncertainty allows for continuous improvement, filling knowledge gaps and improving the precision and accuracy of measurements. While natural variability cannot be reduced, greater representivity of measurements can be ensured to capture variability.

There are two principal aims for measuring and reporting confidence (listed below) and multiple objectives (Table 15) which help to guide the methods used for assessing confidence; these may vary in importance between programs. The aims are:

1. **Accountability -** Demonstrate to the public, stakeholders and policy, the level of trust in the results through data quality and information reported by the programs. This is important for transparent communication with the public and aiding decision-making for stakeholders and policy-makers.
2. **Learning and Improvement -** To assess, at the intra- and inter- program levels, where improvements are needed to focus development and investment, and to ultimately learn more about the environmental processes that are being monitored and evaluated. This is important to help guide the development of these programs in the future and where to focus our investments in time and money.

Table 15. The objectives relating to the two overarching aims for assessing confidence at the whole-of-program, intra-program and inter-program levels. The objectives specific to each aim are listed in each column and therefore there is some overlap between the two.

Accountability	Learning and improvement
1. Communicate the overall level of confidence in the Great Barrier Reef Report Card scores.	1. Ensure we have the capacity to detect change and measure trends.
2. Demonstrate the quality and defensibility of the data that underpin the report card scores and the processes to define the scores.	2. Identify the components within and between programs where confidence can be improved - uncertainty can be reduced and variability better captured.
3. Enable comparisons in confidence between programs.	3. Identify the sensitive measures in the programs – i.e. the elements which show large responses from small changes.
4. Measure improvements in confidence over time.	4. Quantitatively measure improvements in confidence

5.3.2 Semi-quantitative approach

A multi-criteria assessment is currently used to score confidence for each key indicator used in the Great Barrier Reef Report Card. The approach is consistent across all the Paddock to Reef areas, which combines expert opinion with measured data to enable comparison between indicators. The assessment criteria evaluate the key elements that contribute to the outputs of the program outputs and its objectives.

Confidence in the annual results reported as part of the Great Barrier Reef Report Card is evaluated from five criteria, which are weighted and aggregated into a single score:

i. *Maturity of the methodology*: Shows the confidence that the method/s being used are tested and accepted broadly by the scientific community. Methods must be repeatable and well documented. Maturity of methodology is not a representation of the age of the method but the stage of development. It is expected that all methods used would be robust, repeatable and defendable. Weighting = 0.5, as it is confounded by criteria ii to v.

ii. Validation: Shows the degree of validation that has been established for the indicator being measured for reporting progress towards the Reef 2050 WQIP targets. The use of proxies (e.g. remote sensing of turbidity values) is scored lower than direct measures (e.g. in-situ sampling of TSS). The reason for this criterion is to minimise error propagation. Weighting = 1.

iii. Representativeness: Shows the confidence in the representativeness of monitoring/data to adequately report against relevant targets. This criterion takes into consideration the natural spatial and temporal variability embedded in the data as well as the sample size. Weighting = 1.

iv. Directness: This criterion looks at the relationship between the monitored data and the indicator being used. Weighting = 1.

v. Measured error: Incorporates known errors and uses any quantitative data where it exists to make an assessment. Weighting = 1.

To quantify confidence in the results reported by each program area, each criteria is given a score between 1 and 3. A score of 1 indicates the criteria has been met by at least the minimum standards for scientific assessment, a score of 2 indicates the criteria has been met to a certain extent greater than the minimum standards, and a score of 3 indicates that the criteria has been fully met. As an example, the ground cover monitoring program uses the scoring matrix shown in Table 16 to assess each of the indicators it reports against.

The scores are weighted and then aggregated to provide a single score in confidence. This process is repeated for each indicator that a program area reports against. For example, the three indicators reported by the Marine Monitoring Program – seagrass condition, coral condition and water quality – are each scored separately for confidence. The aggregated scores are presented as a rating scale of 1 to 5 bars as shown in Table 17. The scoring system was revised in 2016 to normalise the scoring range and set cut-offs using 20th percentiles. The cut-offs were correlated to the range of possible scores, making the metric more sensitive to lower scores.

Table 16. Example of the scoring matrix for the assessment criteria used by the ground cover monitoring program.

Maturity of methodology (weighting = 0.5)	**Validation** (weighting = 1)	**Representativeness** (weighting = 1)	**Directness** (weighting = 1)	**Measured error** (weighting = 1)
Score = 1 **New** or experimental methodology	**Score = 1** **Limited** Remote sensed data with no or limited ground-truthing or	**Score = 1** **Low** 1:1,000,000 or Less than 10% of population survey data	**Score = 1** **Conceptual** Measurement of data that have conceptual relationship to reported indicator	**Score = 1** Greater than 25% error or limited to no measurement of error or error not able

