Australian Government

Queensland Government

Marine modelling methods

Reef Water Quality Report Card 2021 and 2022

Reef 2050 Water Quality Improvement Plan

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Marine modelling methods

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

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

The Marine Modelling Program was established in 2016 to:

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

Given the scale of the Great Barrier Reef, it is impractical to measure and report water quality through the entire area and at a reasonable frequency using monitoring data alone. Satellite imaging is employed for extensive spatial coverage but can be less accurate in shallow areas and susceptible to seasonal influences such as cloud cover and smoke haze. Consequently, the eReefs marine modelling framework combines monitored data and satellite observations to extend water quality assessments across the entirety of the Great Barrier Reef. This eReefs marine model framework is used to derive the GBR marine water quality metric.

Marine models which integrate physical processes and ecosystem responses play an integral part in supporting resilience-based management and linking science and observations to policy and decision making.

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

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

The metric is underpinned by the eReefs biogeochemical model and integrates multi spectral data from Sentinel 3a/b, and VIIRS for improved accuracy in what is commonly referred to as data assimilation (Baird et al., 2016, Jones et al., 2016). The eReefs marine model has also been used to determine various scenario catchment loads impacts on marine water quality in the GBR (Baird et al 2021) and 67 papers have been published using the eReefs model water quality outputs since the establishment of the 2016 marine modelling program.

The eReefs model has been assessed extensively against *in situ* observations with detailed assessment findings available in the previous technical assessment of the eReefs biogeochemical simulation against observations (Skerratt and Mongin 2023 and Skerratt et al. (2019) (B2p0) and Skerratt et al., 2019 (B3p0).)

This report describes the methods and changes to the eReefs model reanalysis simulation used to generate the marine water quality metric for the period 1 October 2020 to 30th September 2022 (water year 2020-2022).

In this report we present the results of the Reanalysis of the 4 km resolution coupled hydrodynamic – biogeochemical model for the period Oct 1, 2020 – Sep 30, 2022 (designated gbr4_H3p5_BARRAr2_BRAN2020_G2G_B4p1_Cq4b_rean). A brief description of the modelling system is given, with an emphasis on changes since the previous year's report card simulations (Report Card 2020; Table 1).

Table 1 Report Card numbering and water years.

	YEARS DOCUMENTED	YEAR REPORT PUBLISHED
Report Card 2016	Oct 1, 2015 – 30 Sep 2016	2017
Report Card 2017 and 2018 (2 years)	Oct 1, 2016 – 30 Sep 2018	2019
Report Card 2019	Oct 1, 2018 – 30 Sep 2019	2020
Report Card 2020	Oct 1, 2019 – 30 Sep 2020	2022
Report Card 2021 and 2022 (2 years)	Oct 1, 2020– 30 Sep 2022	2024

eReefs coupled hydrodynamic biogeochemical model

Water quality on the GBR is driven by meteorological factors such as winds, waves, and solar radiation, as well as large-scale ocean currents and nutrient and sediment loads from the catchments. In order to accurately model water quality, a comprehensive approach is therefore needed. This involves using a coupled catchment-hydrodynamic-biogeochemical model that is driven by global atmospheric and ocean models. The eReefs Project, developed collaboratively by CSIRO, DESI, AIMS, and BoM, provides such a model (Figure 1). This integrated system allows for a more holistic understanding of water quality dynamics.

The eReefs coupled hydrodynamic, sediment and biogeochemical modelling system involves the application of a range of physical, chemical and biological process descriptions to quantify the rate of change of physical and biological variables.

The process descriptions are generally based either on a fundamental understanding of processes or on actual measurements when a specific process was able to be isolated and studied. The model also requires external inputs, such as observed river flows and pollutant loads (Figure 1 and 2).

