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Sediment texture mapping of the Port of Gladstone

CS15000135 Sediment Dynamics Project Deliverable 2.2

Version 1.3: A report for the Gladstone Ports Corporation from CQUniversity and BMT WBM

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This publication has been compiled by the Coastal Marine Ecosystems Research Centre CQUniversity and BMT WBM for Gladstone Ports Corporation.

Associated attachments

Excel spread sheet collation of name: CS15000135_Particle_Size_Datasheet_CQU_Final.xlsx

Geodatabase with sediment attribute point layer, interpolations and TUFLOW sediment model layers:

CS15000135_GPC_Sediment_Budget.gdb

Raw measurement files from Malvern MasterSizer 3000.

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Background

The Sustainable Sediment Management (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 our 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 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 Port of Gladstone 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, with the exception of oceanic areas to the east of Facing Island and the south-east of Wild Cattle Cutting (Figure 1).

Maintenance dredging is conducted to provide and operate effective and efficient port facilities and services under the *Transport Infrastructure Act 1994* [S162(1)]. The Port of Gladstone maintenance dredging and disposal activities associated with the main channels, swings basins and berth pockets is usually undertaken annually with dredged material placed at the approved East Banks Sea Disposal Site (EBSDS) - first approved in 1980 (Figure 1)

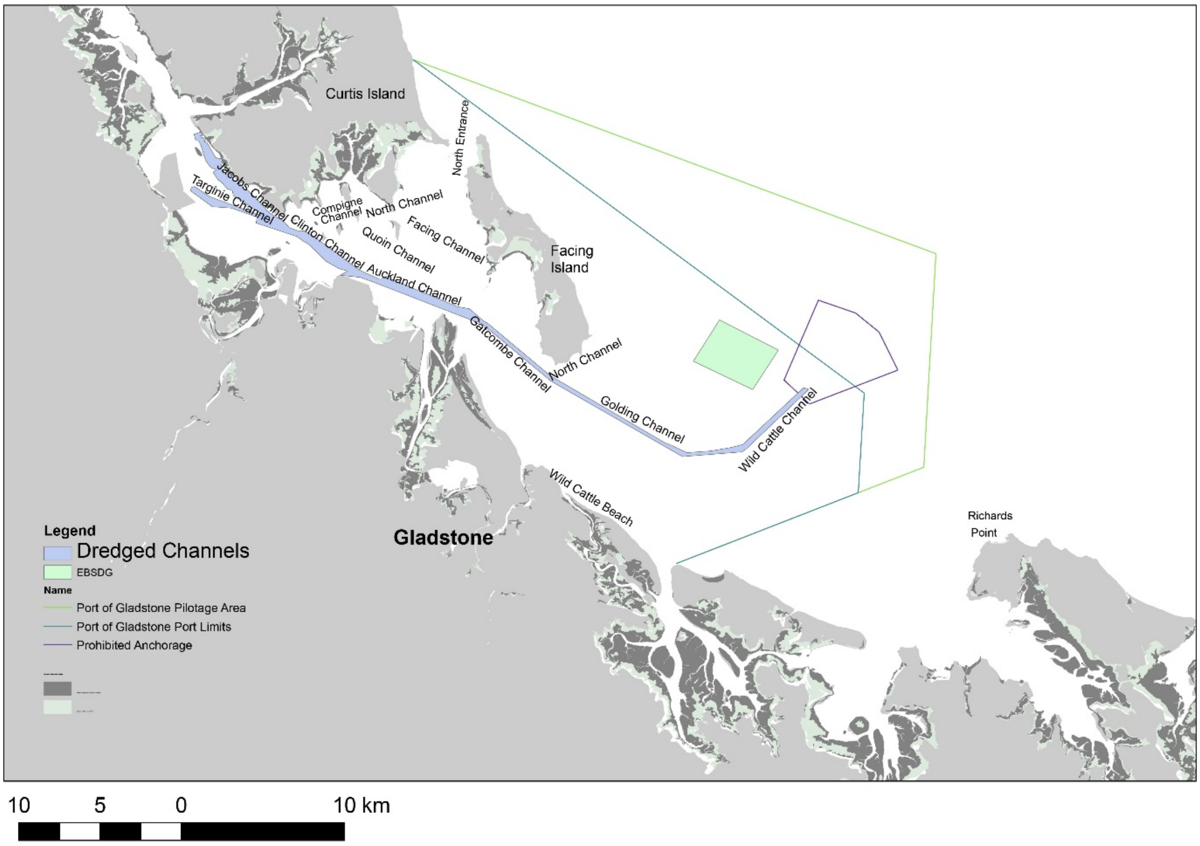


Figure 1 Map of study area with location names mentioned in the text.

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

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

The Deed also reiterates GPC's existing commitments to monitor and manage maintenance dredging and associated sea disposal activities in an environmentally responsible manner. To address the requirements of the Deed, an 'Implementation Strategy' (the Strategy) was prepared by GPC and approved by DoEE, which provides a schedule of proposed programs to be conducted over the term of the Deed. The Deed forms part of GPC's Environmental Management System (EMS) which is certified to ISO 14001:2015 ensuring a robust risk identification, control and improvement process is implemented and maintained.

This report is aimed at providing information to aid a better understanding of how dredging operations impact the local and surrounding environment to assist in long-term sustainable sediment management. Improved understanding of the sediment composition can help to identify the dominant processes driving sediment transport within Port Curtis, which can help to inform local sources and sinks of sediment and inform future numerical modelling.

The Port of Gladstone is within Port Curtis which 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 wave energy and riverine input from the Calliope and Boyne catchments contribute to the natural turbidity of the system and the spatial patterns of sediment deposition and erosion. Sediment transport within the Port Curtis estuary is mainly controlled by tidal currents, although strong wind generated waves can contribute to the re-suspension of sediment. Tidal currents into and out of the estuary occur primarily through the main entrance between Gatcombe Head, at the southern end of Facing Island and Richards Point on the mainland, and also through a secondary entrance between the north of Facing Island and south of Curtis Island (see Figure 1 for locations). Minor tidal currents also flow through the Narrows channel between Curtis Island and the mainland. Outside the Port, sediment transport is mainly controlled by wave-generated resuspension and longshore currents which flow in the direction of the prevailing south-easterly winds. Density gradients due to river outflows may also affect the circulation and sediment transport within the Port during extreme rainfall events but are not usually significant. Sediment input from the Calliope and Boyne Rivers is limited to heavy rainfall events each year and, for the Boyne, becomes significant only in the case of an overflow of the Awoonga Reservoir dam. The Boyne and Calliope estuaries themselves will retain a proportion of the sediment, again limiting input to the Port Curtis Estuary. The Narrows is considered to contribute only a minor sediment flux due to the limited volume of tidal exchange.

Figure 2 illustrates the water quality monitoring reporting zones for the Capricorn Curtis Coast waters' environmental values (EVs) and water quality objectives (WQOs) in Schedule 1 of the *Environmental Protection (Water) Policy—the EPP Water*[1]. These zones were adopted based on natural geographic and hydrographic boundaries, as well as legislative zones, and will be referred to in the report.

