Sustainable Sediment Management Project

Port of Gladstone: Quantitative Sediment Budget

Final 1.0

Gladstone Ports Corporation
Technical Report
November 2019

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ACRONYMS

ARI	Average Recurrence Interval
APLNG	Australia Pacific Liquified Natural Gas
BPAR	Benthic Photosynthetic Active Radiation
CQU	Central Queensland University
DoEE	Department of Environment and Energy
DTMR	Department of Transport and Main Roads
EBSDS	East Banks Sea Disposal Site
EMS	Environmental Management System
GBR	Great Barrier Reef
GBRMP	Great Barrier Reef Marine Park
GBRMPA	Great Barrier Reef Marine Park Authority
GBRWHA	Great Barrier Reef World Heritage Area
GHHP	Gladstone Healthy Harbour Partnership
GPC	Gladstone Ports Corporation
GLNG	Gladstone Liquified Natural Gas
HP	Horsepower
H_s	Significant wave height (the mean wave height of the highest third of the waves)
kt/yr	kilo-tonnes per year
LAT	Lowest Astronomical Tide
LMDMP	Long-term Maintenance Dredging Management Plan
LNG	Liquified Natural Gas
MDS	Maintenance Dredging Strategy
Mt/yr	Million tonnes per year
NRM	Natural Resource Management
PCS	Port and Coastal Solutions
PoG	Port of Gladstone
PSD	Particle Size Distribution
QCLNG	Queensland Curtis Liquified Natural Gas
QLD	Queensland
SI	Surface Irradiance
SSC	Suspended Sediment Concentration
SSM	Sustainable Sediment Management
TC	Tropical Cyclone
TSHD	Trailing Suction Hopper Dredger
t/yr	tonnes per year
WICT	Wiggins Island Coal Terminal
WRB	Wave Rider Buoy

Executive Summary

Gladstone Ports Corporation (GPC) commissioned Port and Coastal Solutions (PCS) to develop a quantitative sediment budget for the Port of Gladstone (PoG) as part of their Sustainable Sediment Management (SSM) Project. The overall aim of this assessment is to produce a quantitative sediment budget for the PoG, which builds on the conceptual sediment budget and uses project information created, collected and collated to date.

A quantitative sediment budget has been developed using all relevant SSM Project information created, collected and collated to date as well as other relevant information. As part of the assessment, anthropogenic impacts to the sediment budget have been considered, this has included maintenance dredging activity as well as trawling, propeller wash from Port vessels and urban and industrial inputs. The key findings from the quantitative sediment budget can be summarised as follows:

- there is a very large mass of existing sediment present in the PoG region. The sediment is likely to have built-up over geological timeframes;
- there is a natural net north-westerly transport of fine-grained sediment along the coastline due to the dominant south-easterly wind and wave conditions. Approximately 15 to 20% of this net transport of fine-grained sediment is transported into the Inner Harbour region of the PoG through the South Entrance;
- the natural resuspension of existing sediment by waves and currents is the dominant process for sediment transport in the region as the annual mass of sediment resuspended by waves and currents is an order of magnitude greater than the input of new sediment to the system. Transported sediment is likely to be reworked multiple times (i.e. deposited during calm conditions and resuspended during more energetic conditions) until it is deposited in a location with consistently calm conditions (e.g. dredged berths and channels or mangroves);
- there is an annual net gain in sediment in the PoG region, with the majority of the increase in sediment being in the Inner Harbour due to the import of some of the suspended sediment being transported to the north-west along the coastline;
- despite the annual net gain in sediment, the budget indicates that there is the potential for insufficient new sediment available in the Inner Harbour to balance the deposition requirements for calmer years when the net import of sediment is predicted to be lower. This could limit the natural accretion of some intertidal areas, potentially resulting in them not being able to accrete at a comparable rate to predicted future sea level rise;
- maintenance dredging and placement activities have a negligible (<1%) contribution to the total mass of sediment resuspended in the PoG region. In contrast, it has been estimated that otter net trawling represents between 3 and 8% of the total resuspension;
- the relative contribution of sediment from maintenance dredging placed at East Banks Sea Disposal Site (EBSDS) to the cumulative flux of sediment into the Great Barrier Reef Marine Park (GBRMP) through the boundaries adjacent to EBSDS is predicted to be less than 5% over the short-term period during and over the six weeks after the maintenance dredging campaign. After this period the contribution is expected to be significantly lower;
- based on the quantitative sediment budget, it is considered unlikely that maintenance dredging operations in the PoG will result in significant, widespread detectable adverse environmental impacts on the sensitive receptors (corals and seagrasses) in the region around the port and EBSDS;
- it is also considered very unlikely that the placement of sediment from maintenance dredging at EBSDS and its subsequent resuspension would result in ecological impacts in the GBRWHA (excluding the EBSDS itself); and

- natural resuspension of existing bed sediment due to waves and currents and resuspension of existing bed sediment and the input of new sediment during extreme events (cyclones and flood discharges) are considered much more likely to result in significant changes in the PoG region (in water quality and sensitive ecological receptors) as opposed to maintenance dredging, which has been shown to only result in relatively small and short duration increases in turbidity.

1. Introduction

Gladstone Ports Corporation (GPC) commissioned Port and Coastal Solutions (PCS) to develop a quantitative sediment budget for the Port of Gladstone (PoG) as part of their Sustainable Sediment Management (SSM) Project.

The SSM Project has been developed to build on the information collected to date within the PoG region. One of the key aims of the SSM Project is to develop a quantitative sediment budget and associated model to better understand the contribution of GPC's activities to the overall sediment system. The overall aim of this assessment is to produce a quantitative sediment budget for the PoG, which builds on the conceptual sediment budget and uses project information created, collected and collated to date. The budget is aimed at quantifying the main sediment sources, sinks and transport pathways with a particular focus on sediment suspended by maintenance dredging activity and the placement of maintenance dredge sediment at East Banks Sea Disposal Site (EBSDS).

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, supporting sustainable development and minimising harm to the environment, Port, surrounding areas and communities.

GPC had discerned the need to further improve their understanding of the interactions between maintenance dredging operations (including sea disposal of dredged material) and the local and regional environment, in order to minimise environmental impacts and ensure the ongoing sustainability of these operations. To progress this need GPC previously entered an informal agreement with the Great Barrier Reef Marine Park Authority (GBRMPA), to investigate this interaction at the Marine Park - Port Limits boundary. 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 *Transport Infrastructure Act 1994*. The PoG maintenance dredging and disposal activities associated with the main channels, swings basins and berth pockets are usually undertaken annually, with dredged material placed at the approved EBSDS (first approved in 1980). In addition, the sediment removed by maintenance dredging of some areas of the PoG (e.g. the Marina and the Boyne River) has historically been placed on land.

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. It is noted that among other things the research and monitoring may include;
  - establishment of a quantitative sediment budget and sediment dynamics model for Port Curtis (the large natural harbour within which the PoG is located), Queensland, including quantifying impacts and extent of sediment transport and resuspension from Dumping Activities at the EBSDS with specific reference to sensitive receptors and potential impacts on the GBRWHA; and
  - monitoring changes in water quality (including turbidity and benthic photosynthetic active radiation (BPAR)) resulting from or as a consequence of dumping activities;
- investigate the possibility of avoiding or reducing the need for further dumping of maintenance dredged material into the marine environment, including the possibility of beneficially reusing the sediment; and

- report to the DoEE the results of any research, monitoring or investigation undertaken by GPC in accordance with the Deed.

The Deed 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 14001:2015, ensuring a robust risk identification, control and improvement process is implemented and maintained.

In addition to the Deed, a Maintenance Dredging Strategy (MDS) has been developed for the ports that are situated within the GBRWHA (DTMR, 2016). The MDS provides a framework for the sustainable, leading practice management of maintenance dredging. It is a requirement of the MDS that each Port within the GBRWHA develop and implement a Long-term Maintenance Dredging Management Plan (LMDMP). The LMDMPs are aimed at creating a framework for continual improvement in environmental performance. Department of Transport and Main Roads (DTMR) have provided guidelines to assist in the development of the LMDMPs which can be applied to ports Queensland wide (DTMR, 2018). The guidelines note that the LMDMPs should include, as well as other aspects, the following:

- an understanding of port-specific sedimentation conditions and processes;
- management approaches (including dredge avoidance and reduction); and
- long-term dredging requirements based on sedimentation rates, port safety and port efficiency needs.

The SSM Project will therefore help to fulfil the requirements of the Deed and will also provide input to the LMDMP. The SSM Project has been developed to build on the information collected to date within Port Curtis, to develop a sediment budget and associated model to better understand the contribution of GPC's activities to the overall sediment system and to investigate possibilities to avoid or reduce the need for further placement of sediment into the marine environment.

1.2. Port of Gladstone

The majority of the PoG is located within Port Curtis on the east coast of Queensland, approximately 525 kilometres (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 sediment transport processes which influence the region.

In the 2018/19 financial year the PoG handled 124 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, petroleum, industrial chemicals, grain and containers were also handled (GPC, 2019).

The PoG covers 4,448 hectares (ha) of land which includes more than 700 ha of reclaimed land. There are ten 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 wharf;

8. Curtis Island LNG Precinct, Queensland Curtis LNG (QCLNG): one wharf;
9. Curtis Island LNG Precinct, Gladstone LNG (GLNG): one wharf; and
10. Wiggins Island Coal Terminal (WICT): one wharf.

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

The PoG consists of approximately 50 km of shipping channels to ensure safe navigation from the entrance of the Port to the wharves (Figure 2). Sediment management practises are undertaken to ensure that the depths of the channels and berths are maintained at their original declared depths (Table 1). The sediment management practises include maintenance dredging, bed levelling and drag barring. Annual maintenance dredging and bed levelling/drag barring practises are undertaken in the PoG, with some areas requiring sediment management at least annually while others require less frequent management.

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
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
Marina	-4.5
WICT departure channel	-16.0

Capital dredging has historically been undertaken in the PoG as the Port has grown. Most recently, between 2011 and 2013, capital dredging associated with the construction of three LNG terminals and the WICT was undertaken. Table 2 provides details of the maintenance and capital dredging, which has been undertaken at the PoG when sediment has been placed at the EBSDS over the last 10 years. It is important to note that the table does not include the volume of sediment removed from the Marina and a number of other areas of the PoG (e.g. Boyne River) as to date the sediment from these areas has been placed on land. Historic maintenance dredging of the Marina has included the removal of 352,000 m^3 (in-situ volume) in 2009 and 305,000 m^3 (in-situ volume) in 2015.

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	
2018	211,102	
Total (2007-2017)	**2,413,891**	**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.

A breakdown of the volumes of sediment dredged throughout the different areas of the PoG during the 2018 annual maintenance dredging[1] is shown in Figure 3. The plot shows that just over 60,000 m^3 was removed from the Golding, Boyne and Wild Cattle Cuttings, approximately 115,000 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 region) and the remaining volume was removed from the area between the RG Tanna Wharves and the eastern end of the Gatcombe Channel. As the PoG Sea Dumping Permit requires GPC to report the in-situ cubic metres that are delivered by the dredger to EBSDS, the reported dredge volumes and sedimentation (measured as the in-situ change in volume based on bathymetric data) will not correlate directly. This is because the dredge volumes placed at EBSDS do not include the volume of sediment which is removed from the seabed by the dredger and subsequently lost during overflowing when the dredger is filling its hopper. Based on monitoring during previous maintenance dredging and advice from expert dredging consultants, the efficiency of the Trailing Suction Hopper Dredge (TSHD) *Brisbane* ranges from 50% to 70% when undertaking maintenance dredging in the PoG (BMT, 2017). This means that between 30% and 50% of the sediment which is dredged from the seabed is lost during the dredging due to overflow, drag head disturbance and propeller wash and of this

[1] Use of the term 'annual maintenance dredging' in this report refers to the maintenance dredging of the main channels, basins and berths of the PoG by the TSHD Brisbane each year and the subsequent placement of the sediment at EBSDS. This does not include the maintenance dredging of other areas where the sediment is currently placed on land (e.g. the Marina).

amount it has been estimated that approximately 15% remains in suspension as a plume and the remainder is locally deposited back into the channel (BMT, 2017). The sediment which is locally redeposited in the channel might subsequently be re-dredged, redistributed by bed levelling, settle into naturally deeper areas of the channel which don't require dredging or be transported away from the region by currents and be deposited outside of the dredged areas.

The PoG can be separated into Inner and Outer Harbour regions as different sediment transport processes influence them; the Outer Harbour region extends from the Wild Cattle Cutting to the Gatcombe Channel and the Inner Harbour is the area inshore from Auckland Channel, which is sheltered from offshore wave activity by Curtis and Facing Islands (Figure 2).

1.3. Report Structure

The report herein is set out as follows:

- a summary of the relevant findings from previous investigations is provided in **Section 2**;
- analysis of numerical modelling results to help inform the quantitative sediment budget is detailed in **Section 3**;
- a summary of the natural sediment transport is given in **Section 4**;
- an assessment of the anthropogenic impacts to the sediment budget is provided in **Section 5**;
- the quantitative sediment budget is presented in **Section 6**;
- the potential ecological implications of the impact of maintenance dredging on sediment transport in the PoG is detailed in **Section 7**; and
- a summary of the key findings from this assessment is provided in **Section 8**.

Unless stated otherwise, levels are reported to Lowest Astronomical Tide (LAT). Volumes presented throughout are in-situ cubic metres calculated from surveyed bathymetry.

Figure 2. Port of Gladstone declared channels and sea disposal site.

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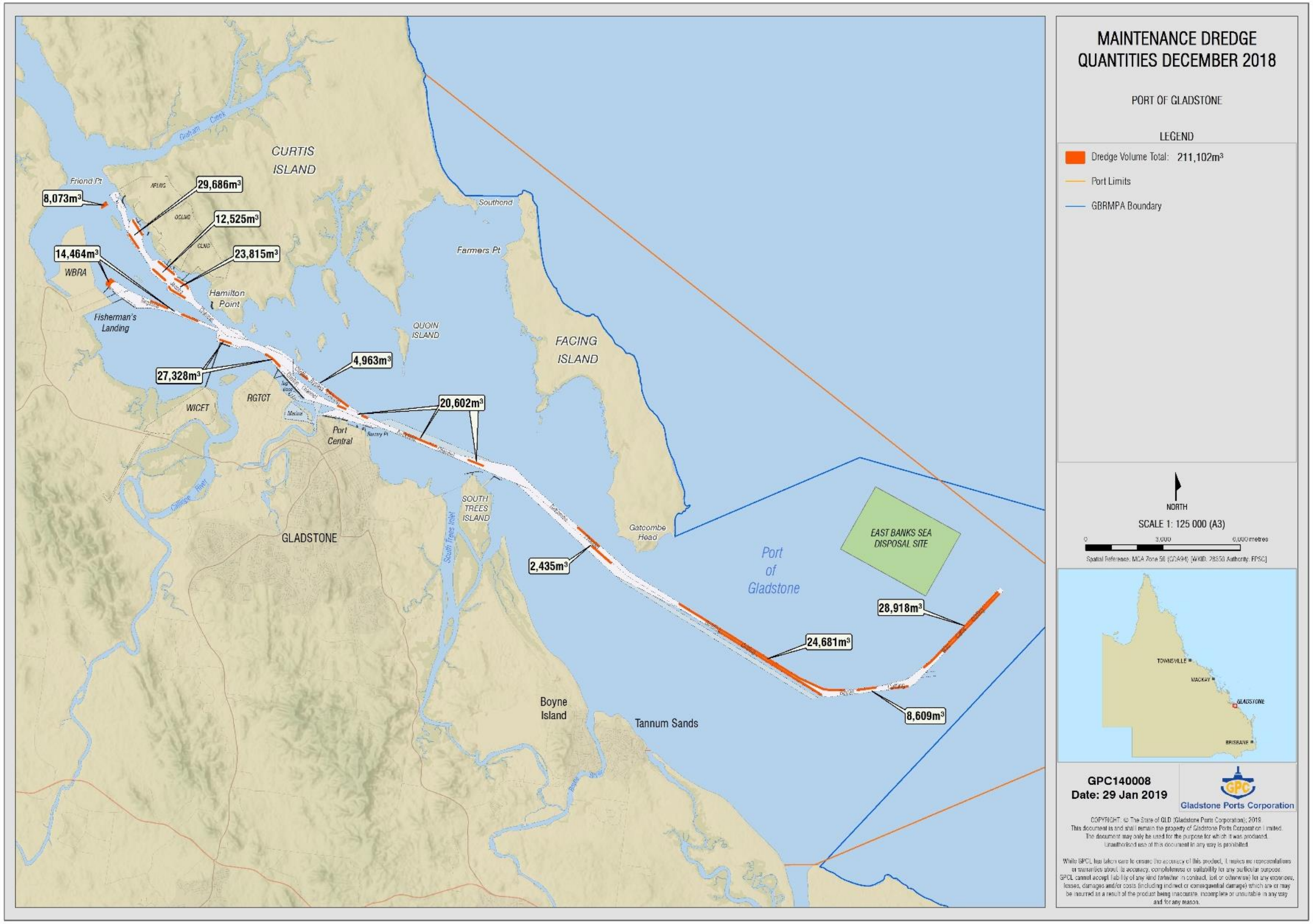

Figure 3. Port of Gladstone annual maintenance dredging volumes from 2018.

2. Previous Investigations

2.1. Introduction

Numerous investigations have been undertaken as part of the PoG SSM Project which are relevant in the development of a quantitative sediment budget for the PoG. These investigations have been reviewed and the relevant findings for the quantitative sediment budget are discussed in this section.

Additional information which is considered relevant for the development of the quantitative sediment budget is also discussed in this section.

2.2. Sediment Texture Mapping

Central Queensland University (CQU) and BMT WBM undertook a study to better understand the composition of the natural sediment within the PoG (CQU & BMT WBM, 2018). The study involved the collation of existing sediment data as well as the collection of additional sediment samples in areas where the existing data was insufficient, with a specific focus on the key areas of interest of the channels and EBSDS.

The final sediment composition map which was prepared using all the available sediment data is shown in Figure 4. The map highlights how the sediment composition varies through the PoG, with predominantly sand in the Outer Harbour, gravel in the Clinton, Auckland and Gatcombe Channels and more silt and clay in the upstream regions such as the Western Basin. The assessment also investigated how the sediment composition varied at EBSDS before, immediately after and two months after the 2017 maintenance dredging campaign. An increase in silt and clay of approximately 5% on average was observed immediately after the campaign and two months later the sediment was similar to its pre-dredging composition.

2.3. Conceptual Sediment Budget

PCS undertook an assessment of the historic bathymetric changes in the PoG and based on this and other available information developed a conceptual sediment budget for the PoG (PCS, 2018a).

The bathymetric analysis found that the highest rates of sedimentation have been occurring in the Western Basin region (including the Jacobs Channel and adjacent LNG terminals and the Fisherman's Landing regions) and in the Outer Cuttings (Golding, Boyne and Wild Cattle Cuttings). The typical ongoing annual sedimentation was estimated as 600,000 m^3 with approximately half of this being in the Western Basin region and 200,000 m^3 being in the Outer Cuttings. It is important to note that this assessment was just in terms of actual sedimentation and not sedimentation above design depths (this was considered as part of the Avoid Assessment, see Section 2.5).

Analysis of historic bathymetric data at EBSDS estimated that between 2007 and 2017 more than 95% of the combined capital and maintenance dredged sediment placed at EBSDS was retained. In addition, the bathymetry at the site was found to be stable, with limited erosion occurring due to large wave events.

The conceptual sediment budget which was developed is shown in Figure 5. The budget shows that different processes control the sediment transport 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. Based on the available information the conceptual budget details the relative sources and sinks of sediment in the regions.

The present study is aimed at building on the conceptual sediment budget to develop a full quantitative sediment budget. The budget will be updated based on the additional data and investigations which have been collected and undertaken since the initial conceptual budget was developed.

