

Environmental degradation of Townsville coast and coastal waters of the Great Barrier Reef, Australia – findings and solutions

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ARTICLE INFO

Keywords:

Coastal ecosystem
Erosion
Dredged spoil dumping
Coral reefs
Megafauna
Sustainability

ABSTRACT

The degradation of the Townsville coast and coastal waters of the Great Barrier Reef Marine Park ecosystem is severe. It involves, among several other symptoms, a large dam that traps riverine sand, land reclamation, extensive dredging, dumping of 400,000 m³/year of unconsolidated mud in coastal water, severe coastal erosion, sandy beaches turning muddy, healthy coral reefs turning to coral rubble, the decrease of water clarity of waters by 87 % since the 1960s, and a decrease of 80 % of the dugong population from 2016 to 2022. It is shown that this degradation is largely due to human activities on land and at sea. Climate change occurred later and is likely to impact mud and sand transport in the future. The degradation is still increasing because the management decisions suffer from the shifting baseline syndrome. For sustainable management, a holistic, ecohydrology-based approach is needed. It must involve all stakeholders and integrates hydrotechnical, biophysical and social approaches over the whole watershed including Magnetic Island, and all coastal waters. Several such solutions are proposed. These solutions may be applicable to all Queensland ports facing the Great Barrier Reef, as they all suffer from similar issues to various degrees.

1. Introduction

1.1. Background statement

The underlying assumptions and practices in coastal management have evolved greatly in the last 100 years. The coast has long been viewed by some as a structure that can be modified to man's wishes by engineering measures. Similarly, coastal waters have long been viewed as a vast body of water that can dilute all pollutants from human activities so much that they become harmless. They have also been viewed by others also as a living treasure with a rich ecology providing plentiful ecosystem services. For decades during the Industrial Revolution in Europe and America and in Japan, and still now in some developing countries, the environmental health of estuaries and coast was ignored (Elliott et al., 2019; Steven et al., 2020). As a result, the environmental problems keep growing. Coastal ecosystems worldwide are now fully enveloped in the Anthropocene inhabited by about 40 % of the human population, and subjected to enormous environmental issues (Wolanski et al., 2019; Reimann et al., 2023). As stated by the Sustainable Development Goals proposed by the United Nations Development Program, the coast needs to be properly managed for the future ([https://www.](https://www.undp.org/sustainable-development-goals)

[undp.org/sustainable-development-goals](https://www.undp.org/sustainable-development-goals)). However, worldwide there are divergent visions on what that management should be following conflicting imperatives driven by different economic, social and environmental visions. In practice it is still rare to find sites where solutions are implemented that effectively address the pressure from all human activities on the coast and in the river catchments. Such activities include land clearing and change to land use, dams on rivers changing the hydrology, seawalls, harbour dredging, dumping of unconsolidated dredged sediment, pollution, changes to species distribution, and the arrival of invasive species often brought by ship ballast (Elliott et al., 2019). There have been several recent attempts, with mixed results, to address such issues in several estuaries and coasts using ecological engineering (Elliott et al., 2016). These are complex problems to solve, and their solution may evolve under climate change (<https://www.eea.europa.eu/publications/how-climate-change-impacts>).

The science addressing these issues largely started with the publication of 'Limits to Growth' by Meadows et al. (1972). There were several other interpretations of the commonality of these problems in subsequent decades (e.g., https://en.wikipedia.org/wiki/The_Limits_to_Growth). These led to the birth of ecohydrology, a prototype for nature-based solutions (Zalewski, 2000, 2002). Ecohydrology considers

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<https://doi.org/10.1016/j.ecohyd.2025.100672>

Received 2 April 2025; Received in revised form 12 May 2025; Accepted 17 May 2025

Available online 30 May 2025

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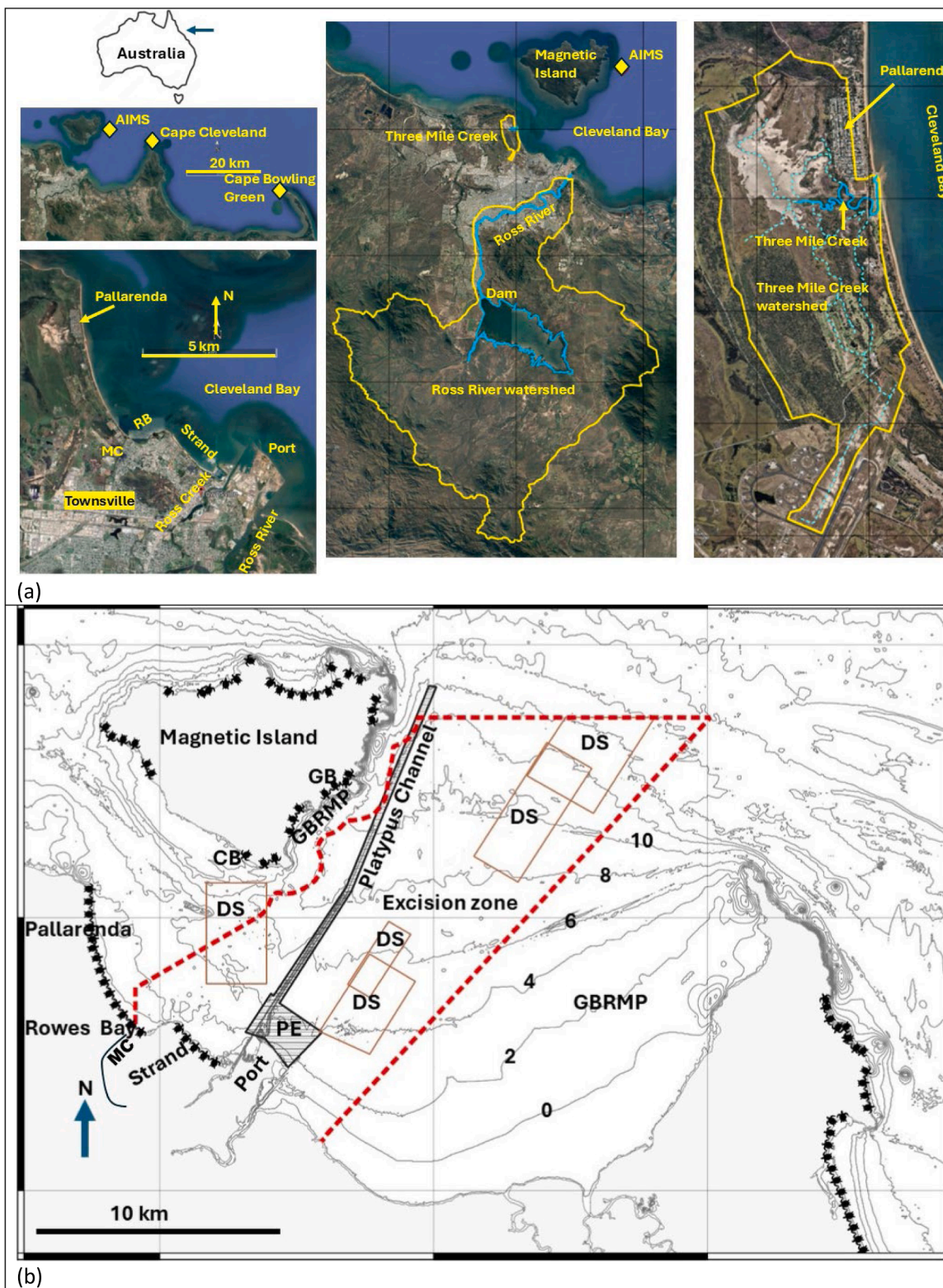


Fig. 1. (a) Location maps of Townsville, watersheds, coastal waters, the location of the weather stations (AIMS, Cape Cleveland, and Cape Bowling Green), and key sites. The white area landward of Pallarenda is a salt flat. (b) Map of Cleveland Bay showing the bathymetry (in m below lowest astronomical tide - LAT), the dredged shipping channel (Platypus Channel), the planned 2040 Port expansion (PE), the past and present dredged mud dumping sites (DS), and the excision zone from the Great Barrier Reef Marine Park (GBRMP). MC: Mundy Creek; CB: Cockle Bay; GB: Geoffrey Bay. The turtle icons show the sea turtle nesting beaches.

the ecosystem properties and their resilience at the broad scale of the river catchments, the estuary, the coast and coastal waters, together with the impact of human activities, including hydrotechnical infrastructure. It explicitly aims at reversing the degradation of water quality

and ecosystem health at the basin scale. The problems and solutions vary worldwide from coast to coast and are complicated by legacy issues of decades, even centuries in some cases, of haphazard developments (Elliott et al., 2019). In some cases, such as Tokyo Bay, these issues are

