APPENDIX C

Hay Point sediment dynamics

APPENDIX C

Hay Point sediment dynamics

SYNOPSIS

Independent technical specialist

Aecom | January 2016

Hay Point sustainable sediment management assessment approach

AVOID OR REDUCE

- *Where do sediments come from?* — *Appendix C*
- *Where do sediments accumulate in the port area?* — *Appendix D, E*
- *What effect will this have on the port?* — *Appendix F, G*
- *Can this be managed without dredging?* — *Appendix H*

REUSE OR RECYCLE

- *What are the engineering qualities of the material?* — *Appendix J*
- *Can the material be used beneficially?* — *Appendix I*

ALTERNATIVES TO AT SEA

- *What are the environmental values to consider on land and at sea?* — *Appendix L*
- *What are the details of onshore containment alternatives?* — *Appendix K*
- *How do all the disposal alternatives compare?* — *Appendix B*

Purpose of study:

The purpose of this study was to develop an understanding of the regional sediment dynamics in order to:

- Identify the key sources of sediment to the navigational areas of the Port of Hay Point, and
- Determine whether these could be effectively managed to reduce or avoid future maintenance dredging requirements at the Port.

Specifically, a conceptual understanding of the sediment dynamics in the region was used to investigate the effectiveness of remote upstream sediment control measures to eliminate or reduce the need for future maintenance dredging at the port of Hay Point.

Broad study approach:

A conceptual model for sediment transport was developed to:

- Identify the major sediment types and distributions in the region
- Estimate of sediment transport rates and fluxes between stores through the development of a conceptual sediment budget.

The conceptual model consisted of four key processes and pathways:

- Littoral drift
- Nearshore turbidity zone
- Inner-shelf bedload transport
- Mid-shelf cyclone pathway.

The conceptual sediment budget for the Port of Hay Point was produced using the ArcGIS and the United States Army Corps of Engineers Coastal Inlets Research Program Sediment Budget Analysis System (SBAS).

Key findings:

Key findings from the study may be summarised as follows:

- Sediment is generally moving northwards, with three defined sediment transport processes in the area:
  - Littoral drift
  - Nearshore turbidity zone
  - Inner-shelf bedload transport.
- The major source of sediments to the Port of Hay Point navigational areas are the large stores of available sediment from the inner continental shelf.
- Results from the sediment budget showed that the area is largely in balance, meaning there is little loss of sediment from the system.
- The model suggests that reducing fluvial sources of sediment through in-catchment sediment control measures will have result in would only result in a reduction of between 0.1 and 4% at the Port, thereby having very little impact on future maintenance dredging requirements.

Port of Hay Point Sediment Dynamics and Budget

North Queensland Bulk Ports

14-Jan-2016

Hay Point Sediment Dynamics

Hay Point Sediment Dynamics

Client: North Queensland Bulk Ports

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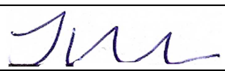
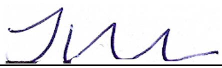
A	15-Jan-2016	For Client Review and Comment	Jemma Purandare Project Manager	
B	18-Apr-2016	For Issue	Jemma Purandare Project Manager	

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Executive Summary

North Queensland Bulk Ports (NQBP) has initiated the Port of Hay Point – Sustainable Sediment Management Assessment for Navigational Maintenance, a long term strategic assessment for the ongoing management of maintenance dredging and the management of marine sediments at and in the vicinity of the Port. The Assessment is to be underpinned by a scientific understanding of the regional sediment dynamics so that the likely sources of sediment to the Port infrastructure can be understood, and therefore better managed.

NQBP have contracted AECOM Australia Pty Ltd (AECOM) to conduct an assessment of existing and available information relating to the coastal processes and sediment dynamics in the Hay Point area, and produce a sediment budget for Hay Point that provides information as to the movement and approximate volumes of marine sediments. This study appears to be the first integrated or consolidate study of sediment transport and dynamics in the central Great Barrier Reef.

The main scientific outcomes of this study are:

- Identification and clarification of the major sediment types and distributions in the region
- Development of an integrated conceptual model of the sediment transport mechanisms
- First estimates of sediment transport rates, and fluxes between stores through the development of a conceptual sediment budget

This scientific knowledge identifies major stores of sediments upstream of the Port infrastructure, and critically, identifies that the dominant source of sediments to the navigational channel and berth pockets are large stores of available sediments on the inner continental shelf. Furthermore, the impact of cyclones on sediment transport, while a contributor to the increase in carbonate sediment transport, is relatively low with respect to the movement of sediments across the region.

Initial sediment budget calculations indicate that sediment is generally moving northwards within the three defined sediment transportation processes in the area – littoral drift, turbidity, and bedload transport. Within most cells, the volume of sediment deposition (storage) within each cell is relatively small compared to the overall volume of sediment moving within the system. In areas where there is high tidal activity or where fluvial currents are strong and dynamics, much higher gravel content is found in the sediment than in other areas where sand, carbonates, or muds are more prevalent. As a result, these cells are considered balanced, meaning almost the same volumes of sediments that are entering the cell are leaving the cell. Sediment is found, however, to be accumulating to the north of Mackay (east of Ball Bay) forming a sand lobe, suggesting that there is more sand entering the cell and being stored, than is leaving the cell.

The model suggests that reducing fluvial sources of sediment through in-catchment sediment control measures will have result in little reduction to future maintenance dredging requirements. Analysis of the model outputs show that even if catchment measures were to halve sediment discharge, this would result in a reduction of supply to the navigational channel of between 4% and 0.1%, which is relative negligible.

1.0 Introduction

North Queensland Bulk Ports (NQBP) undertakes maintenance of the navigation channel, apron area and berth pockets to the Ports of Hay Point, and Abbot Point and Mackay in the Great Barrier Reef (GBR) lagoon. A consequence of maintaining navigational depths through the implementation of maintenance dredging programs is the ongoing requirement to relocate material that is dredged. Traditionally marine sediments derived from maintenance dredging have been relocated to offshore dredged material relocation areas that are within the GBR lagoon coastal environment. However this at-sea disposal is becoming increasingly scrutinised by issues-motivated groups, some sectors of the community, and regulators.

To this end, NQBP has been working with Great Barrier Reef Marine Park Authority (GBRMPA) to seek long term management approaches to the management of dredged material. The proposed NQBP Sustainable Sediment Management assessment (SSM) includes a methodology to achieve this outcome and the first two stages of which aim to generate and integrate key information on the local and regional sediment dynamics (Stage 1), and encapsulate this knowledge in a sediment budget model (Stage 2).

The ultimate objective of the present investigation is to develop the necessary understanding of the regional sediment dynamics in order to better understand and manage the ability to reduce or avoid maintenance dredging and disposal at the Port of Hay Point.

Figure 1 shows the general approach as laid out by NQBP.

Tasks 1 and 2 involve developing a conceptual understanding of the dynamical processes acting in the region under consideration. Task 3 involves gaining an understanding of the ability for NQBP to influence the management of sedimentation at key stages of the sedimentary pathway; including farm management practices, land management opportunities, engineering hydrological and hydraulic controls, as well as port design and operations.

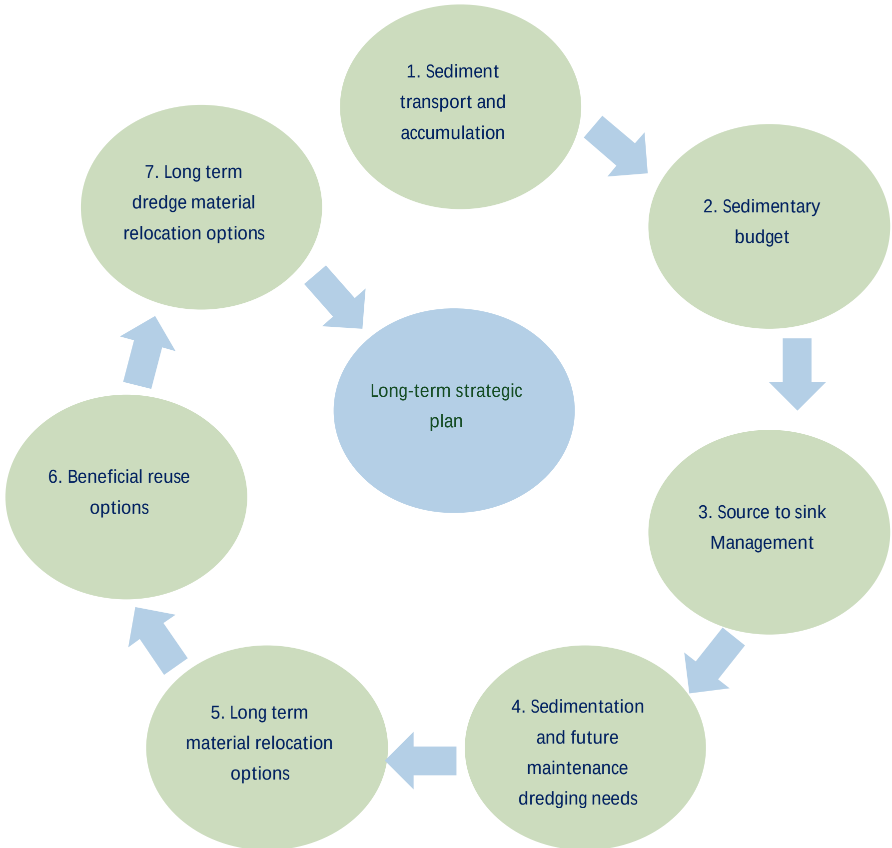


Figure 1 NQBP Sediment investigation approach (Supplied January 2015)

Tasks 4 and 5 are tasks routinely undertaken by environmental and engineering consultants. As such, environmental and engineering consultants commonly use the accepted conceptual understanding (developed in tasks 1 and 2) and then apply commercial numerical hydrodynamic models to simulate a small number of possible proposed development options (developed in Task 3) to gain insight into the possible environmental impacts of the options. The focus of the work presented here is on Tasks 1 and 2, which seeks to gain a fundamental and holistic understanding of the regional sediment dynamics. This includes developing a coherent and internally-consistent understanding of the stores, sources and sediment transport mechanisms and variability.

This knowledge will be integrated into a sediment budget for the central GBR region - the first consolidated attempt for this region.

2.0 Sedimentology and Geomorphology of the Great Barrier Reef

2.1 Geological and geomorphological context

The GBR evolved as a result of continental rifting associated with the opening of the Coral Sea Basin. This opening formed large shallow water plateaus, suitable for coral reef growth, along a carbonate platform. It is understood that a major part of the GBR shelf evolution took place in several phases during the Tertiary period (64 to 1.81 mega-annum (Ma)) (Mathews et al., 2007). Mathews et al. (2007) further identify that the evolutionary platform sequence shows that throughout the Eocene (56 to 34 Ma) and Oligocene (34 to 23 Ma), sedimentation along the continental margin was dominated by subtropical carbonate in the north, and temperate clastic-carbonate in the south. This tectonic evolution of the continental shelf has resulted in stratification (represented conceptually in Figure 2 by Mathews et al., 2007) – i.e. the creation of layers of differing sediment through historical deposition and geological processes. The diagram illustrates the initial basement rifting and uplift that occurred during the late Cretaceous / Palaeocene period, and volcanism and alluvial infilling; later phases of marine transgression (onlap) and regressions (shelf progradation) that led to outbuilding of the continental shelf. Finally, the diagram also shows the final geological layer (the youngest) from the Pleistocene period (1.8 Ma to 10,000 years ago), which marked the onset of periodic reef growth on the shelf edge which continues to recent times (Mathews et al., 2007).

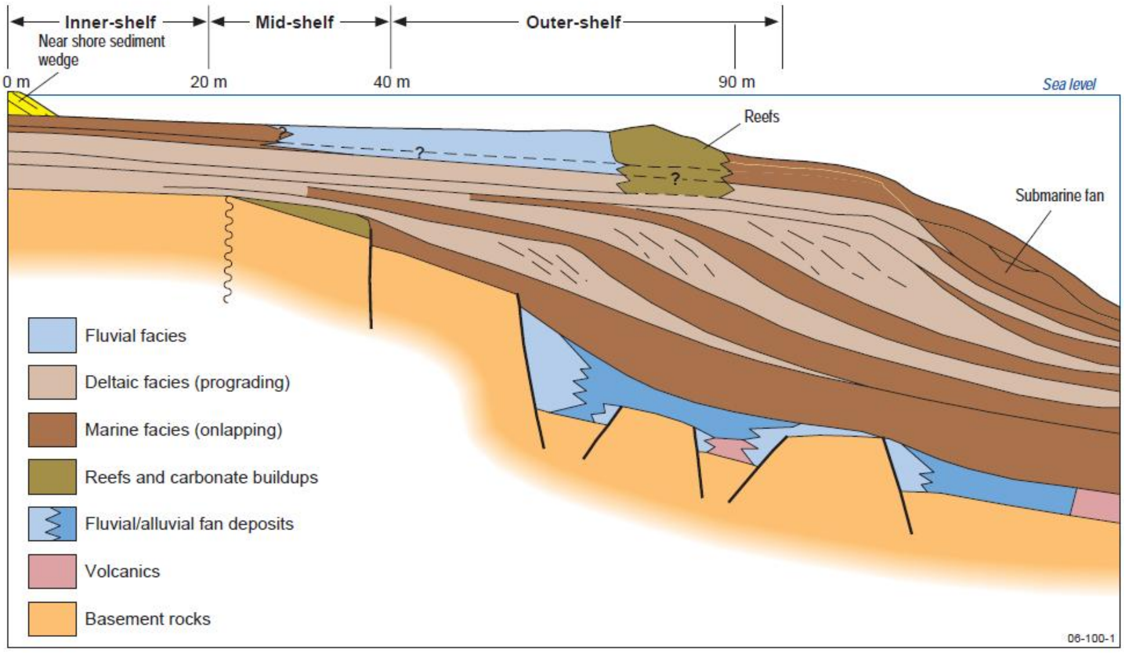


Figure 2 **Schematic diagram of the continental shelf stratigraphy for the central GBR and conceptual representation of the tectonic evolution of the north east Australian margin (Mathews et al., 2007)**

2.2 Sources of sediments to the Great Barrier Reef Lagoon

The classical understanding of the modern day sedimentology of the continental shelf of the GBR coast consists of three sediment facies belts that run parallel to the coast (note, the majority of the research conducted has been done so out of Townsville, north of Mackay).

From the coast out to depths of around 20 m (up to 10 km offshore), a shore-connected inner shelf belt of Holocene sand and mud derived from terrigenous sources can be found most of the way along the GBR coast (Figure 3).

Carter et al. (2009) describe this sediment lens as being typically 4- 5 m thick, but up to 20 m thick in sediment accumulation zones on the north side of major headlands and around major estuaries (Belperio, 1983; Johnson and Searle, 1984, cited in Mathews et al., 2009). This nearshore lens is constantly mixed and hence poorly sorted as a result of ongoing bioturbation.

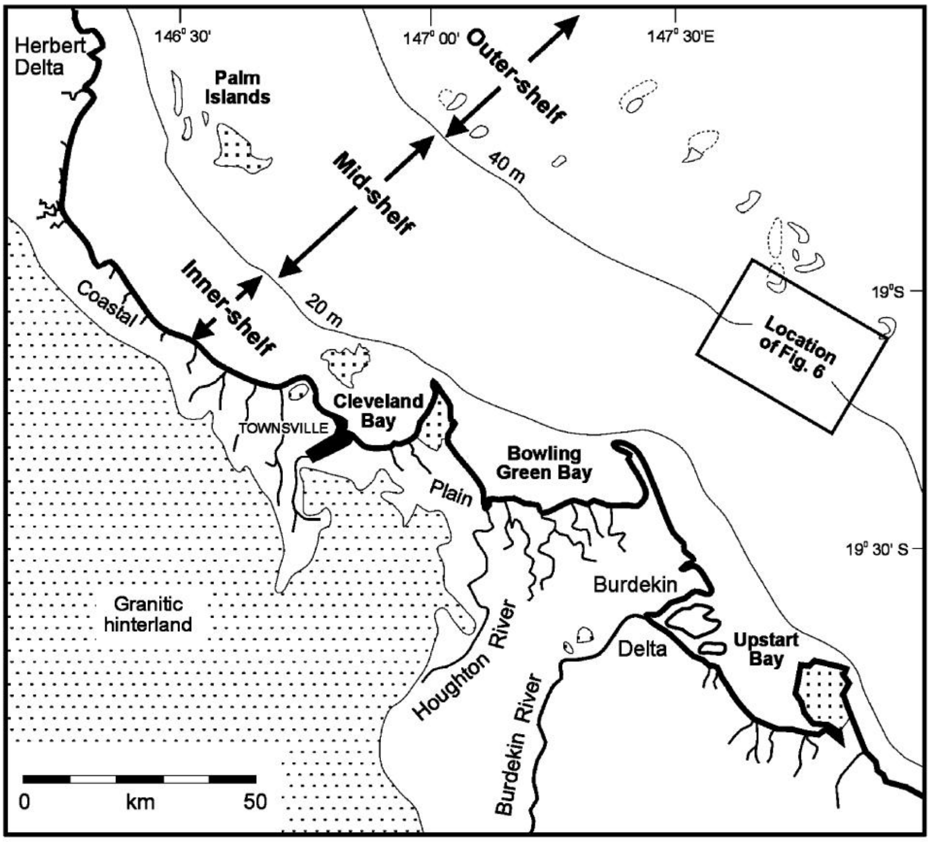


Figure 3 **Bathymetry of the central GBR shelf, including the terminology of the inner, middle and outer shelf (extracted from Larcombe and Carter, 2004)**

2.2.1 Mid-shelf

Further offshore, the middle shelf region lies in water depths of 20 to 40 m, and commonly consists of a thin layer of muddy, shelly calcsand (Ohlenbusch, 1991, citied in Carter et al., 2009). Little accumulation of sediments is believed to occur in this zone. The boundary between the inner shelf zone and middle shelf zone features an increase in carbonate concentration from lower levels inshore (30% or less), to carbonate levels up to around 45% (Carter et al., 2009).

A reconstructed cross-section through typical postglacial sediment faces in the central GBR (produced by Larcombe and Carter, 2004) illustrates three shore-parallel sediment provinces, which are the terrigenous inshore sediment prism (ISP, defined above), the mixed middle shelf condensed muddy calcsand (CMC), and the peri-reef carbonate apron (PCA) which occur within the reef tract (Figure 4). Other carbonate facies (not shown in the diagram below) which occur on the outer shelf include inter-reef micrite pools and *Halimeda* calcsand bodies (Larcombe and Carter, 2004).

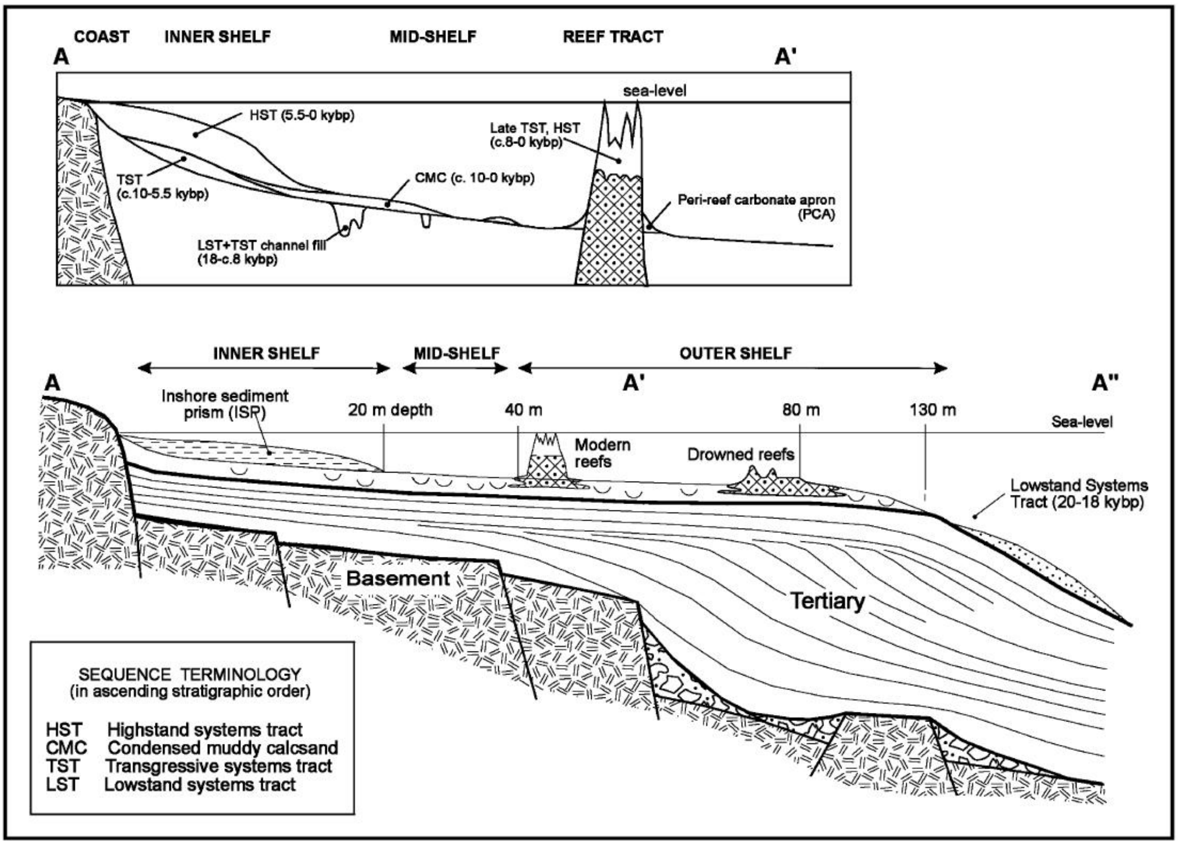


Figure 4 Reconstructed cross-section through the postglacial sediment facies of the central GBR shelf (Larcombe and Carter, 2004)

2.2.2 Outer-shelf

The outer shelf region features the iconic reef structures that are known worldwide. When most people think of the GBR, they are considering this outer barrier reef structure. The surrounding sediments between individual reef pedestals (Figure 5) consist of detrital carbonate sediments that can extend several kilometres on the western or sheltered side of the reefs. *Halimeda* banks are also commonly found between reef pedestals (Harris et al., 2005). *Halimeda* is a moderately to fast growing calcareous macro-algae that is able to colonise these sediment beds.

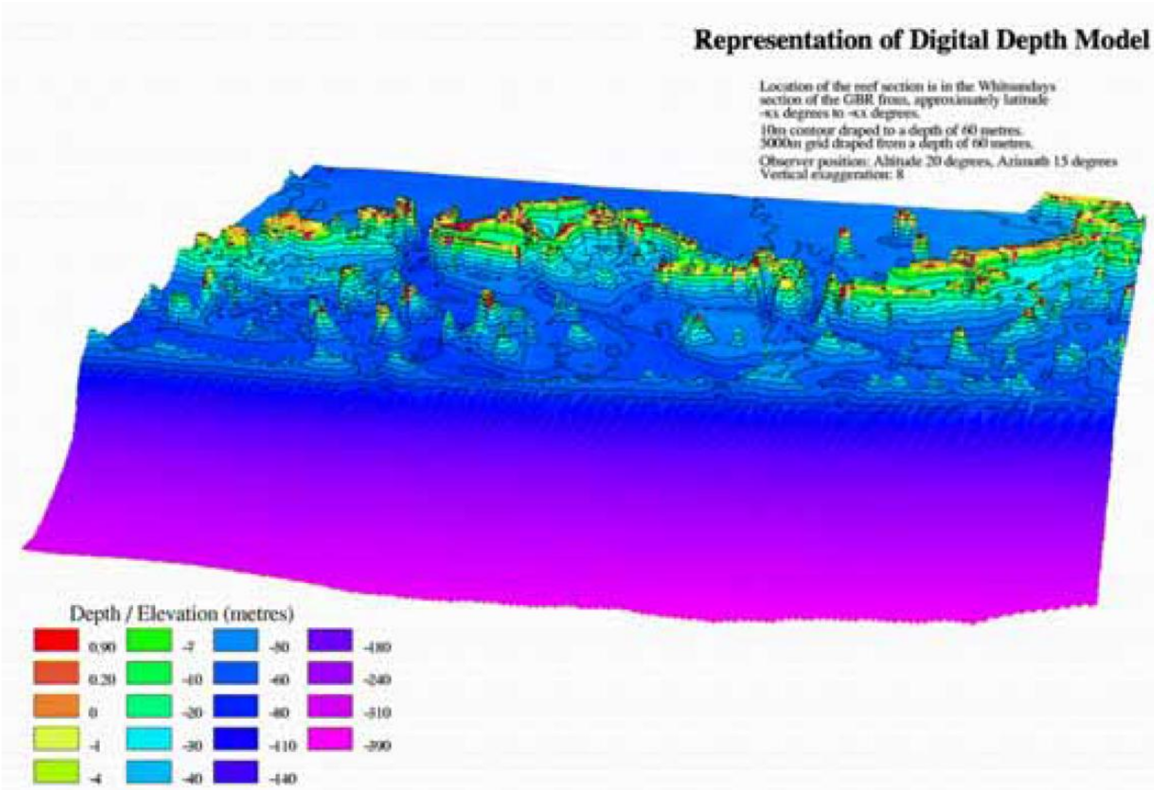


Figure 5 **Bathymetry of the reefs in the Whitsunday Group, showing the geomorphology of large inter reef passages between the islands and reef (Mathews et al., 2007)**

This classical model of the three along-shore orientated bands of sediment facies was primarily developed as a result of a number of studies conducted around and north of Townsville.

More recently, the first GBR-wide comprehensive study of the GBR lagoon has been performed. This study, conducted by CSIRO, Geosciences Australia, and the Australian Institute of Marine Sciences (AIMS) was conducted over the period 2003-2006 and acquired around 1200 new sediment samples. This represents around half of all samples held in the Geosciences Australia sediment sample database for the GBR.

The results from this comprehensive survey are broadly consistent with the classical model described above. However, the larger dataset reveals that there is considerably more spatial variability and complexity than suggested in the classical model. The results from this survey for the central GBR region are discussed in Section 2.2.3.

2.2.3 Modern sediment sources in the GBR lagoon

There are two main sources of sediment to the inter-reefal lagoon areas of the GBR – catchments that drain into the lagoon that deliver terrigenous sediments of a range of particle sizes, and carbonate reefs within or on the borders of the lagoon.

Carbonate grains primarily originate from the ongoing bio-erosion and mechanical destruction of carbonate reef structures, although relic sources continue to supply carbonate grains. These skeletal remains of foraminifers, molluscs, coral and *Halimeda* dominate the sediments in the middle and outer shelf of the GBR. These sediments are diluted by terrigenous grains to varying degrees at different locations across the shelf. Wave action around reefs leads to carbonate sand production – the dominant source of which is foraminifera.

Across the entire GBR, carbonate grains dominate surface sediments. Mathews et al. (2007) highlight that sediments comprising >60% bulk carbonate cover 44.25% of the marine park and sediments containing greater than 80% bulk carbonate cover 25% of the park. By comparison, terrigenous-dominated and relict sediments (bulk carbonate concentrations of <40%) cover 12.5% of the marine park and sediments containing <20% carbonate cover only 4.2% of the marine park. As a result, Mathews et al. (2007) report that:

"The development of sediment facies on the shelf is controlled primarily by the continuous production of carbonate grains in inter-reefal areas, and less so by terrigenous inputs, which have the most influence on the inner shelf."

Terrestrial inputs are derived from ongoing fluvial inputs, and re-mobilisation of relict deposits. Terrestrial gravel inputs are thought to be small as a result of a lack of available gravel in the catchments, and the storage and fluvial gravels in estuary environments.

Similarly, terrigenous sand is exported from estuaries during sporadic major flood events. In a comprehensive study of Keppel Bay, Ryan et al. (2007) identified that bedload transport from the Fitzroy River estuary is variable but dominated by ebb-dominated sediment transport through tidal channels into the outer bay where wave-dominated shoreward transport then lead to a shoreward and northerly directed bedload flux.