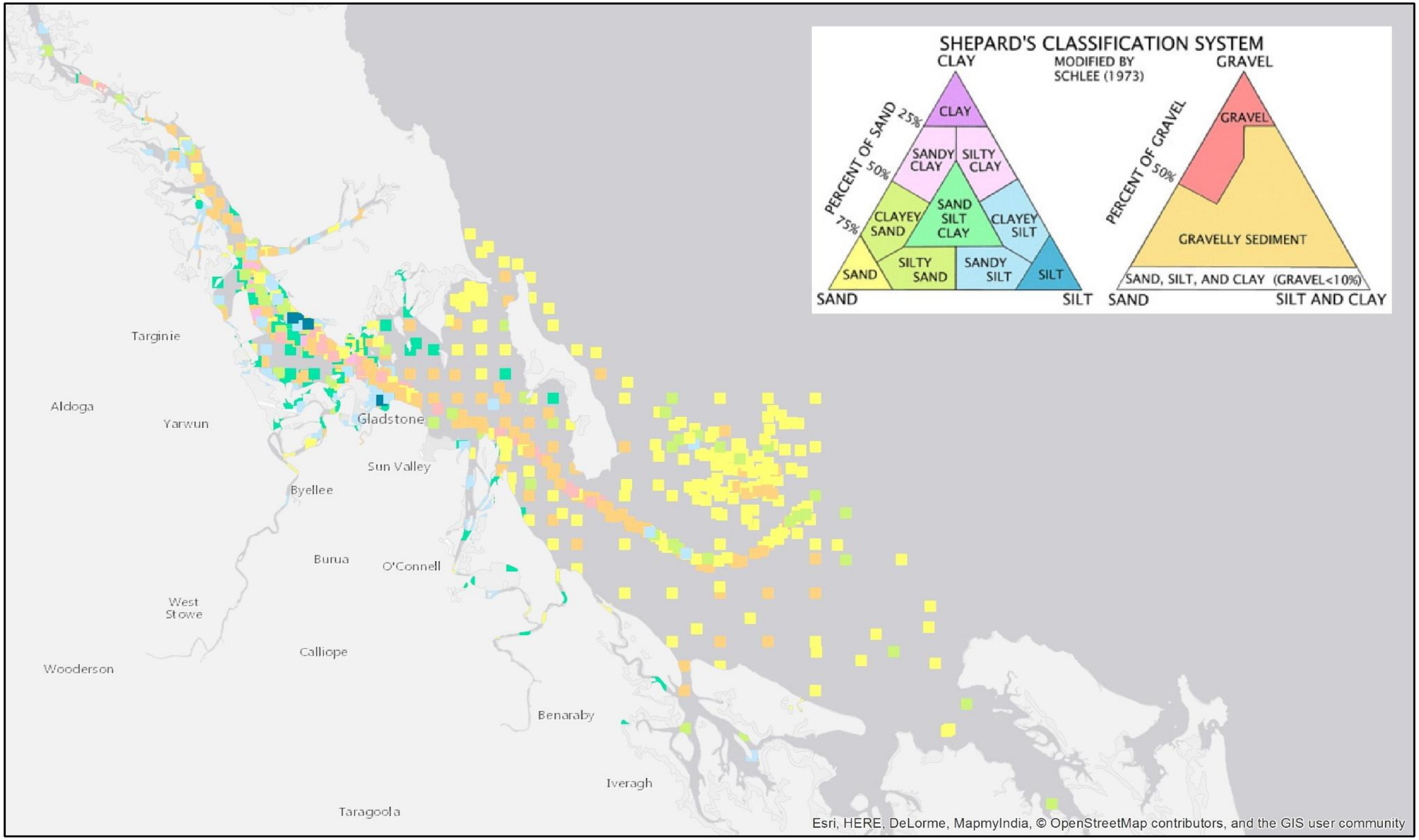

Figure 4. PoG sediment composition map using Shepard's classification system (CQU & BMT WBM, 2018).

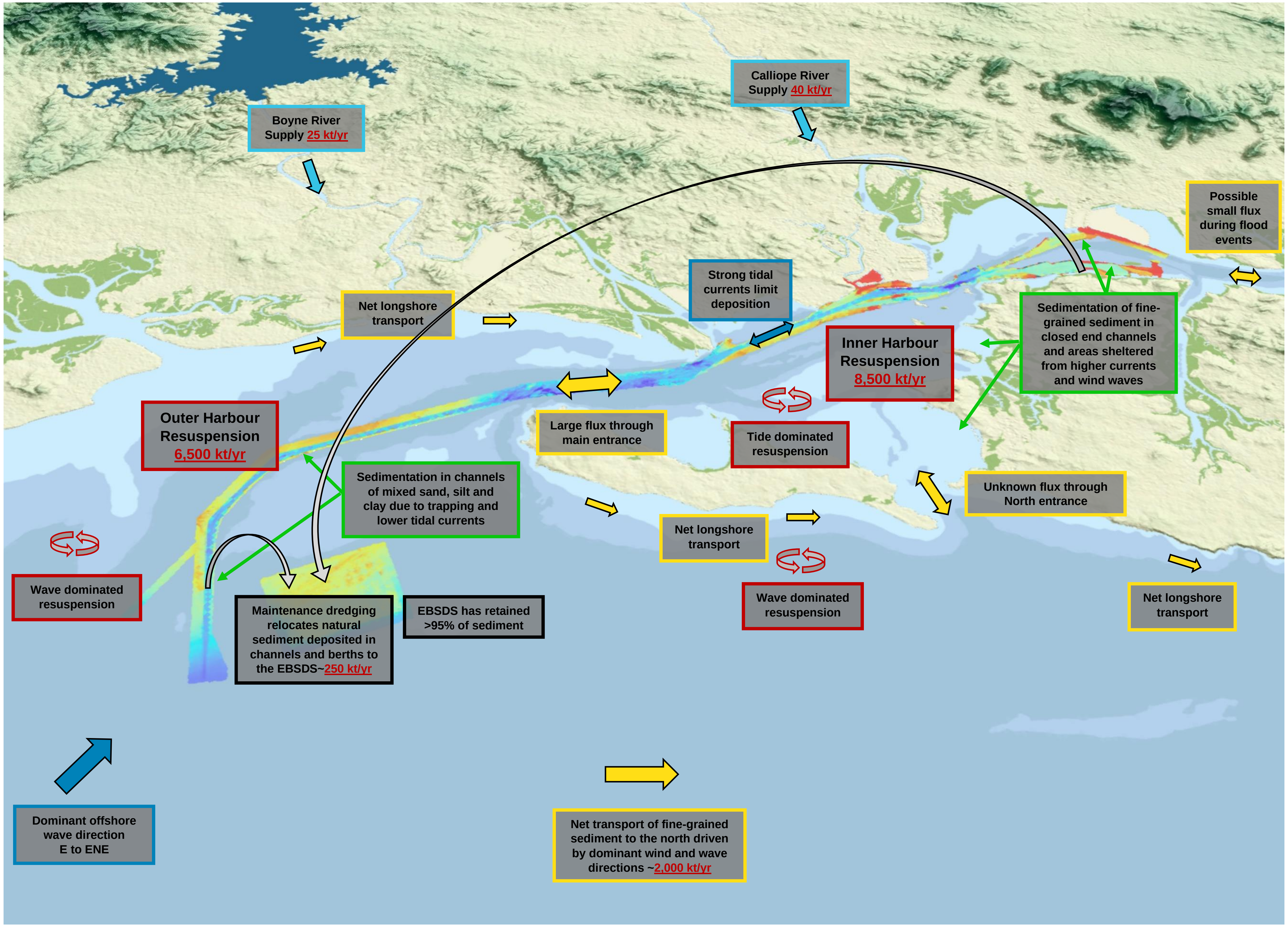

Figure 5. Conceptual sediment transport budget of the PoG (PCS, 2018a). *Note: kt/yr is 1,000 tonnes per year.*

2.4. Gap Analysis and Sampling Strategy

PCS reviewed all relevant previous investigations of the PoG, as well as available measured data, to understand where additional data and investigations were required, to ensure the quantitative sediment budget was as robust as possible and the requirements of the Deed were met (PCS, 2018b). The key data gaps which were identified were as follows:

- Sediment sources: it was noted that although there was sufficient information to inform some of the sources of sediment to the PoG, there were no data available to inform the source of the sediment which is being deposited into the maintained channels and berths of the PoG;
- Fluxes of sediment: although data collected in the Narrows has allowed an assessment of the sediment transport in this area (see Section 2.8), additional data are required to better understand the sediment transport and relative import and export of sediment to/from the PoG through the southern and northern entrances; and
- Transport of sediment from EBSDS: it was noted that there were no measured data to show how suspended sediment resulting from the placement of dredged sediment at EBSDS behaves if it leaves the site.

Based on the gap analysis a sampling strategy was developed which recommended that three separate investigations should be undertaken to cover the three key data gaps. Based on this an investigation into the sources of sediment deposited in the dredged areas of the PoG was undertaken (see Section 2.7) and two data collection campaigns were undertaken in 2018 to collect data to better understand the fluxes of sediment through the southern and northern entrances and the transport of sediment from EBSDS (see Section 2.6).

2.5. Avoid Assessment

As part of the SSM Project, PCS undertook an options assessment for completely avoiding sedimentation, maintenance dredging and the placement of sediment at sea (PCS, 2018c). As part of the assessment it was also necessary to predict future sedimentation within the PoG and the resultant change in declared depths.

Based on the analysis of historic bathymetric data relative to the design depths in the PoG it was predicted that the total annual future maintenance dredging for the PoG will be between 213,000 and 317,000 m^3 (in-situ volume) depending on whether the sedimentation which has occurred is typical or worst case. The LNG Terminals aprons and berths adjacent to the Jacobs Channel were found to have the largest future requirement, while the Marina, berths at Clinton Wharf, WICT, Auckland Point and South Trees and the Outer Cuttings (Golding, Boyne and Wild Cattle Cuttings) were also noted as requiring ongoing maintenance dredging.

Based on historical sedimentation rates, it was determined that worst case sedimentation rates occur once every five years on average. This corresponds with the typical occurrence of extreme events when very high rainfall, strong winds and large waves occur. Over the last ten years there have been two years with very high rainfall and large waves due to extreme events (2010/11 and 2013). The future sedimentation above design depths was predicted with a total volume of 5.85 million m^3 predicted over 20 years (assuming four years with worst case sedimentation and the remaining years having typical sedimentation). The predicted sedimentation results in shallowing of a number of the main navigation channels as well as most of the berths, with access through the Golding Cutting for most unladen cargo vessels being restricted between 10 and 20 years of sedimentation.

The assessment found that although there are possible options to avoid sedimentation and maintenance dredging in some areas of the PoG, none of these could be adopted for the entire PoG.

2.6. Sediment Movement Data Interpretation

PCS undertook a study to collate, process, review and interpret all of the data collected by GPC as part of the SSM Project (PCS, 2019a). The overall aims of the study were to improve the understanding of:

- the natural sediment transport in the PoG;
- the release of sediment from maintenance dredging and sediment placement at EBSDS and the subsequent transport of the sediment; and
- the overall sediment budget for the PoG.

Data from four separate data collection campaigns from 2015 to 2018 were analysed and the relevant findings are detailed below:

- the data suggested that there was a net import of suspended sediment into the Inner Harbour through the Southern Entrance (estimated to be 660,000 tonnes per year (t/yr)) and the Narrows (estimated to be 25,000 t/yr) and a net export through the Northern Entrance (estimated to be 13,000 t/yr);
- turbidity at the entrances to the Inner Harbour was found to be predominantly controlled by the tidal conditions. The data suggest that the increased current speeds combined with the greater inundation of intertidal regions resulting from larger spring tides (i.e. 'overbank' tides) increase the resuspension of sediment within the Inner Harbour;
- the resuspension of bed sediment at East Banks Sea Disposal Site (EBSDS) is controlled by a combination of the wave action and currents, with the wave action being the dominant process;
- during periods with calm metocean conditions there is little advection of suspended sediment beyond the boundaries of EBSDS due to the placement of dredged sediment. During these conditions the plumes resulting from the placement of dredged sediment at EBSDS appear to typically be short duration (less than 1.5 hours) and can be transported up to 1.5 km, indicating that the majority of the suspended sediment will be deposited within EBSDS;
- there is the potential for advection of suspended sediment beyond the boundaries of EBSDS due to the placement of dredged sediment during periods with calm wind/wave conditions and large spring tides, as the bed shear stresses from the strong tidal currents limit the deposition of suspended sediment. However, the calm wind conditions mean that there is no residual transport and so the suspended sediment is likely to be transported similar distances to the west and east cross the EBSDS boundary during the flood and ebb tidal currents until all the sediment is deposited;
- periods with strong winds (20 knots) and moderate wave conditions (H_s[2] 1 – 1.5 m) were found to have the potential to transport the suspended sediment from the placement of dredged sediment the furthest distance (with it still being distinguishable above natural background turbidity). The bed shear stress resulting from the wave conditions limits the deposition of suspended sediment, while not being sufficient to result in widespread natural resuspension of sediment from the seabed. The strong winds influence the currents causing a dominance in one of the tidal current directions, which in turn results in a residual transport of the suspended sediment. When the wind and wave directions were from the east the data showed that the resultant residual westerly current direction resulted in some of the suspended sediment from the placement being transported into the GBRMP. These conditions only occurred on a single day of the 33-day 2018 maintenance dredging campaign;

[2] the significant wave height is the mean wave height of the highest third of the waves. It is widely adopted as a measure of the height of waves and was originally intended to provide a mathematical representation equivalent to the height estimated by a trained observer.

- it was not possible to identify the contribution of recently placed dredged sediment at EBSDS to the elevated turbidity which occurred during the wind/wave events during and following the 2018 maintenance dredging program. However, the data suggest that these events resulted in widespread resuspension of bed sediment from within EBSDS and the areas around EBSDS. Consequently, it is expected that the surface layer of sediment on the seabed within EBSDS would have been resuspended, regardless of whether this sediment had been recently placed during the 2018 maintenance dredging campaign or was existing bed sediment; and
- based on the data, the impact of the placement of dredged sediment at EBSDS on turbidity, benthic light and bed level changes was considered to be insignificant compared to the impacts resulting from natural wind/wave events. A single wind/wave event was found to result in the widespread resuspension of benthic sediment, causing much higher, longer duration and more widespread increased turbidity than a plume from the placement of dredged sediment at EBSDS. In addition, the increased turbidity associated with natural wind/wave events can also reduce the benthic light to zero for periods of weeks and result in significant fluctuations in bed level due to the resuspension and subsequent deposition.

2.7. Sediment Sources

CQU led an investigation into the sources of sediment which had recently been deposited into the dredged areas of the PoG (Jackson et al., 2019). The investigation adopted a multiple lines of evidence approach to try and identify the provenance of sediment which had been deposited in the PoG channels. The investigation included analysis of Rare Earth Elements, Strontium isotope, Beryllium-7 isotope, stable isotope and particle size distribution. The key relevant findings from the investigation were:

- the strontium isotope analysis suggests that fluvial sediment influences the sediment on the mudflats and in the dredged channels of the Inner Harbour. The sediment has increased marine carbonates in the Outer Harbour region;
- the beryllium isotope analysis suggests that sediment in the channels were relatively recently deposited from areas exposed to air, and this is most likely to be from intertidal mudflats within the PoG. Sampling in the wet season (following a rainfall event and a large wave event) compared to the dry season showed increased Beryllium-7 at all sites except for Wild Cattle Cutting. This suggests that the sediment at the majority of the sites was deposited more recently in the wet season sampling than in the dry season, which given the fact it influenced the majority of sites is expected to be predominantly a result of recent reworking of intertidal sediment by the wind and wave conditions. At Wild Cattle Cutting the reduction in Beryllium-7 is likely to be a result of the wave activity over the wet season resuspending any fine-grained sediment present and limiting the deposition of any new fine-grained sediment;
- the stable isotope analysis found that the sediment from Wild Cattle Cutting was very distinctive compared to the sediment from the other channels, with it showing a very dominant marine signal. The analysis also found that the sediment from the Golding Cutting and Auckland and Gatcombe Channels intersection had the most similarities with the intertidal mudflats around Jacobs and Targinnie Channels;
- the rare earth elements analysis showed that the sediment from Wild Cattle Cutting closely matched the sediment from Rodds Peninsula and from the beaches of Wild Cattle Island, indicating that the sediment building up in the channel is marine in origin and from the gradual northern net transport of sediment. In contrast, the sediment collected from the Golding Cutting showed elemental similarities with the intertidal mudflats around Jacobs and Targinnie Channels. In addition, sediment collected at the Auckland and Gatcombe Channels intersection showed a resemblance with the Boyne and Calliope river bed samples; and

- the particle size distribution analysis showed little variability between the dry and wet season sampling, suggesting that the processes controlling the deposition did not change significantly. The only exception to this was the Golding Cutting where the sediment was predominantly fine sand in the dry season and became predominantly silt in the wet season. This shows that following the wet season rainfall and wave event there was an increase in deposition of fine-grained silt in this area compared to during the dry season. Based on the other analyses it is likely that the fine-grained sediment was from erosion of the intertidal mudflats in the PoG.

The sediment provenance investigations have shown that, with the exception of Wild Cattle Cutting, at least some of the sediment deposited in the channels is likely to have at been from the reworking of sediment from intertidal mudflats, with more of this sediment following wind/wave events. The sediment which is deposited in Wild Cattle Cutting was found to be predominantly marine in origin. The sediment in the Inner Harbour was found to be influenced by fluvial origins (this is likely to be over geological timeframes), while the sediment in the Outer Harbour was predominantly marine carbonates.

2.8. Narrows Sediment Transport

RPS Australia West undertook an assessment of hydrodynamic and sediment transport data collected within the Narrows when the Fitzroy River was in flood during the major rainfall event of ex-Tropical Cyclone Debbie (RPS, 2018). The assessment was aimed at better understanding the sediment transport within The Narrows and the exchange of sediment between the Inner Harbour and the Fitzroy River and the relevance of sediment transport through The Narrows to the overall sediment budget of the PoG. The key relevant findings from the investigation were that:

- the sediment transport in The Narrows is dominated by the astronomical tide combined with the occurrence of estuarine processes during the wet season;
- tides with a high water level sufficiently high to inundate the intertidal mangrove areas that border the main channels (‘overbank’ tides) were found to result in higher sediment transport rates compared to tides with a lower high water level (‘within-channel’ tides). The ‘overbank’ tides resulted in an ebb-directed sediment transport (i.e. into the PoG), whereas the ‘within-channel’ tides were found to result in little sediment transport with no net direction;
- during ‘overbank’ tides the peak instantaneous sediment flux through The Narrows was approximately 500 kg/s, with a net flux per flood-ebb cycle of approximately 20 tonnes; and
- based on the analysis of the measured data available it was estimated that the net sediment flux through the Narrows was less than 5,000 tonnes. As a result, the sediment transport through the Narrows was found to be inconsequential to the overall sediment budget of the PoG.

2.9. Beneficial Reuse

GHD undertook an assessment into potential options to beneficially reuse sediment from maintenance dredging in the PoG (GHD, 2019). As part of the study they undertook an assessment of the sediment properties of the sediment which is removed by maintenance dredging in the PoG. The assessment included reviewing sampling undertaken in 2017 (AMA, 2017) as well as sampling which was undertaken as part of their assessment in 2018. The sediment sampling locations were selected to target areas where regular maintenance dredging is required (i.e. areas where ongoing sedimentation occurs).

The particle size distribution (PSD) of sediment samples from similar locations were found to be comparable between the 2017 and 2018 sampling. The sampling showed that the sediment in the Auckland and Clinton Channels consisted of the coarsest sediment, with it being predominantly sand sized but also with some gravel sized sediment (Figure 6). The sediment in the Golding and Wild Cattle Cuttings were similar, with the sediment being predominantly sand sized, but also with some silt and clay (only a trace of clay in the Wild Cattle Cutting). The sediment in the Marina and Western Basin region (Jacobs Channel and Fisherman's Landing) was similar, with it consisting of predominantly clay and silt sized sediment. The relatively coarse nature of the sediment in the Clinton and Auckland Channels suggests that the sedimentation which occurs in these areas is more likely to be a result of changes in bedforms, as opposed to sedimentation of new sediment, as it is unlikely that sediment of these sizes would be consistently transported in suspension to these areas. The bulk density of the samples was found to range from 0.88 to 1.36 tonnes/m^3.

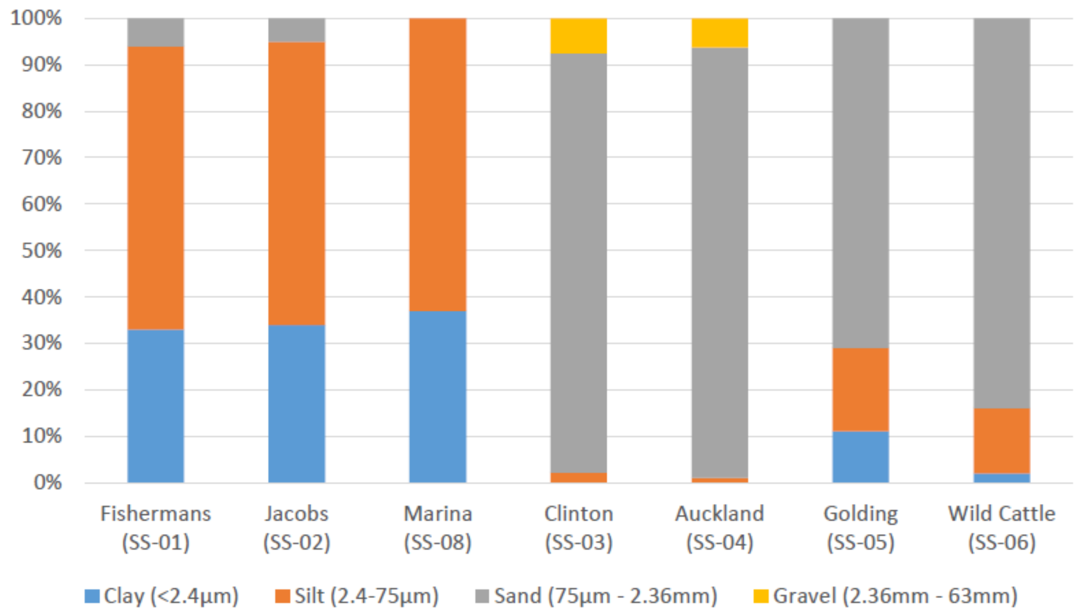

Figure 6. Results of the PSD analysis undertaken as part of the beneficial reuse assessment (GHD, 2019).

