Sustainable Sediment Management Project

Conceptual Sediment Budget

Final 1.0

Gladstone Ports Corporation
Technical Report
August 2018

PORT & COASTAL SOLUTIONS

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ACRONYMS

AHD	Australian Height Datum
APLNG	Australia Pacific Liquified Natural Gas
ARI	Average Recurrence Interval
BoM	Bureau of Meteorology
DES	Department of Environment and Science
DoEE	Department of Environment and Energy
EBSDS	East Banks Sea Disposal Site
EMS	Environmental Management System
GBRMP	Great Barrier Reef Marine Park
GBRWHA	Great Barrier Reef World Heritage Area
GLNG	Gladstone Liquified Natural Gas
GPC	Gladstone Ports Corporation
HAT	Highest Astronomical Tide
H_s	Significant wave height (the mean wave height of the highest third of the waves)
kt/yr	kilo-tonnes per year
LNG	Liquified Natural Gas
MHWN	Mean High Water Neaps
MHWS	Mean High Water Springs
ML	Million Litres
MLWN	Mean Low Water Neaps
MLWS	Mean Low Water Springs
MSL	Mean Sea Level
MSQ	Maritime Safety Queensland
Mt/yr	Million tonnes per year
NAGD	National Assessment Guidelines for Dredging
PCS	Port and Coastal Solutions
PoG	Port of Gladstone
QCLNG	Queensland Curtis Liquified Natural Gas
QLD	Queensland
QPA	Queensland Ports Association
SSC	Suspended Sediment Concentration
SSM	Sustainable Sediment Management
TC	Tropical Cyclone
TSS	Total Suspended Solids
t/yr	tonnes per year
WICT	Wiggins Island Coal Terminal
WRB	Wave Rider Buoy

PORT & COASTAL SOLUTIONS

Executive Summary

Gladstone Ports Corporation (GPC) commissioned Port and Coastal Solutions (PCS) to undertake a number of tasks as part of their Sustainable Sediment Management (SSM) Project for the Port of Gladstone (PoG). The aim of this study is to understand the historic bathymetric changes in the PoG and based on this and other available information develop a conceptual sediment budget for the PoG.

The bathymetric analysis has shown that the highest rates of sedimentation have been naturally occurring in the upstream (Jacobs and Targinnie Channel areas) and Outer Harbour (Golding, Boyne and Wild Cattle Cuttings) regions of the PoG. In addition, some sedimentation also occurred in the Clinton and Auckland Channel regions, but much of this was due to the migration of mega-ripples (sand ridges) rather than net sedimentation. A best estimate of the typical ongoing annual sedimentation, in the areas of the PoG where regular maintenance dredging is required, is 600,000 m^3 and of this almost 300,000 m^3 is in the upstream region and 200,000 m^3 in the Outer Harbour region. As part of future SSM Project studies the relationship between the sedimentation and the dredge and declared depths in the PoG will be further investigated. This will provide a better understanding of how the sedimentation relates to maintenance dredging and how the sedimentation volumes relate to the design and declared depths in the different regions of the PoG.

The bathymetric analysis at the East Banks Sea Disposal Site (EBSDS) has shown that over the last 10 years (2007 to 2017) the site has been retentive. It has been estimated that more than 95% of the combined capital and maintenance dredged sediment placed at the site has been retained (this includes an allowance for consolidation of sediment from maintenance dredging). The bathymetry at the site has been shown to be stable, with limited erosion occurring due to large wave events.

A conceptual sediment budget (the budget) has been developed for the PoG based on all the available information. The budget notes that different processes occur through the PoG, with the Inner Harbour region being dominated by tidal currents while the Outer Harbour region is influenced by a combination of offshore waves and tidal currents. The budget details the relative sources (these are quantified where sufficient data is available) and sinks of sediment in the regions. The budget will be further refined by additional targeted studies (including data collection and numerical modelling) to allow a full quantitative sediment budget to be developed for the SSM Project.

1. Introduction

Gladstone Ports Corporation (GPC) commissioned Port and Coastal Solutions (PCS) to undertake a number of tasks as part of their Sustainable Sediment Management (SSM) Project for the Port of Gladstone (PoG). The scope of the work is as follows:

- Task 1: to develop a conceptual sediment budget (the budget) for the PoG;
- Task 2a: to undertake a gap analysis of the data required to convert the budget into a quantitative sediment budget for the PoG, with specific focus on maintenance dredging and the East Banks Sea Disposal Site (EBSDS); and
- Task 2b: if required, to create a sampling strategy to address any identified data gaps which will allow for the completion of a quantitative sediment budget.

This report is concerned with Task 1, developing the budget for the PoG. A separate report will be prepared to address Tasks 2a and 2b.

1.1. Project Overview

The SSM Project has been identified by GPC as a prerequisite, to allow adaptive long-term environmental management of maintenance dredging, understanding maintenance dredging sediments and how best to manage them, supporting sustainable development and identifying sediment movement within the Port and how this interacts with the environment, port, surrounding areas and communities.

GPC had discerned the need to further improve our understanding of the interactions between maintenance dredging operations (including sea disposal of dredged material) and the local and regional environment, in order to identify best environmental and operational outcomes and ensure the ongoing sustainability of these operations. All PoG infrastructure and activities occur within Port Limits which are within the Great Barrier Reef World Heritage Area (GBRWHA) as inscribed in 1981, but outside of the Great Barrier Reef Marine Park (GBRMP), with the exception of oceanic areas to the east of Facing Island and the south-east of Wild Cattle Cutting.

Maintenance dredging is conducted to provide and operate effective and efficient port facilities and services under the Queensland *Transport Infrastructure Act 1994*. The PoG maintenance dredging and disposal activities associated with the main channels, swing basins and berth pockets are usually undertaken annually, with dredged material placed at the approved East Banks Sea Disposal Site (EBSDS - first approved in 1980). As part of the maintenance dredging activity bed levelling is commonly undertaken at the same time to assist with levelling areas after maintenance dredging and moving sediment into areas to help optimise the dredging activity. In addition, other areas (e.g. the Marina, Boyne River and Gatcombe Head Boat Harbour) are also included in the PoG maintenance requirement, with the sediment currently being placed within existing reclamations rather than at the EBSDS.

In association with obtaining a Sea Dumping Permit for maintenance dredging, a five (5) year Deed of Agreement (the Deed) was signed on the 14th August 2015, between GPC and the Department of the Environment and Energy (DoEE) to:

- undertake research and monitoring relating to the consequences of dumping maintenance dredged material into the marine environment;
- investigate the possibility of avoiding or reducing the need for further dumping of maintenance dredged material into the marine environment; and
- report to the DoEE the results of any research, monitoring or investigation undertaken by GPC in accordance with the Deed.

The Deed also reiterates GPC's existing commitments to monitor and manage maintenance dredging and associated sea disposal activities in an environmentally responsible manner.

To address the requirements of the Deed, an 'Implementation Strategy' (the Strategy) was prepared by GPC and approved by DoEE, which provides a schedule of proposed programs to be conducted over the term of the Deed. The Deed forms part of GPC's Environmental Management System (EMS) which is certified to ISO AS/NZS 14001:2015, ensuring a robust risk identification, control and improvement process is implemented and maintained.

The SSM Project has been developed to build on the information collected to date within Port Curtis (the large natural harbour within which the PoG is located) and develop a sediment budget and associated model to better understand the contribution of GPC's activities to the overall sediment system. This report is aimed at providing a conceptual sediment budget which included details about the following:

- an indication of the main sources of sediment;
- an indication of the main sinks of sediment; and
- details of sediment transport processes and transport pathways which are important for the PoG.

1.2. Port of Gladstone

The PoG is located within Port Curtis on the east coast of Queensland, approximately 525 km north of Brisbane (Figure 1). Port Curtis is a macro-tidal estuarine system that includes an intricate network of rivers, creeks, inlets, shoals, mud banks, channels and islands. Strong tidal flows, wind and swell wave energy and riverine input from the Calliope and Boyne catchments, contribute to the natural sediment transport processes which can influence the region.

In the 2016/17 financial year the PoG handled approximately 120.4 million tonnes of commodities. This was predominantly made up of coal, alumina/aluminium related products and liquified natural gas (LNG), although other products including cement, bulk chemicals, petroleum, grain and containers were also handled (GPC, 2017).

The PoG covers 4,448 hectares (ha) of land which includes more than 700 ha of reclaimed land. There are ten (10) main wharf centres, which together comprise 20 wharves (Figure 1):

1. RG Tanna Coal Terminal: four (4) wharves;
2. Barney Point Terminal: one (1) wharf;
3. Auckland Point Terminal: four (4) wharves;
4. Fisherman's Landing: four (4) wharves;
5. South Trees: two (2) wharves;
6. Boyne Wharf: one (1) wharf;
7. Curtis Island LNG Precinct, Australia Pacific LNG (APLNG): one (1) wharf;
8. Curtis Island LNG Precinct, Queensland Curtis LNG (QCLNG): one (1) wharf;
9. Curtis Island LNG Precinct, Gladstone LNG (GLNG): one (1) wharf; and
10. Wiggins Island Coal Terminal (WICT): one (1) wharf.

Figure 1. PoG wharf locations (from GPC, 2017).

The PoG consists of approximately 40 km of shipping channels to ensure safe navigation from the entrance to Port Curtis to the wharves (Figure 3). Maintenance dredging is undertaken to ensure that the depths of the channels and berths are maintained at their declared depths (Table 1).

In addition, capital dredging has historically been undertaken in the PoG as the port has grown. Most recently, between 2011 and 2014, capital dredging associated with the construction of three LNG terminals was undertaken. Details of the maintenance and capital dredging, which has been undertaken at the PoG when the sediment has been placed at the EBSDS over the last 10 years, is provided in Table 2. The table shows that in total approximately 7.3 Mm^3 of sediment has been placed at the EBSDS over the last 10 years, with approximately 2 Mm^3 from maintenance dredging and the remainder from the capital dredging between 2011 and 2013.

A breakdown of the volumes of sediment dredged throughout the different areas of the PoG during the 2017 maintenance dredging is shown in Figure 2. The plot shows that approximately 70,000 m^3 was removed from the Golding, Boyne and Wild Cattle Cuttings, over 100,000 m^3 was removed from the areas to the north of the RG Tanna Wharves (north of Clinton Channel, WICT berths, Targinnie Channel and Jacobs Channel) and the remaining volume was removed from the area between the RG Tanna Wharves and the eastern end of the Gatcombe Channel.

The PoG is commonly separated into Inner and Outer Harbour regions; the Outer Harbour region extends from the offshore extent of the Wild Cattle Cutting to the north-western end of the Gatcombe Channel and the Inner Harbour is the area to the north-west of this which is sheltered from offshore wave activity by Curtis and Facing Islands (Figure 3).

Table 1. PoG Channels and associated declared depths for maintenance dredging (GPC, 2015).

Channel	Declared Depth (m LAT)
Outer Harbour	
Wild Cattle Cutting	-16.1
Boyne Cutting	-16.1
Golding Cutting	-16.1
South Bypass Channel	-7.3
Gatcombe Channel	-16.3
Gatcombe Bypass	-12.5

Channel	Declared Depth (m LAT)
Inner Harbour	
Auckland Channel	-15.8
Auckland Bypass	-6.8
Clinton Channel	-16.0
Clinton Bypass	-13.0
Targinnie Channel	-10.6
Jacobs Channel	-13.0
WICT departure channel	-16.0

Table 2. PoG dredging volumes where sediment was placed at the EBSDS over the last 10 years.

Year	Maintenance Dredging (in-situ m^3)	Capital Dredging (in-situ m^3)
2007	160,972	
2008	17,995	
2009	282,000	
2010	0 (dredging was at start of 2011)	
2011	309,000	
2012	150,000	5,113,475
2013	0 (dredging was at start of 2014)	
2014	550,366	
2015	68,000	
2016	455,000	
2017	209,456	
Total (2007-2017)	**2,202,789**	**5,113,475**

Note: PoG Sea Dumping Permit requires to report in-situ cubic metres delivered by the dredger to the EBSDS. These in-situ cubic metres are derived from dredge logs hopper dry tonnes by applying a conversion of factor of 1.1 (e.g. 1 m^3 (in-situ) = 1.1 tonne (dry weight)).

Capital dredging has been reported as in-situ cubic metres, taken from contract documentation as calculated between pre-dredge hydrographic surveys and the contract design dredge depth. This calculation is typically indicative of the amount delivered to EBSDS since capital material is of a denser nature than maintenance.

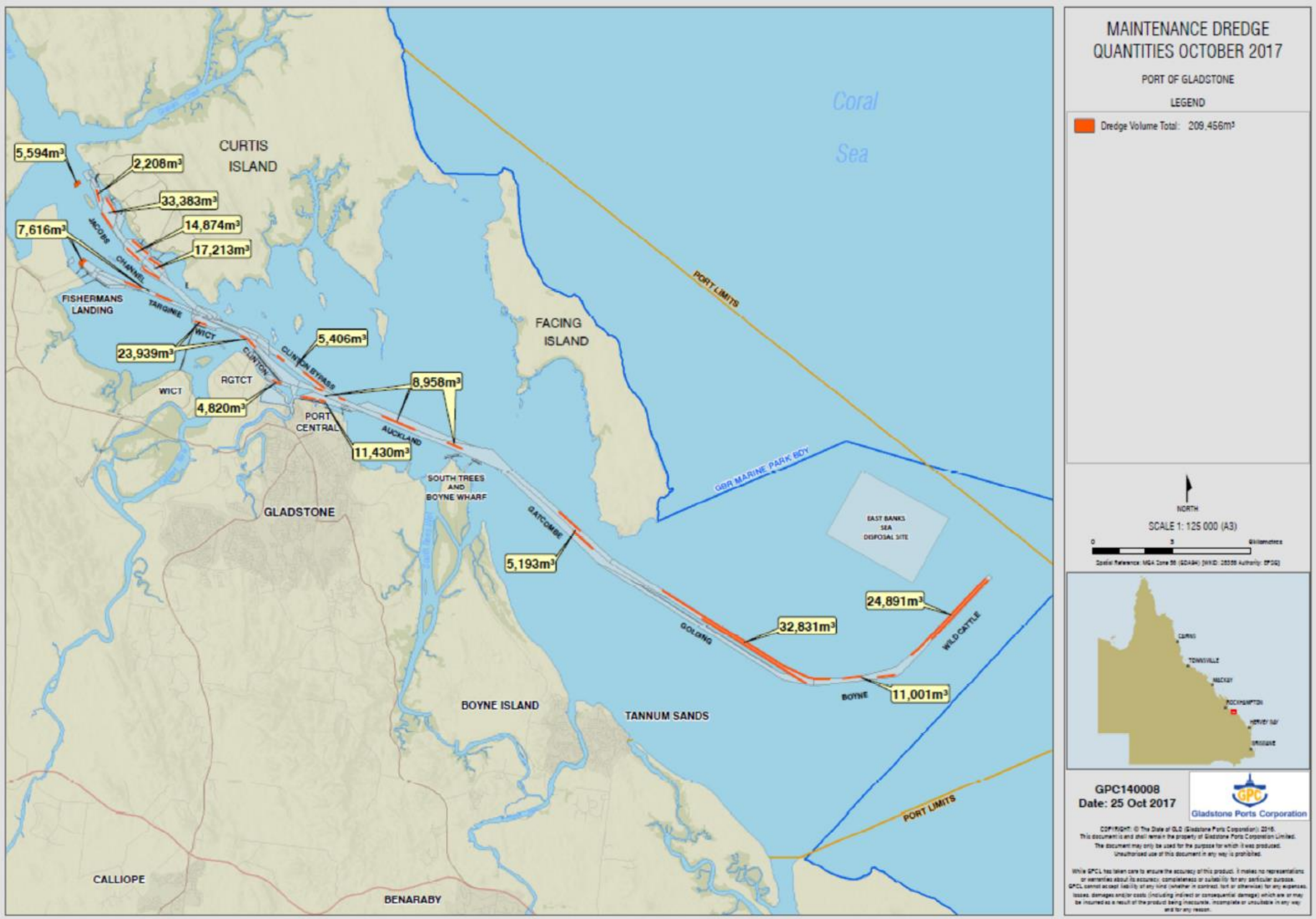

Figure 2. Port of Gladstone maintenance dredging volumes from 2017 (Vision Environment, 2017).

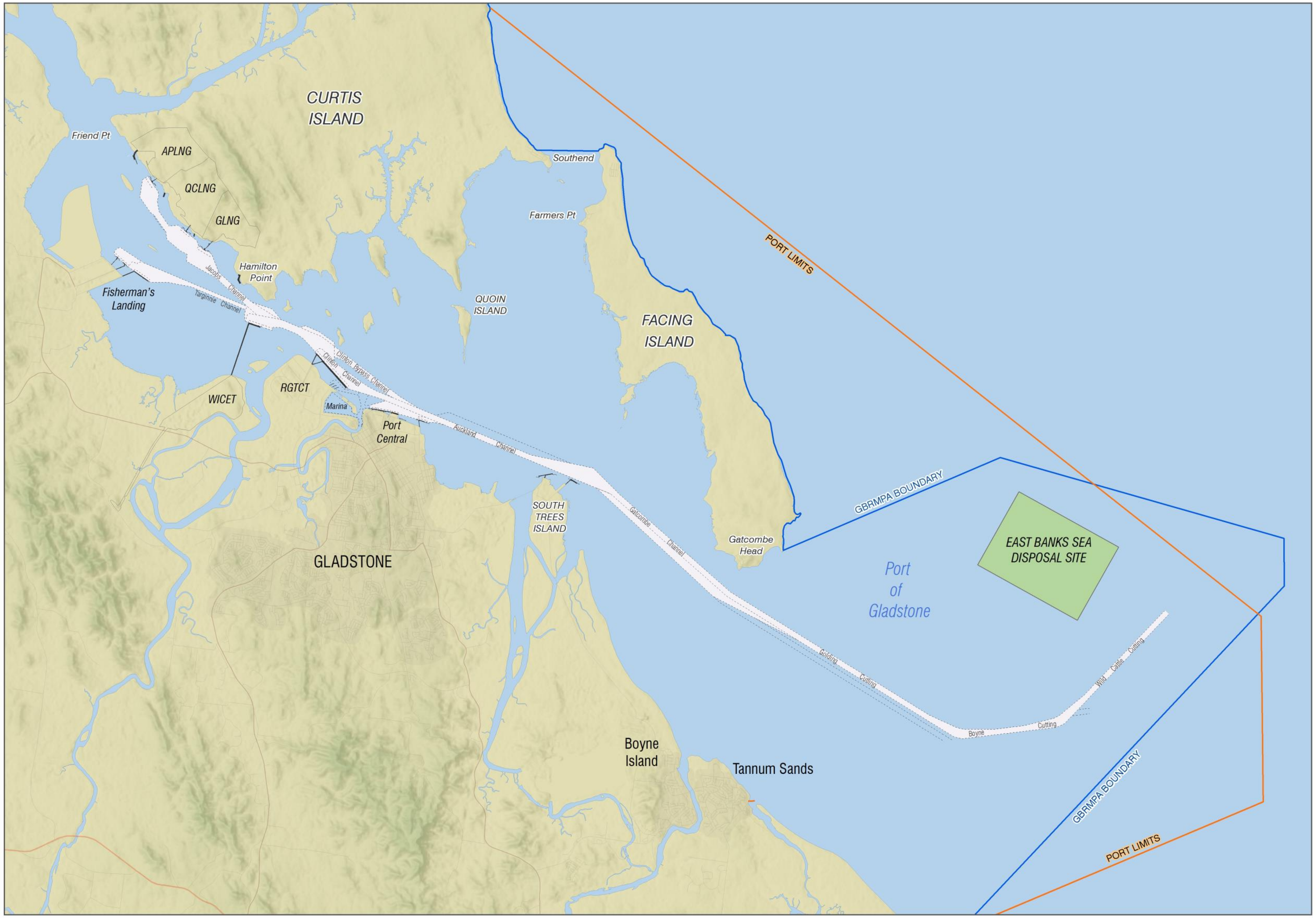

Figure 3. Port of Gladstone declared channels and sea disposal site.

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1.3. Report Structure

The report herein is set out as follows:

- a description of the local conditions at the PoG is given in **Section 2**;
- a review and analysis of historical bathymetric data is provided in **Section 3**;
- a discussion of the sediment transport at the PoG and the conceptual sediment budget is presented in **Section 4**; and
- a summary of the findings is detailed in **Section 5**.

Unless stated otherwise, levels are reported to Lowest Astronomical Tide (LAT). Volumes presented throughout are in-situ cubic metres calculated from surveyed bathymetry except for the volumes relating to historic maintenance dredging which are derived from in-hopper masses.

Wind and wave direction is reported as the direction the wind is coming from in degrees clockwise from True North. Current direction is reported as the direction the current is going to in degrees clockwise from True North.

2. Local Conditions

This section provides an overview of relevant metocean and sedimentological conditions at the PoG based on the available information.

2.1. Astronomical Tides

Port Curtis is a macro-tidal estuarine system with a semi-diurnal tidal signal. The mean spring tidal range is 3.2 m and the mean neap tidal range is 1.5 m. A summary of the tidal planes at the PoG relative to LAT and Australian Height Datum (AHD) is provided in Table 3, with AHD being 2.27 m above LAT.

Table 3. Tidal Planes at the Port of Gladstone (Auckland Point).

Tidal Plane	Elevation (m LAT)	Elevation (m AHD)
Highest Astronomical Tide (HAT)	4.83	2.56
Mean High Water Springs (MHWS)	3.96	1.69
Mean High Water Neaps (MHWN)	3.11	0.84
Mean Sea Level (MSL)	2.34	0.07
Mean Low Water Neaps (MLWN	1.57	-0.70
Mean Low Water Springs (MLWS)	0.72	-1.55

The tide propagates into Port Curtis through the wide opening between Facing Island and the mainland to the south, the narrow channel between Curtis Island and Facing Island and through The Narrows, which separates Curtis Island from the mainland to the north of the PoG. The estuary is made up of naturally deep channels, shallow subtidal shoals, intertidal banks and flats, mangroves and saltpan areas. The inundation of the intertidal, mangrove and saltpan areas is dependent on the tidal range, with smaller neap tides not resulting in much inundation, while the largest spring tides can inundate all of these areas. The high water elevation therefore controls the tidal prism, (volume of water which enters and leaves the estuary over a tidal cycle), which in turn controls the tidal current speeds.

The large tides generate strong tidal currents of up to 1.5 m/s in the main channels and up to 0.35 m/s in the shallower areas of the estuary (GHD, 2009). During large spring tides and strong winds the tidal currents have been reported to reach up to 2 m/s (Herzfeld et al., 2004). The large tides also mean that the waters are well mixed with limited variation in density or suspended sediment through the water column.

Plots showing the modelled spatial distribution of the peak flood and ebb tidal current speeds are shown in Figure 4 and Figure 5. The plots show that during spring tides:

- the ebb current speeds are generally higher than the flood current speeds. An ebb dominance in peak current speeds does not mean that Port Curtis is a net exporter of sediment, a longer duration flood current can result in fine-grained sediment being imported as suspended load while coarser sediment is exported by bedload transport;
- the highest currents occur in the Gatcombe Channel with peak flood currents of around 1.5 m/s and peak ebb currents of around 1.8 m/s. During the ebbing tide current speeds of around 1.8 m/s also occur in the Clinton Channel;
- current speeds within the maintained channels are generally greater than 1.0 m/s (excluding the Boyne and Wild Cattle Cuttings during the flood tide);
- during both the peak flood and peak ebb low current speeds occur over the shallow mudflats and intertidal areas within Port Curtis; and
- current speeds reduce significantly offshore of the shallow East Banks located at the entrance to Port Curtis. Offshore current speeds are generally less than 0.6 m/s.