Siliclastic sand enters the southern boundary along the seaward coast of Fraser Island. This is the same northward flow of sand evidenced along the New South Wales and South East Queensland coastline, which formed Moreton and Fraser Islands. However, unlike the coasts further south, this source of siliclastic sand does not play a major role in the GBR lagoon. As a result of interactions with the East Australian Current and a major canyon seaward of Fraser Island, little of the sand south of Fraser Island is thought to be propagated through the GBR lagoon.

Relic terrigenous fluvial deposits exist across the GBR lagoon seabed. These were most likely laid down during a lowstand period.

The modern rates of sediment generation or inflow have been investigated. Carbonate sedimentation is caused by carbonate destruction, caused by a combination of physical damage (such as storm surges and cyclones) and bioerosion (from sponges, borers, urchins and fish). A study conducted by Browne et al. (2013) sought to develop carbonate and terrigenous sediment budgets to better understand the volume, distribution and movement of carbonate and terrigenous sediments at two inshore turbid reefs on the central GBR (both in reasonable proximity to Townsville). The study, the first high resolution census based carbonate budget for an entire reef on the GBR, calculated net carbonate production and sediment regimes for separate reef zones, based on morphology, depth and benthic cover (Browne et al., 2013). The results of the Browne et al. (2013) assessment of coral carbonate production found that the total gross annual carbonate production varied from 9.6 kg/m^2/year to 13.8 kg/m^2/year, with between 96 and 99% of the carbonates found to be produced by corals. This is expected to be due to high coral cover (>30%) and high calcification rates for the faster growing corals. Production was found to be highest in deep eastern windward zones and along the leeward edge of the reef, whereas the lowest rates occurred in shallow eastern and western windward zones (Figure 6).

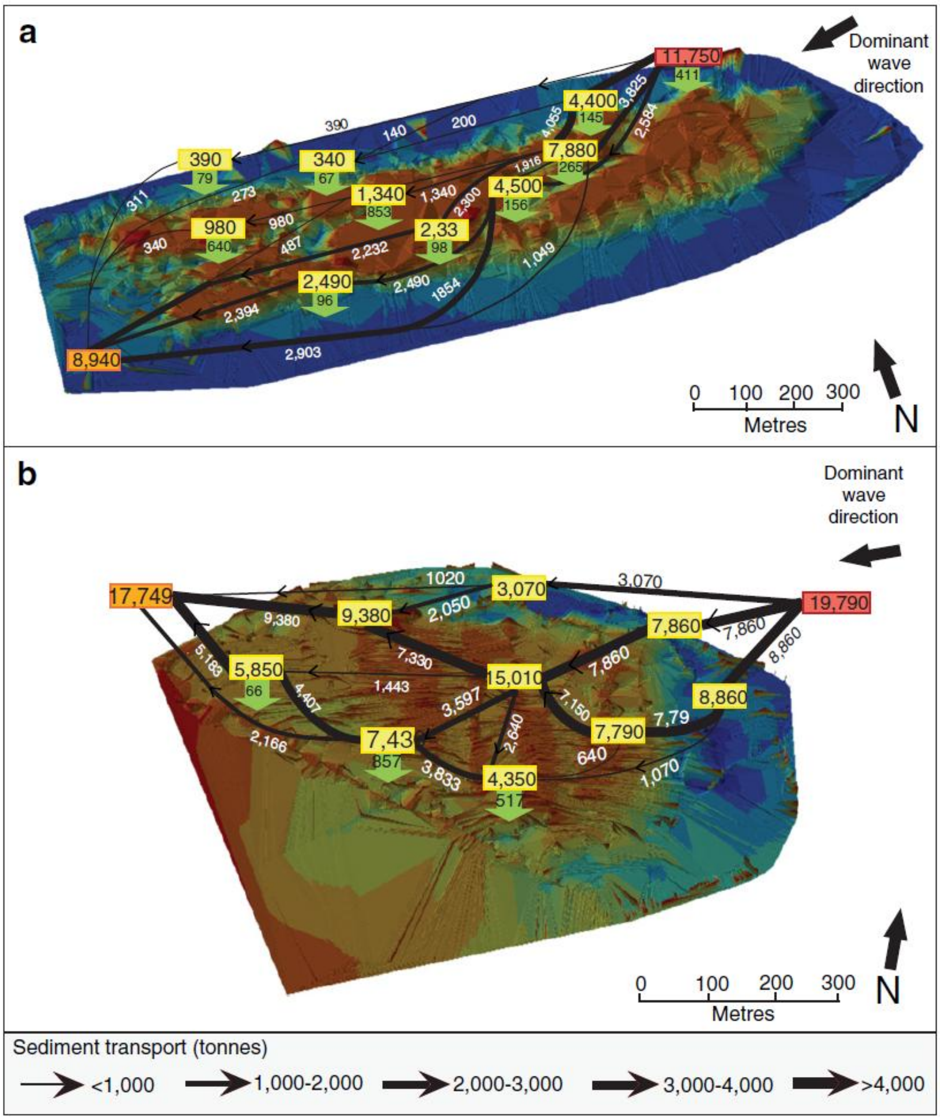


Figure 6 **Sediment dynamics model (during fair weather conditions) showing quantified sediment input on the reef (red box) and into each zone (yellow box), sediment transport (black arrows), deposition (green arrows), and export from the reef (orange box) at Middle Reef and Paluma Shoals – the two study sites (extracted from Browne et al., 2013).**

In the discussion of the findings, Browne et al. (2013) recognise that carbonate production on the study reefs was comparatively higher than those found in studies of other reefs, such as those in the Caribbean and Indonesia. It is understood that this is, in part, due to the two study reefs being subject to high sediment loads, periodic flood plumes, strong wind events (e.g. cyclones), and are characterised by high carbonate production from fast-growing corals, and low carbonate destruction from borers (Browne et al., 2013).

These findings, although specific to Middle Reef and Paluma Shoals, can be applied in concept to other naturally highly turbid reef systems in the GBR.

Over recent decades there has been considerable effort directed towards understanding the present-day inflows of fine sediments (and nutrients) into the GBR lagoon. This work was triggered by speculation that realised post-European (industrialised) increases in mobilisation of sediments in catchments draining into the GBR lagoon is leading to reductions in the condition of near-shore ecosystems. Increases in sediment mobilisation are thought to be around a factor of five greater than during pre-European times. As an aside, this increase is small by comparison to highly urbanised or developed catchments where post-European increases in sediment delivery can 150 times great than pre-urbanisation times. In addition, over geological time-scale the inter-annual variability in river flows is enormous.

These studies were mostly initiated in response to the belief that post-European increases in the volume of fine sediments released from catchments are causing detrimental effect to nearshore coral communities as a result of the suspended sediments reducing light penetration in the water-column.

These studies have been a combination of modelling and experimental studies. The modelling studies, such as Kroon et al. (2012), use coarse resolution waterway network models calibrated against suspended sediment concentrations in waterways to estimate the suspended loads delivered through the waterway network.

These studies, including Kroon et al. (2012), McKergow et al. (2005), Hughes and Croke (2011), Kuhnert et al (2012), commonly assume that all of the estimated waterway suspended sediment load is able to enter the GBR lagoon and hence contribute to reduced turbidity of coastal waters. In reality, these studies produce estimates of suspended sediment entering the landward side of estuaries, rather than the waters of the GBR lagoon.

In other words, the multiple studies of catchment loads in GBR catchments largely assume that all of the sediments mobilised within catchments make their way into the GBR lagoon waters seamlessly. This may be appropriate for finer fractions, especially during major flood events, but is inappropriate for the heavier fractions, which dominate the sediment budget. This is because both suspended and especially bedload flows typically become retarded in estuaries, resulting in a build-up of coarser sediments within estuaries.

As noted by Orpin and Ridd (2012) a comprehensive stratigraphic analysis of the Burdekin delta conducted by Fielding et al. (2006) identified that the majority of Holocene sediment generated within the catchment has been retained within the Burdekin delta region, rather than being delivered into the waters of the GBR lagoon. This is consistent with the recent study of Lewis et al. (2014) which concluded that the majority of fine sediment, defined in this study as < 63 µm, is retained within the estuary and at most, within 50 km of the mouth of the Burdekin River. This result is in direct contradiction with studies such as Brodie et al. (2010) which assume that estuaries form no barrier to the transfer of sediments from catchments to the coastal ocean downstream of point sources.

The implications of this new work are that the previous assumed rates of annual alongshore transport of fine sediments in the GBR lagoon are likely to be over-estimates.

This same process accounts for deposition of terrestrial sands at particular locations that were once estuaries that are now observed on the middle shelf region. During the early Holocene, when the sea level was lower, large delta regions formed over what is now the middle shelf region and these relic deposits remain viable for re-suspension today.

If it is assumed that all of the estuaries behave in a relatively similar manner, then the catchment studies provide guidance over the relative loads delivered to each estuary. In the central and southern GBR, the Burdekin and Fitzroy Rivers deliver the largest volumes of sediments to the estuaries. Conversely, the rivers around the Mackay region often deliver less sediment to coastal estuaries. However, as repeatedly highlighted by these studies, rainfall in the GBR catchments is very 'flashy' and features large inter-seasonal variability. During La Nina seasons, the total seasonal rainfall can be several-fold greater than during El Nino seasons. This can greatly alter the fluvial sediment load. Average load releases in the GBR are illustrated in Figure 7.

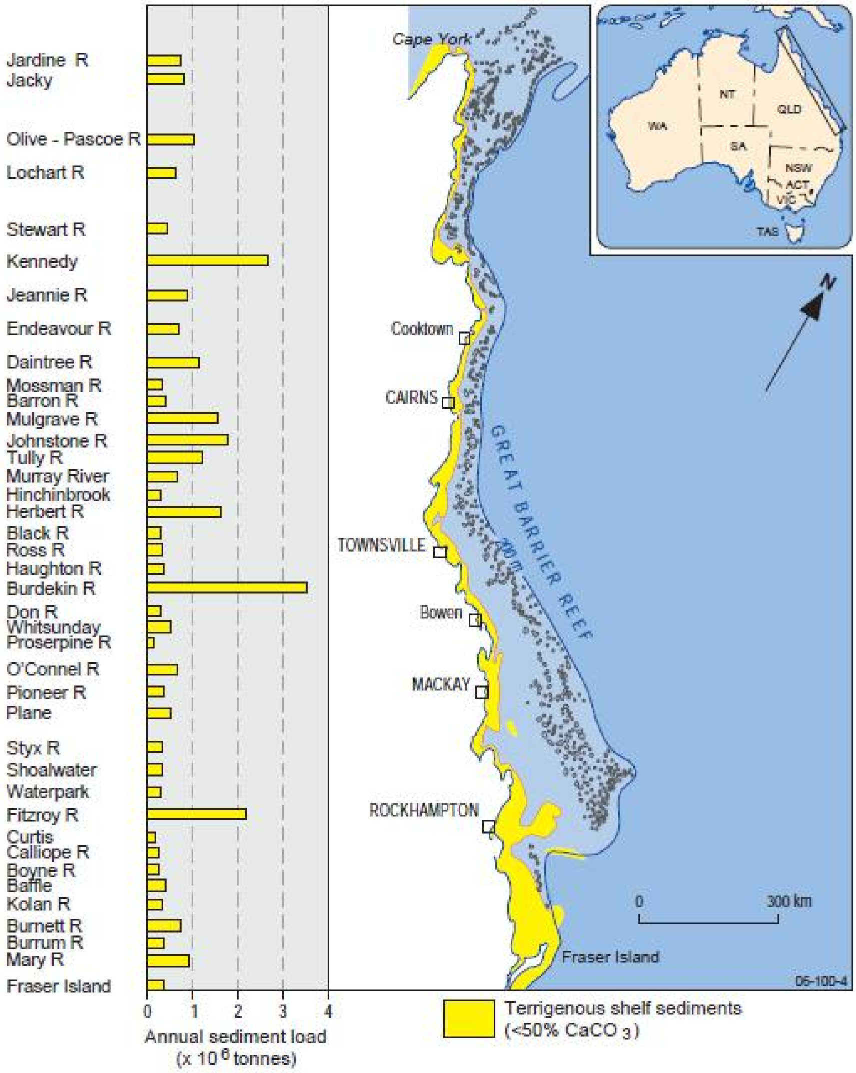


Figure 7 Average sediment load released onto the GBR per annum (Mathews et al., 2007)

The definition of ‘fine sediments’ varies somewhat in these studies and hence comparison between studies can be difficult.

The total volumes of sediment exchanged between the GBR lagoon and the external oceanic region to the north, south, and east is unknown.

Littoral drift delivers sediments northwards along the Fraser island coast into the GBR Lagoon. Similarly, littoral drift discharges littoral sediment from the GBR lagoon into the Torres Strait. Both of these rates have not been estimated. Similarly, there is likely to be some losses of primarily carbonate sediments from the shelf into the Coral Sea.

2.3 Sediment re-distributional processes

The modern-day distributions of sediment facies is the result of historical sedimentological processes, the modification of deposits by sediment transport processes, and changes in sea level. Changes in sea level mean that the mouths of major rivers, which are the source of terrestrial sediments, change over time. In times when sea levels were lower, major rivers have discharged to the coast at locations that are now underwater as a result of a higher mean sea level. This means that there are substantial relic sediment stores of fluvial sediments located offshore of the present coastline. Figure 8 shows the changes in the eustatic sea levels over recent geological history.

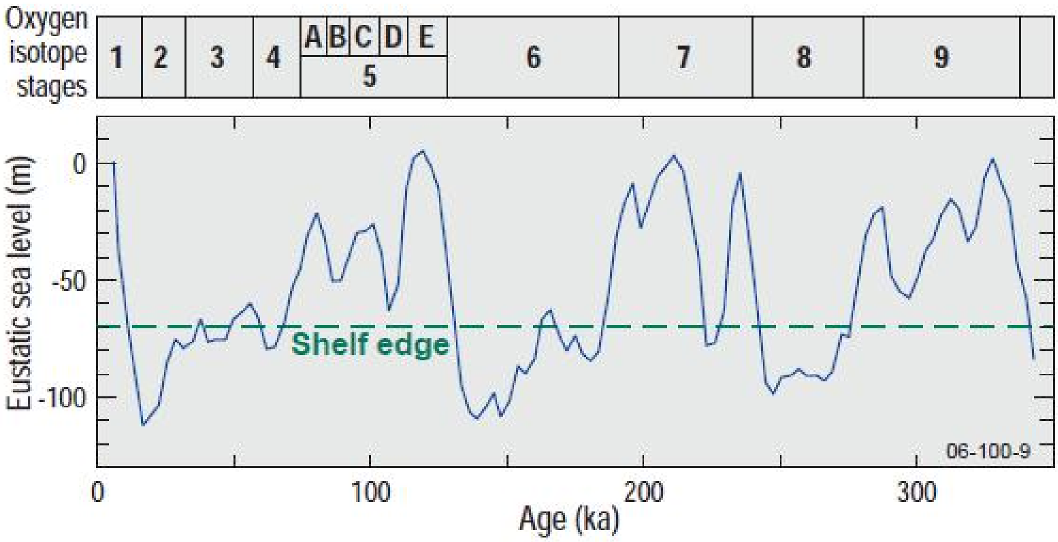


Figure 8 **Eustatic sea level curve for the north Queensland shelf over the last 350 thousand years (ka), relative to the central GBR (Mathews et al., 2007)**

The corresponding sediment depositional processes are shown in Figure 9, which shows the changing shelf environments and movement/behaviour of siliciclastic sediments during highstand (a), transgression (b), and lowstand (c) and the corresponding amount of siliciclastic sediments transported off the shelf during each stage (Mathews et al., 2007).

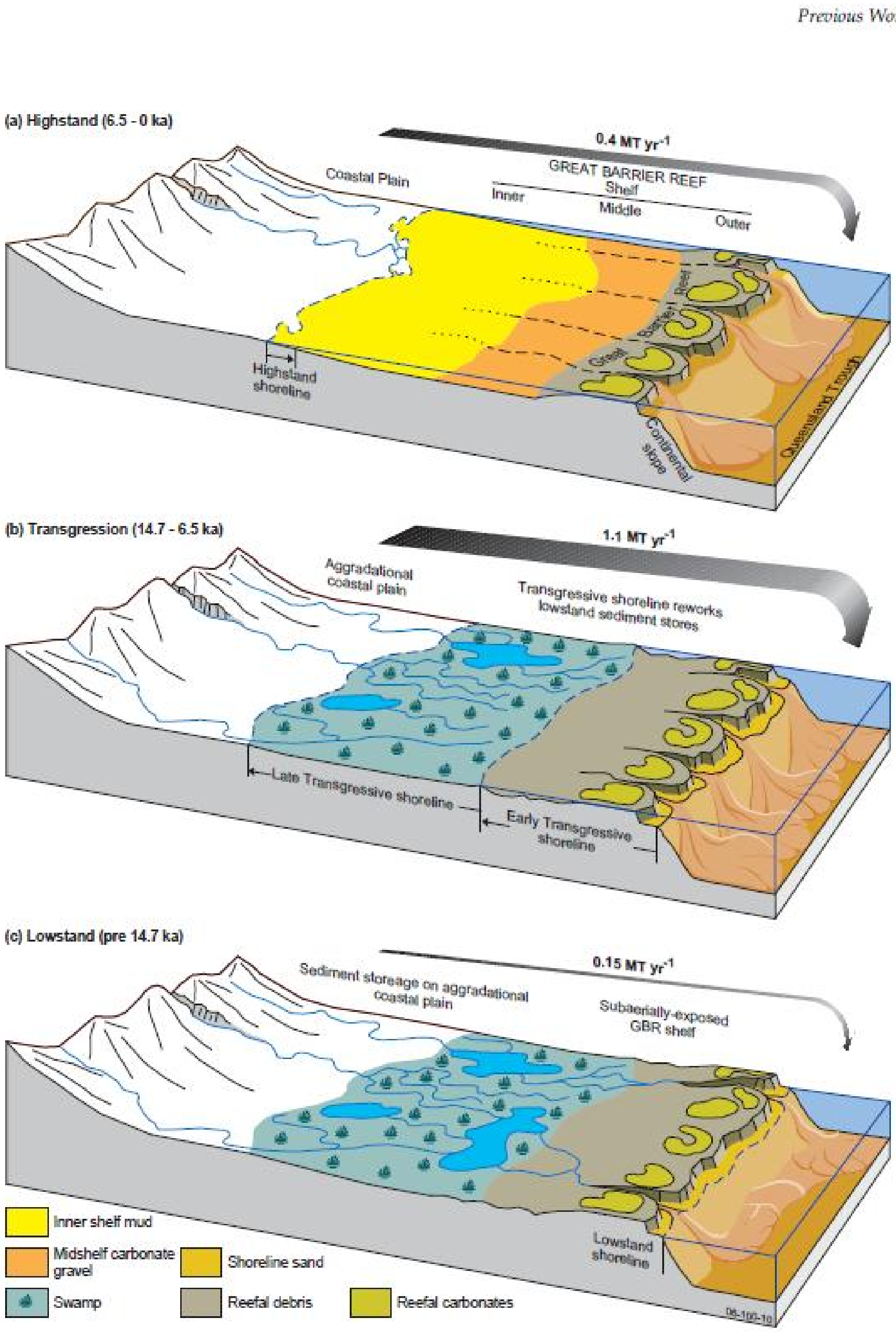


Figure 9 **Model of shelf depositional environments and morphology coinciding with sea level changes on the Queensland continental shelf over the past 15 ka (Mathews et al., 2007).**

The present day sediment distributions are the integrated result of sediments laid down over geological timescales and the transport and redistribution of these sediments by primarily oceanographic processes.

Once again, over recent decades there has been a very strong research emphasis on the transport of fate of the fine sediments that are washed out of catchments during sporadic wet season flood events. Finer fractions discharged from estuaries along the GBR coast are transported generally northwards. The persistent trade-winds that blow across the GBR shelf between March and October generate waves and a nearshore northward alongshore littoral flow along the coast inside the GBR lagoon. This means that river plumes, containing small volumes of suspended sediments are considered to be transported northwards. Finer sediments resuspended by the action of waves and in places tidal currents are also commonly transported northwards. In shallower locations, both near the coastline and over shallow reef structures, the bed shear stress at times is sufficient to mobilise surface sediments, and the associated littoral currents can then transport suspended and bedload material northwards.

Orpin et al. (1999) argue that the majority of the washload sediment discharged from rivers along the coastline of the GBR becomes trapped in shallow (5-20 m depth), northward-facing embayments including Cleveland and Prince Charlotte Bays (Figure 10). These bays are protected from the predominant south-easterly winds and as such northward flowing littoral currents, transporting sediments slow down and allow sediments to fall out of the water-column. Orpin et al. (2004) (including citations from Belperio, 1983; Larcombe and Woolfe, 1999a, b; Lambeck and Woolfe, 2000; Woolfe et al., 2000; and Brunskill et al., 2002) estimate the annual accumulation rates can be as much as 40 cm per year in sheltered north-facing bays that feature adjacent mangrove stands. These represent substantial local sediment stores.

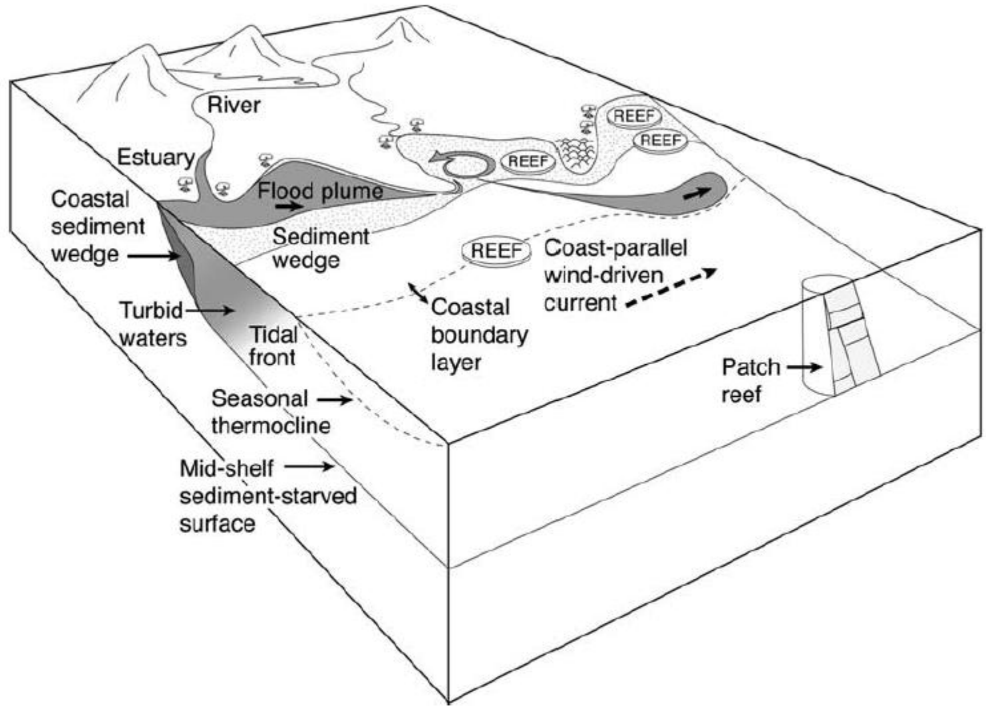


Figure 10 Idealised scheme defining the coastal zone of the GBR, with some key geological and physical oceanographic features (extracted from Alongi and McKinnon, 2005)

Therefore, even during relatively quiescent winter conditions, shallow nearshore areas (<10 m depth) are often turbid as a result of the wave or tide re-suspension of finer fractions. These are then transported northwards, often to become trapped in sediment stores on north-facing embayments and to a lesser extent, man-made coastal infrastructure, such as navigational structures, groynes and small boat harbours.

The volumes of sediment transported in littoral drift currents are generally substantially less than the volume of sand transported along the east coast of Australia south of Fraser Island. This is largely a result of the fact that the offshore reefs protect the inner GBR shelf from ocean swells which are the primarily mechanisms for re-suspending sand particles on more exposed southern beaches. This is also why almost all of the beaches along the GBR coast are classified as tidal beaches that feature large inter-tidal mudflats rather than the steeper sand dominated beach of the cost south of Fraser Island.

The littoral drift is commonly investigated as this process is critical for the maintenance of sand on sandy beaches. By contrast, over continental shelves there is often vast movements of sand that often remain unstudied since these movements generally have no perceived direct impact on high value natural capital or resources.

Bedforms provide evidence of the energetics of the seafloor environment, and can record evidence of historical episodic events. For example, the orientation can provide insight into prevailing sediment transport direction, and the type of bedform gives insight into the near-bottom current flow speeds.

Cyclones effectively act as a sediment transport mechanism, contributing to the sedimentation of the reef system in three ways, as described by Larcombe and Carter (2004):

1) Direct destruction of reef material during cyclone passage across the outer shelf reef tract, resulting in the addition of carbonate gravel and sand to perireef sediment aprons;

2) Erosion of Pleistocene clay and breakage of shells and other biogenic material at the seabed within the middle-shelf cyclone corridor; and

3) Inputs from rainfall-induced terrigenous detritus at river-mouth point-sources.

Larcombe and Carter (2004) describe such cyclonic activity on tropical reef shelves as acting as a 'sediment pump' as cyclones are seen to control the production of the three major types of sediment detritus, which is redistributed by gravity (perireef apron), flood plumes (river jetting), and strong along-shelf flow (wind forcing) within the cyclone corridor. This cyclone-pump sedimentation model, described by Larcombe and Carter (2004) indicates that cyclones are by far the highest energy input at the bed of the middle shelf, and to the shelf generally. As a result, the eroded and flat middle seabed shelf only permits weak offshore sediment flux, and there is subsequently strong sediment partitioning, whereby much of the terrigenous sediment is sequestered into the inner shelf prism, forming a distinct belt to the high carbonate sediments of the offshore reef tract (Larcombe and Carter, 2004).

Cyclone pumping actively resuspends middle shelf sediments onto the shoreward side of the outer shelf zone (Figure 11) and the ocean-ward edge of the inner shelf. Once cyclones have transported sediments across the shelf, this is reworked by south easterly wind-driven currents (Larcombe and Woolfe, 1999, cited in Mathews et al., 2007).

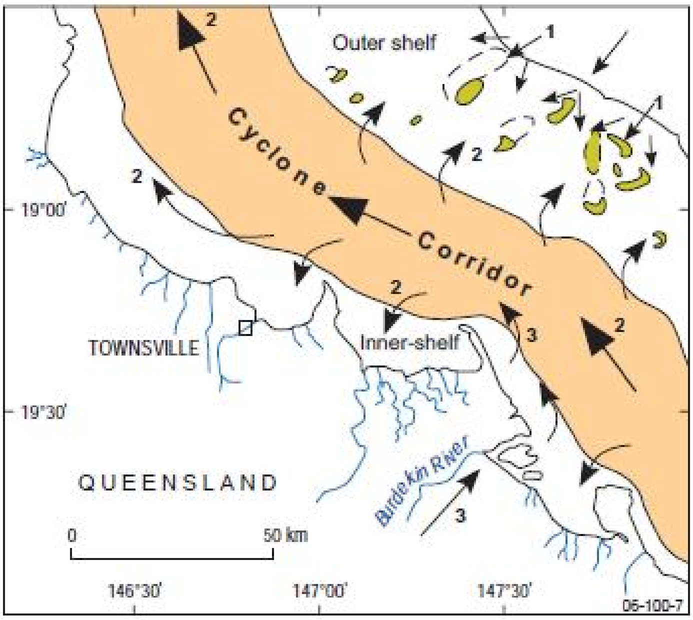


Figure 11 Conceptual model of the middle shelf cyclone corridor caused by cyclone pumping (extracted from Mathews et al., 2007)

Cyclones are an integral feature of the climatology of northern Australia. On average around 4 cyclones cross the Queensland coast every wet season (Figure 12). Nott and Hayne (2001) also use coral core records to suggest that every 2 or 3 centuries a 'super cyclone' impacts the GBR. The majority of cyclones do not reach the most intense category 4 and 5. However even category 1 cyclones represent major synoptic oceanographic events in the GBR lagoon. Importantly, despite the sporadic and episodic nature of cyclones, as opposed to the persistent trade-winds during the dry seasons, over periods of decades and centuries, cyclones are thought to be a dominant long-term sediment re-distribution mechanism (Larcombe and Woolfe, 1999; Orpin et al. 1999).