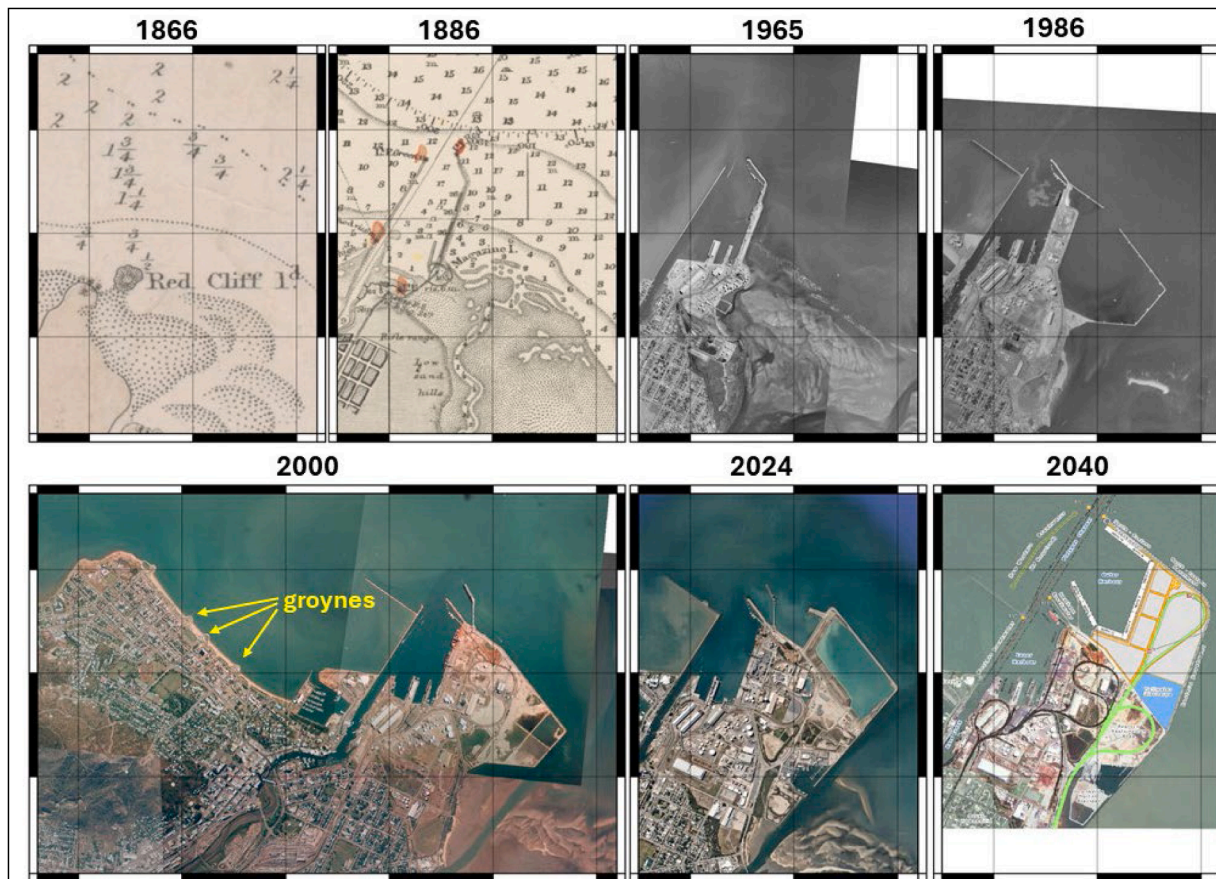


Fig. 2. The growth of the Port of Townsville from 1866 to 2024 visualised from maps, aerial photographs, and (Jones et al., 2020) the future development plan for 2040.

addressed vigorously but with limited success due to 95 % of its intertidal wetlands having been reclaimed (Furukawa and Okada, 2006; Furukawa et al., 2019; Tokunaga et al., 2020). In other cases, economic development centred on harbours still prevails at the explicit cost of environmental degradation (e.g., the Changjiang and Pearl estuaries, Ho Chi Minh City and Jakarta Bay; Wolanski, 2006). A common problem in all coastal development projects is the *shifting baseline syndrome* whereby “the accepted thresholds for environmental conditions are continually being lowered in the absence of past information or experience with historical conditions” (Soga and Gaston, 2018).

Australia also suffers from this legacy issue (Wolanski and Ducrottoy, 2014). In this paper, we present the case of the Townsville coast and coastal waters of the Great Barrier Reef (GBR) in tropical northeast Australia (Fig. 1). Until the 1960s, it had pristine sandy beaches, extensive seagrass meadows, a water clarity of 8 m in the bays of Magnetic Island, rich coral reefs with no mud in those bays, and healthy populations of charismatic megafauna including dugongs and sea turtles, as discussed later. However, all these are now severely degraded due to human activities on land and at sea. The situation is inherently complex because the ecosystem is inherently morphologically diverse, highly dynamic, and subject to pervasive anthropogenic impacts. There is a management plan in place to mitigate these impacts. However, the ecosystem is still rapidly degrading. Thus, the present management practices appear unsustainable in the long term, and a new management strategy is needed.

1.2. Research objectives

In this paper, firstly, we quantify the environmental degradation and its links with biophysical processes. Secondly, we quantify the impact of

climate change on the physical environment, such as the wind and the rainfall, and we compare it with the natural variability. Thirdly, we synthesise the data to quantify how urbanisation and industrialisation - including the growth of the Port of Townsville - have degraded the environmental health of these waters. We then show that climate change did not contribute to this degradation, but it may be starting to have an impact on the environment. Finally, we suggest that this degradation could be halted and partially reversed using a holistic, ecohydrology-based approach to basin, coast and coastal water management.

2. Site description

Townsville is a city located on Australia’s east coast at 19.25°S. The urban area is concentrated along the coast (Fig. 1). The Ross River drains an area of 1707 km². Its delta has two channels, namely the mangrove-fringed Ross River and Ross Creek (Fig. 1a). There is also a small creek, Mundy Creek, which drains Castle Hill and the small wetlands of Rows Bay, and an extensive mangrove-fringed estuary, Three Mile Creek, with extensive salt flats that are only flooded at spring tides. The Ross River flows in Cleveland Bay. Two weirs for storing water were constructed in the Ross River: Aplin’s Weir in 1929, and Black Weir 1935. A dam was also built in 1972 on the Ross River, creating a large reservoir, which is used both for water supply and flood mitigation. The Ross River is very turbid during floods (Lewis et al., 2008). The only other large river that could impact Cleveland Bay is the Burdekin River, located 80 km away to the southeast. The Burdekin River plume is highly diluted by the time it reaches Cleveland Bay, and its inflow of fine sediment is small because much of the sediment has settled out in transit (Bainbridge et al., 2012; Delandmeter et al., 2015). On the eastern side of Cleveland Bay, there are a number of small creeks that are still in a natural to semi-natural



Fig. 3. Historical aerial images of Mundy Creek from 1942 to 2024; photographs of (top right) the 2 m high sand cliff with no beach before beach nourishment and (bottom right) 2 weeks after beach nourishment, showing toe erosion at the bottom and slumping on top. Photos courtesy of the Queensland Government, Bruce Muller and EW.