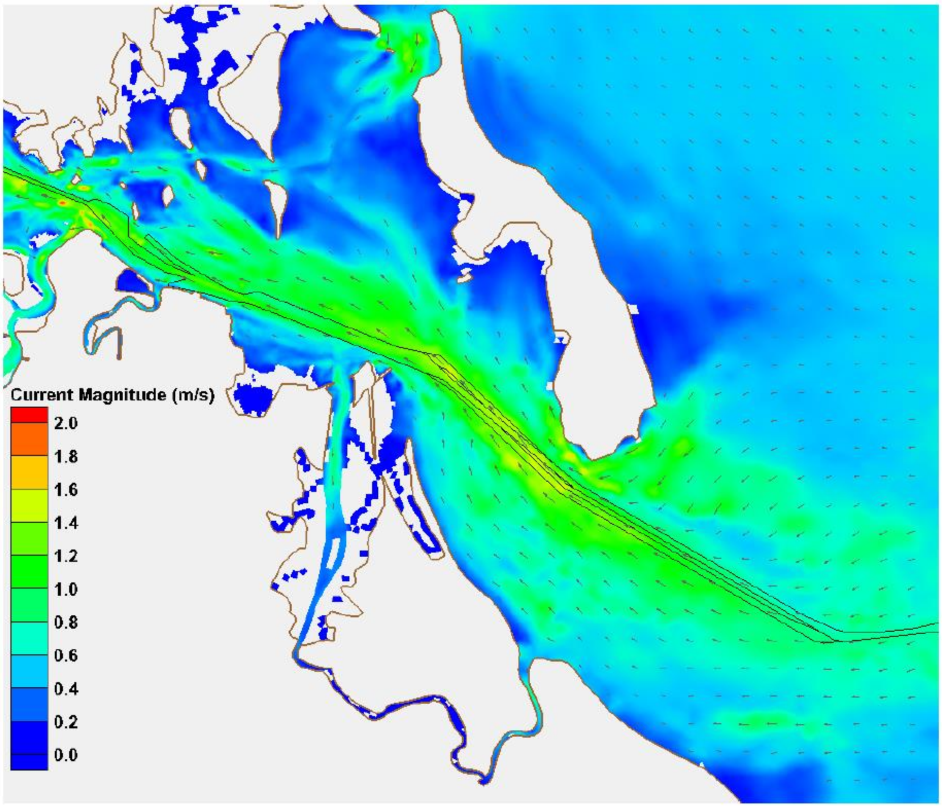


Figure 4. Modelled peak flood currents in the PoG during a spring tide (BMT WBM, 2018a).

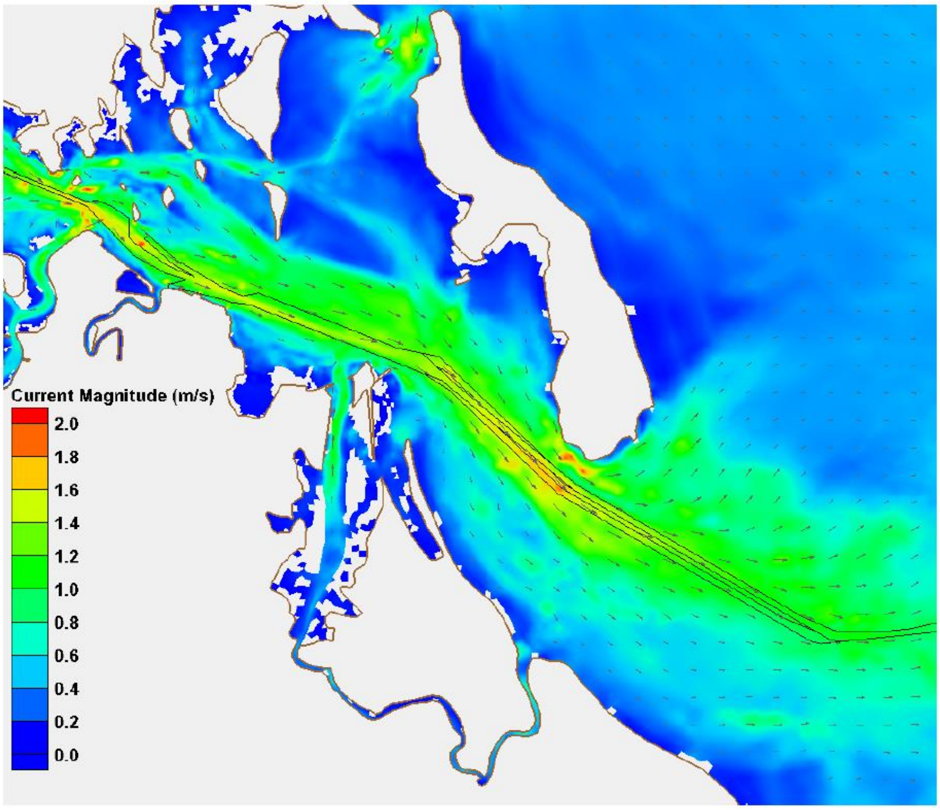


Figure 5. Modelled peak ebb currents in the PoG during a spring tide (BMT WBM, 2018a).

2.2. Wind and Waves

The wind conditions in the Gladstone region are dominated by prevailing easterly to south-easterly winds which occur along much of the east coast of Queensland (Figure 6 and Figure 7). The wind speed at the Gladstone Radar Bureau of Meteorology (BoM) site is typically between 10 and 30 km/hr, with stronger winds occurring during the afternoon due to the sea-breeze developing. The wind conditions vary through the year, with stronger winds occurring during the summer months and weaker winds during the winter months (Figure 8). Note: See Figure 9 for location.

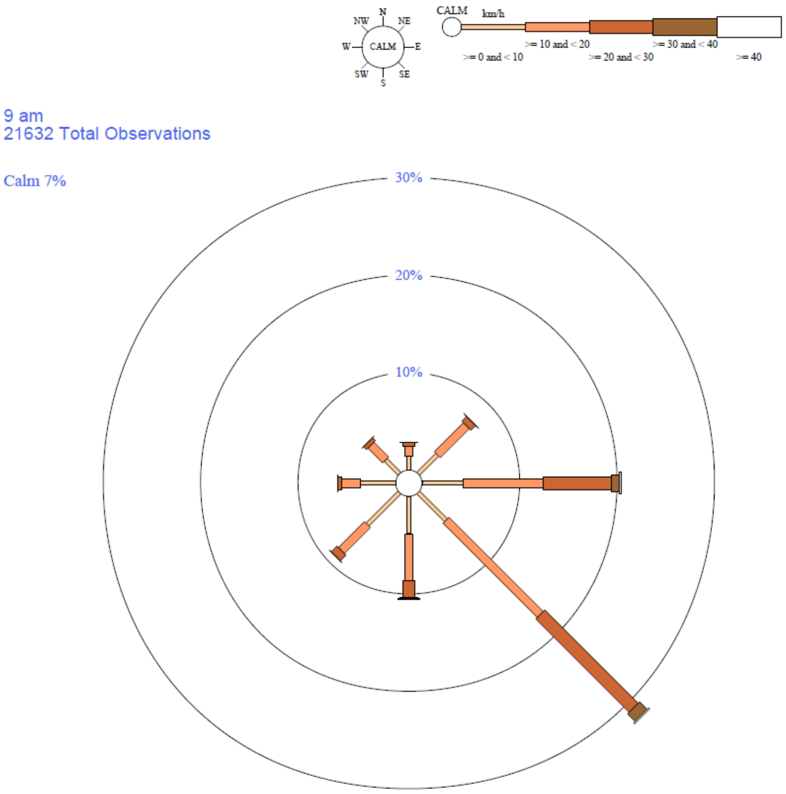


Figure 6. Annual wind rose at 9am at the Gladstone Radar based on measured data from 1957 to 2017 (BoM, 2018).

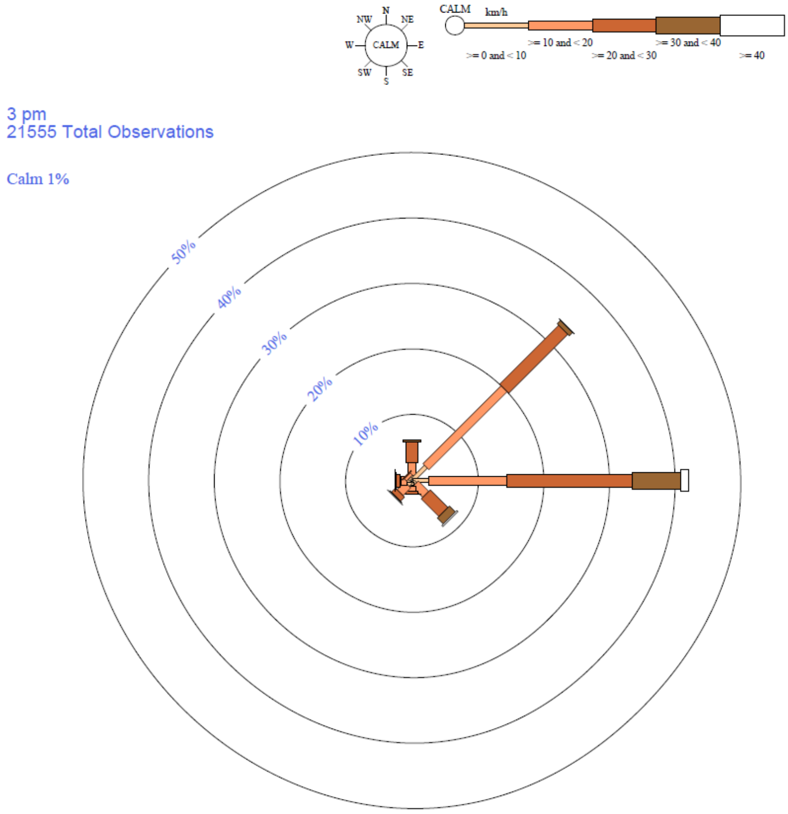


Figure 7. Annual wind rose at 3pm at the Gladstone Radar based on measured data from 1957 to 2017 (BoM, 2018).

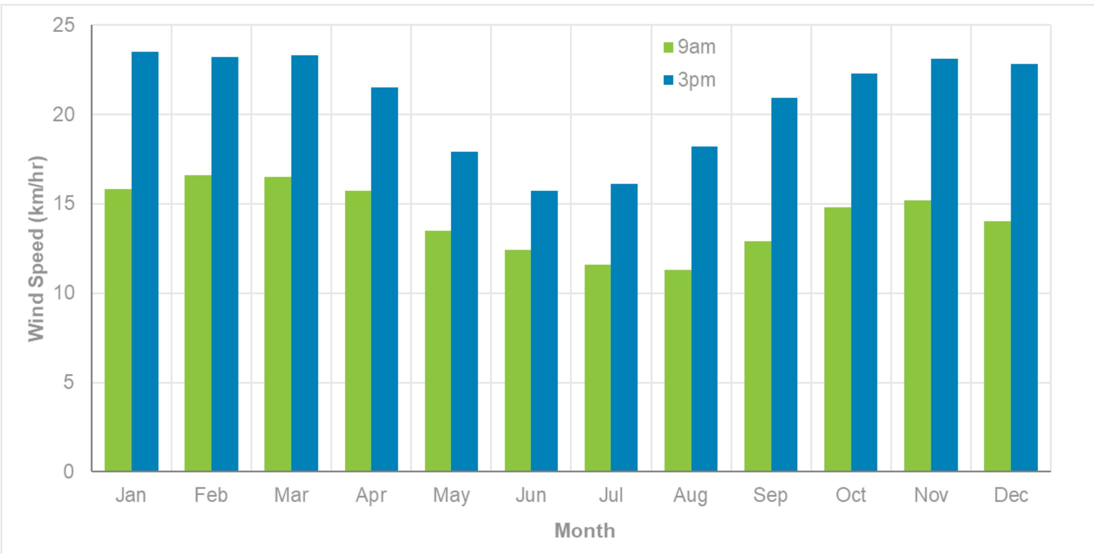


Figure 8. Average monthly wind speed recorded at Gladstone Radar at 9am and 3pm (BoM, 2018).

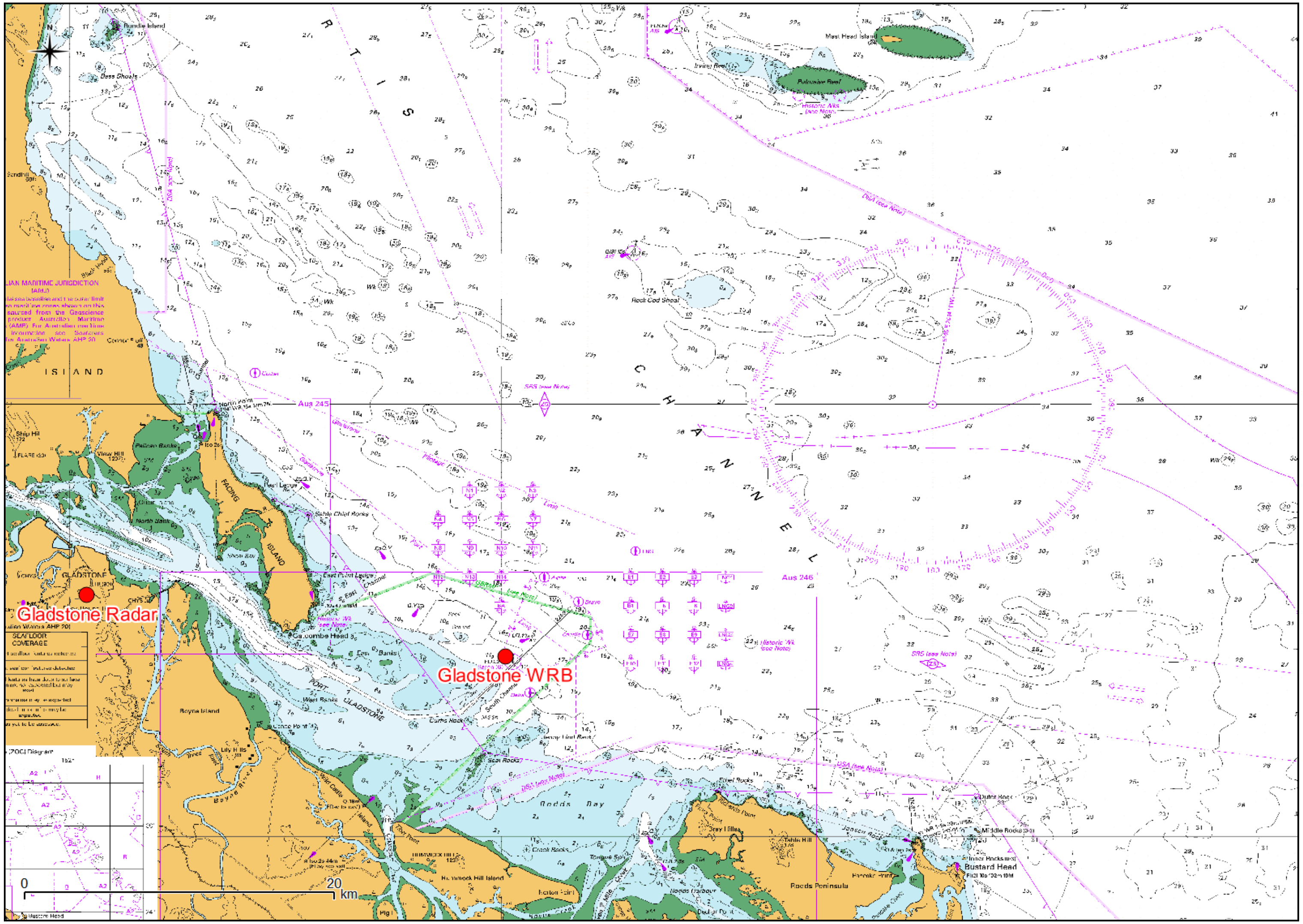


Figure 9. Locations of the measured wind and wave data.

The bed stresses generated by waves can be important to mobilise sediment from the seabed. The majority of the PoG channels are protected from offshore sea and swell waves by Curtis and Facing Islands, but some of the channels are exposed offshore waves (Figure 10). As such, the relative influence of wind and waves on sediment transport varies through the PoG. For the purposes of this study the areas are defined as:

- Inner Harbour: this area is sheltered from offshore sea and swell waves (H_s generally less than 0.3 m), although some locally generated wind waves will occur in this area. In this area tidal currents will generally be the dominant process driving sediment transport. This area has been assumed to extend from Jacobs Channel in the north to the south-eastern end of Auckland Channel; and
- Outer Harbour: the area that is exposed to offshore sea and swell waves (H_s will often be more than 0.3 m). In this area a combination of waves and tidal currents (depending on the location) will drive the sediment transport. This area includes the Gatcombe Channel and the Golding, Boyne and Wild Cattle Cuttings and the EBSDS. The seaward end of the Wild Cattle Cutting and the EBSDS are the most exposed to offshore wave sea and swell waves. It is likely that as the EBSDS is shallower than the adjacent areas (due to the build-up of sediment which has been placed there) it will be more likely to experience resuspension during large wave events.

Measured wave data have been collected by the Department of Environment and Science (DES) at the Gladstone waverider buoy (WRB), located in 16 m water depth adjacent to the offshore end of Wild Cattle Cutting (see Figure 9), since 2009. The data show that significant wave heights (H_s) at the entrance to Port Curtis are typically between 0 and 1.5 m and are from the east to east north-east, with waves from the north also occurring occasionally (Figure 11). The wave periods range from 2 seconds to 18 seconds, with the largest waves typically having a peak wave period of between 6 and 12 seconds (Figure 12). The wave conditions vary seasonally, with the largest waves during the summer months (H_s is typically between 0.5 and 1.5 m) and the calmest conditions during the winter months (H_s is typically less than 1 m).

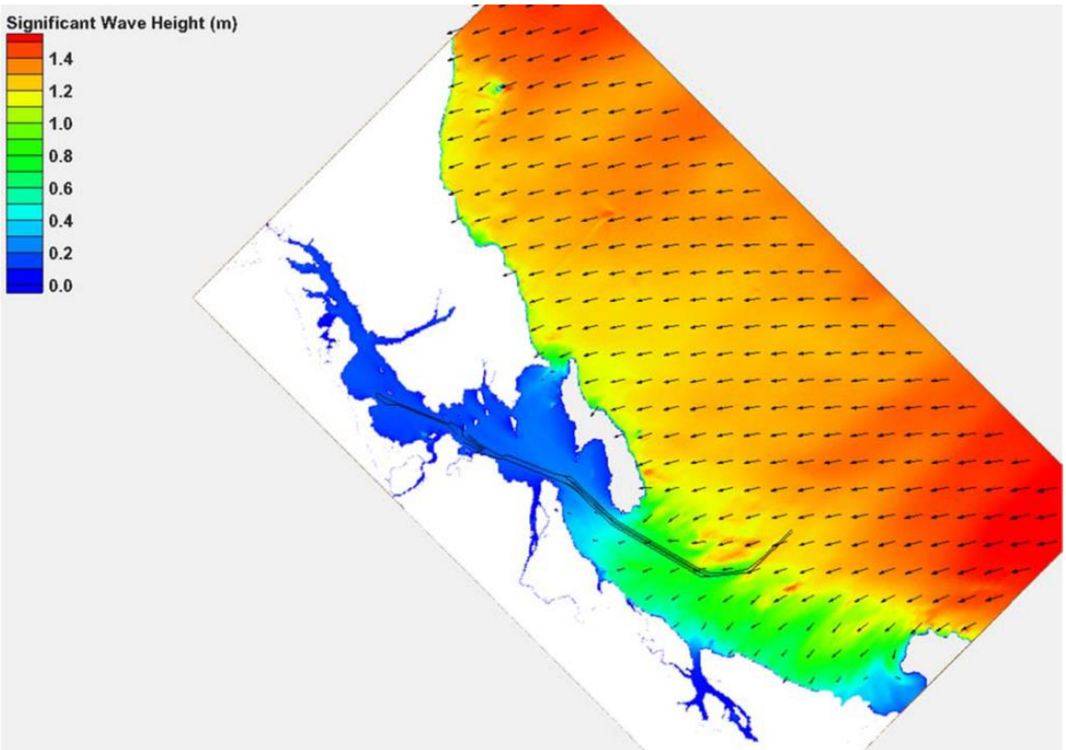


Figure 10. Modelled wave propagation into Port Curtis for an energetic easterly wave event (BMT WBM, 2018a).

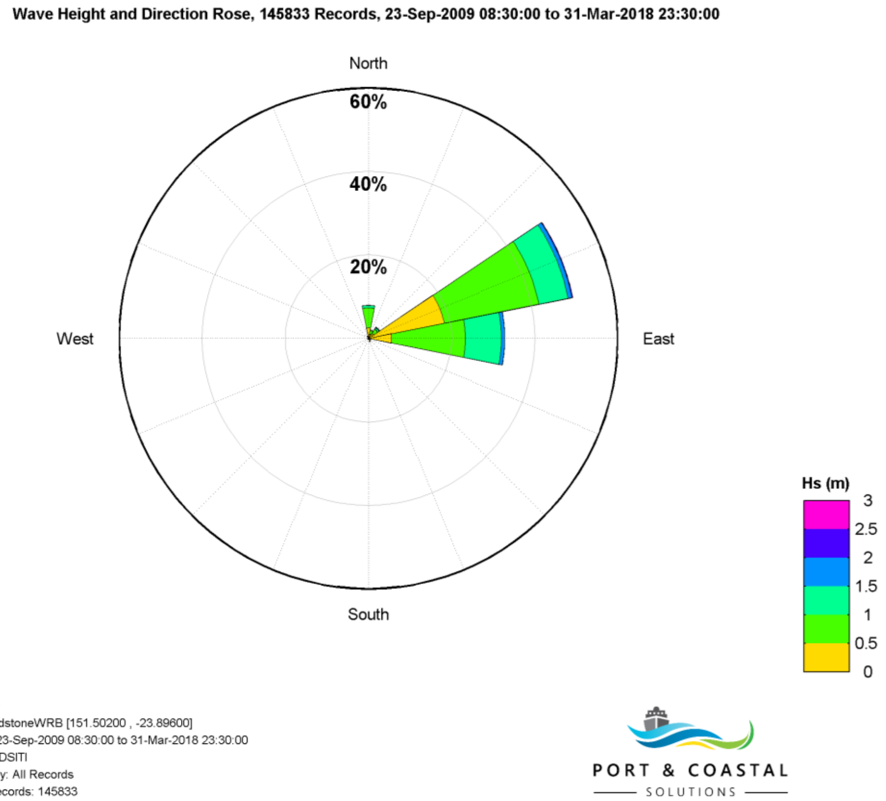


Figure 11. Annual wave rose at the Gladstone WRB.

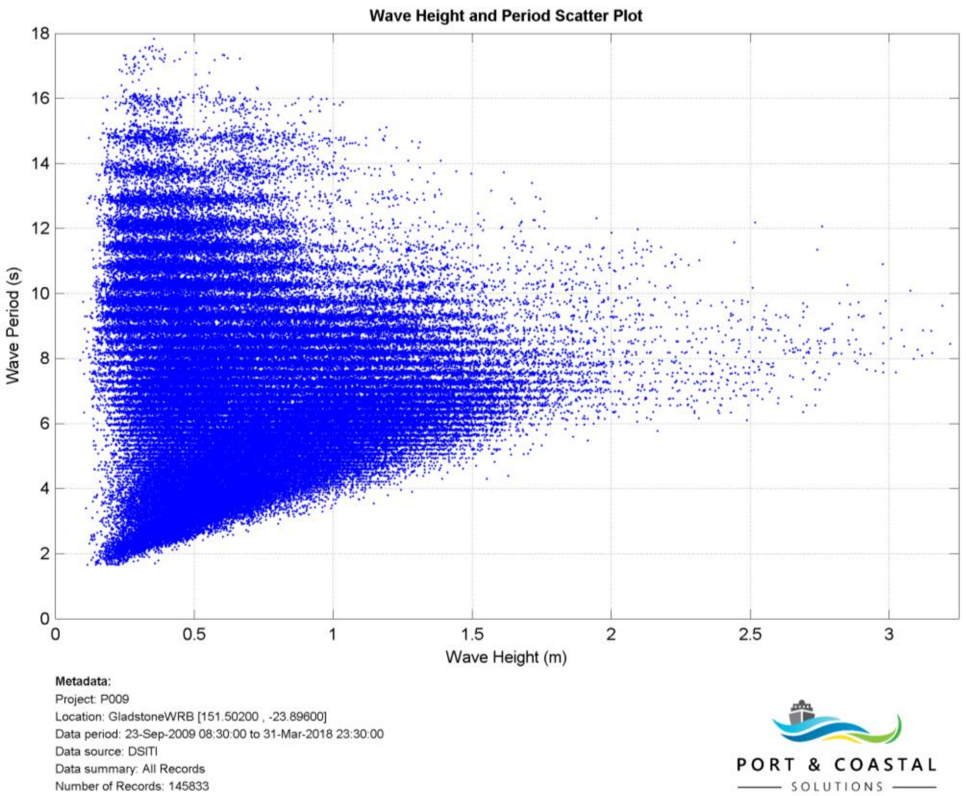


Figure 12. Significant wave height vs peak wave period for the Gladstone WRB.

