Quantifying the environmental impact of a major coal mine project on the adjacent Great Barrier Reef ecosystems

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Abstract

A major coal mine project in Queensland, Australia, is currently under review. It is planned to be located about 10 km away from the Great Barrier Reef World Heritage Area (GBRWHA). Sediment dispersal patterns and their impact on marine ecosystems have not been properly assessed yet. Here, we simulate the dispersal of different sediment types with a high-resolution ocean model, and derive their environmental footprint. We show that sediments finer than 32 µm could reach dense seagrass meadows and a dugong sanctuary within a few weeks. The intense tidal circulation leads to non-isotropic and long-distance sediment dispersal patterns along the coast. Our results suggest that the sediments released by this project will not be quickly mixed but rather be concentrated where the most valuable ecosystems are located. If accepted, this coal mine could therefore have a far-reaching impact on the GBRWHA and its iconic marine species.

Keywords

Great Barrier Reef; Coal mine; Sediments; Environmental footprint; Seagrass; High-resolution ocean model

Research data

- The scripts and data required to run the simulations are available on this repository: https://forge.uclouvain.be/asaintamand/cqc_styx_slim
- The hydrodynamic and sediments models' outputs are available on this online archive: https://doi.org/10.17605/OSF.IO/U8735
- The SLIM model is freely available on the following repository: https://git.immc.ucl.ac.be/slim/slim

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Introduction

The Great Barrier Reef (GBR) is the largest coral reef ecosystem in the world and a renowned natural treasure of high ecological and economic value. The region's economic asset has been estimated at $56 billion (Deloitte Access Economics, 2017) and its global significance was recognized in 1981 when it was inscribed on the World Heritage List for its outstanding universal value (Commonwealth of Australia, 2019). However, GBR ecosystems are threatened by multiple, interacting pressures including climate change, unsustainable fishing practices, and poor water quality. The most recent Outlook Report, published by the Great Barrier Reef Marine Park Authority (2019), stated that "Significant and large-scale impacts on coral reefs from extreme ocean temperatures have resulted in this habitat transitioning from poor to very poor condition". In response, the United Nations Educational, Scientific and Cultural Organization (UNESCO) and the International Union for Conservation of Nature (IUCN) recently recommended placing the GBR on the list of World Heritage in Danger (Morrison, 2021) because the Australian Government's progress has been insufficient in meeting key targets to counter the effects of climate change and water quality (World Heritage Committee, 2021). This recommendation was not followed by the World Heritage Committee, which instead requested the Australian Government host a joint UNESCO/IUCN monitoring mission and provide an updated report to the Committee by February 2022 (Day et al., 2021).

Global warming is most probably the greatest threat to the GBR, but it is not the only one. Threats to the GBR can be sorted into three categories based on the possibility and the level of action to oppose them (Sheaves et al., 2016). Firstly, global change and the resulting ocean warming are global by definition, and hence require actions at this scale. Others, like tropical cyclones, are natural hazards and are therefore unpredictable. Finally, more localized threats result from coastal planning and industrial development decisions. Among those developments, coal mining is one of the main economic sectors in Australia, which is among the leading coal producers and exporters in the world (Cunningham et al., 2018). Coal exports alone represent ~3.5% of Australia's nominal gross domestic product and contribute to almost half of Australia's total export by value (Cunningham et al., 2018; Grech et al., 2013). Significant coal reserves are found in the State of Queensland adjacent to the GBR (Figure 1), much of which is transported through ports and shipping channels throughout the GBR. With both environmental protection and economic development in the balance, these coal mine projects are recurring sources of tension between conflicting and not always reconcilable interests: even if the importance of economic activity cannot be denied, coal and coal mines are particularly controversial as they both have direct impacts on the surrounding environment, while also releasing large quantities of methane greenhouse gas (Sadavarte et al., 2021), and contributing to promoting the use of coal, known to be the first source of carbon dioxide emissions globally (Ritchie and Roser, 2020). As such, they contribute largely to global warming.

The "Central Queensland Coal Project" (CQC) is an open-cut coal mine proposed for the Styx basin, approximately 130 km northwest of Rockhampton in Central Queensland (Figure 1), and is expected to produce up to 10 million tons of coal per year. This project does not escape the usual controversy about environmental concerns, especially because the mine would be less than 10 km away from the GBR marine park. As required by Queensland legislation, the proponents of the mine produced an Environmental Impact Statement (EIS) in November 2017, followed by two supplementary versions in 2018 and 2020. For each EIS, a review was issued by the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development. In the final assessment, the Committee expressed "extreme concern that the predicted impacts are not readily mitigated" (IESC, 2020). In response, the Queensland Department of Environment and Science, in their Assessment Report, found in April 2021 that the project was "not suitable to proceed" (Department of Environment and Science, 2021). However, the Assessment Report recommendation is not the final decision for the project. The Great Barrier Reef, due to its World Heritage Status, is a Commonwealth (Australian) matter and the final decision for approval is with the Australian Government's Minister for the Environment, Hon Sussan Ley MP.

The primary concern of the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development was the discharge of mine-affected water into Broad Sound and the Great Barrier Reef World Heritage Area (GBRWHA). Expected pollutants from coal mines are mostly emissions from machinery, dust and particulate emissions from mine works and wastes, and dissolved pollutants in mine waters (Weng et al., 2012). There are multiple ways for those pollutants to enter the water, like the disposal of mining wastes, or the erosion of stockpiles by wind and water (Ahrens and Morrisey, 2005). The risk of mine spoils entering the water is particularly high in case of mine flooding during major rainfall events (Kroon et al., 2015). Publicly available data about coal concentration in the sediment load is scarce (Kroon et al., 2015). However, Ahrens and Morrisey (2005) argue that suspended coal particles may represent a large proportion of the total sediments, especially in regions adjacent to coal-related activities such as around spoil grounds, loading facilities, and in areas receiving terrestrial runoff from catchments where coal mining occurs.

The region of the GBR next to the CQC is host to multiple marine organisms of interest. A dugong sanctuary has been established in 1997 near Clairview, approximately 60 km North to the CQC (Figure 1). This iconic mammal is herbivorous and feeds mainly on seagrass. Even if the surroundings of the CQC are not known to be regions with a high seagrass cover, the predicted seagrass probability map from Carter et al. (2021) displays important densities of seagrass all along the coast, with particularly large densities in the Clairview dugong sanctuary (Figure 1). The region is also known to be a major breeding area for marine turtles, especially for flatback turtles. Limpus (2009) reports many nesting beaches in the region, with hundreds of nesting females repeatedly observed on Avoid and Wild Duck Islands, 75 km North to the mine project. To a lesser extent, nesting green turtles have also been observed on some beaches in the area, but only out of the bay of Broad Sound (Limpus, 2009).