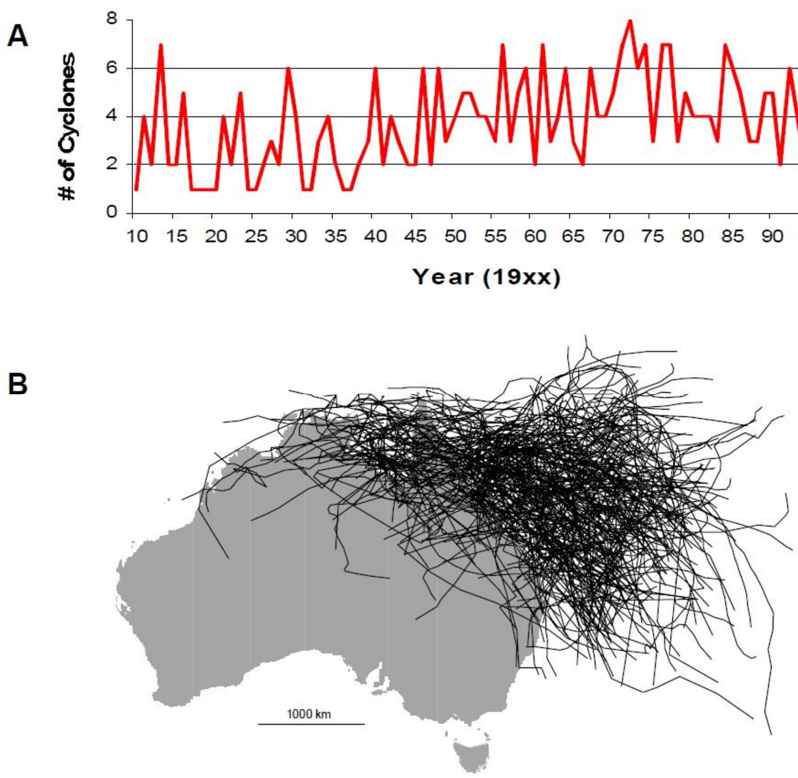


Figure 12 Tropical cyclones in Queensland waters (extracted from Puotinen, 2004)

The majority of the GBR lagoon and shelf experiences tides with ranges typically around 2 metres and of semi-diurnal period (Wolanski et al., 1996). However, the Broad Sound region experiences macro-tides with amplitude greater than 8 m (Harris et al., 2014, see Figure 13).

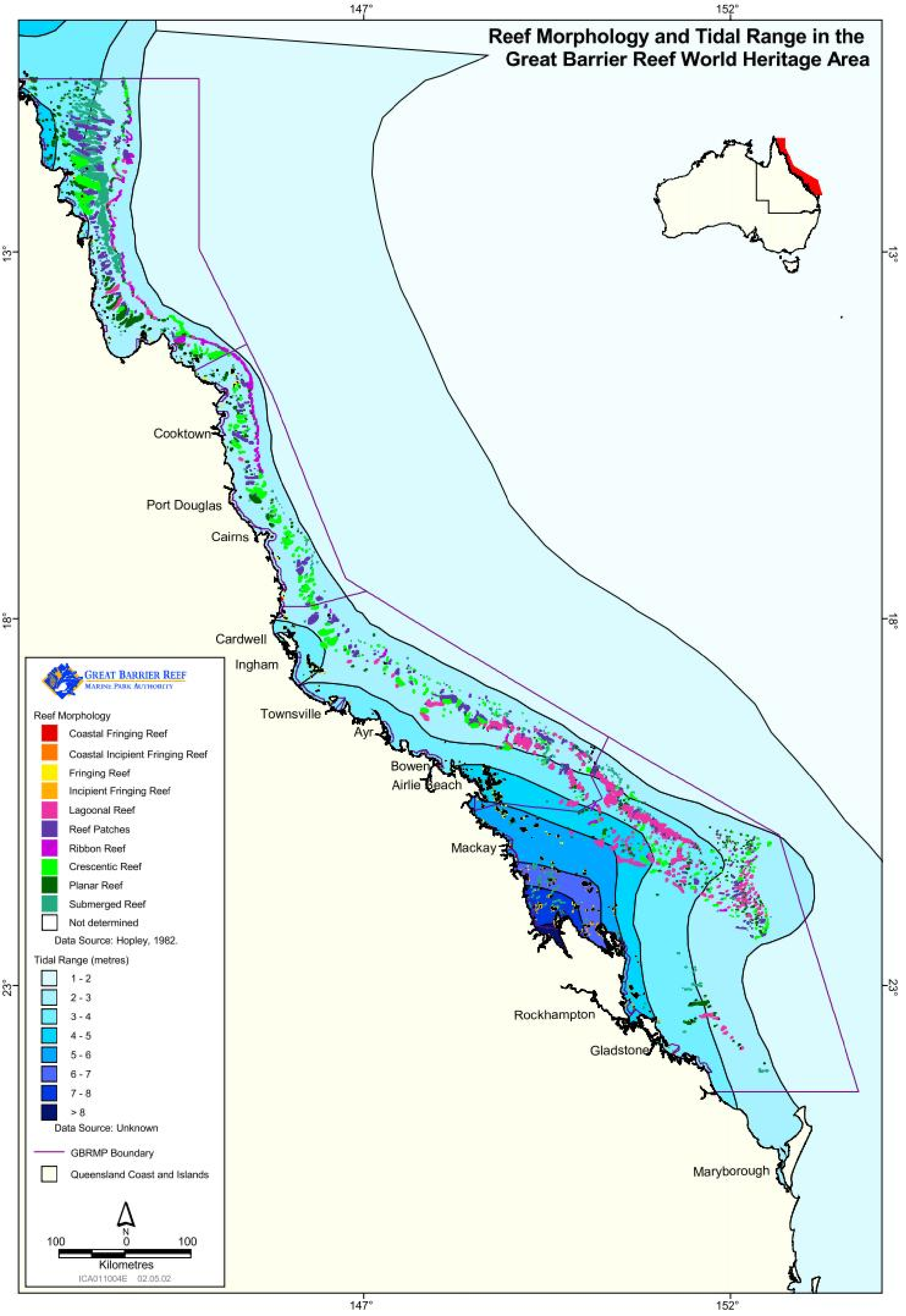


Figure 13 Reef Morphology and tidal range in the Great Barrier Reef World Heritage Area (GBRMPA, 2002)

For most areas across the shelf the combination of sand-dominated sediments and relatively weak tidal currents mean that these tidal currents do not lead to substantive re-distribution of sediments. However there are two major exceptions to this.

Firstly, the macro-tidal range around Broad Sound is associated with strong tidal currents that are able to mobilise surface sediments routinely (refer to Figure 20 later in the report). Secondly, tidal flows between individual reefs, atolls and islands can also be strong enough to scour and re-distribute surface sediments.

Along more open stretches of the lagoon, reversing tidal currents can be strong enough to mobilise surface sediments; however, the reversing tidal flows alone are often insufficient to transport the suspended or bedload considerable distances unless there is also a background flow such as from the East Australian current or local wind driven currents.

The influence of the East Australian Current that transports warm tropical waters southward along the continental slope offshore of the GBR also sporadically enters the lagoon. However unlike along the south-east Queensland or northern NSW coast, the flow across the GBR shelf and lagoon from the East Australian Current can vary considerably both in space and time.

Sediment transport in Keppel Bay provides an example of the complexity and different mechanisms operating. Ryan et al. (2007) noted that observed geomorphology and facies distribution in Keppel Bay results from interactions between macrotidal currents, the input of terrigenous sediment, wave energy, and bedrock outcomes. Figure 14 demonstrates these interactions by using sediment and acoustic facies data, the location and orientation of bedforms, channel structures, and current meter data (provided by Webster et al., 2006, referenced in Ryan et al., 2007) to chart dominant bedload transport directions and sedimentary environments to be constructed for Keppel Bay.

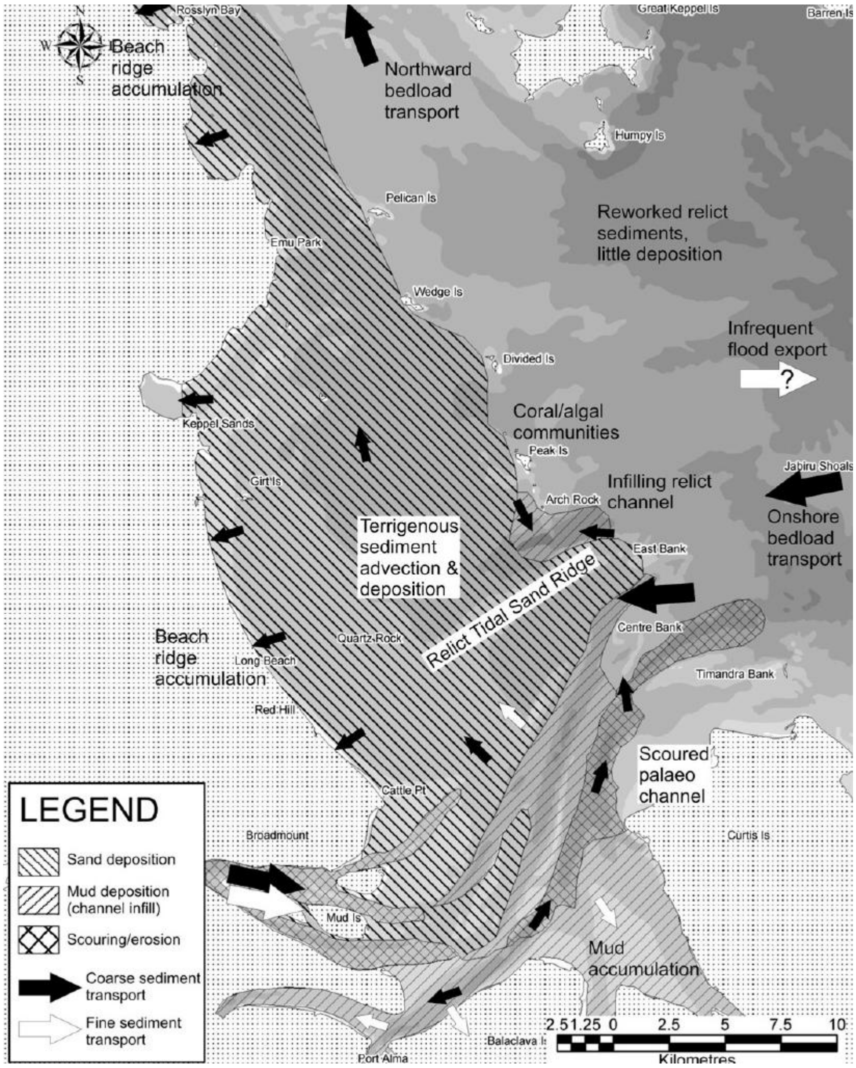


Figure 14 **Process-related conceptual model of Keppel Bay, showing areas of fine and coarse sediment deposition, scouring, and sediment transport pathways (Ryan et al., 2007)**

2.4 Attribution of present day sediment distribution

The present-day distribution of sediments represents the combined effects of sediment inputs and generation, and the redistribution by oceanographic processes.

As highlighted above, Mathews et al. (2007) contain the results of the most comprehensive sedimentological and biodiversity studies of the GBR lagoon. Figure 15 and Figure 16 show the locations of samples taken in the central and greater GBR. These samples were taken using a combination of core and sediment grab methods.

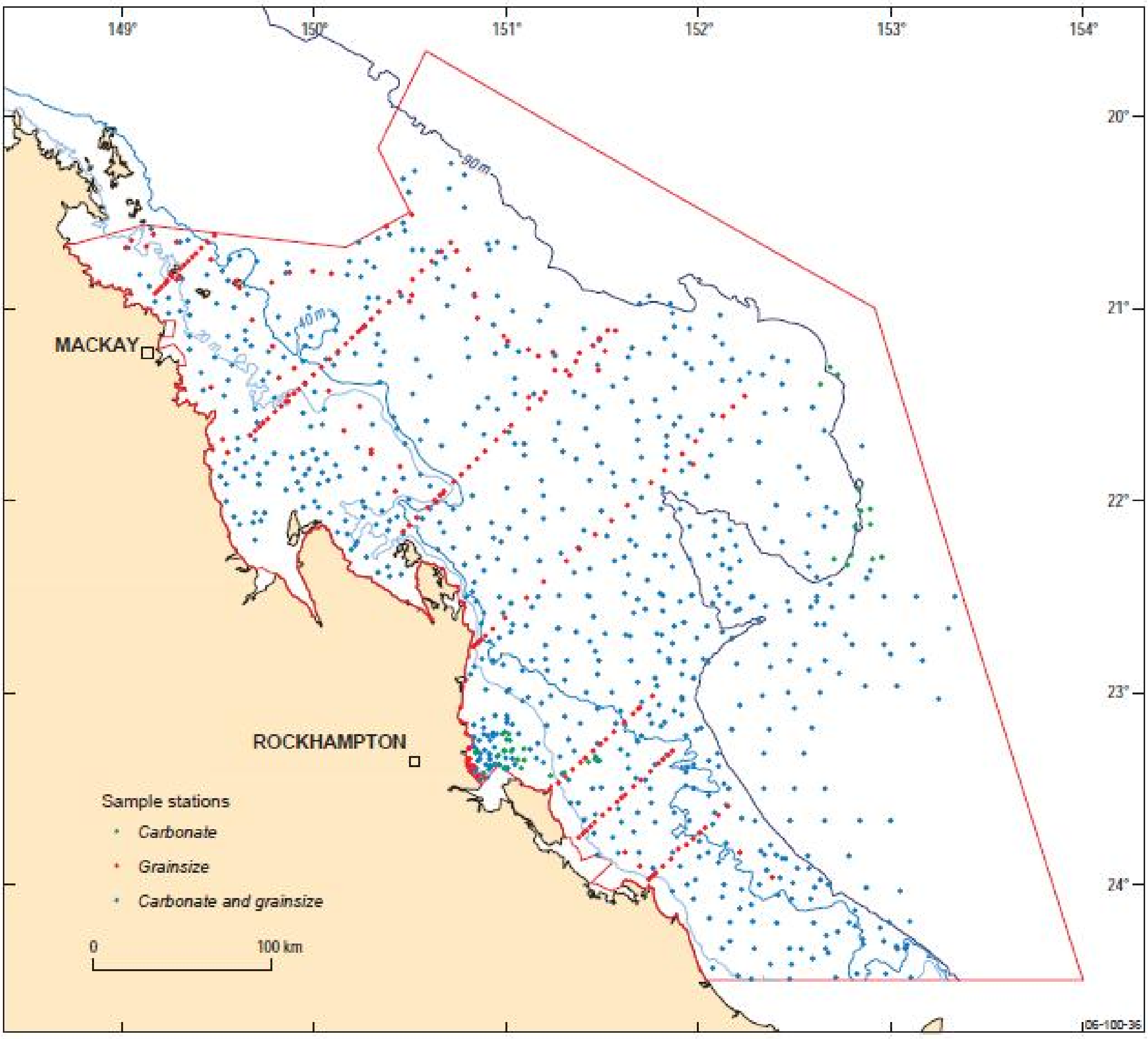


Figure 15 Sample stations across the shelf, within the Mackay/Capricorn Management Area of the GBR Marine Park (Mathews et al., 2007)

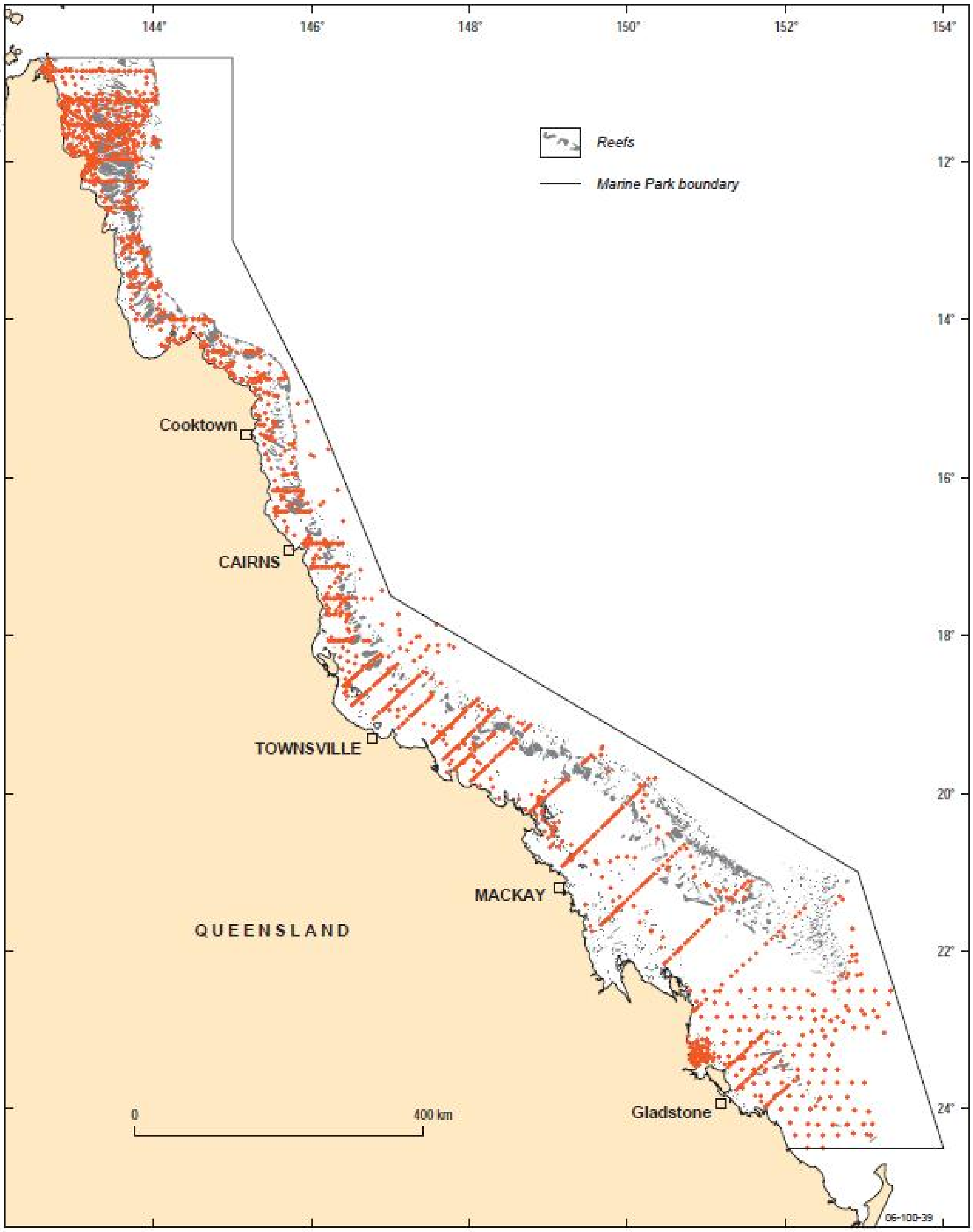


Figure 16 Diagram showing the distribution of all 'other' samples acquired across the entire GBR shelf (Mathews et al., 2007)

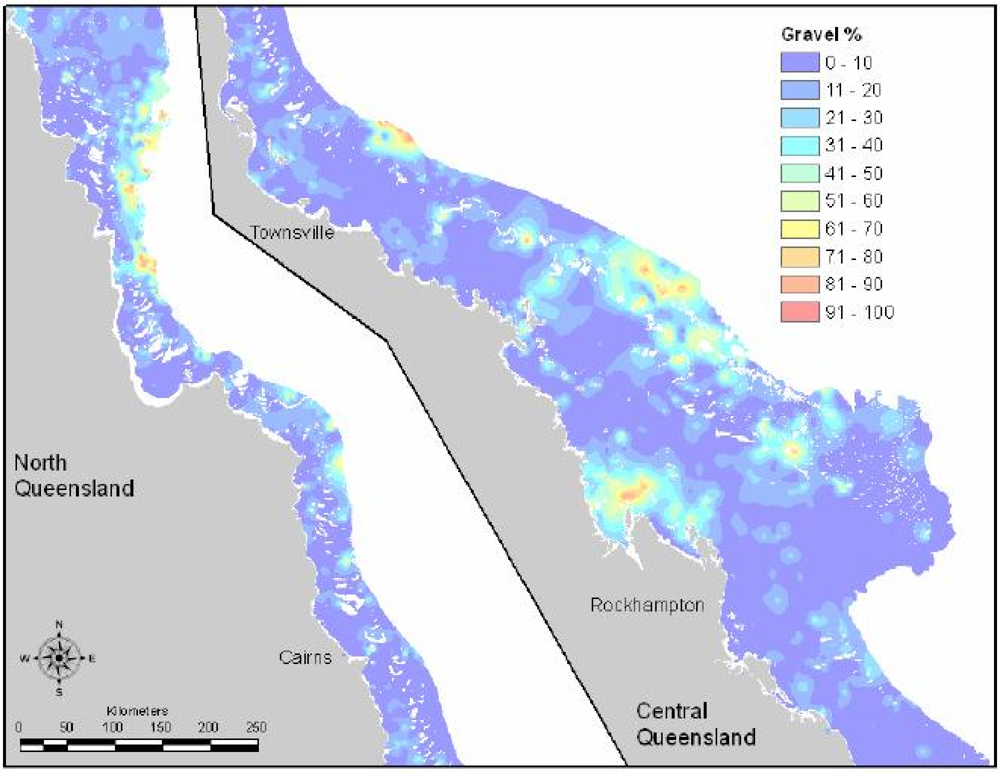
Figure 15 shows sample stations across the central GBR shelf collecting carbonate, grain size, and both carbonate and grain size. Divisions between the inner, middle and outer shelves are illustrated in the figure with blue isobath lines.

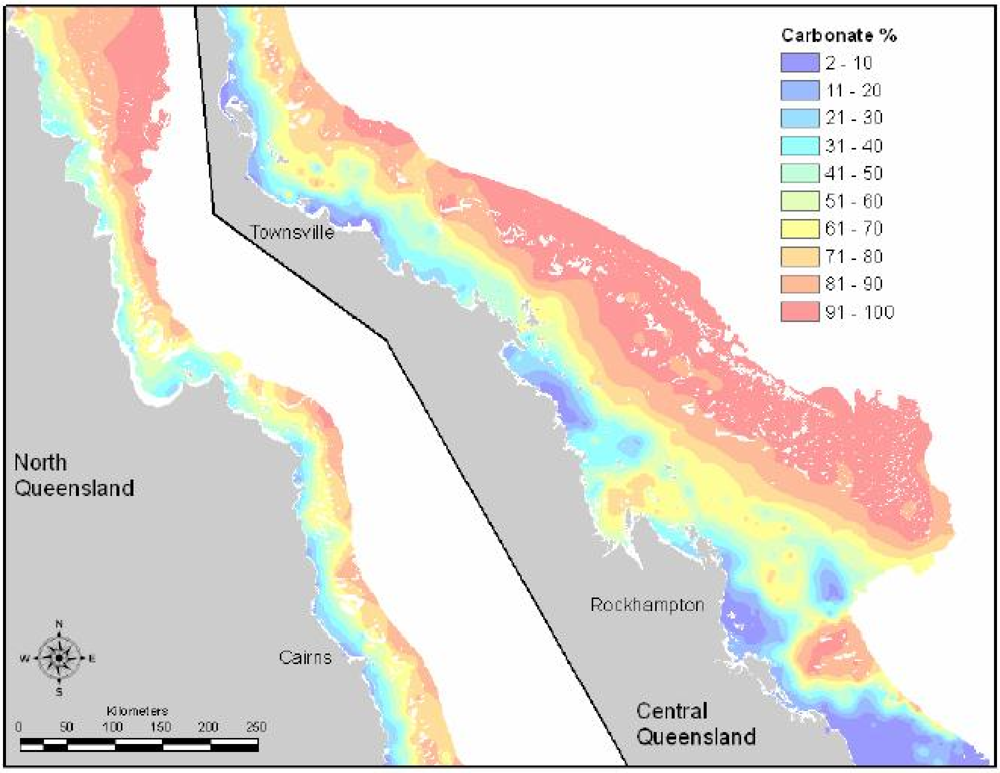
Figure 16 shows the results from the surveys described in Mathews et al. (2007) as the 'other' (i.e. aside from the AIMS data collected) samples gathered across the entire GBR shelf.

In general, the classical model consisting of three cross-shore belts of sediment facies (inner, middle and outer) grading from terrigenous dominated muds over the inner shelf to carbonate dominated sands and gravels over the outer shelf holds. However, this more comprehensive survey reveals considerable more spatial complexity that described in the classical model.

For example, the inner shelf region consists or sequential patches of muddy deposits interspersed with sand dominated facies. A significant patch of carbonate gravel also exists near Broad Sound, over the inner shelf region which is inconsistent with the classical model of sediment distributions.

Figure 17 shows combined sediment attribute data results from the Australian Institute for Marine Sciences (AIMS), Geoscience Australia, and CSIRO surveys conducted in the GBR.


Gravel %
0 - 10
11 - 20
21 - 30
31 - 40
41 - 50
51 - 60
61 - 70
71 - 80
81 - 90
91 - 100
Townsville
North Queensland
Rockhampton
Cairns
Central Queensland
Kilometers
0 50 100 150 200 250


Carbonate %
2 - 10
11 - 20
21 - 30
31 - 40
41 - 50
51 - 60
61 - 70
71 - 80
81 - 90
91 - 100
Townsville
North Queensland
Rockhampton
Cairns
Central Queensland
Kilometers
0 50 100 150 200 250

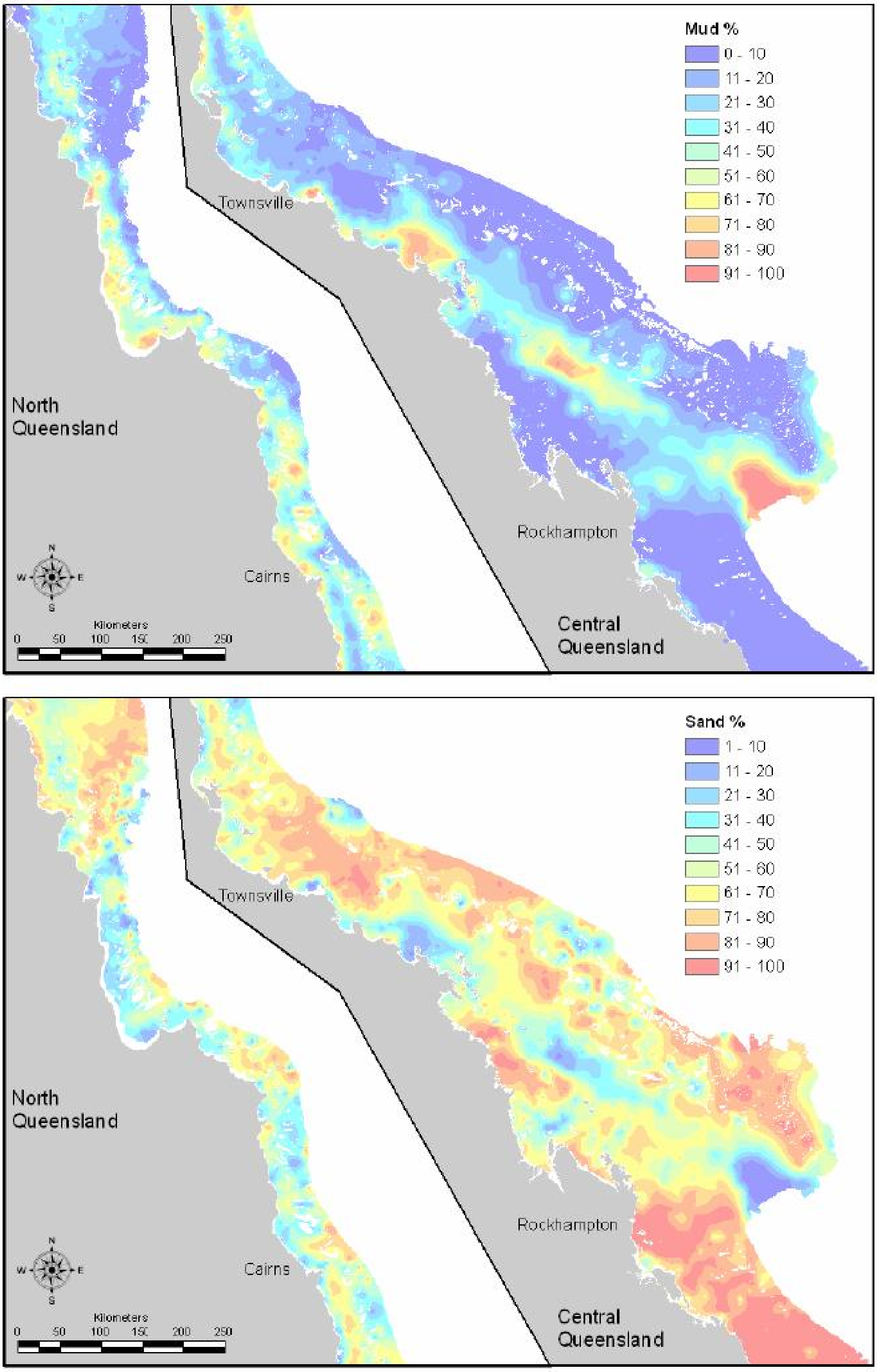


Figure 17 Maps of sediment attributes for the GBR continental shelf: percent mud/sand/gravel grain size fractions and percent carbonate (Geoscience Australia, cited by Pitcher et.al. 2007)

Folk (1954, cited in Mathews et al., 2007) determined the *Folk Classification*, which described inner shelf sediments being of a combination of muds, sandy muds, and muddy sands, sands, and gravelly sands (Figure

18). Conversely, surface sediments on the middle shelf are characterised by relatively high sand concentrations, and moderate carbonate concentrations (Mathews et al., 2007). The middle shelf is influenced by terrigenous inputs from the inner shelf, and carbonate inputs from the outer shelf (Figure 19).