2.10. Numerical Modelling

As part of PoG SSM Project the TUFLOW FV numerical hydrodynamic and sediment transport model has been refined and further validated. The final aim of the numerical modelling was to simulate the sediment dynamics around the PoG and the surrounding GBRWHA to provide additional data and understanding to inform the quantitative sediment budget.

The TUFLOW FV PoG model has been improved over time with additional calibration and validation to new data as part of specific projects and extensions to the model domain and increases to the model resolution having been undertaken. The SSM Project used the latest version of the model with a domain covering 32,000 km^2, extending from Sandy Cape in the south to Cape Manifold in the north (BMT, 2019a). The following was undertaken as part of the numerical modelling:

- calibration of the model using data collected during the 2018/19 monitoring campaigns and validation of the spatial distribution of turbidity during natural conditions and maintenance dredging using satellite-derived turbidity data; and
- simulation of specific periods to represent a range of metocean conditions as well as multiple maintenance dredging campaigns.

Results from the numerical model simulations undertaken for the PoG SSM Project have been provided to inform the quantitative sediment budget. The processing and interpretation of the results are presented in Section 3.

2.11. River Discharges

The most recent studies which have investigated the suspended sediment discharged from the Calliope and Boyne Rivers were undertaken by Dougall et al. (2014) and (BMT WBM, 2015). The key relevant findings from these studies are detailed below:

- Dougall et al. (2014): hydrological modelling was undertaken to determine the average annual discharge from all rivers in the Fitzroy Natural Resource Management (NRM). The modelling predicted that the annual average discharge from the Calliope and Boyne Rivers were 44,000 and 11,000 tonnes/yr. Calibration of the hydrological models to measured river gauge data found that the Calliope modelled discharge volume was underpredicted by 25% while the Boyne modelled discharge volume was underpredicted by 17%; and
- BMT WBM (2015): hydrological modelling of the Calliope and Boyne Rivers was undertaken to provide discharge data to the PoG hydrodynamic model for a range of rainfall events. The models were calibrated to historic measured river discharge at gauges in the rivers for historic flood events in 2010/11 (rainfall was equivalent to a 1:2 year Average Recurrence Interval (ARI) event) and 2013[3] (rainfall was equivalent to a 1:100 year ARI event). Based on the data presented in the report the following discharges have been determined:
  - Calliope River: 1:2 year ARI event = 50,000 tonnes; 1:100 year ARI event = 160,000 tonnes; and
  - Boyne River: 1:2 year ARI event = 80,000 tonnes; 1:100 year ARI event = 260,000 tonnes.

It is important to note that for both modelling studies there is some uncertainty related to the Boyne River estimates for the typical discharge events, because there are no data available to determine the sediment load discharged from the Awoonga Dam for this type of event. During typical conditions and regular flood events it is likely that the dam will trap a significant amount of sediment suspended in the upstream flood waters. The BMT WBM modelling parameterised losses from the dam based on measurements collected during a 1:100 year ARI event and based on this they acknowledge that the loads exiting the dam during the 1:2 year ARI event are likely to be overestimated. This uncertainty regarding the discharge of sediment from the Awoonga Dam could explain the significant difference between the modelled discharges for the Boyne River from the two studies while the discharges for the Calliope River are comparable. During the 1:100 year ARI event the dam would overflow (this was reported during the 2013 event) and as the BMT WBM modelling was calibrated to measured data during this event the estimated discharge of 260,000 tonnes for this event is likely to be representative. Based on the above and considering that the Dougall et al. (2014) models were found to underestimate the discharge volume it is recommended that average annual discharge of suspended sediment of 50,000 tonnes/yr and 15,000 tonnes/yr should be assumed for the Calliope and Boyne Rivers, respectively. There is less confidence in the Boyne River estimation due uncertainties regarding the discharge from the Awoonga Dam. It should also be noted that the discharge can be significantly higher during extreme rainfall events.

2.12. Satellite-Derived Turbidity

Satellite-derived turbidity data can be a very useful tool to help understand the spatial variability in turbidity and how it varies due to different drivers. Satellite-derived turbidity data were obtained from EOMAP as part of the previous PoG Sediment Movement Data Interpretation study. The data were used as part of the previous study to provide a better understanding of the following:

[3] measured river gauge data was only available in the Calliope River for this event and so no validation was possible in the Boyne River.

- the spatial variability in natural turbidity around the PoG and at EBSDS for a range of conditions, including:
  - during spring and neap tidal conditions with calm wind/waves; and
  - during periods with variable wind and wave conditions.
- the spatial variability in turbidity due to the placement of dredged sediment at EBSDS during the 2018 maintenance dredging campaign.

Additional high-resolution satellite-derived turbidity data during the 2017 Fitzroy River flood event have been obtained from EOMAP as part of this investigation (Figure 7 and Figure 8). The data agree with the findings from The Narrows sediment transport assessment by RPS (2018), whereby the increased turbidity within the Fitzroy River did not extend through The Narrows and into the Inner Harbour. Elevated turbidity extended approximately mid-way along The Narrows and then reduced rapidly, meaning that significantly lower turbidity was present in the Inner Harbour compared to the Fitzroy estuary.

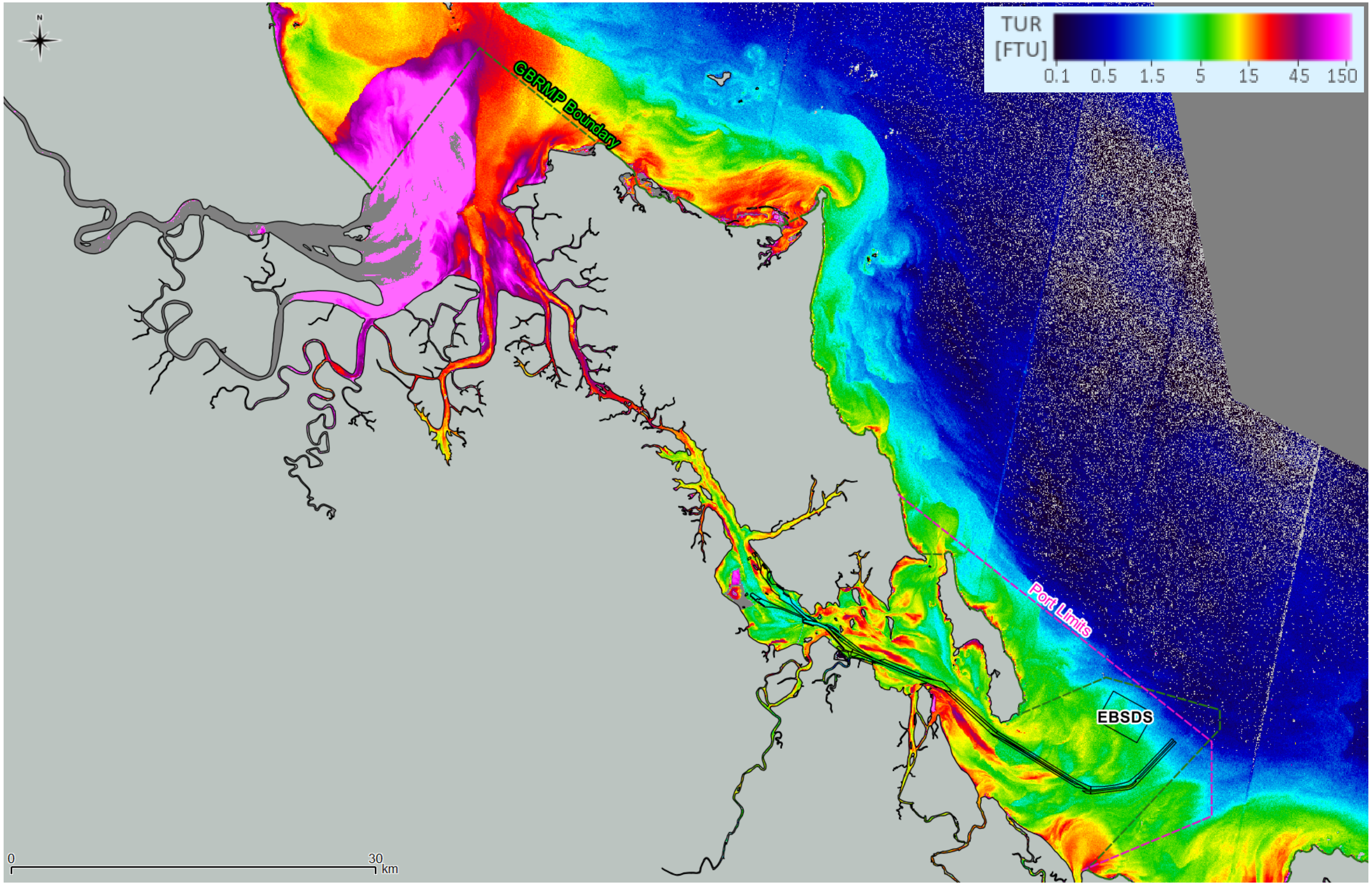

Figure 7. Satellite derived-turbidity when the Fitzroy River was in flood (08/04/2017).

Figure 8. Satellite real colour image when the Fitzroy River was in flood (08/04/2017).

3. Numerical Modelling Results

3.1. Introduction

Results from sediment transport model simulations undertaken by BMT (BMT, 2019a) have been processed and interpreted as part of this study to provide additional information on the natural sediment transport and the influence due to maintenance dredging. The model, which has been calibrated and validated to measured data (BMT, 2019a), can be considered to represent the transport of predominantly fine-grained sediment in suspension, with the model including three sediment factions, fine-grained sand, silt and clay. The model has been focused on reproducing the suspended sediment dynamics, while the bedload transport of coarser sand and gravel is not explicitly modelled (BMT, 2019a). The sediment budget has primarily focused on the suspended sediment transport to allow the sediment which is suspended by maintenance dredging to be put into context with other resuspension processes. However, it is important to note that bedload transport is likely to result in some of the sedimentation in the Outer Harbour Cuttings.

The following periods were simulated by the numerical model:

- November 2012 to June 2013: this period is considered to represent extreme wet season conditions due to the occurrence of ex-tropical cyclone (ex-TC) Oswald in January 2019. The ex-TC resulted in very heavy rainfall as well as strong winds and large offshore wave conditions. Satellite-derived turbidity data presented by PCS (2019a) showed that high turbidity occurred throughout the Inner Harbour and in the offshore waters due to this event. No maintenance dredging was included in this simulation;
- June 2014 to June 2015: this period is considered to represent a typical year, with no extreme events occurring; and
- September 2018 to March 2019: this period is considered to represent moderate wind and wave energy wet season conditions, with strong winds and large waves occurring for much of December, January and February. This period also coincides with the most recent data collection campaign undertaken as part of the SSM Project, with much of the data having been used to calibrate and validate the model (BMT, 2019a). Maintenance dredging of approximately 210,000 m^3 was included in the simulation, with dredging occurring in November and December 2018.

Results from the numerical modelling were processed to estimate the resuspension, sedimentation and gross and net suspended sediment transport. The results were processed for numerous polygons and transects to provide an understanding of the regional and local scale sediment budget (Figure 9 to Figure 12). The polygons covered the Inner Harbour and Outer Harbour regions, extending to the midpoint of the Narrows, offshore to the -30 m LAT depth contour and approximately 17 km to the north north-west of the North Entrance to the Inner Harbour and to Bustard Head which is located 16 km to the east of the entrance to Rodds Bay. For consistency with the polygons, the offshore transects also extend to the -30 m LAT depth contour which means that the lengths of the transects are variable. Results from the 2014-15 dry season period were combined with the 2012-13 and 2018/19 results to allow the annual estimates to be made.

3.2. Model Uncertainties

As part of the model calibration process, adjustments to the model were made to try and better represent the fluxes of water and sediment coming into and out of the Inner Harbour through the South Entrance, North Entrance and the Narrows based on the data collected by BMT (2019b). Following the calibration there were still large differences between the net flux of sediment through the North and South Entrances of the Inner Harbour estimated using the measured data compared to the model predictions. It was noted that a net flux estimated through either measurements or model predictions is difficult to accurately define, as it is the difference between two large numbers (cumulative flux in on the flood tide and cumulative flux out on the ebb), and each of these are subject to large uncertainties due to the difficulty in obtaining accurate measurements and the challenges of accurately replicating the natural sediment dynamics (BMT, 2019a). Based on the comparison between the measured and modelled net sediment flux during normal and spring tides presented by BMT (2019a), the relative error in the modelled sediment flux measurements have been estimated (assuming that the measured flux provides a realistic representation of the net flux):

- The Narrows: the model results in an underprediction of the net import of sediment into the Inner Harbour by a factor of two;
- North Entrance: the model results in an overprediction of the net export of sediment from the Inner Harbour by a factor of four; and
- South Entrance: the model results in an underprediction of the net import of sediment into the Inner Harbour by a factor of five.

It is important to note and consider as part of the subsequent interpretation that there are inherent limitations and uncertainties associated with numerical modelling, even when the model has been calibrated and validated to measured data. The following limitations are considered to be relevant for this study:

- although the model is able to predict the fluxes of sediment through the entrances to the Inner Harbour, it is important to note the potential over and under prediction of the model relative to the measured data (presented above) when interpreting the results;
- it was noted as part of the model calibration process that the model typically overestimated turbidity around EBSDS (based on calibration plots the modelled turbidity is typically two to four times higher than the measured turbidity), while in the Inner Harbour the model underestimated the turbidity (based on calibration plots the modelled turbidity is typically two to four times lower than the measured turbidity) (BMT, 2019a);
- numerical models are not able to represent all the complex deposition and erosion processes which occur in shallow intertidal environments and as such care must be taken when interpreting the mass budget estimations for these areas; and
- although measured data were collected during natural resuspension events around EBSDS, it is not possible to separate the resuspension of natural sediment and recently placed sediment from maintenance dredging from the measurements. While the numerical model is able to separate the natural and maintenance dredging proportions of the sediment, there are uncertainties in the accuracy of the predictions as there is no way of validating the predictions to the measured data which only records the combined sources of sediment. The numerical model will result in a uniform distribution of sediment on the seabed in each cell where sediment is placed as a result of the placement activity and as such it is likely that a large proportion of the seabed in EBSDS would be covered by placed sediment in the model. In reality, there would be an area in the order of 1,000 m^2 with a thicker layer of placed sediment and a much thinner layer further away from this. Therefore, the 141 loads of sediment which were placed at EBSDS during the 2018 maintenance dredging campaign would likely have resulted in thicker layers of placed sediment in 100,000 to 200,000 m^2 of EBSDS, which represents between 1 and 2% of the total area of EBSDS (10.4 Mm^2). In addition, the model setup does not include processes such as bed armouring or consolidation of sediment which would both act to increase the erosion threshold of the sediment and therefore reduce resuspension rates.

Figure 9. Regional scale polygons used to export results from the numerical model to inform the sediment budget.

Figure 10. Inner Harbour intertidal area used to export results from the numerical model to inform the sediment budget.

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Figure 11. Transects used to export results from the numerical model to inform the sediment budget.

Figure 12. Close up of Inner Harbour transects used to export results from the numerical model to inform the sediment budget.

3.3. Natural Conditions

This section provides an overview of the model results for the natural sediment transport in the PoG region which are relevant for the development of the quantitative sediment budget. Results for the regional polygons over the three different years that were modelled are shown in Table 3, and results for the transects are shown in Table 4 (the 2018/19 year is not shown as the results were between the 2012/13 and 2014/15 years). Details as to how the different parameters presented in the tables were calculated are provided below:

- Cumulative mass in suspension: this has been calculated as the cumulative increase in total mass of sediment in suspension within the polygon over the model simulation period;
- Mass resuspended: this has been calculated as the cumulative mass of sediment resuspended from the seabed over the model simulation period. It is important to note that this value will always be lower than the cumulative mass in suspension as the sediment which remains in suspension and is transported around the region can repeatedly be included in the cumulative mass in suspension if it results in an increase in suspended sediment in the region, while the mass resuspended is a direct measure of the total mass of sediment eroded from the seabed in the polygon;
- Change in mass: this is the net residual change in mass of sediment in the polygon (including both sediment in suspension and sediment on the seabed) at the end of the model simulation period. This provides an indication as to whether the region is a source (reduction) or sink (increase) of sediment;
- Gross flux: this is the total mass of sediment which has been transported across the transect (regardless of direction) over the model simulation period; and
- Net flux: this is the net residual transport of sediment across the transect, calculated as a cumulative transport over the entire model simulation period. The direction of a positive net residual flux is detailed in Table 4 to allow the net direction to be determined.

Table 3. Summary of regional scale natural sediment budget results from the numerical model.

Parameter	Inner Harbour	Outer Harbour GBRMP	Outer EBSDS	Outer Harbour	Whole Region
2012/13 Annual Sediment Budget (t)					
Cumulative Mass in Suspension	5,410,000	4,420,000	550,000	35,390,000	40,800,000
Mass Resuspended	2,950,000	2,190,000	130,000	23,230,000	26,180,000
Change in Mass	390,000	130,000	-20,000	540,000	930,000
2014/15 Annual Sediment Budget (t)					
Cumulative Mass in Suspension	2,420,000	3,210,000	300,000	24,180,000	26,600,000
Mass Resuspended	1,190,000	1,200,000	60,000	14,840,000	16,030,000
Change in Mass	50,000	-20,000	-10,000	-70,000	-20,000
2018/19 Annual Sediment Budget (t)					
Cumulative Mass in Suspension	2,440,000	3,070,000	270,000	28,340,000	30,780,000
Mass Resuspended	1,550,000	1,330,000	70,000	16,270,000	17,820,000
Change in Mass	-70,000	-130,000	-30,000	490,000	420,000

The results from the regional scale polygons can be interpreted in terms of the natural sediment budget as follows:

- the cumulative mass of sediment in suspension per year for the whole region (offshore to the -30 m LAT contour) ranges from 25 to 40 million tonnes, with the majority of this occurring in the Outer Harbour region (24 to 35 million tonnes). The total mass of sediment resuspended within the whole region varies from 16 to 26 million tonnes (again with the majority of this occurring in the Outer Harbour region), suggesting that some of the sediment is remaining in suspension for long periods. It is important to consider that as part of the model calibration it was noted that the model typically overestimates the turbidity around EBSDS (by a factor of two to four) and underestimates the turbidity in the Inner Harbour (by a factor of two to four). As a result, the Outer Harbour masses presented in Table 3 are likely to be overpredictions and could be between two and four times lower, while the Inner Harbour masses are likely to be underpredictions and could be between two and four times higher;
- the cumulative mass of sediment in suspension per year for the Inner Harbour is estimated to range from 2.4 to 5.4 million tonnes (based on the model underprediction this is likely to range from 4.8 to 21.6 million tonnes), while the annual local resuspension in the Inner Harbour is estimated to range from 1.2 to 3 million tonnes (based on the model underprediction this is likely to range from 2.4 to 12 million tonnes (average = 7.2 million tonnes)). The annual mass of sediment estimated to be resuspended within the Inner Harbour was previously estimated to be 8.7 million tonnes based on measured turbidity data (BMT, 2018). This value fits within the range of values predicted by the modelling which gives confidence that the numerical model is able to provide information for the quantitative sediment budget;
- for the entire Outer Harbour area, the cumulative mass of sediment in suspension per year is estimated to range from 24.2 to 35.4 million tonnes (based on the model overprediction this is likely to range from 6.1 to 17.7 million tonnes), while the local resuspension is estimated to range from 14.8 to 23.2 million tonnes (based on the model overprediction this is likely to range from 3.7 to 11.6 million tonnes (average = 7.7 million tonnes)). The annual mass of sediment estimated to be resuspended in the Outer Harbour was previously estimated to be 6.7 million tonnes based on measured turbidity data (BMT, 2018). This value fits within the range of values predicted by the modelling which gives confidence that the numerical model is able to provide information for the quantitative sediment budget;
- for the Outer Harbour area which is not in the GBRMP, the cumulative mass of sediment in suspension per year is estimated to range from 3 to 4.4 million tonnes (based on the model overprediction this is likely to range from 0.8 to 2.2 million tonnes), while the local resuspension is estimated to range from 1.2 to 2.2 million tonnes (based on the model overprediction this is likely to range from 0.3 to 1.1 million tonnes);
- the cumulative mass of sediment in suspension per year within EBSDS is predicted to vary between 270,000 and 550,000 tonnes (based on the model overprediction this is likely to range from 70,000 to 225,000 tonnes), with between 60,000 and 130,000 tonnes of sediment locally resuspended per year (based on the model overprediction this is likely to range from 15,000 to 65,000 tonnes); and
- the overall change in mass of sediment for the regions are variable, with the EBSDS region being the only area to show a consistent change over the three years, with a small reduction in mass occurring. This could be due to the varying metocean conditions influencing whether the mass of sediment in a region increased or decreased as well as possible limitations with the model related to the complexities of the processes being modelled.

Table 4. Summary of transect natural sediment budget results from the numerical model.