Sediments, and in particular coal dust, can have both physical and chemical (sub-)lethal impacts on marine organisms. Physical impacts include reduced light penetration, abrasion and smothering of sessile benthic organisms, burial, clogging of respiratory and feeding organs with possible organs damage, and reduced performance of visual predators (Ahrens and Morrisey, 2005; Brodie et al., 2014; Kroon et al., 2015). Those impacts are common to all sediments, but they might be even stronger as coal is far darker and stickier than other sediments (Berry, 2017). On the other hand, coal pollutants can also affect water quality and biodiversity by releasing toxic polycyclic aromatic hydrocarbons (PAHs) and trace elements into water (Kroon et al., 2015; Lucas and Planner, 2012; Weng et al., 2012). As those pollutants accumulate in sediments, they have the potential to affect benthic and bottom-feeding organisms if ingested (Kroon et al., 2015). They can also bioaccumulate and therefore possibly impact marine organisms for decades (Haynes and Johnson, 2000). However, multiple studies have shown that physical impacts appear to be more severe and more immediate than exposure to contaminants (Ahrens and Morrisey, 2005; Kroon et al., 2020, 2015). All these impacts can be followed by more indirect ones such as alteration of sediment texture and stability, habitat and ecosystem changes, reduced biological productivity, and food chain and fishery changes (Ahrens and Morrisey, 2005; Ellis, 1989).

Dugongs, marine turtles, and seagrass could be affected at varying degrees by coal sediments pollution. Seagrass is known to suffer from industrial runoff (Duarte, 2002; Grech et al., 2011). The turbidity created by suspended sediments reduces water clarity which in turn affects seagrass photosynthesis capabilities (Adams et al., 2016; Björk et al., 2008; Miththapala, 2008). On top of this light limitation, high sediment concentrations can also impact seagrass with direct smothering and reduced feeding efficiency (Berry et al., 2016). Growth rates of leaves and shoots have been observed to decline significantly following the burial and shading of seagrass (Benham et al., 2016; York et al., 2013). In most extreme cases, when the disturbance is too strong or lasts too long, plant death, changes in species composition, or even meadow loss can be observed (Collier et al., 2012; Wooldridge, 2017). On the other hand, the risk of direct impacts of coal sediments on dugongs is low, but they would undoubtedly suffer from the loss of seagrass. Dugongs are indeed highly dependent on seagrass for their diet (Marsh et al., 2018; Schaffelke et al., 2000). Reduction in dugongs' population, either by migration or by death from starvation, has been linked to reduced seagrass abundance (Preen and Marsh, 1995; Wooldridge, 2017). Finally, the impact of coal pollution on marine turtles is less evident, except for green turtles which feed on seagrass. Not much is known about the long-term effect of chemical pollutants on those animals (Commonwealth of Australia, 2017). However, toxic metals, which have been linked to poor turtle health, could accumulate in tissues and eggs, and could potentially reach toxic levels (Brodie et al., 2014). Given the >50 years life span of marine turtles, they have the potential to bioaccumulate heavy metals in the long run (Lutcavage et al., 1996). Depletion of prey could also result from high pollution levels.

Mine-affected waters are dispersed by the oceanic currents and can therefore potentially impact downstream ecosystems. Previous studies have shown that the extent of coal pollution was observed 22 km and even 40 nautical miles (~75 km) from the source (Burns and Brinkman, 2011; Wright et al., 2017). In the case of the CQC, the extent of those impacts has not been properly assessed. The goal of this article is therefore to evaluate the environmental footprint of mining activities on the marine environment through sediment dispersal. With the use of a high-resolution hydrodynamic model coupled with a sediment transport model, we will determine the dispersal pattern of those sediments, and assess their ability to reach areas of high ecological interest.