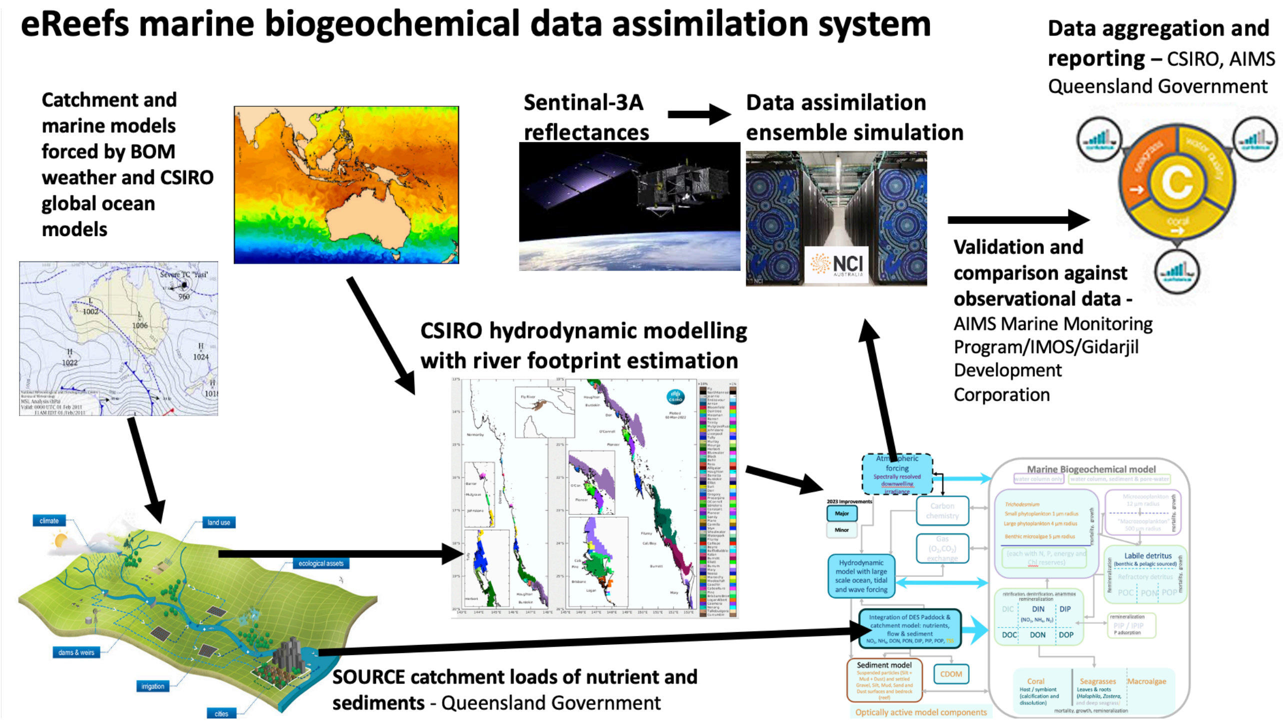

Figure 1 Schematic of the eReefs marine modelling system illustrating the modelling and observational products that are assembled to generate the data assimilating ensemble simulations that are implemented on the National Computing Infrastructure and aggregated to form the Report

Card scores. Enlargement of BGC model in figure 2 dark blue with dark blue arrows showing major process improvements and minor improvements shaded in light blue.

The four main components of the marine model described in more detail later in the report are:

- The hydrodynamic 3-D model based on Herzfeld, 2006 and 2015 which now incorporates improved oceanic and atmospheric forcing and increased river boundaries (Langlais, 2023)
- The sediment transport model, which is a multilayer sediment bed to the hydrodynamic model grid and simulates sinking, deposition and resuspension of multiple size classes of suspended sediment (Margvelashvili, 2009, Margvelashvili et al., 2016)
- The biogeochemical model, which simulates optical, nutrient, plankton, benthic organisms (seagrass, macroalgae and coral), detritus, chemical and sediment dynamics across the whole GBR region, spanning estuarine systems to offshore reefs (Baird et al., 2020) Figure 2)
- The data assimilating biogeochemical model which incorporates remote sensing observations into the marine biogeochemical model to produce the BGC reanalysis (described below).