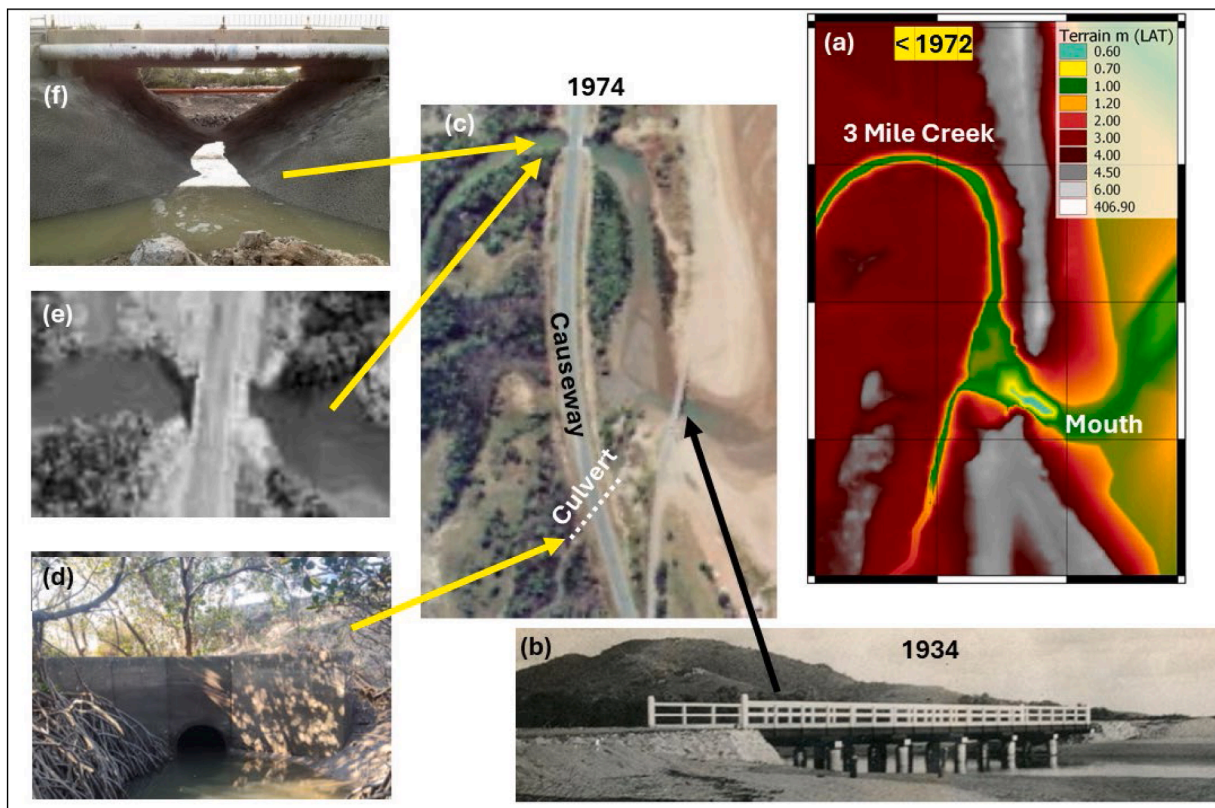


Fig. 4. (a) The pre-1970 topography of the two creeks that drained the Three Mile Creek watershed shown in Fig. 1 with the elevation in m above LAT datum. (b) The original bridge at the mouth of these two creeks; this bridge was later removed. (c) The causeway built in 1972 over the tidal wetlands and the two creeks. (d) The 1 m diameter culvert built under the causeway, replacing the original 5–8 m wide natural channel. The narrowing of the creek by (e) the footing of the bridge on top, and (f) the V-notch weir under the bridge.

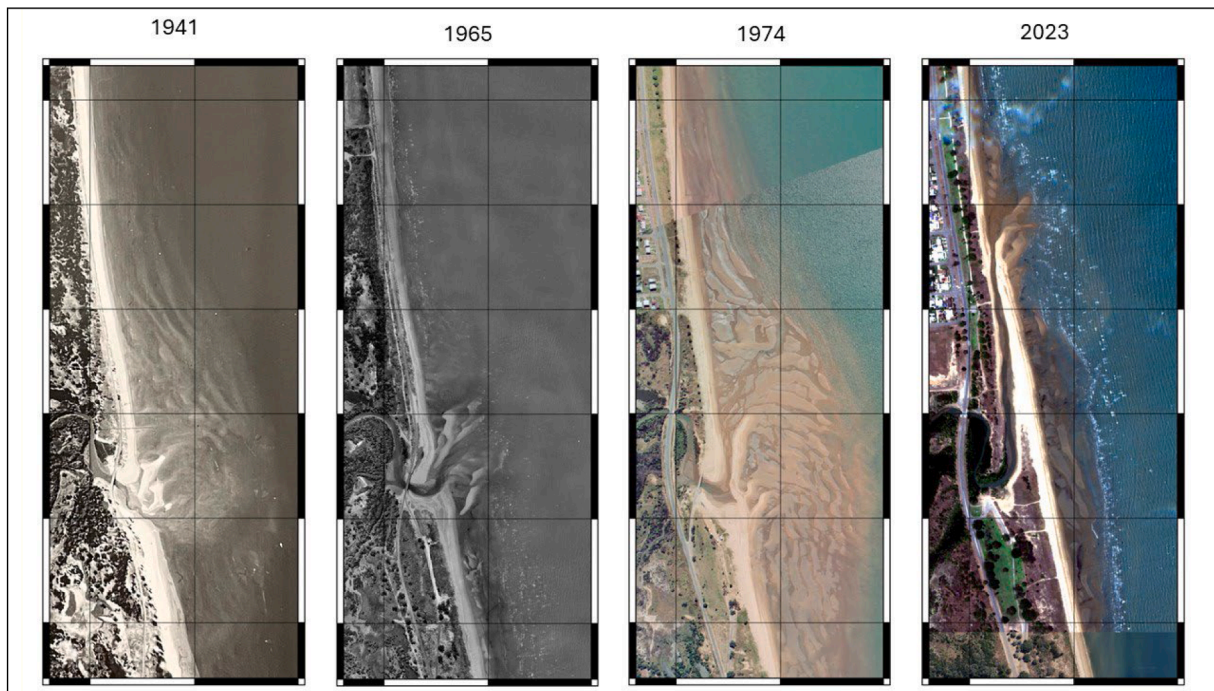


Fig. 5. Georeferenced aerial images of the fan delta of Three Mile Creek in 1941 and 1965, and of the sand spit in 1974, and a SkySat image on 10 November 2023.

state; one of them drains a large Zinc refinery that however prides itself on reusing all stormwater and its own wastewater as well as using recycled city water (<https://www.sunmetals.com.au/sustainability/environment/>). There are two other refineries in the catchments around Townsville with a less glowing environmental record.

Cleveland Bay historically had a rich ecosystem, albeit occasionally severely disturbed by tropical cyclones. In the 1960s, the bays in Magnetic Island were coral-rich with no mud, and the coral reefs were described as equal to anything that could be seen in the clear waters of the outer reef (Brown, 1972). At that time, the water clarity was routinely 8 m. The beaches were sandy and apparently stable (<https://trove.nla.gov.au/newspaper/article/1280417>; Mabin, 2002). The seagrass beds may have been much more extensive in the 1960s than at present due to much clearer water than now (Brown, 1972; Wooldridge, 2017). Cleveland Bay was the most important area for dugongs in the central GBR (Cleguer and Marsh, 2023; Marsh and Cleguer, 2024), with a population of 1171 (\pm se 423 dugongs) in 2016. There is hearsay evidence and newspaper articles from 100 years ago that sea turtles were much more abundant than at present, supporting recreational and commercial sea turtle fishing (e.g., <https://trove.nla.gov.au/newspaper/article/58126067>; <https://trove.nla.gov.au/newspaper/article/61706389?searchTerm=turtle%20townsville>; <https://trove.nla.gov.au/newspaper/article/181830921?searchTerm=turtle%20townsville>), and that many beaches in Cleveland Bay may have been turtle nesting beaches (Fig. 1b). At present, there may be only 5 to 15 clutches laid a year in all the beaches of Cleveland Bay, including Magnetic Island (M. Hamann, pers. comm.).

The Port of Townsville (PoT) is centred on Ross Creek. It had no seawalls before 1866, and it grew slowly until the 1970s (Fig. 2). Since then, The PoT has grown very quickly and it will grow even faster in the future, basically doubling its seaward footprint by 2040. The PoT maintains a shipping channel, Platypus channel, across Cleveland Bay that cuts through a large area excised from the Great Barrier Reef Marine Park (GBRMP; Fig. 1b). About 400,000 m³ year⁻¹ of unconsolidated dredged mud from the maintenance dredging is dumped in Cleveland Bay at sites that changed over time and are shown in Fig. 1b Initially the dumping site was between Townsville and Magnetic Island, and later it was between Magnetic Island and Cape Cleveland (Fig. 1b, Pringle et al.,

1996). The dumped dredged mud is unconsolidated and thus it is resuspended during strong winds (Wolanski et al., 1992). Annual bathymetric surveys show no long-term accumulation of mud at the dump sites. Thus, all the dumped mud is exported away from the dump sites after one year, and nobody has yet investigated where it goes. Esslemont et al. (2004) found, using chemical tracers, that the metal-rich mud dredged from the PoT and dumped in Cleveland Bay reaches the corals of Magnetic Island. There have been no other studies of the fate of that dumped dredged mud. The environmental impact studies of dredging have all focused on the fate of the mud (< 10 % the amount of dredged mud dumped in Cleveland Bay) resuspended by dredging, which muddies the water around the dredger (Wolanski and Gibbs, 1992; Kettle et al., 2018; Jones et al., 2020; <https://platogbr.com/natural-versus-dredge-sediment>).

In 1942 and 1961, the beach off Mundy Creek was wide and gently sloping, and it had a small sand spit at the mouth (Fig. 3). At that time, the beach was not eroding; in fact, it gained 88,000 m³ of sand from 1938 to 1952 (Mabin, 2002). At present, it is eroding and it forms a sand cliff. It is nourished yearly with sand (\leq 17,500 m³ year⁻¹) and all that sand is swiftly eroded away (Fig. 3).