Material and methods

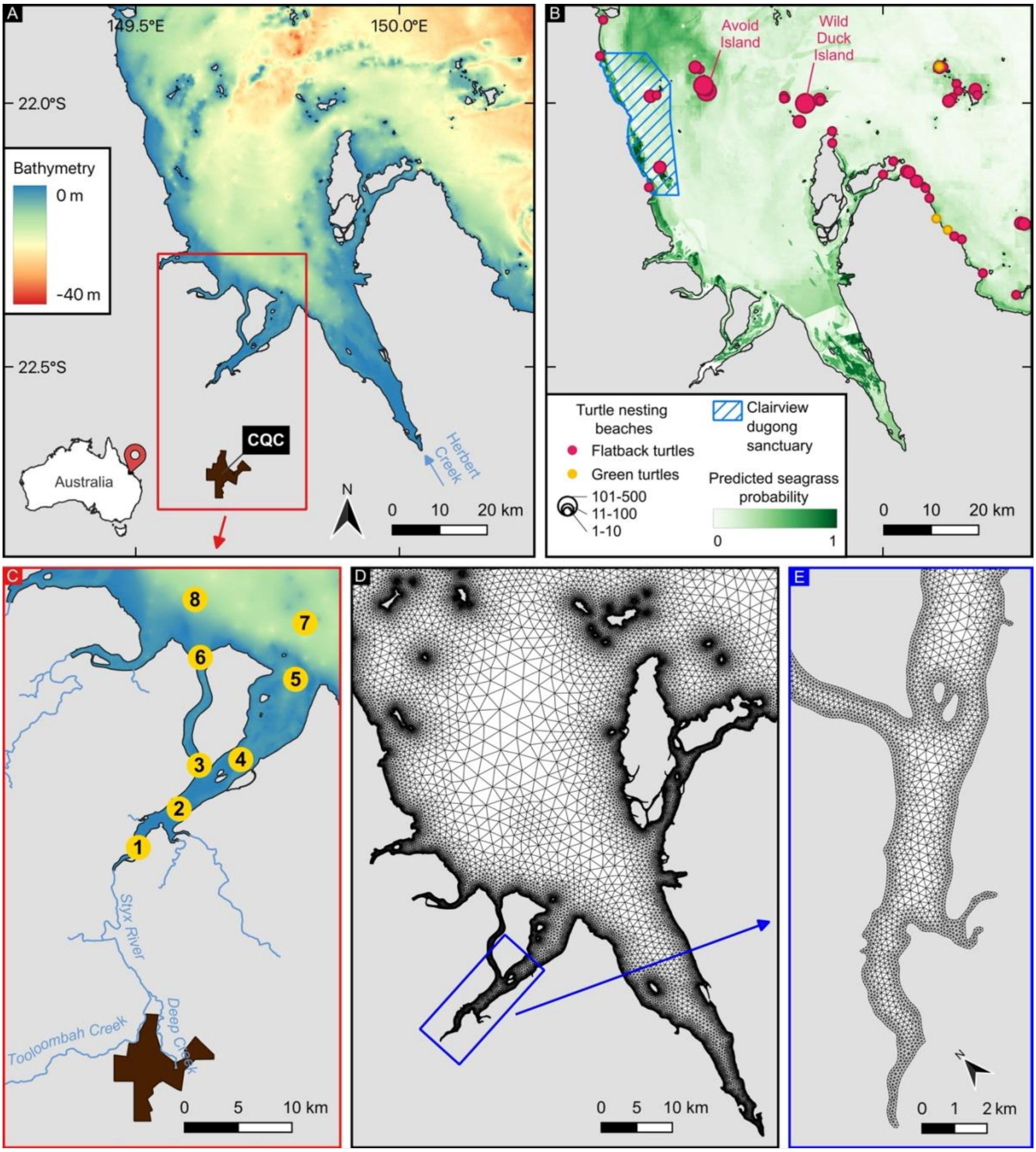

Figure 1*: Overview of the region of interest. A: The bathymetry of the region is not deeper than 40 m. The mine project will be located within the dark "CQC" area. B: Location of selected marine organisms. The two most important turtle nesting islands are Avoid Island in the western part of the bay, and Wild Duck Island in the East. C: Close-up view on the Styx River mouth with its main tributaries. The eight yellow circled numbers correspond to the particle release sites. D&E: Hydrodynamic model unstructured mesh. The mesh resolution reaches 100 m along the coast.*

This work focuses on the potential impacts of the CQC on the downstream GBR. More specifically, the study area covers the surroundings of Broad Sound, which is a large bay located on the North-eastern coast of Queensland, in the Southern part of the GBR. Broad Sound is approximately 80 km long and 40 km broad in its widest part (Figure 1). Several rivers flow into this bay, with the two main catchments belonging to Herbert Creek and the Styx

River. Tooloombah Creek and Deep Creek are the two main tributaries of the Styx River, and they flow respectively on the West and the East sides of the CQC. As the above-mentioned catchments are relatively small, the river discharge is small compared to other larger systems in Queensland. The influence of those rivers on the oceanic circulation in Broad Sound is therefore limited. On the other hand, the water circulation is known to be mostly dominated by the tidal currents in Broad Sound (Middleton et al., 1984).

To evaluate the environmental footprint of mining activities through sediment releases on the marine environment, we first simulated the hydrodynamics within Broad Sound with the multi-scale ocean model SLIM[1]. This model has already been successfully applied several times in the GBR: the model description and validation were presented by Lambrechts et al. (2008) and were followed by many applications, including, for sediment (Lambrechts et al., 2010), marine plastic debris (Critchell et al., 2015; Critchell and Lambrechts, 2016), seagrass propagules (Grech et al., 2018, 2016), and coral larvae (Thomas et al., 2015, 2014) dispersal. SLIM solves the ocean circulation governing equations on an unstructured mesh, which allows the resolution to be refined in areas of interest while keeping it coarser elsewhere. As the region is shallow (less than 40 m deep) and vertically well-mixed, the vertical structure of the flow is quite uniform. We, therefore, chose to use the 2D depth-integrated version of SLIM. Similar dispersal patterns are indeed expected to be close with 2D and 3D models as previously shown in Critchell et al. (2015). Moreover, with the same computational cost, 2D models achieve a significantly higher horizontal resolution. Such models can therefore represent the horizontal flow at a much finer scale than would be achievable with a 3D model. In shallow areas like Broad Sound, those small-scales features are expected to have a greater impact on the large-scale circulation than the vertical dynamics. Hence, the use of a 2D model appears as a reasonable choice for this study.

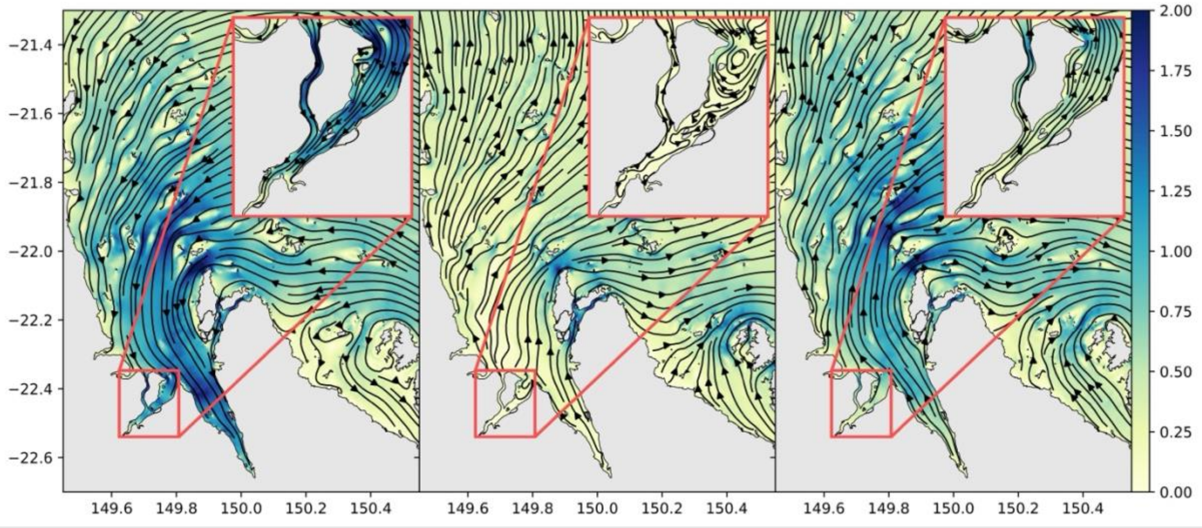

Figure 2: Snapshots of SLIM outputs at three time steps, 3 hours apart each (different stages of the tidal cycle). The background color represents the current magnitude in m/s and shows that currents can reach velocities up to 2 m/s at tidal peaks. Arrows represent current streamlines.

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[1] Second-generation Louvain-la-Neuve Ice-Ocean Model. See https://www.slim-ocean.be for more details about the model. This model is open-source and publicly available here: http://git.immc.ucl.ac.be/slim/slim.

The hydrodynamic model was parameterized to reproduce small-scale flow features in the area of interest. The resolution was increased to 100 m along Broad Sound's coastline. Out of Broad Sound, the resolution varied between 500 m along the coastline to several km in the open sea. The mesh was generated with GMSH (Geuzaine and Remacle, 2009) and its Seamsh python wrapper[2]. The fine mesh resolution in the area of interest allows the model to accurately represent the complex topography, and hence accurately simulate small-scale flow features. The area covered by the model extends over more than 250 km away to the NE (after the offshore reef matrix) and extends over approximately 500 km in the NW-SE direction. This way, the external fluxes are imposed on boundaries far away from the area of interest. On the boundaries, the model is forced by large-scale ocean currents and tides. The large-scale ocean circulation has been computed with the global ocean model NEMO[3] on a regular 1/12° grid with 50 vertical layers (Gurvan et al., 2019). It is available through the CMEMS interface[4]. The tidal signal imposed on the boundaries is constructed from TPXO9.v3 (Egbert and Erofeeva, 2002). A wind forcing, from the ACCESS-R model (available through eReefs[5]) is applied to the whole domain. A discharge is imposed for every river in the domain thanks to the historical data from the GEOGloWS ECMWF Streamflow Service[6]. The model was run for 3 months, from the 1st of January to the 1st of April 2021. There is very little seasonality of the circulation as the flow is mostly tidally driven. The three months of simulation are hence covering a sufficiently long period of time to detect stable sediments dispersal patterns. The model has been validated against sea surface elevation and currents observations at the Capricorn Channel station form the IMOS mooring network[7] (Supplementary Material). This station is located within our computational domain. Simulated and observed currents are in good agreement, both in amplitude (RMSE = 6.5 cm/s) and direction (RMSE = 26.5°).