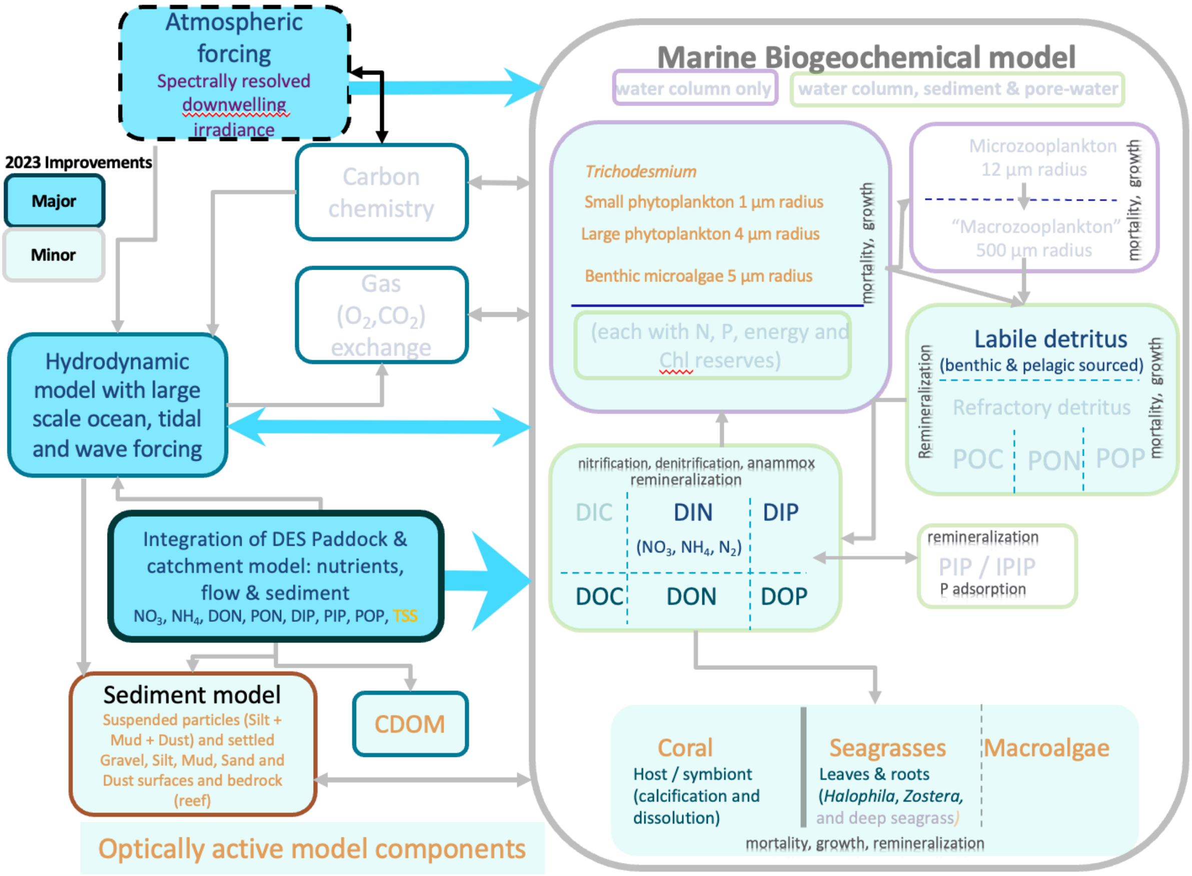

Figure 2. The eReefs marine biogeochemical model conceptual framework with major improvements for this report card shaded in dark blue with dark blue arrows showing major process improvements and minor improvements shaded in light blue. Orange variables are optically active (i.e., either scatter or absorb light) this allows the model to make use of and incorporate remote sensing data.

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

Photosynthetic growth is determined by concentrations of dissolved nutrients (nitrogen and phosphorus) and photosynthetically active radiation. Overall, the model contains 23 optically active constituents (Baird et al., 2016, 2020). The biogeochemistry model also considers ultrafine sediment particles and their impact on matters such as water clarity (Baird et al., 2020).

The model is currently forced with freshwater inputs from rivers along the GBR that enter at the river mouths (Figure 3). River flows for 67 rivers are obtained from The Bureau of Meteorology (BOM) Grid to grid (G2G) model. There are an additional 44 rivers entering as point sources along the coast (i.e. fluxes with load but no flow). The nutrient and sediment loads for all 109 rivers (and 4 river flows for Cape York region) are from the SOURCE catchment model through the Queensland Department of Environment, Science and Innovation (DESI), and the Queensland Department of Resources. For rivers outside the GBR region flows are from the gauging stations supplied by the above QLD department's gauging network. Nutrient concentrations flowing in from the ocean are obtained from the CSIRO Atlas of Regional Seas (CARS) 2009 climatology (Ridgway et al., 2002). 90% of nutrient and sediment loads are delivered with flow and the remaining 10% are as fluxes.