Transect	+ve Net Flux Direction	2012/13 Annual Flux (t)		2014/15 Annual Flux (t)	
		Gross	Net	Gross	Net
South Entrance	North-west	9,510,000	410,000	4,250,000	90,000
North Entrance	North	680,000	160,000	470,000	40,000
Narrows	North	1,010,000	-30,000	260,000	-30,000
Auckland Channel	North-west	6,840,000	350,000	2,630,000	80,000
BarneyPt_MidBank	North-west	2,920,000	-120,000	940,000	-50,000
QuoinIs_MidBank	North-west	1,610,000	280,000	580,000	90,000
Clinton Wharves	North-west	2,680,000	120,000	840,000	20,000
TideIs_MudIs	North-west	2,410,000	-20,000	720,000	-20,000
Fishermans Landing	North	1,180,000	60,000	290,000	-10,000
Jacobs Channel	North	500,000	-10,000	140,000	-10,000
Narrows	North	1,010,000	-30,000	260,000	-30,000
Grahams Creek	West	140,000	10,000	50,000	10,000
Narrows2	North	160,000	-20,000	50,000	-10,000
Narrows3	North	10,000	0	0	0
Narrows4	North	110,000	0	60,000	0
North Channel	North	130,000	50,000	50,000	10,000
Facing Channel	North	550,000	160,000	200,000	40,000
Bustard Head	North	13,100,000	6,630,000	9,150,000	2,610,000
Rodds Peninsula	North-west	26,430,000	7,890,000	19,440,000	2,040,000
Hummock Hill	North-west	30,060,000	11,570,000	24,550,000	2,980,000
GBRMP_E	North-west	9,760,000	2,650,000	6,860,000	670,000
GBRMP_W	North-west	1,780,000	1,440,000	850,000	430,000
GBRMP_N	North	2,450,000	930,000	1,970,000	180,000
GBRMP_Combined	Into GBRMP	11,620,000	50,000	8,730,000	-60,000
Facing Isand	North-west	25,690,000	16,370,000	19,440,000	5,120,000
Curtis Isand	North-west	27,060,000	16,790,000	17,170,000	5,100,000

The results from the transects can be interpreted in terms of the natural sediment budget as follows:

- there is a net northerly flux of fine-grained sediment (fine-grained sand and finer) in the Gladstone region, with the flux varying depending on the metocean conditions. Based on the model simulations undertaken the annual net flux varies from 2.6 to 6.6 million tonnes at Bustard Head (i.e. the input of sediment to the PoG region). The annual net transport of sediment north at Facing and Curtis Islands ranges from 5.1 to 16.4 million tonnes. This is greater than the transport at Bustard Head and this is likely to be related to the deeper water at Bustard Head resulting in less potential for sediment transport across the transect (Bustard Head transect is 10 km in length to extend to the -30 m LAT depth contour, with 17% of the transect being shallower than -20 m LAT, while the Curtis Island and Facing Island transects are 26 and 29 km with both transects having 37% of the length shallower than -20 m LAT.). Although the numerical model was found to overestimate the turbidity in the Outer Harbour region (by a factor of two to four), it was also found to underestimate the net flux from the Outer Harbour region to the Inner Harbour region (by a factor of five). Based on this it must be noted that there is some uncertainty related to the modelled net fluxes through the transects. However, given the information available (including the variability in the scaling of the entrance transects), no scaling of the other transects has been adopted;

- there is gross annual flux of sediment across the GBRMP boundaries around the southern entrance to the Inner Harbour of between 8.7 and 11.6 million tonnes, with the model predicting relatively small net residual transport across the boundaries.
- results from the GBRMP_E transect and the Hummock Hill transect can be compared to provide an estimate of the transport which occurs in the nearshore to mid region (out to the -20 m LAT contour which is approximately 17 km from the shore) and the transport which occurs in the mid to offshore region (from -20 m LAT to -30 m LAT, which extends from 17 km to 34 km from the shore). The results show that both the gross and net flux of sediment in the nearshore to mid region is between 20 and 30% of the transport in the mid to offshore region. This shows that between 70 and 80% of the net residual transport of fine-grained sediment in the region occurs too far offshore to be transported into the Inner Harbour;
- while noting the uncertainties in the modelled net flux predictions at the entrances to the Inner Harbour (see Section 3.2), the fact that the trends in net flux predictions largely agree with the findings of the data interpretation provides additional confidence in the overall findings. The results from the data interpretation (PCS, 2019a) and the numerical modelling (BMT, 2019a) show that there is a net import of sediment through the South Entrance and through the Narrows while there is a net export of sediment through the North Entrance. There are differences in the net transport rates, although when the scaling factors which were presented in Section 3.2 are applied the rates are generally comparable. For the South Entrance the numerical modelling predicted a net annual import of 90,000 to 410,000 tonnes, which becomes 450,000 to 2 million tonnes when the underestimation scaling factor of 5 is applied which compares well with the estimation of a net annual import of 660,000 tonnes predicted as part of the data interpretation study for a typical year. For the North Entrance the numerical modelling predicted a net annual export of 40,000 to 160,000 tonnes, which becomes 10,000 to 40,000 tonnes when the overestimation scaling factor of 2 is applied which compares well with the estimation of a net annual export of 13,000 tonnes predicted as part of the data interpretation study for a typical year. For the Narrows the numerical modelling predicted a net annual import of 30,000 tonnes, which becomes 60,000 tonnes when the underestimation scaling factor of 2 is applied which results in an overestimation of the net flux when compared with the estimation of a net annual import of 25,000 tonnes predicted as part of the data interpretation study for a typical year (i.e. based on the discrepancy between the values it can be assumed that the annual net import of sediment through the Narrows could be between 25,000 and 60,000 tonnes). Based on the scaled model results the net balance of sediment fluxes through the entrances to the Inner Harbour are predicted to range from a net annual input of 500,000 tonnes during typical conditions to a net annual input of 2.1 million tonnes during a year with an extreme wet season. However, it is important to note that the scaling factor was determined based on typical conditions and it is possible that the scaling factor would be different during energetic periods. Consequently, there is uncertainty related to the prediction of the extreme wet season year;
- the net sediment transport patterns within the Inner Harbour are complex, with localised processes influencing the net residual transport directions. The transects across Facing Channel and the channel between Quoin Island and Middle Bank (QuoinIs_MidBank) both show a net north-westerly flux of sediment, with the net flux being approximately twice as high through the Quoin Island and Middle Bank channel compared to the Facing Channel. In contrast, there is net south-easterly flux of sediment through the Barney Point to Middle Bank transect equivalent to approximately half of the north-westerly flux through the Quoin Island to Middle Bank channel. There is limited net transport upstream of the Tide Island to Mud Island transect, with the gross transport remaining relatively high but with low net transport in these regions. It is interesting to note that the gross sediment transport through the channel adjacent to Fishermans Landing is approximately

double the transport through the Jacobs Channel. The North Channel transect shows a consistent net northerly transport direction which corresponds to the net transport at the Facing Channel and the Northern Entrance; and

- the results suggest that there is a tidal divide in the Narrows close to the Narrows3 transect. At this location the model predicts very little gross flux of sediment and no net transport which suggests that this is a point with relatively low tidal current speeds and limited sediment transport.

The predicted annual mass of sediment resuspended and the relative change in mass of sediment in the polygon for two of the years simulated are shown in Table 5 for the intertidal polygons and the Marina and West Banks regions. The results show that natural resuspension of the seabed occurs in all the regions, with the lowest rates being in the Marina which is sheltered from wind waves and experiences very low tidal current speeds. The prediction that resuspension of sediment occurs in all the intertidal regions is in agreement with the findings of the sediment sources study, where recently deposited sediment in the navigation channels were found to have likely come from the intertidal regions.

The results show that the Marina is the only region which the model predicts would have a net increase in sediment over both years, although the annual sedimentation is significantly lower than the annual rate of 44,000 tonnes calculated through analysis of the bathymetric data (PCS, 2018c). For a sheltered environment such as the Inner Harbour, it would be expected that the intertidal areas would act as a sediment sink and would therefore typically have a net increase in sediment mass. Therefore, the model appears to underestimate the natural deposition which occurs on the intertidal regions, this could be related to the complex processes which influence the sediment transport in these regions during the flooding and drying stages of the intertidal regions and the model underprediction of turbidity within the Inner Harbour.

Table 5. Summary of intertidal natural sediment budget results from the numerical model.

Region	2012/13 Mass Balance (t)		2014/15 Mass Balance (t)	
	Resuspended	Change	Resuspended	Change
Intertidal1	37,000	-15,000	14,000	-4,000
Intertidal2	117,000	-42,000	55,000	-4,000
Intertidal3	77,000	-25,000	26,000	1,000
Intertidal4	118,000	-63,000	61,000	-37,000
Intertidal5	80,000	-1,000	37,000	-4,000
Intertidal6	14,000	-7,000	4,000	-2,000
Intertidal7	53,000	-25,000	9,000	1,000
Intertidal8	23,000	-16,000	3,000	0
Intertidal9	19,000	-8,000	5,000	-1,000
Intertidal10	275,000	-80,000	44,000	-6,000
Intertidal11	12,000	-6,000	4,000	-1,000
Intertidal12	19,000	-9,000	7,000	-4,000
Intertidal13	63,000	-18,000	7,000	3,000
Intertidal14	68,000	-42,000	28,000	-18,000
Marina	1,000	8,000	0	2,000
WestBanks	164,000	-31,000	88,000	-16,000

3.4. Maintenance Dredging

The numerical model was setup so that sediment suspended by the dredging and placement activities as well as sediment which settled directly to the seabed at EBSDS during placement were included separately to the natural sediment in the model. Therefore, the results from the numerical model can be used to predict how the sediment resuspended and relocated by maintenance dredging behaves and its relative contribution to the overall sediment budget. However, it is also important to consider the limitations of the numerical model, specifically the uncertainty relating to the natural resuspension of placed sediment at EBSDS (see Section 3.2).

The numerical model simulations were setup to include the maintenance dredging campaign undertaken from November to December 2018. For the campaign the dredging was undertaken by the TSHD *Brisbane* and the maintenance dredging activity and placement at EBSDS was included in the model based on the dredge logs from the TSHD Brisbane. A summary of the mass of sediment released into the model due to the maintenance dredging is provided below:

- November to December 2018:
  - Draghead and Propeller Wash Disturbance = 1,200 tonnes (approximately 70% in the Inner Harbour and 30% in the Outer Harbour);
  - Overflow = 38,400 tonnes (approximately 70% in the Inner Harbour and 30% in the Outer Harbour);
  - Plume from placement = 24,500 tonnes;
  - Seabed from placement = 207,800 tonnes; and
  - Total mass = 271,900 tonnes.

The change in mass and the percentage that represents of the total mass of sediment released due to the maintenance dredging at the end of the model simulation (2.5 months after end of dredging) at a regional scale are shown in Table 6. The results predict that 66% of the sediment suspended and relocated from the maintenance dredging activity and placement is retained within the region, with 34% transported away from the region. However, it is important to consider the limitations of the numerical model in predicting the resuspension of dredged sediment placed at EBSDS, with the model likely to overpredict the resuspension, this is discussed further in Section 3.2. In addition, the predicted percentage of sediment lost is likely to be higher for the 2018 campaign compared to a typical campaign, due to the high energy wind and wave conditions which occurred during the end of the maintenance dredging campaign and continued for much of the following 2.5 months. The results also show that of the sediment predicted to be retained within the region the majority of this is within EBSDS, with little sediment being retained within the local region of the GBRMP. The model predicts that just over 10% of the sediment is retained within the Inner Harbour, suggesting that the majority of sediment released by the dredging activity (i.e. the draghead and overflow) in the Inner Harbour is retained and during certain metocean conditions (calmer wind and wave conditions) some of the sediment from the placement at EBSDS can also be transported into the Inner Harbour.

Table 6. Summary of regional scale maintenance dredging results from the numerical model.

Parameter	Inner Harbour	Outer Harbour GBRMP	Outer EBSDS	Outer Harbour	Whole Region
2018 Maintenance Dredging					
Change in Mass (t)	30,000	150,000	140,000	150,000	180,000
% Dredged Sediment	11%[1]	55%	51%[2]	55%	66%

[1] this represents approximately 75% of the sediment released into the Inner Harbour by maintenance dredging activities.

[2] this represents approximately 60% of the sediment placed at EBSDS.

The net flux of the sediment from maintenance dredging is shown for all of the transects in Table 7 and the change in sediment mass is shown for the intertidal areas in Table 8. The results show the following:

- there was a net import of maintenance dredge sediment through the South Entrance to the Inner Harbour with 2,000 tonnes of sediment predicted to be imported;
- of the maintenance dredge sediment which was retained within the Inner Harbour, the model predicts that 2,900 tonnes is transported to the intertidal regions. This represents 11% of the maintenance dredge sediment retained within the Inner Harbour. The region where the largest mass of sediment was transported to was Intertidal region 10, which is the intertidal area between the Calliope River mouth and Fisherman's Landing. This suggests that the fine-grained sediment resuspended by activities associated with maintenance dredging campaigns (due to the draghead, propeller wash and overflow during dredging as well as subsequent bed levelling activity) within the Inner Harbour act as a form of sustainable relocation, releasing sediment which can subsequently be transported to other natural environments where ongoing sedimentation occurs. The sustainable relocation of fine-grained sediment from the LNG region of the Inner Harbour was one of the preferred approaches considered as part of the PoG Reduce Assessment (PCS, 2019b);
- the model predicts a net northerly transport of maintenance dredge sediment due to the consistent strong easterly winds and large easterly waves over the period following the maintenance dredging; and
- the model predicts that over the six month model simulation period a net flux of approximately 1,200,000 tonnes of natural sediment was transported into the GBRMP through the west and north sections of the GBRMP boundary adjacent to EBSDS, while the net flux of maintenance dredge sediment was predicted to be 78,000 tonnes. It is important to consider the limitations of the numerical model in predicting the resuspension of dredged sediment placed at EBSDS, with the model likely to overpredict the resuspension, this is discussed further in Section 3.2. The natural and maintenance dredge sediment which was transported into the GBRMP was subsequently transported north past Facing Island and Curtis Island and it is expected that the sediment would continue to be transported north until it reached a location sheltered from the dominant south-easterly wind and wave conditions (e.g. some of the north facing creeks and inlets on Curtis Island or the extensive intertidal regions in the Fitzroy estuary).

Table 7. Summary of transect natural and maintenance dredging results from the numerical model for the 2018/19 model simulation (six month duration).

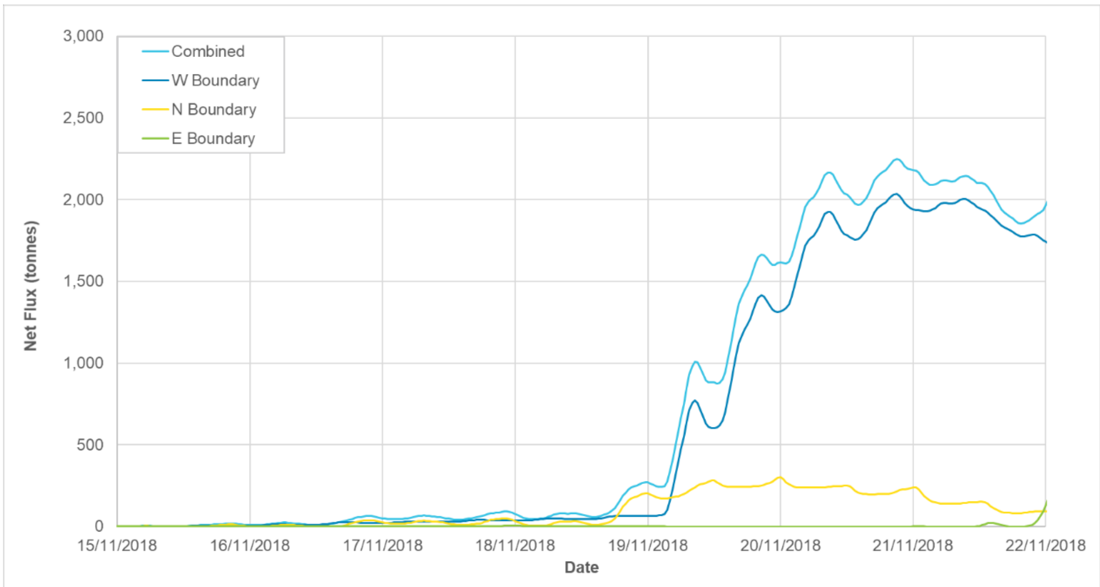
Transect	+ve Net Flux Direction	Natural Net Flux (t)	Maintenance Dredging Net Flux (t)
South Entrance	North-west	20,000	2,000
North Entrance	North	-10,000	1,000
Narrows	North	10,000	1,000
Auckland Channel	North-west	40,000	0
BarneyPt_MidBank	North-west	-60,000	-8,000
QuoinIs_MidBank	North-west	80,000	5,000
Clinton Wharves	North-west	10,000	-1,000
TideIs_MudIs	North-west	-40,000	-3,000
Fishermans Landing	North	-10,000	1,000
Jacobs Channel	North	-20,000	-1,000
Narrows	North	-20,000	1,000
Grahams Creek	West	10,000	0

Transect	+ve Net Flux Direction	Natural Net Flux (t)	Maintenance Dredging Net Flux (t)
Narrows2	North	-10,000	0
Narrows3	North	-10,000	0
Narrows4	North	10,000	0
North Channel	North	20,000	0
Facing Channel	North	50,000	0
Bustard Head	North	4,530,000	0
Rodds Peninsula	North-west	5,320,000	0
Hummock Hill	North-west	8,280,000	1,000
GBRMP_E	North-west	1,070,000	0
GBRMP_W	North-west	520,000	65,000
GBRMP_N	North	670,000	13,000
GBRMP_Combined	Into GBRMP	-110,000	-78,000
Facing Island	North-west	11,550,000	81,000
Curtis Island	North-west	10,920,000	81,000

Table 8. Summary of intertidal maintenance dredging results from the numerical model.

Region	2018 Maintenance Dredging	
	Change (t)	% Sediment in Inner Harbour
Intertidal1	0	0%
Intertidal2	200	1%
Intertidal3	200	1%
Intertidal4	0	0%
Intertidal5	100	0%
Intertidal6	0	0%
Intertidal7	100	0%
Intertidal8	100	0%
Intertidal9	200	1%
Intertidal10	900	3%
Intertidal11	300	1%
Intertidal12	100	0%
Intertidal13	300	1%
Intertidal14	100	0%
Marina	200	1%
WestBanks	100	0%
Total	**2,900**	**11%**

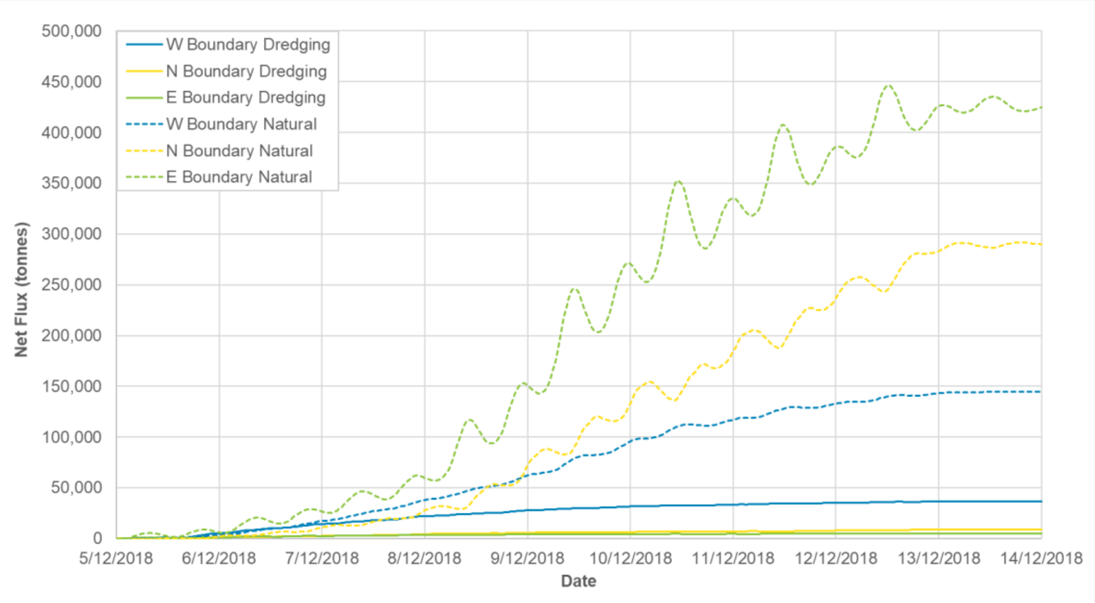
As part of the sediment movement data interpretation study it was noted that during certain metocean conditions (strong winds (20 knots) and moderate wave conditions (H_s 1 – 1.5 m)) the plume generated by the placement of sediment at EBSDS could be seen to be transported into the GBRMP. These conditions only occurred for a single day of the 2018 maintenance dredging campaign (the 19th November 2018). The numerical model was validated to the measured in-situ turbidity data and satellite imagery during this period which provides additional confidence in the numerical modelling results. Results of the net flux of maintenance dredge sediment across the transects located at the GBRMP boundaries adjacent to EBSDS from the numerical model are shown in Figure 13. The figure shows that the majority of the transport occurred through the western GBRMP boundary and that a peak of just over 2,000 tonnes of sediment was transported into the GBRMP. This mass is greater than the amount of sediment that would have been suspended by the primary plume which develops during placement, showing that the model is predicting that some of the bed sediment placed is also transported.



Note: a positive net flux represents transport in a north-westerly direction.

Figure 13. Modelled net flux of maintenance dredge sediment through the GBRMP boundaries adjacent to EBSDS.