A Lagrangian particle tracking model has been implemented to represent the dispersal of several sediment types in Broad Sound, forced by the simulated velocity fields. As sediments' dispersion potential is dependent on the particles size, we decided to simulate a wide range of particle diameters, ranging from 1 to 1000 µm. This range covers sediment sizes extending from fine clay to coarse sand. It was divided into 10 classes, with the following range limits: 1 – 2 – 4 – 8 – 16 – 32 – 64 – 125 – 250 – 500 – 1000 µm. We ran a distinct simulation for each size class, during which individual particle sizes were randomly selected within the diameter range of the simulation. The density of each particle was computed following the relation between mean grain size and density for continental terrace sediments from Hamilton and Bachman (1982).

The sediment transport model is a reimplementation[8] of the Particle Transport Model (PTM) developed by the US Army Corps of Engineers (MacDonald et al., 2006), adapted to be compatible with SLIM's hydrodynamics. Particles are initially released at the sea surface and then undergo horizontal and vertical motions. Vertically, particles' height is mostly driven by

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[2] Seamsh, https://jlambrechts.git-page.immc.ucl.ac.be/seamsh/index.html

[3] NEMO: Nucleus for European Modelling of the Ocean, http://www.nemo-ocean.eu

[4] Copernicus Marine Service, https://marine.copernicus.eu

[5] eReefs project, collaboration between the Great Barrier Reef Foundation, CSIRO, the Australian Institute of Marine Science, Bureau of Meteorology, and Queensland Government., https://research.csiro.au/ereefs/

[6] GEOGloWS ECMWF Streamflow Service, https://geoglows.ecmwf.int

[7] IMOS: Integrated Marine Observing System, http://www.imos.org.au

[8] All the codes required to run the sediments model are available on this repository: https://forge.uclouvain.be/asaintamand/cqc_styx_slim

gravity: the heavier they are, the faster they will settle down, following Soulsby (1997)'s settling velocity. A vertical diffusion is also applied using the Pritchard’s method (Fischer et al., 1979), where the Richardson number is set to 0. Once settled, particles can be resuspended, with a probability of resuspension proportional to current speed and inversely proportional to the particle size. The particle entrainment hence depends on the shear stress following the formulation by van Rijn (1993) and the subsequent dimensionless Shields parameter from Soulsby and Whitehouse (1997). A quasi-3D approach is followed for horizontal transport. It amounts to deriving a vertically variable velocity from the 2D model velocity by assuming a vertical log profile. When suspended, particles are transported at the current velocity. A near-bed zone is also defined based on the settlement velocity of the particles and the time step of the model (set to 200 seconds). When entering this near-bed zone, the horizontal velocity of particles is greatly reduced, and sediments only move with the bed load. This bed load velocity is computed following the approach of Engelund and Fredsøe (1976).

Particles were released from eight distinct areas (Figure 1), half inside the Styx River (sites 1-4), and the other half just outside the river mouth (sites 5-8). We assume that this distinction corresponds to two scenarios: "outside" sites correspond to a river discharge large enough to carry particles out of the river mouth. In contrast, "inside" sites correspond to low river discharge conditions during which particles cannot be transported into Broad Sound solely by the effect of the river flow. A total of 50.000 virtual sediment particles were released from each release area. The release was set to happen continuously at an hourly rate over one full month. This allows for sediments to be released in different tidal conditions (over about two full spring-neap tidal cycles). The particles were then tracked for two extra months after the last release. The settlement/resuspension dynamics of each sediment size class was assessed by computing the mean number of particles resuspensions during the simulation, as well as the fraction of time during which particles remain settled. We were not able to validate the sediment plume transport model in the study area due to the lack of field observations.

From the individual track of each particle, we derived the cumulative density of sediments over a 100 m resolution grid throughout the simulation. The cumulative densities correspond to the sum of the number of particles in each grid cell at each time step. Footprint maps were then computed by representing the extent of the sediment plumes of each size class. This extent is derived from the sediment density grids by keeping all the cells visited by a minimum of 4000 sediment particles since the beginning of the simulation. Sediment footprints are computed on a weekly basis, during the 12 full weeks of simulation. As the densities are cumulative, a particle can be counted multiple times on the same cell if it stays on that cell during several time steps in a row or if it revisits the cell at different stages of the simulation. In this way, the duration of the exposure, and hence the severity of the impact, is included in the design of the sediment footprints.

Sediment dispersal patterns were then intersected with the spatial distribution of ecologically sensitive areas. The exposure of Clairview’s dugong sanctuary was assessed by computing, for each sediment class, the evolution of the fraction of all released particles that ever reached or settled in the sanctuary. We distinguished between sediments released inside and outside the river mouth to account for normal and high river discharge scenarios. Particles are considered as "settled" when they are found in the near-bed zone. In this zone, they can still move, but only with the bedload, and hence much more slowly.

A risk analysis of seagrass meadows' exposure to sediment plumes was also computed by combining the likelihood of exposure to sediment plumes with the likelihood of consequences based on seagrass distribution maps. We consider that consequences would be higher for high-density seagrass meadows. This risk probability was therefore evaluated by multiplying the probability of seagrass presence from Carter et al. (2021) with a probability of sediments exposure. This last probability was determined by adding up all the cumulative sediment densities for each size class after the three months of simulation and then normalizing them by their 99th centile value. Finally, in order to obtain a probability of exposure to sediments between 0 and 1 on the whole domain, values equal or higher than 1, corresponding to locations with sediment densities larger than the 99th centile, were cropped to a 100% probability of exposure.