Maturity of methodology (weighting = 0.5)	**Validation** (weighting = 1)	**Representativeness** (weighting = 1)	**Directness** (weighting = 1)	**Measured error** (weighting = 1)
	Modelling with no ground-truthing or Survey with no ground-truthing			to be quantified
Score = 2 **Developed** Peer reviewed method	**Score = 2** **Not comprehensive** Remote sensed data with regular ground-truthing (not comprehensive) or Modelling with documented validation (not comprehensive) or Survey with ground-truthing (not comprehensive)	**Score = 2** **Moderate** 1:100,000 or 10 -30% of population survey data	**Score = 2** **Indirect** Measurement of data that have a quantifiable relationship to reported indicators	**Score = 2** Less than 25% error or some components do not have error quantified
Score = 3 **Established** methodology in published paper	**Score = 3** **Comprehensive** Remote sensed data with comprehensive validation program supporting (statistical error measured) or Modelling with comprehensive validation and supporting documentation or Survey with extensive on ground validation or directly measured data	**Score = 3** **High** 1:10,000 or 30-50% of population	**Score = 3** **Direct** Direct measurement of reported indicator with error	**Score = 3** 10% error and all components have errors quantified

Table 17. Confidence scoring categories used in the Great Barrier Reef Report Card.

2014 Confidence Score Categories	**Revised Confidence Score Categories**	**Ranking**	**Presentation**
0 < 5	≤ 6	One bar	
5 < 7.5	6.5 – 8	Two bars	
7.5 < 10	8.5 – 9.5	Three bars	
10 < 12.5	10 – 11.5	Four bars	
≥ 12.5	≥ 12	Five bars	

This approach is transparent and can include contributions from a range of sources, however, the qualitative assessments can be subjective. Currently, subjectivity is managed with clear guidance of the assessment criteria. An alternate solution is to replace qualitative assessments with quantitative assessments. However, fully quantified confidence scores would require confidence to be measured for each program area in a way that is consistent and that can be aggregated to represent the relative importance of each indicator to the Reef 2050 WQIP targets, objectives and outcome. Some program areas, for example the Wetland Condition and Pressures Monitoring program, have already invested in quantitative measures of confidence for various components of the design (documented in the Technical Reports for individual program areas). Efforts will be boosted in this phase of the Paddock to Reef program to integrate more quantitative measures of uncertainty and variability into the current approach.

6. Recommended improvements, 2018-2022

6.1 As described in Section 3.1, a key principle of the Paddock to Reef program is continuous improvement through adaptive management. The program improvements already adopted in each program area were described in Section 4. The program integrates the best available information, recognising that data confidence varies across the indicators and regions. The confidence in results and data quality is continually improving as new methodologies are applied and more information becomes available. The principle deliberately adopted since the original design is to seek and use multiple lines of evidence where possible to validate results and interpretation. Recommendations for further improvement

The recommended improvements for this third phase of the Paddock to Reef program identified in the Paddock to Reef program review are shown in Table 18. These recommendations were informed by the program design workshops and the internal review processes implemented for each program area. The review processes for each program area are summarised in Appendix 1, and will provide the primary mechanism for incorporation of the following recommendations and continuous program improvement.

Table 18. Recommended improvements for each program area in the Paddock to Reef program, 2018-2022.

Program Area	Recommended improvements
Agricultural management practice adoption (Stewardship)	Implementation of the following recommendations will assist in improving adoption benchmark quality, encourage realistic reporting of farm changes and improve the baseline assessments: • Increase sample sizes of landholder's adoption of management practices wherever possible, for example, through the adoption of new techniques including imagery to validate practices improvement. • Continue to build multiple lines of evidence related to farm inputs (fertiliser and pesticide use). • Validate the prevalence of certain practices through remote sensing. This could include the development of a program to undertake remote sensing of representative sites 1-3 years post implementation to ascertain legacy impact and/or dis-adoption. • Implement a contractual requirement by funding providers to ensure that validation of effort and measurement of intended outcomes is undertaken. • Implement independent follow-up assessments (included as contractual obligations from investors) to confirm that reported changes have occurred. • Develop standardised approaches to assessing ground cover and land condition in grazing and consider input use efficiency metrics in cropping.
Agricultural management practice adoption (Social factors influencing management pratice adoption)	• Develop a formal monitoring component in the Paddock to Reef program for agricultural stewardship in the Great Barrier Reef catchments to progress our understanding of the social factors that influence management practice adoption. • Adopt a phased approach to implementation, with the first steps including the development of draft indicators and the establishment of a monitoring baseline.
Non-agricultural land use stewardship	• Develop a formal monitoring and reporting component in the Paddock to Reef program for urban, industrial and public land uses for improving water quality in the Great Barrier Reef catchments. • Adopt a phased approach to implementation, with the first steps including: – Develop the ABCD water quality risk frameworks and reporting for urban and industrial land uses. – Develop reporting for the updated of Public Lands Strategy once established.