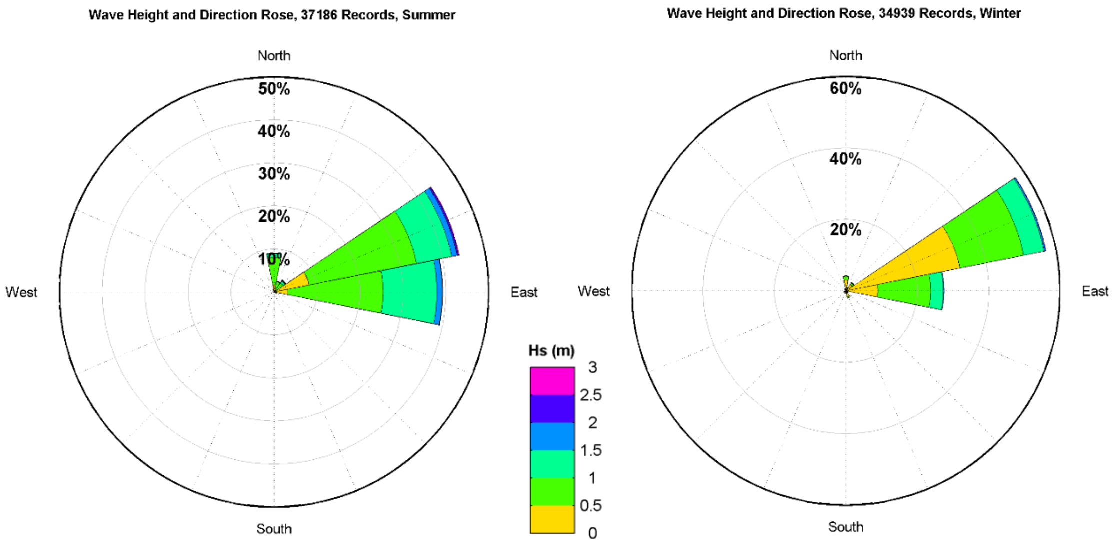


Figure 13. Wave roses for summer and winter at the Gladstone WRB.

2.3. Rainfall and River Discharge

The Gladstone region has a tropical savannah climate as it is classified as having an overall dry climate. Based on measured data (1957 to 2018) at the BoM Gladstone Radar station the mean annual rainfall is 894 mm (BoM, 2018). The mean rainfall and the measured monthly rainfall since 2009 are shown in Figure 14 and Figure 15. The plots show the following:

- the majority of the annual rainfall occurs over the summer months from December to March (the wet season). During the wet season there are on average 8 days per month with more than 1 mm of rainfall;
- there is less rainfall during the remainder of the year (the dry season), with monthly averages varying from 25 to 68 mm (BoM, 2018). During the dry season on average there are 4 days per month with more than 1 mm of rainfall; and
- there is significant annual variability in the rainfall, this is influenced by the development and intensity of El Niño (resulting in dry conditions) and La Niña (resulting in wetter conditions) events in the Pacific Ocean. The highest monthly rainfall of 840 mm occurred in January 2013 due to ex Tropical Cyclone Oswald, this monthly rainfall was more than the total annual rainfall in some years (e.g. 2009, 2011, 2012 and 2015) (BoM, 2018). This is important to note as it will be the periods with high monthly rainfalls which have the potential to result in high river discharges and the associated discharge of suspended sediment.

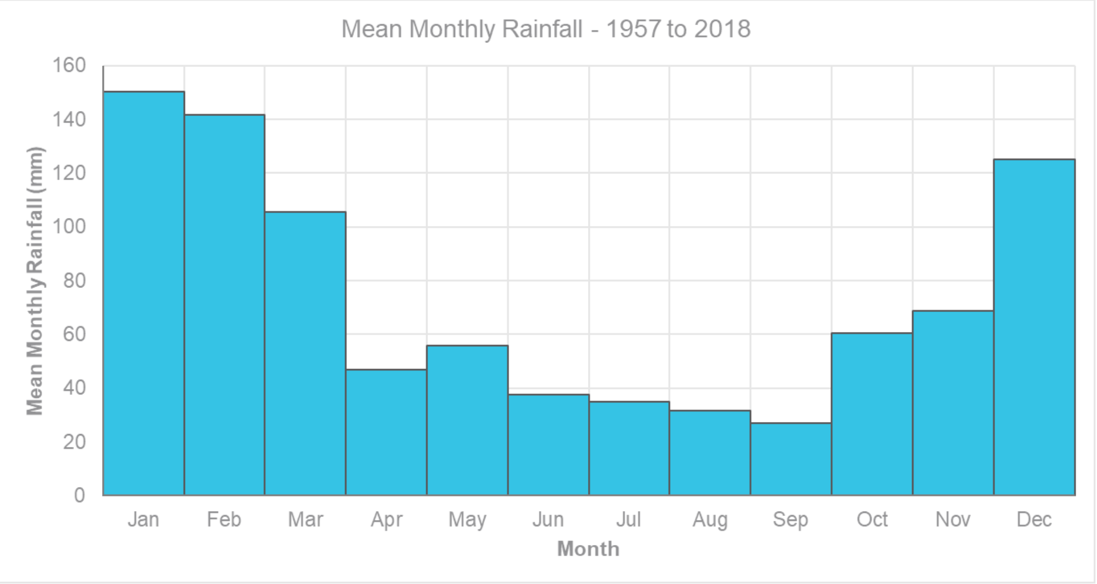


Figure 14. Mean monthly rainfall at the Gladstone Radar station (BoM, 2018).

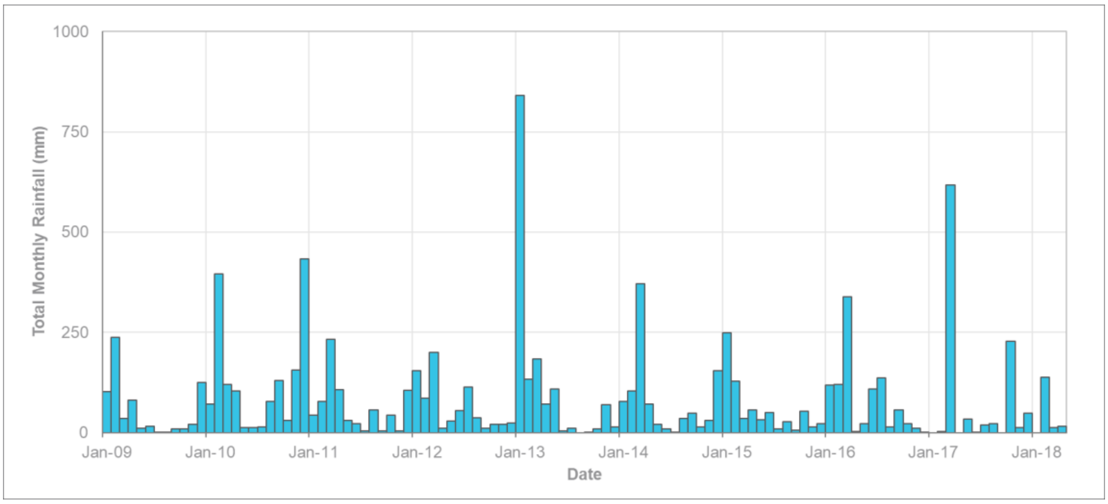


Figure 15. Measured monthly rainfall at the Gladstone Radar station since 2009 (BoM, 2018).

There are two main catchments which discharge directly into the PoG, the Calliope and the Boyne. There is also the potential that the Fitzroy could influence the PoG by suspended sediment being transported through The Narrows into the PoG. Details of the potential contribution of these three catchments are provided below:

- Calliope: the annual river discharge has been estimated to be approximately 150,000 Million Litres (ML) (Castlehope gauging station) (C&R Consulting, 2005). The average annual load of suspended sediment released into the region from the Calliope has been modelled as 44,000 t/yr (Dougall et al., 2014). The sediment fluxes have also been estimated using the TUFLOW FV sediment transport model, which indicated that around 160,000 t of suspended sediment released during a 100 year Average Recurrence Interval (ARI) flood event (as experienced in 2013), but only 600 t of suspended sediment released in a typical dry season period (2 months) (BMT WBM, unpublished model run).
- Boyne: the annual river discharge has been estimated to be approximately 385,000 ML (boyneisleec.eq.edu.au). Approximately 20 km upstream from the mouth of the Boyne a dam has been built to create a reservoir with a capacity of 270,000 ML (Lake Awoonga).

Assessments of how much sediment has been captured in the Awoonga Dam since its construction have not been carried out. Modelled estimates of the average annual load of suspended sediment released into the region range from 11,000 t/yr (Dougall et al., 2014) to 43,000 t/yr (Kroon et al., 2012). Most recently TUFLOW FV modelling has been undertaken which indicates that minimal sediment input from the Boyne occurs under ambient dry season conditions. During a 100 year ARI flood (as experienced in 2013) with Awoonga Dam overflowing, the model indicates a sediment load of around 300,000 t (BMT WBM, unpublished model run).

- Fitzroy: the annual river discharge has been estimated to be 5,900,000 ML, showing that it is a considerably larger river system and catchment than the Boyne and Calliope. The Fitzroy River is located to the north of Port Curtis and the two are connected by a shallow channel (The Narrows) which runs between the mainland and Curtis Island. It has been suggested that the Fitzroy may contribute to the suspended sediment present in Port Curtis during intense flood events, such as those experienced in 2011. Kroon et al. (2012) modelled the average annual load of suspended sediment released into the region by the Fitzroy as 3.4 Mt/yr. The residual flow from the mouth of the Fitzroy is northwards, which is why the net transport of suspended sediment from the Fitzroy through The Narrows could be minimal.

It is worth noting that all three estuaries have extensive tidal flats, some of which are covered by seagrass and mangrove forests. In addition to a net flow reduction, the mangrove forests may reduce the amount of sediment leaving the estuaries and entering the adjacent water bodies (including Port Curtis).

Port Curtis also receives sediment from other smaller creeks and tributaries, for example Auckland Inlet, Boat Creek, Graham Creek, Colosseum Inlet, and from direct runoff from the land (including but not limited to Curtis and Facing Island and the Rodds Bay Peninsula), especially in large flood events. However, the contributions of these creeks and urban runoff have not been quantified, but is likely to be minimal in comparison to the main rivers.

It was suggested by Conaghan (1966) that the source of the majority of fine-grained silt and clay sized sediment in Port Curtis was likely to be from the seasonal flooding of the rivers over geological timeframes. Much of this sediment was thought to be retained within the estuary and over time it becomes added to the existing shoals and mudflats/mangroves within the estuary.

2.4. Tropical Cyclones

Tropical Cyclones (TCs) regularly form in the Coral Sea during the wet season and have the potential to result in strong to gale force winds, large wave heights and heavy rainfall along much of the Queensland east coast. Due to the latitude of the PoG, TCs do not occur as regularly as they do for the ports located further north in Queensland. Between 1969 and 2018 a total of 7 TCs have passed within 100 km of the PoG (Figure 16). Therefore, the high wind speeds which occur when a TC passes close are not expected to occur that regularly at the PoG. However, there is still the potential for large swell waves generated by TCs further north to reach the Outer Harbour of the PoG and for heavy rainfall due to the TCs or subsequent tropical lows (ex-TCs). The largest waves which have been recorded at the Gladstone WRB have generally been due to TCs or ex-TCs which have formed following the cyclones (e.g. the largest and second largest waves recorded were due to TC Olga (2010) and TC Edna (2014)). Numerical modelling undertaken by BMT WBM predicted that despite the infrequent occurrence of TCs in the Gladstone region, a 1:100 year TC could result in significant wave heights of 2.5 m in the Inner Harbour (specifically in the dredged channels around Fisherman's Landing) (GHD, 2009).

Despite the fact that TCs do not directly influence the Gladstone region very often, the large swell waves from TCs which have tracked north of Gladstone have the potential to regularly (e.g. every two to five years) result in substantial resuspension in the Outer Harbour region and the resultant transport and redistribution of the sediment in the region. In addition, the heavy rainfall which occurs over large areas due to TCs and ex-TCs have the potential to regularly (e.g. every two to five years) result in increased discharge of suspended sediment from the local river catchments. Locally generated wind waves within the Inner Harbour resulting from cyclonic winds also have the potential to infrequently (once every 20 to 100 years) result in widespread resuspension in the Inner Harbour region and the resultant transport and redistribution of the sediment in the region.

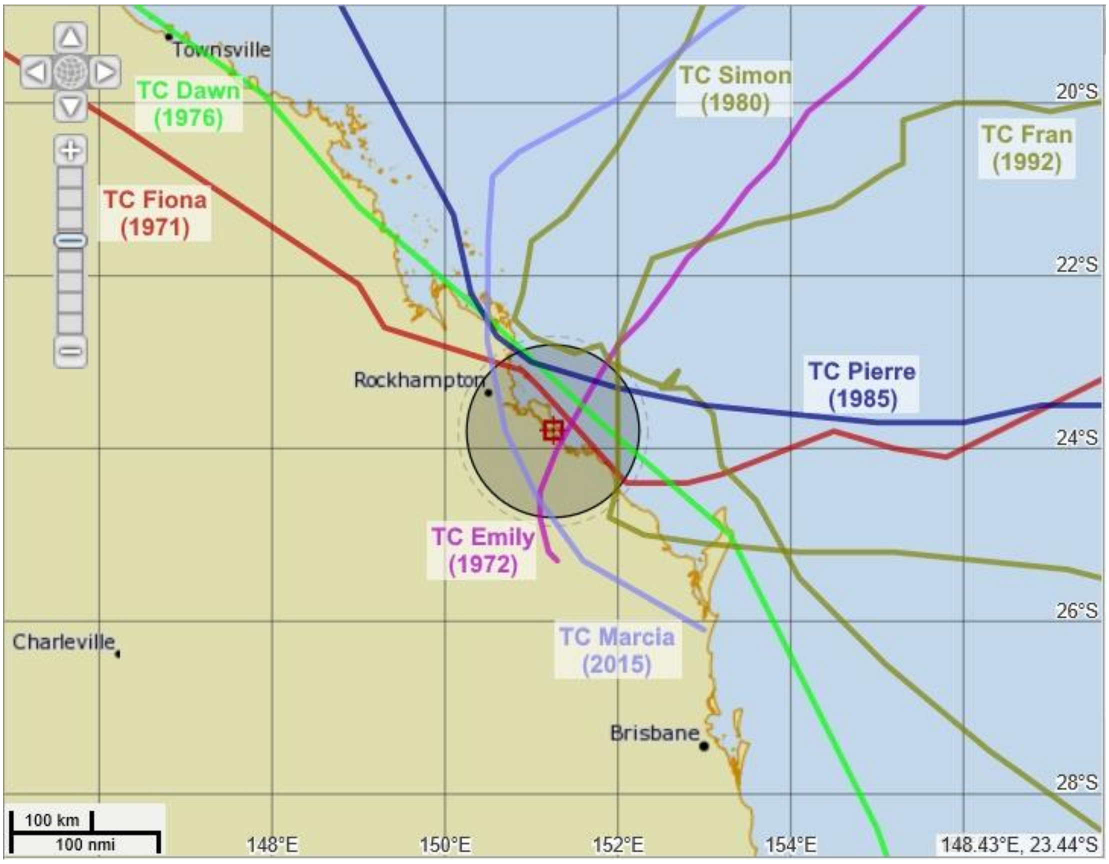


Figure 16. Historic TC tracks for any TCs which have passed within 100 km of the PoG since 1969 (BoM, 2017).

2.5. Sediment Characteristics

There has been extensive sampling and analysis of the surface sediment within the PoG as part of scientific research, industry projects and ongoing port activities. All available surface sediment data has been collated, reviewed and combined in a single dataset by CQU (2018). The sediment data has been processed using a consistent sediment classification system (Shepard (1954), modified by Schlee (1973)) to provide an overview of the spatial variability in the composition of the surface sediment in the PoG (Figure 17). The sediment composition map shows the following:

- the Outer Harbour region is predominantly made up of sand and sandy silt/clayey sand, although some gravelly sediment is also present in the channels and the EBSDS. The sampling shows that the surface sediment present at the EBSDS is similar to the sediment in the adjacent areas, with it being mainly sand with some clayey/silty sand and gravelly sand; and
- the Inner Harbour region is made up of a range of sediment types, from gravelly sediment to silt. The gravelly sediment is typically located within the main channels where current speeds are highest, while the finer-grained sediment is located along the landward edges of the estuary where shallow intertidal and subtidal mudflats have built up.

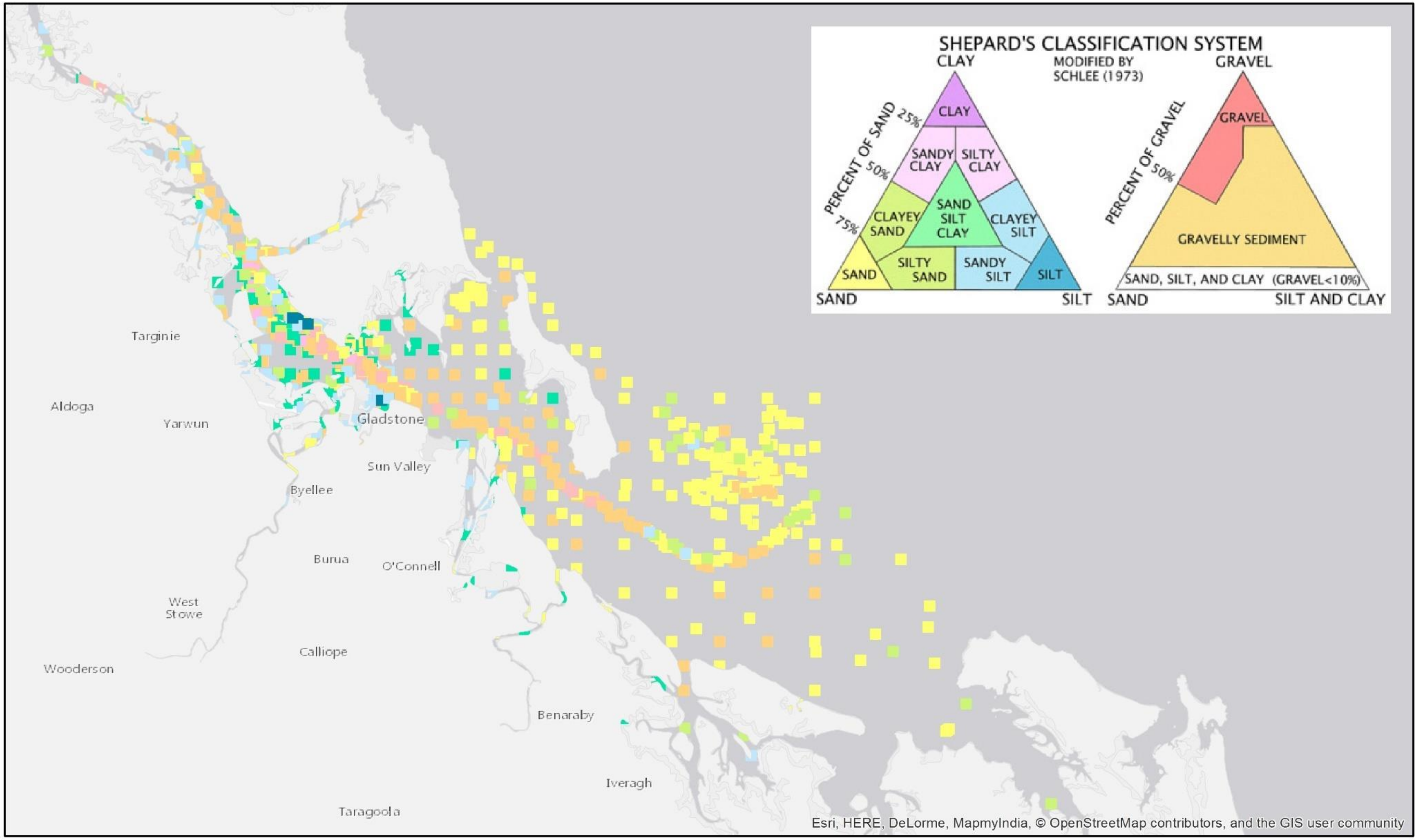


Figure 17. Classification of surface sediment in the Port of Gladstone (from CQU, 2018).

Recent sediment sampling has been undertaken within the maintained channels of the PoG as part of the requirements associated with the ongoing maintenance dredging. A random sampling approach was adopted within the dredged channels in accordance with the National Assessment Guidelines for Dredging (NAGD) (Commonwealth of Australia, 2009) and additional targeted sampling of the areas where regular maintenance dredging is required was also undertaken (AMA, 2018a and 2018b). The analysis found that within the channels in the Inner Harbour there were two distinct seabed types:

1. Jacobs Channel: the seabed was largely dominated by fine-grained sediment in the clay and silt size; and
2. Clinton Channel to Gatcombe Channel: the seabed was made up of coarser sediment, with the majority of the sediment in the gravel and sand size classes.

The targeted sampling in the areas where regular maintenance dredging is required showed that, within the Jacobs Channel region and some areas around Fisherman's Landing the sediment was predominantly made up of fine-grained silt and clay (classified as silty clay and clayey silt). In contrast, in the Outer Harbour region the sediment in the areas of the Golding, Boyne and Wild Cattle Cuttings, where regular sedimentation has occurred, was found to have a higher percentage of sand (40-90%), with fine-grained silt and clay also present (10-60%), resulting in the sediment generally being classified as sand to clayey sand. Within the remaining channels in the Inner Harbour (Clinton Channel to Gatcombe Channel), the results showed that the sediment was predominantly gravelly sediment, although the areas where regular maintenance dredging has been required were small isolated patches and so it is possible that the sampling represents the natural seabed rather than any recently deposited sediment.

Repeat sediment sampling at the same locations was undertaken at the EBSDS immediately before (pre), immediately after (post) and two months after the 2017 maintenance dredging campaign (CQU, 2018). The only statistically significant conclusion which could be made was that there was a reduction in the percentage of sand in the surface sediment between the pre and post sampling, showing that immediately after the dredging some of the fine-grained sediment was retained at the EBSDS. The results indicated that the percentage of sand subsequently increased over the following two months (suggesting that some of the fine-grained silt and clay was lost from the surface sediment), but the findings were not statistically significant.

2.6. Sediment Transport

The relative importance of tidal currents and waves in the resuspension of bed sediment differs between the Inner and Outer Harbour regions. In the Inner Harbour region, the tidal currents can be considered to be the dominant driver for sediment resuspension and locally generated wind waves are of secondary importance (specifically the small wind waves can resuspend sediment in the shallow areas). In the Outer Harbour region, the wave energy is higher and tidal current speeds are lower, meaning that the waves are a more important driver for sediment resuspension.

Measured turbidity data[1] within Port Curtis shows how the amount of sediment being transported in suspension varies depending on the tidal range (Figure 18). The measured data show that the Suspended Sediment Concentration (SSC) varies with peaks of up to 100 mg/l during the largest spring tides and only up to 10 mg/l during the smallest neap tides. The variation in turbidity due to the tidal range is a result of the variation in tidal currents caused by the tidal range along with the relative coverage of intertidal areas resulting at high water (i.e. whether it is an overbank tide or not). If all intertidal areas are submerged then there is an increased potential for the resuspension of loosely consolidated fine-grained sediment on the intertidal areas (i.e. overbank tides result in higher turbidity than non-

[1] converted to Suspended Sediment Concentration (SSC) or Total Suspended Solids (TSS) based on a correlation developed using water sampling results.

overbank tides). In addition, the data show that the SSC fluctuates over the individual tidal cycles, suggesting that much of the suspended sediment is subsequently deposited during the slack water periods (either high water or low water) and then the sediment which has been deposited in areas with sufficiently high current speeds will be resuspended during the subsequent flood or ebb tidal currents.