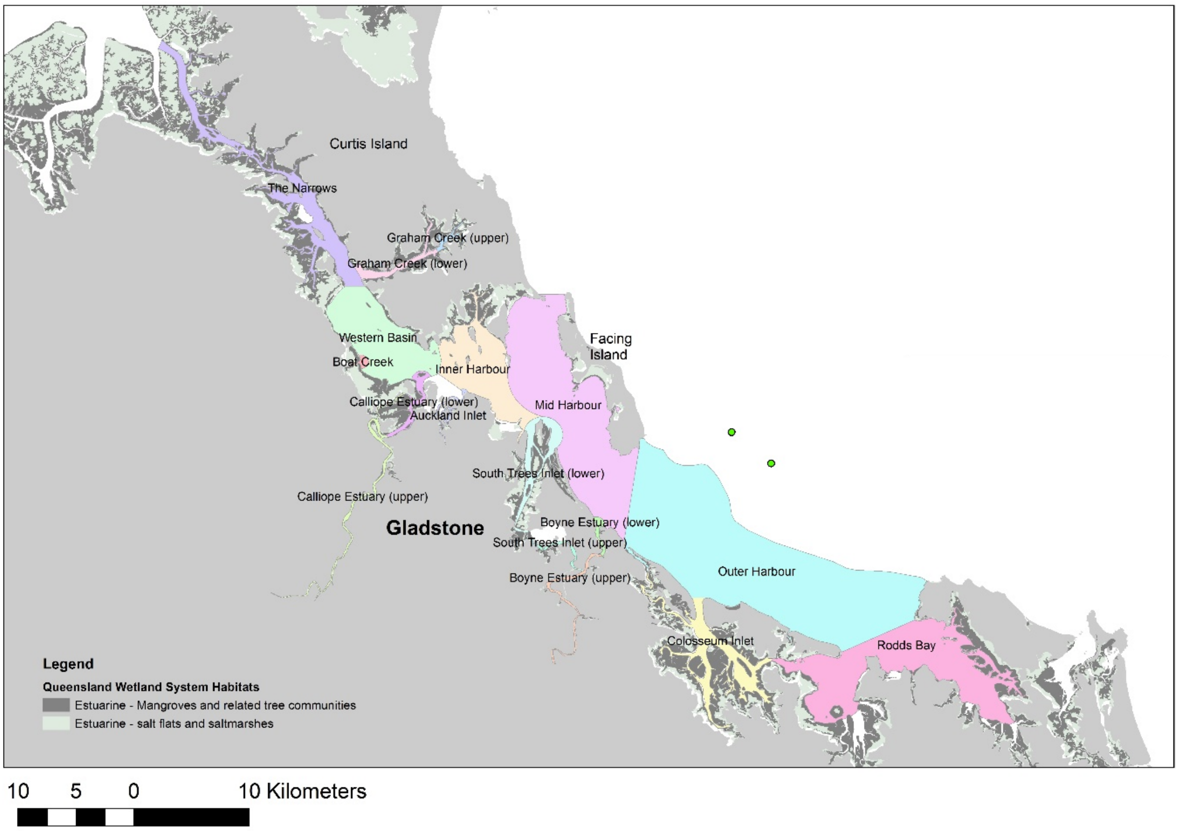


Figure 2 Water quality monitoring zones with the Port of Gladstone (Source EHP[1]).

To understand the sediment movements within Port Curtis, empirical data are needed to provide comprehensive knowledge of the key mechanisms and processes that influence sediment transport, including delivery, residency and export. Importantly, we need to understand the interconnectivity of the subsystems within Port Curtis, the extent, focus and reliability of the datasets, the reduction of uncertainties in measurements, techniques and a critique of the confidence of the estimates and assumptions that are being considered as part of the modelling efforts. Determining sediment sources, transport pathways and sinks, requires a clear picture of the wider spatial distribution of sediment particle size and composition.

The TUFLOW FV model was developed by BMT WBM for GPC (BMT WBM 2009). The numerical model is a finite Volume 2D / 3D Hydrodynamics Solver and includes baroclinic terms, 3D hydrodynamics, freshwater inflows, wave coupling, wind/pressure / heat flux boundary conditions, ocean current forcing, one-way / two-way coupling with SWAN and a sediment transport module. The Sediment Transport Module models the exchange of sediment between the bed and the water column. It can

[1] https://www.ehp.qld.gov.au/water/policy/capricorn-curtis-coast.html

include effects of flocculation and hindered settling, advection and dispersion with locally derived mixing coefficients and can accommodate multiple sediment fractions and multiple bed layers. Due to the requirement for a detailed full coverage dataset of particle size (ratio of clay: silt: sand), the model itself is currently used to determine the spatial distribution of particle sizes on the seabed. The modelled seabed is initially defined as spatially uniform with a representative bulk average particle size distribution. Prior to running model simulations, the model is run with sediment to prime the model domain and create a “seabed” based on currents and seabed rugosities. This allows the distribution of sediment within the model so that the particle size distribution within different parts of the modelled seabed varies according to the local hydrodynamic regime. For example, fine sediment will be removed from high energy channel areas (leaving a coarser particle size distribution in the bed), and will tend to accumulate in shallow intertidal areas (leading to a higher percentage of fines in the seabed particle size distribution).

Actual particle size distribution (PSD) data are required for comparison with the TUFLOW sediment transport module model environment. The utilisation of a more comprehensive sediment texture map as an initial condition for the model would increase the predictive abilities of the model. This approach was taken in the absence of good sediment data however, it is acknowledged that it creates a circular logic which may weaken simulations.

A sediment texture map can also be used to inform the model about seabed roughness and potential for resuspension, and more directly to identify potential spatial gradients and sediment transport pathways, including the identification of sources through particle type characterisation. For example, with distance from the mouth of an estuary there is likely to be a gradual decrease in the proportion of silt and mud fractions. Finally, the data can be used to assess seabed density and estimates of deposition.

Given the large volume of surveys carried out to support developments within the Port of Gladstone the current study aimed at collating this information into one dataset and complimenting it by identifying and filling data gaps, providing recent data on key areas of change (for example the EBSDS), dredged channels and sensitive receptor habitats such as seagrass). Knowledge of the particle size component below 63 µm is limited for many locations. Collecting new data with a higher resolution of data for silt and clay fractions provides a more useful dataset for the interpretation of sediment transport (including sources and sinks) in Port Curtis.

Specifically the objectives of the current report on the sediment texture of Port Curtis are to:

- Collate and review all relevant benthic sediment PSD data;
- Develop a sediment texture map(s) of the Port Curtis seabed, with a focus on the EBSDS;
- Compare recently collated data with the TUFLOW FV sediment transport module model environment.

Approach

Collation of sediment data

To collate sediment data from peer-reviewed published literature, publicly available reports, and non-public reports and data, we employed a multilevel search:

1. Peer reviewed and publicly available reports and journal articles. We utilised the following search engines Scopus, Google Scholar, CQUniversity Acquire database. Using combinations of the following search terms: Sediment, Sedimentary, Turbidity, Dynamics, Budget, Port Curtis, Australia, Tropics, Gladstone, Queensland, Great Barrier Reef, Environmental Impact Assessment/Statement, Sediment transport, Catchment, Coastal processes; Model, Modelling, Hydrodynamics.
2. Searching publication pages, databases and metadatabases of relevant organisations (e.g. CQUniversity Centre for Environmental EM database; GPC database; PCIMP; GHHP metadatabase; DES; Local industry).
3. Finally we contacted organisations and requested access to publications and data without direct public access.

Data were included where they met the following criteria:

1. The data included sediment PSD data;
2. The sampling points had a geographical position, or were presented on a map at a resolution which allowed the map to be georeferenced to calculate positions;
3. The data were less than 20 years old (due to the potential for large scale dredging and reclamation, and flood events to have significantly changed the sediment composition, and the differences in the way PSD were analysed and recorded);
4. The data were publically available or available for inclusion in an interpolated dataset.

Data were entered into a geodatabase as point data. Positions were converted to WGS84 decimal degrees and the following attributes were recorded where available:

- Filename or citation;
- Date;
- Station code;
- Depth;
- Sampling method;
- Latitude (Decimal degrees WGS84);
- Location name;
- Total dry weight of the sample.

The sediment particle size data were used to calculate combined percent values for clay (<2 µm), silt (2-63 µm), sand (63 – 2000 µm), and gravel (>2000 µm) to aid classification (e.g. textural triangle) and interpretation of the data. Classification of the sediment using a textural triangle, ensures continuity in the sediment classification across all samples and helps to improve the understanding of the system. Textural classification was carried out using the USGS Visual Basic software Sedclass (Poppe and Eliason 2007) which uses percentages of gravel, sand, silt, and clay to classify sediments based on systems from Shepard (1954) and Folk (1954). For each sample, the actual particle size fractions were recorded as presented by the report or dataset. Where given the method of particle size analysis was noted, these included laser diffraction size analysis, pipette method and sieving. Each method defines particle sizes differently, with no method showing 'true' results, rather just measurements of different properties of the same material (Konert and Van den Berghe 1997). Laser diffraction size analysis defines the particle size based on the cross-sectional diameter of the particle. The pipette method defines particle diameter as equivalent to that of a sphere (usually assigned the density of quartz) settling in the same liquid with the same speed as the unknown sized particle (Stokes-diameter, Preining 1967). Finally, the sieve method defines a particle diameter as the length of the side of a square hole through which the particle can just pass. Differences in the methods used to classify sediment particle size may influence the final distribution representation, which is difficult to correct for during collation of data. Previous comparisons of laser grain size analysis, with pipette and sieve analysis (using certified quartz based materials and natural sediments) found good correlation between the sieving, pipette and laser particle analysis for the certified materials (Konert and Van den Berghe 1997), with the laser methods giving slightly coarser results. However, there is consensus that from the point of view of laboratory efficiency laser sizing techniques are far superior. Laser particle analysis (for example using the Malvern Mastersizer 3000) measures sediment composition percentage by volume, whereas traditional sieving methods calculate the percentage by dry weight. For the purposes of this combined dataset we have assumed that the density of all particles was 1 $g.cm^{-3}$, and therefore the conversion of volume to mass percentages was assumed to be 1:1.