Program Area	Recommended improvements
Economic benefits of agricultural management practices	• Reinstate a formal economic monitoring and modelling component in the Paddock to Reef program. • Adopt a phased approach to implementation, with the first steps including: – Develop an approach for updating economic modelling to align with the Paddock to Reef program water quality risk framework for agricultural management practices. – Update the water quality risk frameworks to incorporate farm economic outcomes. – Establish techniques for reporting the economic data in the Paddock to Reef program reporting framework. – Investigate linkages and opportunities to incorporate economic information into management prioritisation assessments.
Paddock monitoring of water quality benefits	• Extend current projects for 2018-2019. • Develop a four-year implementation strategy, informed by the priority paddock and catchment modelling needs and research and development gaps. • Encourage complementary research and development funding of priority projects.
Paddock modelling of water quality benefits (water quality outcomes)	• Engage regional expertise in reviewing and updating the modelled agricultural management practices through regional expert workshops. • Expand the number and type of model scenarios e.g. including irrigation management for sugarcane in Mackay Whitsunday and Burnett Mary. • Update the modelling framework to allow modelling of daily pesticide concentrations. Specific model improvements for sugarcane: • Increase the number of planting dates represented in sugarcane; • Develop a mill mud model for nitrogen loss pathways; • Develop a model for enhanced efficiency fertilisers; • Develop a phosphorus fertiliser/mill mud model; • Assess the run times for APSIM sugarcane model to identify where the model process can be sped up. • Expand the soil types modelled in APSIM for sugarcane (currently limited to experimental sites); and • Develop a model for run-off of imidacloprid (and other chemicals) typically applied subsurface. Specific model improvements for other industries: • Develop models for pesticides in bananas; • Improve soils mapping for cropped areas in the Fitzroy; • Revise method for modelling grains using statistical data from remote sensed crop areas per year (from DES); and • Replace the RUSLE model for grazing with a model linked to 1) runoff occurring, 2) peak runoff rate, as well as remote sensed cover and slope.
Catchment loads monitoring	• Investigate the inclusion of uncertainty in loads calculations. • Investigate methods for trend analysis in monitoring data. • Investigate methods to detect anomalies in real time data. Specific recommendations for improving data access and reporting include: • Expand near real time monitoring to support rapid management response • Web delivery of data for wider and faster access via eagle.io.

Program Area	Recommended improvements
	• Improvement in data handling including ReLo for automated loads calculation, and potential new online data base based on the Queensland Waterways Database 2. • Digital metadata management in Obzervr. • Preparation of online Tier 3 Technical Reports. *Note: Independent review of the catchment monitoring program is proposed with the United States Geological Survey (USGS) in late 2018 which may identify further recommendations.*
Catchment loads modelling	• Incorporate updated gully maps (Herbert, lower Fitzroy, Mary, Burnett, and lower Burdekin). • Develop techniques to incorporate the LiDAR 3D mapping acquisition across the Great Barrier Reef catchments (recently commissioned by the Australian Government) into the models. • Refine parameter sensitivity/model uncertainty. A project is underway to look at model parameter sensitivity and from this load uncertainty. The Australian National University (ANU) will complete a two year project in March 2019. The work will assist in identifying what parameters are most sensitive to change and hence where effort should be focused to improve parameters. Secondly some indication of the uncertainty in modelled loads both spatially and temporally will be quantified. • Incorporate new baseline practice adoption layer based on updated water quality risk framework. • Define new paddock model runs reflecting the updated water quality risk framework. • Improve the characterisation of gully types (and their distributions) to allow spatially differentiated representations of generation and delivery of sediment. • Further develop the models to account for the contribution of bio-available nutrients from particulate sources. • Incorporate alternative erosion models for landscapes, either based wholly on fine scaled modelling, or replacements for broadscale modelling. • Develop alternative representation of in-stream sediment deposition and re-mobilisation processes with stronger linkages to observed Queensland river properties and published literature. Recommendations for improving data access and reporting include: • Visualisation of modelled outputs through an online dashboard. *Note: Next independent review of the catchment modelling program will occur in April 2019 which may identify further recommendations.*
Ground cover monitoring	• Utilise data from new satellites: Landsat + Sentinel 2. • Explore the potential to improve seasonal composites with Landsat and Sentinel 2 in combination. • Develop regional and climate-related targets. • Develop additional metrics that assist in targeting management practice improvement e.g. patchiness/land condition. • Develop a method to represent short and long-term trends in ground cover. Recommendations for improving data access and reporting include: • Add contextual information to interactive Great Barrier Reef Report Card e.g. rainfall information.
Riparian vegetation extent monitoring	• Investigate the incorporation of new data from airborne LiDAR and systems to process and analyse these data which can mean very high-resolution data products (e.g. vegetation height and cover) which can inform riparian vegetation structural assessments to assess ecological function and condition.