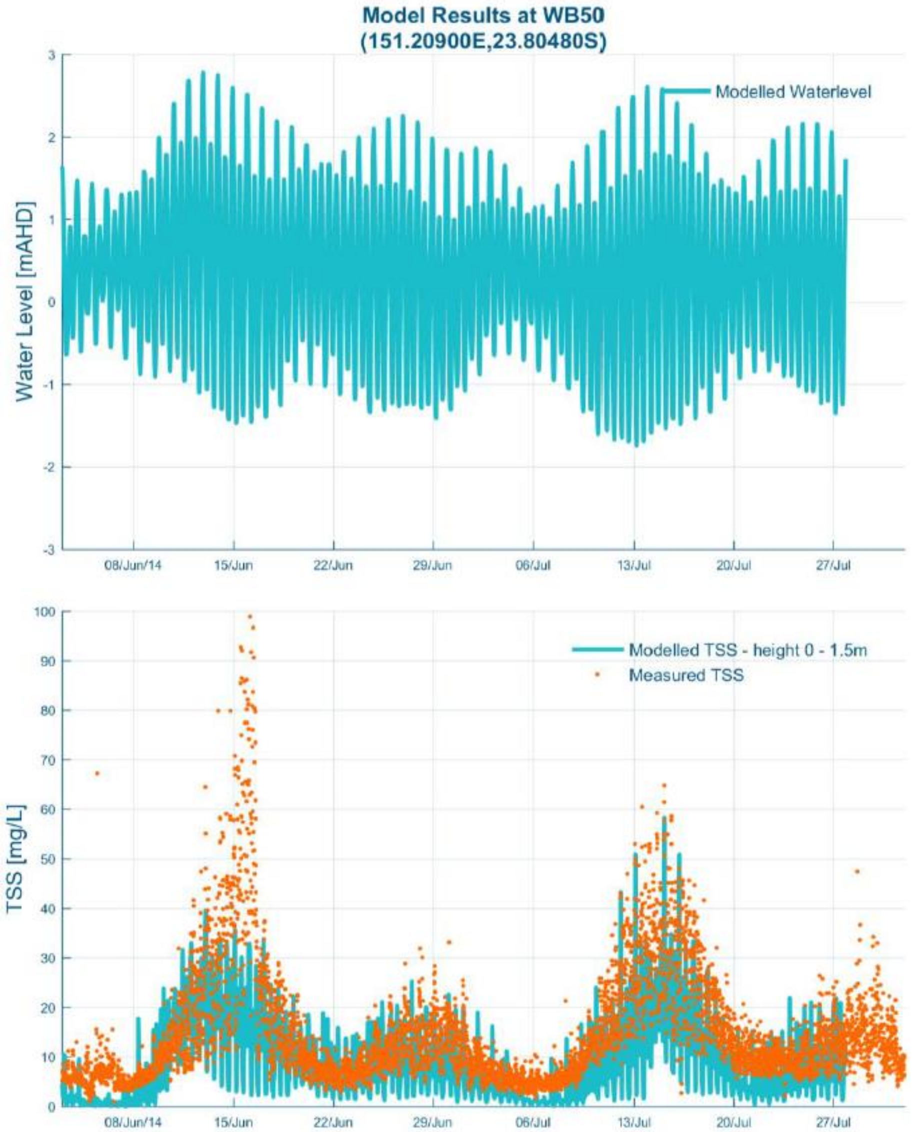


Figure 18. Measured and modelled SSC at the northern end of Clinton Channel (from BMT WBM (2017a)).

The turbidity in the Gladstone region also varies spatially, with the spatial variability also being controlled by the offshore wave conditions (i.e. if the offshore wave conditions are calm then the turbidity in the Inner Harbour will be higher than offshore, but if the offshore waves are large then the Outer Harbour turbidity could be higher than the Inner Harbour). The spatial distribution of the turbidity in the region is shown in Figure 19, the plot shows the following:

- the turbidity in the Inner Harbour region is higher than the turbidity in the Outer Harbour region. The turbidity offshore is much lower than in Port Curtis and at its entrance, this is because the time shown represents a spring tide with calm offshore wave conditions (H_s of less than 0.3 m). It is worth noting that the turbidity appears to be higher in the Wild Cattle Cutting, indicating that suspended sediment can become trapped in the channel;

- the highest turbidity in the Inner Harbour is around the main channels between Jacobs and Gatcombe Channels where relatively high current speeds occur, suggesting that the turbidity is locally generated due to the resuspension of fine-grained sediment within Port Curtis. This agrees with the findings of Conaghan (1966) who noted that the key processes influencing resuspension, transport and deposition of sediment within Port Curtis was the regular reworking of sediment by tidal currents and waves; and
- the turbidity in the Fitzroy river mouth, which The Narrows connects to, is significantly higher than it is in Port Curtis. The fact that the turbidity in The Narrows remains relatively constant over a 15 km length north of Jacobs Channel, before increasing due to the influence of the higher turbidity in the Fitzroy River, suggests that at this time there was little exchange in suspended sediment between Port Curtis and the Fitzroy River. A detailed investigation to assess the contribution of suspended sediment from the Fitzroy River when it is in flood is being undertaken as part of the SSM Project.

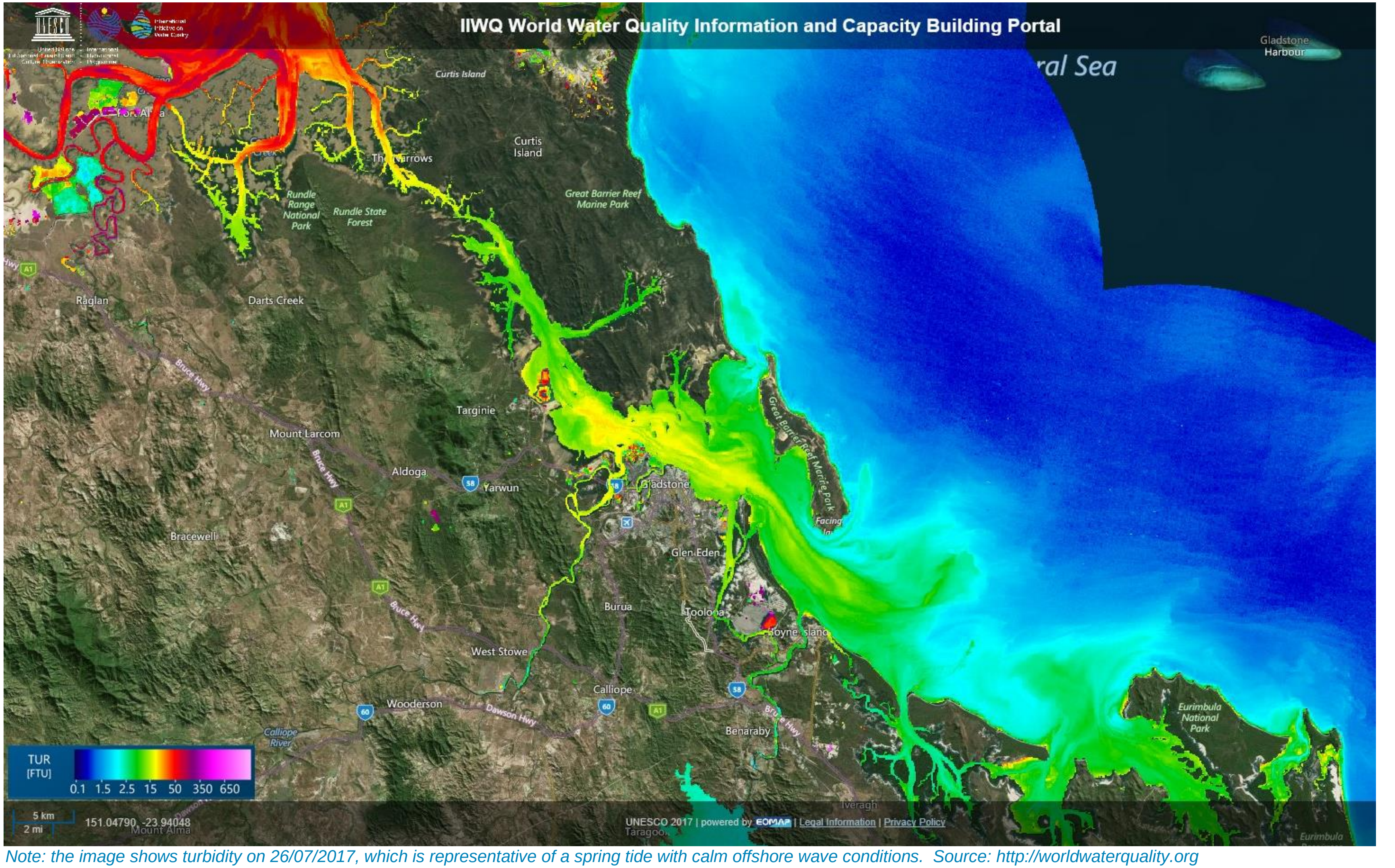
A high-level sediment budget[2] was developed by the Queensland Ports Association (QPA) for Port Curtis (from The Narrows to the northern and southern entrances adjacent to Facing Island) and the area directly offshore (extending to the -15 m LAT depth contour) for Water Quality Action 17 (WQA17) as part of the Reef 2050 Long Term Sustainability Plan (BMT WBM, 2018b). The budget was based on long-term (at least 12 months in duration) measured water quality data as well as numerical model simulations. The study found that within Port Curtis over 8.5 Mt of sediment was resuspended each year, and in the area directly offshore over 6.5 Mt was resuspended. As such, it was calculated that the natural resuspension for the PoG region was in the order of 15 Mm^3 per year (BMT WBM, 2018b). It is important to note that although the primary source of new fine-grained sediment to Port Curtis is thought to be from the local river systems, the relative contribution of fine-grained sediment from the rivers is small compared to the mass of sediment resuspended by tidal currents and waves.

Along nearshore areas (to depths of approximately 10 m) which are influenced by wave action a net northerly transport of fine-grained sediment occurs. The fine-grained sediment is mobilised by the oscillatory currents generated by the waves and it is then transported by the wave-generated and wind-driven currents. Due to the dominant wind and wave directions relative to the shoreline orientation, the dominant longshore transport direction is to the north-west. Recent calculations by BMT WBM using the calibrated TUFLOW FV model of Port Curtis, indicate that the natural longshore transport rate of fine-grained sediment is around 2 Mt/yr. It is unknown how much of this fine-grained sediment is transported into Port Curtis, but it is expected that at least some will be (this will be investigated further as part of the SSM Project).

Local longshore drift of sand sized sediment driven by wave breaking along the shoreline in the entrance to Port Curtis can result in a northerly transport of sand towards Port Curtis. It is important to note that Conaghan (1966) suggested sands which do enter the harbour through longshore transport are likely lost in the deeper channels, and that the nature of grain-size distributions suggest that the reworking and erosion of channel sediments is more important than the processes introducing sand through the channel entrances. Conaghan (1966) did not observe significant mineralogical dissimilarities between harbour sands and those from the outer coasts of the islands and proposed that the role of wind in contributing sand to the harbour was evident.

This sediment transport understanding is further discussed as part of the conceptual understanding in Section 4.1.

[2] the sediment budget developed by QPA provides a useful estimate of resuspension masses for this conceptual sediment budget, but further analysis will be undertaken to develop a more detailed and thorough quantitative sediment budget specifically for the SSM Project.



Note: the image shows turbidity on 26/07/2017, which is representative of a spring tide with calm offshore wave conditions. Source: http://worldwaterquality.org

Figure 19. Satellite derived water quality for the Gladstone region.

3. Bathymetric Analysis

Hydrographic survey data of the PoG channels and berths collected by Maritime Safety Queensland (MSQ) have been made available for this project. Survey data from 2007 to 2017 have been provided to allow a thorough analysis of bathymetric changes in the areas where depths are maintained, as well as at the EBSDS.

Details of the hydrographic survey data available for the analysis are provided in Table 4. The surveys have been undertaken by MSQ, with a range of different echosounders used, ranging from single-beam to multibeam. Despite the differences in echosounders, all the surveys were reported to have a similar vertical uncertainty of ±0.15 m.

The vertical uncertainty of the surveys is important to consider when analysing the hydrographic survey data and when interpreting any corresponding changes in the bathymetry. To quantify the vertical uncertainty in terms of potential volume errors we can multiply the total area of the dredged areas at the PoG (18.8 Mm^2) by the vertical uncertainty (±0.15 m), which gives a total potential volumetric error of ±2.8 Mm^3. This is more than the total volume of sediment removed by maintenance dredging over the last 10 years (2007 to 2017). However, it is considered unlikely for a survey to be consistently offset by the maximum vertical uncertainty and therefore, the total potential volumetric error should be significantly lower than this. The relative confidence which can be placed in the surveys will be assessed by reviewing the volumetric and sectional changes and comparing these with the typical trends based on the natural conditions. By adopting this approach, it is anticipated that any erroneous results due to survey error will be identified and can be excluded from the analysis.

Table 4. Details of the Port of Gladstone hydrographic surveys available for this assessment.

Year	Surveys	Notes
2007	Post-dredge (Dec)	Excludes southern bend of Boyne and Wild Cattle Cuttings
2008	Pre-dredge (Oct)	Includes all areas
2009	Post-dredge (May), Pre-dredge (Oct), Post-dredge (Nov)	Includes all areas
2010	Pre-dredge (Nov)	Includes all areas
2011	Post-dredge (Mar), Pre-dredge (Nov), Post-dredge (Dec)	Post (Dec) survey excludes the Gatcombe Channel and the Golding, Boyne and Wild Cattle Cuttings
2012	Pre-dredge (Oct), Post-dredge (Dec)	Post survey only includes middle section of the EBSDS
2013	Pre-dredge (Dec)	Excludes the bypass and cutting channels. First survey to include the newly dredged Jacobs Channel and LNG terminals
2014	Post-dredge (Mar), Pre-dredge (Nov)	Post survey excludes the Gatcombe Channel and the Golding, Boyne and Wild Cattle Cuttings
2015	Post-dredge (Jan), Pre-dredge (Dec)	Includes all areas
2016	Post-dredge (Feb), Pre-dredge (Oct), Post-dredge (Oct)	Includes all areas
2017	Pre-dredge (Oct), Post-dredge (Oct)	Includes all areas

3.1. Analysis

The hydrographic survey data were used to create high resolution (3 m) gridded Digital Elevation Models (DEMs) for each of the surveys provided. The DEMs were analysed and processed to determine how the bathymetry has changed over time. The following has been included in the analysis:

- Spatial Maps: high resolution spatial map plots have been produced showing the change in bathymetry between subsequent surveys;
- Volumetric Changes: volumetric changes have been calculated to quantify the erosion or accretion which has occurred between the surveys for the dredge areas and the EBSDS. For the dredge areas the volumetric changes have been calculated separately for different channels regions (see Figure 3). The volumetric changes have been calculated between the post dredge and subsequent pre-dredge surveys so that they represent natural changes and are not influenced by the annual maintenance dredging; and
- Long and Cross Sections: long and cross-sectional changes over time have been extracted from within the EBSDS. The sections help to visualise how the bathymetry has changed over time.

3.2. Results

The results from the bathymetric analyses are discussed for the channels, berths and the EBSDS separately in the following sections.

As noted in Section 3.1, it is also important to consider the potential survey error of ± 0.15 m when analysing the results, as any bias in individual surveys could result in an apparent change that could be artificial.

3.2.1. Dredged Areas

The bathymetry in the dredged areas of the PoG from the 2017 post dredge survey is shown in Figure 20 to Figure 22. The plots show the following:

- there is a large difference in depth between the adjacent natural bathymetry and the Jacobs Channel region (Figure 20);
- there are some isolated areas with naturally deeper bathymetry, for example in the Clinton Channel and Clinton Bypass Channel the areas to the south of Tide Island and Picnic Island, suggesting that high tidal current speeds occur in these areas;
- the Gatcombe Channel region is naturally deep, with the channel not having any batter slopes indicating that limited capital dredging was required to create the channel;
- mega-ripples (sand ridges) naturally form in some areas of the channels, for example in the Clinton Channel directly to the north of the Clinton Wharf berths and along the sides of the Auckland Channel small ripples are present (Figure 21). It is likely that these bedforms are regularly disturbed by maintenance dredging and so do not become fully developed;
- mega-ripples are present in the Wild Cattle Bypass Channel, to the east of the Wild Cattle Cutting (Figure 22). The ripples are fully developed suggesting that maintenance dredging does not occur in this area. The ripples are asymmetrical suggesting they were formed by tidal currents, with their configuration indicating that they have been formed by the ebbing currents (which are stronger than the flood tidal currents in this area, see Figure 4 and Figure 5); and
- the bathymetry within the EBSDS is noticeably shallower than the adjacent natural seabed (especially along the northern end), clearly showing that the site is retentive (Figure 22).

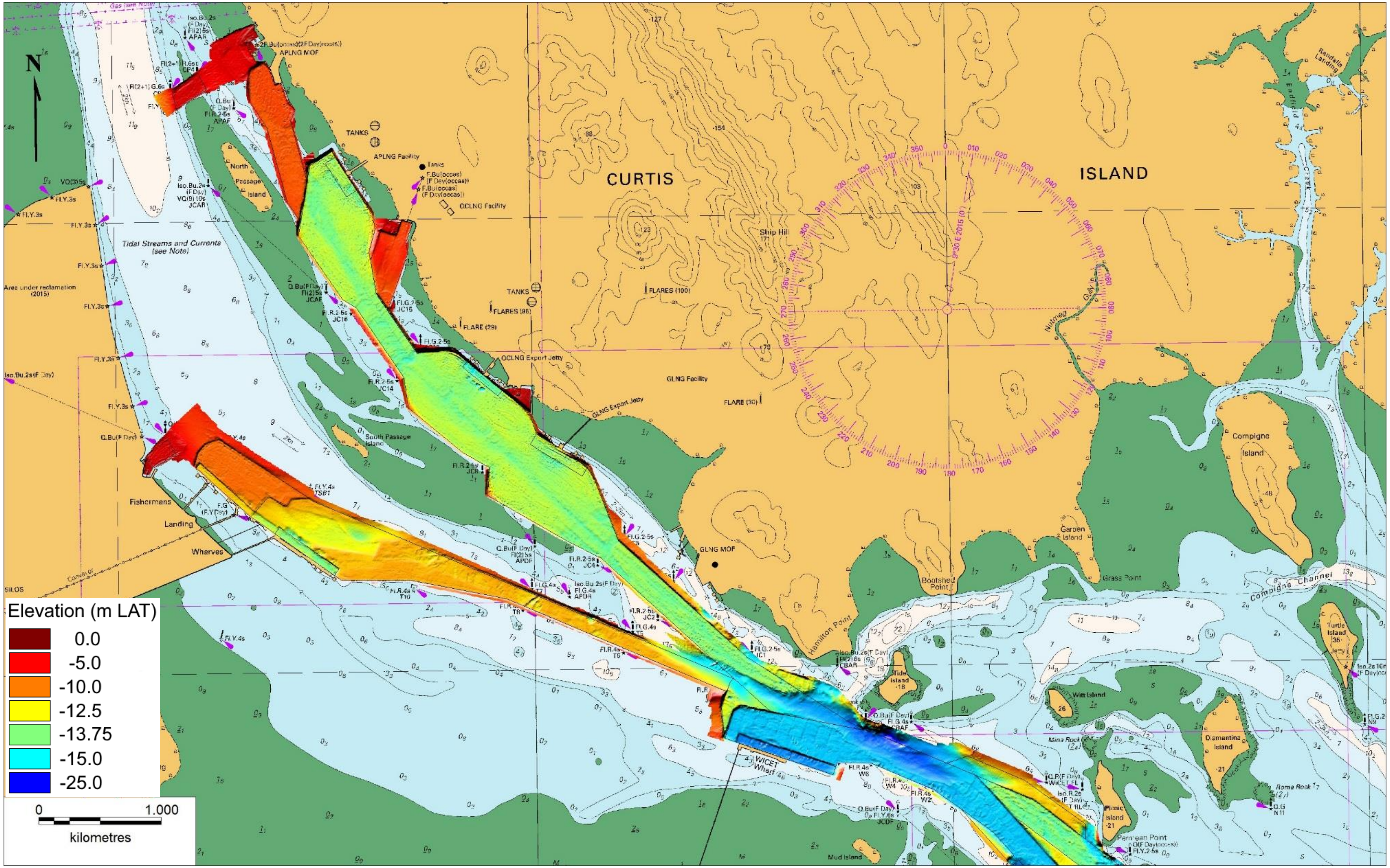


Figure 20. Bathymetry from the October 2017 post dredge survey for the Jacobs and Targinnie Channels region.

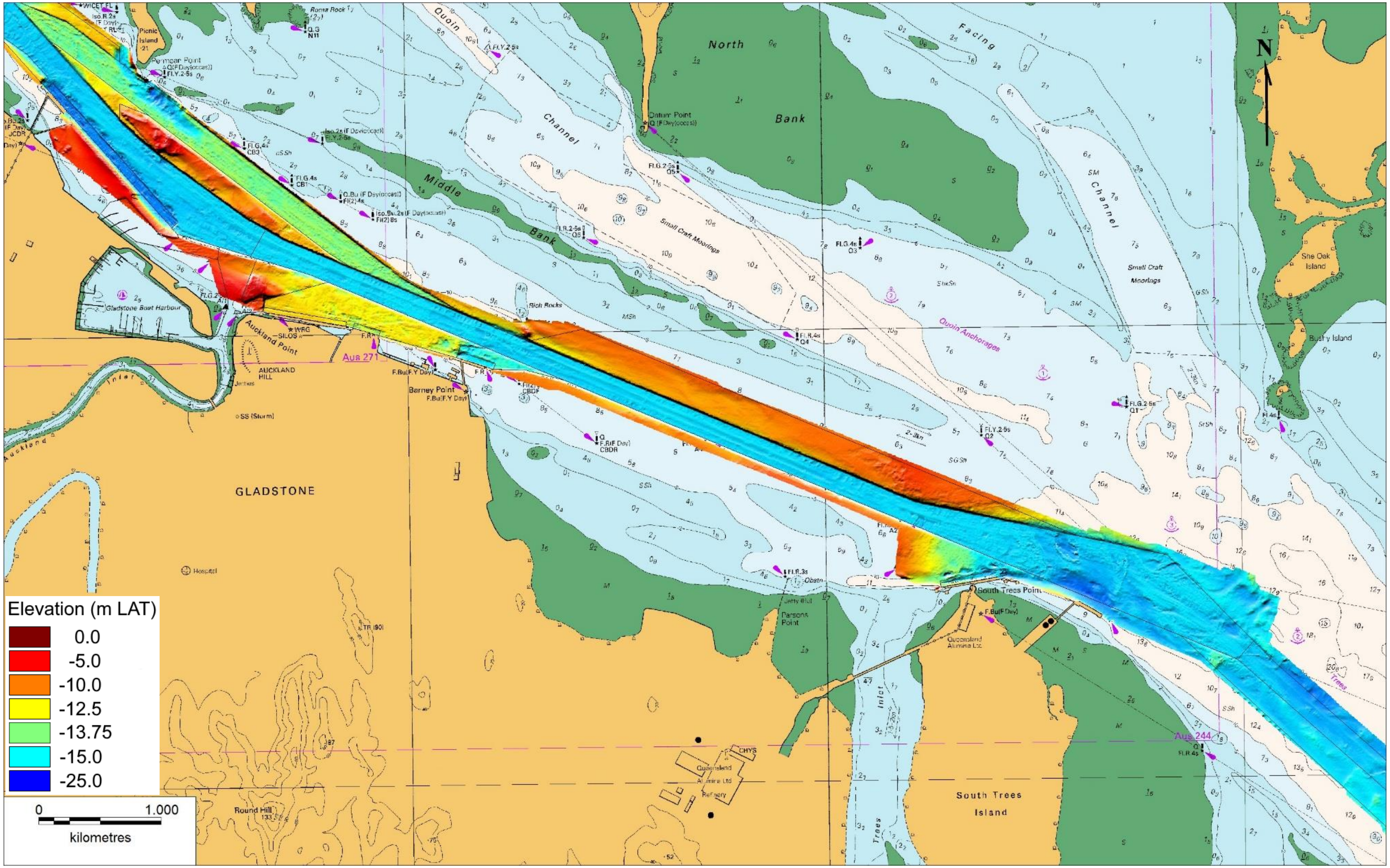


Figure 21. Bathymetry from the October 2017 post dredge survey for the Clinton and Auckland Channels region.