The Three Mile Creek watershed had two creeks that merged at the mouth (Fig. 4a). There was a bridge over the mouth of the creek, but its design did not significantly interact with the tidal flows (Fig. 4b). In 1972, a causeway was built across the tidal wetlands and the two creeks of Three Mile Creek (Fig. 4c). The small creek to the south, 5–8 m in width, was replaced by a circular culvert 1 m in diameter (Fig. 4d). Three Mile Creek itself was left as an open channel, but at the bridge the width of the creek on top was halved by the footing of the bridge (Fig. 4e). Below the bridge, the width of the creek was further reduced by a V-notch (Fig. 4f). For over 100 years (from 1866 to 1972), the tidal outflow from Three Mile Creek interacted with the water currents and the dynamics in shallow coastal waters to created a stable sandy fan delta at the mouth of the creek (Animation 1; Fig. 5). After 1972, the fan delta changed to a sand spit hugging the coast.

3. Methods

Monthly rainfall data were provided by the Commonwealth Bureau

of Meteorology (BoM) at the Townsville Pilot Station for 1871–1950, and at the airport for 1941 to 2023. These were combined to form one continuous time-series. Wind data in Cleveland Bay (2000–2023) and Cape Bowling Green (1988–2021) were provided by the Australian Institute of Marine Science (AIMS), and at Cape Cleveland (1957–1987) by the BoM. Water temperature data at 1 m depth at the AIMS weather station in Cleveland Bay were provided by AIMS. A fourth weather station with wind data exists at the Townsville airport; these data were not used because they are aliased by the wind shadow behind Castle Hill. Mean sea level data at the coast were provided by the Permanent Service for Mean Sea Level. Two Hobos loggers logging water level data at 10 min interval were deployed in Three Mile Creek from June 2 to July 8, 2024, in the dry season, at sites 1 and 2 shown in Figure S1. These loggers were deployed again in Three Mile Creek from December 11, 2024, to March 9, 2025, in the wet season, at sites 2 and 3 shown in Figure S1, logging data at 1 hr interval. These water elevation data were corrected for the atmospheric pressure fluctuations, data for which were provided by the BoM. Their datum was set to the lowest astronomic tide (LAT) using a RTKGPS unit with a vertical accuracy of < 10 cm.

Historical maps and aerial pictures of the coast were provided by the Queensland Government and the Townsville City Council (TCC). Other images were obtained from Google Earth, Landsat and Skysat satellites, and from a drone flown frequently over the Pallarenda coast in 2023 and 2024. From these images and our GPS data, the length sand spit at the mouth of Three Mile Creek was measured. The volume of sand in the sand spit was quantified from the GPS data by collecting XYZ point data with a RTKGPS to create a Triangulated Irregular Network (TIN) raster using the linear method in QGIS. A Raster surface volume calculation was then performed to calculate the volume of sand. We collected all the available topographic data to reconstruct the topography of the terrain of the Three Mile Creek watershed pre- and post-bridge. For modelling the hydrodynamics of that creek for these different historical topography we used the HECRAS 6.5 2D hydrologic model (<https://www.hec.usace.army.mil/software/hec-ras/download.aspx>).

The large-scale sand dynamics in coastal waters of Cleveland Bay were modeled following Wolanski and Hopper (2022). Thus, the unstructured grid numerical model SLIM of Lambrechts et al. (2010) was used for the oceanography, with the addition of a wind shadow effect behind Magnetic Island and the hill at Kissing Point. The numerical mesh was that of Wolanski et al. (2024a). These current data together with the wave-ride buoy data of Lambrechts et al. (2010) were used to calculate the bed load transport of sand following Borsje et al. (2013). The model was verified against the sand export data offshore from the Strand beach of Muller et al. (2006).

For modeling the small-scale morphology of the sand in the shallow coastal waters off Pallarenda and Three Mile Creek, the finite-difference hydrodynamic model of Falconer et al. (1986) was used. The model domain extended 1000 m seaward and 2000 m longshore both northward and southward of the mouth of Three Mile Creek. The wave amplitude and period were taken from TPL (2020). The open boundary conditions were the SLIM model predictions of water level and currents. The HECRAS-predicted discharge at the mouth of Three Mile Creek for pre- and post-bridge scenarios was forced as a lateral inflow in the hydrodynamic model. The sand transport model of Borsje et al. (2013) was used and every half hour the bathymetry was changed by calculating the difference between sand erosion and deposition over every cell. This generated a continuous feedback between the hydrodynamics and the sand transport. The initial condition of the bathymetry was a smooth, linearly sloping seafloor starting at 1 m depth at the coast, with a 1 m deep rectangular opening at the coast representing Three Mile Creek.

The likely fate of the dumped dredged mud was predicted for a steady 10 m s^{-1} southeasterly wind for 48 hr with the model of Lambrechts et al. (2010). The dumped dredged mud was assumed to swiftly settle down on the seabed following spoil dumping as per the observations of Wolanski and Gibbs (1992). That settled mud was unconsolidated and it was resuspended during strong winds as per the observations

of Wolanski et al. (1992). At the same time, it was assumed that the underlying mud, being consolidated, did not resuspend during this moderate wind forcing, as opposed to the cyclonic wind forcing used by Lambrechts et al. (2010).

4. Results

4.1. Environmental degradation

4.1.1. Beach erosion

The Ross River dam and the PoT's seawalls have starved the coast of sand (GHD, 2021). The Strand is the first beach 'downstream' of the mouth of the Ross River. It eroded severely post-dam, and in 2000 it was successfully stabilised by groynes (see the 2000 image in Fig. 2). In 1961, work had commenced on diverting Mundy Creek northward by dredging a canal. In 1965, Mundy Creek was fully diverted to the canal that was open to the sea. Following that, the coast eroded severely, resulting in a sand cliff and no beach, while mangroves colonised the old sand delta in Rows Bay (Fig. 3). The Pallarenda coast north of the mouth of Three Mile Creek and behind the sand spit started eroding severely in 2020. Sand cliffs developed in late 2022 and they are still moving landward (Figure S3a).

4.1.2. Simultaneous formation of a sand spit and beach erosion

The outflowing tidal currents at the mouth of Three Mile Creek were reduced in 1972 by a causeway and a bridge over Three Mile Creek (Fig. 4). At the same time, the coastal waters still received legacy sand from Cleveland Bay (about $12,000 \text{ m}^3 \text{ year}^{-1}$; Figure 6; Muller et al. (2006)). The reduced peak tidal outflow interacted with this sand supply to form a sand spit (see the 2023 image in Fig. 5). This sand spit grew steadily after 1972 (Animation 1) and its growth accelerated after 2020 (Fig. 7 bottom).

This sand spit appears stable and unaffected by river floods. The reason for that is the hydrodynamics. The sand spit created a shoal near the new mouth (Figure S1). This shoal and the narrowing of Three Mile Creek at the bridge ponded the creek near mid-tide elevation (Figure S2a). This ponding prevented the outflowing tidal currents to become large enough to breach the sand spit. This stability even occurred during a severe flood event. Following an intense rainfall event in February 2025 (761 mm over 4 days), ponding occurred in the creek and its salt pans. Water was trapped in the salt pans and slowly released during 14 days (Figure S2b). Pre- and post-flood satellite images of the sand spit reveal no apparent changes to the sand spit (not shown). It is stated in the engineering literature that a sand spit protects the coast by inhibiting wave erosion. However, in the case of Three Mile Creek, the coast behind the sand spit is eroding and has become a sand cliff (Figure S3a). The reason is that the peak tidal currents in the creek between the sand spit and the coast are large enough (we measured 0.7 m s^{-1}) to erode the steeply inclined coast in the absence of waves.

The resulting impact of these changes in Three Mile Creek on the Pallarenda coast was evaluated by modeling. Our hydrodynamic model of Three Mile Creek was successfully verified (Figure S2a) for the present topography against the water level data at sites 1 and 2. The tidal dynamics of Three Mile Creek are complex and controlled by small scale processes (Animation 2). The predicted tidal currents at the mouth of Three Mile Creek with/without the bridge and causeway were used as lateral inflow in our small-scale oceanography-sand dynamics model. That model predicted a fan delta for the pre-bridge scenario and a sand spit for the post-bridge scenario (Fig. 8). The comparison between the observed and predicted shapes of the coast is pleasing. Indeed, the shape of the predicted fan delta in Figure 8 α resembles the observed shape in 1941 in Fig. 5, the shape of the predicted fan delta in Figure 8 β resembles the observed shape in 1965 in Fig. 5, and the shape of the predicted sand spit in Figure 8 γ resembles the observed shape in 2023 in Fig. 5.