<table>
<tr><th>Program Area</th><th>Recommended improvements</th></tr>
<tr><td></td><td>Recommendations for improving data access and reporting include:
Publish riparian forest extent data and landscape connectivity metrics on Open Data portals (e.g. QSpatial and TERN).</td></tr>
<tr><td>Wetland extent monitoring</td><td>Incorporation of 30 year Landsat satellite data derived waterbody extent to improve pre-clearing and baseline 2001 wetland extent.
Incorporation of monthly Landsat satellite data derived waterbody extent to improve the capture of wetland extent change from 2001 onwards.
Continue progress towards improved integration with other parts of the Paddock to Reef program (modelling, riparian, management practice).</td></tr>
<tr><td>Wetland condition and pressures monitoring</td><td>Scope and cost an intensified monitoring program design for region scale reporting during the 2018-2019 program year.
options for improving the precision of Great Barrier Reef wide reporting using regional scale sampling will be developed.
Continue progress towards improved integration with other parts of the Paddock to Reef program (modelling, riparian, management practice).
Investigate options for improving data access (within the scope of landholder privacy and conditions of access to wetlands).</td></tr>
<tr><td>Marine Monitoring Program</td><td>Recommendations for the MMP over the next five years are being considered through the RIMReP design process and will be resolved in 2019. These include:
Reporting of water quality trends in the Great Barrier Reef Report Card.
Re-establish monitoring in the Fitzroy NRM region and establish monitoring in the Burnett Mary NRM region (resources permitting).
Formalise link with e-Reefs development of the water quality metric.
Increase the spatial scope of seagrass monitoring (resources permitting)
Increase the spatial and temporal scope of coral monitoring (resources permitting)
Review the in situ water quality Index and seagrass index to assess sensitivity to pressures and drivers.
Recommendations for improving data access and reporting include:
Reduce time between sampling and public reporting using online tools (i.e. transparency).
Transition to the msPAF risk metric for pesticide reporting.
Transition to reporting of key indicators beyond inshore areas where data is available.</td></tr>
<tr><td>Marine Modelling Program</td><td>Further develop the water quality metric using eReefs and continue to improve the application of other eReefs outputs in the Paddock to Reef program.
Improve modelling of TSS concentration and impact on water clarity by better accounting for the fate of very fine sediments.
Improve modelling of the impact of freshwater discharge by trialling high frequency river forecasting models developed by the BoM and using source modelling and gauged data where suitable to expand the number of river inputs into eReefs.
Systematically implement the higher resolution version of the eReefs model to improve predictions in enclosed coastal areas.
Review the indicators and relevant guidelines and thresholds underpinning the water quality metric for the Great Barrier Reef Report Card.</td></tr>
<tr><td>General</td><td>Add drivers and pressures metric to assist in interpreting results in the context of other drivers including climate (e.g. sea surface temperature would be useful as a trend).
Explore options to quantify the climate signal in trend analysis of indicators.</td></tr>
</table>

Specific consideration will also need to be given the potential implications of a changing climate on the monitoring approach, indicators and metrics. For example, changes in rainfall regimes and the frequency of more intensive weather events is likely to impact benchmarks of a number of catchment-based indicators such as ground cover, riparian and wetland condition, and marine ecosystems. While these influences are likely to be longer term that this five-year implementation phase of the Paddock to Reef program, investigations should commence in this period and may include direct linkages to research and development projects, modelled scenarios to inform potential implications and tailored expert workshops.

Additional improvements to program delivery arrangements include implementing mechanisms to improve integration and synthesis across the program. For example, integration meetings will be held at least annually for Program Leaders to share their methods and results. This will allow the project teams to see the program-wide perspective of the results, provide feedback to each other, potentially suggest and work through improvements and achieve greater cohesion.

6.2 Knowledge needs and essential research, development and innovation

Research, development and innovation is essential for the Paddock to Reef program to maintain its credibility, ensure the most up-to-date evidence is used, increase confidence in results, improve data quality, expand our understandings of the ecological and environmental processes being monitored, and advance the tools and methods for monitoring and modelling. Several knowledge needs were highlighted in the design process a number of which are essential for the implementation and improvement of the Paddock to Reef program.

Research, development and innovation is recognised in the Reef 2050 WQIP as an important component of the Plan for reaching the long-term outcome. The Reef 2050 WQIP includes an action to identify, prioritise and fill knowledge gaps through the Reef 2050 Water Quality Research, Development and Innovation (RDI) Strategy. The strategy is delivered in two stages. The first stage extracts and prioritises the identified knowledge needs from the 2017 Scientific Consensus Statement to support the effective and efficient generation of knowledge required to underpin evidence-based decision-making in relation to Great Barrier Reef water quality. The second stage is a more detailed plan for implementing the RDI strategy with a key focus on research impact and engagement. The specific knowledge needs for the Paddock to Reef program are presented in the second stage of the strategy.

The Queensland Reef Water Quality Program undertakes research and development projects to improve understanding of the link between land management practices and environmental impacts. The Australian Government National Environmental Science Program Tropical Water Quality Hub also funds applied research to inform investment priorities for Great Barrier Reef outcomes. There is an opportunity to provide substantial efficiencies in human resource and personnel and ensure alignment of these research and development activities with the Paddock to Reef program. Additional benefits of these collaborations include synthesis of data and information from multiple programs into consolidated material and messages for stakeholders, efficient dissemination of results to end users, joint communication products where different parties contribute to the interpretation of results, and data sharing from one project to be used in other projects.

The Paddock to Reef program has a commitment to supporting and implementing innovative approaches to monitoring, modelling, reporting and communication. The Program Leaders consider new approaches to their program area as part of the review cycles. They also work closely with research and development programs and industry groups that are developing new methods and approaches. In addition, the program partners participate in the Great Barrier Reef Water Quality Science Synthesis Workshop in 2018 and 2019 which will continue to provide an avenue for sharing and progressing innovative ideas for water quality management, monitoring and evaluation. Specific mechanisms for identifying innovative approaches to support the Paddock to Reef program will be explored in this phase.

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Appendix 1: Summary of the review and improvement processes adopted for the Paddock to Reef program, 2013-2018.