Collection of sediment data

New sediment collection focused on areas where the suitability of existing data was insufficient in terms of detailed PSD, or age (i.e. when was the sample taken) with a focus on key areas of interest, namely along the channels (e.g. data collected as part of the Dredging SAP) and around the EBSDS. The focus on channel areas allowed an assessment of how sediment varies through the dredged channels, which in turn provides an indication of the sedimentation patterns. Sediment sampling around the EBSDS over time allowed an assessment of the likely fate of dredged sediment after disposal. In addition to this report on the underlying data and the sediment map, the spatial data are provided as both point data (shapefile) and interpolated raster datasets.

Intertidal samples were collected using a 150 mm diameter core (to 200 mm depth). In the subtidal, grab samples were collected using a Van-veen grab and a piston suction corer (150 mm diameter). Sediments for the sediment texture layer were characterized by their PSD. Samples were collected, processed using the research operating protocol described below.

Sediment Processing Research Operating Protocol

Samples were thoroughly mixed by shaking and were then split into two representative subsamples. One sample split was archived in case of instrument or other error. The second sample was dried in an oven at 60°C, weighed on an analytical balance to two decimal places, re-wet and dispersed using a 10% sodium hexametaphosphate (Calgon) solution. Temperatures less than 100°C only drive off unbounded water and do not affect the grain size (Poppe et al. 2000). The sample was then wet sieved through a sieve stack comprising an ISO standard 2000 µm sieve, ISO standard 63µm sieve and a receiving pan. Gravels were retained on the 2000 µm sieve, sands on the 63µm sieve and silt and muds were retained in the receiving pan. Gravel and sand fractions were again dried and weighed on the analytical balance. The dry weight of the silt and clay fractions was derived by subtracting the dry gravel fraction and sand fraction weights from the original dry weight. The silt-and clay, and sand fractions we then combined and retained as a wet sample for direct use in the MasterSizer 3000. The relative proportion of all three fractions was calculated as a weight percent of the original dry weight.

Following this initial processing the gravel fraction, if present (> 2000 µm), was dry sieved through a 4000 µm and 64 mm sieve to separate gravel, pebble and cobble fractions. The sand and mud fraction (<2000 µm) was analysed wet using the Malvern MasterSizer 3000. The Malvern MasterSizer 3000 is a sediment grain size-measuring instrument that uses laser diffraction to infer particle size from light scattering in a fluid in which the sediment sample is suspended. A standard operating protocol was set up for non-spherical particles, which uses Mie Theory and the optical properties of the sample to calculate a particle size distribution. For the current study particle refractive index was set at 1.52, adsorption index 1 and density ($g.cm^3$) at 1 (Malvern Instruments Ltd 2007). Ultrasonication was used to disperse flocculated particles (duration of 20 seconds), and samples were measured three times and the average taken. The equipment was triple cleaned and degassed between samples.

Data interpolation

Interpolations were carried out on the point data for percent clay, percent silt and percent sand, and also for the percent <63 µm fraction. The purpose of the interpolations was to aid visual identification of broad changes and patterns in sediment texture throughout the study area and highlight areas of high heterogeneity Interpolations improve with the density and accuracy of the underlying data.

To interpolate the point data, we used Empirical Bayesian Kriging (EBK) in ArcGIS (version 10.3.1) Geostatistical tools. Empirical Bayesian Kriging is an interpolation method that accounts for the error in estimating the underlying semivariogram through repeated simulations, which is especially useful for environmental monitoring data where repeated observations of the random field are made (Le and Zidek 1992). For each interpolation frequency histograms were examined to check the assumption of normality in the data. A geostatistical layer was created to store the model parameters from the interpolation. Geostatisical layers were used to identify areas where further sampling would greatly increase the predictive capability of the interpolation model (see densifying samples below). Due to the localised disposal of dredge spoil, sediments at the EBSDS are likely to have a patchier distribution than naturally found. To allow this detail to be visible, we utilised a different interpolation technique for a comparison of the EBSDS over the course of the 2017 maintenance dredging campaign. Inverse Density Weighted Interpolation predicts values for interpolation based on the assumption that locations close to each other are more alike than those farther apart. The advantage of this interpolation is that unlike EBK there is no assumption of normality in the data.

Temporal changes

To assess the potential temporal changes, we examined sediment texture classification before and after major capital dredging works which began in 2009 and looked at the differences in percent silt, mud and sand at locations which had multiple samples over time. This included the EBSDS where samples dated back to 2003, the Western Basin and the Golding Cutting. Temporal data are available for most parts of the dredged channel, however a targeted investigation was undertaken using the Golding Cutting, to assess how the sediment composition varied over time and the implications of this in terms of the comparison with the modelled sediment composition map, due to the good temporal spread of data in this area. For the EBSDS, 35 samples were collected from fixed sites during the current project immediately before, immediately after and two months after the 2017 maintenance dredge campaign. Percent silt, clay and sand were compared using a repeated measures ANOVA and Tukey HSD post hoc comparison of means.

Comparison with TUFLOW FV Model

Currently the TUFLOW sediment dynamics model uses the model itself to determine the spatial distribution of particle sizes in the seabed. The sediment composition of the seabed is initially defined as spatially uniform in the model, with a representative bulk average particle size distribution. Prior to running model simulations, the model was run until the model reached equilibrium in terms of the sediment composition distribution (termed priming the model domain), to create a modelled sediment composition map based on currents and seabed rugosities. A comparison of the modelled sediment composition map and the existing available particle size data provides an assessment of how well the modelling approach aligns with the actual sediment composition map. The utilisation of a more comprehensive sediment texture map underlying the model may improve model calibration and increase the predictive abilities of the model. We examined the differences between modelled and observed for percent silt, percent clay and percent sand, with those samples (from the past 5 years) which provide information on those fractions. We also combined the silt and clay proportions from the TUFLOW FV modelled data and compared this to the larger number of observations of percent < 63 µm. The difference in the percentage of each fraction between the modelled layer and observed data points was calculated by using the "extract multi-values to point tool" in ArcGIS Spatial Analyst. Values from the modelled clay, silt and sand layers were attributed to the point layer of observed values, and a new attribute calculated based on the sum of the square of the differences, for clay, silt, sand and a combination of all three. The data were interpolated to visually identify the areas of greatest and smallest difference between modelled and observed data.

Results

Collated data

The study collated 1171 sediment samples from across the port. Notable gaps still exist along the inshore coast of Facing Island, along Wild Cattle and Hummock Hill Island and within the Colosseum Inlet and Rodds Bay. Of the 1171 samples, 48% did not split size fractions below 63µm. However, 90% of samples collated in the database provided data on the percent fraction less than 63µm. Appendix 2 details the datasets and reports collated.

The first comprehensive assessment of the sediments and sedimentary processes in the Port of Gladstone was carried out by Conaghan (1963). The study aimed to assess the type and distribution of the marine sediments in the Gladstone Harbour, the dominant factors controlling them, and the influence of provenance. Sediment cores were collected from over 200 locations in the inner and middle harbour, with four broad sediment suites identified within Gladstone Harbour "Super- estuary" (as termed by the authors), which can be further subdivided into 15 smaller lithofacies. The study provides sediment particle grain size distribution data for over 100 positions across the mid and inner harbour regions. However, this data was not included in the data collation due to its age and the representation of particle size within the report as distributions of modal diameters on a phi scale.

Since the 1990s numerous studies have been carried out in support of dredging, sea disposal and reclamation projects, by GPC, Industries and research organisations. Six port wide maintenance dredging sediment quality studies were carried out for sea disposal approval in 1992, 1996, 2000, 2006/7 and 2012 (Central Queensland Ports Authority 2006, Gladstone Ports Corporation 2009, URS 2009, BMT WBM 2014). An additional sediment quality report was completed for maintenance dredging of channels and berths within the Western Basin Dredging and Disposal Project (WBDDP) (BMT WBM 2014). These studies examined sediment quality and the concentrations of metals, metalloids and nutrients, but also analysed particle size. Particle size of sediments was also part of benthic macro-invertebrate monitoring studies conducted from 1992 to 2012 in relation to disposal of maintenance dredge material at the EBSDS (BMT WBM 2006, 2014) and seagrass and mangrove monitoring (Davies et al. 2015, Houston et al. 2016)). For example, the Port Curtis Biogeochemical and Seagrass Growth Model developed by the Gas Industry Social and Environmental Research Alliance (GISERA) provided a qualitative description of sediment type (fine sand, sand, mud, shell, a combination thereof), from seagrass meadows at Wiggins Island, South Fisherman's Landing, North Fisherman's Landing, Pelican Banks, Quoin Island, South Trees, Rodd's Bay, Black Swan and Channel Islands. GPC seagrass monitoring provides sediment particle size data for intertidal seagrass meadows (Davies et al. 2016). Between 2000 and 2009 sediment studies for major proposed capital dredging works associated with the Wiggins Island Coal Terminal (Connell Hatch 2006), Fisherman's Landing Northern Expansion & Targinnie Channel (Douglas Partners 2005) and Curtis Island LNG facilities (GHD 2006, 2007, 2009, URS 2009) were carried out. In total there were 238 sediment samples ranging from the surface up to 22m depth in the central and northern reaches of the harbour (GPC, 2014).