4.1.3. Wetland reclamation

There are several bridges over the Ross River, and another bridge over the estuary is presently under construction by the Transport and Main Roads Queensland (TMRQ; Figure S3b). The braided channel has been reduced to one narrow channel, small tidal creeks in the fringing tidal wetlands have been blocked, and part of the wetland was destroyed.

4.1.4. Dredging and spoil dumping

We attempted to predict where that unconsolidated dumped dredged mud goes. During calm weather and a South Equatorial Current of 2 Sverdrup in the Coral Sea, the currents between Townsville and Magnetic Island are tidal and weak (Animation 3 for a spring tide). In that animation, the colour bar is the scale of the current in m s^{-1} , 'bath' is the depth in m below LAT – Lowest Astronomical Tide). For a 10 m s^{-1} southeasterly wind, a strong net northward longshore current prevails, modulated by the tidal currents (Animation 4). We used these findings to predict the fate of the dumped mud. That mud is not consolidated, and it may take months to a year to fully consolidate. Thus, it is easily resuspended during windy days. By contrast, the underlying substrate is highly consolidated and hard to resuspend (Mehta, 2013; Meshkati Shahmirzadi et al., 2015). The oceanography-mud model suggests (Animation 5) that the mud has travelled in 48 h around Magnetic Island and over the seagrass meadows 1, 2 and 3. Seagrass meadow 4 is not impacted. These model predictions explain the findings of Esslemont et al. (2004) that the metal-rich mud dredged from the PoT and dumped in Cleveland Bay reaches the corals of Magnetic Island.

4.1.5. Riverine mud

The Ross River typically has one to four floods a year. There are no floods in some years. The largest flood on record occurred in 2019 at $1888 \text{ m}^3 \text{ s}^{-1}$. These floods last typically about a week. There can be years with no floods. There were four floods in 2008, with peak flows of $400 - 600 \text{ m}^3 \text{ s}^{-1}$. 2008 was thus an exceptional year with a riverine fine sediment (mud) discharge of 26,500 tonnes (Lewis et al., 2008). Assuming a sediment density of 1.8, this equates to $47,700 \text{ m}^3$, i.e., about 12 % the amount of dredged mud dumped in Cleveland Bay. Ross River floods commonly occur during strong winds with an easterly component, resulting in the river plume spreading longshore northwards along the coast of Townsville (Fig. 9a and b), as was also observed for the 2006/2007 flood by Liessmann et al. (2007). The satellite data showed only one instance when the river plume was advected slightly offshore, towards the south coast of Magnetic Island (Fig. 9c). This was due to an unusual rotating wind event. We found no evidence in the satellite data of the Ross River plume spreading along the eastern shore of Magnetic Island, where most coral reefs occur, or eastward towards Cape Cleveland. Our model predicts that the riverine suspended fine sediment commonly deposits slightly offshore and west of the PoT (Animation 6). The findings of Lambrechts et al. (2010) support this prediction.

4.1.6. Water clarity and coral reef die-off

The historically sandy beaches on the south coast of Magnetic Island have turned to muddy mangrove habitats (Fig. 10a). The healthy coral reefs in bays on the east coast of Magnetic Island have mostly become coral rubble (Brown, 1972; Fig. 10b). Water clarity has decreased from an average of 8 m in 1961–1965 to 2 m in the 1970s (Brown, 1972), and 0.7–0.85 m nowadays (DES, 2009). This coral die-off cannot be attributed to climate change increasing the water temperature. The coral reefs of Magnetic Island experienced annually stressful water temperature and they did bleach in 2002 (Figure S4; Berkelmans et al., 2004). However, these authors found that the coral reefs had recovered by 2004. Cyclone Yasi in 2011 physically destroyed these reefs and they have not recovered, likely because these legacy reefs have lost their resilience by being constantly in turbid waters (Jones et al., 2016).

4.1.7. Charismatic megafauna

Cleguer et al. (2023) reported an 80 % reduction in the estimated number of dugongs found in Cleveland Bay from 2016 to 2022, i.e., $1171 \pm \text{se } 423$ dugongs in 2016, and $228 \pm \text{se } 135$ dugongs in 2022. From 2014 to 2017, green turtles had health issues associated with poor water quality (Brodie et al., 2014), some were associated with a suite of trace elements, in particular cobalt (Flint et al., 2019). The high metal levels in Cleveland Bay turtle blood affected their eyes. 9 % of the green turtles in Cleveland Bay suffered from eye deformities from 2014 to 2018, but only 0.2 % of the green turtles in a pristine environment in the northern GBR, a clear indication that the bay was polluted (Bell et al., 2019).

4.1.8. Seagrass

The seagrass meadows of Cleveland Bay have been mapped yearly since 2007 (Taylor and Rasheed, 2009; PTL, 2020; Zabarte-Maetz et al., 2021; Flowers et al., 2024). The seagrass meadows are found most commonly in the lower inter-tidal and shallow sub-tidal areas of depth less than about 2 m. There are four main seagrass meadows, shown in Fig. 9a. The dominant species include *Halophila ovalis*, *Halodule uninervis*, *Zostera muelleri*, and *Cymodocea serrulata*. The reef flats surrounding Magnetic Island support small areas of *Thalassia hemprichii*. In some years, seagrass meadows in deeper waters were found, but not in other years; these are ephemeral meadows. The coastal seagrass meadows no 2 and 3 are directly in the path of the Ross River plume during most floods (Figs. 9a and b) and the seagrass meadow no 1 on the south coast of Magnetic Island was in the path of the 2019 flood plume (Fig. 9c). We found no evidence in the satellite data of the Ross River plume ever reaching seagrass meadow no 4. The extent of seagrass meadows no 1 to 3 varied greatly interannually. They both vanished in 2011 after cyclone Yasi and they slowly recovered in the following years, while seagrass density has not yet recovered (McKenna et al., 2020). In contrast, the seagrass meadow no 4 was reduced in size by cyclone Yasi in 2011, but it did not vanish, and it had largely recovered a year later.

4.1.9. Flooding risks

Following heavy tropical rains, the bridge and the shoal between the coast and the sand spit are choking the seaward outflow of runoff water from the watershed. This is raising the flood level and the flood risk for Pallarenda. This risk was assessed by using the Three Mile Creek hydrodynamic model to estimate the flood level in the salt pans around Pallarenda. This was done for the 2019 rainfall event and the tides at that time for the pre-bridge topography, for the post-bridge topography of 1976, and for the 2024 topography. The model suggests (Fig. 11) that the flood level would reach 3.45 m LAT for about 1 hr for the pre-bridge topography, 3.56 m LAT for a few hours for the post-bridge topography, and 4.3 m LAT for four days for the 2024 topography. In 2019, the flood level around Pallarenda in 2019 reached a peak of 3.7 m LAT on February 2 (M. Higgie, pers. comm.). Thus, the growth of the sand spit and its associated shoal at the mouth between has raised the flood level for Pallarenda by 0.85 m from 1972 to 2024, and 0.6 m from 2019 to 2024.

4.2. Climate change

The yearly rainfall in Townsville varied at decadal time scales, between a maximum of $2482 \text{ mm year}^{-1}$ and a minimum of 211 mm year^{-1} (Figure S6). From 1885 to 2023, there was no significant increase or a decrease of either the ten-year averaged monthly rainfall (trend = $-0.11 \text{ mm year}^{-1}$; $R^2 = 0.001$) or the ten-year averaged mean annual rainfall (trend = $-0.32 \text{ mm year}^{-1}$; $R^2 = 0.0036$). Intense rainfall occurred mainly in the wet season (January to March), with a maximum monthly rainfall of $1141 \text{ mm month}^{-1}$. There is some evidence that climate change may increase the intensity of strong cyclones in the GBR, but the data for Cleveland Bay is inconclusive (Duke et al., 2024).