Table A-1. Summary of the independent review and improvement processes adopted for each program area.

Program Area	Review processes between 2013 and 2018	Future review
Agricultural land management practice adoption	Response to QAO Audit Recommendation 4: *A rigorous verification process is applied to data on land management practice change, and deficiencies in model inputs be addressed, to improve confidence in, and the accuracy of, inputs into catchment modelling.* Extensive ongoing review by ISP. Independent review by industry experts.	Ongoing review of the water quality risk frameworks
Paddock monitoring	External expert review in 2015. Queensland Government formal response to external review.	To be determined.
Paddock modelling	External expert review in 2015. Queensland Government formal response to external review.	External expert reviews in 2019.
Catchment loads monitoring	Response to QAO Audit Recommendation 3: *Catchment monitoring is expanded to aid in determining the effectiveness of practice management change and to enhance the confidence in modelled outcomes.* Great Barrier Reef Water Science Taskforce, 2015-16. Ongoing review by ISP.	Review by USGS in 2018.
Catchment loads modelling	Response to QAO Audit Recommendation 4: *A rigorous verification process is applied to data on land management practice change, and deficiencies in model inputs be addressed, to improve confidence in, and the accuracy of, inputs into catchment modelling.* External expert review in 2015. Queensland Government formal response to external review. Annual external peer review of modelling results. Ongoing review by ISP.	External expert review in 2018 (external review every three years).
Ground cover	Extensive ongoing review by ISP. Independent review by experts.	To be determined.
Riparian extent	Extensive ongoing review by ISP. Independent review by experts.	To be determined.
Wetland extent	Extensive ongoing review by ISP.	To be determined.

Program Area	Review processes between 2013 and 2018	Future review
	Independent review by experts.	
Wetland condition	**Independent review:** Program design, assessment and data collection methods and analysis methods 2016. Baseline condition report 2017. **Internal review:** Repeatability study. Sensitivity analysis of assessment instrument. Ongoing review by ISP.	Proposed approach to regional intensification sampling and design externally reviewed. External Biometrician to review details of proposed trend analysis method for wetland condition and pressures.
Marine Monitoring Program	External independent review in 2014. Ongoing review by ISP. Tier 3 reports externally peer reviewed.	Incorporated within the RIMReP expert working group review of program design for seagrass, coral and physico-chemical processes undertaken in 2017/18.

Appendix 2: Tools for delivery of the Paddock to Reef program outputs

Several tools have been developed to provide access to, and in some cases interrogation of, data generated in the Paddock to Reef program. The tools available in 2018 are described below.

Paddock to Reef Project Selector - P2R Projector Tool

The Paddock to Reef Project Selector (P2R Projector Tool) is a prioritisation tool created to support groups who are working with farmers on improving their water quality. It assists in the process of assessing and prioritising funding for projects, which propose changes in agricultural management practices for the sugarcane, bananas and grains industries in the Great Barrier Reef region.

The P2R Projector is an online application based on Paddock to Reef program paddock and catchment modelling outputs. Users login to their specific industry-region group and can create collections of projects which can be exported as spatial files (GeoJSON format). Existing collections of projects can be loaded from files, such as those created using the 'Collector for ArcGIS' application for the Agricultural Management Practice Adoption reporting.

Each project is comprised of responses to a set of before and after practice questions, its spatial extent (multiple paddocks) and proposed budget. The tool predicts a change in sediment, nutrients and pesticides due to implementation of the project. Estimates are based on the underlying soil type, climatic conditions and the management practices before and after the project. Users can select multiple projects from a map to display a list of projects that can then be sorted (e.g. by maximum DIN reductions, or by maximum reduction in soil loss).

An example of the online user interface is shown in Figure A2-1.