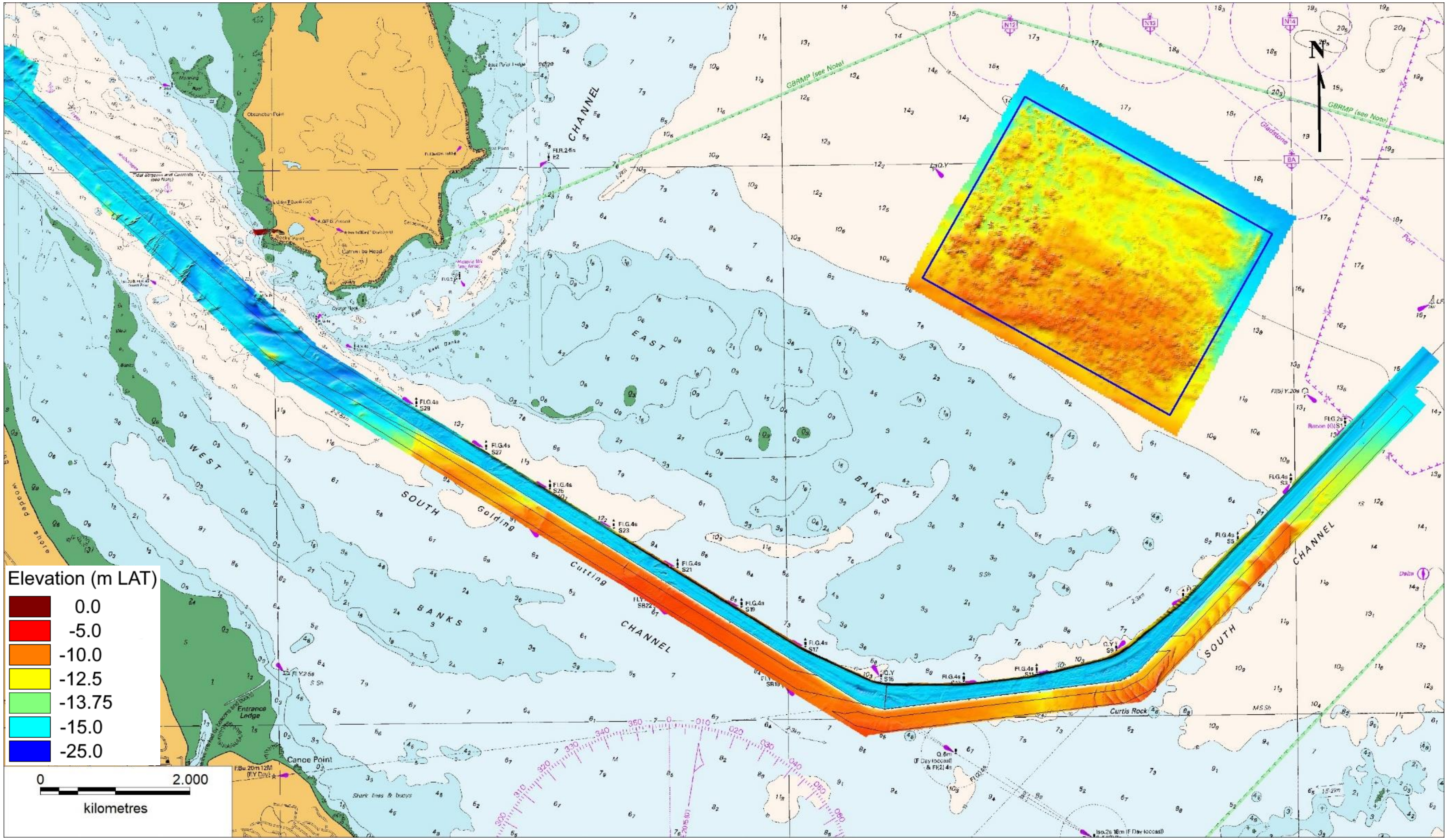


Figure 22. Bathymetry from the October 2017 post dredge survey for the Gatcombe Channel, Golding, Boyne and Wild Cattle Cuttings and the EBSDS.

The natural sedimentation and erosion which has occurred within the dredge areas each year, has been determined by calculating the difference in the bathymetry between the pre-dredge survey one year and the post dredge survey the year before. All of the annual changes between 2007 and 2017 have been summed together to provide a spatial indication of the sedimentation and erosion patterns in the PoG over this 10 year period (Figure 23 to Figure 25). The plots of the summed changes show that in most of the main channels both erosion and sedimentation has occurred (with the migration of mega-ripples showing striped changes in the Clinton and Auckland Channels and the South Bypass Channel), with more erosion than sedimentation commonly occurring. The exceptions to this are:

1. Jacobs Channel: the centre of the channel has been subject to some erosion from the propeller wash of the vessels, while the sides of the channel and the berths have been subject to extensive sedimentation. It is important to note that the sedimentation in this area is based on 3 years of data (as the capital dredging was completed in 2014) while everywhere else in the PoG is based on 10 years of data;
2. Targinnie Channel: the northern areas of the Targinnie Channel close to Fisherman's Landing and the berths at Fisherman's Landing have been subject to regular sedimentation, while the remainder of the channel shows localised areas of erosion and sedimentation. Localised erosion adjacent to the berths has also occurred due to the propeller wash of the tugs;
3. Golding and Boyne and Wild Cattle Cuttings: sedimentation has occurred along the edges of the cuttings, with some erosion occurring along the centrelines due to propeller wash (this is most noticeable along the south-eastern end of the Golding Cutting). It appears that the propeller wash has limited sedimentation in the centre of the cuttings, but as the vessels do not sail along the sides of the cuttings sedimentation has occurred in these areas; and
4. South Bypass Channel: the majority of the South Bypass Channel adjacent to the Golding Cutting has been subject to sedimentation, indicating that this area is naturally accreting. The area of the South Bypass Channel adjacent to the Boyne and Wild Cattle Cuttings where the mega-ripples are present shows stripes of erosion and sedimentation as the ripples have migrated offshore (at an average rate of 10-15 m/yr), while the remainder of this stretch of the bypass channel has been subject to sedimentation similar to the stretch adjacent to the Golding Cutting.

In addition to the berths in the Jacobs and Fisherman's Landing areas, the berths at Auckland Point have also been subject to sedimentation throughout the majority of the berth. The results also show that some sedimentation has occurred in the other berths in the PoG, with the sedimentation typically being at the ends of the berths and along the wharf side of the berth. The results also show that the Tug Base, Auckland Inlet and the Gladstone Marina have been subject to sedimentation (noting that the changes in the marina are only based on two complete surveys of the marina).

Throughout much of the PoG, both erosion and sedimentation have occurred. Consequently, it is necessary to separate the sedimentation from the overall net changes which have occurred. Table 5 quantifies the sedimentation (i.e. positive changes in volume) within the different regions of the PoG over the last 10 years and Table 6 provides a statistical summary of the sedimentation. The results show that:

- the total annual sedimentation in the PoG varied from 300,000 m^3 to 1.3 Mm^3 over the 10 years, with a total volume of 6.7 Mm^3 deposited over the 10 year period;
- since the capital dredging was completed in 2014, the sedimentation in Jacobs Channel has been the highest out of all the channels within the PoG; and
- the total sedimentation in the Inner and Outer Harbour regions was similar from 2007 to 2014. However, from 2015 to 2017 there has been approximately 50% more sedimentation in the Inner Harbour region (due to Jacobs Channel becoming operational).

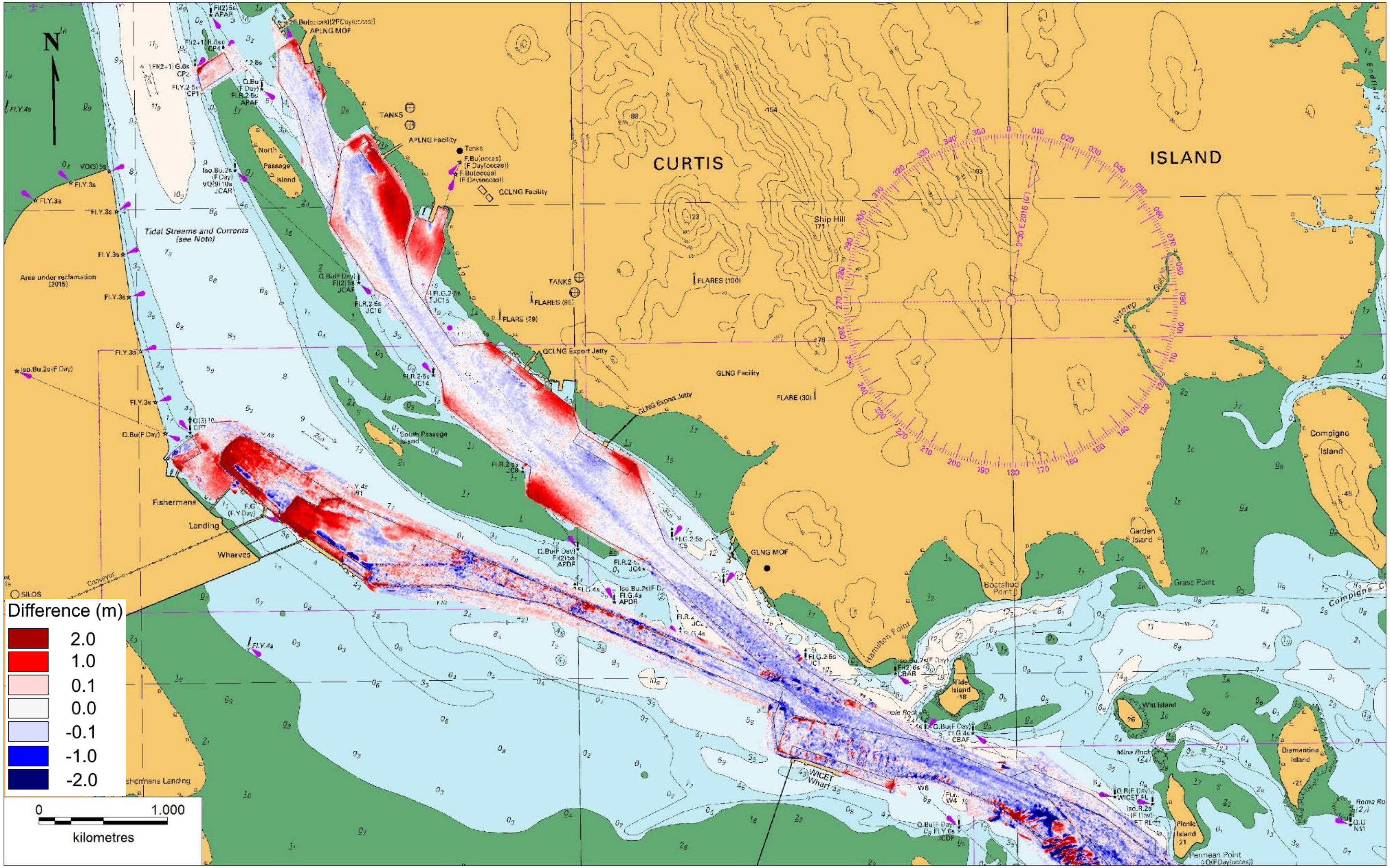


Figure 23. Summed change in bathymetry from 2007 to 2017 for the Jacobs and Targinnie Channels region.

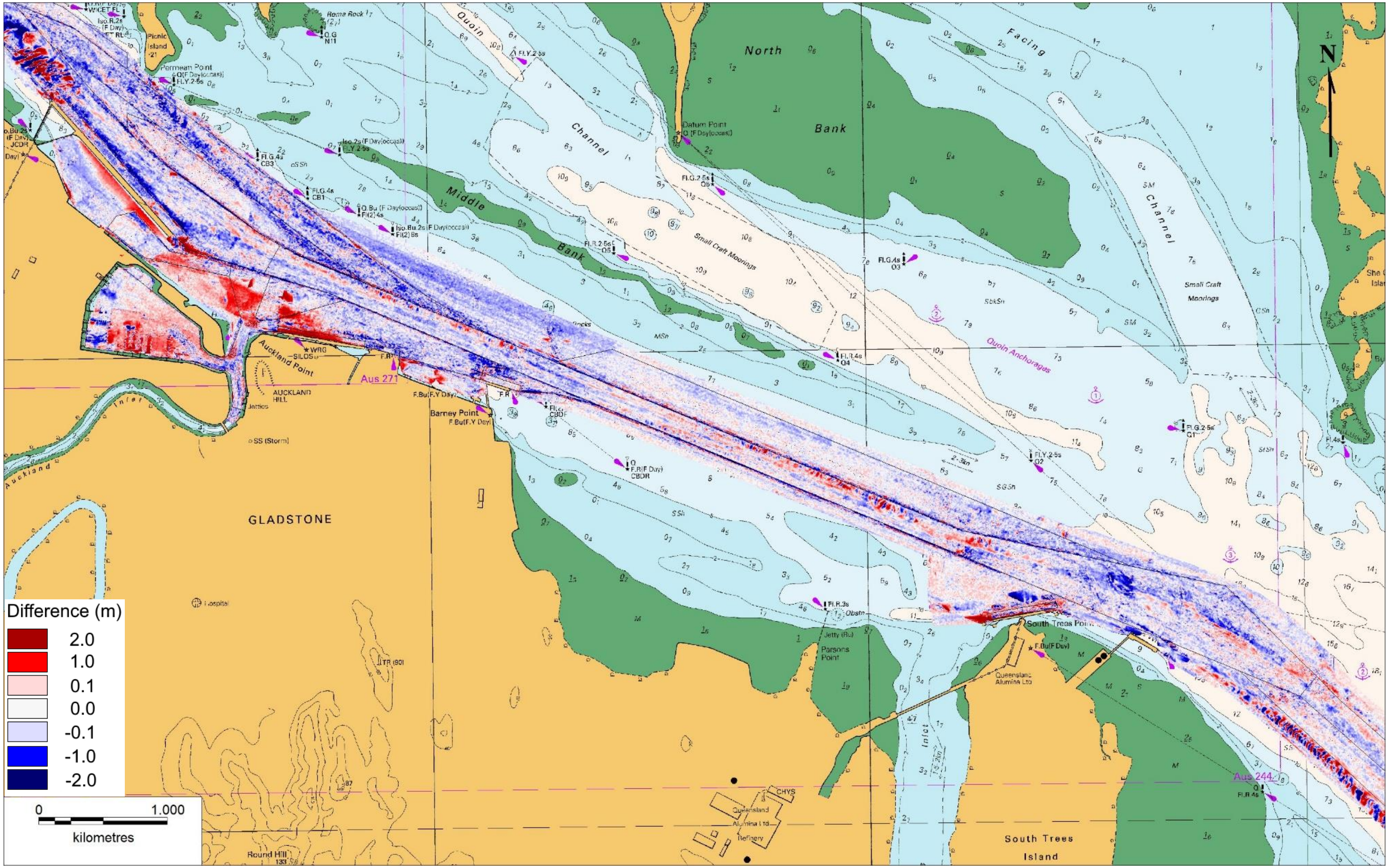


Figure 24. Summed change in bathymetry from 2007 to 2017 for the Clinton and Auckland Channels region.

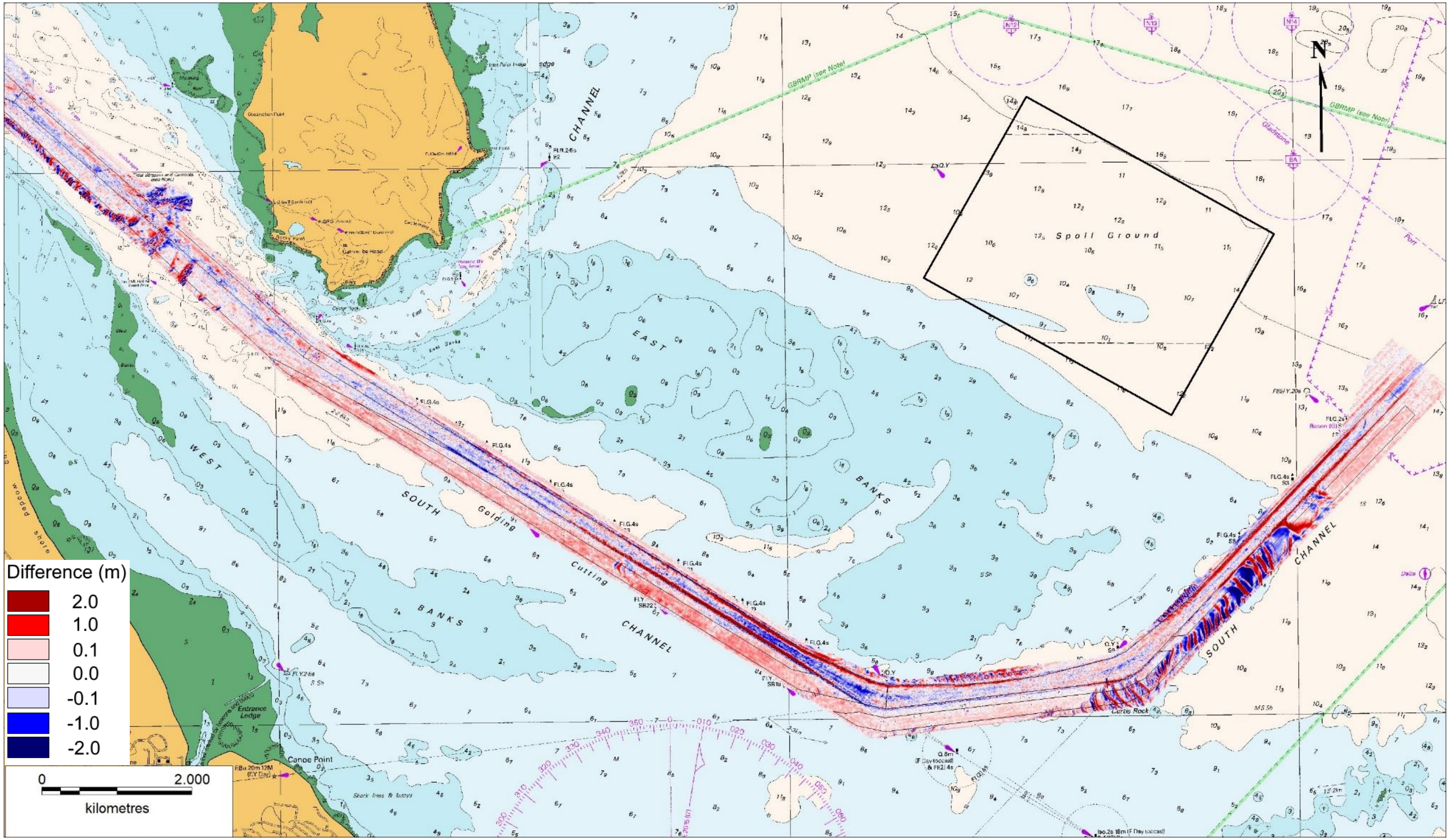


Figure 25. Summed change in bathymetry from 2007 to 2017 for the Gatcombe Channel, Golding, Boyne and Wild Cattle Cuttings and the EBSDS.

Table 5. Annual sedimentation (m³) at the Port of Gladstone from 2007 to 2017.

Region	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Total	*2007-2014*	*2015-2017*
Jacobs Channel								208,229	177,685	160,193	**546,107**		*546,107*
Jacobs area berths and approaches								88,137	93,066	66,239	**247,443**		*247,443*
Targinnie Channel	40,361	23,779	84,221	43,874	32,149	145,351	20,120	69,358	48,356	28,844	**536,412**	*389,854*	*146,558*
Fisherman's Landing area berths and approaches	1,140	677	6,318	7,031	10,685	25,253	1,381	7,149	5,371	5,408	**70,412**	*52,484*	*17,928*
Clinton Channel	36,277	28,515	96,075	50,124	31,257	41,376	53,891	68,420	76,198	13,126	**495,258**	*337,514*	*157,744*
Clinton Bypass	38,108	11,951	67,835	22,868	17,629	83,185	24,420	34,844	35,083	6,633	**342,557**	*265,997*	*76,560*
Clinton area berths and other areas	5,006	3,907	13,895	11,289	5,882	13,466	2,063	15,707	9,454	1,922	**82,589**	*55,507*	*27,082*
Marina					44,448		39,129				**83,576**	*83,576*	
Tug Base	1,104	945	3,027	2,204	1,049	13,415	3,157	11,847	6,143	922	**43,813**	*24,901*	*18,912*
Auckland Channel	88,180	22,256	121,653	139,851	26,970	60,368	80,488	82,920	158,830	8,003	**789,519**	*539,766*	*249,753*
Auckland Bypass	15,222	15,631	36,287	52,942	15,159	8,044	20,134	28,605	37,871	8,008	**237,902**	*163,419*	*74,483*
Auckland area berths and approaches	25,791	12,205	28,787	19,918	10,239	45,382	6,981	28,060	25,087	9,392	**211,842**	*149,303*	*62,539*
Gatcombe Channel	39,437	4,414	40,554	52,693		22,015		22,326	57,861	8,258	**247,558**	*159,114*	*88,444*
Gatcombe Cutting	115,473	22,390	79,845	29,910		4,696		76,883	91,029	36,911	**457,136**	*252,313*	*204,823*
Golding Cutting	117,909	30,907	159,314	53,729		161,368		67,447	137,353	49,165	**777,193**	*523,228*	*253,965*
South Bypass Channel (Golding)	53,648	40,644	26,467	100,222		2,749		12,490	126,981	19,492	**382,693**	*223,731*	*158,962*
Boyne and Wild Cattle Cuttings	49,476	18,582	111,392	107,653		96,948		74,503	101,140	17,588	**577,282**	*384,051*	*193,231*
South Bypass Channel (Wild Cattle)	92,225	70,048	71,152	126,312		255		74,893	121,133	56,300	**612,317**	*359,991*	*252,326*
Total	**719,357**	**306,851**	**946,822**	**820,620**	**195,467**	**723,871**	**251,764**	**971,818**	**1,308,641**	**496,404**	**6,741,609**	**3,964,749**	**2,776,860**
Inner Harbour Total	*251,189*	*119,866*	*458,098*	*350,101*	*195,467*	*435,840*	*251,764*	*643,276*	*673,144*	*308,690*	*3,687,430*	*2,062,321*	*1,625,109*
Outer Harbour Total	*468,168*	*186,985*	*488,724*	*470,519*		*288,031*		*328,542*	*635,497*	*187,714*	*3,054,179*	*1,902,428*	*1,151,751*

Note: the years shown represent the year of the pre-dredge survey.
[1] the Outer Harbour region was not surveyed in these years.

Table 6. Sedimentation (m^3/yr) statistics for the Port of Gladstone based on data from 2007 to 2017.

Region	Minimum	Median	Mean	Maximum
Jacobs Channel[1]	160,193	177,685	182,036	208,229
Jacobs area berths and approaches[1]	66,239	88,137	82,481	93,066
Targinnie Channel	20,120	42,118	53,641	145,351
Fisherman's Landing area berths and approaches	677	5,863	7,041	25,253
Clinton Channel	13,126	45,750	49,526	96,075
Clinton Bypass	6,633	29,632	34,256	83,185
Clinton area berths and other areas	1,922	7,668	8,259	15,707
Marina[2]	39,129	41,788	41,788	44,448
Tug Base	922	2,615	4,381	13,415
Auckland Channel	8,003	81,704	78,952	158,830
Auckland Bypass	8,008	17,882	23,790	52,942
Auckland area berths and approaches	6,981	22,502	21,184	45,382
Gatcombe Channel	4,414	30,881	30,945	57,861
Gatcombe Cutting	4,696	56,897	57,142	115,473
Golding Cutting	30,907	92,678	97,149	161,368
South Bypass Channel (Golding)	2,749	33,556	47,837	126,981
Boyne and Wild Cattle Cutting	17,588	85,725	72,160	111,392
South Bypass Channel (Wild Cattle)	255	73,022	76,540	126,312
Total	**392,562**	**936,103**	**969,108**	**1,681,270**
Inner Harbour Total	*331,953*	*563,344*	*587,335*	*981,883*
Outer Harbour Total	*60,609*	*372,759*	*381,773*	*699,387*

[1] based on data from 2015 to 2017.
[2] based on data from two years (2012 and 2014).

The results show that the sedimentation in Jacobs Channels and at the LNG terminal berths has reduced since 2015. To further investigate how the sedimentation has changed over this period, plots showing the annual sedimentation in 2015 and 2017 are shown in Figure 26 and Figure 27. The plots show that during 2015 there was sedimentation occurring throughout Jacobs Channel as the whole area stabilised following the capital dredging. In 2017 there has been some erosion in the centre of the channel due to the propeller wash of the vessels, with sedimentation limited to the edges of the channel and the berths. This indicates that the reduction in sedimentation volume which has occurred over the three years can at least be partially attributed to the channel stabilising following the capital dredging and it is therefore likely that the ongoing sedimentation will be closer to the values from 2017.