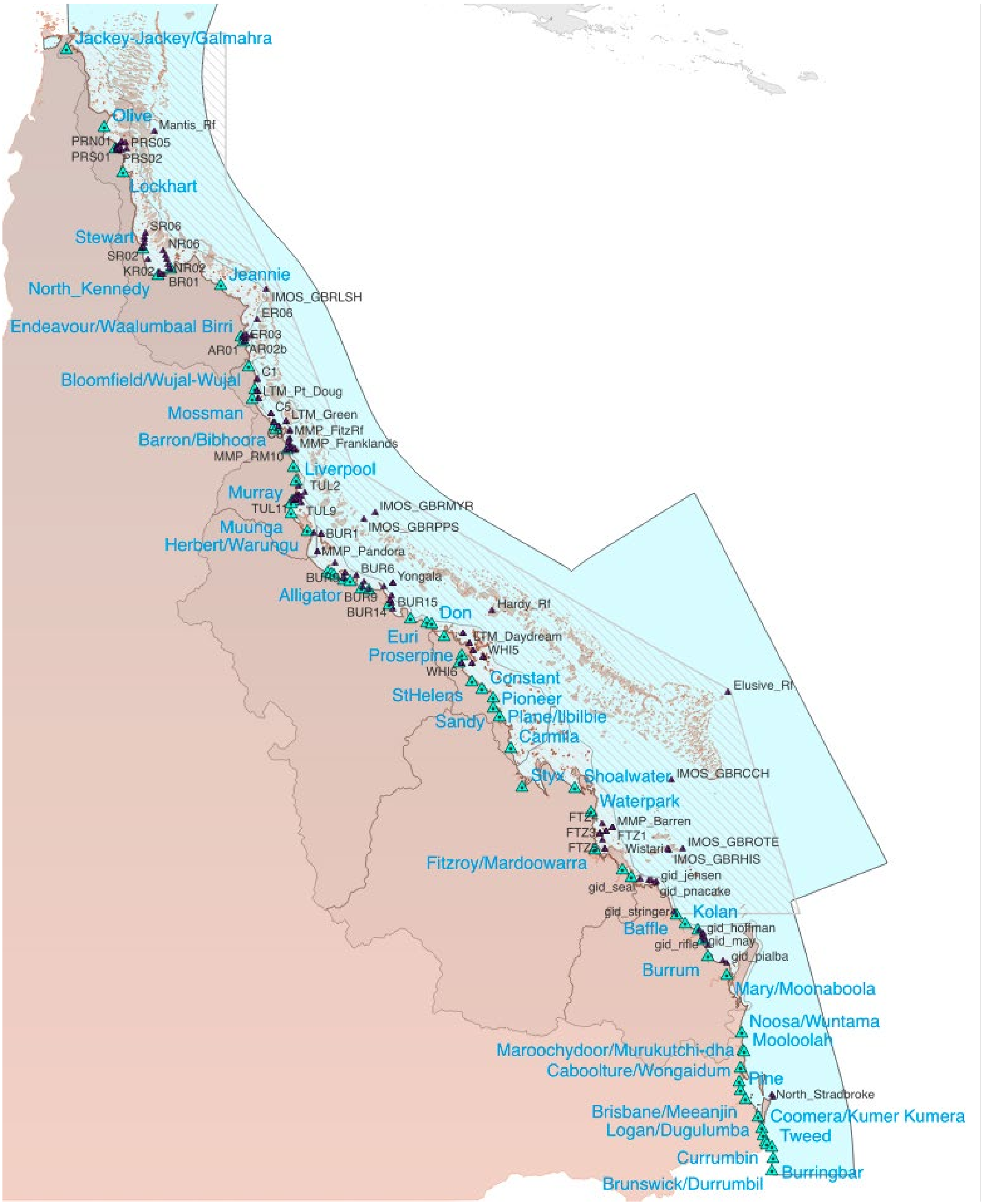

Figure 3 River entrances in blue along the GBR with marine monitoring sites used to compare and validate the marine model in black. Outline of GBR1 and the GBR World Heritage Area shown in blue and hashed respectively. Coral mapping in brown. The 6 NRM (land) catchment areas shown as outlines.