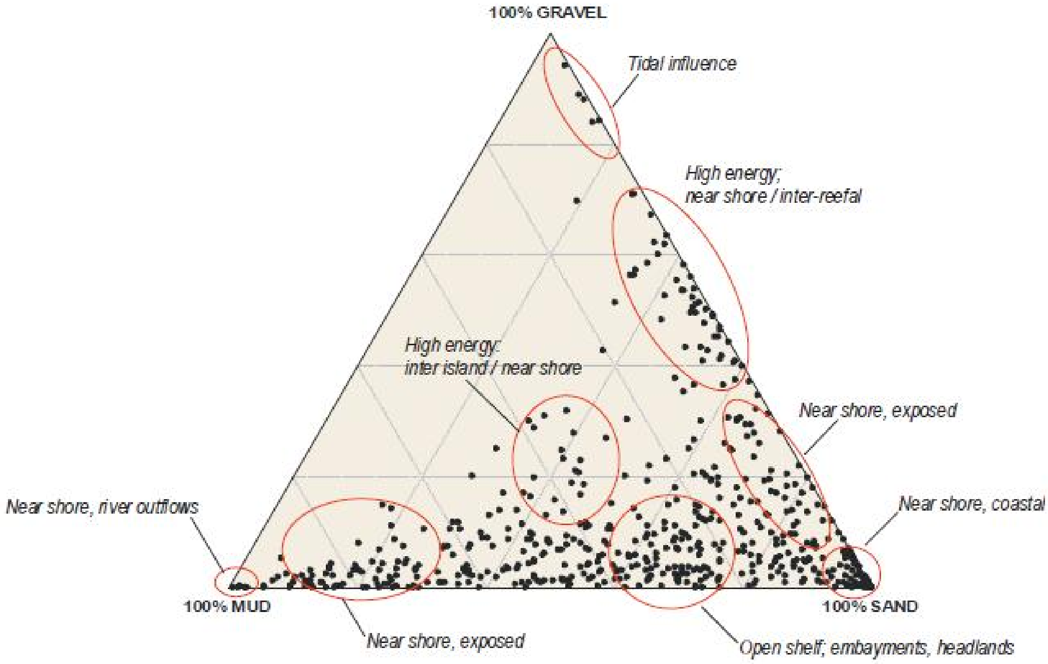


Figure 18 **Ternary diagram showing the textural characteristics and associated environments of inner shelf sediments (Mathews et al., 2007)**

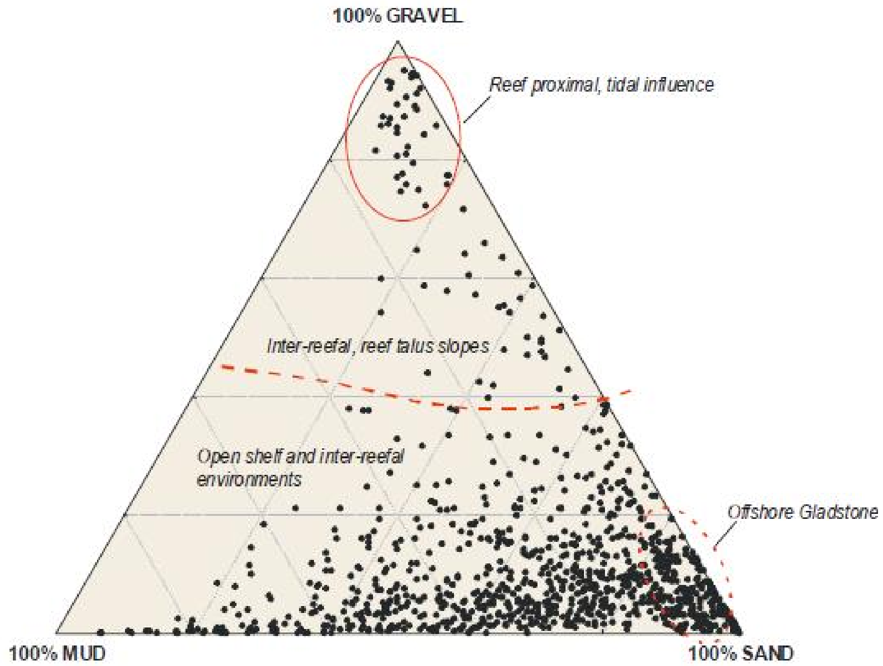


Figure 19 **Ternary diagram showing the textural characteristics and associated environments of middle shelf sediments (Mathews et al., 2007)**

Both the broad distributional features and specific features can be explained from an understanding of the key sediment source and re-distributional process:

1) The facies of low carbonate sand in the southern GBR is most likely connected to the progression of sand along the NSW and south-east Queensland coastline.

2) The patch of high-carbonate gravel to the north of Rockhampton is probably a result of ongoing scour from the strong tidal currents in the region. Figure 20 shows locations where tidal currents are likely to be greater than the threshold bed shear stress required to mobilise sediment. Inspection of the figure reveals strong tidal currents in the location where the gravels are co-located; suggesting that the tidal flows continuously erode sediments.

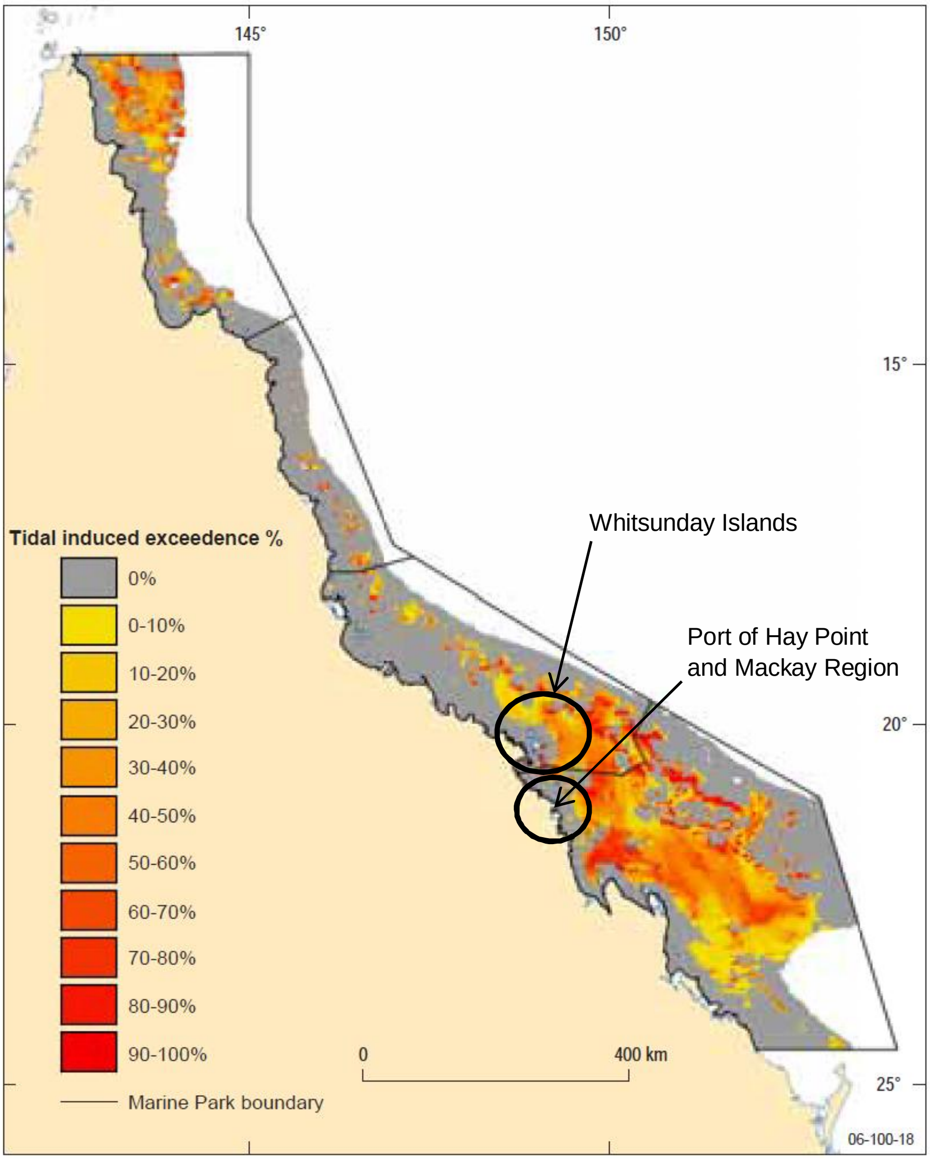


Figure 20 GEOMAT Tidal-induced threshold exceedance caused by tidal currents on the GBR shelf (adapted from Passlow et al., 2005, cited in Mathews et al., 2007)

The large patch of muddy sediments north-west of the Whitsunday Group is not easily explained. The largest sources of terrestrial muds are the Burdekin River (to the north), and Fitzroy River (to the south). However, it is possible that these deposits were laid down during a lowstand period, and have remained in place over the intervening geological period. This area does not feature overly strong tidal currents (although tidal currents between the Whitsunday Islands to the south are strong, or an energetic wave environment (Figure 21).

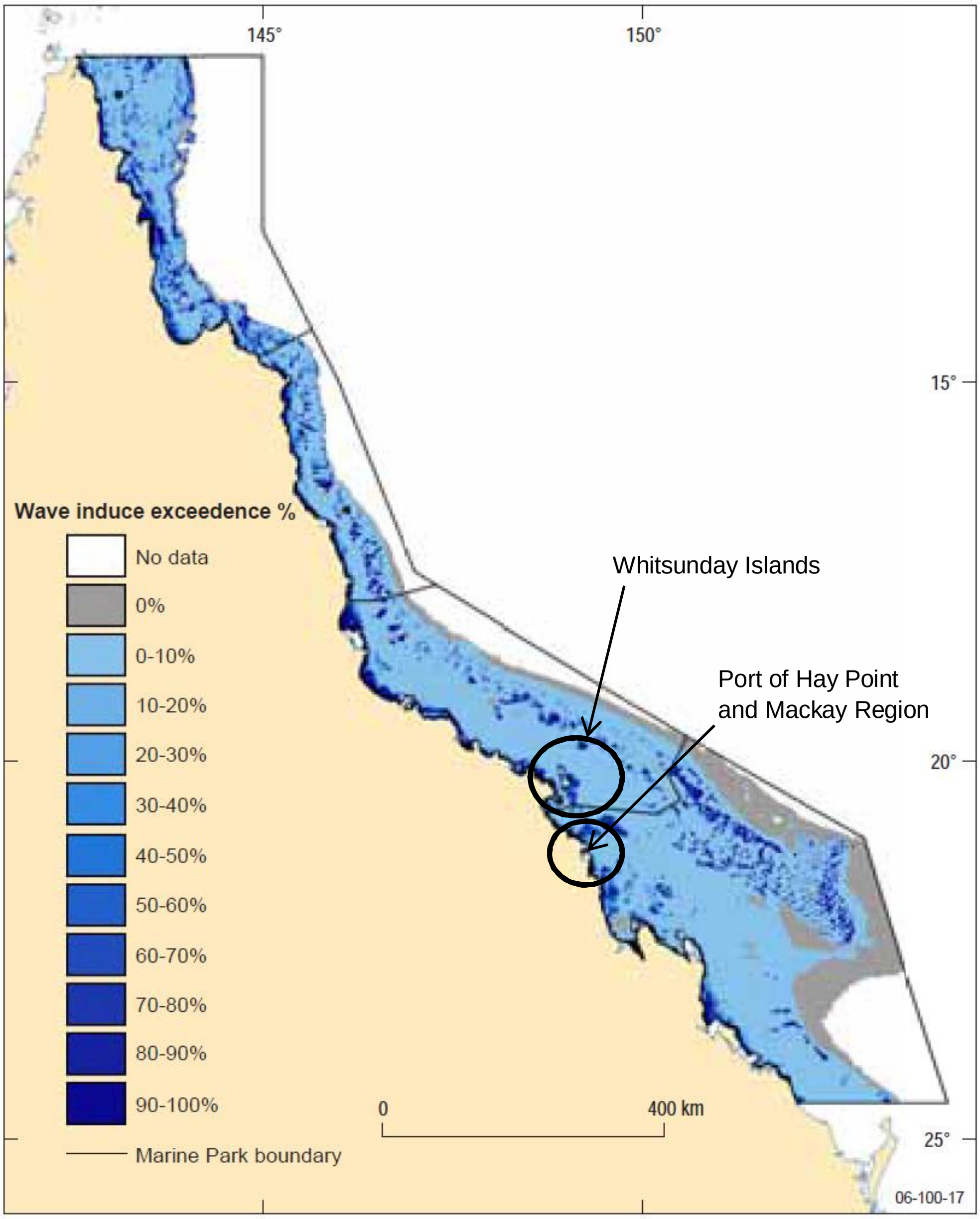


Figure 21 **GEOMAT Wave-induced threshold exceedance due to swell waves on the GBR shelf (from Passlow et al., 2005, cited in Mathews et al., 2007)**

The alongshore band of high carbonate deposits over the outer reef is consistent with the reefal source of sediments.

3.0 Sediment Transport in the Hay Point Region

The most problematic parameters in any sediment budget are often the transport rates of sediments between stores. Hence consideration of the transport rates is provided in this section.

3.1 Conceptual model

Previous studies of sediment transport processes along the central GBR coast have principally focused on two areas:

- Studies of the volumes and fate of fine sediment discharged from waterways during wet season flood events; and
- Studies of coarse sediment movements in the littoral zone.

The former studies have focused on gaining a better understanding between the cause-effect pathway whereby the rivers discharge additional fine sediments that then propagate along the nearshore zone of the GBR and reduce water clarity, which then negatively impacts the condition of sensitive ecological receptors, such as seagrass meadows and corals.

The second type of study is typically commissioned in response to coastal erosion issues whereby the generation, transport and fate of coarser, beach-building sands are investigated.

However, the ongoing management of the navigational channel and berths at Hay Point requires consideration of both coarse and fine sediments. To this end, an integrated model of sediment transport pathways is proposed.

The integrated model is based on the following results:

- A number of beaches exist in the region, despite being impacted by sporadic erosional processes such as cyclonic events. This suggests an active littoral transport of courser sediments occurs.
- Repeated photographs and turbidity measurements of the nearshore zone along the central GBR coastline demonstrate that nearshore waters commonly feature observable fine suspended sediments.
- Research studies, and modelling (Orpin et al 1999) suggest that non-extreme wave and tide action is able to re-suspend courser fractions in depths beyond the littoral zone
- Observations from major cyclones (for example, cyclone Winfred in 1986) have demonstrated that substantial sediment movement occurs across the GBR lagoon during cyclonic events.

These results suggest that an integrated coastal sediment transport pathways model will consist of four key processes and pathways:

- Littoral drift,
- Near-shore turbidity pathway,
- Inner-shelf bed load pathway, and
- Mid-shelf cyclone pathway.

3.1.1 Littoral drift

In nearshore studies of sediment transport and beach dynamics, the transport process under investigation is commonly classical littoral drift. This classical littoral drift requires the following dynamical processes to occur:

- Waves breaking on beaches mobilises both fine and coarse sand sediments
- Waves breaking obliquely to the beach establish a longshore drift (primarily to the north in the GBR lagoon) that transports the re-suspended sediments alongshore.

The dominant swell direction along the east coast of Australia is from the south-east, and hence littoral drift is a very important process for transporting sand northwards along the coast. This process, acting over geological time scales has led to the formation of the major sand spits and sand islands including Fraser Island, Moreton Island, and South and North Stradbroke Islands.

The offshore reefs of the GBR act as efficient dissipaters of ocean swells and hence the energy contained in the wave environment by the time it reaches the coast is substantially reduced by comparison to coastal areas south of Fraser Island.

This pathway is shown schematically in Figure 22 This figure also highlights the fluvial, synoptic or 'new' sources of fluvial sand. Whilst these are important, the magnitude of these new sources is small by comparison to the existing available seabed sources of coarse sediments available for littoral transport as demonstrated by the extensive relic sources of sediment stores (refer to Figure 17).

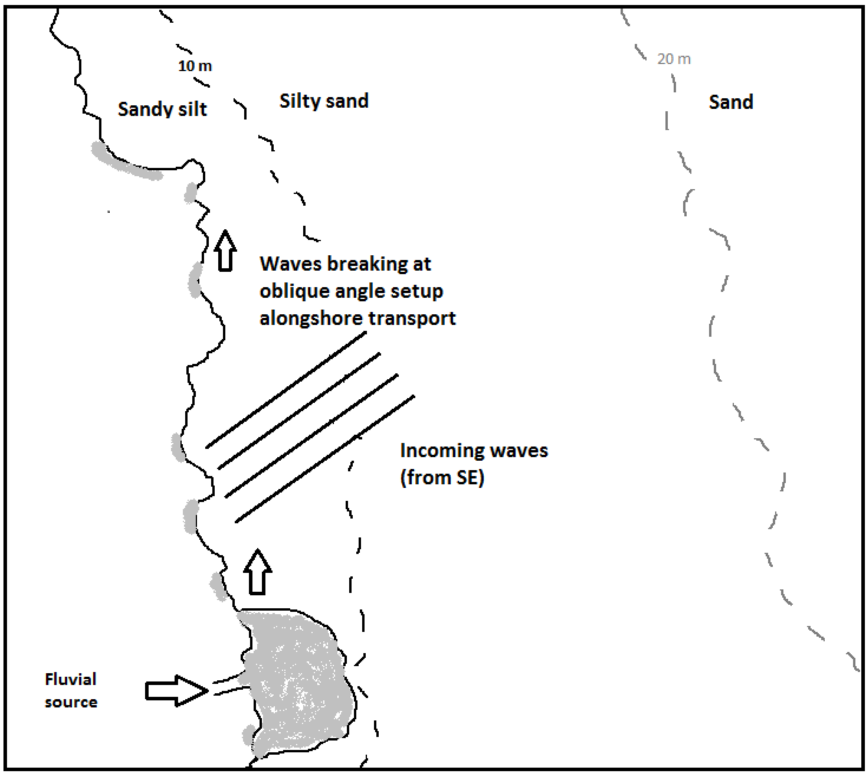


Figure 22 **Schematic littoral sediment pathway on east coast Australia**

3.1.2 Nearshore turbidity pathway

Photographs of the Hay Point region commonly show that the nearshore waters exhibit visible levels of suspended sediments, especially silts.

The re-suspension is not driven by breaking waves as these primarily occur in the very nearshore surf zone – rather the transient orbital flows beneath waves, along with tidal flows acting on the seafloor create a bed shear stress large enough to mobilise fine sediments (< 100 μm; clay, silt, very fine sand). Once these fine sediments are mobilised, Ekman transport driven by the alongshore component of the predominant wind field is able to transport these finer particles northwards along the coastline.

A major sink of these finer particles are the north-facing headlands and small man-made coastal shore protection and navigational structures. This is shown schematically in Figure 23. In this figure the nearshore turbidity zone is shown. This zone of suspended sediments is maintained by relentless re-suspension of 'old' silts on the seabed, enhanced by sporadic wet seasons flood plumes.

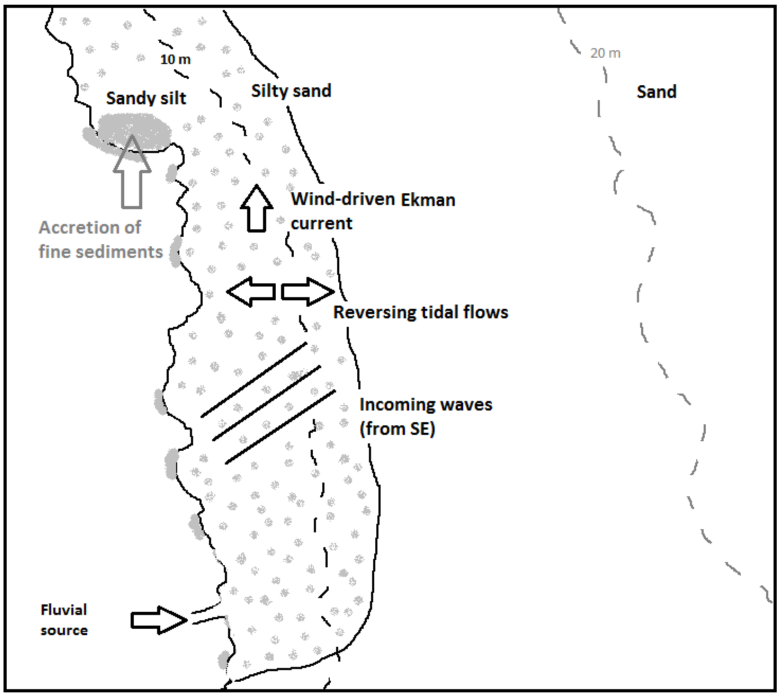


Figure 23 Schematic diagram of the nearshore turbidity pathway showing sink sources of finer particles by north-facing headlands

3.1.3 Inner-shelf bed load pathway

Larger waves (~ 1 m) and stronger tidal currents (> 0.25 m/s) are able to re-suspend larger sand particles. As in the turbidity pathway, once the bed shear stress is sufficient to mobilise sand particles, a near bottom current flow is required to generate the transport of material. The orbital flows beneath waves are by definition rapidly reversing flows, although second-order Stokes drift does lead to very weak average flows in the direction that the waves are propagating. Similarly, semi-diurnal tidal flows reverse around every 6 hours. Hence neither of these processes is necessarily effective at net sediment transport. However, the Ekman transport established during prolonged wind events – the same winds that generated the waves – are able to mobilise the sands and transport these as bedload transport northwards.

This is illustrated schematically in Figure 24 which shows the main dynamical processes that lead to the bedload transport of sands over the inner shelf region during larger (but not extreme) waves and tidal flows.

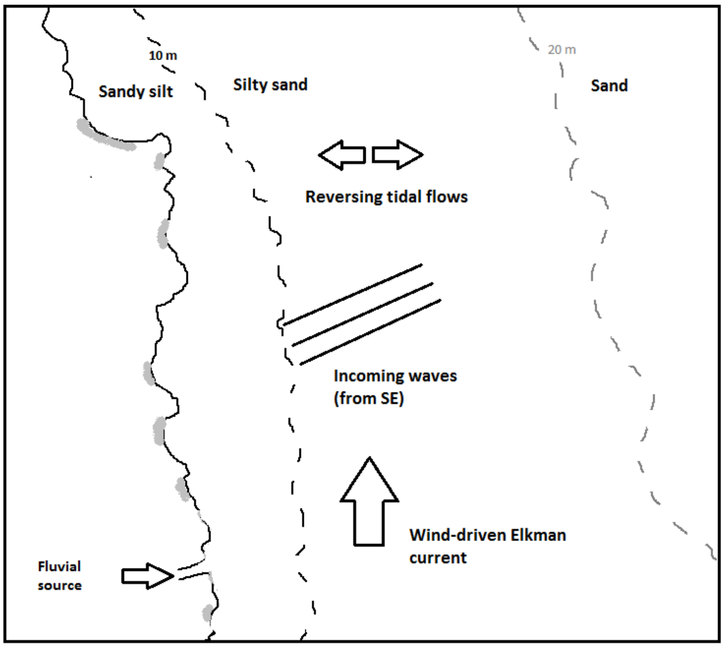


Figure 24 Schematic diagram showing the inner-shelf bedload pathway. This shows the main dynamical processes that lead to the bedload transport of sands over the inner shelf region during larger (but not extreme) waves and tidal flows

3.1.4 Mid-shelf cyclone pathway

Sporadic episodic cyclones are considered to play a major role in the re-distribution of sediments along the GBR shelf. Cyclonic conditions can lead to significant wave heights of > 5 m (>10s period), and currents in excess of 1 to 3 m.s^{-1} (Carter et al., 2009). Gagan et al. (1987; 1990; cited in Carter et al., 2009) observed that following the passage of cyclone Winfred in 1986, large tracts of the seabed were eroded to depths of 15cm or more.

Importantly, the passage of cyclones can mobilise sediments in much deeper depths than any of the other three transport pathways. This also means that the potential area and volume of sediments potentially available for re-suspension is larger by comparison to the other pathways.

The cyclone sediment transport pathway is therefore an infrequent, but impactful mechanism. As highlighted by Larcombe and Carter (2004), over periods of decades and centuries, cyclones therefore represent a dominant sediment transport pathway over the GBR lagoon.

Cyclones can also lead to enhanced catchment rainfall after they cross the coast, and flood plumes containing suspended fine sediments are commonly observed. However the volume of sediment contained in these very thin plumes are typically orders of magnitude less than the volumes of ‘old’ or existing sediment re-mobilised across the shelf. This is schematically presented in Figure 25.

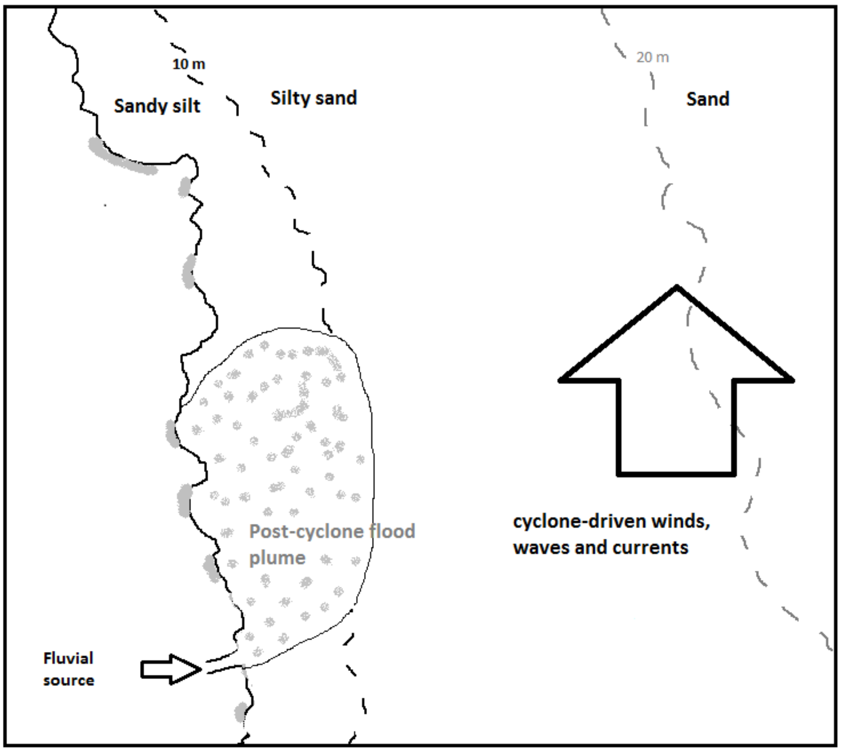


Figure 25 Mid-shelf Cyclone Pathway

These pathways are summarised in Table 1.