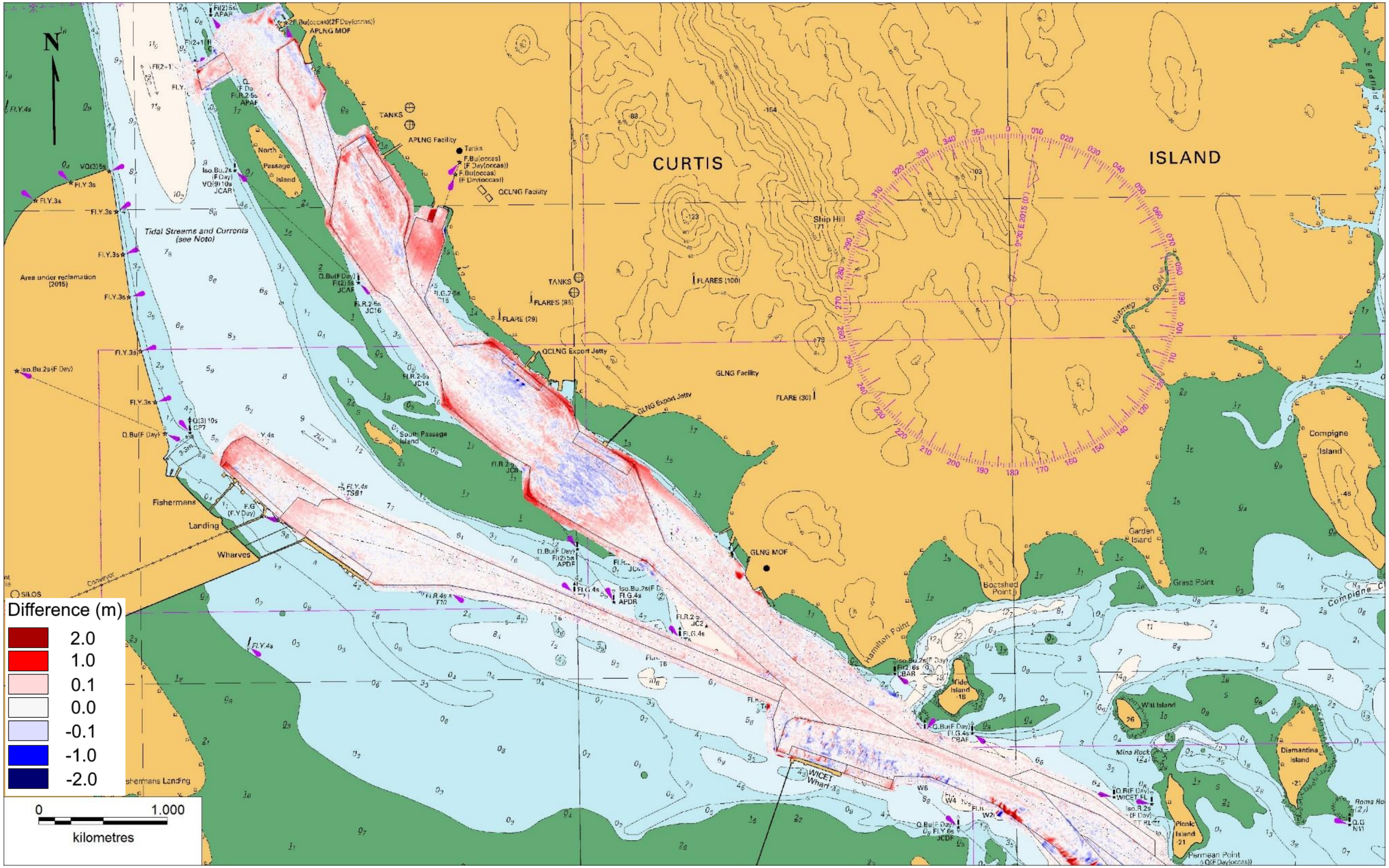


Figure 26. Change in bathymetry between January 2015 and December 2015 for the Jacobs and Targinnie Channels region.

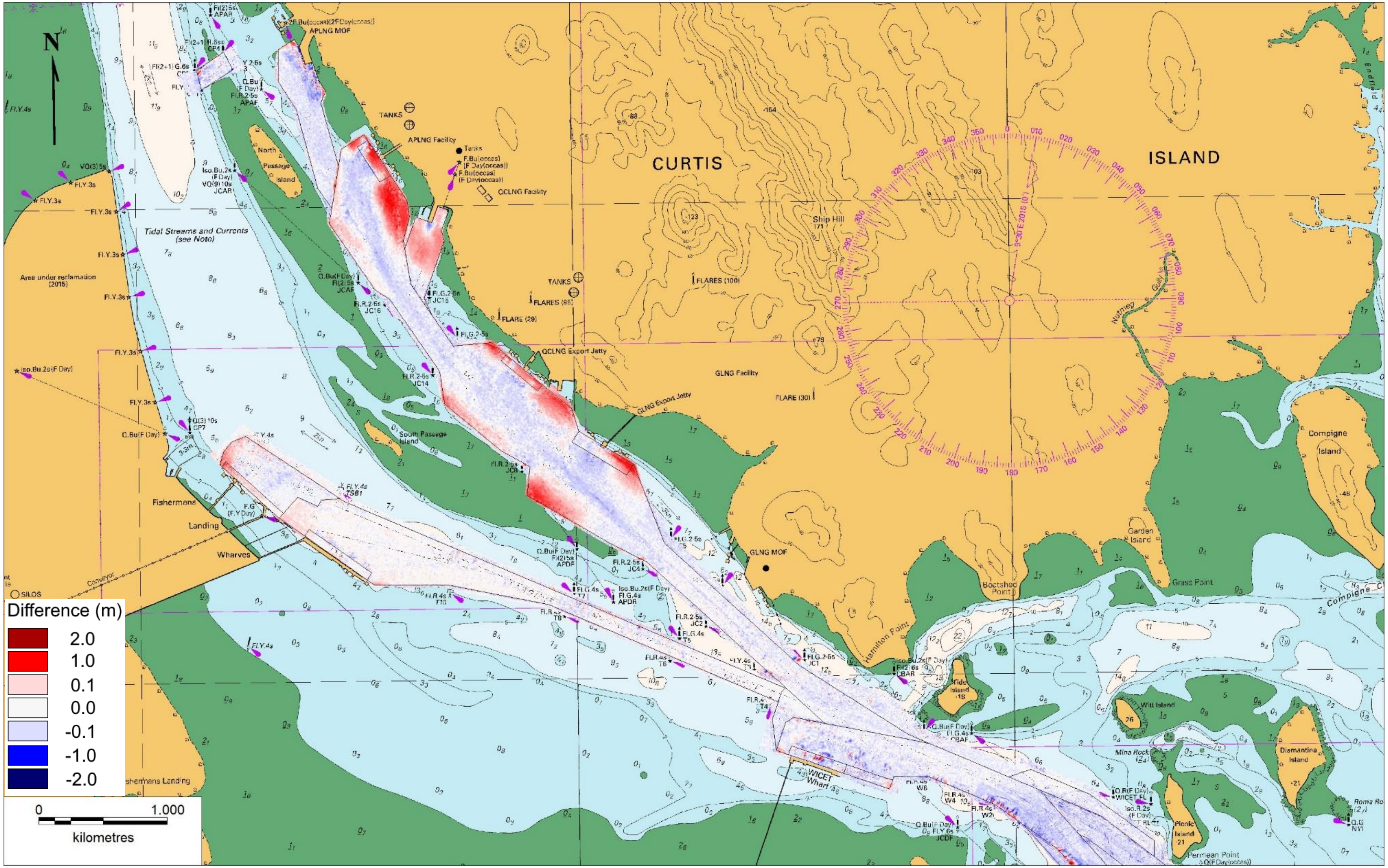


Figure 27. Change in bathymetry between October 2016 and October 2017 for the Jacobs and Targinnie Channels region.

It is important to note that this assessment is based on the comparison of subsequent bathymetric surveys and does not consider the declared depths of the regions in the sedimentation calculations. The sedimentation values therefore will not directly relate to the maintenance dredging requirement, as some of the sedimentation will be below the declared depths (especially in areas where mega-ripples are migrating). In addition, the summed values detailed in the tables above are for all regions of the PoG, but some of these regions are not subject to regular maintenance dredging or the sediment is placed on land (e.g. the Marina) and is therefore not included in the annual maintenance dredging volumes, which is primarily sediment placed at the EBSDS. A best estimate of the typical ongoing sedimentation in the areas where regular maintenance dredging is required is provided below:

- Jacobs Channel region = 225,000 m^3 (sedimentation from 2017);
- Targinnie Channel and Fisherman's Landing region = 50,000 m^3 (from mean and median values);
- Clinton Channel region = 50,000 m^3 (from mean and median values, excluding the Bypass);
- Auckland Channel region (including berths) = 100,000 m^3 (from mean and median values, excluding the Bypass);
- Golding Cutting = 95,000 m^3 (from mean and median values, excluding the Gatcombe Channel as this is a naturally deep area where minimal maintenance dredging is required and the South Bypass Channel);
- Boyne and Wild Cattle Cuttings = 80,000 m^3 (from mean and median values, excluding the South Bypass Channel); and
- **Total = 600,000 m^3/yr.**

As part of future SSM Project studies the relationship between the sedimentation and the dredge and declared depths in the PoG will be further investigated. This will provide a better understanding of how the sedimentation relates to maintenance dredging and how the sedimentation volumes relate to the design and declared depths in the different regions of the PoG.

3.2.2. EBSDS

The EBSDS is located in water depths ranging from approximately 10 m to 16 m below LAT. Based on this and the wave climate in this area, there would be limited regular longshore or cross-shore transport expected due to wave action either at the site or in the areas directly adjacent to the site. During extreme events such as tropical cyclones when very large waves can be generated some resuspension and transport of sediment could potentially occur, both at the site and in the adjacent areas. As the EBSDS is shallower than the adjacent areas (due to the build-up of sediment which has been placed there) it will be more likely to experience resuspension during any large wave events.

Sediment has been regularly placed in the EBSDS from both capital dredging and ongoing annual maintenance dredging campaigns undertaken at the PoG. Over the last 10 years (since 2007) approximately 7.3 Mm^3 of sediment has been placed at the site, with approximately 5.1 Mm^3 of this being from the capital dredging from 2011 to 2014. It is expected that on average 5% of the capital dredged sediment would have been lost during the dredging activity[3], so the actual volume placed at the EBSDS is likely to be closer to 7.1 Mm^3. The density of the sediment placed will have been variable between the sediment from the capital dredging (higher density) and the maintenance dredging (lower due to the material being less consolidated as because the volume is based on wet in-hopper volume

[3] based on dredging source terms defined by BMT WBM using measured data (BMT WBM, 2017b) and assuming approximately half of the fine-grained sediment released into passive plumes would be deposited either within the dredge footprint (and would be re-dredged) or within the boundary of the EBSDS. As the maintenance dredge volumes are in-hopper we can assume no losses.

compared to in-situ volume). To allow an approximate conversion of the maintenance dredge volumes from wet in-hopper to wet in-situ volumes (which the sediment will start to return to as it consolidates) the volumes have been halved (based on data from the Port of Cairns in RHDHV (2016)). As such, if all of the sediment placed at EBSDS remained there and the sediment from maintenance dredging consolidated back to the wet in-situ density when it was dredged, then the total in-situ volume at the EBSDS will be approximately 6 Mm^3.

The EBSDS bathymetry in 2007 and 2014 is shown in Figure 28 and Figure 29. Note: the 2014 survey is shown, as this is the only survey which covered an extensive area adjacent to the EBSDS at a sufficiently high resolution (5 m compared to 50 m for most other surveys) for realistic interpolation. The black dashed line in the plots shows the approximate extent of the placement site before the early 1990's. From the early 1990's the placement site was extended to the west, changing it from a square to a rectangular site. The plots show the following:

- in 2007, the bathymetry to the west of the dashed line representing the original square disposal site is generally deeper than the rest of the site, indicating that no significant placement activity has occurred in this area;
- the bathymetry in the northern half of the original square placement site has not changed significantly over the seven years, indicating that the bathymetry has remained relatively stable;
- in 2014, mounds from the placement of material are clearly visible, this is likely to be mainly from the capital dredging which occurred in 2011 to 2014; and
- the natural bathymetry adjacent to the EBSDS is deeper than within the site, with no indication that there is a gradual shallowing away from the site due to sediment being transported away from the site.

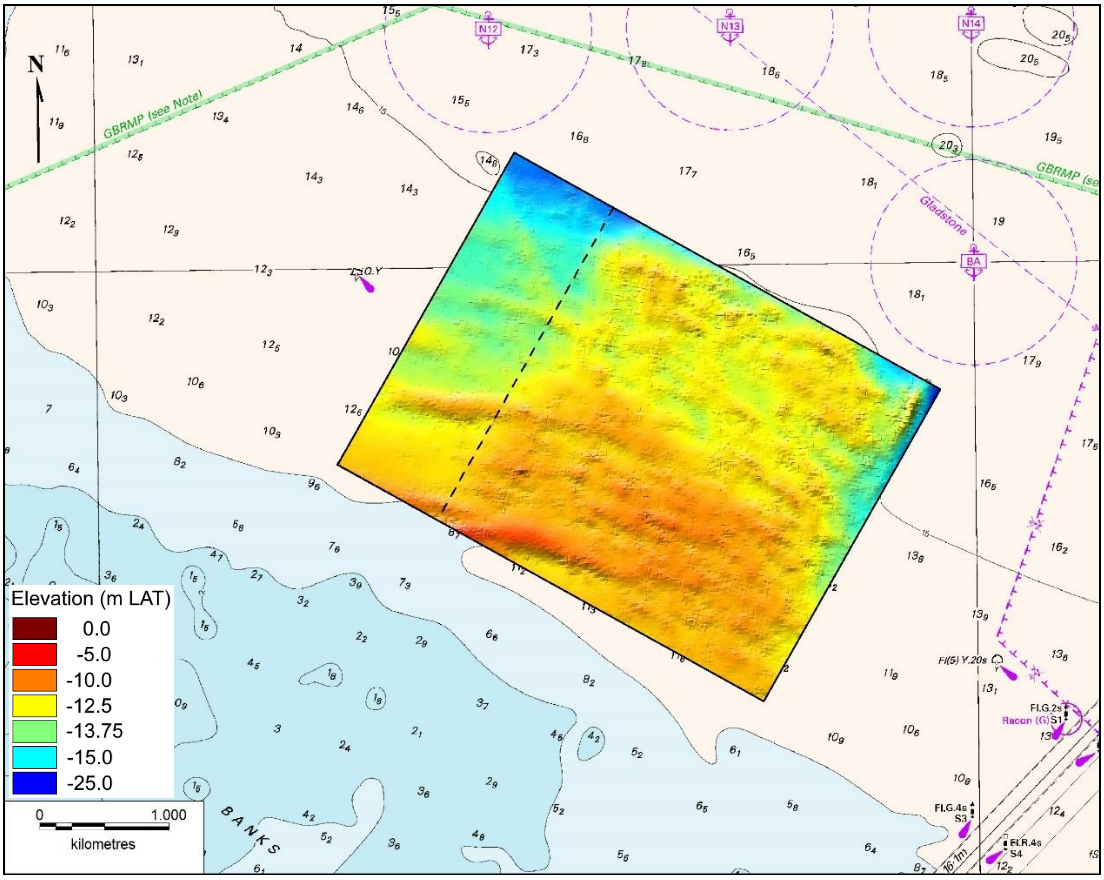


Figure 28. EBSDS bathymetry in December 2007.

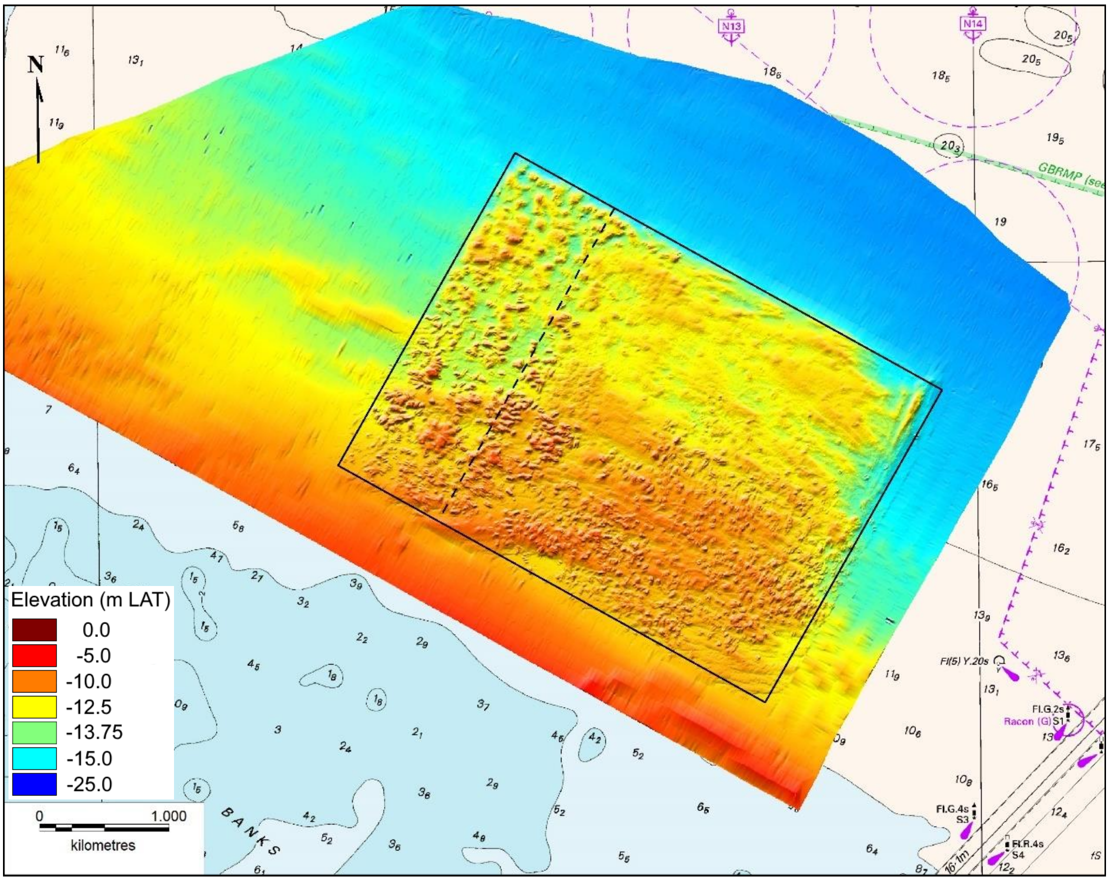


Figure 29. EBSDS bathymetry in March 2014.

Spatial maps of the change in the bathymetry and the in-situ volume changes at the EBSDS are shown in Figure 30 to Figure 33 and in Table 7. The figures and table show the following:

- between 2007 and 2011 (prior to the 2011-2014 capital dredging) the volume of sediment within the EBSDS increased in volume by approximately 850,000 m^3, with the majority of the increase being in the western site extension area. Over this period there was approximately 770,000 m^3 of sediment placed at the site from maintenance dredging, (400,000 m^3 when converted from wet in-hopper to in-situ volume to allow for consolidation), indicating either that some of the increase in volume has been due to natural sedimentation or that survey inaccuracy has influenced the results;
- between 2011 and 2014 the volume of sediment within the EBSDS increased by approximately 4.8 Mm^3, with the majority of this sediment being placed in the western extension area. This increase was primarily related to the capital dredging of 5.1 Mm^3 which occurred between 2011 and 2014. The spatial change in bathymetry shows individual mounds where sediment has been placed within the EBSDS, indicating that limited reworking of the sediment has occurred. The combined capital and maintenance dredging volume of sediment placed at the site over this period was approximately 5.8 Mm^3 (5.2 Mm^3 when losses during dredging (capital dredging) and conversion from wet in-hopper to in-situ volume for consolidation (maintenance dredging) are considered). Therefore, if we assume that limited natural sedimentation has occurred over this period, the results indicate that over 90% of the sediment placed at the EBSDS between 2011 and 2014 has been retained within the site;
- between 2014 and 2017 the volume of sediment within the EBSDS increased by approximately 270,000 m^3. Over this period the gross change in volume was significantly higher (sedimentation of 1.3 Mm^3 and erosion of 1 Mm^3). When the spatial change plot (Figure 32) is also considered it is apparent that the elevations of the higher mounds have

reduced and there has been increased sedimentation in the deeper areas adjacent to the mounds. It is understood that between 2013 and 2014 bed levelling was undertaken at EBSDS to reduce the elevation of the mounds formed by the capital dredging. It is therefore assumed that these changes were primarily due to the bed levelling as opposed to natural reworking, although some natural reworking could also have occurred during large wave events. The plot also shows that the northern half of the site appears to have been subject to net erosion, while in the southern half both erosion and sedimentation have occurred. Over this period there was approximately 730,000 m^3 of sediment placed at the site from maintenance dredging (380,000 m^3 when converted from wet in-hopper to in-situ volume to allow for consolidation). The results therefore indicate that approximately 70% of the sediment placed at the site has been retained over this period. However, the bed levelling activity will have resulted in both the redistribution and resuspension of sediment from the peaks of the higher mounds, with some of this sediment depositing adjacent to the peaks (as shown in the surveys) and some of the suspended sediment also likely to have been transported by tidal currents away from the EBSDS. As such, although the results suggest that 70% of the sediment from maintenance dredging has been retained within the EBSDS, it is likely that a higher percentage has been retained and that some of the loss is due to the resuspension of sediment from the capital dredging due to the bed levelling activity. Unfortunately, due to the bed levelling activity it is difficult to accurately define the retention of the maintenance dredging sediment over this period. Further investigations of the EBSDS will be undertaken as part of the SSM Project to better understand how retentive the EBSDS is and where any sediment transported away from the EBSDS is transported; and

- between 2007 and 2017 there has been an overall increase in volume throughout the EBSDS, with a net increase in volume of approximately 5.9 Mm^3. If it is assumed that the majority of the increase in volume is due to the dredged sediment placed there (approximately 6 Mm^3 between 2007 and 2017 when dredge losses and consolidation of maintenance dredge sediment is considered), as opposed to natural sedimentation (based on the spatial changes around the site, discussed after this section, this assumption seems reasonable), then it can be calculated that the EBSDS has retained more than 95% of the sediment placed at the site, with less than 5% of the sediment lost. As such, the EBSDS is considered to be a retentive placement site. It is important to note that this is based on a combination of capital and maintenance dredged sediment (with the majority being from capital dredging). However, the results over the only period without any capital dredging or bed levelling suggests that much of the sediment from maintenance dredging was also retained.

Table 7. Volumetric change at EBSDS (+ve = accretion, -ve = erosion).

Comparison	Change in Volume (m^3)		Total (m^3)
	+ve (m^3)	-ve (m^3)	
Dec 2007 – Mar 2011	1,151,450	-305,094	846,356
Mar 2011 – Mar 2014	5,197,470	-408,610	4,788,860
Mar 2014 – Oct 2017	1,318,328	-1,050,413	267,915
Total (2007 – 2017)	**7,667,248**	**-1,764,117**	**5,903,131**

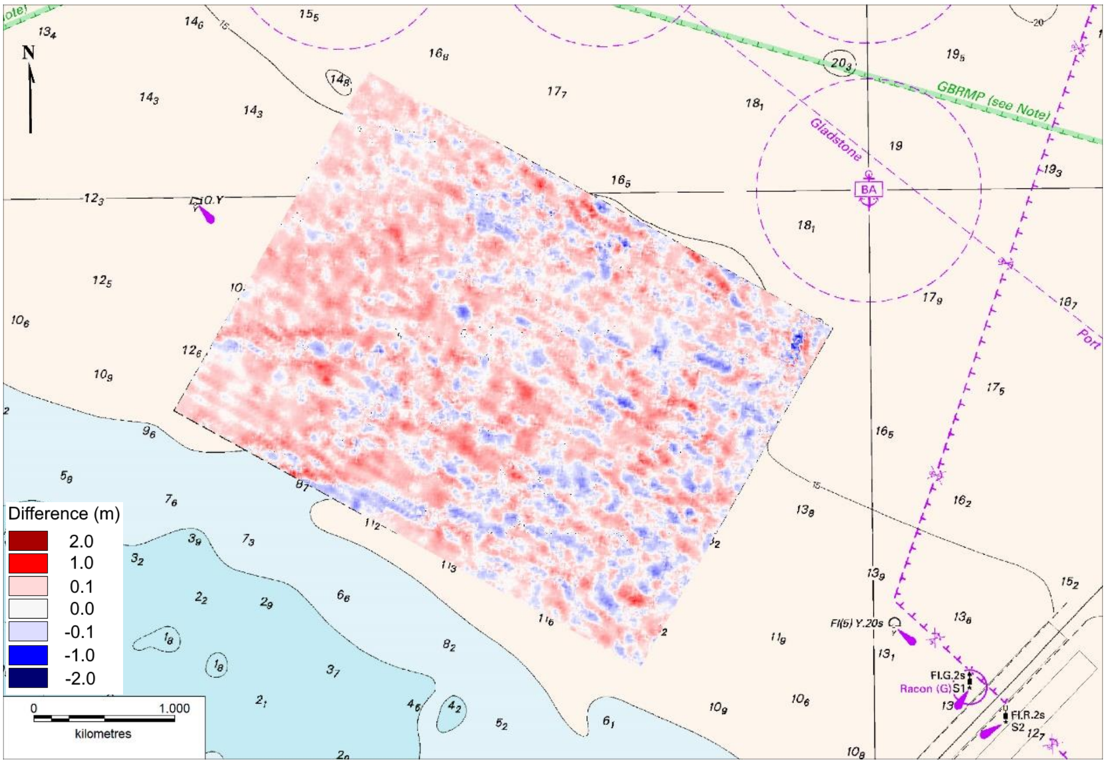


Figure 30. Bathymetric change at EBSDS, from December 2007 to March 2011, showing erosion in blue and accretion in red.