Due to the relationship between sediment, metal and organic material with particle size, the majority of studies sampling for metal, acid sulphate and macrofauna were carried out using particle size analysis (Currie 2003, Apte 2006, BMT WBM 2006, Andersen 2008, Angel 2010, Vision Environment 2011, Flint et al. 2016). For some reports the raw data was not accessible through GPC and individual consultancies would need to be contacted for these data. However, others provided the data within report appendices and these data have been included in the GIS database on sediment texture collated as part of the current project. Sediments sampled and analysed as part of regular monitoring, for example Port Curtis Integrated Monitoring Program PCIMP, will allow an assessment of spatio-temporal variability. For example, Flint et al., (2016) showed that the proportions of all three sediment size classes were different across all zones with a propensity for higher proportions of clay/silt (<63 µm) sediments during December 2013 than June 2014. Sediment sampled and analysed showed that in June 2015 data was more similar to the same month in 2014, suggesting that differences may be related to seasons/rainfall and resulting differences in terrestrial runoff.

GeoCoastal (Australia) Pty Ltd produced a sediment map for the Western Basin and inner and outer harbour regions, with particle size classifications to 7 µm (GeoCoastal Australia 2009). The coverage was interpolated from data with an uneven spatial distribution which does not reflect the heterogeneity of substrata but rather the focus on areas of interest relating to the WBDDP, and sediment data available from PCIMP sites. This interpolated layer has been used to model sediment dynamics in at least a couple of instances (Dunn et al. 2015), however the present study collates data at a greater spatial extent and resolution providing a more suitable layer for modelling.

Figure 3 shows a heat map of sediment data density, with the white areas showing where there is less than 1 sample per square kilometre. Sediment characteristics data collected to date shows a coverage across much of the area at a resolution of at least 1 sample site per square kilometre. Channel and spoil disposal sites are not only relatively homogenous, but also have a high data spatial resolution. However, in many areas where the seabed is more heterogeneous seabed, including intertidal regions and those with marine vegetation or significant amounts of bioturbation, the resolution is insufficient.

Another issue is the difference in particle size classifications used by historical studies (Wentworth 1922, Folk 1965) and some that are specific to the task at hand. Some studies provided size classes below 63 µm diameter, but the majority do not differentiate here. For example, Dhanasekar (1996) examined seabed sediments covering the Boyne River and South Trees Inlet, with samples collected from 27 cross sections at the mid and third points of the channel width at mean sea level (see Figure 4.4 in Dhanasekar, 1996). Dhanasekar's (1996) thesis was limited to the transport of non-cohesive particles larger than 75 µm and smaller than 2 mm. However, initial trials with a LISST 100X (multi-parameter system for in-situ observations of particle size distribution) showed that the majority of suspended particles were less than 40 µm (BMT WBM 2016).

Collected samples

Three hundred new samples were collected and analysed as part of the current project, with a focus on channel regions, the EBSDS and sensitive receptor areas of seagrass (at Pelican Banks, Rodds Bay, Black Swan and Lilly's Beach) and mangroves (Fisherman's Landing and South Trees).

Density and attributes of samples

Figure 3 illustrates the density of samples across the study area. Data collected and collated to date shows a coverage across much of the area. Channel and spoil disposal sites have a greater data spatial resolution. Over half the samples were collected in the last 10 years, with over 20% collected during 2017 (Figure 4). The most recent sediment samples were collected for the Western Basin, the dredged channels and EBSDS (Figure 5).

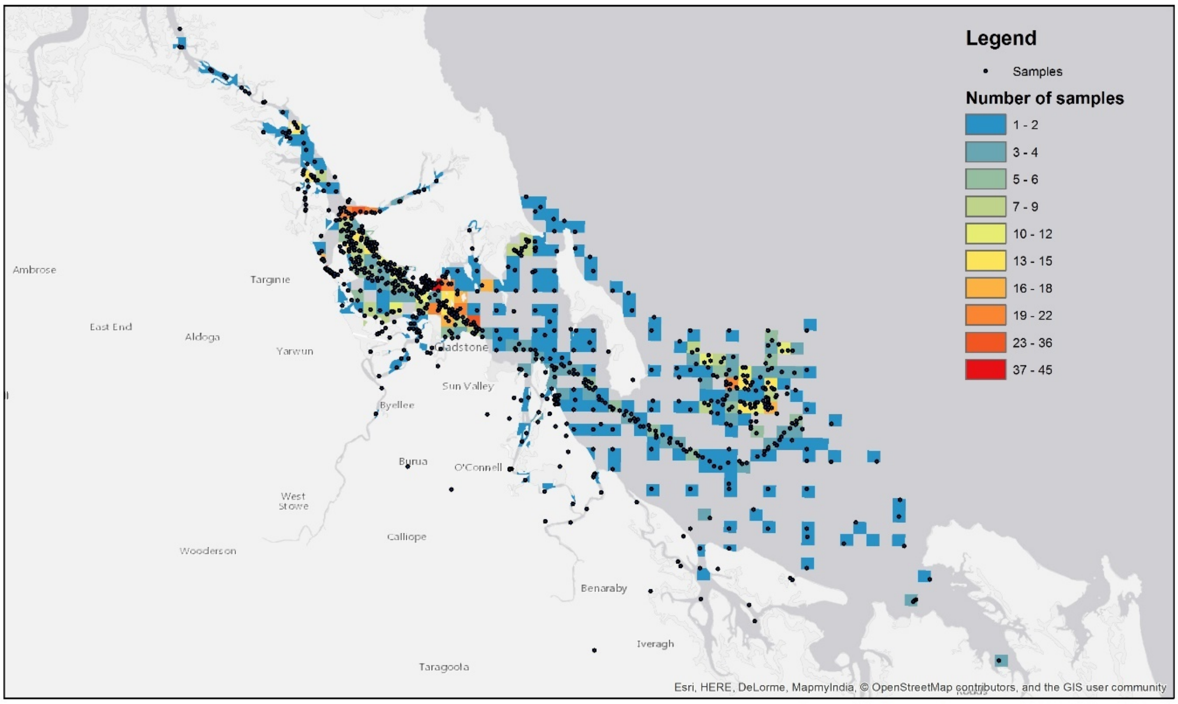


Figure 3 Sample density of all collated and collected data.

The percent clay, silt and sand in the collated samples are presented in Figure 6, Figure 7 and Figure 8, respectively. The figures show that: a greater percentage of clay is found in samples from The Narrows, Western Basin and Inner Harbour as well as the various creek systems. Areas of higher percent clay compared to surrounding sediments are also noticeable to the northwest and southeast of the EBSDS. Except for Targinnie and Jacobs Channels the percentage of silt is low (<7%). Percentage silt shows a similar pattern but with slightly higher percentages in the Golding Cutting and EBSDS samples. The Outer

Harbour is generally sandy with greater than 50% sand in most of the areas sampled, again with the exception of the Golding Cutting and EBSDS where sand is less than 30% in some samples (Figure 8).