The sediment movement and data interpretation study also noted that it was not possible to determine the relative contribution of maintenance dredge sediment to the sediment resuspended during natural wind/wave events during and immediately after maintenance dredging. The modelled cumulative net fluxes of sediment through the three GBRMP boundaries adjacent to EBSDS are shown in Figure 14 for both natural and maintenance dredge sediment over the duration of a wind/wave event during the 2018 maintenance dredging campaign. The natural cumulative net flux of sediment transported through all the boundaries at the end of the wind/wave event is approximately 20 times greater than the cumulative net flux of maintenance dredge sediment through the boundaries. This suggests that over the duration of a wave event the maintenance dredge sediment has the potential to increase the fluxes through each of the GBRMP boundaries by approximately 5%. The cumulative mass of natural and dredged sediment transported into the GBRMP through the three boundaries over the 2018 maintenance dredging campaign and the following six weeks is shown in Figure 15. The plot shows that over the first three weeks of the campaign, which are characterised by relatively calm metocean conditions, the cumulative flux of natural sediment transported into the GBRMP was approximately three times higher than that of the sediment from maintenance dredging. When the natural wind/wave events occur the cumulative flux of natural sediment becomes more than an order of magnitude greater than the cumulative flux of sediment from maintenance dredging. The combined natural net flux of sediment into the GBRMP six weeks after the end of the maintenance dredge campaign (after approximately 10 weeks in total) are approximately 20 times greater than the combined net flux of maintenance dredge sediment through the boundaries, suggesting that the sediment from maintenance dredging can potentially increase the cumulative net flux into the GBRMP by approximately 5% over the maintenance dredging campaign and six weeks after. Although there are limitations associated with the numerical modelling related to these predictions, with the limitations most likely resulting in the model overpredicting the relative contribution from maintenance dredging, the results can be used to provide an indication of the upper limit of the resuspension of maintenance dredge sediment from EBSDS and its relative contribution to the overall sediment transport during a natural wind/wave resuspension event.



Note: a positive net flux represents transport in a north-westerly direction.

Figure 14. Modelled net flux of natural and maintenance dredge sediment through the GBRMP boundaries adjacent to EBSDS during a natural wind-wave resuspension event.

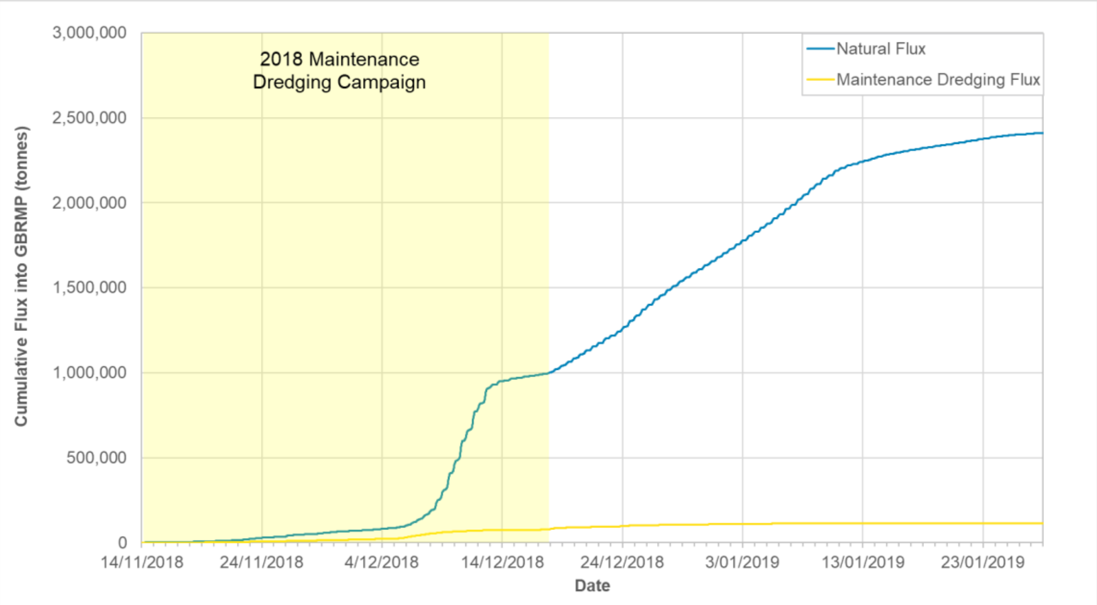


Figure 15. Modelled cumulative flux of natural and maintenance dredge sediment into the GBRMP during the 2018 maintenance dredging campaign and over the following six weeks.

4. Natural Sediment Transport

4.1. Introduction

This section provides a summary of the sediment properties, high-level assessments of the sinks and sources of sediment in the PoG and a summary of the natural sediment transport processes which occur in the PoG. The information is based on the findings of the previous SSM Projects as well as other relevant available information.

4.2. Sediment Characteristics

The variability in the physical characteristics of the sediment on the surface of the seabed in the PoG is clearly shown in Figure 4. The sediment composition is discussed for the Outer and Inner Harbour regions of the PoG below:

- Outer Harbour: this region is predominantly made up of sand, with some sandy silt/clayey sand and gravelly sediment also present. The surface sediment present at EBSDS is similar to the sediment in the adjacent areas, with it being predominantly sand with some clayey/silty sand and gravelly sand; and
- Inner Harbour: this region is made up of a range of sediment types, from gravelly sediment to silty clay. The gravelly sediment is typically located within the main channels (Clinton, Auckland and Gatcombe Channels) where high current speeds occur. There is more finer-grained silt and clay present in the Western Basin region and along the landward edges of the estuary where shallow intertidal and subtidal mudflats and mangroves have developed.

Targeted sediment sampling undertaken in the regions of the PoG where regular sedimentation has required ongoing maintenance dredging to be undertaken has shown the following:

- the sediment in the Golding and Wild Cattle Cuttings were similar, with the sediment being predominantly sand sized (70 to 85%) with some silt and clay (only a trace of clay in the Wild Cattle Cutting);
- the sediment in the Auckland and Clinton Channels consisted of the coarsest sediment, with predominantly sand sized sediment (>90%) with some gravel present. The relatively coarse nature of the sediment in these areas suggests that the sedimentation which has occurred is a result bedform growth and migration as opposed to sedimentation of new sediment; and
- the sediment in the Marina and Western Basin region (Jacobs Channel and Fishermans Landing) was similar, with it consisting of predominantly clay and silt sized sediment (>95%).

4.3. Sediment Transport

The natural conditions in the Inner and Outer Harbour regions are different and as a result the drivers for the resuspension and transport of sediment are also different. A summary of the dominant sediment transport processes which occur in the two regions is provided below:

- Inner Harbour: 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 (i.e. intertidal mudflats). It is likely that fine-grained sediment within the Inner Harbour is regularly mobilised, transported and redeposited until it is transported to a sheltered sediment sink where ongoing sedimentation occurs or until it is transported 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. 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 currents (both tidal and wind generated). The wave action is the dominant process for resuspending sediment in the Outer Harbour, with widespread resuspension occurring in the region when the Gladstone WRB measures an H_s of more than 1.5 m. The tidal and wind generated currents are the dominant processes for transporting the suspended sediment, with a net northerly transport dominating due to the dominant south-easterly trade winds. The majority of the Outer Harbour region is an ebb tidal delta which has developed over time at the southern entrance of the Inner Harbour. 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). Due to the influence of the offshore wave action limiting the deposition of fine-grained sediment, the majority of the sediment which has accumulated is sand.

4.4. Sediment Sinks

Based on the findings from the previous investigations the following are considered to be the main ongoing sediment sinks in the PoG which are relevant to the PoG quantitative sediment budget:

- Intertidal Areas: the sediment sources investigation suggested that the intertidal areas within the Inner Harbour of the PoG are important sources of fine-grained sediment for the region. However, for these environments to exist during a period with sea level rise they have to act as sediment sinks, with a net accretion occurring over time. Therefore, it is likely that the majority of the intertidal areas within the Inner Harbour of the PoG are sediment sinks despite the numerical modelling predicting that the majority of these areas were subject to a net loss of sediment. Based on the detailed investigation of the intertidal areas by Connolly et al. (2006) there are approximately 17,500 hectares (excluding saltflats which are not expected to be accreting as quickly as the other intertidal areas) of intertidal wetland in the Inner Harbour of the PoG, with the majority of these being mangroves and mudflats. If it is assumed that over the next 80 years the intertidal areas will accrete at an average rate of 0.01 m/yr to keep up with the 0.8 m sea level rise predicted to occur by 2100 (IPCC, 2014; and Queensland Government, 2018) then approximately 700,000 t/yr of predominantly fine-grained sediment will be deposited in these areas (assuming a dry density of 0.4 t/m^3 to represent medium to highly consolidated sediment (Van Rijn, 1993));
- East Banks and West Banks: these shallow areas located to the north and south of the Golding Cutting represent a natural ebb bar at the southern entrance, which has the largest fluxes of water and sediment of three entrances, to the PoG Inner Harbour. Although there are no data available to clearly show ongoing sedimentation at East and West Banks and the numerical modelling predicted net erosion of sediment from the areas, data from the bathymetric analysis showed that between 2007 and 2017 accretion of 0.1 to 0.2 m had occurred along the majority of the natural seabed of the South Channel, directly to the south of the Golding Cutting. If it is assumed that average accretion of 0.1 m has occurred over both East and West Banks over a 10 year period (i.e. 0.01 m/yr) and that the sediment is predominantly sand (dry density of 1.6 t/m^3 (Soulsby, 1997)), then the average mass of sand deposited on both East and West Banks would be 600,000 t/yr;
- Dredged Area: the bathymetric analysis showed that some of the dredged areas of the PoG act as sediment sinks, with ongoing natural sedimentation resulting in channels, aprons and berths silting up. Based on the results of the analysis, including the sedimentation which occurs in the Marina and assuming that the net sedimentation which

typically occurs in the Clinton and Auckland Channels is due to bedform growth and migration as opposed to sedimentation of new sediment, the annual mass of sediment deposited in the dredged areas of the PoG has been approximately 500,000 t/yr (assuming a dry density of 1 t/m^3 to represent the fact that the sediment is a combination of fine-grained silt and clay and sand); and

- EBSDS: the annual maintenance dredging which is undertaken in the PoG removes sedimentation which has occurred above the design depths of the channels, aprons and berths. The mass of sediment removed is typically in the order of 200,000 and 300,000 m^3/yr (if a dry density of 1 t/m^3 is assumed due to the combined fine-grained and sand in the sediment, then the mass is the same as the volume) and this sediment is then placed at EBSDS. The bathymetric analysis found that over the last 10 years EBSDS had been predominantly retentive (> 95% of sediment retained), although the majority of the sediment placed there over this period was from capital dredging. However, analysis of a period with no capital dredging suggested that much of the sediment maintenance dredging was also retained. Therefore, of the 500,000 t/yr of sedimentation which occurs in the dredged areas of the PoG between 200,000 and 300,000 t/yr is placed at EBSDS with the majority of this remaining at the site.

Based on the above high-level assessment, it is estimated that approximately 1.8 million tonnes of sediment is deposited in the main sediment sinks in the PoG each year. Approximately half of this is predominantly sand-sized sediment in the Outer Harbour region and the other half predominately fine-grained. Of the sediment deposited between 10 and 15% is relocated to EBSDS where it is retained.

4.5. Sediment Sources

Based on the findings from the previous investigations, the following are considered to be the main ongoing sources of sediment to the PoG which are relevant to the PoG quantitative sediment budget:

- Natural Resuspension: the resuspension of existing natural sediment in the PoG region occurs regularly, with an estimated average 7.2 and 7.7 million tonnes per year (Mt/yr) of sediment resuspended from the Inner and Outer Harbour regions respectively (combined is approximately 15 Mt/yr). The resuspension occurs predominantly as a result of tidal currents and local wind waves in the Inner Harbour and waves and currents (tidal and wind driven) in the Outer Harbour;
- River Input: numerical modelling has predicted that the typical annual input of sediment from the Calliope and Boyne Rivers are in the order of 50,000 and 15,000 t/yr, respectively. However, analysis undertaken as part of the bathymetric analysis found that rainfall did not directly influence sedimentation in the dredged areas of the Inner Harbour, suggesting that the new sediment input from the rivers is small relative to the resuspension and transport of existing sediment due to currents and waves. The predicted input of new sediment from the Calliope and Boyne Rivers during a 100 year rainfall event is 420,000 t (see Section 2.11), while the average annual natural resuspension of existing sediment within the PoG by currents and waves has been estimated to be in the order of 15 Mt/yr. Therefore, 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 PoG is still primarily controlled by the reworking and redistribution of existing sediment in the system;
- Net Northerly Transport: there is a net northerly transport of fine-grained sediment in a 2 to 10 km wide coastal region of the Great Barrier Reef (GBR) (Larcombe & Carter, 2004). Wave conditions result in the natural resuspension of fine-grained bed sediment and the dominant south-easterly trade winds result in a residual northerly current direction, which results in the resuspended sediment being transported in a net northerly direction. Based on the numerical modelling results the natural net northerly longshore transport of fine-grained sediment in the PoG region is in the order of 3 to 12 Mt/yr. Based on the

numerical modelling results and the data interpretation assessment it is estimated that between 450,000 and 2,000,000 t/yr of the fine-grained sediment enters the Inner Harbour of the PoG through the southern entrance; and

- Longshore transport: local longshore drift of sand sized sediment due to wave breaking occurs in the Gladstone region. The longshore transport is in a net northerly direction due to the dominant wave direction from the east and the orientation of the shoreline. The configuration and bathymetry of the Outer Harbour region of the PoG suggests that the longshore transport in the Outer Harbour region is relatively low, indicating that there is a net build-up of sand sized sediment in the region. There is no direct information available to define the longshore transport rates in the Gladstone region. Based on the quantitative estimates of the sinks of sand sized sediment in the Outer Harbour of the PoG, it is likely that the input of new sand sized sediment to the Outer Harbour is at least 100,000 t/yr with the remaining input to the sinks potentially being from the reworking of existing sand sized sediment in the region.

5. Anthropogenic Impacts

5.1. Introduction

As well as the natural processes which influence sediment transport in the PoG, a number of anthropogenic activities can also influence it. This section discusses the activities which are considered to result in the largest impacts to the PoG sediment transport. High-level assessments are presented to allow the potential impacts of the anthropogenic activities to the PoG sediment transport to be quantified.

5.2. Vessel Disturbance

Vessels have the potential to disturb sediment from the seabed both directly and indirectly. Direct disturbance of the seabed can occur when activities being undertaken by the vessel result in direct contact with the seabed, while indirect disturbance of the seabed typically occurs due to the propeller wash resulting from the vessel causing high near-bed current speeds which has the potential to result in erosion of the seabed. Maintenance dredging has the potential to result in both direct and indirect disturbances to the seabed, but as this activity is a specific focus of this assessment it is discussed separately in Section 5.4.

5.2.1. Direct Disturbance

The primary regular anthropogenic activity which can result in the direct disturbance of the seabed in the PoG region is through the commercial fishing practise of trawling[4]. A previous trawling assessment of the Townsville region estimated that 63 to 94 million m^3 of sediment was disturbed by trawling per year (Morton et al., 2014), highlighting the potentially high disturbance which this activity can result in.

Commercial trawling in the Gladstone region is primarily undertaken using an otter trawl to catch prawns. It is a requirement for commercial fishers operating in the Gladstone region to complete daily catch and effort logbooks and these are then made available from the QFish database which is maintained by the Queensland Department of Agriculture and Fisheries. The data are recorded in 30 x 30 nautical mile grid cells and so can only provide an approximate location of the fishing activity. The otter trawling undertaken within grid cells S30 and T30 was used to inform the commercial fishing undertaken in the PoG region, these cells cover the majority of the Inner and Outer Harbour regions of the PoG as well as adjacent offshore areas. The total number of days that otter trawling was undertaken in the two regions was extracted from the QFish database for 2018, with 337 days undertaken in S30 and 309 days in T30.

The potential disturbance of the seabed by otter trawling was investigated by collecting bathymetric, turbidity and sediment composition measurements during and following trawling (Palanques et al., 2001). The assessment found that on average 0.02 to 0.03 m of the seabed surface was disturbed by the trawl net, which was approximately 4 m wide. It was estimated that the trawling undertaken (approximately 10 hours in total) resulted in the resuspension of approximately 3,000 tonnes of bed sediment. Of this mass, approximately 10% was found to still be in suspension four to five days after the trawling and it was assumed that the remaining 90% settled back to the seabed in the region where the trawling was undertaken.

By adopting the same assumptions as Palanques et al. (2001) in terms of erosion depth (0.02 m), erosion width (4 m) and trawl speed (3 knots) it is possible to estimate the volume of sediment resuspended by trawling in the PoG region each year. If it is assumed that between 25% and 75% of the total days that otter trawling was undertaken was active trawling time, then it can be estimated that between 1.7 million to 5.2 million m^3 of sediment per year is disturbed in the PoG region by otter trawling. Further, if it is assumed that the

[4] maintenance dredging is discussed separately.

average sediment composition where trawling was undertaken was 50% sand sized sediment and 50% silt and clay sized sediment with a dry density of 0.65 t/m^3 (based on Van Rijn (1993) and Whitehouse et al. (2000)), then the mass of sediment disturbed can be estimated to be between 1.1 and 3.4 Mt/yr. Based on the assumption that 50% of the average sediment composition is made up of sand sized sediment it is likely that this portion of sediment will settle out from suspension relatively quickly, meaning that between 0.55 and 1.7 Mt/yr suspended by otter trawling has the potential to remain in suspension long enough to be transported away from where it was released. For the purposes of the sediment budget a high level assumption that half of the trawling is undertaken in the Inner Harbour region and half in the Outer Harbour region has been adopted.

5.2.2. Indirect Disturbance

The primary regular anthropogenic activity which can result in an indirect disturbance of the seabed in the PoG region is the high near-bed current speeds resulting from vessels propellers. The region with increased currents resulting from a vessels propeller is referred to as the propeller wash. All vessels generate propeller wash, but the relative impact of the propeller wash on the seabed is dependent on the vessel characteristics (such as engine specifications, vessel draft and propeller diameter) and the local conditions (water depth and bed sediment type).

The bathymetric analysis undertaken as part of the PoG SSM Project found that erosion had occurred along the centreline of the Jacobs Channel, Golding Cutting, Boyne Cutting and Wild Cattle Cutting (PCS, 2018a). As the erosion was predominantly along the centrelines of the channels it is assumed to have been due to erosion of the seabed from the propeller wash of the large commercial vessels operating at the Port. Figure 16 provides further evidence that propeller wash erosion occurs in the Outer Cuttings as the image shows increased turbidity in the Golding, Boyne and Wild Cattle Cuttings due to the propeller wash from a Cape-sized vessel departing the Port. Figure 17 shows that propeller wash erosion also occurs in the Jacobs Channel area due to the LNG vessels navigating the channel.

The bathymetric survey data also showed that bed erosion had occurred adjacent to the berths in the tug base, indicating that localised erosion of the seabed has occurred due to the propeller wash from the tugs manoeuvring into and out of the berths. Given the relatively shallow depth of the Marina (depths generally between -3 and -4 m LAT) it is also likely that some erosion due to propeller wash also occurs here. However, due to the semi-enclosed nature of the Marina and low current speeds it is expected that the majority of the sediment would be redeposited within the Marina and not provide a potential contribution to the regional PoG sediment budget. As a result, any resuspension of sediment from propeller wash in the Marina has not been included in this assessment.

Previous field and laboratory testing have been undertaken to allow propeller wash flow velocity fields to be predicted using empirical equations (Maynord, 2000; PIANC, 2008; BAW, 2011; and de Jong, 2014). The coefficients adopted in the empirical equations were varied by Symonds et al. (2016) to determine the most suitable coefficients for the propeller wash resulting from vessel sailing and manoeuvring. The empirical approach and coefficients recommended by Symonds et al. (2016) have been adopted in this assessment. In addition, the following assumptions have been made to allow an estimation of the annual mass of sediment resuspended by the propeller wash from commercial port vessels:

- the average laden and unladen drafts of the different vessel classes which operate the Port were calculated based on vessel data provided by GPC for July 2017 to October 2018 (see Table 9). It was generally found that the unladen cargo vessels did not result in any propeller wash erosion in the Outer Cuttings due to the large difference in draft, but the LNG vessels were found to potentially result in some erosion when navigating the Jacobs Channel unladen;
- representative engine power in Horsepower (HP) and propeller sizes for the different vessel were assumed a detailed in Table 9;

- based on the findings from the previous bathymetric analysis it has been assumed that propeller wash erosion can occur along 13.2 km (all of the Wild Cattle and Boyne Cuttings and 5 km of the Golding Cutting) of the Outer Cuttings and 3 km of the Jacobs Channel;
- an average vessel speed of 12 knots has been assumed for the vessels navigating the Outer Cuttings and Jacobs Channel;
- the assessment has assumed average water levels. It has been assumed that all vessels are operating at mean sea level (2.34 m LAT) with the exception of Cape sized vessels which navigate the Outer Cuttings at mean high water neaps (3.1 m LAT) to ensure there is sufficient under keel clearance for safe navigation;
- propeller wash erosion at the tug base has been assumed to be due to the manoeuvring of the tug vessels into and out of the berths, with four separate five second duration bursts of thrust assumed to be required for this; and
- the sediment on the bed of the channel has been considered to be similar to the upper layer of the natural seabed, with a critical erosion threshold of 0.35 N/m^2 assumed for the finer-grained sediment present based on the findings of PCS (2019a). Based on Soulsby (1997) and Van Rijn (1993) this value approximately represents the threshold for the resuspension of fine sand or weak to medium consolidated silt and clay (i.e. deposited for up to one month). To understand the relative sensitivity of the assessment to this parameter, calculations were also made with the critical erosion threshold doubled to 0.7 N/m^2, which represents the resuspension threshold for fine to medium sand and medium to highly consolidated silt and clay (i.e. deposited for between one month and one year). The two thresholds are referred to as the lower erosion threshold (0.35 N/m^2) and the higher erosion threshold (0.7 N/m^2) in Table 10.