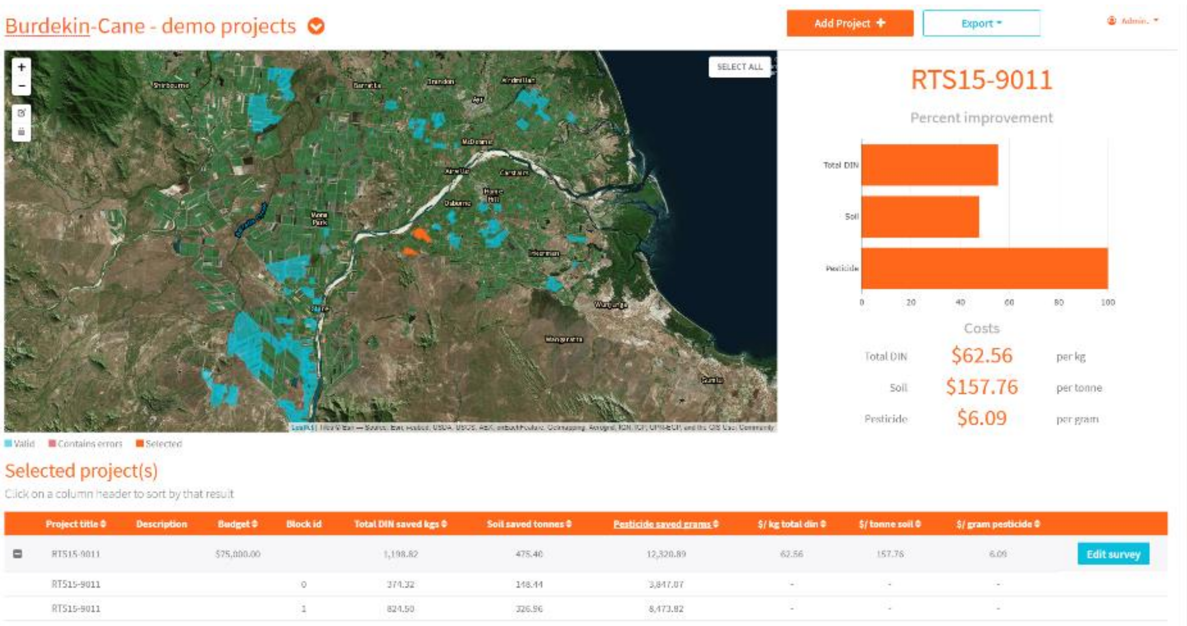
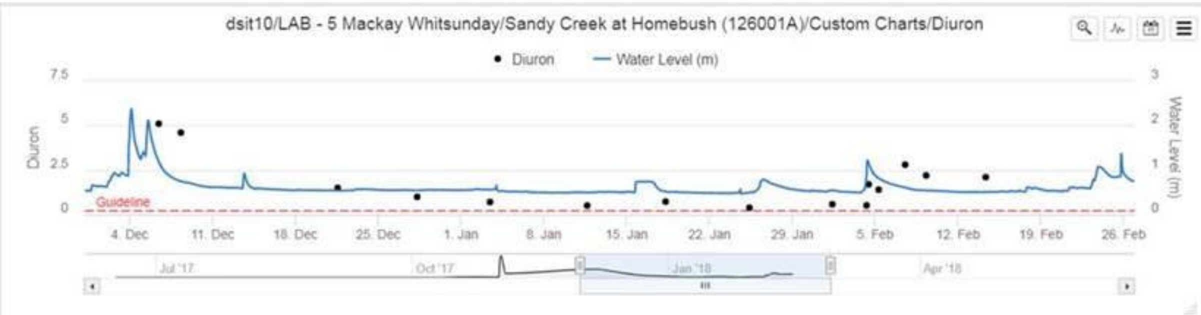


Figure A2-1. Screenshot showing an example of the P2R Projector Tool interface for a single project with two paddocks.

eagle.io Remote Visualisation and Control Platform

eagle.io is a cloud-based data acquisition, storage and visualisation platform. The Great Barrier Reef Catchment Loads Monitoring Program uses eagle.io to monitor and control the operational status of all its automated monitoring station. It permits the visualisation of various aspects of the monitoring station instruments, including battery status, fridge status, river height and sampling events. eagle.io also permits remote control of the monitoring station, including programmed instructions for water sampling over events. At those monitoring sites where near real time sensors are installed (i.e. Trios nitrate sensors, YSI turbidity sensors), eagle.io permits visualisation of these water quality parameters.

Although still in the development stage, eagle.io is also being used to report laboratory-based water quality parameters (i.e. nutrients and pesticides). There is a substantial time-lag between collection of water samples and upload to eagle.io; however, it is anticipated that the platform will be used to provide web-based reporting of all water quality parameters and including pesticide guideline exceedances.



Paddock to Reef Catchment Modelling Dashboard

The Paddock to Reef Catchment modelling dashboard is being created to support the broader community (including policy staff, NRM groups, researchers and general public) who are interested in accessing more detailed modelling outputs than the report card. It will provide summarised outputs of loads by industries by basin, management unit and by erosion process. The outputs are summarised into easily downloadable graphs and or tables. This will make the data more rapidly accessible to a range of audiences and will assist in the process of assessing and prioritising funding for projects for the sugarcane, bananas and grains industries in the Great Barrier Reef region.

The Dashboard is an online application based on Paddock to Reef program paddock and catchment modelling outputs.

An example of the online user interface is shown in Figure A2-2.