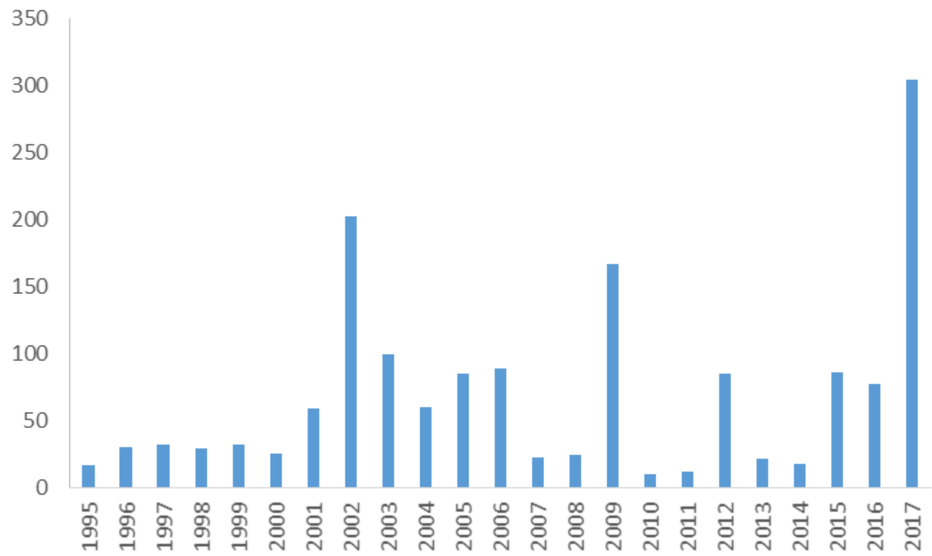


Figure 4 Number of samples by year with data on the proportion of sediment <63µm

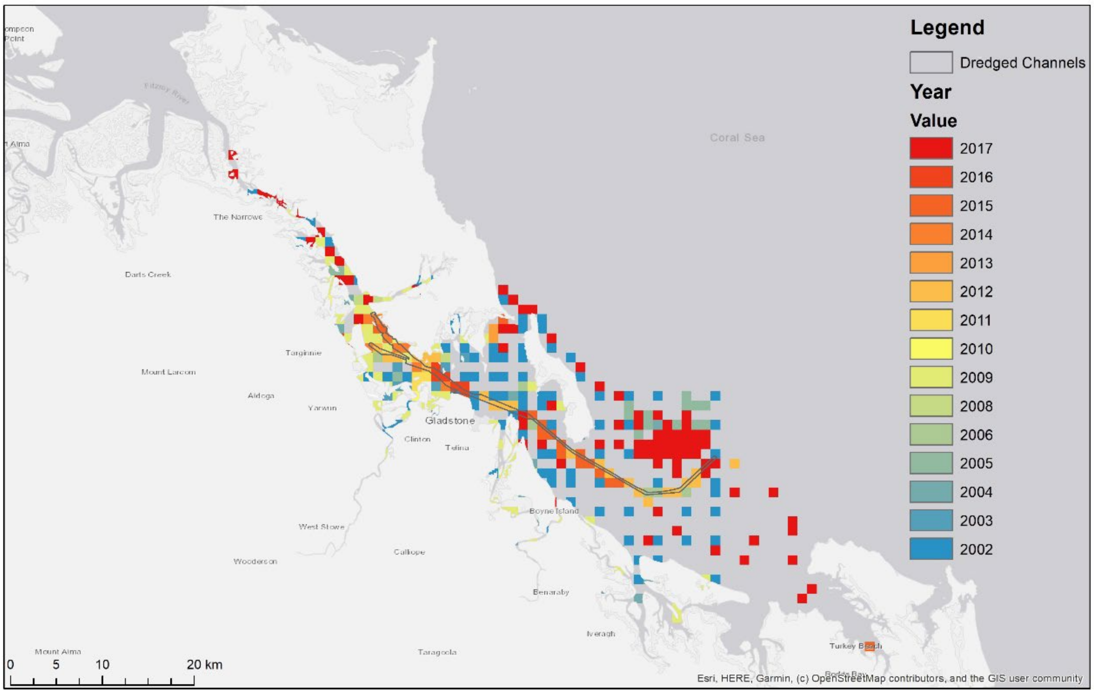


Figure 5 Distribution of samples by the most recent year of sampling (cell size 1km²).

Classification of the samples using the Shepard sediment texture scheme illustrates that most of the channel regions would be classed as Gravelly Sediment and the outer harbour is predominantly sand (Figure 9). Intertidal flats in the Mid and Inner Harbour, Western Basin and The Narrows are classified as Sand Silt Clay, in other words an approximately equal amount of sand, silt and clay in the sediment.

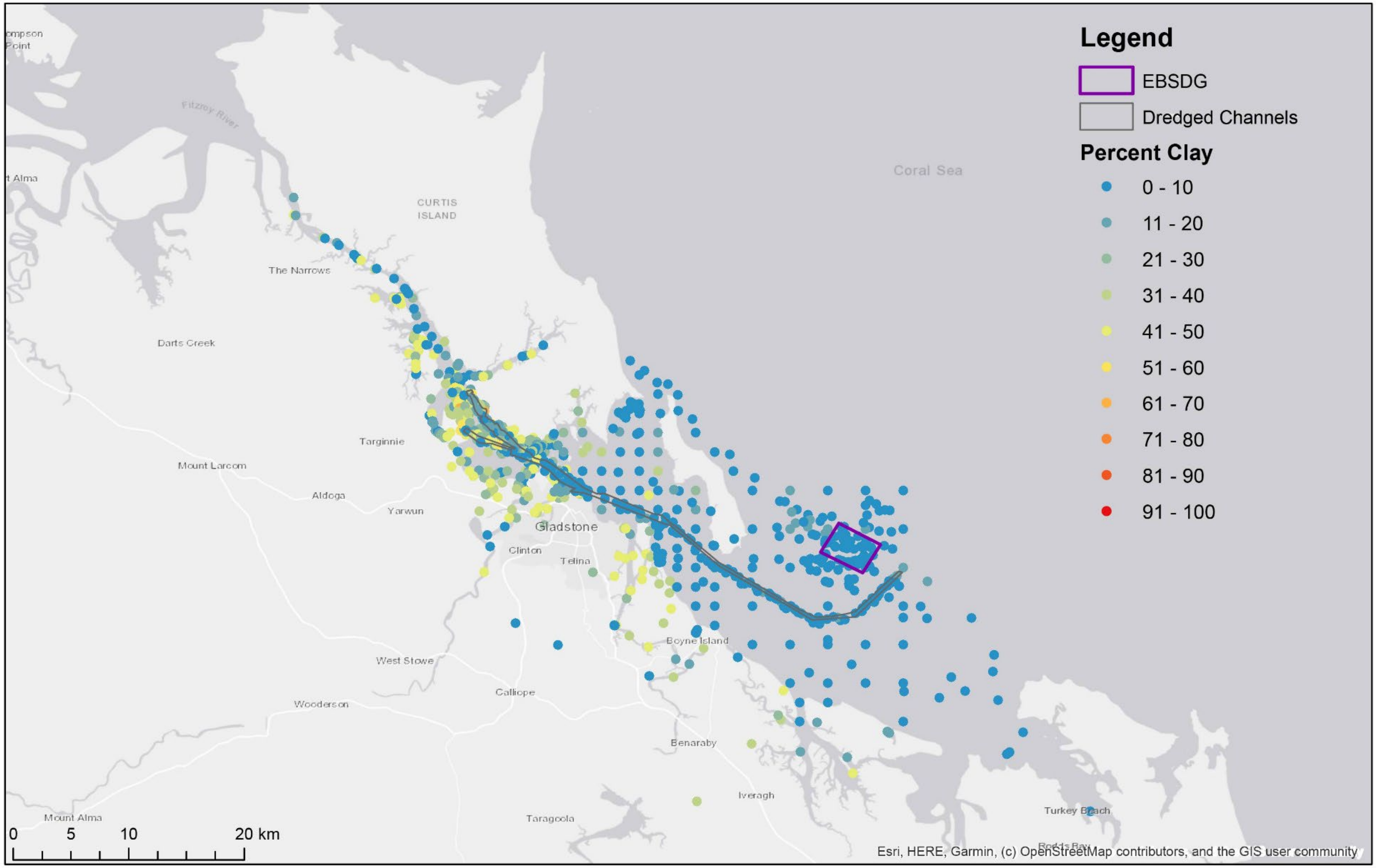


Figure 6 Observed percent clay in collated samples.