Table 1 Sediment transport pathways

Pathway	Grain size	Forcing mechanism	Cross-shore scale
Littoral drift	sand	Breaking waves	0 – 5 m isobath
Nearshore turbidity zone	silt	Small waves (orbital flows), tidal flows, Ekman currents	0 – 10 m isobath (except during flood events)
Inner-shelf bedload transport	sand	Larger waves (orbital flows), tidal flows, Ekman currents	0 – 20 m isobath
Mid-shelf cyclone pathway	sand	Cyclones (extreme waves and currents)	Lagoon-wide

Clearly some of these sediment transport processes can act concurrently. For example, during cyclonic conditions the waves and currents driven by the passage of a cyclone will active all of the individual sediment transport processes. This has been described as the cyclone pump in Larcombe and Carter (2004).

3.1.5 Magnitude of sediment transport pathways

Littoral drift

Littoral transport along the surf zone is one of the major sediment transport pathways on exposed coastlines. Therefore understanding the rate of littoral drift is important in order to understand the connectivity between sediment stores.

It is beyond the scope of this report to undertake extensive numerical littoral sediment transport modelling.

The most useful source of information for littoral drift or sediment transport in the region of Hay Point is from the nearby Mackay Coast Study (hereafter MCS; EPA, 2004). This was a comprehensive investigation that included consideration of the coastal processes in the region.

Figure 26 shows the region that was investigated, in relation to Hay Point. The study region was immediately to the North of Hay Point, and hence the results can be considered in this report.

Figure 26 Location of the Mackay Coast Study in relation to Hay Point (EPA, 2004)

The MCS identified that the major source of 'new' fluvial sediments is the Pioneer River. From Figure 27, it can be seen that discharges from the Pioneer River are one of the smaller sources of new fluvial sediments into estuaries along the GBR coast. Kroon et al. (2012) estimated the present day average suspended sediment load on the upstream side of the estuary to be around 50 kT/y, by comparison to an estimated suspended sediment load to the estuary of the Fitzroy River of 3,400 kT/y. This is because the Pioneer catchment is small (Catchment 125 in Figure 28) compared to catchment 130; the Fitzroy catchment and the Plane catchment, which contains the Port.

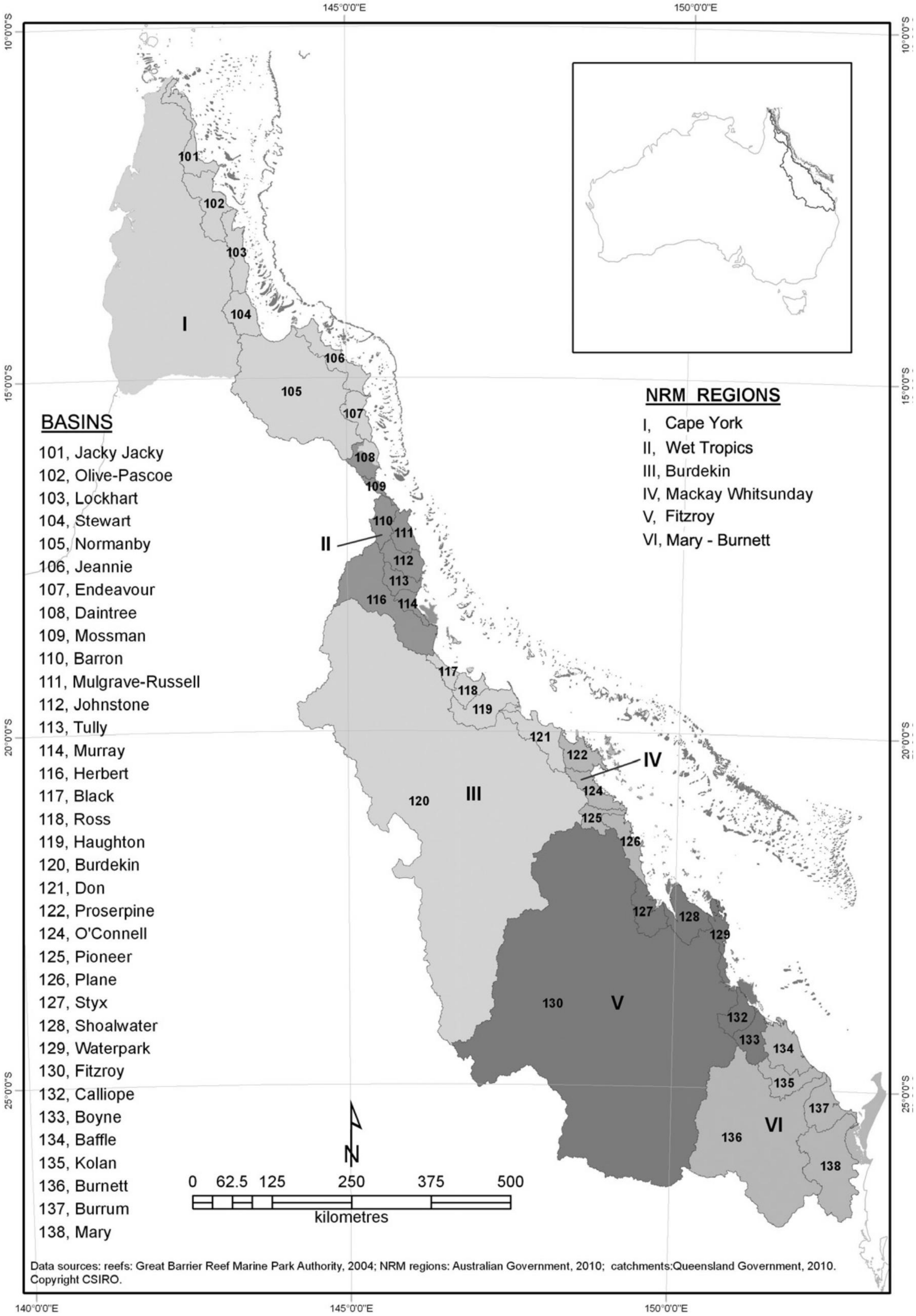


Figure 27 Great Barrier Reef catchment basins (Kroon et al., 2012)

Figure 28 Image of the lower Pioneer River (EPA, 2004)

These estimates are not estimates of either catchment sediment delivery to the coastal ocean, or estimates of alongshore littoral or sediment drift. This is because these estimates do not account for sediments trapped within the estuary/mangrove system, or consider that the littoral drift is a result of wave action rather than sporadic inflows of suspended sediments contained within episodic flood plumes.

Therefore the fact that for example the suspended sediment delivery to the landward side of the Fitzroy estuary is considerably larger than to the Pioneer estuary, it does not then necessarily imply that alongshore sediment transport in the littoral zone around the Pioneer estuary will be less or greater.

Figure 28 shows an image of the lower Pioneer River, extracted from the MCS. The Pioneer River has weirs installed at Dumbleton, Marian and Mirani, and these act to restrict the delivery of coarser sediments to the estuary. However, as seen in Figure 29 the lower reaches of the estuary still store considerable volumes of coarser sediments. These may have accumulated prior to the construction of the weirs, or be the result of flood events when some sediments were able to pass through the weir systems but were still retained in the lower reaches of the waterway.

In the particular case of the Pioneer River, once sediments reach the seaward side of estuary, the training walls established to facilitate navigating during the last century facilitate passage of sediments into the coastal ocean.

To the east and south of the Pioneer River are the Town and Far Beaches, which feature extensive tidal flats. These intertidal areas, sometimes more than three kilometres wide, suggest that much of the historical sediments that pass through the estuary system are retained in these coastal tidal flat stores (MCS 2005).

Along the central GBR coast, coastal areas that are exposed to the dominant south-east trade winds tend to have different sediment properties than coastal areas exposed to winds from the north.

Coastal areas exposed to the south-east trade winds are often classified as ultra-dissipative and composed of fine sands. By contrast, north facing embayment's feature very wide and shallow inter-tidal mud flats areas composed of silts and clay particles. These are often bounded by extensive stands of mangroves. These north-facing embayment's including Bowling Green Bay, Cleveland Bay, and Trinity/Mission Bay are thought to contain accumulative material that was delivered to the coastal zone over geological times-scales and represent substantial sediment stores.

The MCS estimated the littoral drift using the methodology of van Rijn (1989), embedded in the Unibest CL+ modelling system.

This model uses measured wave data and D50 and D90 grain size distributions to estimate the littoral drift. The grain sizes used ranged from 350 to 700 µm for D50, and 750 to 1000 µm for D90.

The MCS estimated typical annual alongshore transport rates of 20 200 to 35 900 m^3/y for different sections of the Mackay coastline. It was estimated that almost all of the littoral drift occur within 500 m of the coastline, as shown in Figure 30.

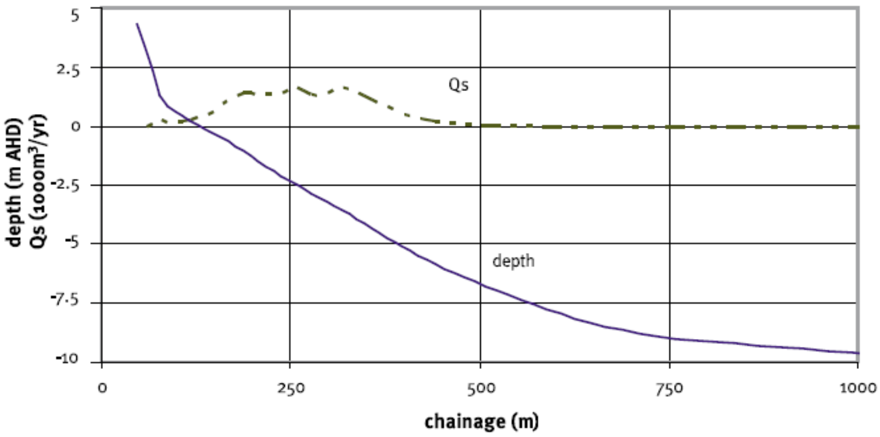


Figure 29 Cross-shore distribution of longshore sediment transport (Q_S) at Harbour Beach (EPA, 2004)

The most studied littoral drift system in Queensland, if not Australia is the Gold Coast region. This is because of the dense urbanisation of the region, high value beaches and importance of keeping key navigation channels such as the Gold Coast Seaway navigable.

The estimated littoral drift of nearshore sediment transport along the Mackay coast is substantially less than by comparison to the estimated transport rates along the Gold Coast of around 500 - 630 $m^{3/}$y. This is because of the relative roles of tides and waves. On the Gold Coast the tidal range on the open coast is small (<2 m), and significant wave height commonly > 2m. By contrast, GBR beaches are classified as tidal dominated in that the tidal range is often > 2m and the wave heights often < 1 m. This is shown in Figure 30. Tide dominated beaches are generally wide and flat and feature smaller grain sizes by comparison to non-tide or wave dominated beaches.

Finally, as the littoral drift only extends typically around 500 m offshore along the GBR coast; major rocky headland can act as barriers to littoral drift. Therefore, whilst littoral drift occurs along many stretches of the GBR coast, it is not a continuous flow of sediment material. Rather, there are relatively short sections where littoral drift occurs, interspersed by barriers in the form of rocky headlands. This accounts for many pocket beaches and small coastal sediment stores that occur along the coast.

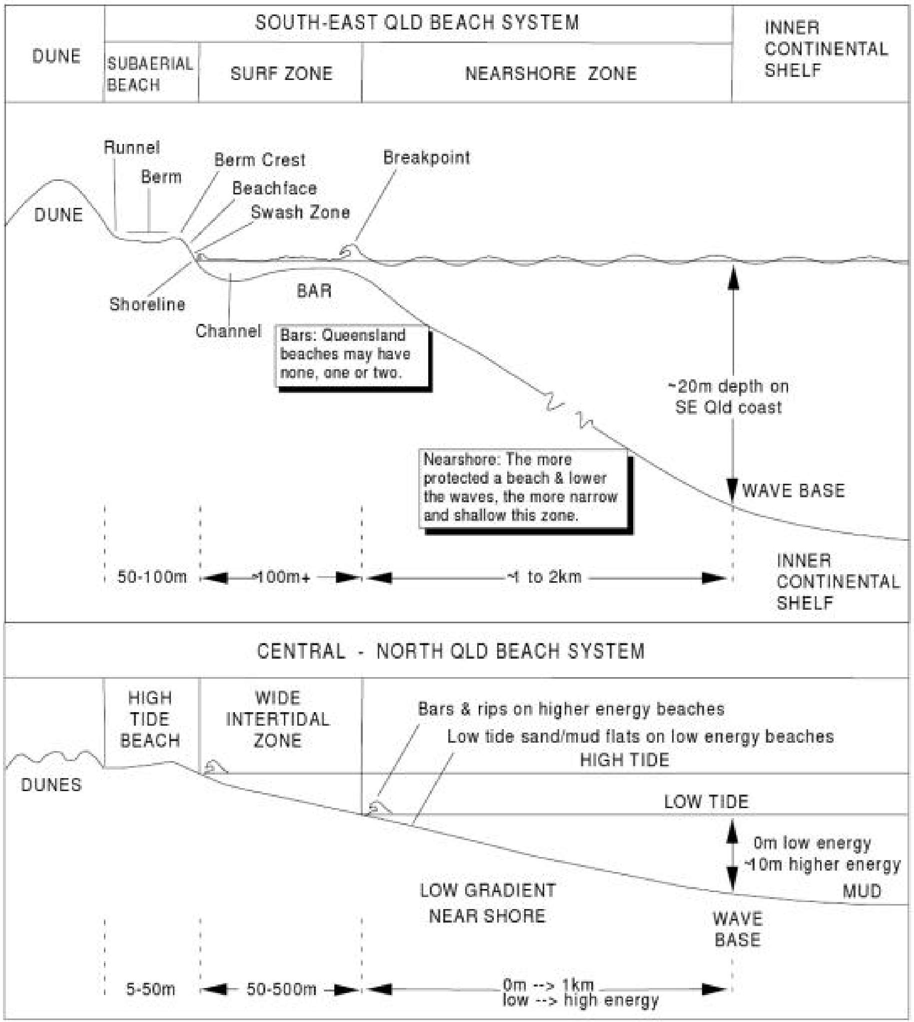


Figure 30 Illustration of two typical Queensland beach systems (Short et al., 1993)

Nearshore turbidity zone

The focus of coastal sediment studies is common only on littoral transport. This is often because many sediment studies are commissioned in order to understand coastal erosion issues. Therefore there is often considerably less effort directed towards understanding the movement of sediments over continental shelves.

In the case of the GBR, the majority of studies that have considered sediment movement have focused on attempting to understand the fate of the relatively small of volume of 'new' fine sediments that enter the GBR lagoon during sporadic flood events.

Therefore, there has been little consideration of the movement of sediment across the lagoon itself. Several studies have considered large scale movement of sediment and changes to bedforms during cyclone events, but there has been little or any consideration of background sediment movement during more ambient conditions.

Therefore, unlike for the littoral transport, there are no obvious previous studies that can be used to provide a first-order estimate of the range of transport rates across the GBR shelf in the central GBR.

Therefore, a modelling exercise was undertaken in order to develop a first-order estimate. It must be highlighted that the objective of this exercise is not to develop and apply a full two or three dimensional regional numerical sediment transport model as this is beyond the scope of this study.

Rather, a first-principles approach coupled with a well-accepted one dimensional numerical model has been used in order to understand the fundamental dynamical process acting over the inner shelf region of the central GBR.

The key variables for understanding the shelf sediment transport are the wind and wave climate, the tidal variability and the underlying sediment grain size.

In order for sediment transport to occur, the sediment must first be potentially available for transport through being re-suspended. Once re-suspended, current flows are required to transport or advect the suspended or bed load sediments.

Re-suspension and transportation do not have to be performed by the same coastal processes. As shown in Figure 31, often a combination of processes is required. Tidal flows can be effective at re-suspending particles, but as a result of the fact that they reverse every 6 hours can be in-effective at transporting sediments over long distances. Tidal residual or tidally averaged flows are often small and hence ineffective at sediment transport.

Similarly, local winds can generate waves as a result of the transient orbital currents that occur beneath waves passing over shallower waters. However these transient orbital currents are generally ineffective at net sediment transport. Hence whilst these flows can re-suspend sediments, they are generally inefficient at transporting the re-suspended sediments.

The winds that generate the local waves can also generate along-shore current flows through Ekman transport. These along-shore currents can be effective at transporting re-suspended sediments.

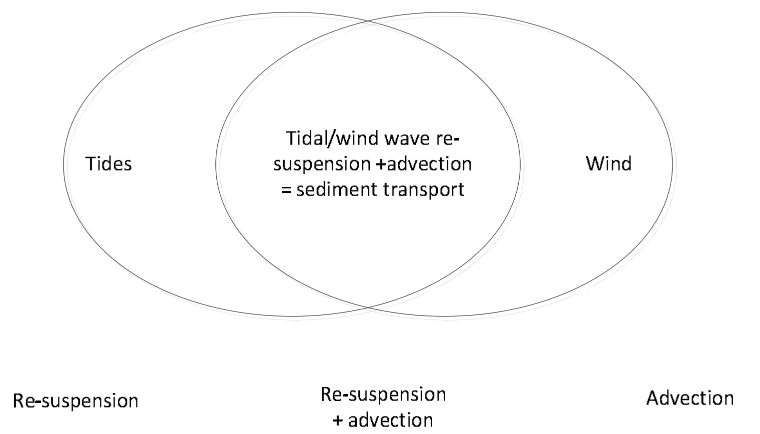


Figure 31 Diagram showing influences of re-suspension and transportation

The actual sediment transport therefore often requires multiple oceanographic processes. Hence, the assessment, prediction, or hindcasting of sediment transport across continental shelves needs to consider all of these processes.

These fundamental driving processes for the Hay Point region are described below

<u>Characteristics of the wind field</u>

The characteristics of the wind field play a major role in determining the sediment transport characteristics, and therefore the distribution of sediments in the central GBR.

Wind data from Mackay airport was extracted from the Bureau of Meteorology database for the period 1975 – June 2015.

A key source of variability in weather along the GBR coast is the inter-annual ENSO (El Nino Southern Oscillation, Hendon et al., 2009). During El Nino conditions the Queensland coast generally experiences less cyclones and lower rainfall. La Nina conditions are generally expected to result in stronger and more persistent south-easterly trade winds.

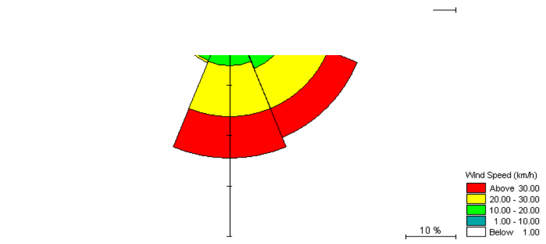
It is recognised that the inter-decadal Pacific oscillation (IPO) plays a role in influencing the strength of ENSO events. For example, cyclone activity is often stronger during the negative phase of the IPO (Callaghan and Power, 2010). Therefore the wind data was clustered into specific El Nino and La Nina years (Table 2, Figure 32 and Figure 33).

Table 2 Wind data from El Nino and La Nina years

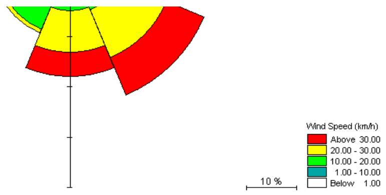
El Nino		La Nina	
Strong	Very Strong	Strong	Very Strong
1987-88	1982-83	1998-99	1975-76
	1997-98	2007-08	1988-89
			1999-00
			2010-11

El Nino

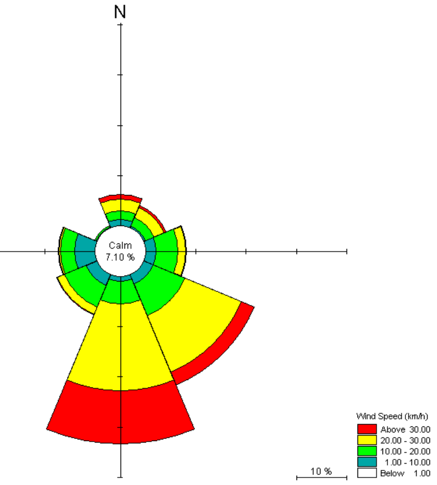
1987 (strong El Nino)



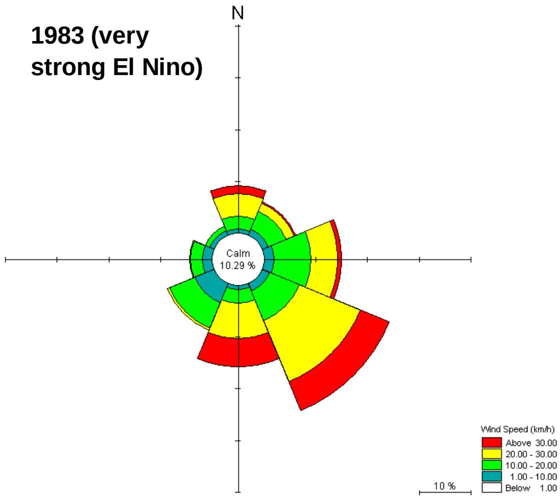
1988 (strong El Nino)



1982 (very strong El Nino)



1983 (very strong El Nino)



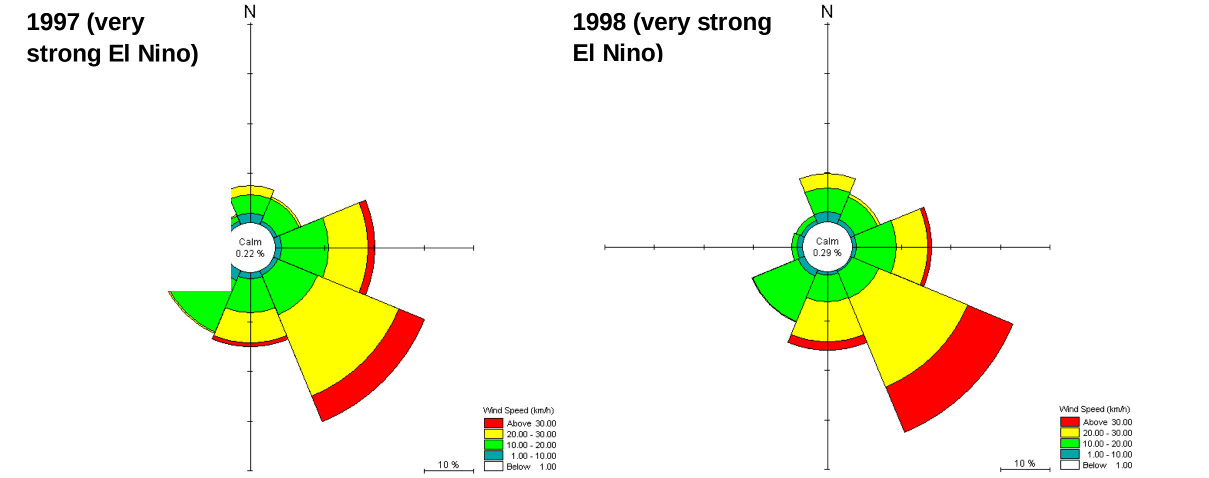
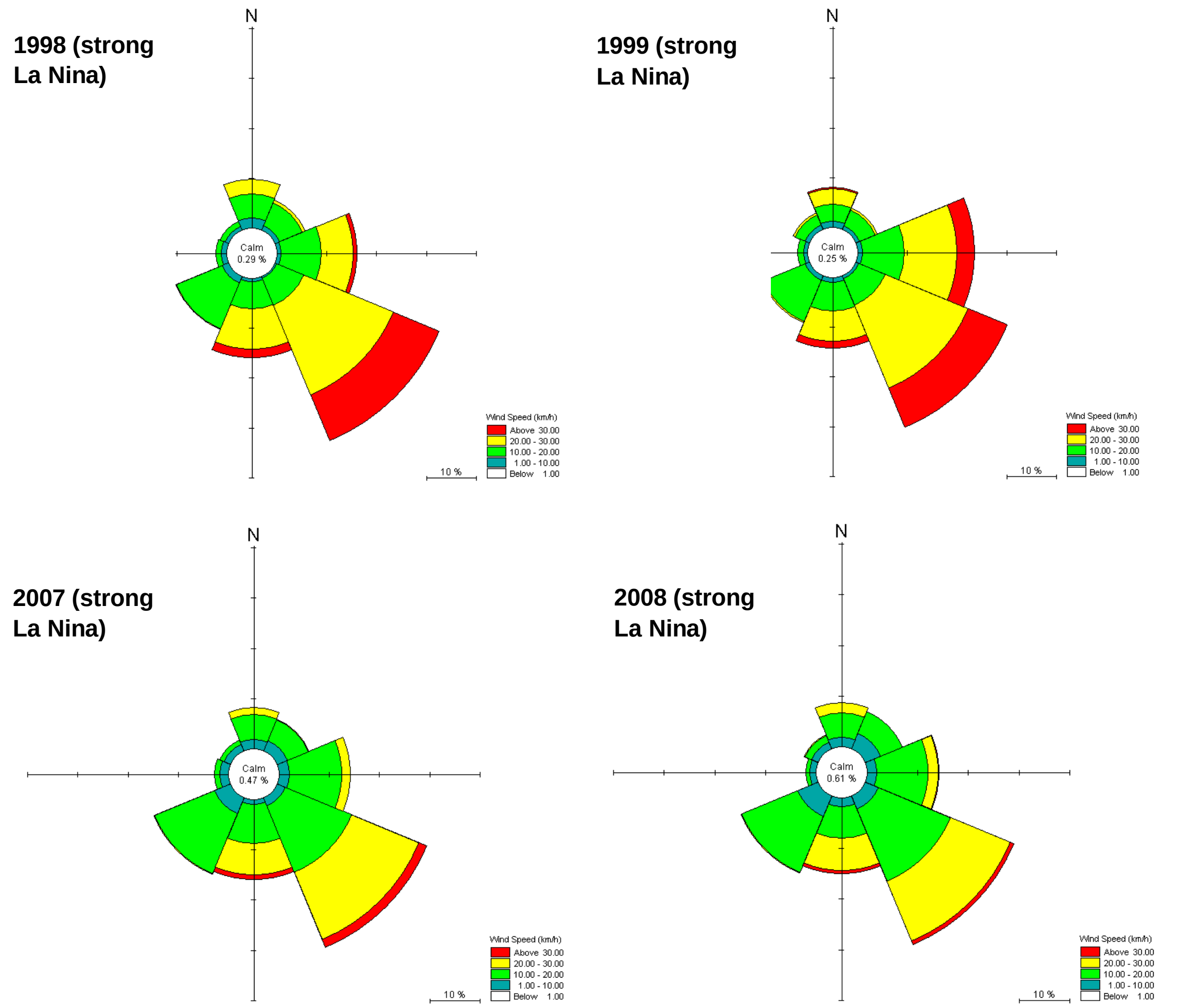
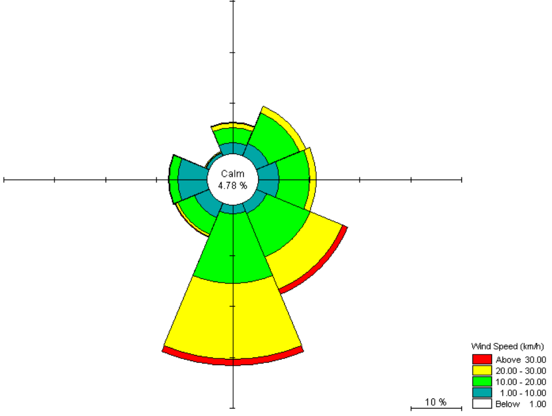