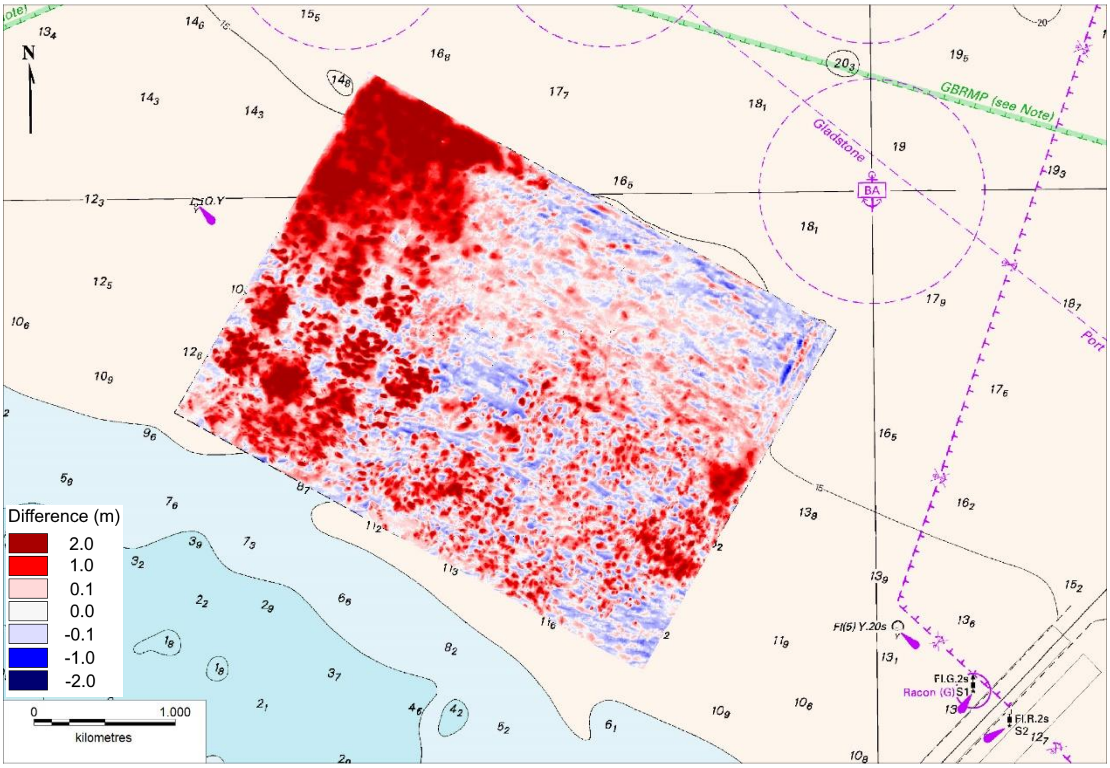


Figure 31. Bathymetric change at EBSDS, from March 2011 to March 2014, showing erosion in blue and accretion in red.

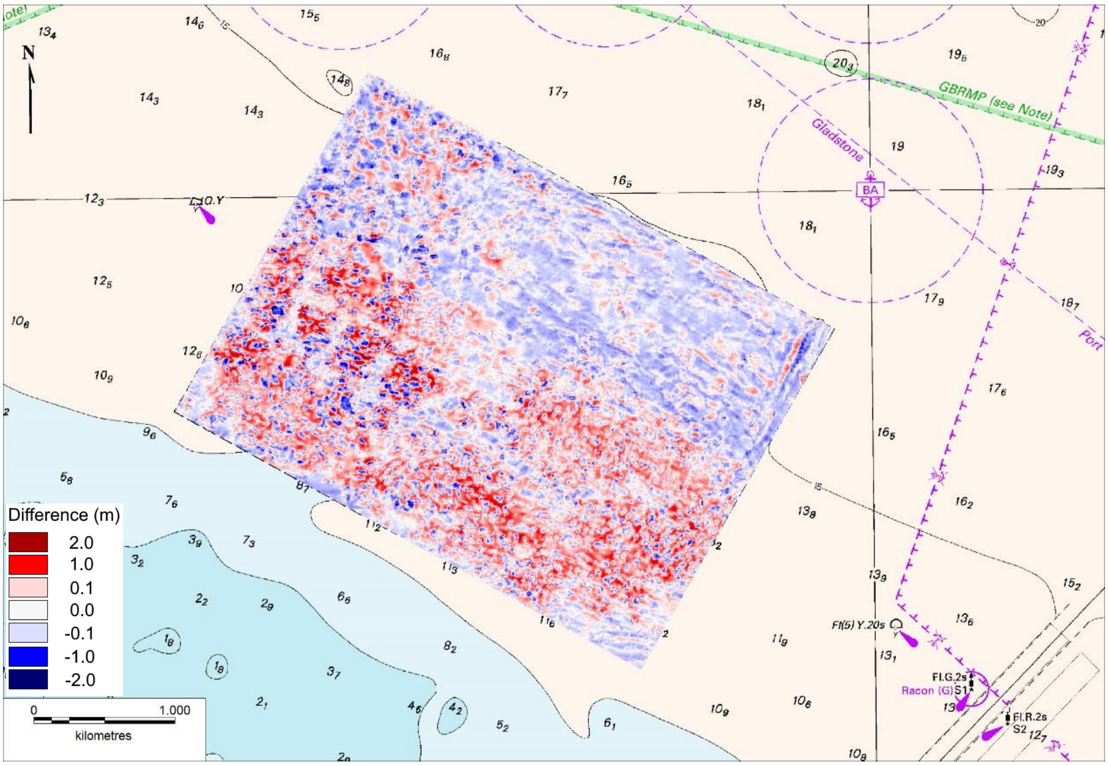


Figure 32. Bathymetric change at EBSDS, from March 2014 to October 2017, showing erosion in blue and accretion in red.

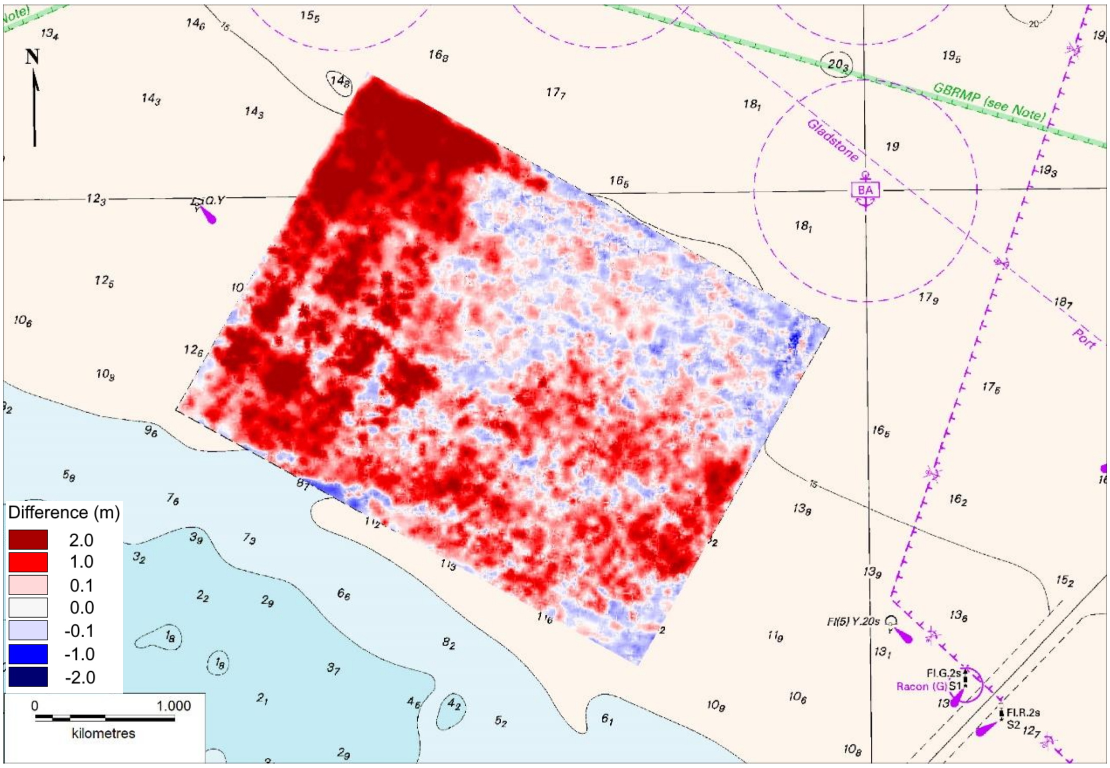


Figure 33. Bathymetric change at EBSDS, from December 2007 to October 2017, showing erosion in blue and accretion in red.

To further show how the bed elevation has changed since December 2007, three long-sections and four cross-sections have been extracted from the December 2007, March 2011, March 2014 and October 2017 DEMs at specific locations as shown in Figure 34. The transects from 2007 and 2014 extend beyond the EBSDS due to the extent of the bathymetric surveys in these years, while the 2011 and 2017 surveys are limited to the EBSDS. The transects are shown in Figure 35 to Figure 41. The plots show the following:

- there were only small changes in the bathymetry between 2007 and 2011, with the most noticeable change being a slight increase in the elevation of the western half of Long 1 and 2;
- between 2011 and 2014, there was a significant increase in the elevations in the EBSDS, especially along the western side;
- between 2014 and 2017, there was a minor increase in the overall elevations in the EBSDS. Some erosion of the highest spots in the site occurred, with sedimentation in the adjacent areas; and
- between 2007 and 2014, there was little change outside of the EBSDS. The long-sections show that the bathymetry to the west of the site has remained similar, while to the east of the site there could have been some natural bedform migration. The cross-sections show that there has been little change in the bathymetry to the south of the site, while the bathymetry to the north (offshore) of the site has eroded by approximately 0.2 m. The reason for the erosion unclear but it could be due to wave action or related to the EBSDS limiting the supply of sediment to the area.

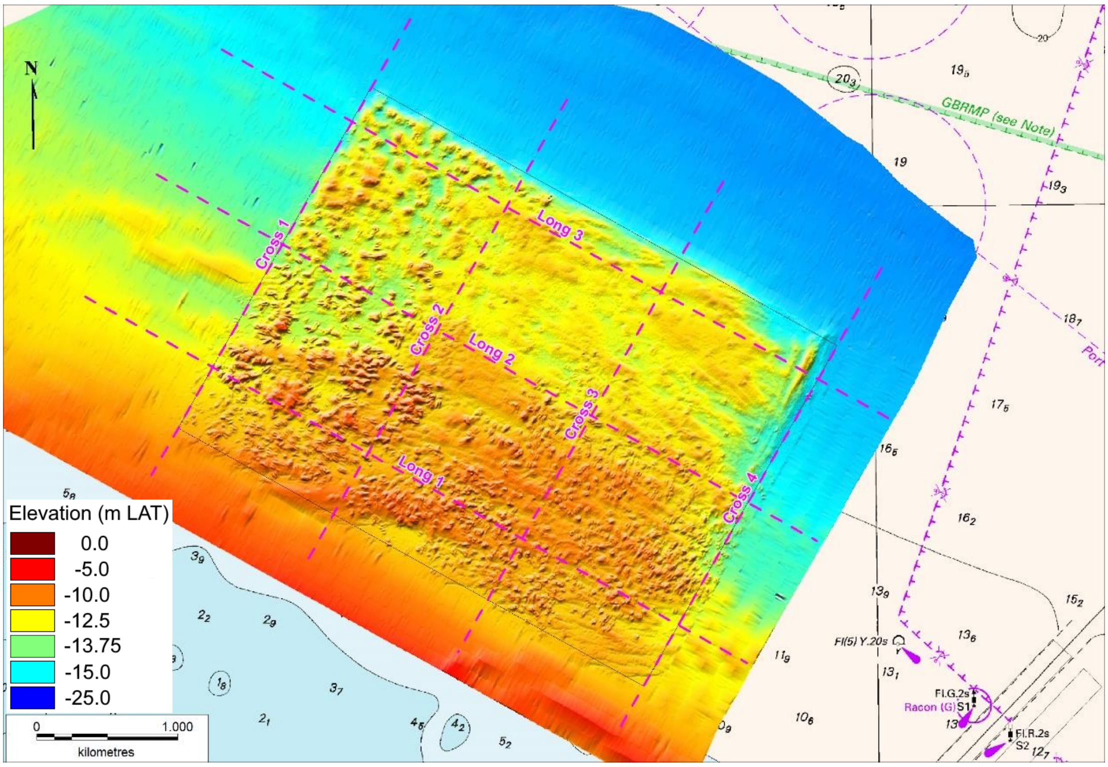
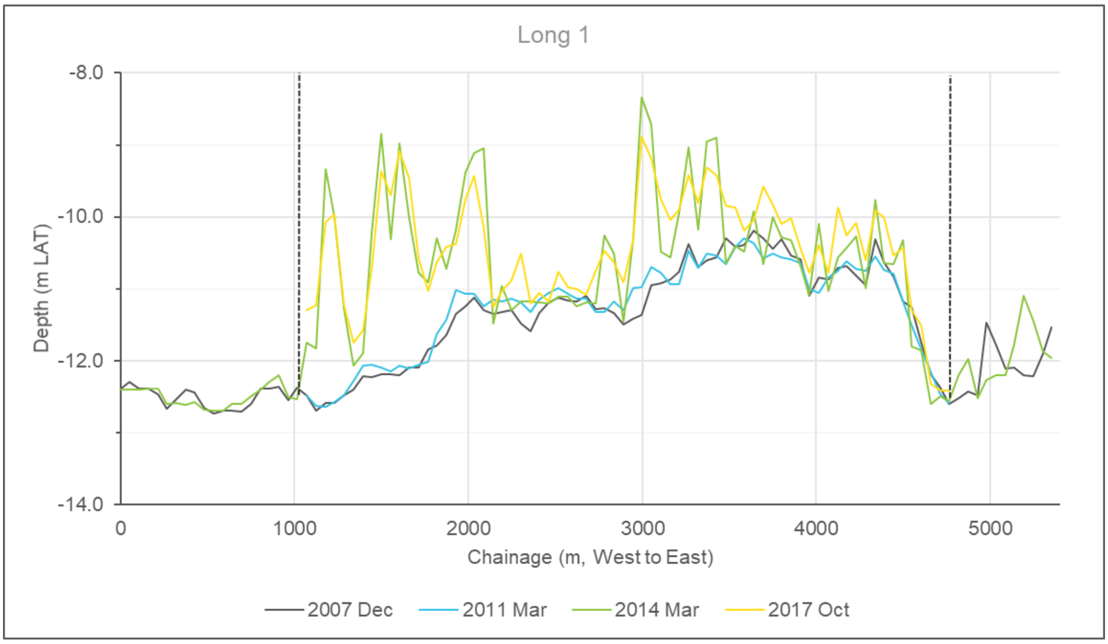
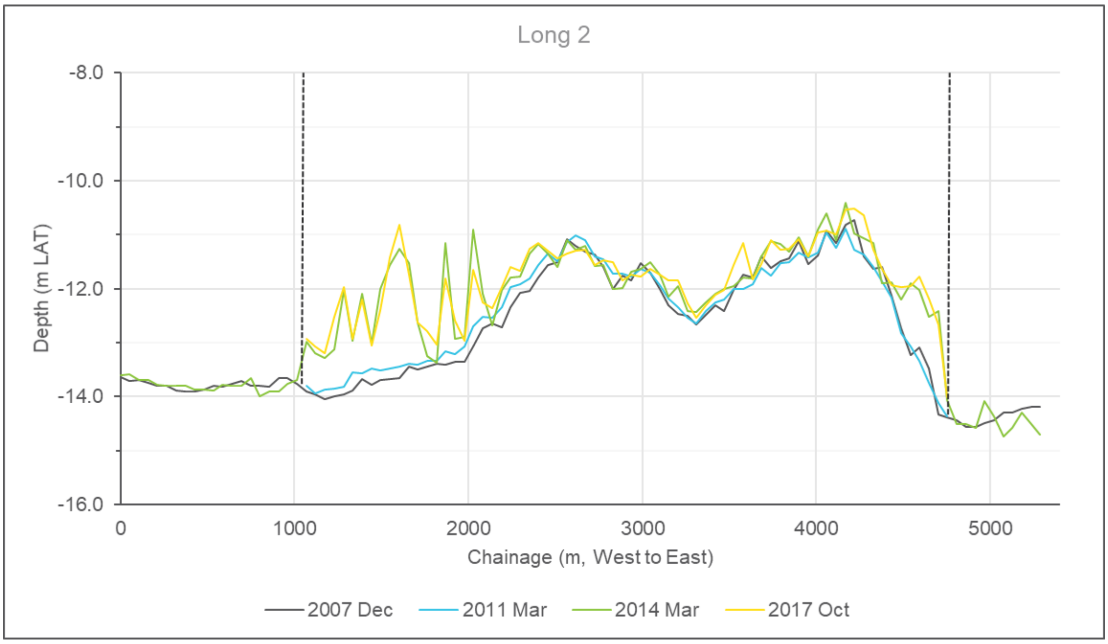


Figure 34. Transects adopted for the EBSDS with bathymetry from March 2014 shown (post-capital dredging).



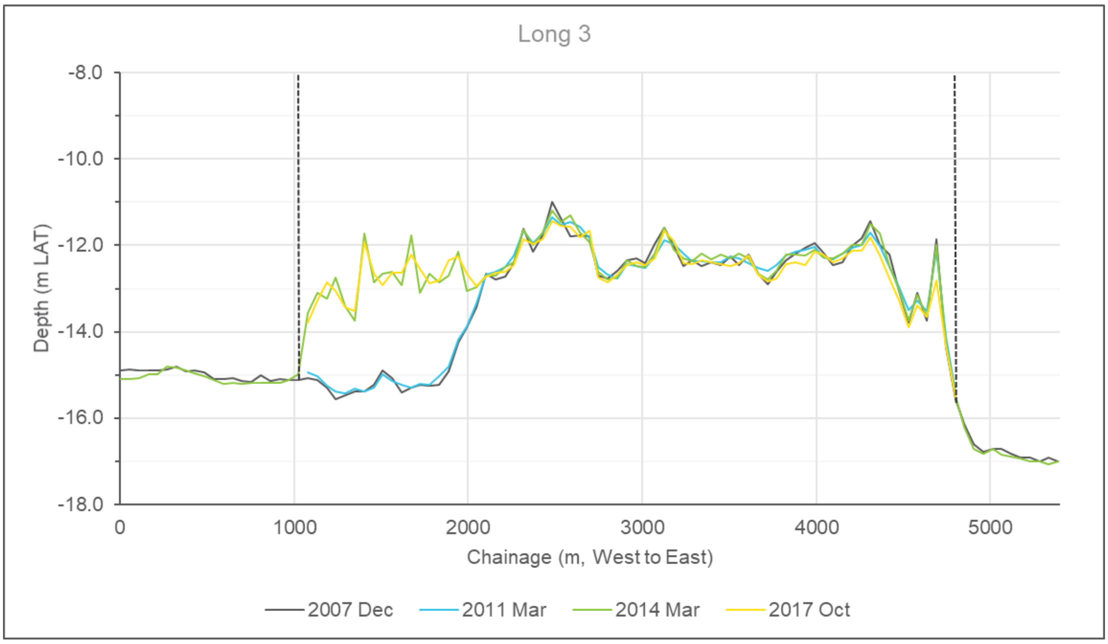
Note: the dashed lines represent the EBSDS boundaries.

Figure 35. Plot of the bathymetry at Long 1.



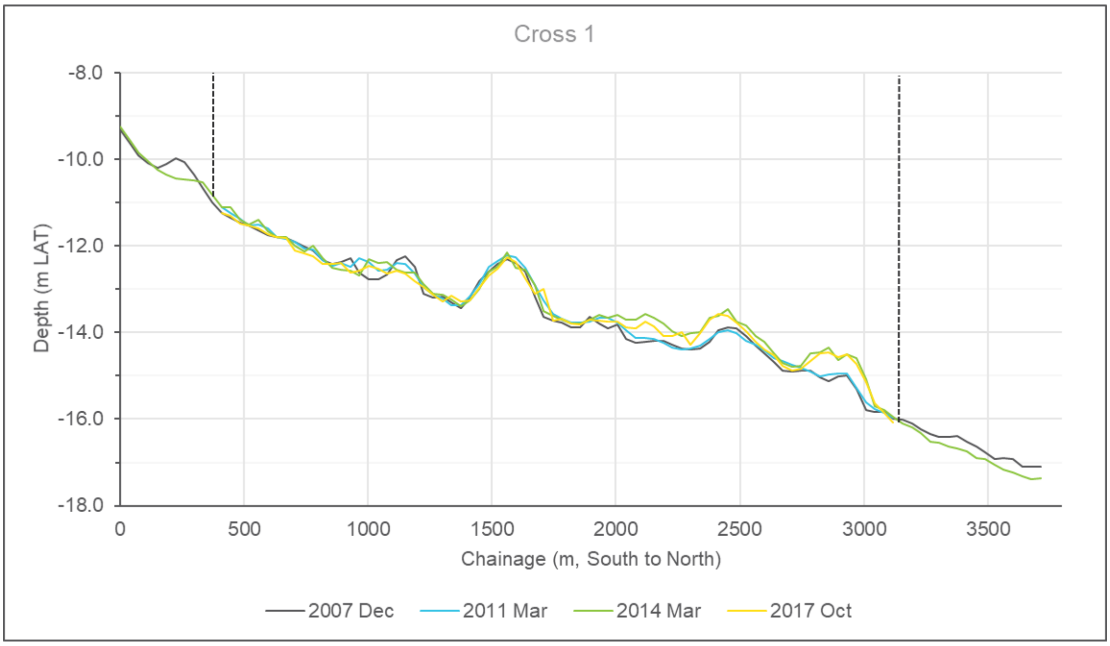
Note: the dashed lines represent the EBSDS boundaries.

Figure 36. Plot of the bathymetry at Long 2.



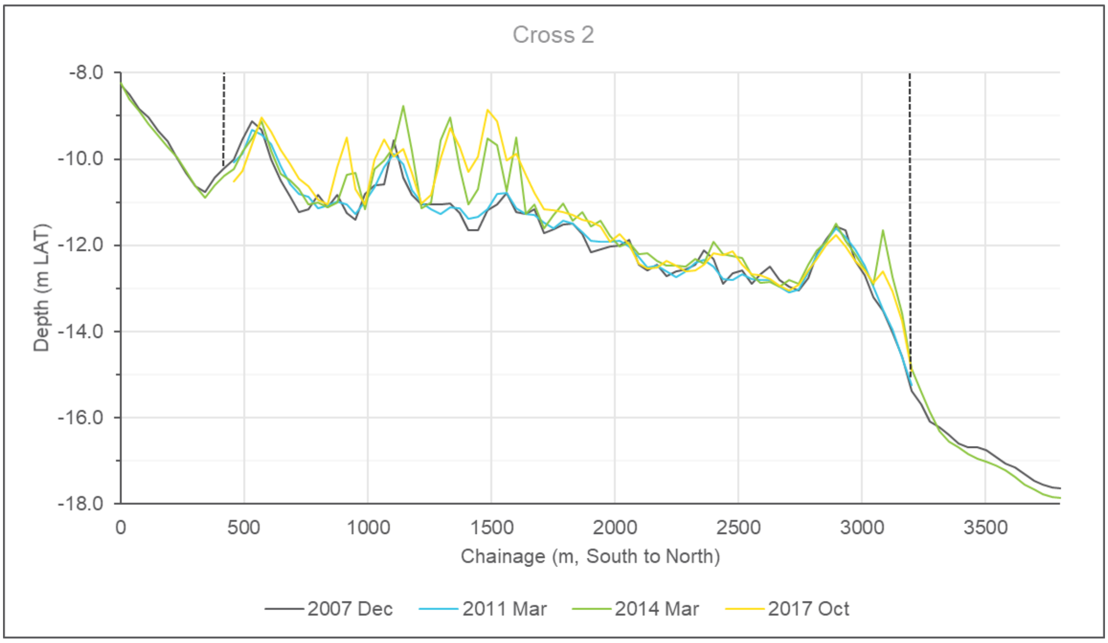
Note: the dashed lines represent the EBSDS boundaries.

Figure 37. Plot of the bathymetry at Long 3.