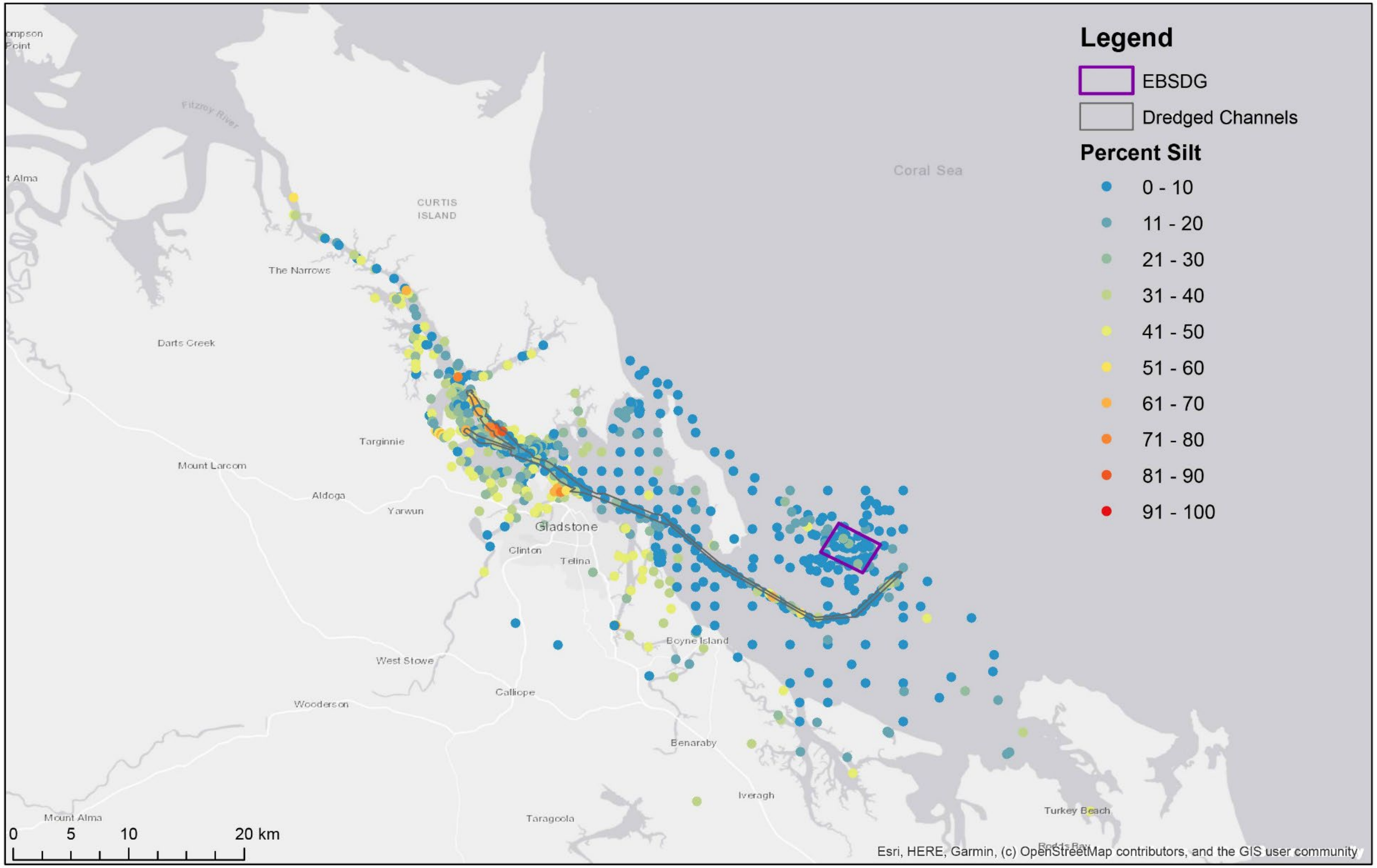


Figure 7 Observed percent silt in collated samples.

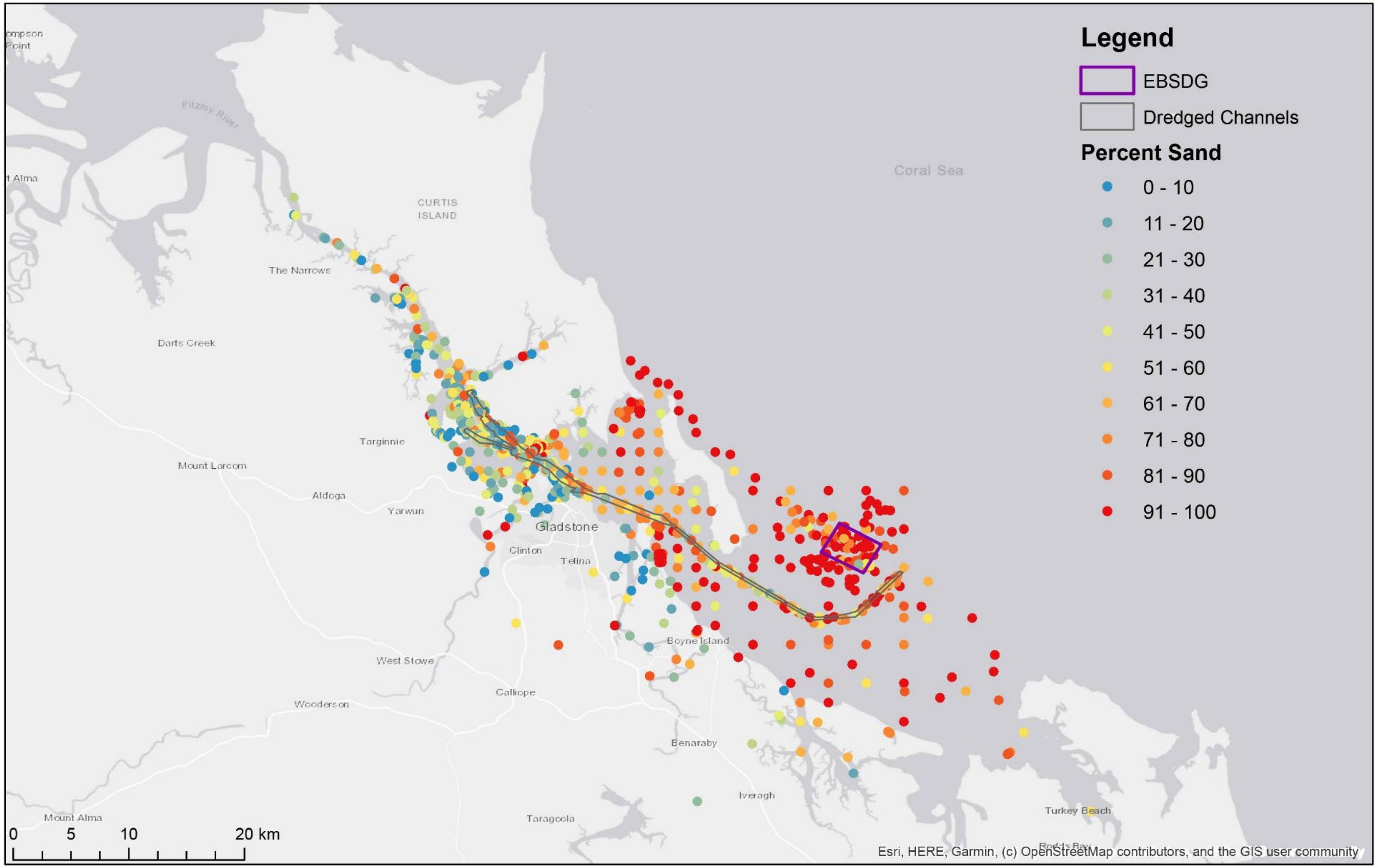


Figure 8 Observed percent sand in collated samples.