Figure 32 **Wind roses from Mackay airport during El Nino years**

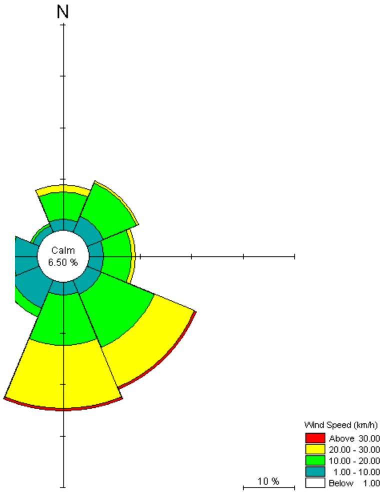
La Nina (stronger trade winds)



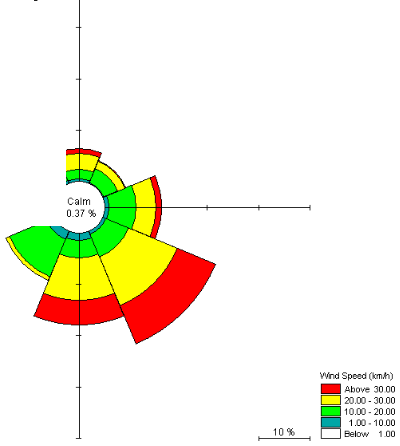
1975 (very strong La Nina)



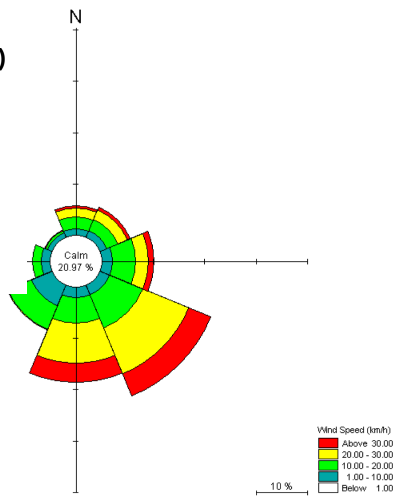
1976 (very strong La Nina)



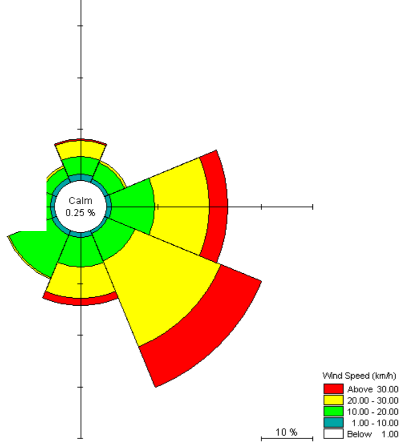
1988 (very strong La Nina)



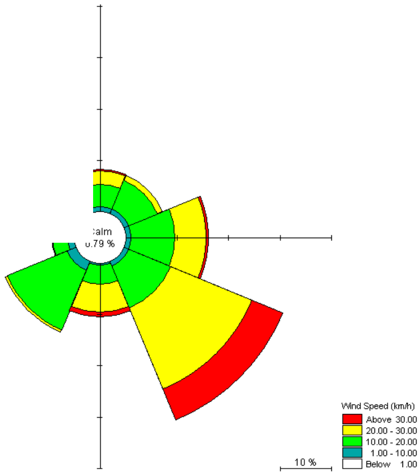
1989 (very strong La Nina)



1999 (very strong La Nina)



2000 (very strong La Nina)



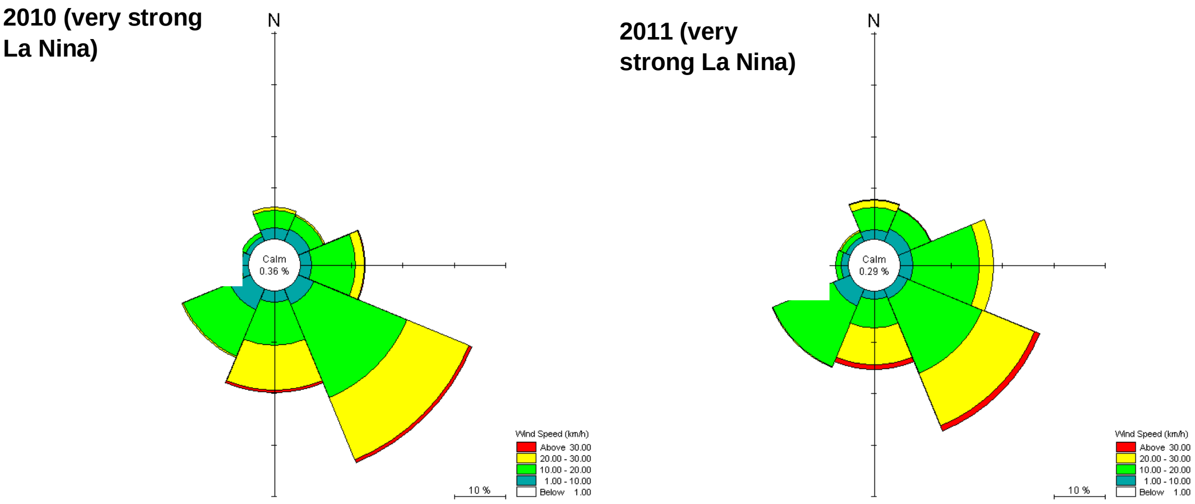


Figure 33 Wind roses from Mackay airport during La Nina years

Mackay Airport 1975 – 2015

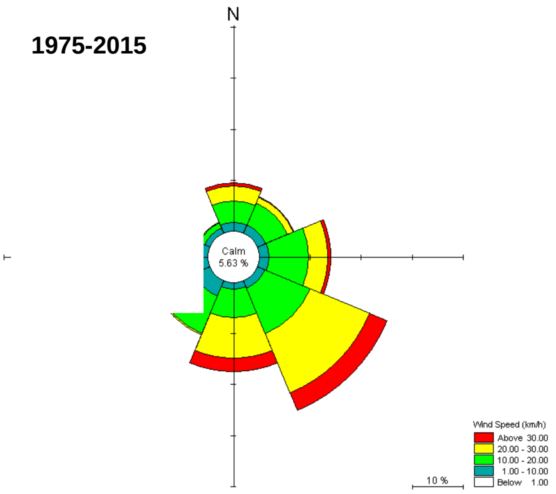


Figure 34 Wind rose from Mackay airport for 1975 - 2015

Figure 32 and Figure 34 demonstrate the dominance of the wind climate by the south-easterly trade winds, followed by winds from the south. North-westerly winds occur very infrequently.

The El Nino and La Nina wind roses do not display obvious differences. The mean and median wind speeds for the El Nino and La Nina years were therefore calculated (Table 3).

The results shown in Table 3 shows that for the years 1975-2015, there was little difference in either the median or mean wind speeds during El Nino as opposed to La Nina years.

Table 3 Mean and median wind speeds for El Nino and La Nina years

ENSO state	Years	Median (mean) wind speed [km/h]
El Nino	1987-88 (strong)	18.4 (19.2)
	1982-83 (very strong)	20.5 (19.7)
	1997-98 (very strong)	18.2 (19.6)

ENSO state	Years	Median (mean) wind speed [km/h]
La Nina	1998-99 (strong)	18.3 (18.9)
	2007-08 (strong)	14.8 (16.1)
	1975-76 (very strong)	13.0 (14.3)
	1988-89 (very strong)	18.4 (20.5)
	1999-00 (very strong)	20.5 (20.6)
	2010-11 (very strong)	14.8 (16.0)

Strong wind events in the region are commonly associated with cyclone events.

Strong wind events measured at Mackay as captured in the wind data set are shown in Table 4 and represented graphically in Figure 35. Named cyclones that occurred in the region at the time have also been identified.

From this table is can been seen that the majority of events where sustained wind speed were over 60 kph were associated during the warmer months and a result of cyclone activities.

Table 4 Strong wind event data (> 60 kph) captured at Mackay airport

Date	Cyclone
17 January 1975	Cyclone Gloria
17 February 1977	
3 February 1978	
11 January 1979	Cyclone Gordon
1 March 1979	Cyclone Kerry
30 September 1996	
9 March 1997	Cyclone Justin
28 June 2003	
14 February 2005	Cyclone Nancy
26 October 2008	
21 March 2010	Cyclone Ului
30 January 2014	Cyclone Dylan

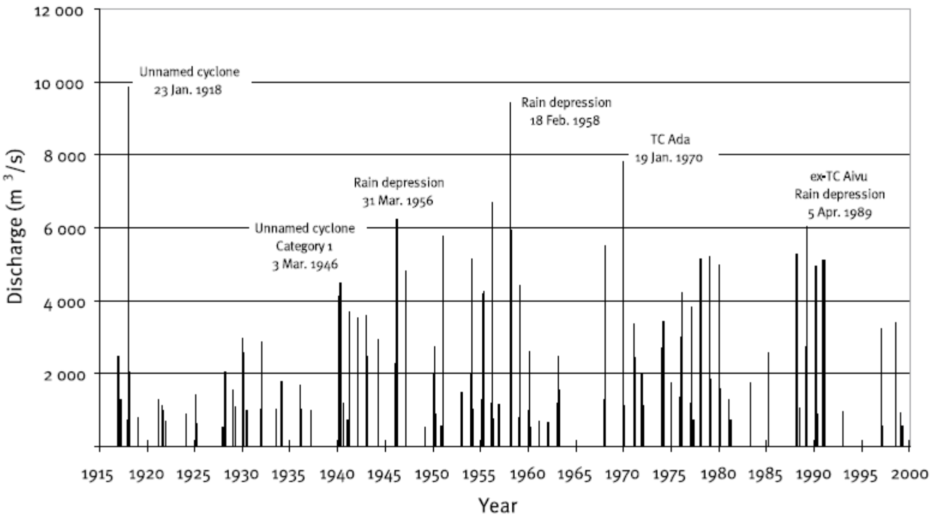


Figure 35 Pioneer River peak flood discharge data at Mirani with corresponding cyclonic information (EPA, 2004)

<u>Characteristics of the Wave Field</u>

As described in the previous section, waves are an important mechanism for controlling the distribution of sediment through two processes:

- In the littoral zone (0.5 -1 km from the shore) breaking waves mobilise sediments and if the waves strike the shore at an oblique angle then these mobilised sediments can be transported alongshore the shoreline (littoral drift).
- Over shallower parts of the inner shelf region, orbital flows beneath waves can be strong enough to routinely mobilise finer sediments. During extreme events such as cyclones, larger waves can mobilise large tracts of the seabed.

The wave climate over the shelf in the central and southern GBR is strongly influenced by the outer reefs that act as significant wave attenuators (Gallop et al 2014), meaning that the propagation of ocean swell waves into the GBR coastline can be very sporadic and spatiality variable. This also means that for much of the inner shelf and coastline, the wave climate is dominated by locally forced waves, or waves that are generated by the local winds as opposed to long ocean ground swells that are generated from winds blowing in faraway regions. This does not imply that large waves never occur inside the GBR lagoon. Sporadic cyclone events have been shown to generate large waves inside the GBR lagoon.

Mackay data from the Queensland Government wave-rider buoy at Hay Point was acquired for the period 1975-June 2015. Figure 36 shows the distribution of the significant wave heights for the full dataset. The solid line in these plots shows the cumulative contribution. For this figure at can be seen that almost all of the waves measured were less than 1.5 m significant wave heights, and 80% were 1 m significant wave height or less. The most common wave significant wave height was 0.3 m.

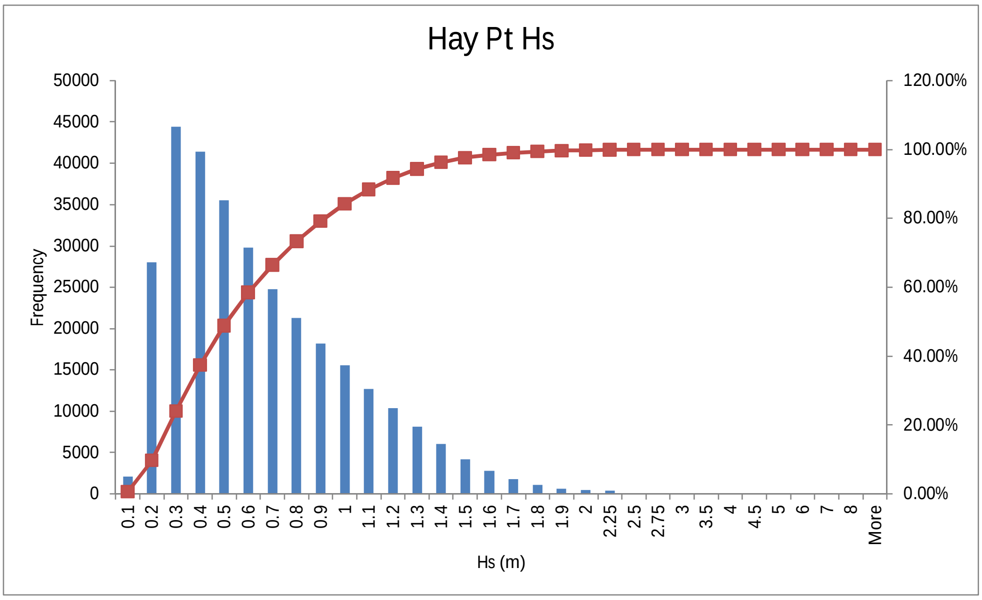


Figure 36 **Significant wave height histogram for Mackay (graphed from data available from the Queensland Government, September 2015)**

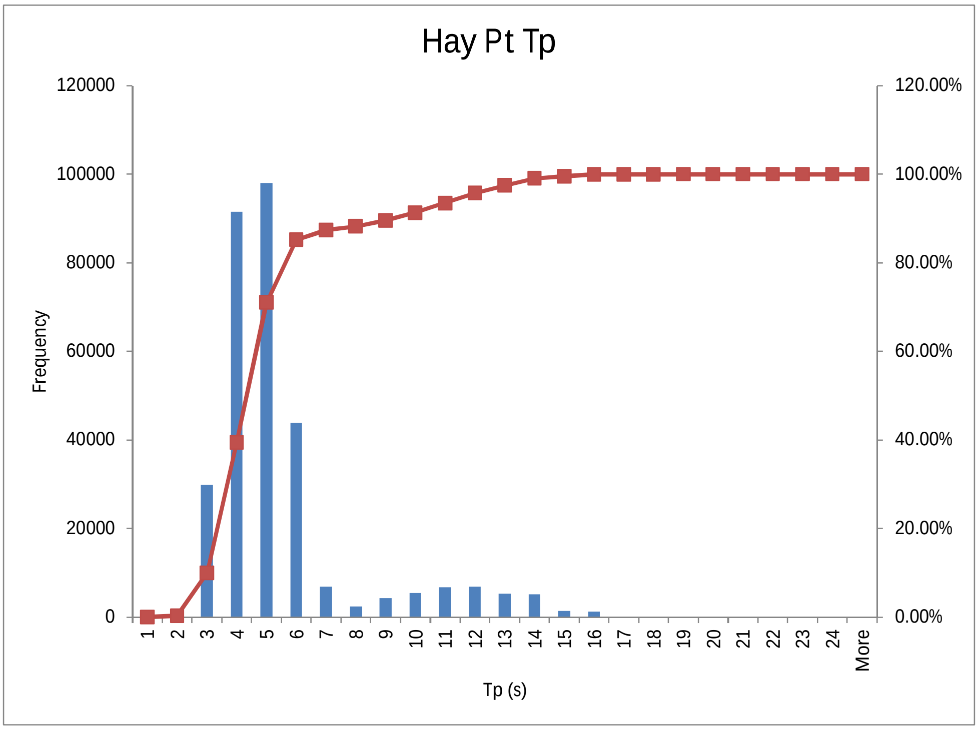


Figure 37 **Wave period histogram for Mackay (graphed from data available from the Queensland Government, September 2015)**

Figure 37 shows the wave period from the same dataset. The most common wave specific period was 5 s. Once again, 80% of the waves were of period 5 s or less.

The histogram also shows evidence of longer period ground swells of periods of 10-14 s. These are likely to be ocean swells that have managed to traverse through the outer reef. The average significant wave heights of these swells were 0.1 to 0.3 m.

The largest wave height events were identified in the dataset and these are shown in Table 5.

Table 5 Largest recorded wave height events (Mackay)

Data	Hs (Tz)	Details
21 March 2010	5 - 6 m (8 -9 s)	Cyclone Ului (Cat 3 when crossed coast at Airlie Beach)
9 March 1997	3 m (6 – 7 s)	Cyclone Justin (crossed North of Cairns as Cat 2)
16 February 2008	2.8 m (6.5 s)	Cyclone Gene (did not cross Qld coast but most deadly South Pacific storm of 2007-2008 summer.

Of these events, Cyclones Ului and Justin also featured sustained strong wind events that were recorded in the Mackay aero-wind dataset.

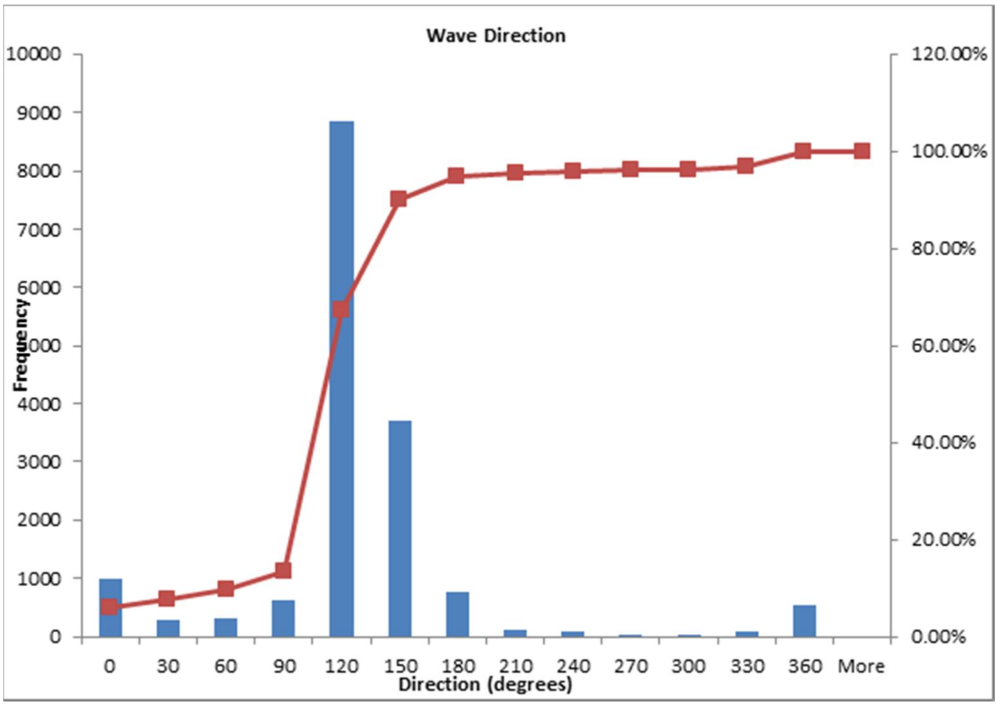


Figure 38 Wave direction histogram for Mackay (graphed from data available from the Queensland Government, September 2015)

Figure 38 shows the distribution of wave directions. The direction here uses meteorological oceanographic conventions in the wave direction refers to the direction in which waves are coming from.

Around 90% of waves at Mackay arrive from the south-east quadrant. Figure 39, taken from the MCS, shows fetch data demonstrating that the dominant wave direction is 120°T.

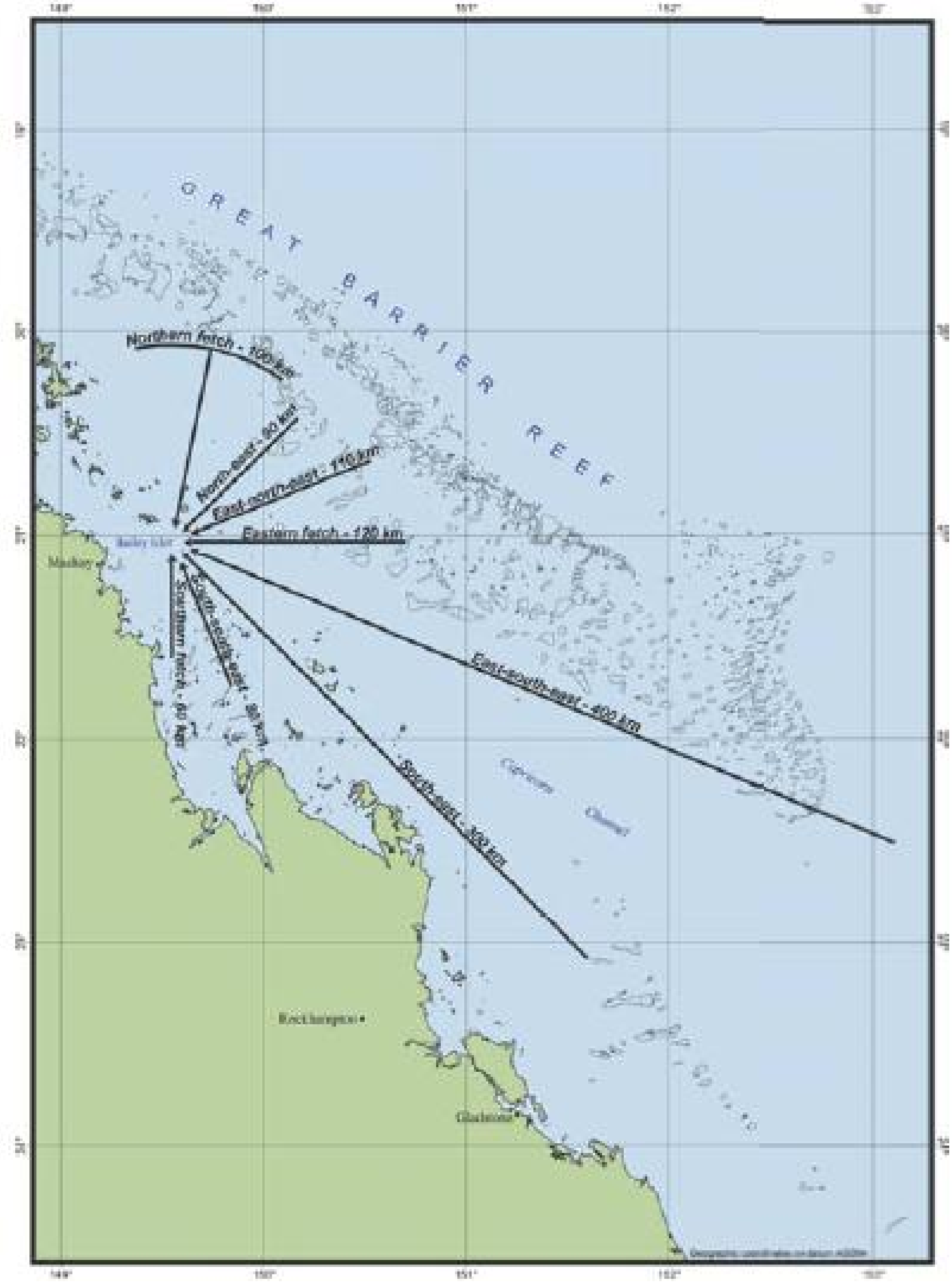


Figure 39 Fetch distances at Mackay (EPA, 2004)

3.2 Shelf sediment transport key features

The wind, wave and tide information was used as inputs into the Sedtrans05 (Neumeier et al. 2008) one-dimensional numerical model. Sedtrans05 is used globally as both a stand-alone model, and as the basis for sediment re-suspension and transport algorithms in a number of well-known three-dimensional numerical hydrodynamic models.

In this application Sedtran05 was used to predict re-suspension and generation of suspended and bedload sediment concentrations based on the wave and tide data. The wind data was used to develop estimates of the actual sediment transport.

A number of diagnostic calculations using Sedtrans05 were firstly performed in order to gain a better understanding of the principal processes of sediment re-suspension in the region.

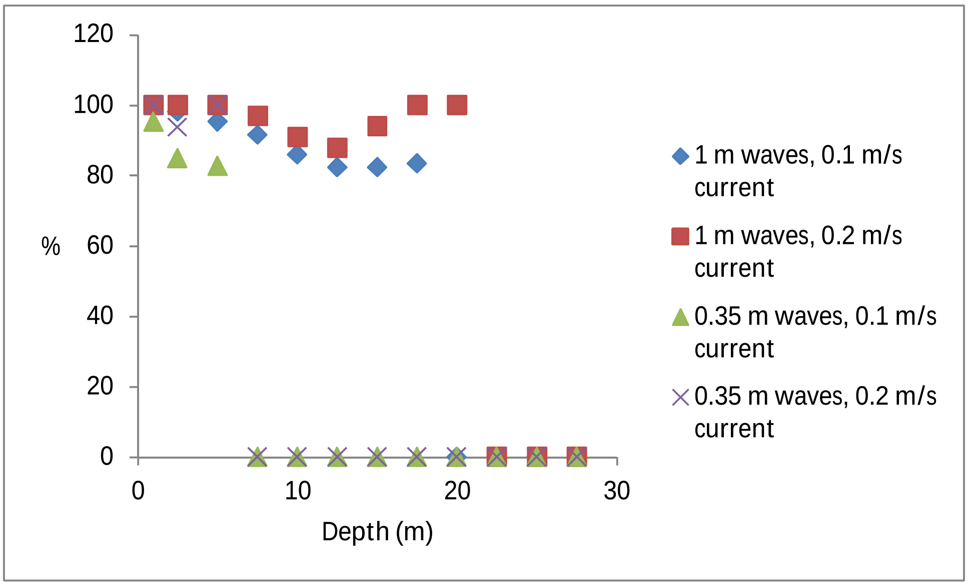


Figure 40 Cross-shore distribution of sediment transport potential for D50 of 100 µm

Figure 40 shows the cross-shore distribution of sediment transport potential for different combination of waves and currents for a D50 grain size of 100 µm developed from the Sedtrans05 model. The vertical axis shows the percent of time that either suspended or bedload transport is occurring under these conditions.

For this median grain size, even the smaller wave and current conditions are able to mobilise sediments out to depths of around 8 m. During slightly larger wave conditions (1 m significant wave height), sediment of this median grain size can be re-suspended to depths of over 20 m. The inshore extent of the main wharf at the Port is located in water depths of around 17m. However, the continental shelf upstream (to the south) shallows out and, therefore, sediments mobilised in waters between 10 and 20m depth upstream can potentially find themselves in the channel and berth pockets.

It is important to highlight that this does not imply that the whole water-column will appear turbid during these conditions. Rather, it does imply that sediment will be available for transport in the water-column.

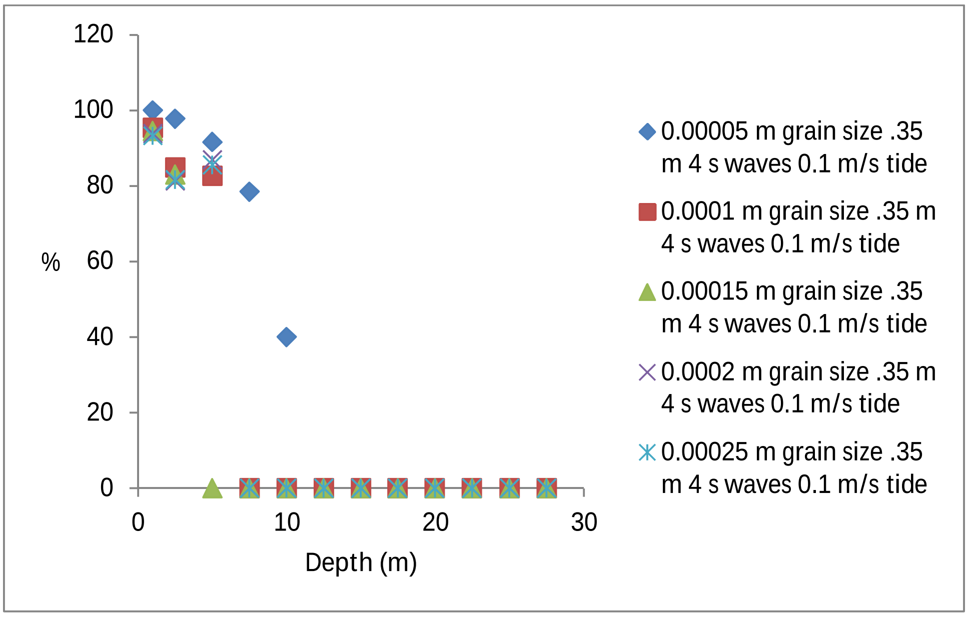


Figure 41 Cross-shore distribution of sediment transport potential for a range of grain sizes under low wave and current conditions

Figure 41 shows the cross-shore distribution of sediment transport potential for a range of D50 grain sizes from 50 µm (silt) to 250 µm (sand) under small wave and low current conditions.