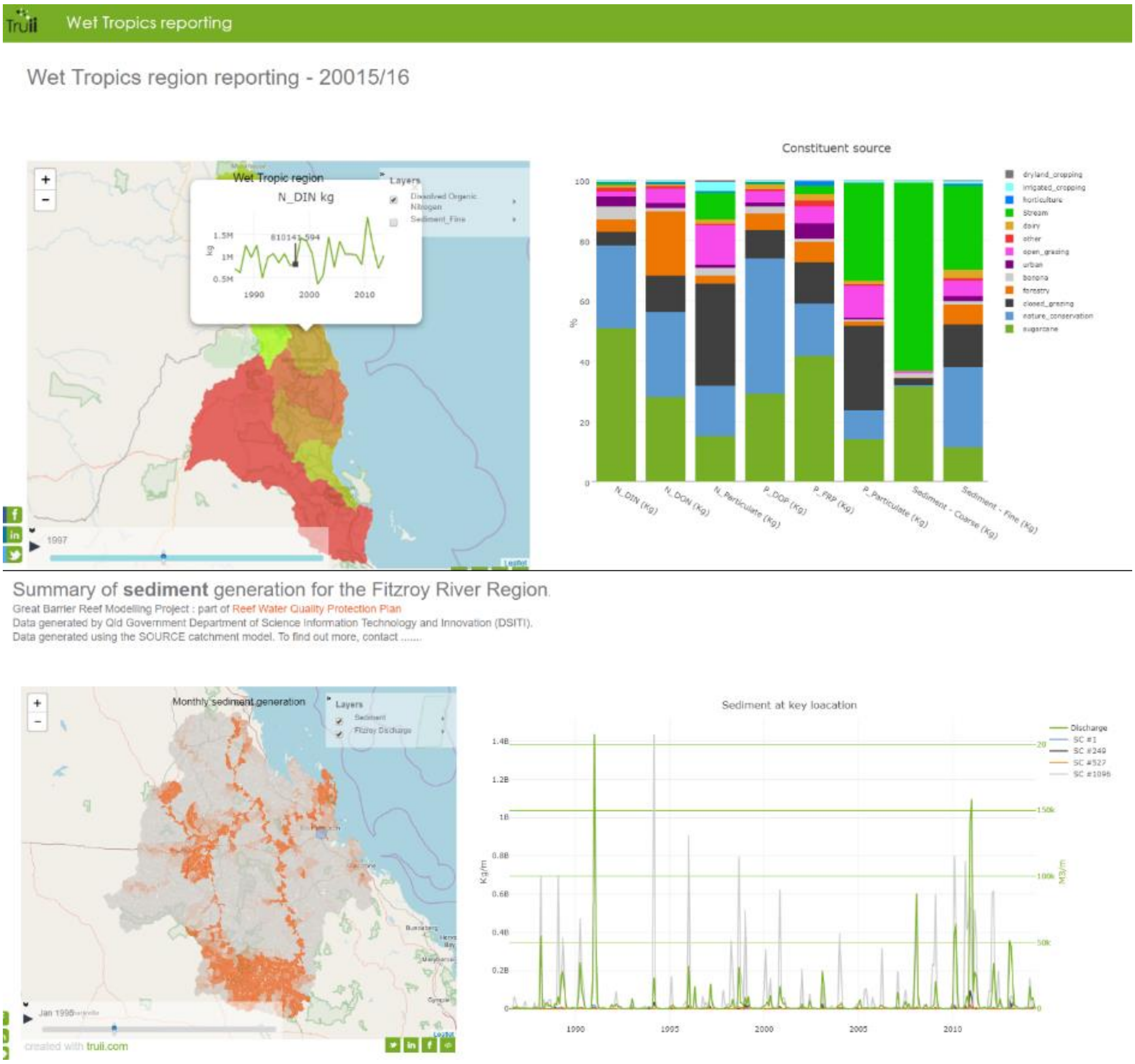


Figure A2-2. Screenshots showing two examples of the Paddock to Reef Catchment Modelling Dashboard online interface: (top) modelled outputs of DIN loads by land use for the Wet Tropics region with a spatial interactive user interface for catchment outputs; (bottom) modelled outputs of sediment generation for the Fitzroy NRM region at a location selected by the user.

FORAGE

FORAGE is an online system that generates and distributes, in customised PDF reports, information for rural Lots on Plan greater than five hectares in area. It incorporates a number of products such as SILO climate data, satellite imagery (linked to the Paddock to Reef program ground cover reporting) and modelled pasture growth, delivering them by email as PDF property-scale reports, to help decision-making in grazing land and environmental management. FORAGE reports can be requested by Lot on Plan. The option of multiple adjoining Lots on Plan is also possible.

Available reports include:

- Rainfall and Pasture report
- Rainfall and Pasture by Land Type report
- Ground Cover report

- Regional Comparison Ground Cover report
- Indicative Land Type report
- Foliage Projective Cover report
- Rainfall and Pasture Growth Outlook report
- Regional Climate Projections report
- Drought Assessment report
- Erodible Soils report
- Crop Frequency report
- Landsat satellite imagery (e.g. Ground Cover, Foliage Projective Cover)

The Ground Cover report shows a ground cover and minimum ground cover map for the selected Lot or Lots on Plan generated from satellite imagery. The ground cover map displayed is for the season and the year selected. The minimum ground cover map indicates the lowest ground cover for each satellite pixel in the selected Lot (or Lots) on Plan since the early 1980s. The report also shows a time series graph (1988 to the present) of percentage ground cover values derived from two sources: pasture modelling and satellite imagery.

The Ground Cover - Regional Comparison report shows the ground cover levels over time for the dominant land types for the selected Lot (or Lots) on Plan. Property ground cover levels are compared to the ground cover levels over time for the same land types on similar land tenures in the local region, defined by a 25km or 50km radius around the selected area depending on the size of the area.

The Foliage Projective Cover (FPC) report shows the percentage of ground area occupied by the vertical projection of the foliage of woody vegetation. Woody vegetation can have a major impact on grass production. FPC is considered to give a better indication of the influence of woody vegetation on grass productivity than tree basal area. This is because FPC is more closely related to light interception and tree water use.

An example of a FORAGE Ground Cover report is provided here.