Table 9. Vessel specifications assumed for the propeller wash calculations (MAN Diesel, 2014).

Vessel Type	Unladen Draft (m)	Laden Draft (m)	Power (HP)	Propeller Diameter (m)
Cape-sized	9.7	16.6	15,000	8.5
Post Panamax	9.0	12.2	10,000	7.5
Panamax	8.7	11.2	9,000	7.0
LNG	9.4	11.1	9,000	7.0
Handy Max	8.7	10.8	8,000	6.0
Handy	7.1	8.9	5,000	5.5
Tug	4.2	4.2	2 x 2,500	2 x 2.8

Based on the propeller wash calculations it is estimated that between 10,000 and 20,000 tonnes of fine-grained sediment is resuspended each year in the Port of Gladstone due to the propeller wash of commercial Port vessels. The vast majority of the sediment resuspended occurs due to the Cape sized vessels navigating the Outer Cuttings of the Port, when fully laden due to their large draft relative to the water depth in the region and the length of the channel over which propeller wash erosion occurs. Analysis of the bathymetric data for the Golding, Boyne and Wild Cattle Cuttings shows that the average annual erosion has been 44,000 m^3 in the channels. It has been assumed that this erosion is primarily due to vessel propeller wash. However, it is more likely that the erosion will have been caused by a combination of the propeller wash causing the resuspension of fine-grained sediment and the bedload transport of coarser sand sized sediment. Over time the bedload transport of the sand sized sediment has resulted in the sediment being moved from the centre of the channel to the sides, which explains why the volumetric changes are greater than the propeller wash resuspension calculations. The propeller wash calculations are considered to be in general agreement with the bathymetric analysis, both in terms of the rates and locations.

Table 10. Assumed vessel movements and resultant mass of sediment resuspended by vessel propeller wash.

Vessel Type	Annual Vessel Movements	Mass Resuspended (tonnes/yr)	
		Lower Erosion Threshold	Higher Erosion Threshold
Cape-sized	474	14,740	9,210
Post Panamax	442	2,570	670
Panamax	465	650	300
LNG	313	1,540[2]	200[2]
Handy Max	440	400	100
Handy	473	120	-
Tug	10,424[1]	50	-
Total		**20,070**	**10,480**

[1]this is based on 2,600 commercial vessels visiting the Port each year and each vessel requiring four tugs.
[2]approximately 30% of this is in the Outer Cuttings and the remainder in the Jacobs Channel region.

Figure 16. Satellite image showing increased turbidity in the propeller wash (yellow ellipses) of a Cape-sized vessel departing the PoG through Wild Cattle Cutting (Source: EO Browser).

Figure 17. Satellite image showing increased turbidity in the propeller wash (yellow ellipse) of an LNG vessel after sailing along the Jacobs Channel (Source: EO Browser).

5.3. Urban and Industrial Inputs

There are no direct measurements or estimates available to provide an indication of the potential urban and industrial inputs of suspended sediment into the PoG. Information available from the literature has therefore been used to calculate high-level estimates of the potential contribution from runoff in urban and industrial areas. However, it has not been possible to obtain information to allow direct inputs of suspended sediment to be determined from industrial activities.

The yield of fine-grained sediment has been quantified per hectare for the different land uses of the Fitzroy NRM region, which includes the Gladstone region (Dougall et al., 2014). The yield for urban areas was the lowest of the land uses, with a yield of 0.05 t/ha/yr, while cropping had the highest yield of 0.17 t/ha/yr. The area of urban land in the Gladstone Regional Council area is approximately 1,500 hectares and the area of lower density residential use is 6,500 hectares (Queensland Treasury and Trade, 2012). If it is conservatively assumed that all of the urban and lower density residential use areas result in the direct input of sediment to the PoG then the annual input would be 400 tonnes/yr. As the urban and lower density residential areas are for the whole of the Gladstone Regional Council area, and this extends south to the Burnett River and includes towns such as Agnes Water and inland of here to areas outside of the Inner Harbour catchments, it is expected that this is an overestimation of the input of sediment from urban sources. However, the estimate can be used to provide a comparison of the input from urban sources to other inputs and to the overall sediment budget for the PoG.

The National Pollutant Inventory does not provide a measure of the total suspended solids discharged into water by industrial activities and as a result it is not possible to quantify the relative contribution of industrial activity to the input of fine-grained sediment into the PoG. The input is expected to be relatively small, with much of the input being through stormwater pond discharges. Therefore, calculating the input of sediment from direct runoff can be used to provide an indication of the potential magnitude of the contribution. The total area of industrial zoned land within the industrial precincts of the Gladstone region is approximately 500 hectares, and of this approximately 185 hectares is developed (SGS Economics & Planning, 2012). If the same yield of fine-grained sediment is assumed as for urban areas then the potential input of fine-grained sediment from developed and undeveloped industrial areas is 9 t/yr and 16 t/yr, respectively.

5.4. Maintenance Dredging

A number of activities associated with maintenance dredging result in the resuspension of sediment. These include the disturbance of the seabed by the dredgers’ draghead and propeller wash and the release of suspended sediment through overflow and the placement of dredged sediment at EBSDS. Based on the calibrated source terms applied in the numerical model (detailed in Section 3.4), the release of suspended sediment from the overflow results in a much larger release than the draghead and propeller wash.

The TSHD Brisbane ensures that the amount of sediment in its hopper is optimised by operating an overflow system. The overflow removes the excess water from the hopper as well as some fine-grained sediment in suspension at the top of the hopper. This means that a percentage of the sediment (estimated to be between 30% and 50%) which is dredged from the seabed is lost during the overflow process. Some of this sediment will remain in suspension as a plume and the remainder will be locally deposited close to the dredger (BMT WBM, 2017). The amount of sediment lost through overflowing and the subsequent fate of the sediment is dependent on the composition of the sediment being dredged and the local currents. When the sediment is predominantly fine-grained silt and clay the loss of sediment during overflow will be significantly higher than when the sediment is predominantly coarser sand and gravels (when overflow loss would be expected to be much less than 30%). In addition, there is more potential for sediment released by the overflow to be advected away by local currents when the sediment is predominantly fine-grained silt and clay as opposed to sand. As discussed in Section 3.4, some of the fine-grained sediment suspended by maintenance dredging is predicted to subsequently be transported to natural environments which require ongoing sedimentation and as such it can be considered to act as a form of sustainable relocation.

As the PoG Sea Dumping Permit requires GPC to report the in-situ cubic metres that are delivered by the dredger to EBSDS, the reported dredge volumes do not directly correlate with the in-situ volume changes calculated. There are two reasons for this discrepancy:

- because the dredge volumes placed at EBSDS do not include the volume of sediment which is removed from the seabed by the dredger and subsequently lost during overflowing when the dredger is filling its hopper; and
- the conversion factor of 1.1 tonne of dry sediment measured in the hopper of the dredger being equal to 1 m^3 in-situ volume is a PoG wide average value which will vary depending on the sediment type being dredged. The conversion factor will be lower for areas of predominantly fine-grained sediment and higher for areas of predominantly sand and gravel.

The in-situ volume of sediment removed by dredging during the 2017 maintenance dredging campaign has been compared with the volume reported as being transported by the dredger to EBSDS for the LNG Terminals region and the Outer Cuttings:

- LNG Terminals: the in-situ volume of sediment removed from this region was calculated based on the 2017 pre and post dredge bathymetric surveys as being approximately 210,000 m^3, while the in-situ volume relocated by the dredger to EBSDS was estimated based on the dry mass of sediment in the hopper of each load to be approximately 68,000 m^3. The difference between these numbers is due to a combination of sediment being lost to overflow and subsequently being transported out of the dredged areas and the fine-grained composition of the sediment meaning the PoG region wide average conversion factor is higher than the sediment present in the region (based on RHDHV & AMA (2016) a value of around 0.7 would be appropriate for this region). Based on this, it is appears that approximately 50% of the sediment dredged from the seabed in the LNG Terminals region was lost due to the suspension of sediment from the draghead, propeller wash, overflow and bed levelling and this was not subsequently re-dredged and so must have been transported out of the area by the tidal currents and redistributed in other areas. This can be considered to be a form of sustainable relocation as it keeps some of the fine-grained sediment in the Inner Harbour sediment system and is similar to the sustainable relocation approach suggested for the LNG Terminals region by PCS (2019b); and
- Outer Cuttings: the in-situ volume of sediment removed from this region was calculated based on the 2017 pre and post dredge bathymetric surveys as being approximately 55,000 m^3, while the in-situ volume relocated by the dredger to EBSDS was estimated based on the dry mass of sediment in the hopper of each load to be approximately 70,000 m^3. Due to the sediment in this region being predominantly sand it is expected that the majority of sediment lost through overflowing would be re-deposited within the channels and so the difference between these values is likely to be mainly because of the sediment being predominantly sand meaning the PoG region wide average conversion factor is lower than the sediment present in the region.

Field based monitoring of the plumes resulting from the dredging activity and the placement of the dredged sediment at EBSDS has been undertaken in the PoG during maintenance dredging. The monitoring was specifically undertaken during relatively calm wind/wave conditions and average to neap tidal ranges (< 2 m), to allow any increased turbidity resulting from the maintenance dredging to be differentiated from any natural turbidity.

The monitoring found that the plumes resulting from the dredging activity were generally transient and typically dissipated to background concentrations within 2 hours after cessation of the dredging. The measurements showed that the plumes typically were transported in the direction of the navigation channels, although they did also extend into some adjacent areas. The distance the plumes were transported varied from 500 m at the Gatcombe Channel to 3 km around the LNG Terminals.

During calm metocean conditions the monitoring showed that there was little advection of suspended sediment beyond the boundaries of EBSDS due to the placement of dredged sediment. During these conditions the plumes resulting from the placement of dredged sediment at EBSDS were typically short duration (less than 1.5 hours) and with transport distances of up to 1.5 km, indicating that the majority of the suspended sediment will be deposited within EBSDS.

During periods with increased wind/wave conditions and spring tides the monitoring showed more potential for suspended sediment to be transported outside of EBSDS as the bed stresses from the waves and tidal currents act to limit deposition of fine-grained sediment placed by the maintenance dredging and the wind can increase currents and result in a residual transport direction. Over the 33 day duration of the 2018 maintenance dredging campaign, the metocean conditions resulted in a measurable increase in turbidity outside of EBSDS due to the placement of dredged sediment on a single day. The bed shear stress resulting from the wave conditions limited the deposition of suspended sediment, while not being sufficient to result in widespread natural resuspension of sediment from the seabed within EBSDS and the adjacent areas. The strong winds influenced the currents causing a dominance in one of the tidal current directions to the west, which in turn resulted in a residual transport of the suspended sediment to the west. Satellite imagery showed that these conditions also resulted in some of the suspended sediment from the placement being transported into the GBRMP.

It was not possible to determine the contribution of recently placed dredged sediment at EBSDS to the elevated turbidity which occurred during the wind/wave events during and following the 2018 maintenance dredging program based on measured data. However, the data suggest that these events resulted in widespread resuspension of bed sediment from within EBSDS and the areas around EBSDS. Consequently, it is expected that the surface layer of sediment on the seabed within EBSDS would have been resuspended, regardless of whether this sediment had been recently placed during the 2018 maintenance dredging campaign or was existing bed sediment. Despite limitations associated with the modelling of these conditions, which are expected to result in the model overpredicting the contribution of maintenance dredging, the modelling results can be used to provide an indication of the relative contribution of maintenance dredging. The results predicted that sediment from maintenance dredging contributed to less than 5% of the sediment being transported into the GBRMP through the GBRMP boundaries adjacent to EBSDS over the duration of the maintenance dredging campaign and the six weeks immediately after. Following this period, the modelling predicted that there would be very little additional contribution to the flux of sediment through the GBRMP boundaries due to sediment from maintenance dredging placed at EBSDS.

Based on the monitoring undertaken, the impact of the placement of dredged sediment at EBSDS on turbidity, benthic light and bed level changes can be considered to be insignificant compared to the impacts resulting from natural wind/wave events. A single wind/wave event was found to result in the widespread resuspension of benthic sediment, causing much higher, longer duration and more widespread increased turbidity than a plume from the placement of dredged sediment at EBSDS. In addition, the increased turbidity associated with natural wind/wave events can also reduce the benthic light to zero for periods of weeks and result in significant fluctuations in bed level due to the resuspension and subsequent deposition.

6. Quantitative Sediment Budget

6.1. Introduction

The overall aim of this study is to develop a quantitative sediment budget to better understand the sediment transport which occurs in the PoG and what contribution maintenance dredging has to the overall system. The quantitative sediment budget aims to quantify the main sediment sources, sinks and transport pathways in the PoG, with a specific focus on the sediment suspended by maintenance dredging activity and the placement of maintenance dredge sediment at EBSDS.

To estimate the quantitative sediment budget, results from numerical modelling (detailed in Section 3) have been used along with the interpretation of measured data, in addition to the anthropogenic impacts detailed in Section 5 and findings from relevant previous studies described in Section 2. The relative contribution of maintenance dredging has been estimated based on results from the numerical modelling and interpretation of measured data.

6.2. Sediment Budget

Due to the range of potential contributions to the overall sediment budget and variability in their quantum, the values presented in the sediment budget have been rounded to the nearest 1,000, 10,000 or 100,000 tonnes. Therefore, the combined sediment budget appears to be providing an estimate which is accurate to the nearest 1,000 tonnes of sediment, but this is just to allow smaller contributions to the budget to also be captured. It is also worth noting that the level of confidence which can be placed in the estimates varies, this is noted in brackets after each input into the sediment budget as low, medium or high. Low confidence indicates that the value is a high-level estimation which is not directly based on any field measurements, medium confidence indicates that the value has been informed through field measurements or model predictions but that some uncertainty still remains and high confidence means that the value is directly based on measured or modelled data with little uncertainty. Further discussion regarding the confidence of the estimations are provided in the previous sections of the report.

Detailed quantitative sediment budgets for the Inner Harbour and Outer Harbour regions of the PoG are shown in Figure 18 and Figure 19. The sediment budget is summarised below for the Inner Harbour region in terms of the existing sediment in the system, the import and export of sediment from the system, the resuspension of sediment from the seabed and the deposition of sediment:

- Existing Sediment: the Inner Harbour region has an area of approximately 200 km^2 and if it assumed that on average there is a depth of 5 m of terrigenous sediment present (with the majority of this being highly consolidated) then the total mass of sediment present will be **more than 1 billion tonnes** (low);
- Import/Export of Sediment: **increase in sediment of 320,000 to 2,005,000 t/yr.**
  - South Entrance: import of 450,000 to 2,000,000 t/yr (medium);
  - North Entrance: export of 10,000 to 40,000 t/yr (medium);
  - The Narrows: import of 5,000 to 60,000 t/yr (medium);
  - Calliope River: import of 50,000 to 160,000 t/yr (high); and
  - Maintenance Dredging: export of 175,000 t/yr (high).
- Resuspension of Sediment: **2,731,000 to 12,831,000 t/yr.**
  - Natural Currents and Local Waves: 2,400,000 to 12,000,000 t/yr (medium);
  - Maintenance Dredging: 30,000 t/yr (medium);
  - Propeller Wash: up to 1,000 t/yr around LNG terminals (low); and
  - Otter Net Trawling: 300,000 to 800,000 t/yr (low).

- Deposition of Sediment: **1,050,000 t/yr** in the main locations where ongoing, regular sedimentation is expected to occur.
  - Within Dredged Regions: approximately 350,000 t/yr of new sediment is deposited, this excludes the sedimentation in the Clinton and Auckland Channels which is predominantly a result of the migration and growth of bedforms as opposed to the input of new sediment (high); and
  - Intertidal Areas: in order for the intertidal areas to accrete at a similar rate to predicted sea-level rise it is estimated that 700,000 t/yr of sediment is required to be deposited (low).

The quantitative sediment budget for the Inner Harbour region shows that there is a large existing supply of sediment available in the region. The suspended sediment present in the system is dominated by the natural resuspension of existing sediment in the Inner Harbour. The relative contribution of maintenance dredging to the annual mass of sediment resuspended in the Inner Harbour is low, with a contribution of 1% or less. In contrast, the mass of sediment predicted to be resuspended by otter net trawling is between 7 and 12% of the sediment naturally resuspended. Comparison of the net balance between the import/export of sediment into the Inner Harbour and the deposition of sediment within the region suggests that when the import of sediment is towards the lower mass estimated (less than 1 Mt/yr) either the deposition rates in the dredged regions or intertidal areas will be lower, or erosion will occur elsewhere in the Inner Harbour as part of the natural resuspension processes. Therefore, although the sediment budget predicts that there is generally a net gain in sediment in the Inner Harbour region of the PoG, in some years this might not be sufficient for all of the intertidal regions of the PoG to deposit at a rate comparable to projected sea level rise. It is worth noting that the numerical modelling predicted that between 10 and 30% of the sediment released by maintenance dredging activity in the Inner Harbour was subsequently transported to intertidal areas six weeks after the end of the maintenance dredging campaign.

The sediment budget is summarised below for the Outer Harbour region in terms of the existing sediment in the system, the import and export of sediment from the system, the resuspension of sediment from the seabed and the deposition of sediment:

- Existing Sediment: the Outer Harbour region adopted for this assessment has an area of approximately 1,750 km^2 and if it assumed that on average there is a depth of 5 m of terrigenous sediment present (with the majority of this being sand) then the total mass of sediment present will be **more than 10 billion tonnes** (low);
- Import/Export of Sediment: **increase in sediment of 190,000 to 435,000 t/yr.**
  - Boyne River: import of 15,000 to 260,000 t/yr (medium); and
  - Maintenance Dredging: import of 175,000 t/yr from the Inner Harbour to EBSDS (relocation of an additional 75,000 t/yr from the Outer Cuttings to EBSDS) (high).
- Resuspension of Sediment: **4,050,000 to 12,460,000 t/yr.**
  - Natural Waves and Currents: 3,700,000 to 11,600,000 t/yr (medium);
  - Maintenance Dredging: 40,000 t/yr (plumes from dredging and from placement activities) (medium);
  - Propeller Wash: 10,000 to 20,000 t/yr around LNG terminals (low); and
  - Otter Net Trawling: 300,000 to 800,000 t/yr (low).
- Flux of Sediment into GBRMP: **2,620,000 t/yr**.
  - Natural Processes: 2,500,000 tonnes over a 10 week wet season period (medium); and
  - Maintenance Dredging: 120,000 tonnes over a four week maintenance dredging campaign and the following six weeks (low).
- Deposition of Sediment: **740,000 t/yr** in the channels and at East and West Banks where ongoing, regular sedimentation is expected to occur.

- Within Dredged Regions: approximately 140,000 t/yr of new sediment is deposited in the Outer Cuttings, with an additional 50,000 t/yr of apparent deposition being due to the redistribution of existing bed sediment by propeller wash erosion (high);
- East and West Banks: based on limited bathymetric data it has been assumed that both East and West Banks are naturally accreting, with an average deposition rate estimated to be in the order of 600,000 t/yr (low); and
- East Banks Sea Disposal Site: 250,000 t/yr of sediment is relocated to EBSDS by maintenance dredging. Based on results from the numerical modelling, which are likely to overestimate the losses of sediment from EBSDS, it was estimated that approximately 60% of the sediment placed due to maintenance dredging is retained at EBSDS (medium).

The quantitative sediment budget for the Outer Harbour region shows that there is a very large existing supply of sediment available in the region. The suspended sediment present in the system is dominated by the net longshore transport of fine-grained sediment as well as the natural resuspension of existing sediment in the region. The relative contribution of maintenance dredging to the annual mass of sediment resuspended in the Outer Harbour is low, with a predicted contribution of 1% or less. In contrast, the mass of sediment resuspended by otter net trawling is predicted to be around 8% of the sediment naturally resuspended. The relative short-term (10 weeks) contribution of maintenance dredging to the sediment transported into the GBRMP is predicted to be less than 5%, and over the longer term (e.g. annual) the contribution is expected to be significantly lower. The sediment budget predicts that there is a net increase in the mass of sediment in the Outer Harbour region, but that this increase is less than the predicted deposition which occurs in the region. However, given the extent of the region, it is expected that the difference is due to the local redistribution of sediment within the region resulting in some areas of erosion and some areas of deposition.