Results

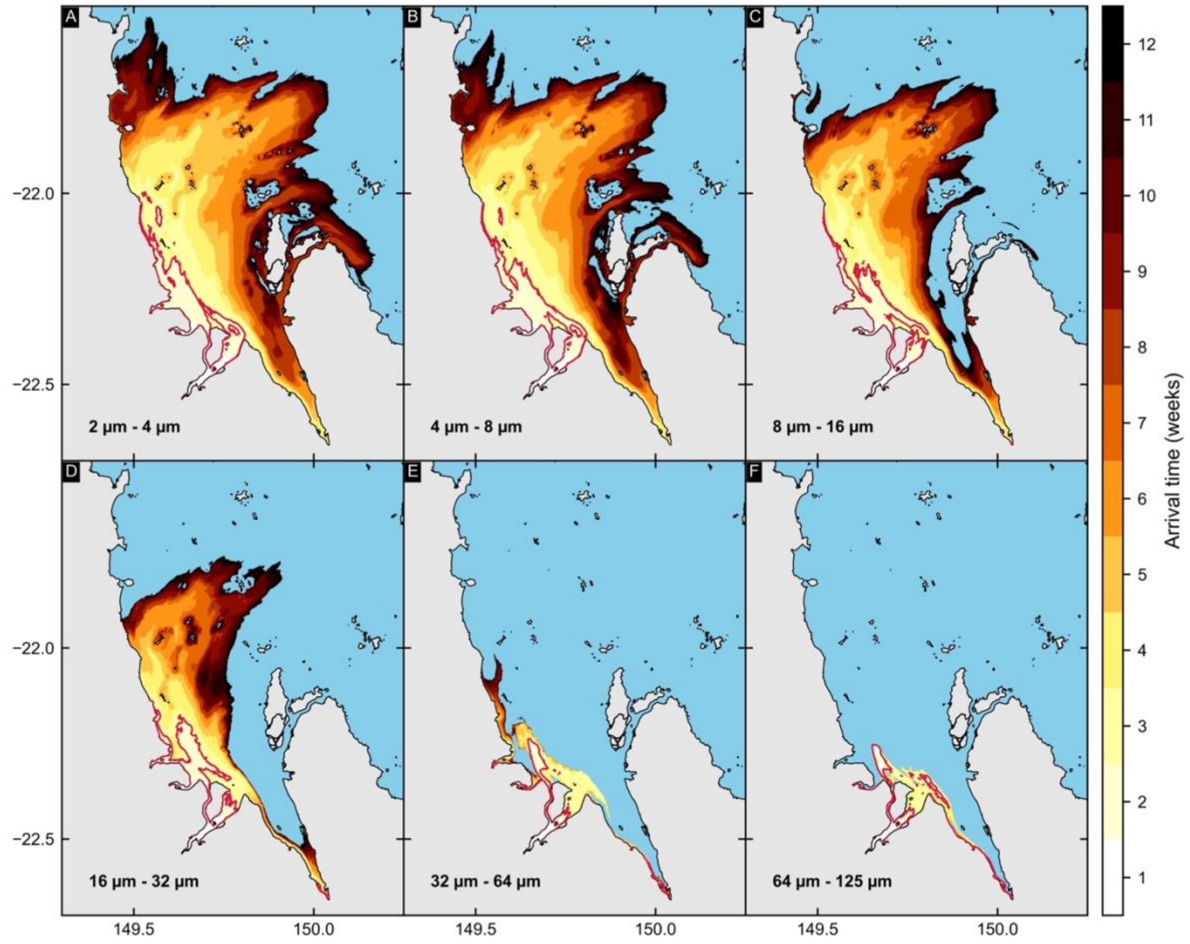

Figure 3: Footprints of sediment dispersal for several size classes. Sediments from the 8 release zones are considered for this figure. The color scale represents the number of weeks elapsed since the beginning of the simulation. The red line delineates the plume extent after two weeks of simulation.

Patterns of sediments dispersion display a clear distinction between fine particles (< 32 µm) and coarser ones (Figure 3). Fine-grained sediments have the potential to travel far away in the bay within a few weeks. The plume for those particles extends more than 35 km away North from the river mouth into Broad Sound after only two weeks. Some of those particles are hence able to reach the dugong sanctuary within this short period. After approximately 7 weeks, some of them even start to leave Broad Sound, but then their progress slows down. Except for the first days of simulation, there are almost no differences between the dispersal patterns of particles released inside or outside the Styx River mouth (not shown here). The sediment plume of particles released from the sites located inside the river tends to stay closer to the Western coast of the bay than the plumes of particles released outside of the river. This is due to the very strong tidally-driven currents in the bay. Sediments coming into Broad Sound will be transported by those currents tangentially to the coast, either towards the bottom of the bay or towards the GBR, with the inversion of the direction of the tidal currents happening approximately every 6 hours. Most of the particles are transported northward, while a smaller fraction of sediments moves southward, to the bottom of the bay, but nearly none of them are transported offshore.

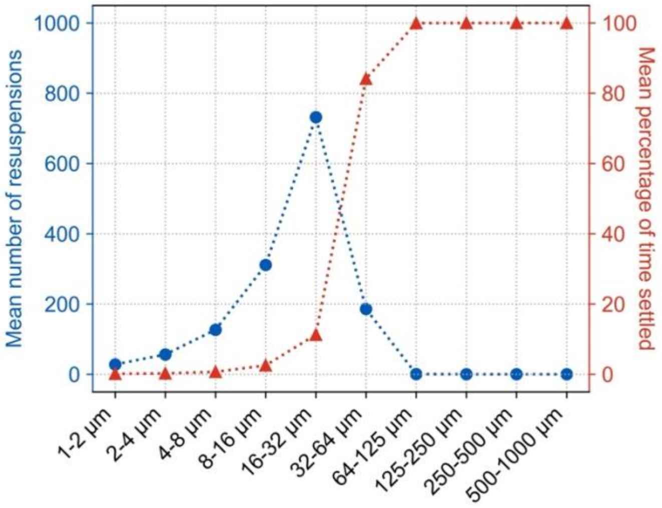

Figure 4: Left axis, blue circles: Average number of resuspensions that particle experience during the 3 months of simulation, by size class. Right axis, red triangles: Mean percentage of time that particles remain settled, meaning located on the sea bed or in the near-bed zone.

Sediments coarser than 32 µm have a dispersion potential limited to a few kilometers inside the Styx River as they settle quickly and then remain in the near-bed zone. Those sediments hence tend to stay close to their release point. This implies that nearly no sediments released at sites located inside the Styx River mouth leave the river to Broad Sound. The dispersal extent of sediments outside the river shown in Figure 3E and F is almost exclusively due to particles released outside of the river. The dispersal pattern for sediments coarser than 125 µm is very similar to the one shown in Figure 3F. In this last panel, the color range indicates that after about 4 weeks, the extent does not evolve anymore, suggesting that sediments quickly settle after being released, and then remain deposited on the sea bottom with nearly no observed displacements. This is confirmed by the average percentage of the time those particles remain settled (Figure 4): starting from 64 µm, particles remain almost entirely on the sea bottom or in the near-bed zone. The mean number of resuspensions also exhibits these dynamics: while particles up to 64 µm seem to undergo several settlements and resuspensions — more than 700 in 3 months for particles between 16 and 32 µm — coarser particles are never resuspended once settled. When settled, the finest particles (< 4 µm) remain on the bottom for less than 5 minutes on average. This duration increases to around 15 minutes for the 16-32 µm class, and then over several days for coarser particles.