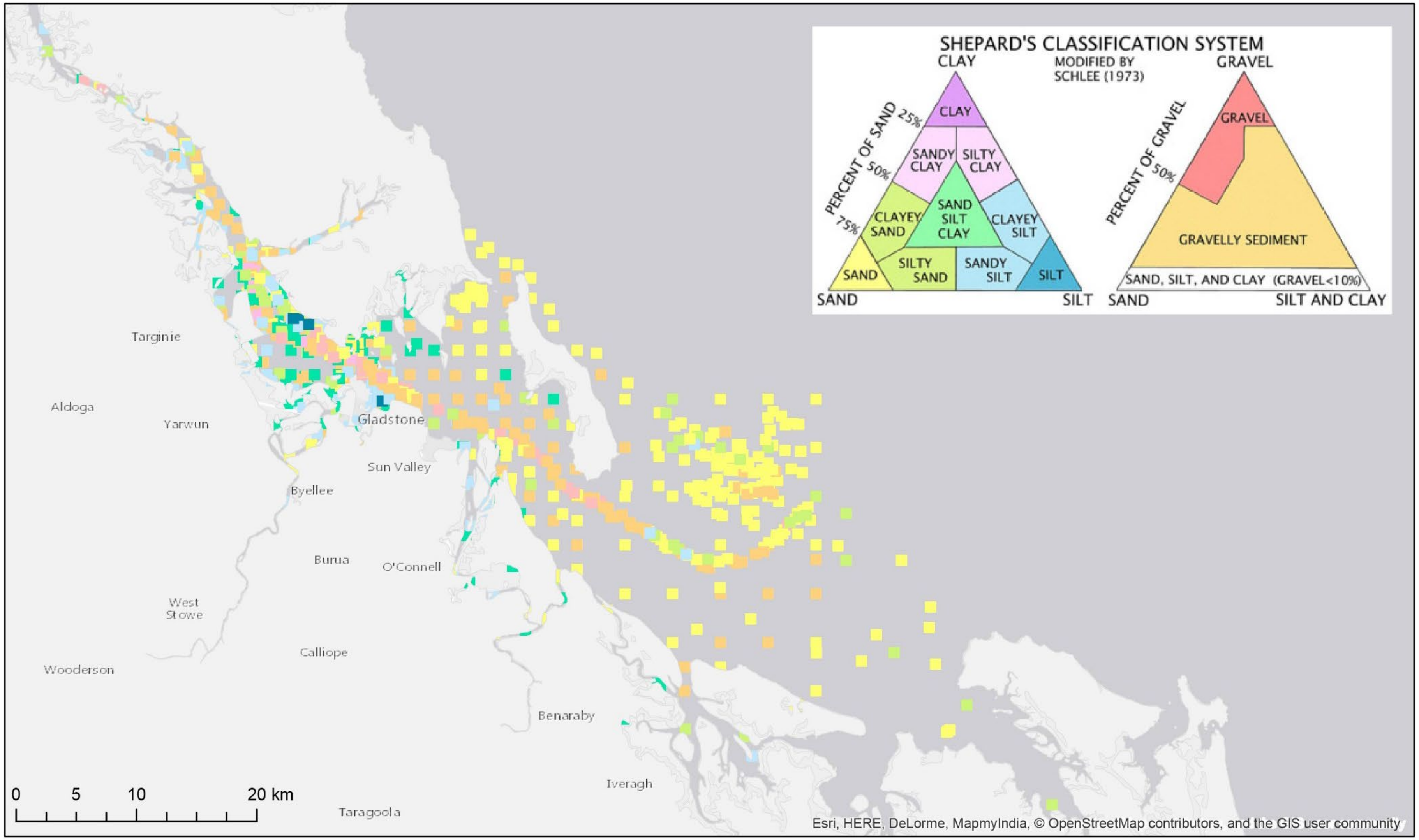


Figure 9 Shepard sediment texture classification applied to samples based on percentage clay, silt, sand and gravel.

Where there were repeat samples for locations the standard error was plotted to identify those areas with the greatest relative variation in the percent of the sediment sample that was less than <63 µm (Figure 10). Over the years the percent of the sediment sample that was <63 µm showed the most variation in The Narrows, Western Basin and Golding Cutting, and in some locations adjacent to the EBSDS.

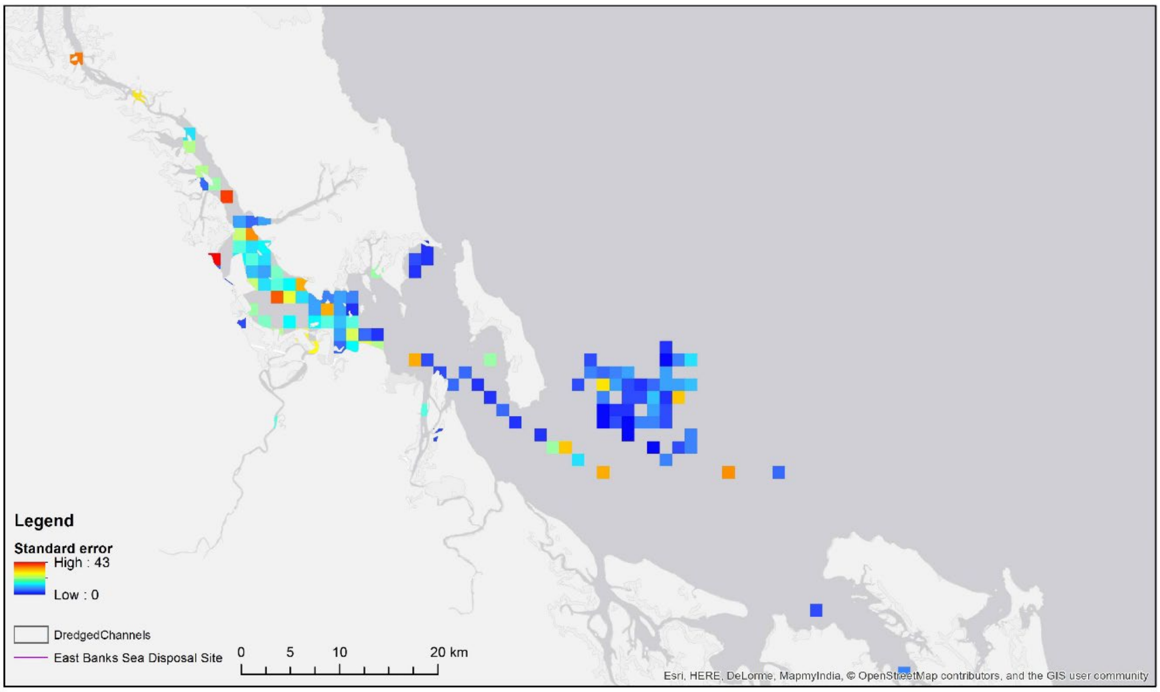


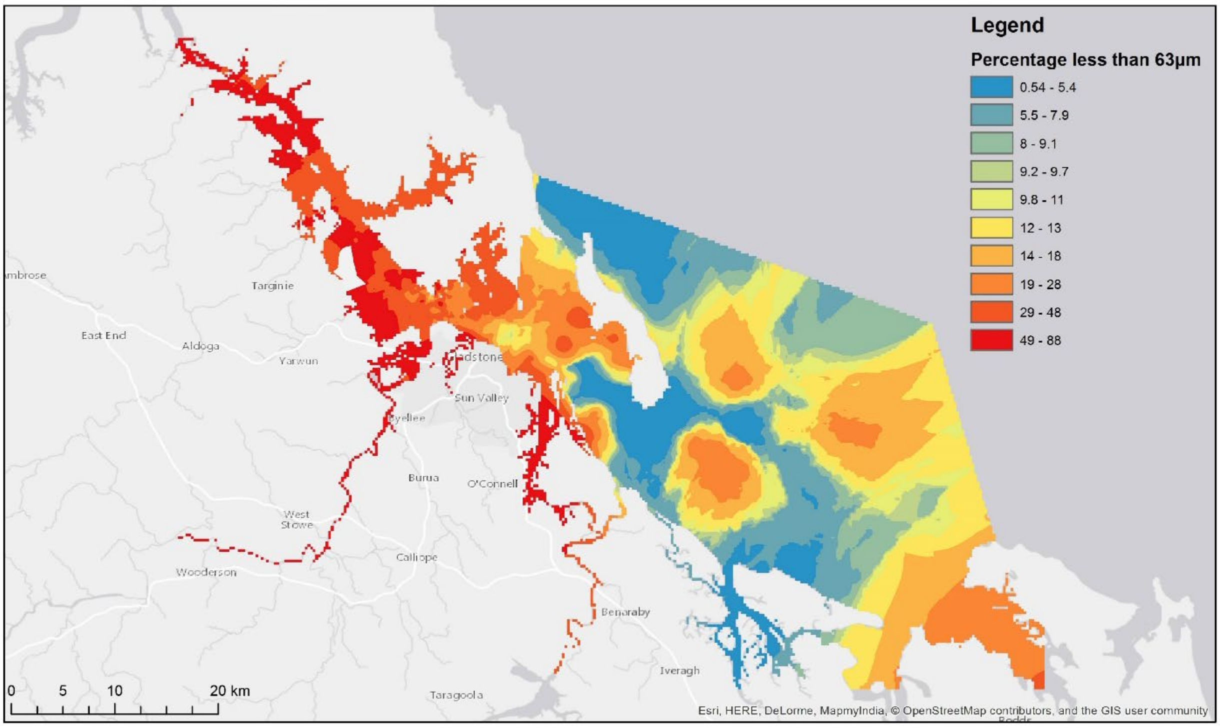
Figure 10 Standard error of repeat sample values of the percent of the sediment sample <63µm.

The interpolated representation of the data based on the data points being categorised by percentage less than 63 µm (Figure 11) and clay, silt and sand (Figure 12) show a general trend of coarser sediments in the outer harbour region, with the exception of the EBSDS and finer sediments in The Narrows, Western Basin and Rodds Bay. Whilst this representation of the data provides general trends, the resolution is coarser than the TUFLOW FV model mesh and so additional processing would be required for the data to be incorporated into the model. It is also useful to compare how the observed data correlate with the TUFLOW FV sediment distribution outputs. This is discussed in the following section.