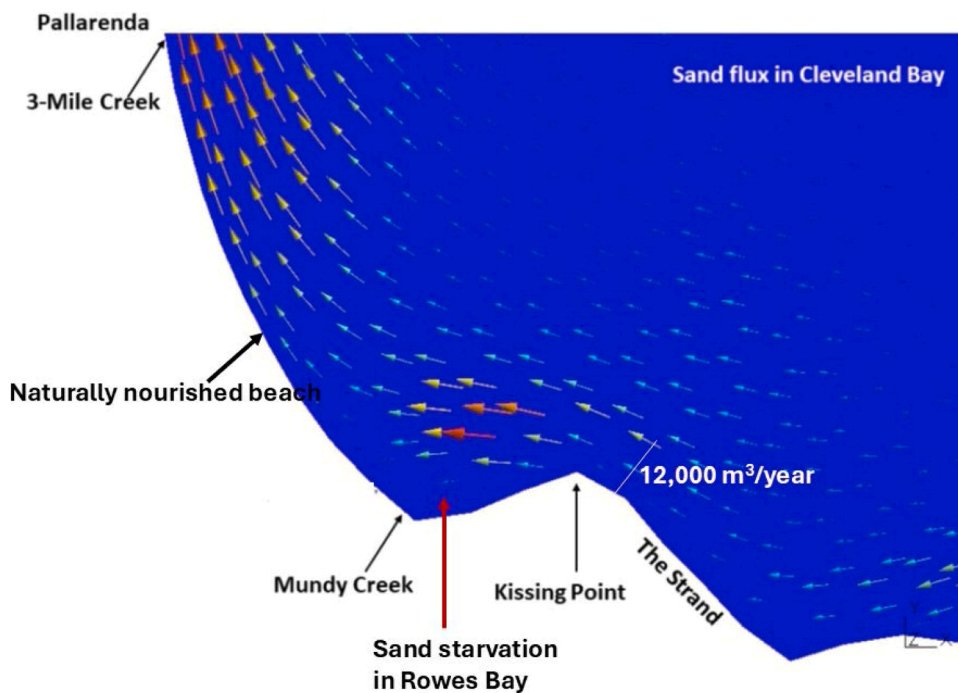


Fig. 6. The predicted annual sand flux in the shallow coastal waters of Cleveland Bay from the Strand to Pallarenda. The arrows represent the sand flux in $\text{kg m}^{-1} \text{day}^{-1}$. The $12,000 \text{ m}^3 \text{ year}^{-1}$ label is the measured sand flux (Muller et al., 2006).

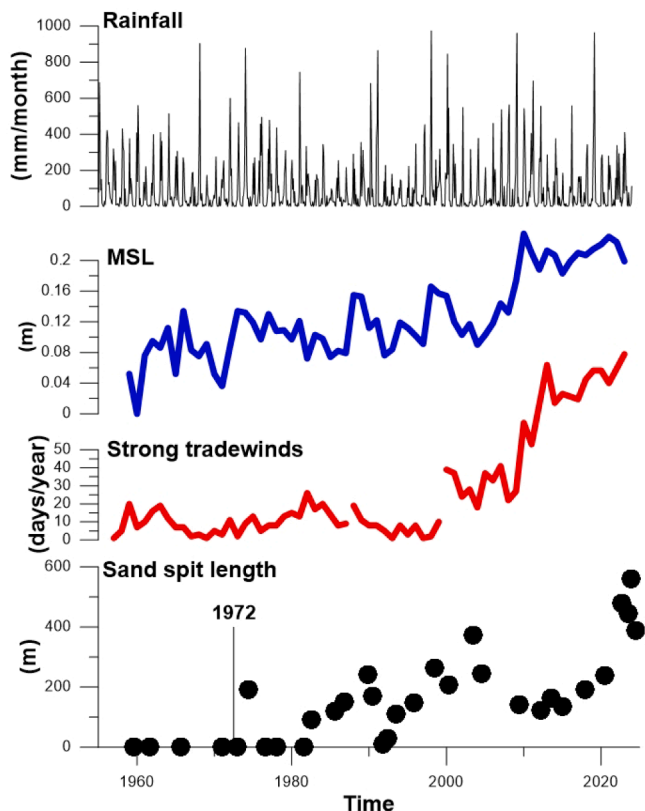


Fig. 7. Time-series plot from 1957 to 2023 of the monthly rainfall, the yearly-averaged mean sea level in Townsville (MSL), the number of days per year of strong southeasterly winds at Cape Cleveland (1957–1987), Cape Bowling Green (1988–1999) and at the AIMS weather station in Cleveland Bay (2000–2023), and the length of the sand spit at the mouth of Three Mile Creek.

The 1957–2023 mean sea level (MSL) and wind data reveal a 0.2 m rise in the MSL in the last 60 years, and a large increase of the number of windy days per year, but only in the last 20 years (Fig. 7). Cleveland Bay is commonly windy, with the dominant wind being the southeasterly trade wind (Figure S5a). A 10 m s^{-1} wind occurred frequently and more frequently in the last 20 years

(Figure S5b). The water currents in Cleveland Bay are controlled by the tides, the wind and the inflowing South Equatorial Current in the Coral Sea (Wolanski et al., 2024b). In view of increasing wind (Figs. 7 and S6), these stronger longshore northward currents have now become more common in recent years.

5. Discussions

Human activities historically and possibly climate change in recent years have greatly degraded the coast and coastal waters of Townsville. In turn, this degradation has socio-economic and environmental implications. The reasons for the decrease of megafauna in Cleveland Bay have not been investigated. It has been suggested that it could be due to increased turbidity, to boat traffic that results in boat strikes, to alienating dugongs from suitable habitat due to underwater noise, and to harassment preventing dugongs accessing intertidal seagrasses accessible only at high tide (Marsh and Cleguer, 2024). The population of nesting turtles is not known. It is also threatened by boat strikes causing mortality (<https://eisdocs.dsdip.qld.gov.au/Townsville%20Port%20Expansion/AEIS/chapter-08-marine-ecology.pdf>). The finding in 2014–2018 of eye deformities in the green turtles suggests that Cleveland Bay was polluted. However, there was apparently no search for the source of that pollution and no remediation measures were implemented to address that issue.

The erosion of the beach at Rows Bay makes it largely inaccessible for the residents. This erosion started following the diversion of Mundy Creek (Fig. 3). It may be exacerbated by urbanisation that has paved much of the lower slopes of Castle Hill, which hinders the provision of sand to the creek. For the last 13 years, the TCC sand nourished this eroding beach every year. Every year, that sand is swiftly eroded away. The stretch of beach from just North of Rows Bay to Three Mile Creek is

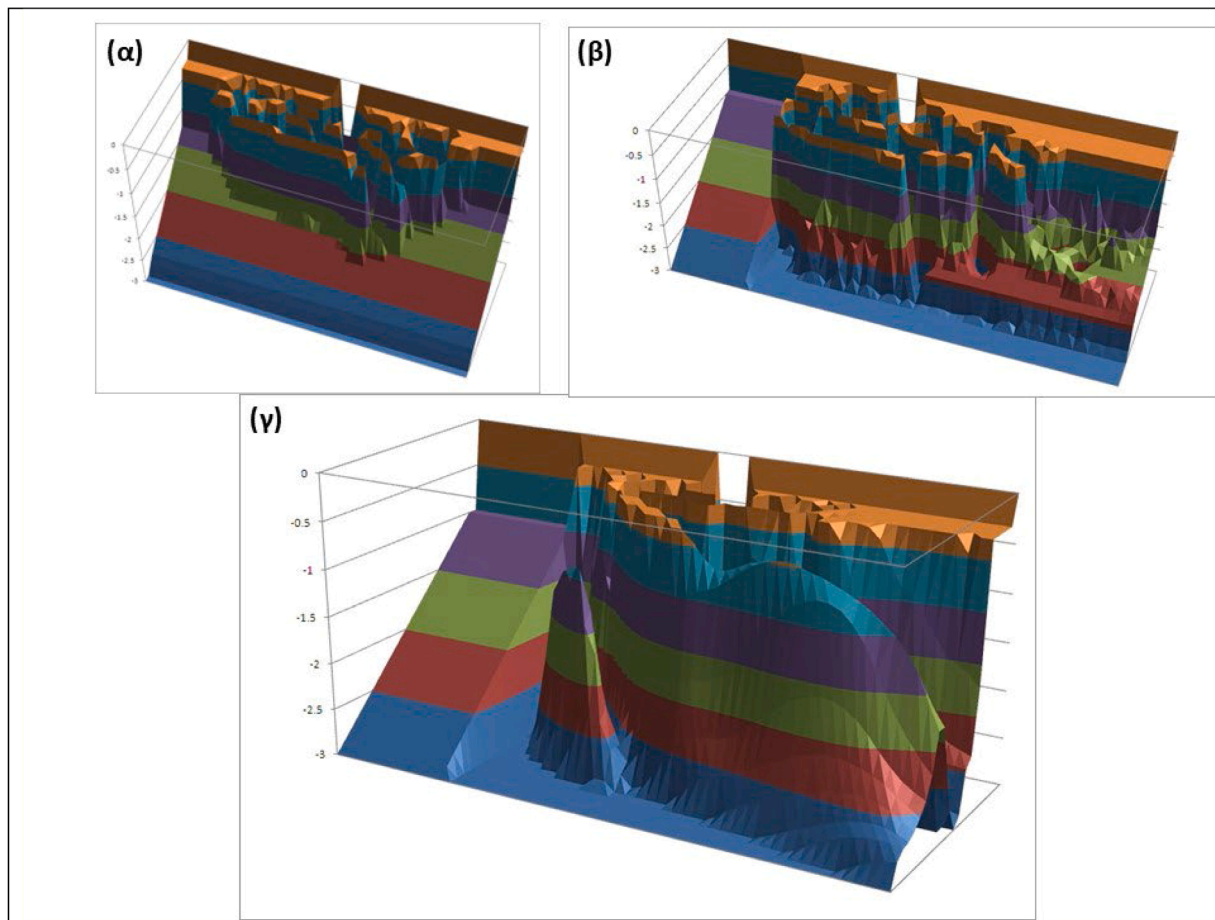


Fig. 8. Model predictions of a fan delta for no wind (scenario α) and for an average tradewind (scenario β) for the pre-bridge situation, and of a sand spit (γ) for the post-bridge situation and an average tradewind.

not eroding, a finding that supports our model predictions that this beach is nourished with legacy sand from further east (Fig. 6). Our sand transport model suggests that the sand eroded from Rows Bay ends up in Pallarenda in 1–3 months during trade winds.