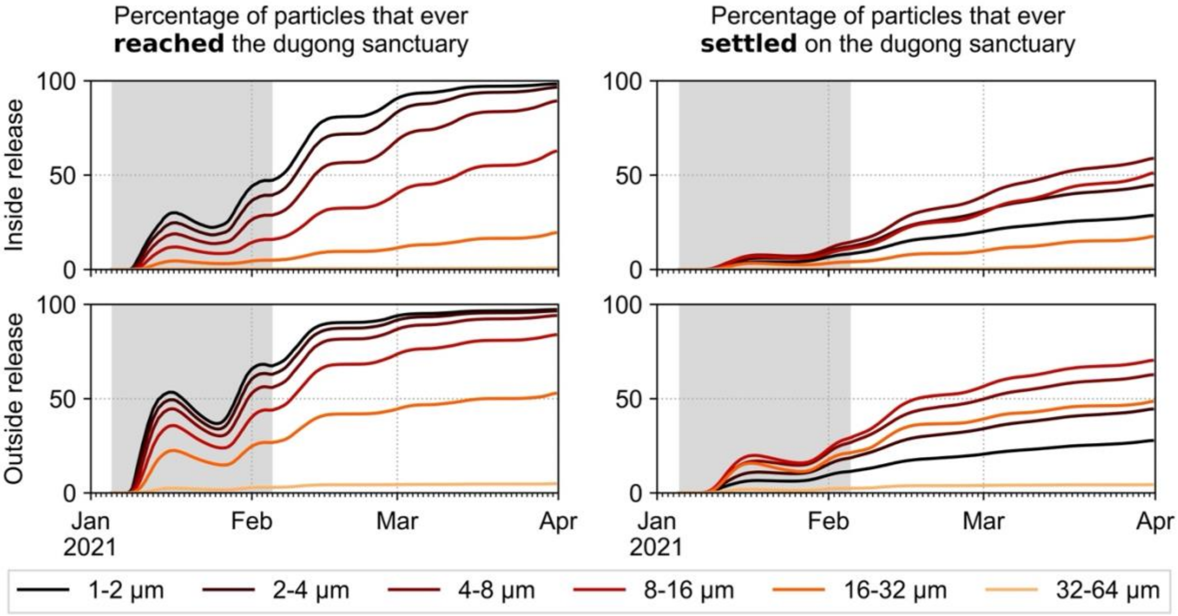

Figure 5: Evolution of the percentage of particles that ever reach (left) and settle on (right) the Clairview dugong sanctuary during the simulation. The distinction is made between particles released inside (top) and outside (bottom) of the Styx River mouth. The grayed area displays the period of particle release. During this period, the percentages displayed on the graphs alternate between increasing and decreasing phases. A decreasing percentage corresponds to periods when the rate at which particles reach (or settle on) the sanctuary is lower than the release rate.

Given its location along the coast north of the Styx River, the dugong sanctuary is directly impacted by fine sediments. The impact of sediments on dugongs is of course mostly indirect, by reducing the seagrass cover and therefore limiting dugong foraging resources. Seagrass found in the region will however notably suffer from reduced light penetration as a vast majority of sediments finer than 16 µm reach this sanctuary during the three months of the simulation (Figure 5). For particles under 8 µm, this proportion is even close to 100 %. Conversely, nearly no particles coarser than 32 µm are able to reach the dugong sanctuary. The proportion of particles reaching the sanctuary does not grow linearly, but is rather influenced by the alternation between spring and neap tides: during spring tides, peak current speed is larger, and sediments are therefore transported over longer distances, allowing a significant fraction to reach the sanctuary. In general, the smaller the sediments, the faster they reach the sanctuary. Also, the differences between particles released inside and outside the river mouth are quite small. Except for particles between 8 and 32 µm, a larger fraction of those released outside of the river mouth have already reached the sanctuary by the end of the simulation. However, this fraction seems to be still increasing at the end of the three-month simulation for the particles released inside the river. This suggests that this fraction could reach the same values as the one for the outside particles after a few extra weeks. This is somehow expected, as the distance separating the dugong sanctuary from the most upstream release sites inside the river is nearly twice as large as the one to the most downstream release sites outside of the river.

Seagrass will moreover suffer from smothering and burying due to particles settling on them. On the one hand, sediments most likely to settle within the sanctuary are those between 4 and 16 µm, with nearly 60 % of those particles settling in this zone at least once during the simulation. A vast majority of finer particles also reach the area, but their settlement rate is too small given their limited weight. On the other hand, sediments coarser than 32 µm settle down much more quickly and are thus not able to reach the sanctuary. It is worth noting that the percentage of fine sediments settling within the dugong sanctuary is still linearly increasing at the end of the simulation. This suggests that the fraction of fine particles that ever settles on this area would probably keep on increasing after 3 months.

As green turtles' diet is dominated by seagrass, they are expected to suffer from seagrass smothering and burying in the same way as dugongs. Flatback turtles however have a carnivorous diet and will thus not be impacted directly. When focusing on the main known turtle nesting beaches, it appears that Avoid Island, in the Western part of the bay, would be quickly and largely hit by a fine grain sediments plume. Contrastingly, the surroundings of Wild Duck Island, in the eastern part of Broad Sound, are mostly spared (Figure 3). Less important nesting beaches located on the coast when leaving the bay to the South are only impacted by a small fraction of the very fine sediments (< 8 µm), while nesting beaches located in the dugong sanctuary will be impacted at the same rate as the seagrass, as described above.

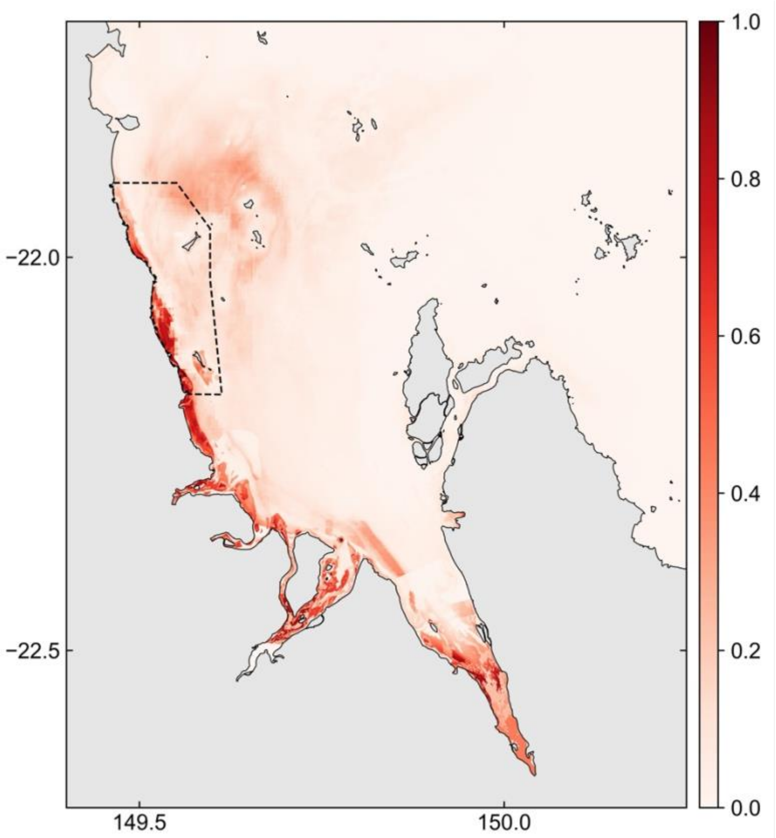

Figure 6: Risk map of seagrass exposure to sediments. The dugong sanctuary is delimited with the dashed line.