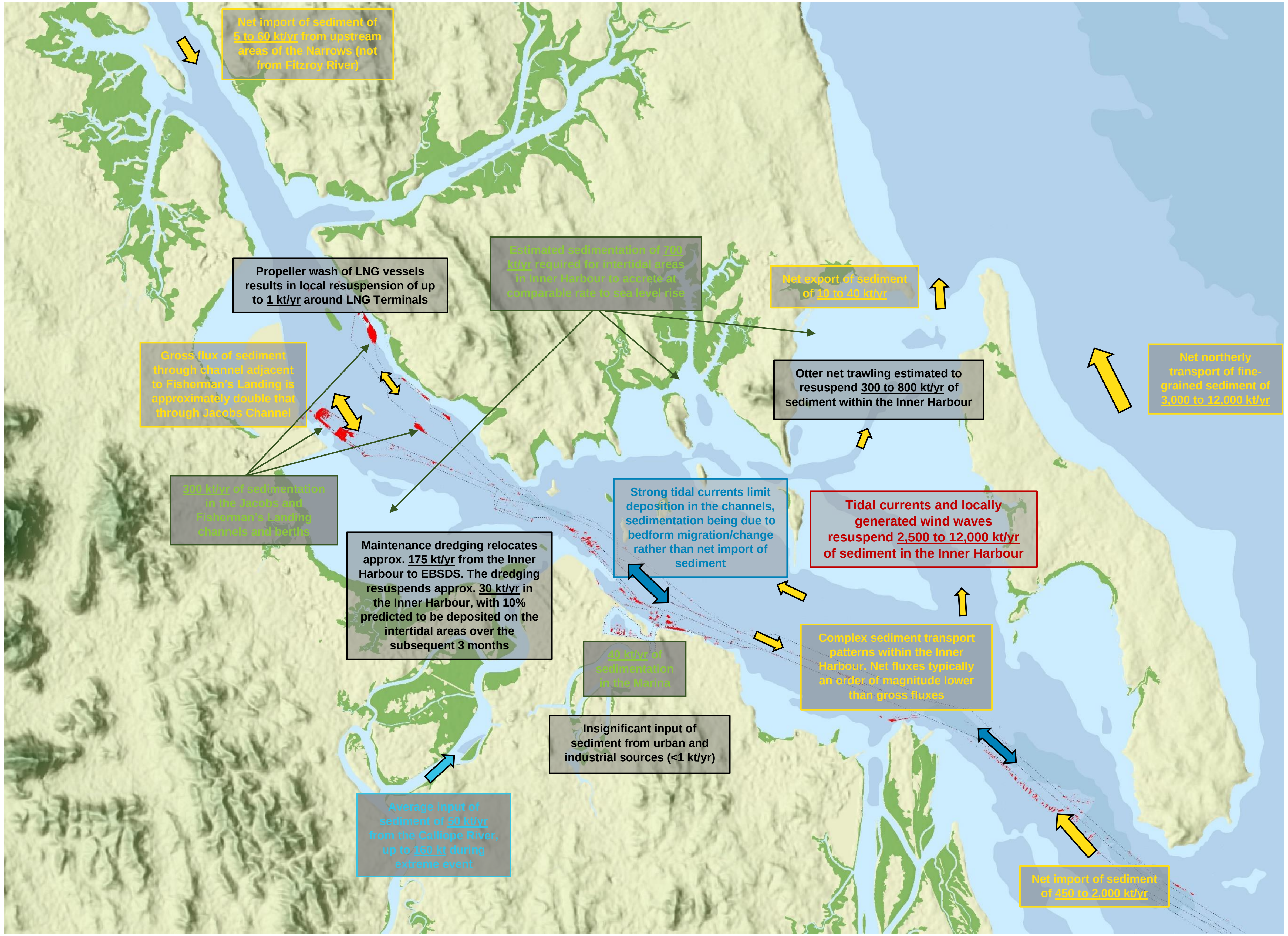
A higher-level quantitative sediment budget for the entire PoG region shown is in Figure 20. The overall sediment budget is summarised below for the entire PoG region (Inner Harbour results plus Outer Harbour results) relative to maintenance dredging in terms of the existing sediment in the system, the import and export of sediment from the system, the resuspension of sediment from the seabed and the fluxes of sediment into the GBRMP:

- Existing Sediment: the entire PoG region adopted for this assessment has an area of approximately 1,950 km^2 and if it assumed that on average there is a depth of 5 m of terrigenous sediment present (with the majority of this being sand) then the total mass of sediment present will be **more than 10 billion tonnes**;
- Import/Export of Sediment: increase in sediment of **510,000 to 2,440,000 t/yr**, with the majority of this being in the Inner Harbour region. Although the maintenance dredging results in net imports/exports for the Inner Harbour and Outer Harbour regions, it does not result in any net change in sediment for the entire PoG region;
- Resuspension of Sediment: the total resuspension of sediment from natural and anthropogenic sources is **6,781,000 to 25,291,000 t/yr**. The resuspension from the maintenance dredging and placement activities represents less than 1% of the total resuspension. In contrast, the resuspension from otter net trawling represents between 3 and 8% of the total resuspension; and
- Flux of Sediment into GBRMP: the cumulative flux of sediment into the GBRMP over a 10 week period which includes a four week maintenance dredging campaign and the following six weeks has been estimated to be **2,620,000 tonnes**. The relative contribution of sediment from maintenance dredging has been estimated to be less than 5% over this period and is likely to be significantly less over the subsequent periods.

The key findings from the quantitative sediment can be summarised as follows:

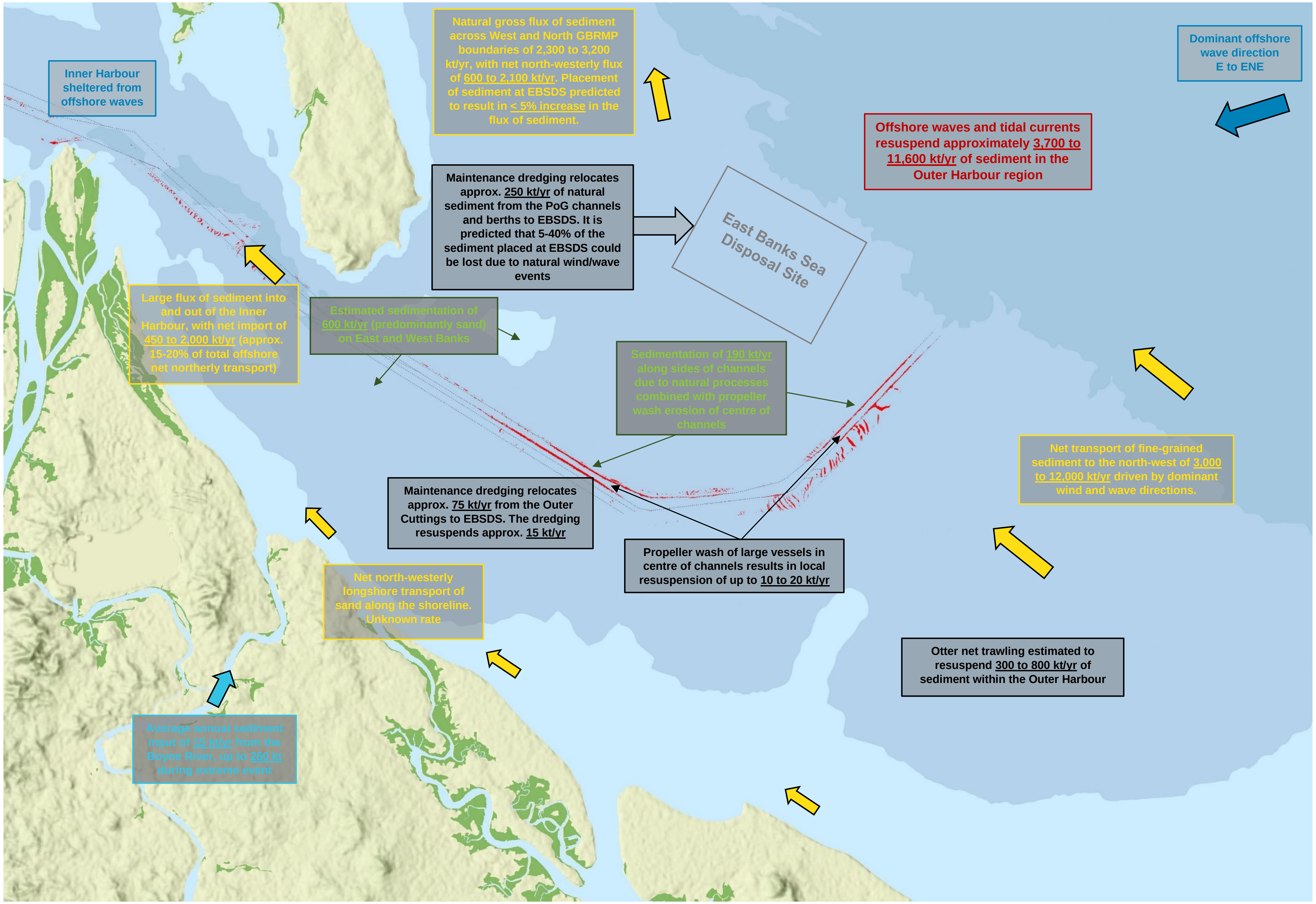
- there is a very large mass of existing sediment present in the PoG region. The sediment is likely to have built-up over geological timeframes;

- there is a natural net north-westerly transport of fine-grained sediment along the coastline due to the dominant south-easterly wind and wave conditions. Approximately 15 to 20% of this net transport of fine-grained sediment is transported into the Inner Harbour region of the PoG through the South Entrance;
- the natural resuspension of existing sediment by waves and currents is the dominant process for sediment transport in the region, as the annual mass of sediment resuspended by waves and currents is an order of magnitude greater than the input of new sediment to the system. Transported sediment is likely to be reworked multiple times (i.e. deposited during calm conditions and resuspended during more energetic conditions) until it is deposited in a location with consistently calm conditions (e.g. dredged berths and channels or mangroves);
- there is an annual net gain in sediment in the PoG region, with the majority of the increase in sediment being in the Inner Harbour due to the import of some of the suspended sediment being transported to the north-west along the coastline;
- maintenance dredging and placement activities have a negligible (<1%) contribution to the total mass of sediment resuspended in the PoG region. In contrast, it has been estimated that otter net trawling represents between 3 and 8% of the total resuspension;
- the relative contribution of sediment from maintenance dredging placed at EBSDS to the cumulative flux of sediment into the GBRMP through the boundaries adjacent to EBSDS is predicted to be less than 5% over the short-term period during and over the six weeks after the maintenance dredging campaign. After this period the contribution is expected to be significantly lower; and
- despite the annual net gain in sediment, the budget indicates that there is the potential for insufficient new sediment to be available in the Inner Harbour to balance the deposition requirements for calmer years when the net import of sediment is predicted to be lower. This could limit the natural accretion of some intertidal areas, potentially resulting in them not being able to accrete at a comparable rate to predicted future sea level rise.



Note: Red areas show where > 1m of sedimentation has occurred over 10 years.

Figure 18. Quantitative sediment budget for the Inner Harbour of the PoG.



Note: Red areas show where > 1m of sedimentation has occurred over 10 years

Figure 19. Quantitative sediment budget for the Outer Harbour of the PoG.

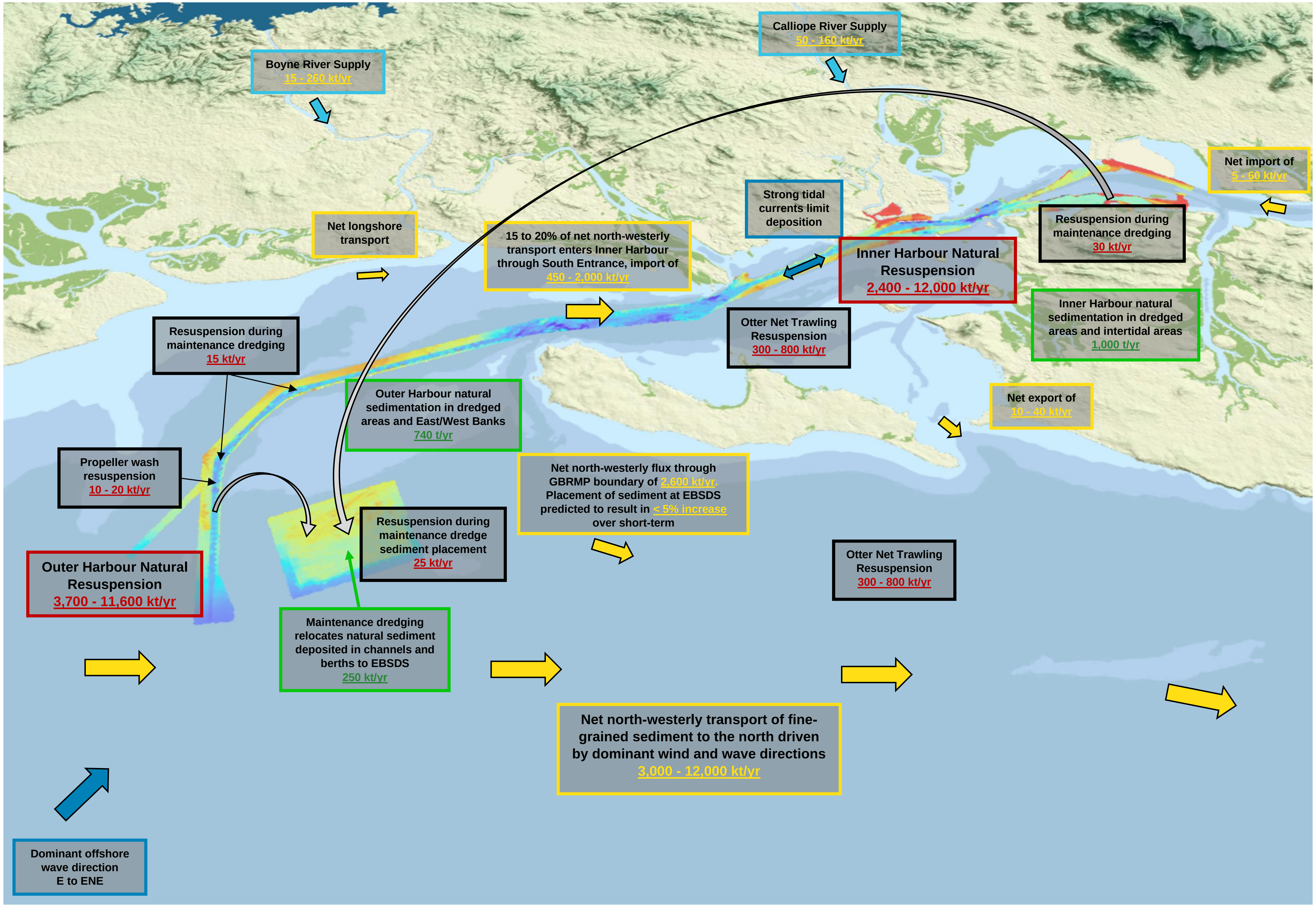


Figure 20. Quantitative sediment budget for the entire PoG region.

7. Ecological Implications

This chapter presents an ecological assessment that addresses the potential implications of maintenance dredging on the ecology of the PoG region and around the offshore dredge placement site (EBSDS).

7.1. Introduction

Dredging and disposal activities have the potential to affect the health of sensitive biological receptors (e.g. seagrasses, corals) and sensitive life stages (e.g. eggs, larvae). Dredging and disposal can cause considerable changes to the abiotic environment (sediment disturbance, effects on water quality, seabed alteration, changes to hydrodynamics and bathymetry). Where sensitive receptors are present within the area of influence of the dredging or spoil placement it is critical to understand the thresholds of receptors to these changes in order to avoid or minimise potential environmental impacts through reactive management.

7.2. Cause-effect Pathways

When addressing the potential ecological implications of dredging operations, it is important to identify the relevant (abiotic) environmental variables of concern (Bray, 2008). Typically, a set of the most relevant environmental variables are selected on the basis of the following selection criteria:

- that they are the most likely variables to be affected by dredging and disposal;
- that they are known to potentially cause adverse impacts on sensitive receptors; and
- that sufficient information is available to allow for predictive modelling and monitoring.

Seabed disturbance by dredging and disposal (Wolanski and Gibbs, 1992) can lead to:

- increased turbidity/Suspended Sediment Concentration (SSC);
- release of nutrients and contaminants (from the seafloor sediments upon disturbance); and
- increased sedimentation.

Dredging can affect receptors through several cause-effect pathways[5] (PIANC, 2010):

- elevated turbidity/SSC can block light passing through the water column that is required by photosynthetic biota (such as seagrasses and corals);
- elevated turbidity/SSC can interfere with reproductive processes (e.g. blocking egg fertilisation in broadcast spawners); and
- elevated rates of sedimentation can result in smothering of sessile habitats and species.

7.3. Sensitive Receptors and Tolerance Limits

7.3.1. Key sensitive receptors at Port of Gladstone

The term ‘sensitive receptors’ here is defined as environmental values within the area of influence of a planned dredging operation that require protection from potential impacts. Such values typically comprise ecologically important habitats or species (especially those of particular importance to conservation or fisheries) that could be affected by the dredging or

[5] In some cases, dredging can cause mobilisation of contaminated sediments, which can have toxic effects on ecological receptors. However, dredging of contaminated sediments is governed by separate (much stricter) environmental regulations, not permitting placement of such material in the marine environment. It is as such not considered relevant for the present discussion.

disposal activities. In a wider context, they can also refer to sites or species of particular importance to tourism, recreation, heritage preservation or local/indigenous communities.

The PoG region supports a variety of habitat types (e.g. coral reefs, seagrass beds, mangroves and mudflats) and associated communities of molluscs, crustaceans, fish, marine mammals and birds (Gladstone Healthy Harbour Partnership, 2018). Key sensitive receptors within the dredge area of influence (i.e. in vicinity of the maintenance dredging and disposal site) at the PoG include:

- Corals;
- Seagrasses; and
- Mangroves and tidal mudflats.

7.3.1.1. Corals

Reefs within the PoG region include fringing, platform, headland and rubble fields with both hard and soft corals (Gladstone Healthy Harbour Partnership, 2018). Reef communities include a variety of coral genera, including *Porites, Turbinaria, Acropora, Goniopora, Favites* and *Pocillopora*, as well as a variety of soft corals. Within the Gladstone region, reefs have been recorded in the intertidal zones that have suitable substrata and sufficient light penetration around Turtle, Quoin, Rat, Facing and Curtis islands and at Seal Rocks (Figure 21). Coral communities have also been recorded within deeper channels (>5 m) in The Narrows and around Passage Island and the North Passage. Regions of hard and soft coral also occur along the northern edge of Hummock Hill Island and limited coral reef development has also been identified in Rodds Bay.

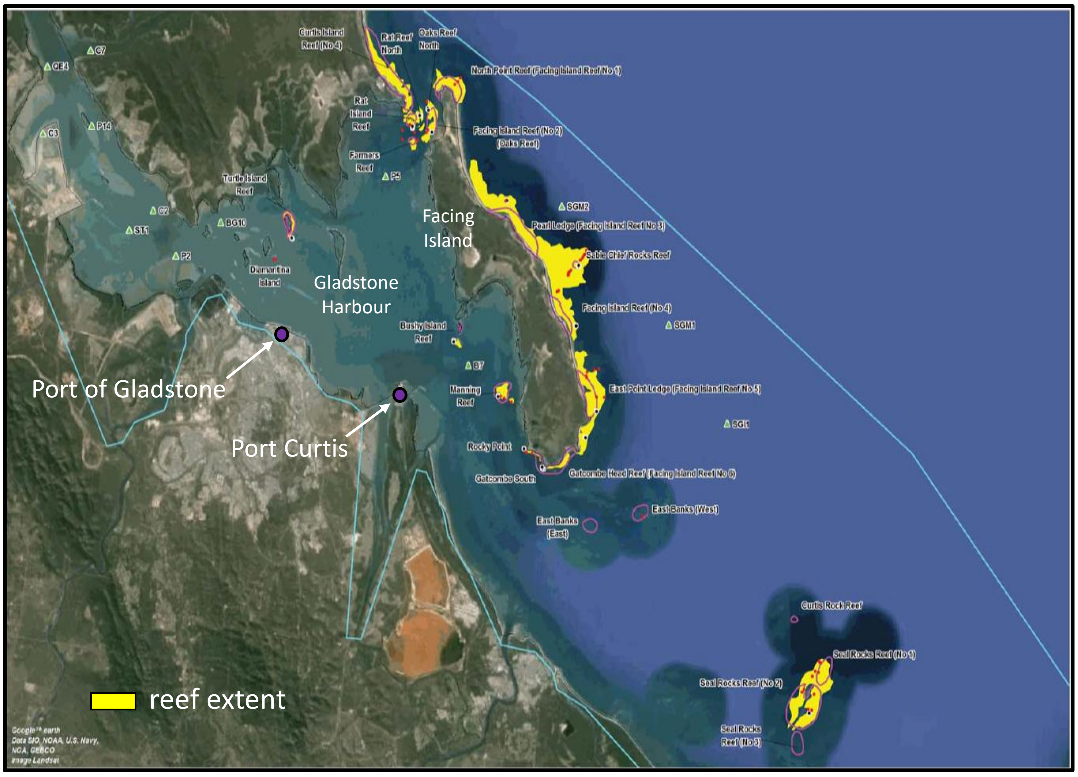


Figure 21. Location and extent of coral reef communities in the vicinity of the Port of Gladstone (adapted from Figure 3-2 in: Jones et al., 2015a).