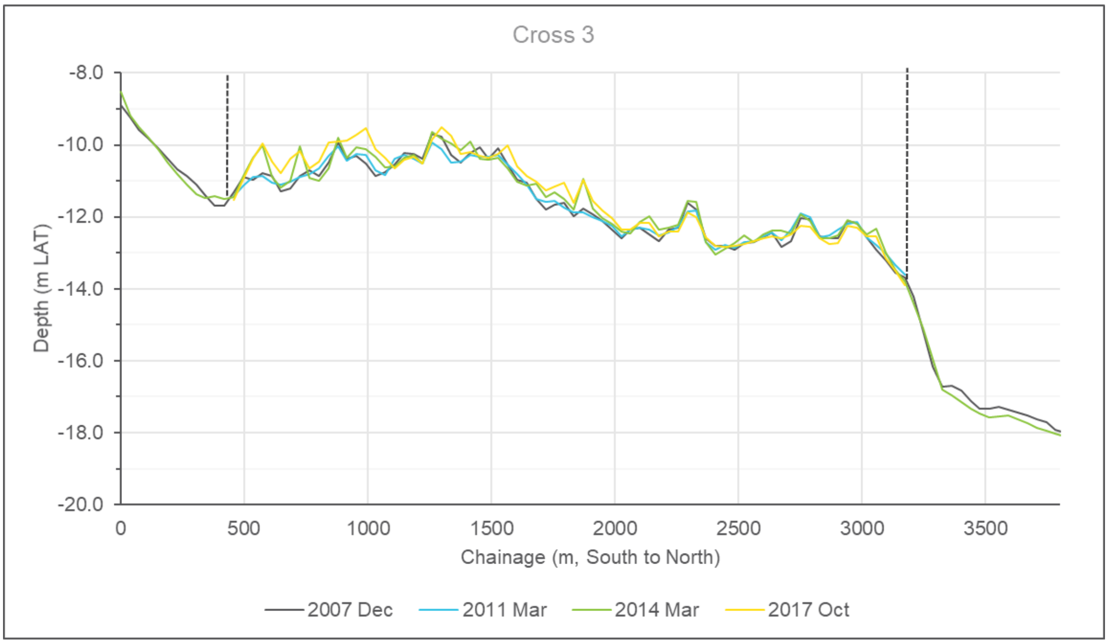
Note: the dashed lines represent the EBSDS boundaries.

Figure 38. Plot of the bathymetry at Cross 1.



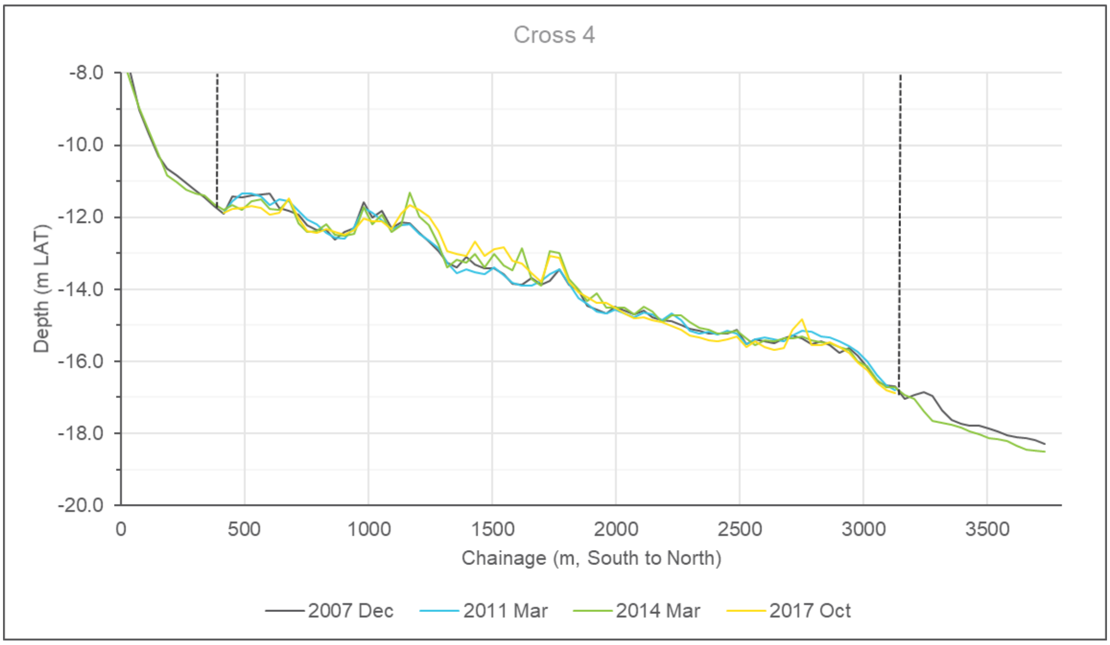
Note: the dashed lines represent the EBSDS boundaries.

Figure 39. Plot of the bathymetry at Cross 2.



Note: the dashed lines represent the EBSDS boundaries.

Figure 40. Plot of the bathymetry at Cross 3.



Note: the dashed lines represent the EBSDS boundaries.

Figure 41. Plot of the bathymetry at Cross 4.

4. Sediment Transport

This section presents a conceptual sediment budget, which details the processes which influence sediment transport at the PoG based on the available bathymetric, metocean and sediment transport data. The relative influence of the different processes on the supply, resuspension, transport and deposition of sediment in the region is discussed.

Future SSM Project work will refine the sediment budget and provide sufficient detail to allow a quantitative budget to be developed using a combination of measured data and targeted numerical modelling.

4.1. Conceptual Budget

The bathymetric analysis has shown that historical sedimentation in the PoG has regularly occurred in the upstream (Jacobs Channel and Fisherman's Landing areas) and Outer Harbour (Golding, Boyne and Wild Cattle Cuttings) regions. As such, the natural conditions at the two locations are different and so the drivers for the sedimentation are also expected to differ. The targeted sediment sampling showed that the sediment which was deposited in the upstream region of the PoG was predominantly fine-grained silt and clay, while in the Outer Harbour region it was more variable with approximately equal proportions of sand to silt/clay in the Golding Cutting but predominantly sand in the Wild Cattle Cutting.

The annual sedimentation results, along with the total time each year when the H_s was above 1.5 and 2 m (indicating large wave events associated with strong low pressure systems, TCs or ex-TCs) and the annual rainfall over the period is shown in Figure 42. The plot does not show any clear correlation between sedimentation and the wave conditions or rainfall in the Inner or Outer Harbour areas, suggesting that the sedimentation is a result of a complex interaction of processes. The lack of data for the Outer Harbour region in 2012 and 2014 combined with the influence of the capital dredging on the sedimentation in the Inner Harbour since 2014 make it difficult to determine any relationships. However, the results do suggest that the rainfall does not directly influence the sedimentation in the Inner Harbour, indicating that the new sediment input from the rivers is small relative to the resuspension and transport of existing sediment within the Inner Harbour due to tidal currents. To further demonstrate this, the predicted input of new sediment from the Calliope and Boyne Rivers during a 100 year event (i.e. rainfall from a TC) is 460,000 t (see Section 2.3) while the typical annual natural resuspension of existing sediment within the Inner Harbour by tidal currents and wind waves has been estimated to be in the order of 8,500,000 t (BMT WBM, 2018b). As such, although extreme flood events can result in significant irregular inputs of new fine-grained sediment to the system, the overall water quality and sedimentation in the Inner Harbour is primarily controlled by the reworking and redistribution of the existing fine-grained sediment in the system.

Based on the findings from the bathymetric analysis, along with an understanding of the existing processes which has been developed using all available information, conceptual sediment transport budgets for the Inner Harbour and Outer Harbour regions of the PoG have been developed (Figure 43 and Figure 44). In addition, a summary oblique conceptual sediment budget for the whole Gladstone region has also been developed (Figure 45). A summary of the conceptual budget is provided below for the Inner and Outer Harbours and for the EBSDS:

- Inner Harbour: resuspension and sediment transport in the Inner Harbour region is dominated by the tidal currents (Petus & Devlin, 2012). The strong tidal currents are the dominant process for resuspending sediment in the Inner Harbour, although small locally generated wind waves and wind induced currents can also result in resuspension in shallow areas where fine-grained sediment is present. Therefore, the bed sediments in the Inner Harbour are regularly mobilised, transported and redeposited until they are either transported to a sheltered location where ongoing sedimentation occurs or out of the region by the ebb tidal currents. The Inner Harbour region can be considered a sediment sink, with extensive sources of fine-grained and coarser sands and gravels already present due to deposition over geological timeframes. In addition to the available sediment already present in the Inner Harbour, new sediment is added to the region by the suspended sediment being discharged from the Calliope River and from fluxes of suspended sediment being transported through the three entrances to the Inner Harbour. Although it is likely that the gross flux of suspended sediment through the main entrance of the Inner Harbour will be high during a spring tide, the net flux is likely to be comparatively small compared to the mass of sediment resuspended within the Inner Harbour. The relatively high tidal current speeds which occur throughout much of the Inner Harbour limit the build-up of fine-grained sediment in the main channels. However, in sheltered areas adjacent to the channels, in closed-end channels (e.g. Jacobs and Targinnie Channels) and in vegetated areas (e.g. areas with seagrass or mangroves which promote deposition) regular sedimentation of fine-grained sediment can occur.

- Outer Harbour: the Outer Harbour is influenced by a combination of offshore waves and tidal currents. The wave action is the dominant process for resuspending sediment in the Outer Harbour, while the tidal currents will be the dominant process for transporting the suspended sediment. The majority of the Outer Harbour region is an ebb tidal delta which has developed over time at the mouth of the Port Curtis estuary. Therefore, the region is a natural sediment sink, which is further highlighted by the presence of the East and West Banks (located to the north and south of the Golding Cutting) and is expected to continue to act as a sink over time. Due to the influence of the offshore wave action the majority of the sediment which has accumulated is sand. In addition to the available sediment already present in the Outer Harbour, sediment is added to the region by the net northerly longshore transport of sediment (sand and fine-grained silt/clay) along the coastline (is it currently unknown how much of this is transported into the Inner Harbour region, but this will be further investigated as part of the SSM Project), the suspended sediment being discharged from the Boyne River and from fluxes of suspended sediment being transported out of the Inner Harbour through the two entrances. The relatively high tidal current speeds which occur close to the entrance to the Inner Harbour limit sedimentation of fine-grained sediment in this area. As the current speeds reduce and the trapping efficiency of the channels increase (i.e. depth of channel below adjacent seabed), some deposition of sand and silt/clay sized sediment occurs. Along the sides of the Golding Cutting a combination of sand, silt and clay has built-up, while in the Wild Cattle Cutting the sediment is predominantly made up of sand. The reason for this difference is thought to be a combination of the trapping efficiency of the channels (Wild Cattle Cutting has a lower trapping efficiency due to the naturally deeper adjacent bathymetry), the exposure to wave action (Wild Cattle Cutting is more exposed as East Bank will provide some shelter to the Golding Cutting) and the configuration of the channel (the bend between the Golding and Wild Cattle Cuttings will also influence the trapping efficiency and local conditions. In both channels the sedimentation which has occurred has been predominantly along the edges of the channels, this is due to the natural current speeds being lowest along the edges of the channels and the propeller wash from vessels sailing along the centreline of the channel resulting in increased disturbance along the centre of the channel and therefore preventing sediment from building up here.
- EBSDS: the dominant process for resuspending sediment at the EBSDS is wave action. The site has been found to have been retentive over the last 10 years, with more than 95% of the capital and maintenance dredged sediment placed at the site being retained. It is important to note that it has not been possible to determine separate retentive properties for sediment from capital and maintenance dredging, but this will be further investigated for sediment from maintenance dredging as part of the SSM Project. Over this period bed levelling of some of the highest peaks in the EBSDS was undertaken which reduced the elevations and is likely to have also resulted in some loss of sediment from the site. There were also numerous large wave events associated with TCs and ex-TCs which could have resulted in some reworking of the sediment in the EBSDS, and despite this the majority of the sediment has been retained within the site. As such, the

EBSDS can be considered to be acting as a sediment sink, with the majority of the sediment which is placed there from the PoG remaining in place.

Notes: bathymetric surveys were not available for the Outer Harbour to quantify sediment in 2012 or 2014. Wave data were available from the end of September 2009, so values for 2009 are representative of a quarter of the year.

Figure 42. Annual sedimentation, duration H_s was above 1.5 and 2 m and annual rainfall for 2009 to 2017.

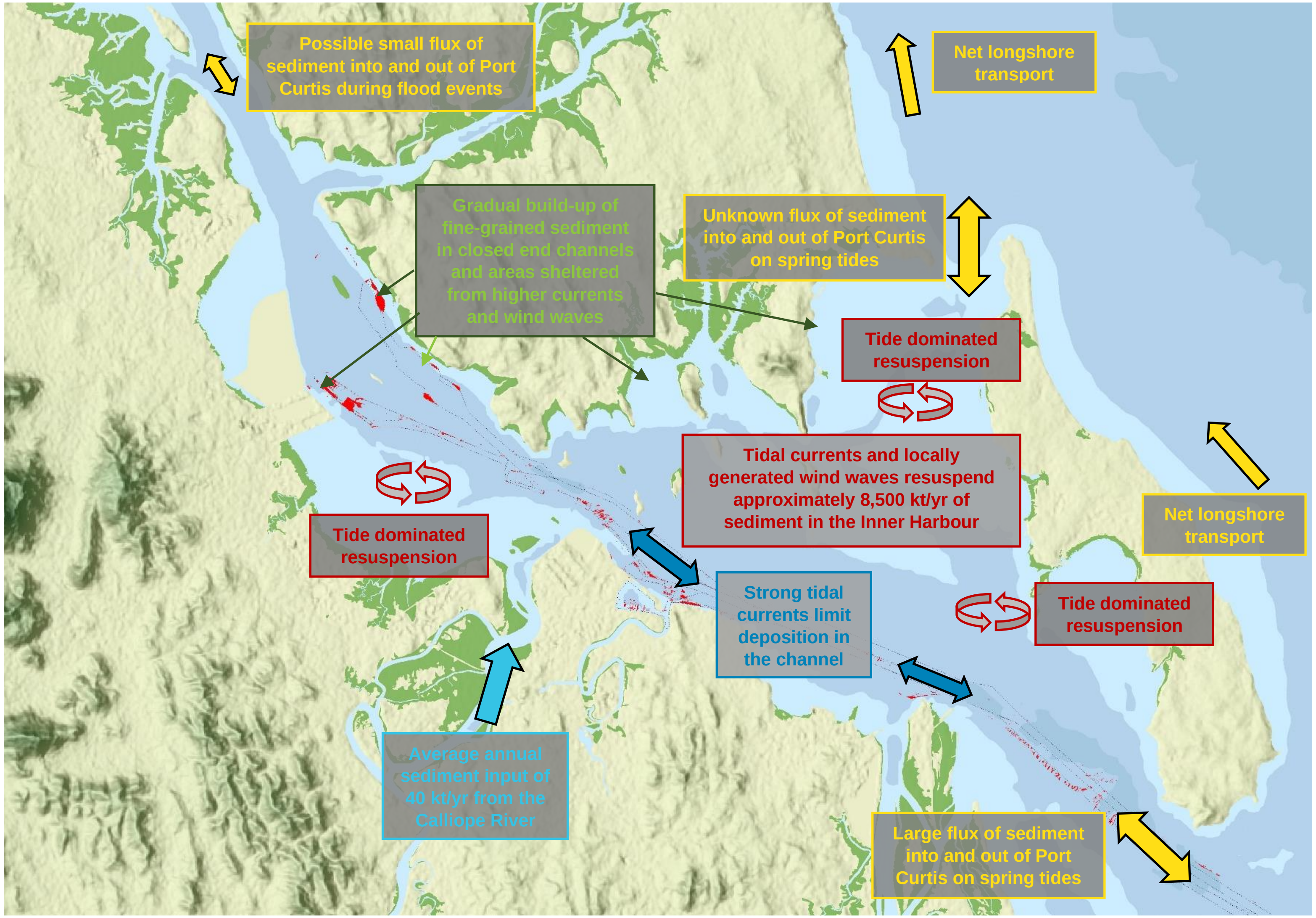


Figure 43. Conceptual sediment transport model of the Inner Harbour at the PoG. *Red areas show where > 1m sedimentation has occurred over 10 years.*

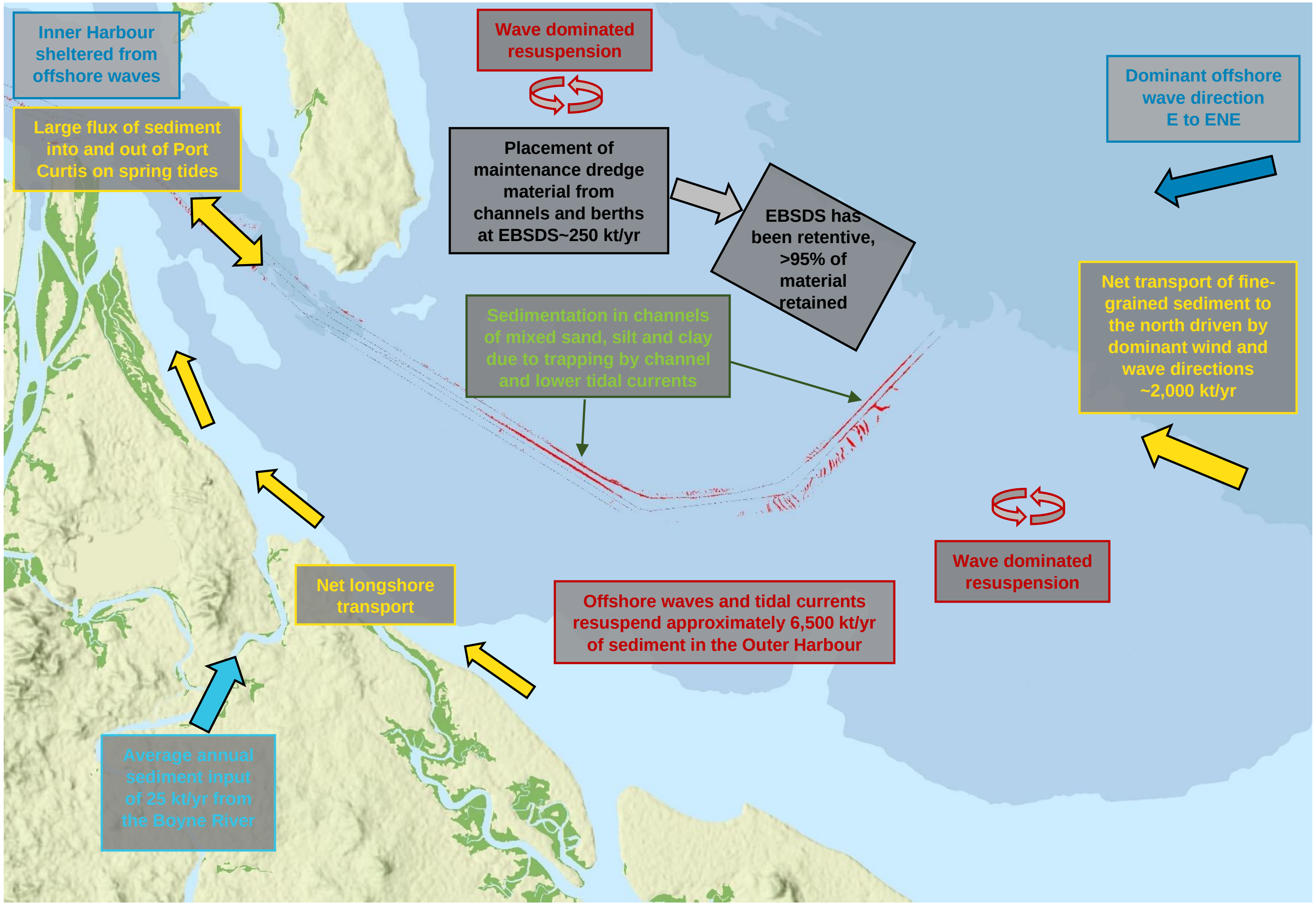


Figure 44. Conceptual sediment transport budget of the Outer Harbour at the PoG. *Red areas show where > 1m sedimentation has occurred over 10 years.*

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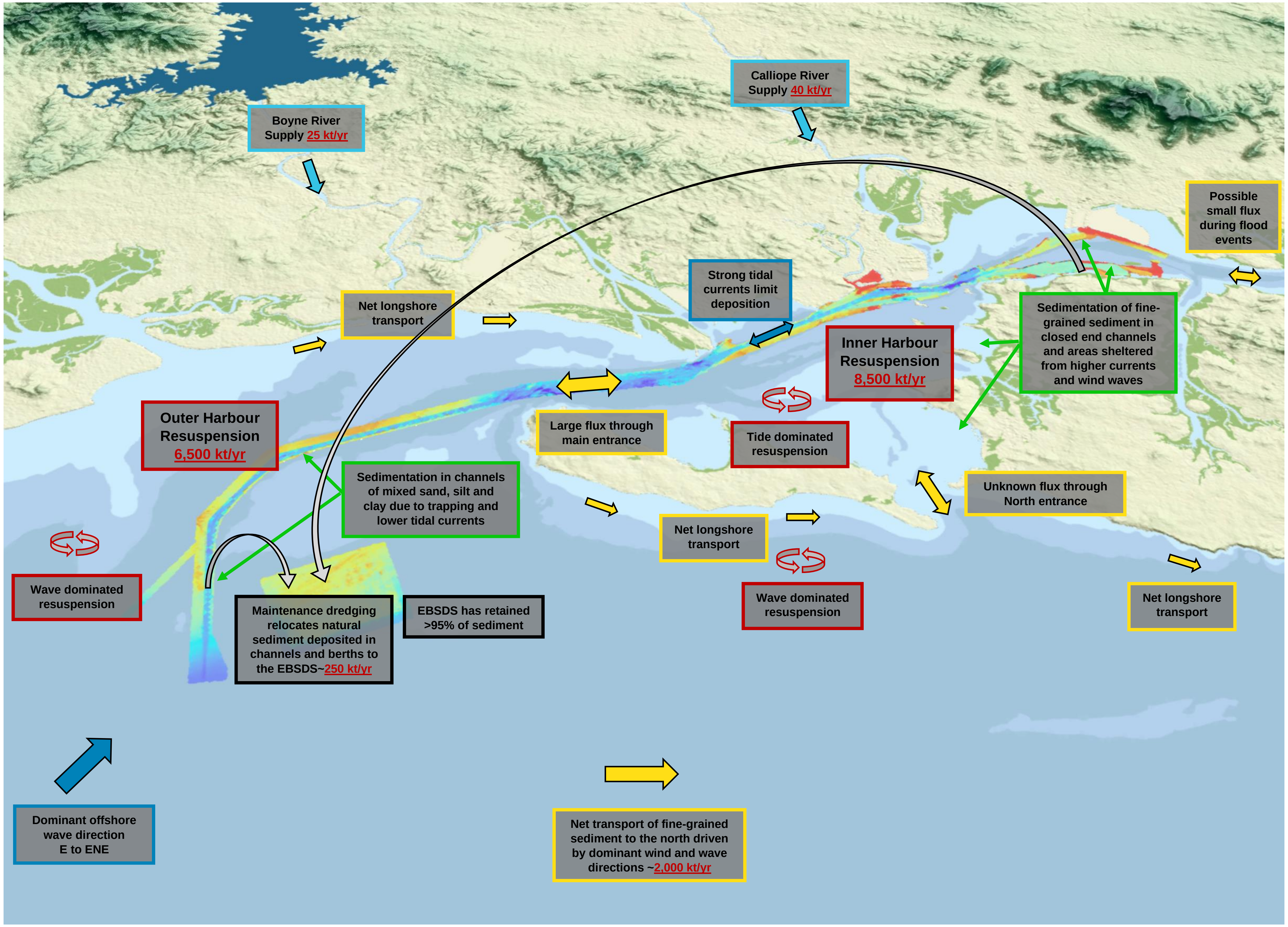

Figure 45. Conceptual sediment transport budget of the PoG.

5. Summary

The bathymetric analysis has shown that the highest rates of sedimentation have been naturally occurring in the upstream (Jacobs and Fisherman's Landing areas) and offshore (Golding, Boyne and Wild Cattle Cuttings) regions of the PoG. In addition, some sedimentation also occurred in the Clinton and Auckland Channel regions, but much of this was due to the migration of mega-ripples (sand ridges) rather than net sedimentation. A best estimate of the typical ongoing annual sedimentation, in the areas of the PoG where regular maintenance dredging is required, is 600,000 m^3 and of this almost 300,000 m^3 is in the upstream region and 200,000 m^3 in the Outer Harbour region. As part of future SSM Project studies the relationship between the sedimentation and the dredge and declared depths in the PoG will be further investigated. This will provide a better understanding of how the sedimentation relates to maintenance dredging and how the sedimentation volumes relate to the design and declared depths in the different regions of the PoG.

The bathymetric analysis at the EBSDS has shown that over the last 10 years (2007 to 2017) the site has been retentive. It has been estimated that more than 95% of the combined capital and maintenance dredged sediment placed at the site has been retained (this includes an allowance for consolidation of sediment from maintenance dredging). The bathymetry at the site has been shown to be stable, with limited erosion occurring due to large wave events.

A conceptual sediment budget has been developed for the PoG based on all the available information. The budget notes that different processes occur through the PoG, with the Inner Harbour region being dominated by tidal currents while the Outer Harbour region is influenced by a combination of offshore waves and tidal currents. The budgets detail the relative sources (these are quantified where sufficient data is available) and sinks of sediment in the regions. The budget will be further refined by additional targeted studies (including data collection and numerical modelling) to allow a full quantitative sediment budget to be developed for the SSM Project.

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