Areas of high seagrass density are located where sediments are mostly found along the coast and in rivers estuaries (Figure 1). Those areas appear again clearly on the map of sediments impact on seagrass (Figure 6). The dispersal of fine sediments is mainly driven by tidal currents, which drive sediments along the coast either northward or southward once they are into the bay. The only high-density seagrass areas that will not be impacted by sediment plumes are those located in the north-eastern part of the bay and in the regions to the West and the South while leaving the bay.

Discussion and recommendations

Our study suggests that the proposed CQC open-cut coal mine could have a profound and far-reaching impact on some iconic species and ecosystems of the GBRWHA. Fine sediments (smaller than 32 µm) have the potential to disperse far from the Styx River mouth and reach areas with dense seagrass meadows. Sediments between 32 µm and 64 µm could also disperse into the bay, but their plume extent is much smaller, and this dispersal would only occur in the case of river discharges high enough to quickly transport sediments out of the Styx River. The dispersal footprint of coarser sediments was smaller, and particles stayed close to the river mouth. We also showed that sediment transport and dispersion in Broad Sound is not an isotropic process that would uniformly spread sediments throughout the bay and hence quickly reduce their concentration. Instead, sediments are mostly transported in the western part of the bay, where they overlapped with ecologically sensitive regions such as areas of a high predicted probability of seagrass, the Clairview dugong sanctuary, and turtle nesting beaches on Avoid Island.

While we present here our results with reasonable confidence, we had of course to make some assumptions in the modeling sequence mostly because of the lack of information on processes at stake. Firstly, in the absence of discharge measurements for the Styx River, we simply considered that the water flow would be sufficient during the high river discharge season to flush sediments out of the river into Broad Sound. We hence did not properly assess intra- or inter-annual variability of potential sediment dispersal patterns. However, as the water motion is strongly tidally driven in Broad Sound, we can reasonably assume that the water circulation, and the resulting particles sediments dispersal patterns, would remain mostly stable over time. We also did not consider flocculation processes for the sediments, nor studied the effective kind of particles that could escape from the mine, but instead, we assumed they could potentially be diverse and tested therefore several scenarios with different sediment size classes. As the exact load of sediments that could escape from the mine is unknow, we did not assess here how seagrass precisely respond to sediments. This response could vary greatly between different sediment types and sizes, and is probably not linear. The risk map presented on Figure 6 should therefore only be seen as a sediment exposure risk, and not as a measure of the actual damage incurred by the seagrass meadows. Lastly, we also did not take into account the higher bottom roughness of seagrass meadows, which would weaken the flow and hence further increase sediment retention in those areas. The dispersal potential of particles might be a bit reduced compared to what we show in this work, but this would also result in a greater impact on seagrass meadows with higher smothering and increased turbidity.

Based on the results of this study, we formulate three recommendations regarding the CQC project. Those recommendations would remain valid for any other project alike. They concern (1) the necessity of reactive mine management systems; (2) the incorporation of downstream effects into EIS; and (3) the incorporation of cumulative impact assessment in decision making. Those recommendations are detailed here below.

Recommendation 1: Implement reactive mine management systems

Fine-grained sediments up to 64 µm diameter, corresponding to clays and silts, are commonly found amongst coal mine spoil run-off and coal dust particles (Hilton et al., 2019; Qian et al., 2019; Sapko et al., 2007; Spain and Hollingsworth, 2016). Such fine-grained sediments settle very slowly and remain mostly suspended in the water column, even in decantation ponds. Those ponds will therefore mostly retain large particles and are less effective to retain fine sediments. Particles with the highest dispersion range are also the ones that could probably leave the mine most easily. If those particles find their way to escape from the proposed CQC open-cut coal mine, we showed that they could reach Broad Sound in only a few days before dispersing to the dugong sanctuary and areas of a high predicted probability of seagrass. The short time between the release of particles from the ponds and dispersal in Broad Sound necessitates reactive management systems that increase the likelihood of a timely response and effective mitigation. For instance, installation of silt fences in case of a large sediment release – following, for example, extreme weather events like intense rainfall or flooding – are required to avoid exposure of the sensitive downstream marine ecosystems. Continuous monitoring of sediment releases into the Styx River that are linked to an adaptive decision-making process is required to support rapid intervention capacities that mitigate or contain such sediment releases.

Recommendation 2: Include downstream effects into EIS

In the specific context of the CQC, no study on the potential dispersal of sediments like the one presented in this work was conducted. Yet, the potential impacts of the mine-affected waters on marine ecosystems could occur on relatively broad spatial and temporal scales. We therefore suggest studies like ours should be conducted and taken into account within Environmental Impact Assessments to allow projects like the Central Queensland Coal open-cut coal mine to pursue. Building a coal mine so close to the ocean is probably unprecedented in Australia. This proximity to marine ecosystems, where pollutants are easily transported, results in impacts that might be broader than for an inland project not directly connected to marine environments through drainage systems. Those broader impacts resulting from being connected to marine ecosystems should therefore always be included in the Environmental Impact Assessment of any project presenting this specificity.

Recommendation 3: Incorporate cumulative impact assessment in decision making

While considering the broader impacts appears necessary, assessing the context in which the project takes place, and hence the potential cumulative impacts, seems just as important. The same disturbance could indeed have very different consequences for healthy or already threatened ecosystems. In the case of the CQC, the neighboring GBRWHA is known to be already disturbed by multiple impacts, including unsustainable fishing, poor water quality, and climate change. The potential impacts of a sediments' leakage from the mine would therefore be in addition to the numerous already existing disturbances. For example, dugong populations along the coast of Queensland faced dramatic loss during the second half of the 20th century (Marsh et al., 2005), and those populations are still on a decreasing trend in the southern Great Barrier Reef (the location of this current study, Marsh et al., 2019). Dugongs are hence considered as threatened under the International Union for Conservation of Nature (IUCN) status. There is conversely no IUCN status for Flatback turtles because of "data deficiency", but all marine turtle species are recognized as threatened species under State (Queensland) and Commonwealth (Australian) legislation. Moreover, the number of observed stranded turtles is increasing with time (especially for green turtles), and this could potentially be linked to climate change and coastal developments (Flint et al., 2015). Finally, the loss of seagrass meadows is also observed around Australia as a result of natural and anthropogenic perturbations (Statton et al., 2018). The species covered in this study are hence all already threatened and could be further exposed to more disturbances with projects like the CQC. This suggests that assessing the broader context and the potential cumulative impacts should always be required in EIS.