River pollutant loads were obtained from the SOURCE catchments modelling outputs (Ellis and Searle, 2013) up to 1st November 2022 (Figure 3). These provide daily time series prediction of pollutant loads past 30 April 2020, 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.

Data assimilation/Reanalysis

The eReefs model can be run without ingesting observations from the marine environment, which is referred to as a non-assimilating simulation. However, optimally configured data assimilation systems provide the best estimate of the biogeochemical state of the Reef by combining model predictions with observations (Jones et al., 2016). The assimilation of observations improves the model's predictive skill (Skerratt et al., 2019). Data assimilation methods can be thought of as using a model to dynamically interpolate between observations.

For shallow inshore waters, using remote sensing observations to estimate in-water properties is challenging due to the interactions between chlorophyll *a*, sediment, coloured dissolved organic matter and benthic communities, which all absorb and scatter light in the blue, green and red wavebands. Instead of using remote sensing to estimate in-water properties, the water quality metric is based on the optical calculations of the biogeochemical model, which simulates the normalised remote-sensing reflectance. The data assimilation system uses the mismatch between observed and modelled remote-sensing reflectance to constrain the biogeochemical model (Jones et al., 2016).

The use of data assimilating biogeochemical models to quantify the state of marine ecosystems is becoming an important management tool globally (Jones et al., 2016; Fennel et al., 2019). The eReefs Project has developed a sophisticated data assimilating system (Figure 1) based on the eReefs 4 km configuration of a coupled hydrodynamic - biogeochemical model. The output of such a data assimilating system is described as a **reanalysis**. A biogeochemical reanalysis was used to estimate spatially and temporally resolved water quality properties for the previous Great Barrier Reef (GBR) Water Quality Report Cards (Robillot et al., 2018, Baird et al, 2020). For naming see Table 1.

For the GBR, only remote sensing platforms provide the density of observations required to undertake a large-scale data assimilation (see <eReefs home page | eReefs>). The data assimilation system combines model simulations with data obtained from the European Space Agency (ESA) Sentinel-3A and 3B ocean colour sensors and Visible Infrared Imaging Radiometer Suite (VIIRS) sensors (Figure 1). Specifically, the data assimilation system uses the mismatch between satellite-derived remote-sensing reflectance and the simulated remote-sensing reflectance in a 100-member ensemble of simulations to alter the state of the biogeochemical model ensemble thus providing a better estimate of water quality than can be obtained from either models or observations alone.

The dynamic 100 member ensemble is then sub-sampled by selecting all members that have a lower independently calculated (i.e. observations that are not assimilated), in-situ root mean square (RMS) and Bias than the non-assimilating control run. In this case 21 members were used. The estimate of the biogeochemical state used in the report card is the mean of these 21 members. While the model assimilates ocean colour data from satellite, it is independently assessed against the *in situ* observations of chlorophyll *a* concentration, from which the skill of the system can be quantified.

For more information on the eReefs simulations see biogeochemical -simulation naming protocol (https://research.csiro.au/ereefs/models/models-about/biogeochemical-simulation-naming-protocol/)

The data assimilation technique used in this report is described as an Ensemble Kalman Filter (EnKF). We utilized a 100-member ensemble, which was informed by observed ocean colour data collected by the Sentinel-3A/B and VIIRS satellites. The system is described in detail in Jones et al. (2016). When the ocean colour data is assimilated, it means that the data is incorporated or ingested into the model. In this case, the model incorporates the ocean colour data from satellite observations to update and adjust the relevant variables in order to improve the accuracy of the model's predictions. The model adjusts several optically active in situ variables, including phytoplankton concentration, in all the ensemble members in a way that aligns with the internal properties of the biogeochemical model. The model's performance was then evaluated against in situ observations of chlorophyll concentration (monitored water samples and sensor networks), which allowed us to quantify the system's accuracy.