Under these low energy conditions the finer fractions are available for re-suspension out to depths of at least 10 m. By contrast for the larger sand fractions under these low energy conditions the sediment transport potential is restricted to depth of less than around 6 m. With regards to Hay Point the berth pockets are located in surrounding depths of around 11 m LAT and hence during low energy conditions the sand fractions are not expected to be mobilised along the length of the main channel.

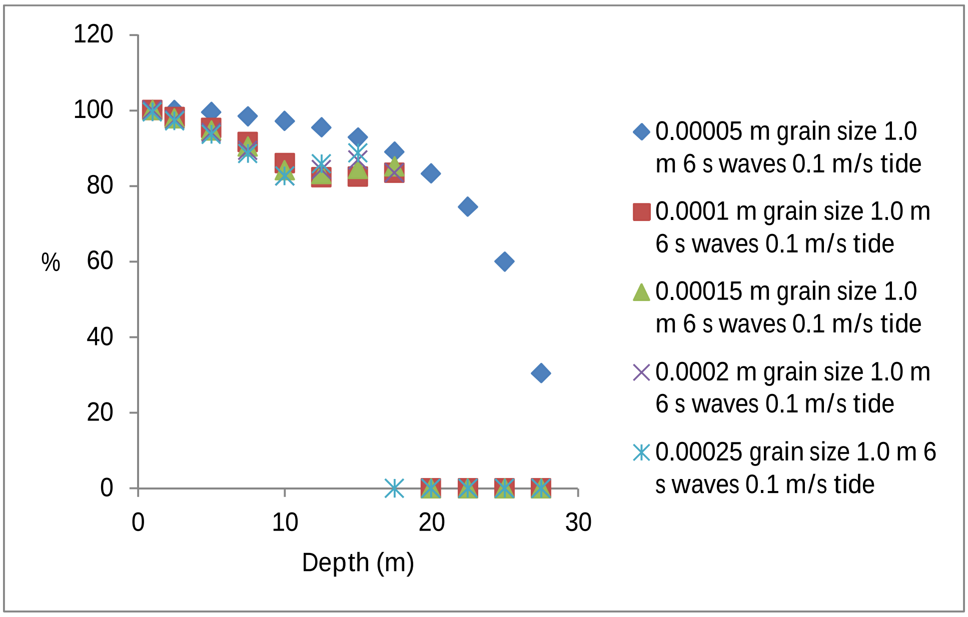


Figure 42 Cross-shore distribution of sediment transport potential for a range of grain sizes under moderate wave and low current conditions

Figure 42 shows the same information but for medium waves (1 m significant wave heights).

Under these conditions the finer silt fractions are available for re-suspension and transport out to depths of nearly 30 m. Similarly, the finer sand fractions are available for re-suspension and transport out to depths of 20 m. The end of the Hay Point dredged channel is in depths of around 15 m LAT. Therefore during these more moderate conditions (that occur around one third of the time), even finer sand fractions are available for transport along the shelf surrounding the channel.

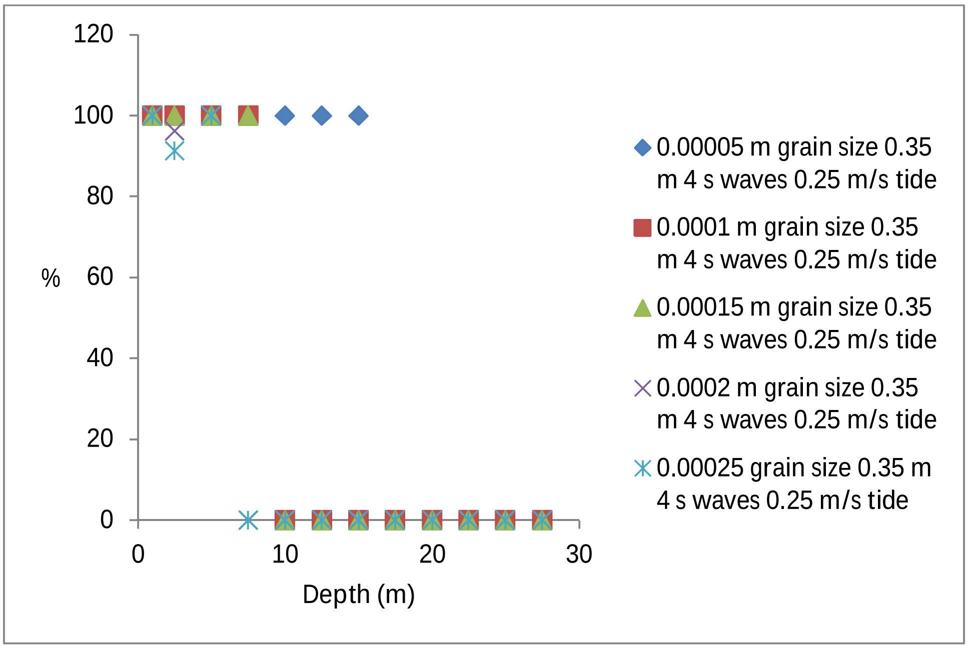


Figure 43 Cross-shore distribution of sediment transport potential for a range of grain sizes under low wave and stronger current conditions

Figure 43 shows the same information but for slightly stronger tidal flows (average of 0.25 m s^{-1}). Under these conditions the finer sands are available for transport out to depths of around 10 m. Silt fractions are available for transport to depths out to at least 16 m, which means that for Hay Point silt fractions would be re-suspended along the shelf either side of the main channel under these conditions.

Simulations of larger cyclone-type swells (3 m significant wave height, 7.2 s period) for grain D50 of 0.0002 m and 1 m/s flows revealed that re-suspension was 100% for depths out to at least 25 m under these conditions.

The implications of these diagnostic simulations for the identified sediment transport pathways are identified in Table 7 Littoral drift was not modelled as Sedtrans05 does not simulate breaking waves.

Table 6 Implications for sediment transport pathways

Pathway	Implications – small waves/currents	Implications – larger waves/currents
Littoral drift	Not modelled	Not modelled
Nearshore turbidity zone	Winds and waves can re-suspend and transport sand particles out to depths of 6 m	Stronger winds and waves can re-suspend and transport finer silt particles out to depths past 20 m of depth
Inner-shelf bedload transport	In milder conditions only smaller sand particles re-suspended in shallow depths (< 5 m)	Stronger winds and waves are able to re-suspend sand particles but only in shallower depths (<5-6 m)
Mid-shelf cyclone pathway	n/a	Cyclone conditions lead to re-suspension of sand out to depths at least 25 m

3.2.1 Grain sizes

The diagnostic simulations identified the changes to rates of re-suspension for different grain sizes. Grain size measurements for the region are discussed in this section.

Regional Grain Size

Using the results from Mathews et al. (2007), the sediment distributions were clustered into four areas, as shown in Figure 44.

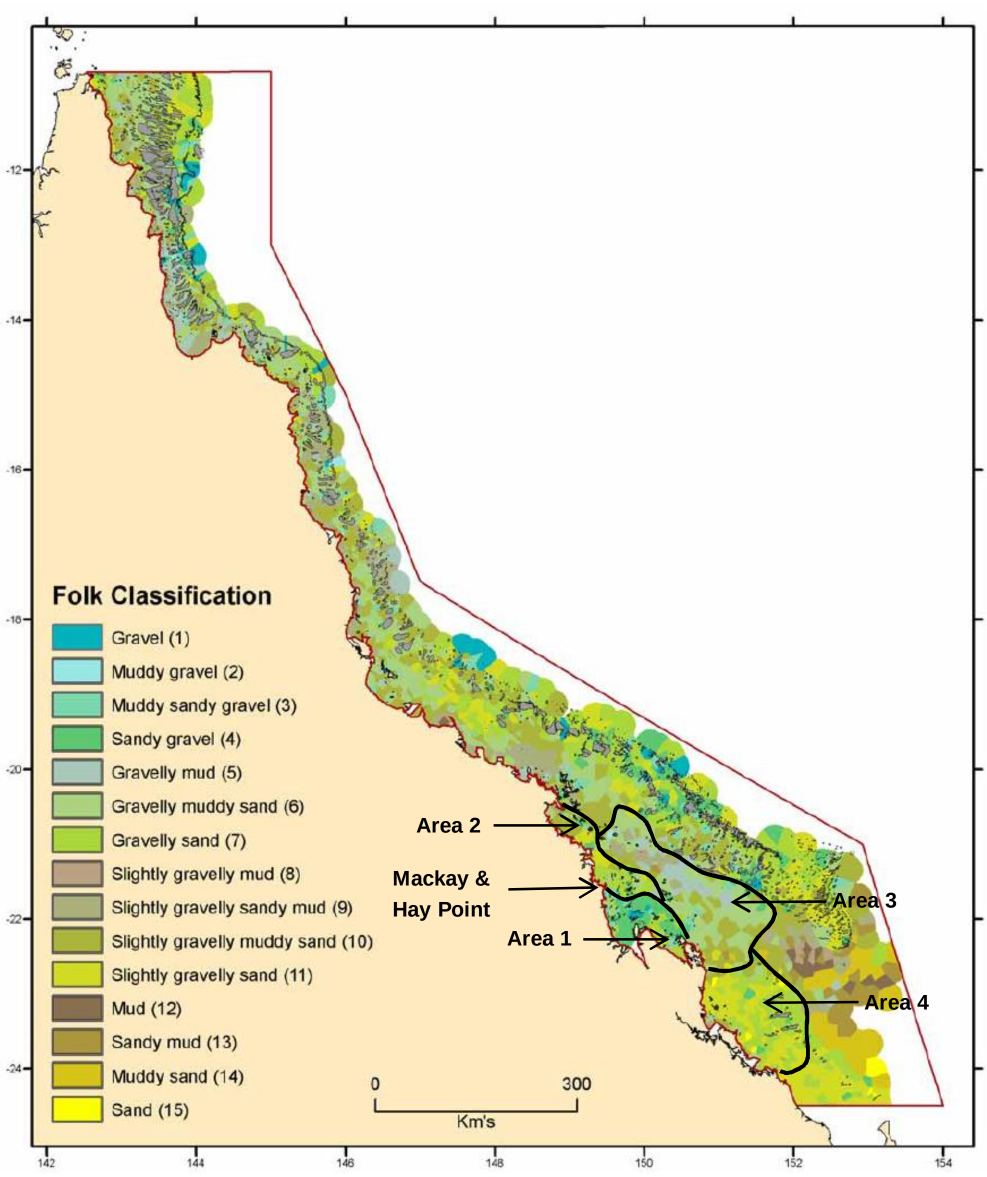


Figure 44 Areas of different sediment classifications (using the Folk Classification) in the GBR (Adapted from Mathew et al., 2007)

Figure 45 to Figure 48 show the D50 (median) and D90 (90th percentile) grain sizes for the four areas.

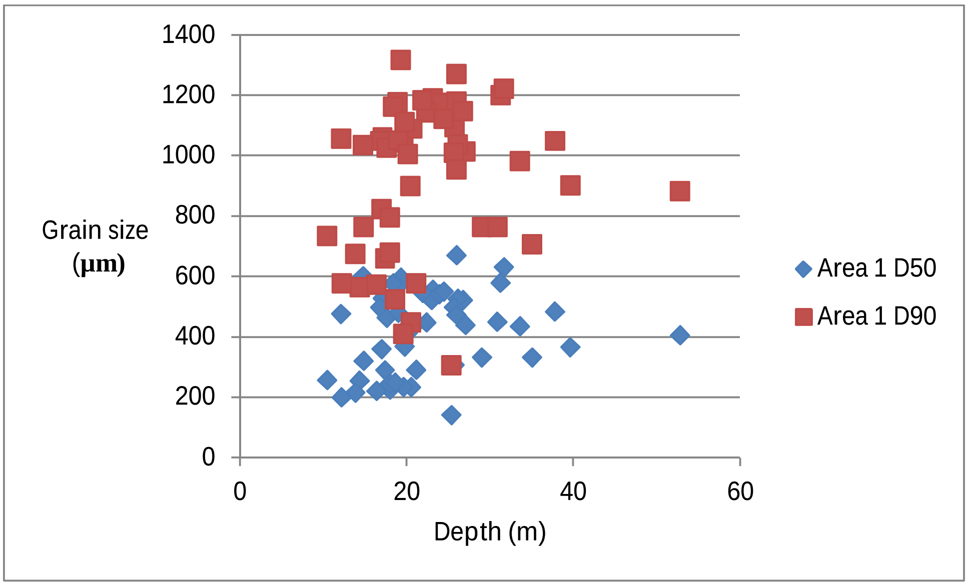


Figure 45 **D50 and D90 grain sizes (Area 1)**

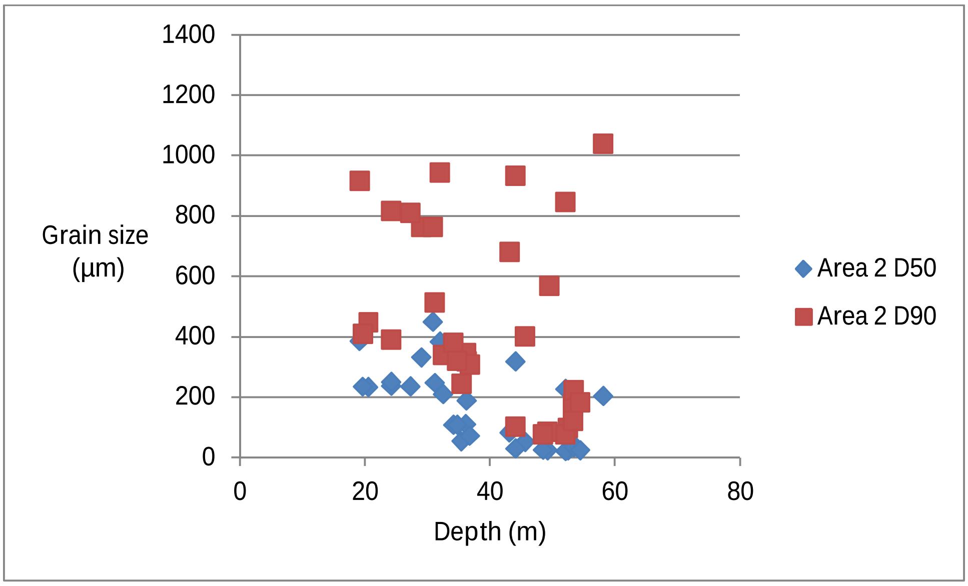


Figure 46 **D50 and D90 grain sizes (Area 2)**

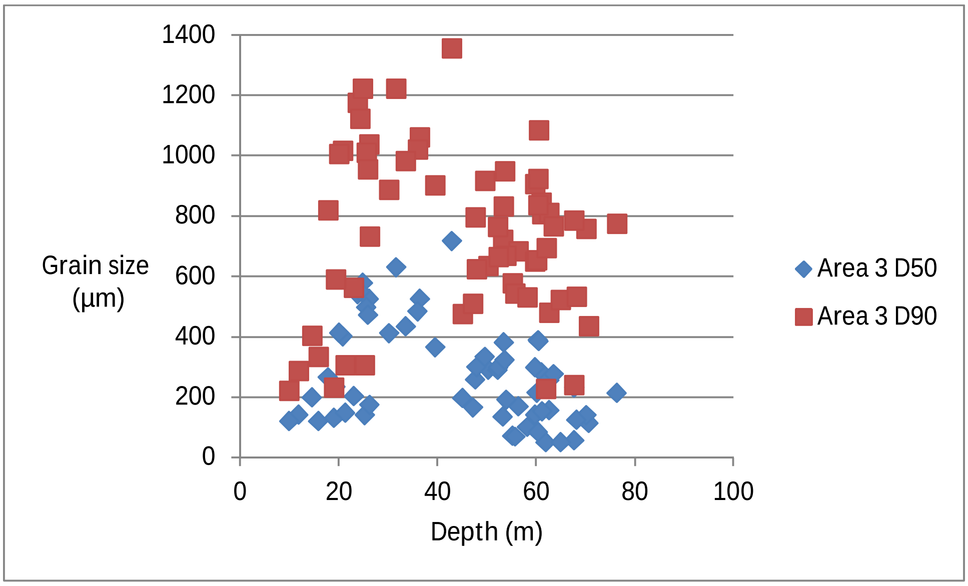


Figure 47 **D50 and D90 grain sizes (Area 3)**

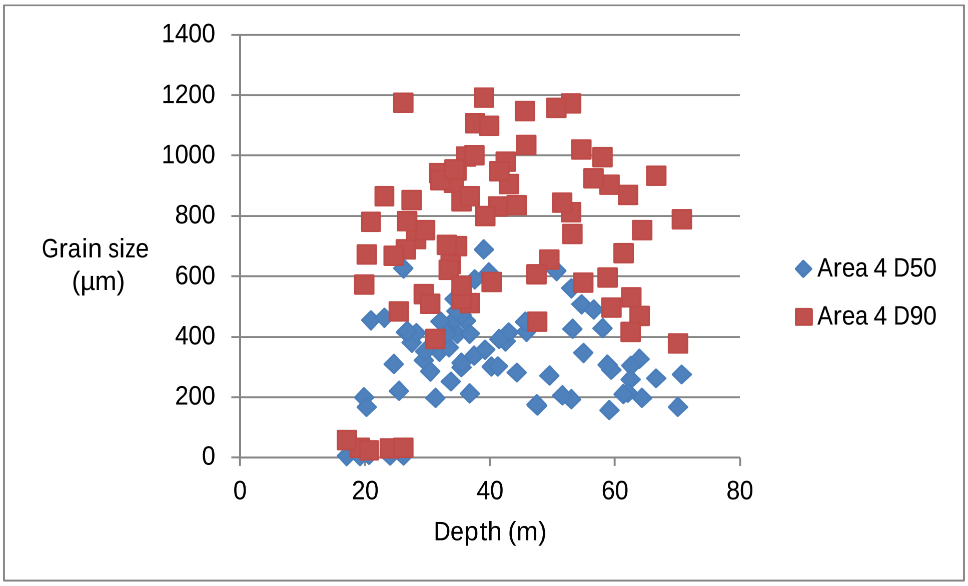


Figure 48 **D50 and D90 grain sizes (Area 4)**

Inspection of the grain size distributions reveals the following key attributes:

Area 1 encapsulates the region of strong tidal flows and gravels identified in the GA report. This is reflected in the D50 and D90 distributions that reveal little contribution from the smaller size fractions.

Similarly, Area 4 that included Keppel Bay and offshore of Curtis Island also displays consistently larger grain sizes (> 200 µm) except for the very nearshore shallow areas.

Area 2, located over the middle and inner shelf off Hay Point features a range of grain sizes, including size fractions < 50 µm at several locations over the middle shelf.

Area 3, located north of Keppel Bay also features a range of grain sizes with many of the small size fractions located in the deeper middle shelf region.

These measured grain sizes are generally consistent with the regional maps shown previously in Figure 17, which were developed using many of the samples. A key conclusion from both these sediment distribution maps, and the individual samples is that there is considerably more spatial variability in the distribution of sediments by comparison to more northern regions of the GBR lagoon.

Hay Point Local Grain Size Distribution

The most recent investigation of the sediment characteristics of the port itself can be found in the 2013 report: Port of Hay Point: Sediment Characterisation Report - 2013 (Ports and Coastal Environmental, 2013).

In total 97 samples were submitted for analysis. The samples were clustered into the areas identified in Table 7.

Table 7 Locations of sediment samples taken from Hay Point

Location	Depth range (m)
HP1 (Berth 1; Hay Pt)	21
HP2 (Berth 2; Hay Pt)	21
DBCT 3/4 (Dalrymple Bay Coal Terminal)	17 – 22
HTA (Half Tide Approaches)	7 - 9
HTB (Half Tide Berth)	7 - 10
Apron	21
Dep Path (Departure path- channel)	21

The aggregated grain size distributions are shown in Figure 49. The key results from this program, in terms of grain size, can be summarised as:

- The outer sites in the departure path (main navigational channel) are dominated by sand fractions (2 mm – 0.06 mm).
- The berth pockets, especially HP 1 are dominated by gravels and sands. The gravel content suggests strong tidal currents flows through this area.
- By contrast, the sheltered water of the Tug harbour and DBCT Berths 3 and 4 featured high silt and clay content.

These results are consistent with the early models of Belperio (1983) that highlight accumulation of fine silts and sands in areas protected from tidal flows and waves driven by the predominant south-easterly trade-winds. Inshore areas (<20 m) exposed to reasonable tidal flows and south-easterly trade-winds often feature sandy substrates, and high gravel context especially in areas of high tidal current flows.

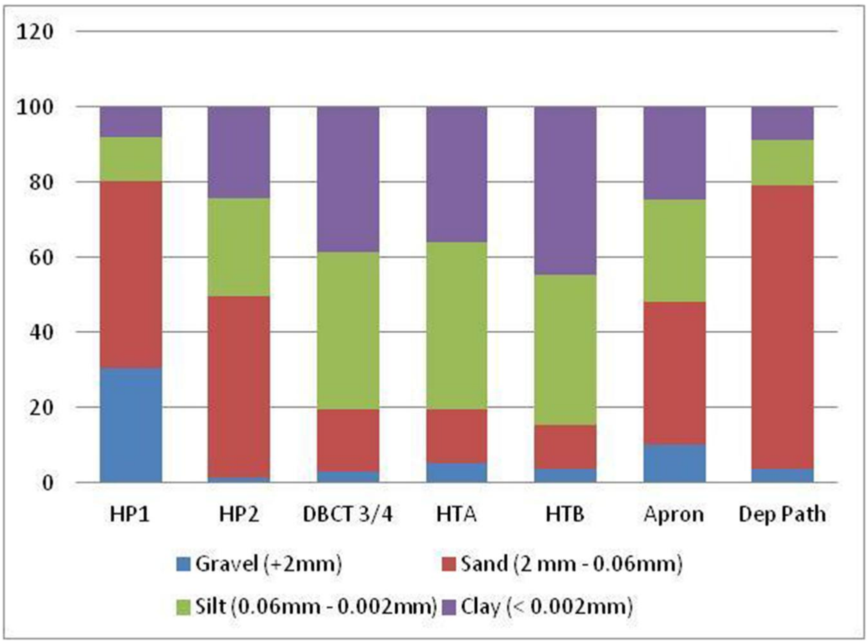


Figure 49 **Aggregated grain size distributions form Hay Point Port**

3.3 Indicative estimates of key sediment transport rates

The intrinsic annual sediment transport volumes were estimated using the Mackay wind and wave data, published tidal heights and rates, available grain size data and the Sedtran05 1-d model (Table 8).

Firstly, a large number of simulations were performed using plausible ranges of grain sizes, waves, winds etc. and a large lookup table was created for both bedload and suspended transport. The model then time-steps through the time-series of data, and estimates the averaged sediment transport for each transport process over the appropriate depth range at each point in the time series. The integrated annual transport is then determined for each year of the dataset (1975- 2015).

Table 8 **Model parameters**

Pathway	Grain size (D50 m)	Forcing mechanism	Cross-shore scale	Depths modelled
1) Littoral drift	0.0002	Breaking waves	0 – 5 m isobath	Not modelled
2) Nearshore turbidity zone	0.0001	Small waves (orbital flows), tidal flows, Ekman currents	0 – 10 m isobath (except during flood events)	5, 10
3) Inner-shelf bedload transport	0.0002	Larger waves (orbital flows), tidal flows, Ekman currents	5 – 20 m isobath	5,10, 15, 20
4) Mid-shelf cyclone pathway	0.0002	Cyclones (extreme waves & currents)	> 15 m Lagoon-wide	10, 20, 30

The results from this analysis of the intrinsic sediment transport rates are shown in Table 9. The units are annual total transport (m^3) per unit width of the shelf under which the relevant process acts.

The right-hand column shows the transport past the Hay Point region per annum.

The analysis also revealed that for around 80% of the time pathway 2 is operating (accounting for 35% of total sediment volume transported), and for around 40 % of the time pathways 1 and 3 are likely to be operating. In general, it means that more often than not, at least one of the sediment transport pathways will be operating. In addition, given that all of the pathways are dependent upon some sort of wave action, often multiple pathways will be operating at the same time. This is consistent with the estimates contained in Orpin et al (1999).

Table 9 Indicative sediment transport estimates

Location	Indicative sediment transport volumes (m^3/m/yr)
1) Littoral drift	72 (from MCS)
2) Nearshore turbidity zone	22
3) Inner-shelf bedload transport	15 m (3.3), at depth 10 m (6.7), at depth 5 m (32.9)
4) Mid-shelf cyclone pathway	No major cyclones in dataset

These estimates feature high uncertainty, like any sediment transport estimates. The Sedtrans05 model is a research tool and hence likely to perform better than many of the commercial models typically in use. However, the fundamental variability, and lack of robust numerical algorithms available ensures that any sediment transport estimates will feature large uncertainty.

4.0 Sediment Budget

4.1 Introduction

A conceptual sediment budget for the Hay Point region was produced using ArcGIS and the United States Army Corps of Engineers Coastal Inlets Research Program Sediment Budget Analysis System (SBAS).

SBAS calculates cell balances based on a conservation of volume (volume flux) equation:

$$\Sigma Q_{source} - \Sigma Q_{sink} - \Delta V + P - R = Residual$$

Where:

Q_{source} = input of sediment into a cell

ΣQ_{sink} = loss of sediment from a cell

ΔV = volume change within a cell

P = placement into a cell (e.g. beach fill, dredged material)

R = removal from a cell (e.g. dredging)

Residual = 0 for a balanced cell (i.e. the same quantity of sediment entering the cell is leaving the cell)

The budget was created for the existing coastal condition, and therefore does not take into consideration any existing or proposed dredging or disposal.

Sediment cells were mapped using information provided in Figure 17 and Figure 44, locating areas of gravel, carbonates, sands and muds and categorising them into the littoral zone (0 to 5-metre offshore contours), turbidity zone (5 to 10-metre offshore contours) and the bedload zone (10 to 15-metre or greater offshore contours). The budget also took into consideration the input volume of sediment from the Hervey Bay sand stores and the Pioneer River, and the transport rate estimates in the previous section of this report. The values utilised for the bedload fraction are provided in Table 10.

Table 10 Key SBAS values

Area Ref	Contour Range	Shelf Area (m2)	Flux ('000 m3/yr)
Bedload 1	5-10m	108,060,649	23
	>10m	533,174,997	136
Bedload 2	5-10m	23,495,568	54
	>10m	169,443,376	76
Bedload 3	>10m	875,037,678	27
Bedload 4	5-10m	211,573,386	152
	>10m	1,430,154,425	364
Bedload 5	>10m	70,610,115	23
Bedload 6	5-10m	356,738,361	134
	>10m	1,860,484,646	322
Bedload 7	>10m	367,687,084	42
Bedload 8	5-10m	40,350,708	36
	>10m	1,429,673,356	264
Bedload 9	>10m	436,369,536	118

The alongshore transport in the littoral cells is typically in the order of $36m^3$/yr.

4.2 Outputs

The following figures provide snapshots of the budget from ArcGIS. SBAS automatically provides a colour coding for each cell dependent on whether the cell is experiencing a sediment loss (yellow), gain (purple) or is balanced (blue). Black arrows indicate the flux of sediment (movement of sediment from one cell to another).

Figure 50 provides an overview of the area studied, the sediment cells, and the overall result of the sediment budget.