Conclusion

Following the Environmental Impact Assessment of the CQC project, major concerns were raised about the discharge of mine-affected waters in the GBR. The risk posed by this potential discharge was not completely assessed by the project proponent. In this work, we tried to fill in this gap by evaluating the dispersal potential of mine-affected waters from the CQC project to Broad Sound and the adjacent GBR through the Styx River. We ran sediment dispersal simulations for a wide range of particle sizes, from clays to coarse sands. Our results show that sediments finer than 32 µm can be transported over dozens of kilometers in a few weeks by the very strong tidal currents that are always present in Broad Sound. Those fine sediments could therefore quickly reach ecologically sensitive areas like a dugong sanctuary and turtle nesting beaches.

The CQC mining project appears to pose a serious risk for GBR ecosystems. The proximity of this project to marine ecosystems means that any release of sediments in the nearby wetlands would reach Broad Sound, which is just 10 km downstream. From there, intense tidal currents could rapidly transport sediments over large distances. That clear threat, which is common to many industrial developments directly connected to marine ecosystems, requires specific evaluation and management procedures. During the project evaluation, it requires to properly account for the downstream and cumulative effects of the industrial activities. Those effects can be felt far away from the project and could have a particularly deleterious effect on already weakened ecosystems. If such a project was to be accepted, it would require stringent monitoring procedures that would be quick enough to mitigate and contain any sediment release. We believe that those recommendations should guide the decision process and management of industrial projects close and/or directly connected to marine environments.

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Quantifying the environmental impact of a major coal mine project on the adjacent Great Barrier Reef ecosystems

Supplementary material: Hydrodynamic model validation

A. Saint-Amand, A. Grech, S. Choukroun, E. Hanert

Our ocean circulation model was validated with respect to currents and sea surface elevation observations collected at the IMOS Capricorn Channel (CCH) Mooring[1]. The IMOS network contains a collection of mooring arrays in Australian coastal waters, but CCH is the only mooring station located in our model domain. It is located at 22.4095° S and 151.9928° E, about 250 km from the Styx River mouth. It has been operational since 2007. CCH current measurements were depth-averaged to allow a comparison with the 2D barotropic currents simulated by our model. Overall, model results agree well with the observations (Table 1), both for the sea surface elevation (RMSE = 22.9 cm, Figure 1) and the currents (RMSE = 6.5 cm/s and 26.5°, Figure 2).

TABLE 1 – Measures of Root Mean Square Error (RMSE), Mean Average Error (MAE) and bias for the sea surface elevation, the current amplitude and the current direction. The comparison of modelled and observed sea surface elevation are conducted on hourly measurements to take the tidal cycle into account, whereas the comparisons for the current variables are computed on daily averaged time series to explicitly remove much of the tidal signal and hence focus on the mean circulation.

	RMSE	**MAE**	**Bias**
Sea surface elevation [m]	0.229	0.173	0.0003
Current amplitude [m/s]	0.0651	0.0603	0.0545
Current direction [°]	26.46	24.10	-23.72

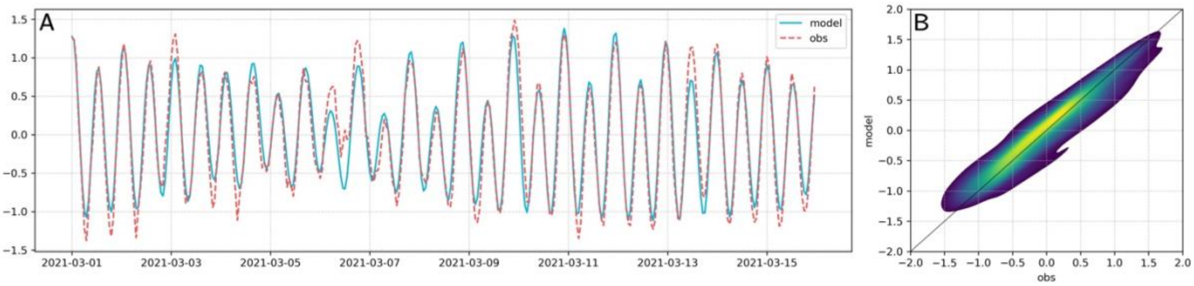

FIGURE 1 – Comparison of the observed and simulated sea surface elevation. The mean value of the time series was subtracted from all measures to obtain a signal with a zero mean in both cases. A: Subset of the observed and simulated sea surface elevation time series between March 1, 2021 and March 15, 2021. B: Density plot of hourly observed and simulated sea surface elevation for the entire simulated period.

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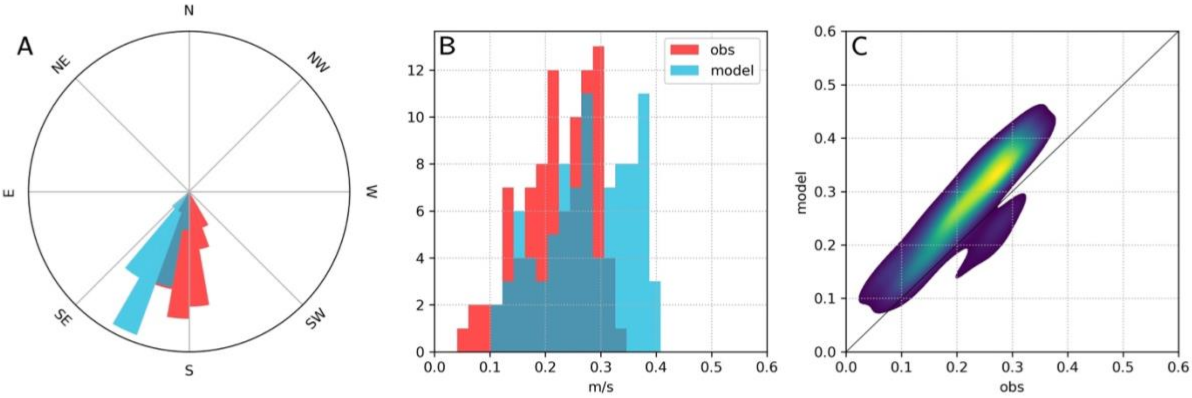

FIGURE 2 – Comparison of the observed and simulated currents. A: Histogram of daily current direction. B: Histogram of the daily current amplitude. C: Density plot of daily observed and simulated current amplitude.