River exposure

The calculation of river footprints is not required for the biogeochemical data assimilation but is used in this report to explain the model behaviour. The calculation of river footprints is explained in detail in Baird et al. (2017) and Skerratt et al (2023) and river footprint examples are shown in Figure 1.

In this modelling approach, each river flow is assumed to have a unit concentration, for example a concentration of 100%. This assumption allows for a proportional relationship between the flow of each river and the corresponding pollutant load. The outflow from the rivers is then transported and dispersed by the hydrodynamic model. For instance, the example of a mid-shelf grid cell with concentrations of Burdekin = 7 and Haughton = 2 while all other river tracers are negligible. This indicates that 7% of the water in that cell at that time entered the model through the Burdekin River, and 2% entered through the Haughton River since the start of the simulation. The remaining 91% represents ocean water, either because it originated in the ocean at the beginning of the simulation or entered through offshore ocean boundaries.

The river plume extents predicted from Jan 1, 2011 to 2022 are given here.

Major improvements in the eReefs marine model system 2023

The eReefs coupled hydrodynamic-biogeochemical model is a variant of the CSIRO Environmental Modelling Suite, which is utilized for various applications in fields such as Defence, Aquaculture, and Coastal Management (Baird et al., 2020, Steven et al., 2019). The model is regularly updated and improved both within the eReefs Project and from other applications (Figure 1 and 2).
Summary of relevant changes in the hydrodynamic model (Langlais 2023):

1. Increased coastal distribution for the 109 rivers along the coast.
2. Improved large-scale circulation for shelf break currents upwelling and chlorophyll signature.

Summary of relevant changes in the data assimilation system were:

1. Use of a revised 2023 SOURCE catchments run with updated catchment condition.
2. The input of an atmospheric source of dissolved inorganic phosphorus (DIP) at the Redfield ratio.
3. Improved the data assimilation system through:
    a. Addition of Sentinel 3B satellite data stream (Oct 2019 onwards)
    b. Updated version of EnKF-C data assimilation software (v2.4.0)
    c. Assimilation update vector limited to top 50 m and includes DIN, DIP, Large and Small Zooplankton biomass, and 3 sediment classes (mineral, carbonate and dust)
    d. Hybrid ensemble used to prevent ensemble collapse, requiring addition of 94 static members to the existing 100 dynamic members
    e. Simplified the (data assimilation) analysis step with an analytical expression to update the DIN and DIP nutrient field
    f. Run on a 2d cycle (previous reanalysis runs prior to 2023 used a 10d cycle).

Present reanalysed fields as the mean of the 21members [#0, 1, 3, 16, 23, 28, 31, 36, 42, 44, 45, 47, 48, 53, 57, 59, 70, 83, 91, 93, 94, 95] closest to the MMP in situ chlorophyll extractions.

How the metric is calculated, and information reported

The Reef water quality report card marine water quality metric is calculated as follows:

1. Chlorophyll *a* concentration and Secchi depth data are extracted from the assimilated eReefs biogeochemical model at a 4km spatial resolution and daily temporal resolution (midday snapshot) for the entire Reef

2. The data is partitioned temporally into water years (from 1 October to 30 September of the reporting year) and spatially into zones representing combinations of 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 4 km model resolution near the coastline.

3. The site-level data (4 km x 4 km) for each of the three measures are standardised to indices on a continuous scale of zero (very poor) to 100 (very good). This is done by assessing individual values relative to the appropriate water quality guideline value according to a ‘modified amplitude indexation routine’ (fsMAMP: base 2 logarithm of the ratio of observed value to threshold)

4. Scores for each parameter are aggregated (averaged) temporally over the water year into annual scores and spatially in the open coastal reporting zone. The resulting scores for chlorophyll *a* and Secchi depth are then averaged to generate a single score for each region

5. A Reef score is calculated as the weighted (relative areas) average of regional scores

6. All reported scores are mapped onto a five-point (A–E) colour-coded grading scale (see Table 1).

Table 2: Marine water quality metric score to grade scale

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

Semiquantitative confidence ranking

Data confidence

●●●○○

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

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