Monitoring studies by Jones et al. (2015a) of the present-day condition/health of coral communities within the Inner Harbour provide evidence of major declines since baseline surveys in 2009. The inshore reefs at Gladstone have been significantly affected by flood waters in recent years (especially the 2013 flood event), with lowered salinities and high turbidity driving major changes in coral cover. In contrast to 2009 surveys, the Inner Harbour reefs had negligible living hard coral cover in 2014 and were numerically dominated by turfing algae and bare substrate (typically dead coral), and macroalgae. Within the Inner Harbour reefs, almost all coral taxa declined in cover between time periods, but most especially *Acropora* spp., which are among the most susceptible hard corals to changes in water quality. Further south, reef communities at Seal Rocks also had low hard coral cover, which differed from the results of a rapid survey in 2012 which recorded coral cover >30%. Nearby reefs along the eastern coastline of Facing Island had diverse and abundant hard coral cover, similar to survey results from 2010, suggesting that these reefs were not affected by the 2013 flood event.

7.3.1.2. Seagrasses

Seagrass meadows are one of the most important habitat types in the Gladstone region. Within the Gladstone Healthy Harbour Partnership (GHHP) reporting area, there are 14 monitored seagrass meadows (Bryant et al., 2018). These are located within six harbour zones: The Narrows, Western Basin, Inner Harbour, Mid Harbour, South Trees Inlet and Rodds Bay (Figure 22). Five seagrass species from three families are commonly found in the Gladstone region: *Halodule uninervis, Halophila decipiens, Halophila ovalis, Halophila spinulosa* and *Zostera muelleri* subsp. *capricorni*. The area and distribution of the seagrass meadows can vary annually, but at peak distribution seagrass meadows in the Gladstone region can cover approximately 12,000 ha. This area can include intertidal, shallow subtidal and deep-water habitats.

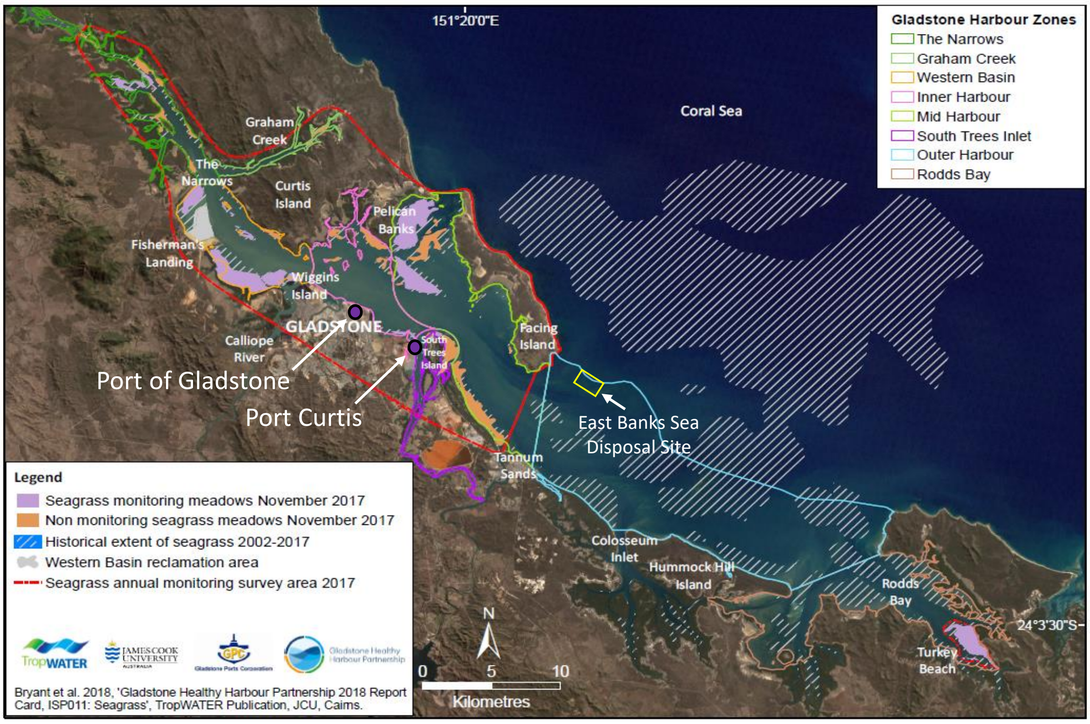


Figure 22. Location and extent of seagrass communities in the vicinity of the Port of Gladstone (adapted from Figure 2 in: Bryant et al., 2018).

Seagrasses are sensitive to reductions in available light and are susceptible to changes in a range of water quality parameters that affect light penetration. High nutrient levels from agricultural or urban run-off can cause algal blooms that shade seagrass. Increases in water turbidity from suspended sediments can reduce both seagrass growth and the size and extent of seagrass meadows. This is due to a decrease in available light and the effects of sediments settling on seagrass leaves. In the Inner Harbour, increases in turbidity associated with flooding or dredging can result in light reduction and deposits of silt on seagrass. The large tidal movements in this area has also been found to result in a significant (natural) resuspension of fine sediments.

Seagrass monitoring in the Gladstone region has been implemented on an annual basis since 2004. Based on the latest annual monitoring results from the 4th to the 10th November 2018, the seagrass in the Gladstone region has improved substantially over the previous year to be in an overall satisfactory condition (Bryant et al., 2018). The most significant increases in seagrass meadow conditions was in The Narrows, Western Basin and Rodds Bay zones while the meadows in South Trees, Inner Harbour and Mid Harbour regions remained stable. The footprint of the subtidal monitoring meadow in the Western Basin zone showed a substantial increase with the highest biomass for this meadow since monitoring began. The recovery of the seagrass meadows and gain in seagrass extent was considered to be due to a lack of major rainfall and flooding events over the 2017/18 wet season (Bryant et al., 2018).

7.3.1.3. Mangroves and tidal mudflats

There are also substantial areas of mangroves (around 5,013 ha in 1999) and adjacent tidal mudflats along extensive stretches of shorelines in the Gladstone region (Gladstone Healthy Harbour Partnership, 2018). Mangroves have changed considerably within the Inner Harbour region since the 1940s especially around the central port area where there has been substantial urban and port development resulting in the loss of tidal wetland areas. There has been a total loss of mangrove area of 1,470 hectares (22%) between 1941 and 1999, mostly due to reclamation. Recent (natural) fluctuations in climate (such as rainfall variability, rising sea levels, effects of floods or cyclones) have resulted in further losses and gains of mangroves and tidal wetland areas and in ecotone shifts (Duke et al., 2003). Migratory shorebirds feed on the extensive tidal flats in the Gladstone region, with up to 15,000 shorebirds regularly being present. They are dependent on access to benthic invertebrates at low tide, and sediment deposition is known to negatively affect the birds although some deposition is required to maintain the intertidal regions due to ongoing sea level rise. The major 2011 flood event, for example, caused large quantities of sediment to settle onto the tidal flats in Gladstone, driving rapid shorebird redistributions (Clemens et al., 2012). While ecologically important, mangroves and mudflats are significantly less sensitive to increased turbidity and deposition from dredging (Erftemeijer et al., 2013) and are unlikely to be affected by the levels of sediment disturbance associated with maintenance dredging and disposal activities at the PoG. Consequently, they are not considered any further in this section.

7.3.2. Tolerance limits

7.3.2.1. Corals

While corals are susceptible to reduced availability of light caused by increased turbidity, this impact is generally experienced more strongly by corals growing in deeper areas of a reef than by corals growing in shallower areas, and is also dependent on the coral growth form, with branching corals more sensitive than massive or plating corals (Erftemeijer et al., 2012; Jones et al., 2016). Tolerance limits of corals for total suspended matter (or suspended-sediment concentration) reported in the literature vary widely and geographically, and can be as high as >100 mg/l in 'marginal' reefs in turbid nearshore environments. The duration that corals can survive high turbidity levels above their tolerance limits ranges from several days (sensitive species) to at least 5 – 6 weeks (tolerant species). In the shallow inshore turbid zone of the GBR, resuspension of bottom sediment by waves affects coral communities on an estimated 110 days/yr (Orpin et al., 2004). Mapstone et al. (1989) reported critical thresholds of corals/reefs for Total Suspended Sediment in the order of 75 – 120 mg/l for the nearshore fringing reefs at Magnetic Island (GBR), while Hopley et al. (1993) reported tolerance limits of 100 – 260 mg/l for nearshore fringing reefs at Cape Tribulation (in the GBR).

Recent work by Jones et al. (2016, 2017) suggests that light availability (and not just simply exposure to increased SSC or sedimentation) can have a major effect on coral health. Experiments on the effects of elevated SSC revealed no negative impacts on any of the corals at any sediment concentrations, as long as light levels were still sufficient and no sediments had settled on and smothered the corals. The implications are that it is the light attenuation properties of the suspended sediment that is more important to corals than the concentration of SSC for predicting impacts. Experiments on the chronic effects of long-term low light exposure revealed that the crustose coralline algae, which are important for settlement of new coral recruits, were more sensitive to low light conditions than adult/juvenile corals. Overall, corals could adapt to a 3-fold decrease in light levels, and a combination of 10 mg/l and 2.3 mol/m^2/day over a 42-day period was tolerated by most corals. No impacts of low light are expected if total benthic light availability is >4 mol/m^2/day. In the absence of sedimentation, if daily light levels are and maintained at >2.2 mol/m^2/day *and* SSCs remain below 10 mg/l, there may only be sub-lethal effects without mortality.

Increased sedimentation can cause smothering and burial of coral polyps, shading, tissue necrosis and population explosions of bacteria in coral mucus. However, there are several studies that suggest that many coral species and reefs are capable of surviving sedimentation rates as high as 100 mg/cm^2/day for several days to weeks without any major negative effects. Some (nearshore) reefs naturally experience sedimentation rates well over 200 mg/cm^2/day. Nearshore fringing reefs in the GBR region that are characterised by high and variable sedimentation rates, ranging from 2 to 900 mg/cm^2/day (short-term rates) with long-term means of 50 – 110 mg/cm^2/day, were found to harbour highly diverse coral growth with a mean coral cover of 40 – 60% (Ayling and Ayling, 1991).

Turbidity and sedimentation can also reduce the recruitment, survival and settlement of coral larvae (Jones et al., 2015b). Research suggests that some (but not all) of the early life stages of selected coral species are more sensitive than adult corals. The available laboratory and field studies suggest that one of the most sensitive stages is the effects of sediment on settlement and subsequent metamorphosis.

7.3.2.2. Seagrasses

For seagrasses, the critical threshold for turbidity and sedimentation, as well as the duration that seagrasses can survive periods of high turbidity or excessive sedimentation vary greatly among species (Erftemeijer and Lewis, 2006). Minimum light requirements of most seagrass species seem to vary between 15% and 25% of Surface Irradiance (SI), but for some species (including most *Halophila* spp.) minimum light requirements as low as 3 – 8% of SI have been reported (Erftemeijer and Lewis, 2006). Laboratory experiments have shown that some seagrasses can survive in light intensities below their minimum requirements for periods ranging from a few weeks to several months. Larger, slow-growing climax species with substantial carbohydrate reserves show greater resilience to such events than smaller opportunistic species, but the latter display much faster post-dredging recovery when water quality conditions return to their original state. The seagrass species in the PoG region belong primarily to the latter category.

A recent synthesis by Collier et al. (2016) defined critical light thresholds (in absolute units of light energy) to protect seagrasses in the GBR region during dredging operations. Colonising species that dominate in deep-water habitat in the GBR are the most sensitive to light reduction and therefore have the lowest light thresholds (2 – 6 mol/m^2/day) and shortest duration (14 – 28 days) to tolerate low light conditions below their minimum requirements (Collier et al., 2016). Opportunistic species have higher light thresholds (5 – 6 mol/m^2/day) and can survive low light conditions for longer periods of time (28 – 50 days) before being impacted. The seagrass species that occur in the PoG region fall under the first category (colonising), although *Zostera muelleri* ssp. *capricorni* is sometimes classified as an opportunistic species, showing some resilience until significant declines set in between 4 and 8 weeks after shading during the growing seasons when light conditions were maintained below 6 mol/m^2/day (Chartrand et al., 2016).

Besides these 'acute' light thresholds, there would be value in considering long-term light thresholds as well – particularly in relation to chronic water pollution and frequently recurring sediment disturbances – but for now these cannot yet be clearly defined owing to a paucity of data (Collier et al., 2016). As an estimate, 10 – 13 mol/m^2/day is likely to prevent light limitation (in long-term settings) for *Zostera muelleri* ssp. *capricorni*, but not for *Halophila* spp., which require less light. In some regions, there could be merit in considering seasonally varying light thresholds during dredging works, to account for the seasonally variable underwater light climate, but data are currently too limited to confidently define and implement such measures anywhere in the GBR (Collier et al., 2016).

7.3.3. Natural dynamics and resilience

The nearshore region of the GBR (including the Inner and Outer Harbour regions of the PoG) is characterised by particularly strong natural dynamics (due to seasonality, macro-tides, cyclones and floods), which exert their influence on the nearshore habitats and species. The sensitive receptors (esp. corals and seagrasses) in the region are exposed to a large natural variability in turbidity/SSC, sediment transport processes and climatic events, governed by periodic river floods, large tidal movements, seasonal metocean conditions and relatively frequent tropical storms and cyclones. Consequently, nearshore turbid water coral reefs in the GBR region are thought to be resilient to change, showing rapid recovery following disturbance (Browne et al. 2010). Recovery rates of these reefs, however, are dependent on the ambient local environmental conditions (Browne, 2012).

A recent study of dynamics of a deep-water seagrass population in the GBR over an eight-year period (which included a capital dredging project) revealed considerable seasonal and inter-annual changes in seagrass presence and extent (York et al., 2015). The seagrass population was found to occur annually, generally present between July and December each year. Extensive and persistent turbid plumes from a large capital dredging program over an eight month period resulted in a failure of the seagrasses to establish in the year of the dredging operations (2006). However, substantial recruitment (from seed) occurred the following year and the regular annual cycle was re-established. Results show that despite considerable inter-annual variability, deep-water seagrasses had a regular annual pattern of occurrence, low resistance to reduced water quality but a capacity for rapid re-colonisation on the cessation of impacts. In contrast, intertidal *Zostera muelleri* spp. *capricorni* meadows in the Port of Mourilyan have had no recovery four years after their loss (York et al., 2014). Although this loss was unrelated to port activity it demonstrates the variety of potential trajectories for seagrass recovery in the GBR region.

An extensive multi-year research and monitoring program concluded that capital dredging operations in the PoG were unlikely to have contributed to the observed period (2014-2018) of significant decline in the Inner Harbour seagrasses (Bryant et al., 2018). The decline in their condition was already being observed as early as 2009/2010, commencing well over a year before the onset of the Western Basin capital dredging activities (May 2011 to September 2013). Declines also occurred at the out-of-port reference meadows in Rodds Bay, and more broadly along Queensland's east coast during the same period. The timing of flood-related seagrass declines during 2010 and 2011 immediately prior to the onset of capital dredging makes it difficult to determine what additional impact dredging and dredge material placement may have had on seagrass condition, or the influence it has played on the subsequent rate of recovery. However, a comprehensive water quality monitoring program during the Western Basin Dredging and Disposal Project has shown that light levels were maintained above locally derived light requirements at seagrass meadows outside of the immediate dredging locations during the dredging campaign (Bryant et al., 2018).

7.4. Potential ecological impacts

In order to conclusively evaluate the potential impacts of maintenance dredging operations on the ecological receptors, it would be necessary to understand how the intensity, duration and frequency of turbidity events caused by dredging differ from natural turbidity events associated with river plumes, storms and cyclones in the region (McCook et al., 2015). However, based on the following understanding of the sediment dynamics in the PoG region, it is considered unlikely that maintenance dredging operations in the PoG will result in significant, widespread detectable adverse environmental impacts on the sensitive receptors (corals and seagrasses) in the region around the Port and EBSDS:

- the observed level of natural dynamics in the PoG region (controlled primarily by natural resuspension, climatic variability, river flood plumes and cyclonic/storm events);
- the lack of ecological impacts detected during previous (much larger) 'capital' dredging campaigns in the PoG;
- findings from monitoring during maintenance dredging campaigns which found that the plumes generated by the dredging and placement activities were localised and of a short duration (hours); and
- monitoring and numerical modelling results have shown that dredged sediment placed on the seabed at EBSDS can be resuspended during natural wind and wave events, but that resuspension of the adjacent natural seabed also occurs during these events. As such, the resuspension of dredged sediment at EBSDS has the potential to result in a relatively small increase in turbidity/SSC (estimated to be in the order of 10% close to EBSDS) and as the increase occurs during natural resuspension events it would be very unlikely to cause any ecological tolerance limits to be exceeded which hadn't already been exceeded by the natural turbidity/SSC.

To evaluate potential impacts of dredging on the GBRWHA, it is important to understand the long-term fate and transport of fine-grained sediment that is disturbed by the dredging activity, released during placement and subsequently resuspended from the dredge material disposal area. In the case of maintenance dredging, it is important to note that maintenance dredging does not add new sediment to the system; rather, it resuspends and relocates natural sediment that has recently been transported and deposited into the dredged areas of the Port. For the PoG region, the quantitative sediment budget has shown that there is a large natural net flux of fine-grained sediment to the north-west along the coastline driven by the dominant south-easterly wind and wave conditions. Some of this sediment is transported into the Inner Harbour and it is the largest source of new fine-grained sediment to the Inner Harbour region. As such, any resuspension and subsequent transport of fine-grained sediment from maintenance dredging placed at EBSDS is likely to be similar to the natural fine-grained sediment transported in suspension during wind/wave events in the Outer Harbour region. Given the predicted relatively small contribution of sediment from maintenance dredging placed at EBSDS to the net northerly flux of sediment to the north-west along the coastline and the likely similarity in sediment properties, it is considered very unlikely that the placement of sediment from maintenance dredging at EBSDS would result in ecological impacts in the GBRWHA (excluding the EBSDS itself).

Based on the findings of the quantitative sediment budget, the nearshore area of the GBRWHA in the PoG region can be considered a naturally highly variable and turbid environment due to natural resuspension from waves and currents and the input of new sediment during extreme events (cyclones and flood discharges). These natural processes have previously been observed to have the potential to result in significant changes in the PoG region (in water quality and sensitive ecological receptors) and therefore they are considered much more likely to result in future impacts as opposed to maintenance dredging which has been shown to only result in relatively small and short duration increases in turbidity.

PORT & COASTAL SOLUTIONS

8. Summary

A quantitative sediment budget for the PoG has been developed as part of this assessment. The budget has built on the previous conceptual sediment budget and has used all relevant SSM Project information created, collected and collated to date as well as other relevant information. As part of the assessment, anthropogenic impacts to the sediment budget have been considered, this has included maintenance dredging activity as well as trawling, propeller wash from Port vessels and urban and industrial inputs. The key findings from the quantitative sediment can be summarised as follows:

- there is a very large mass of existing sediment present in the PoG region. The sediment is likely to have built-up over geological timeframes;
- there is a natural net north-westerly transport of fine-grained sediment along the coastline due to the dominant south-easterly wind and wave conditions. Approximately 15 to 20% of this net transport of fine-grained sediment is transported into the Inner Harbour region of the PoG through the South Entrance;
- the natural resuspension of existing sediment by waves and currents is the dominant process for sediment transport in the region as the annual mass of sediment resuspended by waves and currents is an order of magnitude greater than the input of new sediment to the system. Transported sediment is likely to be reworked multiple times (i.e. deposited during calm conditions and resuspended during more energetic conditions) until it is deposited in a location with consistently calm conditions (e.g. dredged berths and channels or mangroves);
- there is an annual net gain in sediment in the PoG region, with the majority of the increase in sediment being in the Inner Harbour due to the import of some of the suspended sediment being transported to the north-west along the coastline;
- despite the annual net gain in sediment, the budget indicates that there is the potential for insufficient new sediment available in the Inner Harbour to balance the deposition requirements for calmer years when the net import of sediment is predicted to be lower. This could limit the natural accretion of some intertidal areas, potentially resulting in them not being able to accrete at a comparable rate to predicted future sea level rise;
- maintenance dredging and placement activities have a negligible (<1%) contribution to the total mass of sediment resuspended in the PoG region. In contrast, it has been estimated that otter net trawling represents between 3 and 8% of the total resuspension;
- the relative contribution of sediment from maintenance dredging placed at EBSDS to the cumulative flux of sediment into the GBRMP through the boundaries adjacent to EBSDS is predicted to be less than 5% over the short-term period during and over the six weeks after the maintenance dredging campaign. After this period the contribution is expected to be significantly lower;
- based on the quantitative sediment budget, it is considered unlikely that maintenance dredging operations in the PoG will result in significant, widespread detectable adverse environmental impacts on the sensitive receptors (corals and seagrasses) in the region around the port and EBSDS;
- it is also considered very unlikely that the placement of sediment from maintenance dredging at EBSDS and its subsequent resuspension would result in ecological impacts in the GBRWHA (excluding the EBSDS itself); and
- natural resuspension of existing bed sediment due to waves and currents and the input of new sediment during extreme events (cyclones and flood discharges) are considered much more likely to result in significant changes in the PoG region (in water quality and sensitive ecological receptors) as opposed to maintenance dredging, which has been shown to only result in relatively small and short duration increases in turbidity.

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