Our modelling suggests that the dramatic changes of the coast at Pallarenda were also caused by human activities. Recreating a fan delta at the mouth of Three Mile Creek would restore the beach and enable the quality of life that the people looked for when settling there. There is another need for that restoration effort, namely flood prevention for Pallarenda. As shown in Fig. 11, the growth of the sand spit and its associated shoal at the mouth has raised the flood level for Pallarenda by 0.85 m from 1972 to 2024, which is significant enough to consider when planning a flood prevention strategy.

Jones et al. (2020) found a high water turbidity near the dredged channel following dredging. The PoT interpreted this turbidity as minor compared to ‘normal’ historical values assumed to be due to wind and riverine runoff (PTL, 2020). However, that ‘normal’ did not refer to pre-dredging years; it referred to post-dredging years. The increase in water turbidity occurred after dredging and spoil dumping started in the 1970s. This is the shifting baseline syndrome. The waters around Magnetic Island were very clear in pre-dredging years (Brown, 1972). Further, the riverine mud is not the cause either of the present high turbidity around Magnetic Island because it does not reach the island (Animation 6). The figure that emerges is that the dumping of unconsolidated mud is likely responsible for the high turbidity around Magnetic Island (Animation 5).

There is no evidence to suggest that climate change is measurably impacting the rainfall and the cyclones in this area (Figure 7; Duke et al., 2024). The increase in the MSL is small but it may start to impact the

beach dynamics and the tidal dynamics in the wetland-fringed Ross River estuary, Mundy Creek, and Three Mile Creek. The increase in the number of windy days occurred post-2000, and it is now large enough to start to impact the transport of sand and mud in Cleveland Bay. Thus, climate change may start to impact the biophysics of Cleveland Bay.

6. Conclusion and management recommendations

The environment of Cleveland Bay is severely degraded. Cleveland Bay has clearly joined other regions of the GBR that have been degraded by mud from human activities, such as the inner shelf of the central GBR with a decreased water clarity in much of in the dry season (Fabricius et al. 2014), the halving of the secchi disk visibility in the dry season at Lowes Isles from 1928 to 1990–2003 (Wolanski et al., 2004), and the transformation of the Cairns city beach from sandy to muddy from 1897 to 1999 (Wolanski and Duke, 2002).

Townsville beaches are all suffering from erosion, likely due to sand trapping by the Ross River dam starving the coast of sand, by the PoT’s seawalls, and by engineering modification of Mundy Creek at Rows Bay and Three Mile Creek at Pallarenda. A nature-based solution to this problem for Rows Bay is to trap the sand on the beach after beach nourishment by building two groynes, one near the mouth of Mundy Creek, and one at the northern end of Rows Bay. This would create a stable beach that the local community can access. A nature-based solution for the coastal and flooding problems of Pallarenda would be to restore what was there before 1972, i.e., before the human impact. This will require engineering works to the Three Mile Creek bridge and the culvert under the causeway to restore the natural tidal flows. It will also require cutting a channel through the present sand spit where the mouth

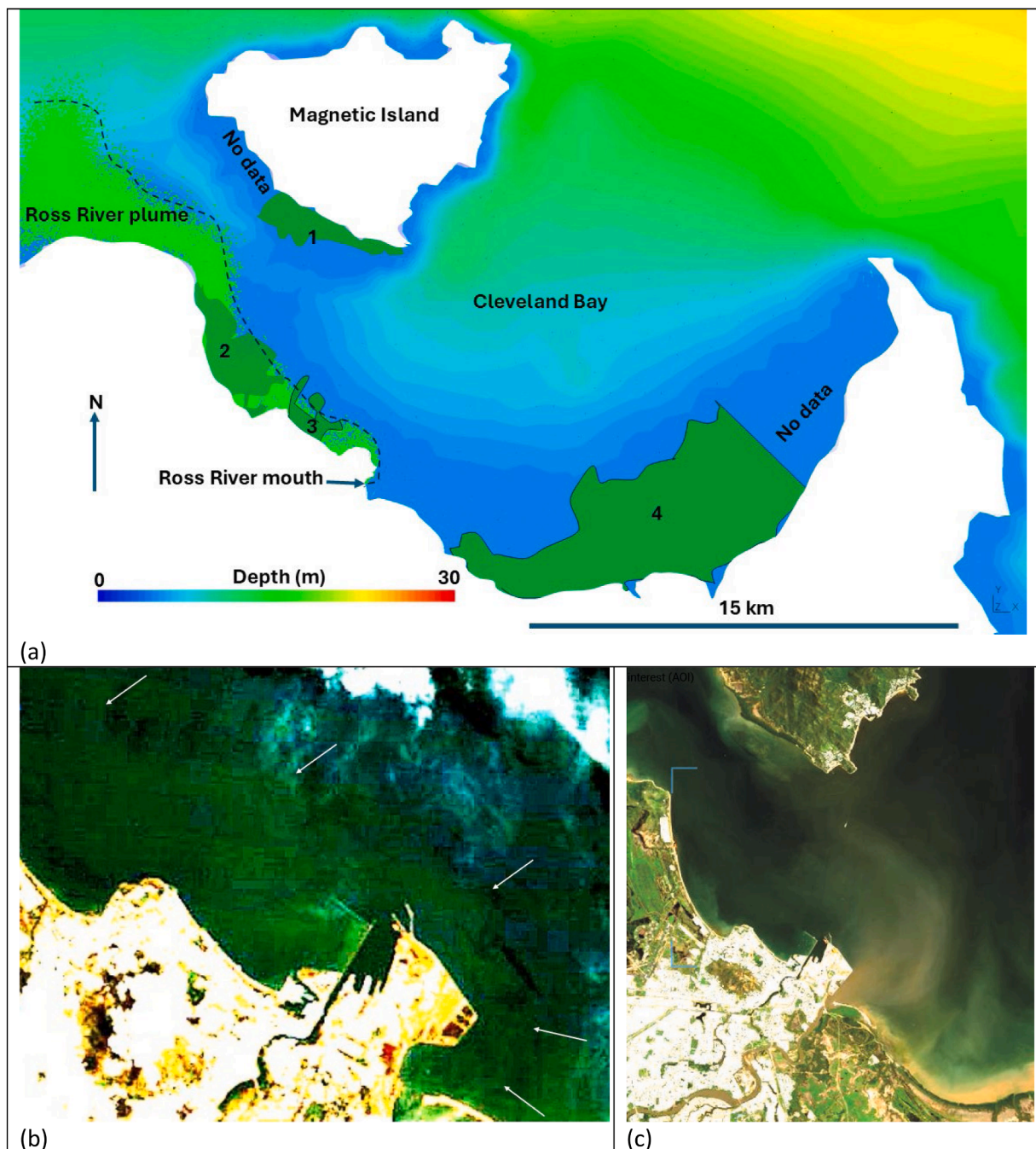


Fig. 9. (a) The distribution of the seagrass meadows in Cleveland Bay in 2019 (PTL, 2020) and the SLIM model predicted Ross River flood plume following the 2007 Ross River flood peaking at $650 \text{ m}^3 \text{ s}^{-1}$ and the wind was southeasterly at about 30 m s^{-1} . (b) A Landsat 5 image of the Ross River plume on 12 January 2008, at the start of a flood, when a 14 m s^{-1} east-northeasterly wind prevailed. The arrows point to the edge of the plume. (c) A Landsat 8 image of the Ross River plume on 11 February 2019 when the Ross River flow was about $220 \text{ m}^3 \text{ s}^{-1}$, 7 days after its peak flood flow of $1888 \text{ m}^3 \text{ s}^{-1}$; the wind speed was about 12 m s^{-1} , the wind direction rotating from north-westerly to east-southeasterly on that day.

was before 1972, and to armour that channel at least until natural processes restore the fan delta. Breaching a sand spit off the river mouth to reduce flooding risks on land was a success for the Senegal River in West Africa; it reduced flooding risks and the sand spit is eroding away (Niang and Kane, 2014).