VegMachine®

VegMachine® is an online tool that uses satellite imagery to summarise decades of land cover in grazing lands. The tool allows users to select areas of interest, then generate simple reports and analyses of how land cover is changing in those areas over time. It can generate comprehensive ground cover monitoring reports, assess land cover change or estimate soil erosion rates, enable viewing of satellite image land cover products and contributes to better understanding of the links between management, climate and cover in grazing land.

The land cover data used in VegMachine® is derived from satellite imagery. The bulk of these datasets are produced by the Remote Sensing Centre in DES, using the Landsat archive which began earth observations in 1986. Landsat imagery has been developed into multiple products used in VegMachine® including Fractional Cover and Ground Cover.

VegMachine® is funded by the Fitzroy Basin Association in conjunction with the Commonwealth and Queensland governments.

An example of the online user interface is shown in Figure A2-3.

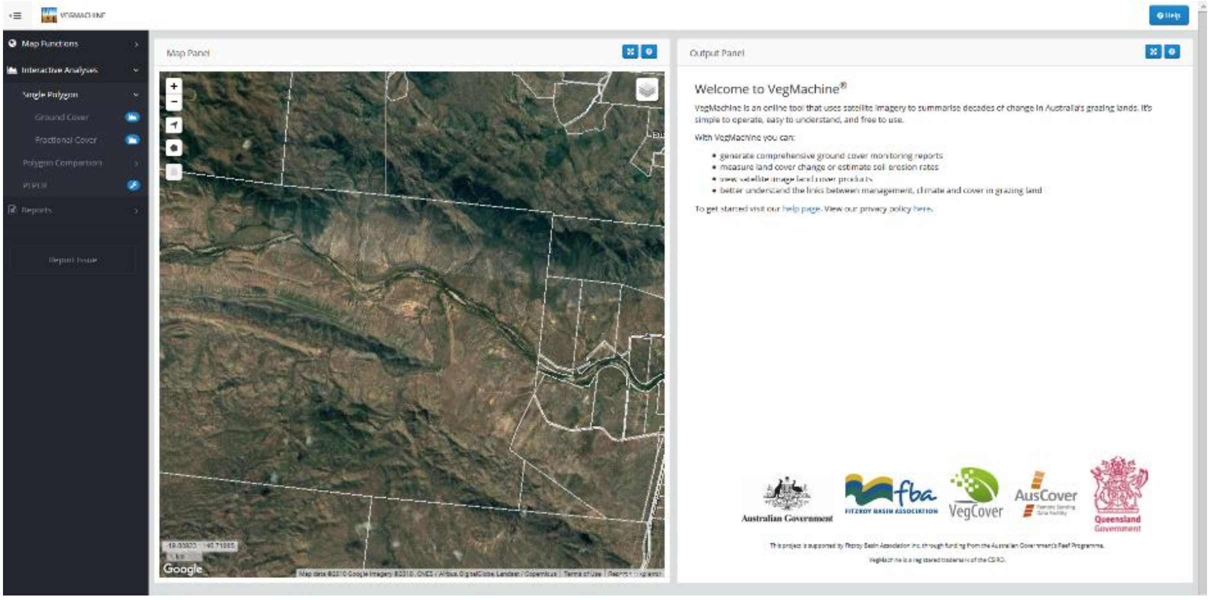


Figure A2-3. Screenshot showing an example of the VegMachine online interface.

WaTERS - Water Tracking and Electronic Reporting System

The Water Tracking and Electronic Reporting System (WaTERS) has been developed to improve the tracking of regulated activities in Queensland that involve water releases to the environment. WaTERS allows approval holders to regularly submit their monitoring data electronically to the government using a secure web portal. A range of data can be submitted but typically relate to water storage quality, treatment performance, release quantity and quality, or environmental condition. The system automatically checks this data against approval limits.

WaTERS can also receive notifications, often required by approvals, when water releases occur and/or when activities are operating outside of the specifications of the approval.

Point source monitoring information can also be accessed for sewage treatments facilities.

Wetland*Info*

WetlandInfo is a first-stop-shop for wetland information in Queensland providing a range of tools and resources to assist with the sustainable management of wetlands.

Information is provided by a range of stakeholders, including Australian, Queensland and local governments, regional NRM bodies, research institutions and other reliable sources.

The wetland extent mapping is accessible on this site, in addition to a wide range of resources including interactive tools and case studies, reports and publications, education products for schools, on-line education modules and videos and interactive maps.

eReefs Visualisation Portal

The AIMS eReefs Visualisation Portal has been built to provide access to eReefs data products. The portal provides both direct visualisations of the key variables from the eReefs Hydrodynamic and BioGeoChemical models and aggregations of the hourly and daily data to longer time periods, such as monthly, annual and all-time (approx. six years).

The portal processes large volumes of model data outputs for user access by:

- Generating videos that map multiple related variables, allowing the connections between key processes to be easily seen.
- Generating aggregations over time (daily, monthly, seasonal, annual, all-time) to show typical spatial patterns of variables without the noise of short-term processes.

- Generating exposures maps to identify regions where organisms are being exposed to harsh conditions that might adversely affect their health.

The products on this website are updated in near real-time from the National Computing Infrastructure data services.