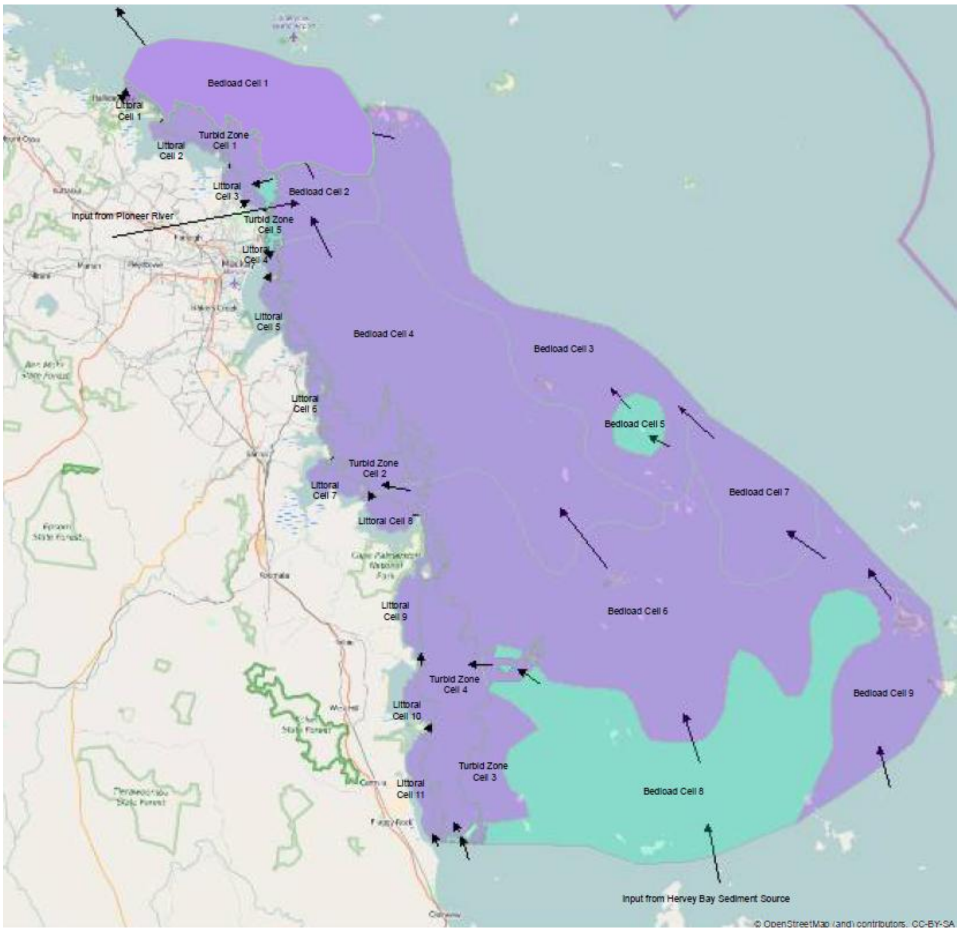


Figure 50 Budget assessment area with cells marked

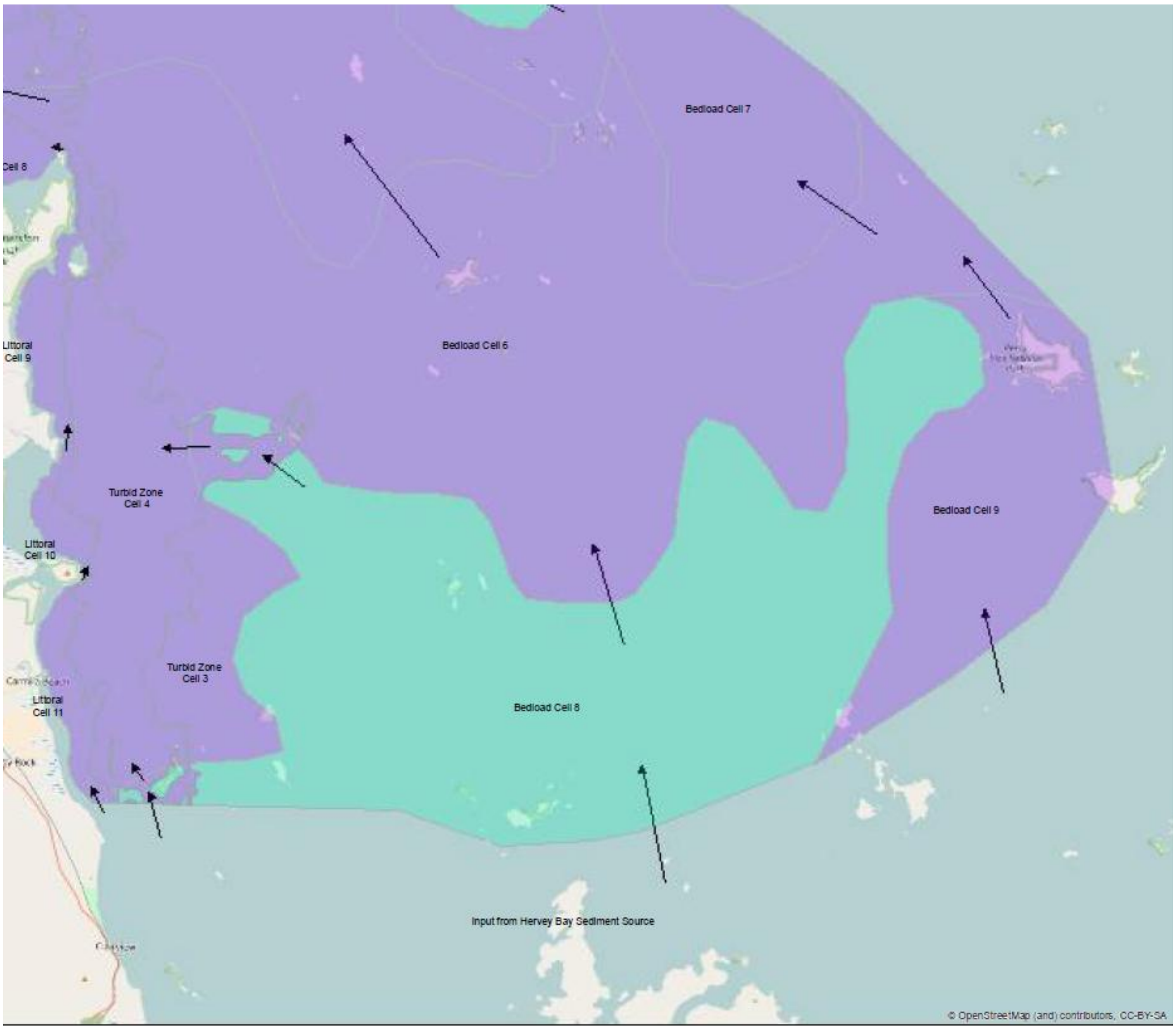


Figure 51 Southern assessment area

In Figure 51, sediment approaches the southern section of the assessment area from Hervey Bay. Bedload Cell 8 was found to predominantly consist of gravel, indicating that there is limited deposition of sediments, and as such, the cell is balanced. All other cells in this area were calculated to have a net gain, with a proportion of sediment being deposited as bedload currents, littoral drift and turbidity factors move the sediment north, shoreward, and out towards the open ocean.

Figure 52 Central Assessment Zone

Figure 52 shows the central assessment zone for the budget. This includes (in the top left) Hay Point, shows that the majority of cells experience a net gain in sediment as a result of the contribution of sediment from southern cells. The exception to this is Bedload Cell 5, which is understood to be a gravel lobe and, therefore, has little to no sediment deposition (and as such is considered a balanced cell). The other exception to this is the turbid zone north of Hay Point (Turbid Zone Cell 5), which is discussed in more detail in the next figure (Figure 53).

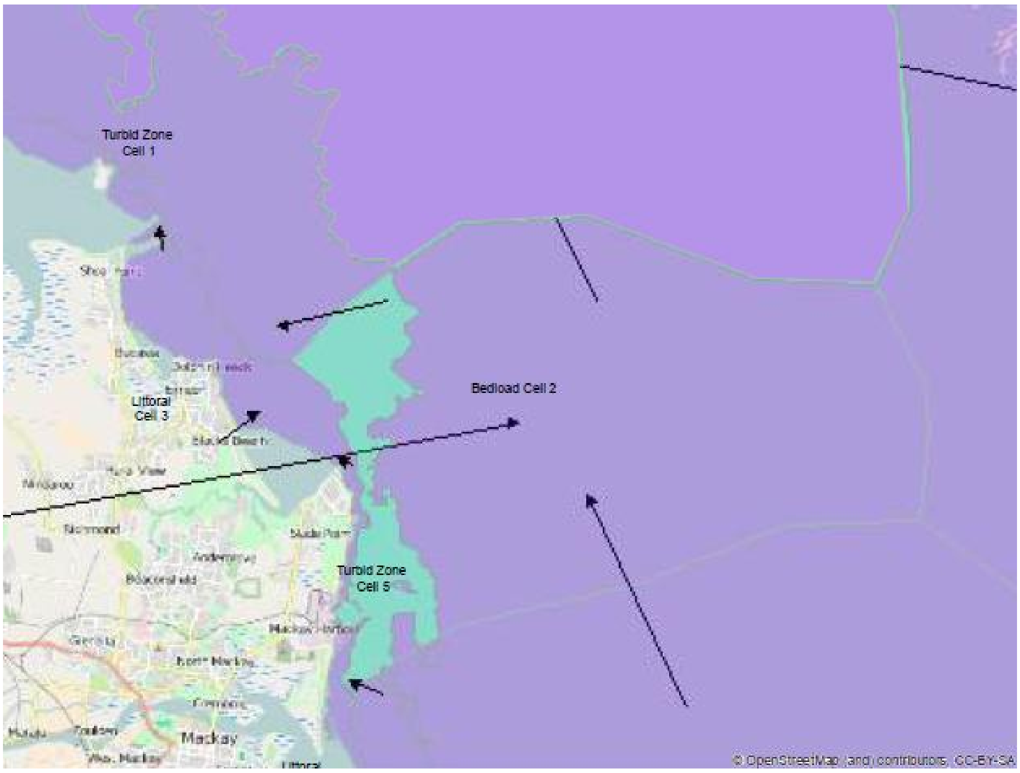


Figure 53 Turbid zone cell 5 and the Pioneer River contribution

Figure 53 shows the sediment cells north of Mackay. Turbid Zone Cell 5, north of the Pioneer River and Mackay, indicates a balanced cell due to the high understood presence of tidal currents, resulting in a highly turbid area with little sediment deposition. This may be due to the contribution of the Pioneer River to the sediment budget, and the northward movement of sediment across the system.

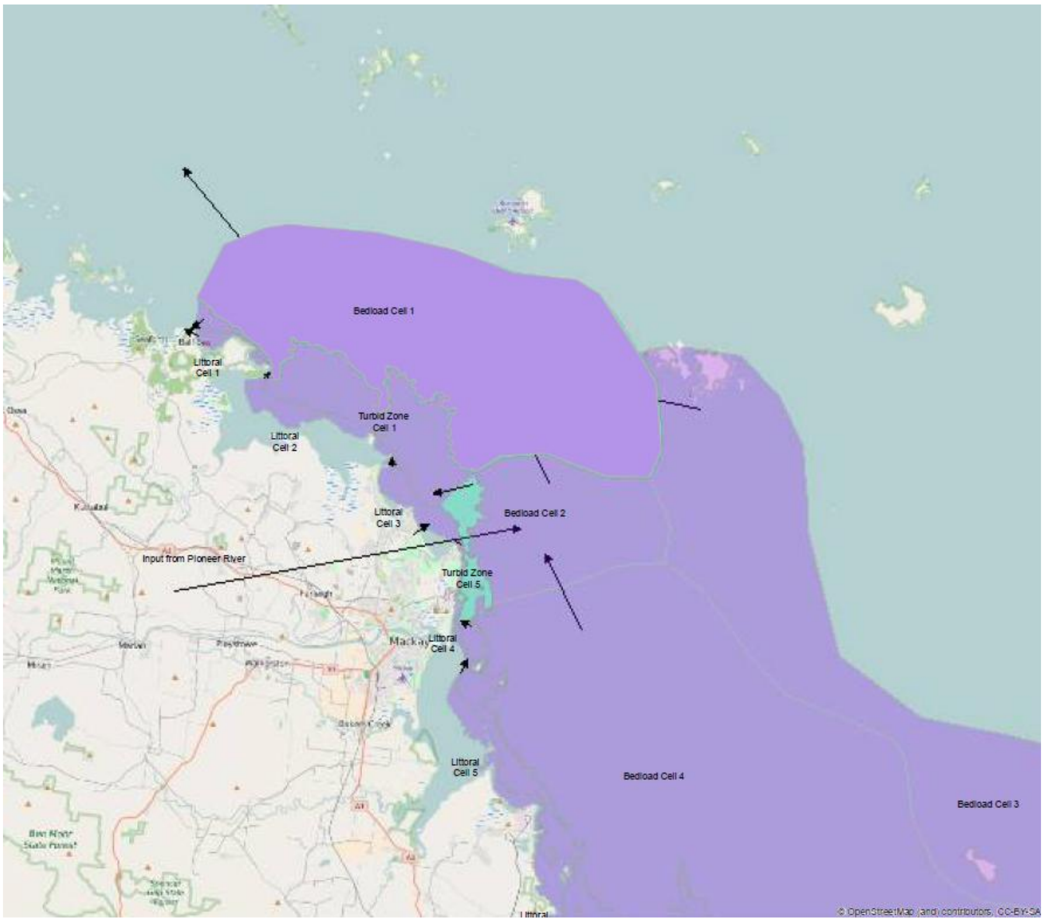


Figure 54 Northern assessment area

Figure 54 shows the northern assessment area. The area to the north of Hay Point, and the northern extent of the sediment budget assessment area indicated that large volumes of sediment (predominantly sands and carbonates) are being deposited in Bedload Cell 1. As such, much lower volumes of sediment are believed to be leaving Bedload Cell 1 (indicated in Figure 17 as a sand store).

4.3 Conclusions

As indicators in the figures show, the sediment budget for the study area is, largely, in balance. This means that there is little loss of sediment from the system (and therefore no yellow cells shown). Three key areas of sediment inflow where little to no sediment is being deposited were identified (in cyan on the figures). This is assumed to be as a result of the predominant sediment type mapped in the area (gravel, as shown on Figure 17). Largely, the sediment budget shows that most cells are experiencing level of deposition, with a sizeable volume of sediments in flux between cells. The influences from cyclonic activities were not modelled as part of the sediment budget due to the lack of attributable sediment data available.

5.0 Management Implications

The overall intent of the SSM assessment is to investigate ways of reducing or avoiding the need for at sea disposal of material dredged during maintenance dredging operations at Hay Point. An obvious approach to achieving this objective is to reduce the required dredging volumes. In theory this could be achieved through:

1) Altering the local depositional conditions;

2) Reducing the available sediment sources.

Harbour designs generally consider ways to ensure that vessel berthing and transitioning conditions are maintained whilst minimising harbour siltation. Unfortunately these observations are often conflicting as reducing the depositional environment is often best achieved by maintaining high current flows, that can make berthing and navigation problematic.

In the case of Hay Point, such options are also limited given the offshore trestle nature of the loading facilities.

Sediment traps are also commonly established upstream of navigation channels. However whilst these can be effective at intercepting sediments that might have been deposited within the navigation channel and berth pockets, ultimately they do little to reduce the overall volumes of dredging required. Sediment traps can be effective at prolonging dredging campaigns, but are generally less effective for minimising long term dredged volumes.

Reducing the sediment load to the Hay Point region clearly has the potential to reduce deposition in the channel and berth pockets, and hence future maintenance dredging requirements. Therefore it is worthwhile considering how this may be achieved.

The contextual understanding of sediment dynamics in the region of Hay Point developed in this study can be used to investigate the potential effectiveness of remote upstream sediment control measures in reducing the future dredging maintenance requirements for the Port.

In particular, a key question is whether in-catchment sediment containment measures will be able to substantively decrease the ongoing maintenance dredging requirements for the Port.

This question is investigated here, based on the understanding of sediment stores, pathways and transport mechanisms developed in this study, along with *in-situ* measurements of sediment deposition rates from the region.

For catchment sediment management measures to be effective, fluvial sediments delivered during future wet seasons must be a major source of sediments at Hay Point.

If it assumed that the major sediment transport pathway for the delivery of sediments to the navigation channel and berthing pockets is the inner shelf bed load pathway, then the major upstream local source of sediment is the large sand sediment cell immediately to the south-east of the Port (Figure 52). If fluvial sources play a major role in the delivery of sediment to this store and to the navigational channel, then the fluvial sources must be able to maintain sediment supply to the upstream (southern) boundary of this store.

In order to verify if this is possible, the estimated sediment delivered to the upstream sediment store (r_u) is estimated by back calculating the sediment requirement based on measurements of the deposition rate with in the sediment store (*d)*, as follows:

Let:

d = the average annual deposition rate ($m^3/m^2/yr$)

R_d = the average deposition ratio (non-dimensional)

D = the annual average discharge from the major catchment source (m^3/yr)

A = the surface area of the store of available sediment upstream (m^2)

r_u = the annual upstream sediment flux (m^3/yr)

It can be estimated that:

> $r_u = d/R_d$ where d is determined from measurements and scaled up over the entire sediment store using the measured area A.

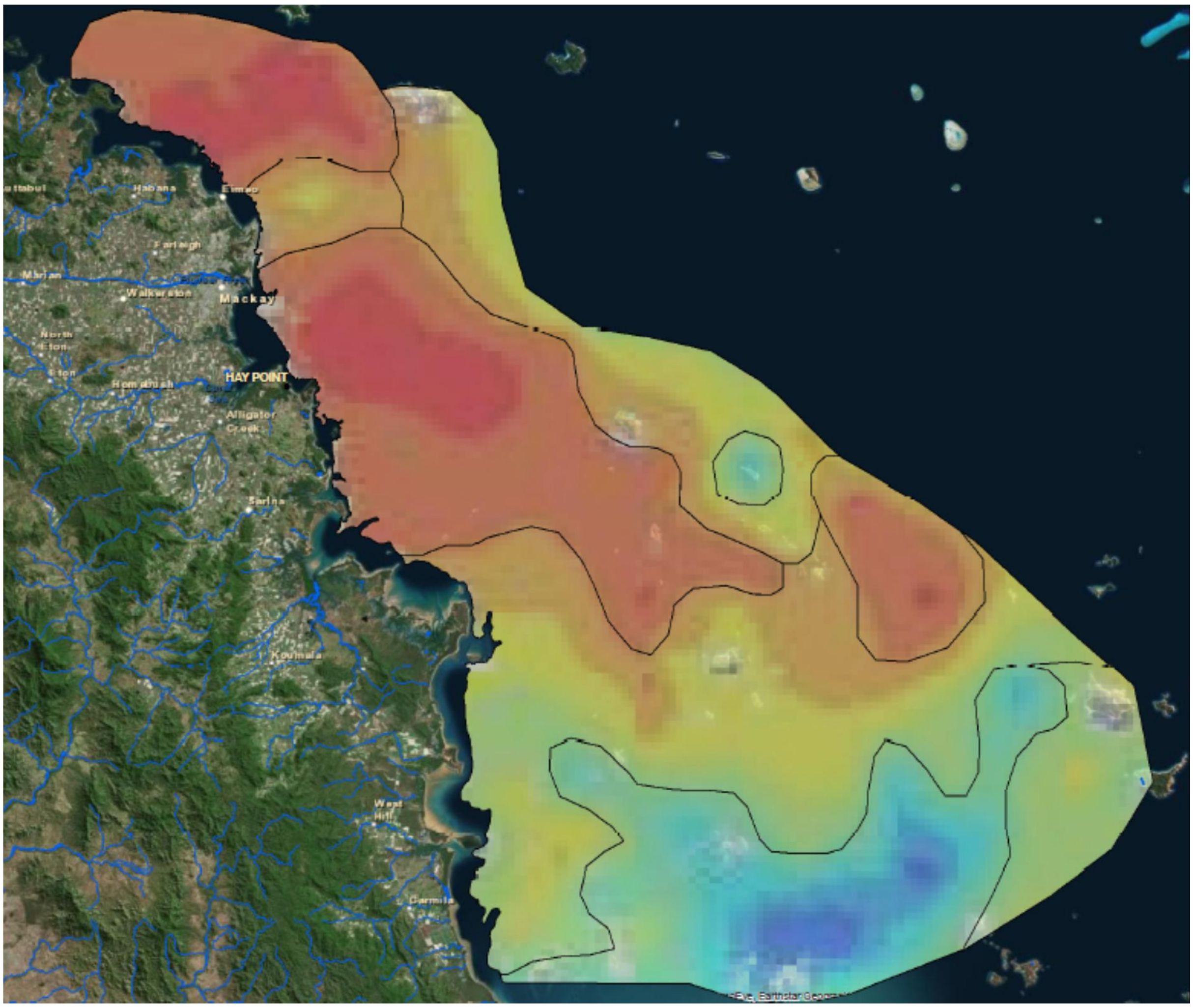


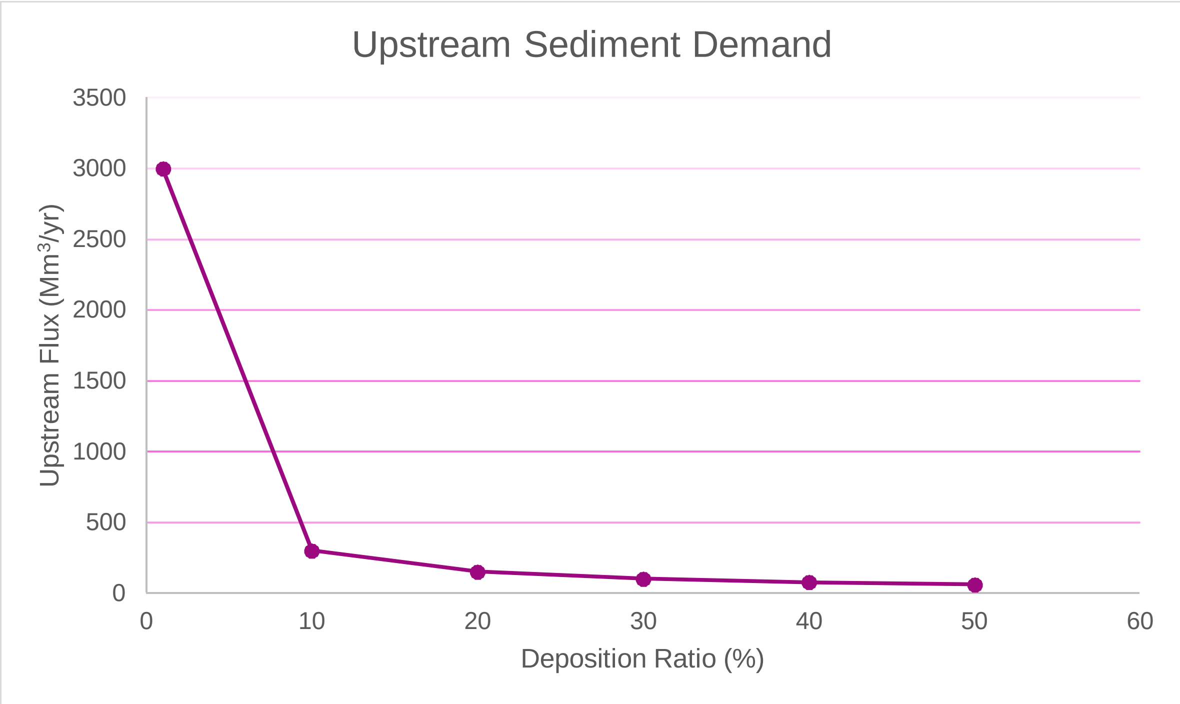
Figure 55 Sediment Cells – Sources and Stores

Figure 55 provides a graphical representation of the sediment cells, sources and sinks in the study area adjacent to Hay Point. The heat mapping indicates the areas of sand sediment concentration, where the red areas indicate higher volumes of sand (stores) and the blue areas show sand deficits. Figure 53 also shows the relationship between the R_d and the corresponding sediment delivery requirement at the upstream or southern end of the sediment store using the parameter values shown in Figure 17.

Table 11 shows the values used in this analysis.

Table 11 Model Parameters

Parameter	Value
d	5 mg/cm^2/day (A. Symonds and P. Ridd pers. Comm.)
R_d	Varied
D	4.1 Mt/yr (Kroon et al., 2012)
A	1 641 726 861 m^2
r_u	Estimated from calculation



These results show that even if 50% of the incoming bedload and suspended sediment is deposited in this store, than the required incoming sediment would need to be at least 50 Mm^3/yr.

If these upstream sediments were to be supplied from the major fluvial source, then this would have to be of magnitude at least 50 Mm^3/yr. However, the major upstream fluvial source is the Fitzroy River region (Kroon et al., 2012).Best estimates of the average annual discharge of suspended sediment from this major fluvial source is 4.1 Mt/yr. Using a conversion rate of unity, this equates to 4.1 Mm^3/yr (Kroon et al., 2012).

Even if catchment measures were to halve this discharge to say 2 Mm^3/yr, then this would result in a reduction of supply to the navigational channel of between 4% and 0.1%.

Therefore it can be concluded that for the Port of Hay Point navigational channel and berth pockets, catchment sediment management measures are unlikely to substantively alter future dredging maintenance requirements.

This result is consistent with the largest single component of the suspended sediment budget is the ongoing re-suspension of relic sediments, especially over the inner shelf. The substantial stores of sediments within the inshore sediment lens represent by far the largest store and source of sediments available for routine resuspension (Orpin and Ridd, 2012); vastly outweighing the contribution of ‘new’ fluvial derived sediments.

Therefore by implication, at any given time the fraction of suspended sediment that is from a ‘new’ fluvial source is likely to be small except close to river mouths directly following sporadic flood events.

6.0 Glossary of Terms

µm	Micron / Micrometre – equal to one millionth (10^{-6}) of a metre
Alluvial infilling	Deposition of river-derived sediments in a depression or hole
Bioturbation	The disturbance or movement of sediments by environmental influences (such as fauna or flora)
Calcareous	Composed or containing calcium carbonate
Calcsand	Sands derived from calcium carbonates
D50 Grain Size	The median diameter or median value of the particle size distribution
D90 Grain Size	The particle diameter value where 90% of the sample is smaller than that value (the 90^{th} percentile)
Eocene	The division of the geological timescale relating to 56 to 34 million years ago
GBRMPA	Great Barrier Reef Marine Park Authority
GBR	Great Barrier Reef
Halimeda Calcsand	*Halimeda* is a genus of macroalgae where the thallus is commonly calcified and, as such, produced calcium carbonates which contribute to calcium carbonate sand creation
Highstand	Geological timeframe where sea levels were at their highest
Ka	Thousand years ago
Leeward	Direction downwind from the point of reference
Ma	Million years ago / mega-annum
Macrotidal	Coastal areas where the tidal range is in excess of 4 metres, and where coastal processes are dominated by the tidal range
Marine Onlap	Where a successively younger (in terms of geological timescales) wedge-shaped section of rock strata extends progressively further across an erosion surface than in older rock
Marine Transgression	The process associated with the rising of sea levels relative to the land, where the shoreline moves to higher ground, resulting in flooding and inundation
Micrite	Fine particle limestone formed by marine-derived calcium carbonates
Oligocene	The division of the geological timescale relating to 34 to 23 million years ago
NQBP	North Queensland Bulk Ports
Perireef apron	The perireef occurs where marine reef becomes exposed as a result of changing sea levels. The apron is the area in which the perireef occurs
Quiescent	In a period of inactivity or dormancy
Regression	The exposure of the marine floor above sea level
Rifting	The formation of fissures or breaks in rock or the ocean floor where plates or crusts move apart from one another
Sediment detritus	The formation of secondary sediments from the erosion of sedimentary rocks, forming layers in low-lying areas
Sediment facies	Sediments distinguishable from the surrounding environment due to their characteristics, which reflect the environment of their deposition
Shelf Progradation	The growth of the shelf overtime as a result of changing sea levels (usually

	linked to marine transgression)
Siliclastic	Clastic non-carbonate rocks and sediments which are almost exclusively comprised of silicon
SSM	Sustainable sediment management
Stratification	Formation of layers of rock and material over time
Terrigenous	Sediments derived from the erosion of rocks on land
Tertiary period	The division of the geological timescale relating to 64 to 1.81 million years ago
Volcanism	Eruption of molten rock onto the surface of the earth
Washload (sediment)	The portion of sediment carried by a fluid flow (either in a river or by ocean currents
Windward Zone	Facing the wind

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