The coral reefs of Magnetic Island are turning into rubble, and the water clarity has reduced from 8 m in the 1960s to about 1 m nowadays. A likely cause for decreased water clarity is the dumping of unconsolidated dredged mud in Cleveland Bay. The environment is still allowed to degrade because the management decisions about dredging and spoil dumping suffer from the shifting baseline syndrome whereby

the present, post-dredging turbid environment is judged as normal. There is a clear need to study the fate of the unconsolidated dredged mud dumped in Cleveland Bay.

Additional studies of the dynamics of mud are also needed for the Strand. For instance, the PoT expansion for 2040 is predicted to decrease the currents off the Strand (PTL, 2020). A study is needed to determine whether this may favour the settling of suspended fine sediment and turn the Strand beach from sandy to muddy, mimicking the history of the Cairns coast that did change from sandy to muddy (Wolanski and Duke, 2002). By modifying the mean sea level and the wind, climate change may now start changing the currents and waves. This may



Fig. 10. Historical pictures of (a) of Cockle Bay on the south coast of Magnetic Island showing that the sandy beach has been transformed in a muddy mangrove coast between 1937 and 1991, and (b) of Geoffrey Bay on the east coast of Magnetic Island at low tide showing the die-off of its coral reef between 1995 and 2017. Source: (a) is adapted from Wolanski (1994), (b) is courtesy of the Cleveland Bay Consortium.

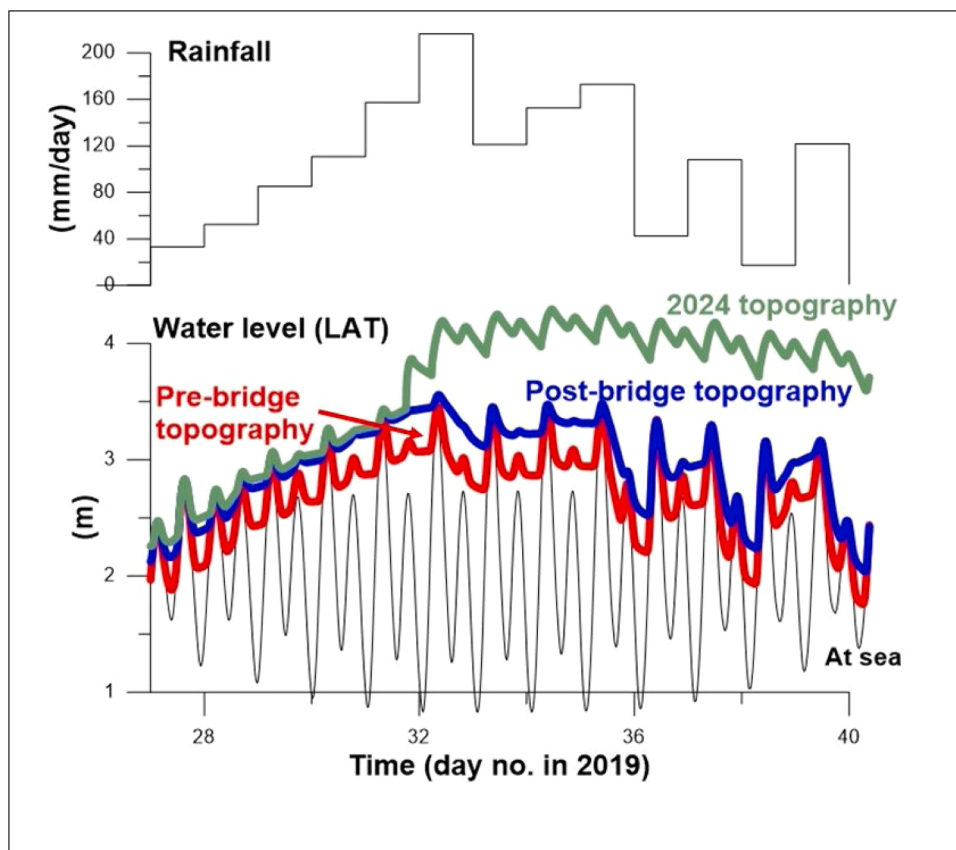


Fig. 11. Time-series plot of the observed rainfall and sea level, and the predicted water level on LAT datum for the pre-bridge topography, the post-bridge topography of 1976, and the 2024 topography.

impact the sand and mud dynamics, and it may have implications for the health of seagrass and coral. This also needs to be investigated.

A solution must be found to recover a healthier environment. We suggest that this is best done by adopting science-based, nature-based solutions combined with green engineering and hydrotechnical solutions, while following the ecohydrology methodology of [Zalewski \(2021\)](#). Adopting such an approach would prevent the present issue of the PoT, the TCC, the TMRQ, the Great Barrier Marine Park Authority, the Queensland Department of Agriculture and Fisheries, the Queensland Environment Department, and the local managers of specific activities, to each manage their patch individually without considering the cumulative effects. For instance, the Townsville City Council (TCC) is informed by the PoT and the TMRQ about their development plans, but it has no veto power on these plans (TCC, pers. comm.). As another instance, TCC has no control on emissions from the PoT creating an airborne pollution plume spreading over Townsville ([Wolanski and Ducrotoy, 2014](#); [Berger et al., 2019](#)). Adopting this holistic approach and a collaboration between the stakeholders, a study should be undertaken as a priority to address the key issue of the fate of unconsolidated dredged dumped mud and, if advisable, to determine the feasibility of disposing of it on land or in a large, contained disposal site in the bay, such as the Slufter in Rotterdam Harbour ([Vellinga and Eisma, 2005](#)). This would decrease water turbidity in Cleveland Bay and likely help recover the seagrass and its fisheries and its megafauna. To evaluate the economics of that solution, the stakeholders should compare the cost of that solution against an economic valuation of the ecosystem services provided by the waters, the seagrass and its fisheries, the megafauna and the coral reefs. Another example of what collaborating stakeholders could achieve, is to resolve the issue of the boat strikes killing charismatic animals such as sea turtles and dugongs. At present, it is not known if these boat strikes are caused by the slow and large ships entering or leaving the PoT, and/or by the small and fast boats of recreational anglers. As a result, neither the PoT (that would be the responsible agency if the boat strikes were due to large ships) nor the Queensland Government Departments (that would be responsible if the boat strikes were due to recreational fishing boats) take responsibility. Thus, no remediation measures are now implemented to minimise the boat strikes. However, these agencies could readily collaborate to reduce the boat strikes on the megafauna, as follows. The seagrass meadow no 4 is particularly important for dugongs. Boat traffic over that meadow is mainly by recreational anglers to reach the tidal creeks on the east side of Cleveland Bay. These boats should be restricted to corridors clearly marked by buoys giving access to these creeks, and boat speed limits need to be set and enforced. Roads and boat ramps should also be built to provide the recreational anglers land-based access to those creeks. All this will decrease boat traffic over the seagrass meadow and reduce boat strikes. To reduce boat strikes by large ships, acoustic deterrents (<https://www.osc.co.uk/services/acoustic-mitigation-devices-3/>) could be fitted on the large ships and on the pilot ships accompanying them when they traverse Cleveland Bay. All coastal towns and ports facing the Great Barrier Reef suffer from similar environmental degradation to various degree (<https://outlookreport.gbrmpa.gov.au/>), and the above solutions and management implications may also apply to them.

It will likely not be possible to restore the Cleveland Bay coast and coastal water ecosystem to its semi-pristine state during the 1960s because of the legacy effects ([Duarte et al., 2009](#)). However, it should be possible to restore a healthy ecosystem and a sustainable economy using ecohydrology principles based on the biophysics of the system ([Zalewski, 2007](#); [Wolanski and Elliott, 2015](#)). This restoration would start with a comprehensive and in-depth analysis of the abiotic conditions of the ecosystem, followed by a similarly in-depth study of its biota status and its degradation. From this knowledge, realistic and cost-efficient solutions will emerge. In such a serious scale effort, the implementation of proposed solutions should be done according to the methodology 'Adaptive Assessment Management', which means step by step, and, with monitoring of the efficiency of the measures, and fine

tuning the management. The experience elsewhere with adapting management of a socio-ecological system (e.g., [Holling, 1978](#); [Lee, 1999](#); [Gunderson and Light, 2006](#); [Allen and Garmestani, 2015](#); [Sellberg et al., 2021](#)) suggests that implementing such a governance system for Cleveland Bay coast and coastal waters should result, if the stakeholders collaborate, in significant social and environmental improvements and a more sustainable economy.

CRediT authorship contribution statement

Eric Wolanski: Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Chris Hopper:** Visualization, Validation, Software, Methodology, Investigation, Data curation.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.ecohyd.2025.100672](https://doi.org/10.1016/j.ecohyd.2025.100672).

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