Comparison with TUFLOW modelled data

Figure 11 and Figure 12 show the interpolated sample data alongside the predicted data from the TUFLOW FV model. Visual inspection shows some general agreement between the two, for example a higher percentage of <63 µm in The Narrows, Western Basin, Inner Harbour, Rodds Bay and on the tidal flats of the Mid Harbour. There are also some inconsistences, for example the samples available for the Colosseum Inlet were from sandy locations, and the TUFLOW model predicts a high percent of the sediment to be below 63 µm.

a)



b)

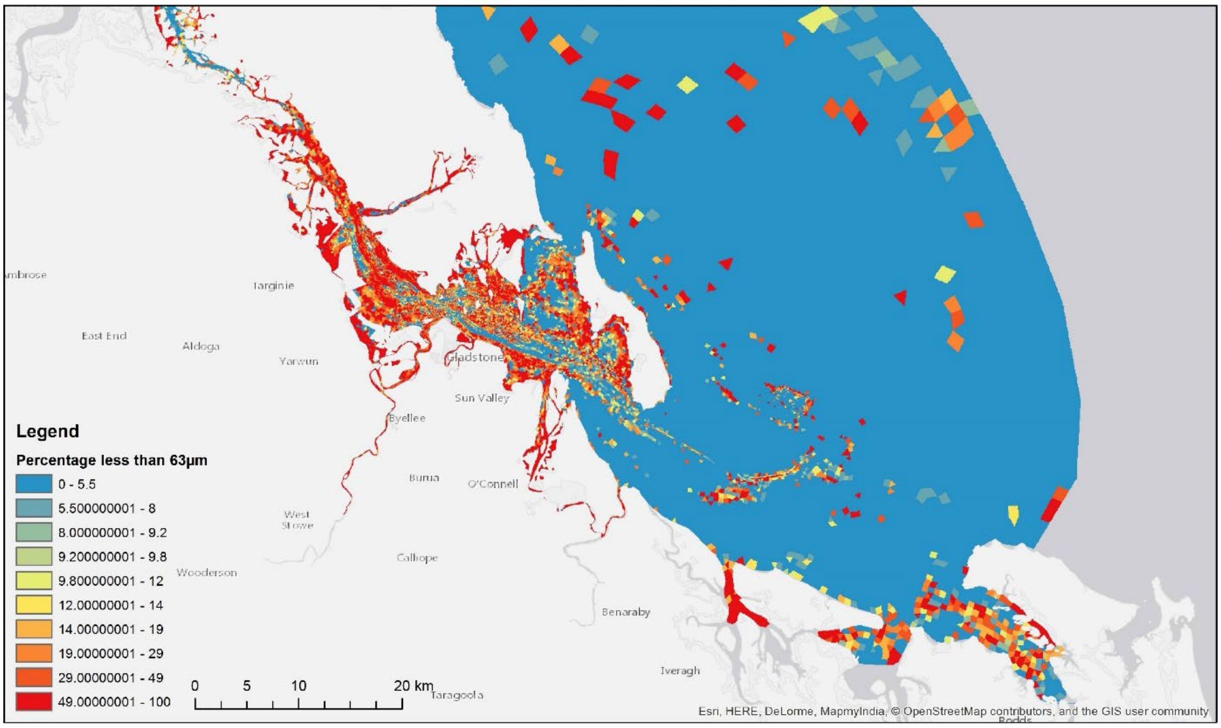
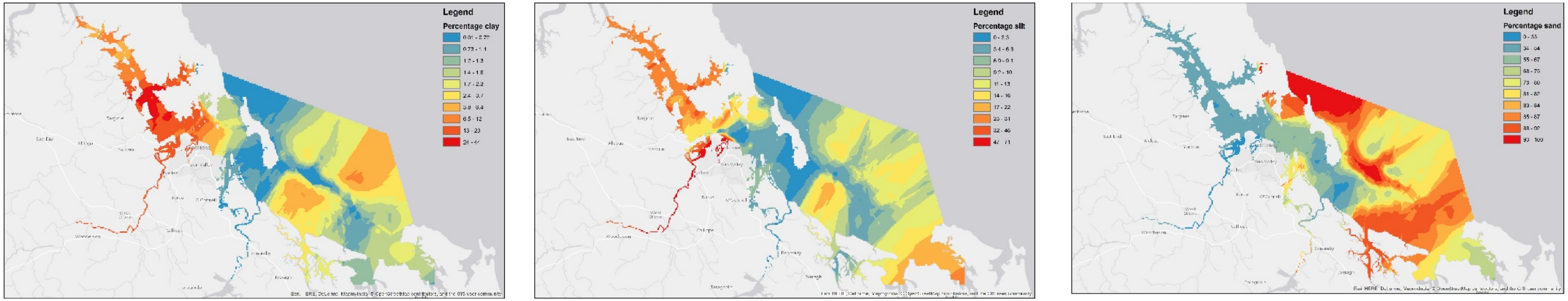


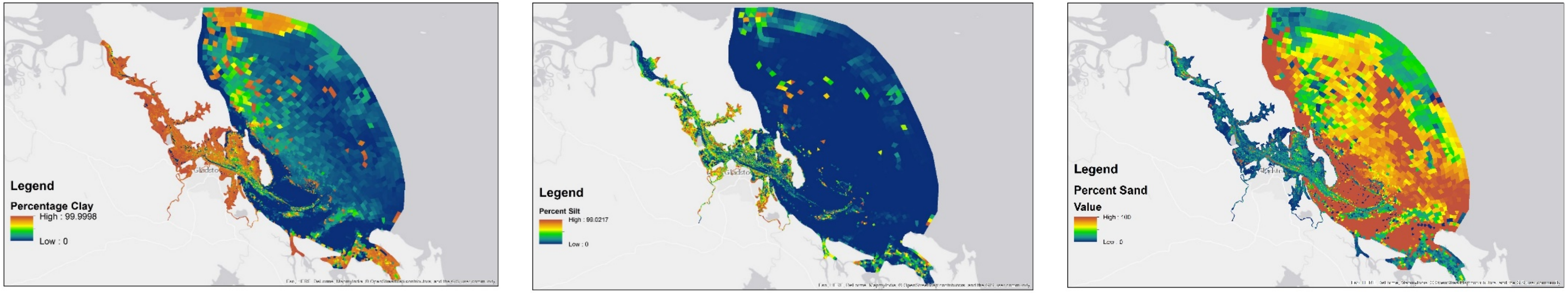
Figure 11 Percentage less than 63µm interpolated from sample data (a) and TUFLOW FV model (b).

The greatest differences between model values and recorded data were observed in The Narrows, the Inner Harbour and the Colosseum Inlet, where the modelled % below 63µm was greater than that observed. Alongside Fisherman's Landing, at the mouth of the Calliope, along the Golding Channel and adjacent to the EBSDS, observed values of % below 63µm were higher than the values predicted by the model.

There is a general agreement between the model values and observed values over percentage silt in the Inner Harbour and in the Western Basin and Mid Harbour. In the Outer Harbour a low percentage of silt is common in both the modelled and observed values. Inconsistencies are most conspicuous in the Golding Cutting, northwest and southeast of the EBSDS where the observed data suggest higher percentage of silt than the model. Percentage clay estimates from the model are higher than the observed values in The Narrows, Rodds Bay and the Mid Harbour, but in all other zones the model underestimates the percent silt and clay. Percentage sand shows the greatest agreement between modelled and observed. Disparities in percent sand occur at the mouth of the Boyne Estuary, The Narrows and adjacent to Fisherman's landing, where the observed data show higher percent sand. Along the Golding Cutting, the percent sand estimated by the model is greater than that observed.



a) Percent clay interpolated sample data b) Percent silt interpolated sample data c) Percent sand interpolated sample data



d) TUFLOW modelled percent clay e) TUFLOW modelled percent silt f) TUFLOW modelled percent sand

Figure 12 Percent clay, silt and sand fractions interpolated from the sample data (a-c) and as created by the TUFLOW model run.

Temporal changes

Collated samples for the EBSDS date back to 2003. Figure 13 illustrates the percent of sand in sediments sampled in 2003. Whilst sampling does not cover the entire ground or the sampling locations, interpolations (Inverse Density Weighting, IDW) illustrate that the EBSDS sediments were predominantly greater than 90% sand. Northwest of the EBSDS percentage sand was as low as 56%, due to a higher percentage of silt and clay.

Figure 13 Percent sand in sediments sampled from the EBSDS in 2003. Point data interpolated using Inverse Density Weighting with a smoothing factor of 2. Grey areas represent regions outside the extent of the point data distribution.

More recently sampling was carried out immediately before, immediately after and two months after the 2017 maintenance dredge campaign dredge disposal for the same positions at the EBSDS. Sediment texture at EBSDS varied across sites sampled, however some patterns emerged (see Figure 14). A repeated measures ANOVA showed that there was a significant difference in the percent sand in samples from across the EBSDS between the three times ($F_{(2, 36)}=3.43$, $p=0.04$). The percent sand in August samples being significantly larger than in October ($p=0.04$). There was no significant difference in percent sand between December samples and the other two sampling events. Figure 15 illustrates the spatial trends in percentage sand over the three sampling periods, with EBSDS being predominantly composed of high percentage sand immediately prior to dredge disposal, this decreases after disposal as the percentage of clay and silt increases. However, by December the site is returning to a sandy seabed, which suggests that some of the finer grained silt and clay which is placed at the site during maintenance dredging is eroded from the surface sediment between October and December, resulting in an apparent increase in the percentage of sand in the sediment. It could be hypothesised that some of the finer-grained sediment is transported to the northwest and southeast of the site.

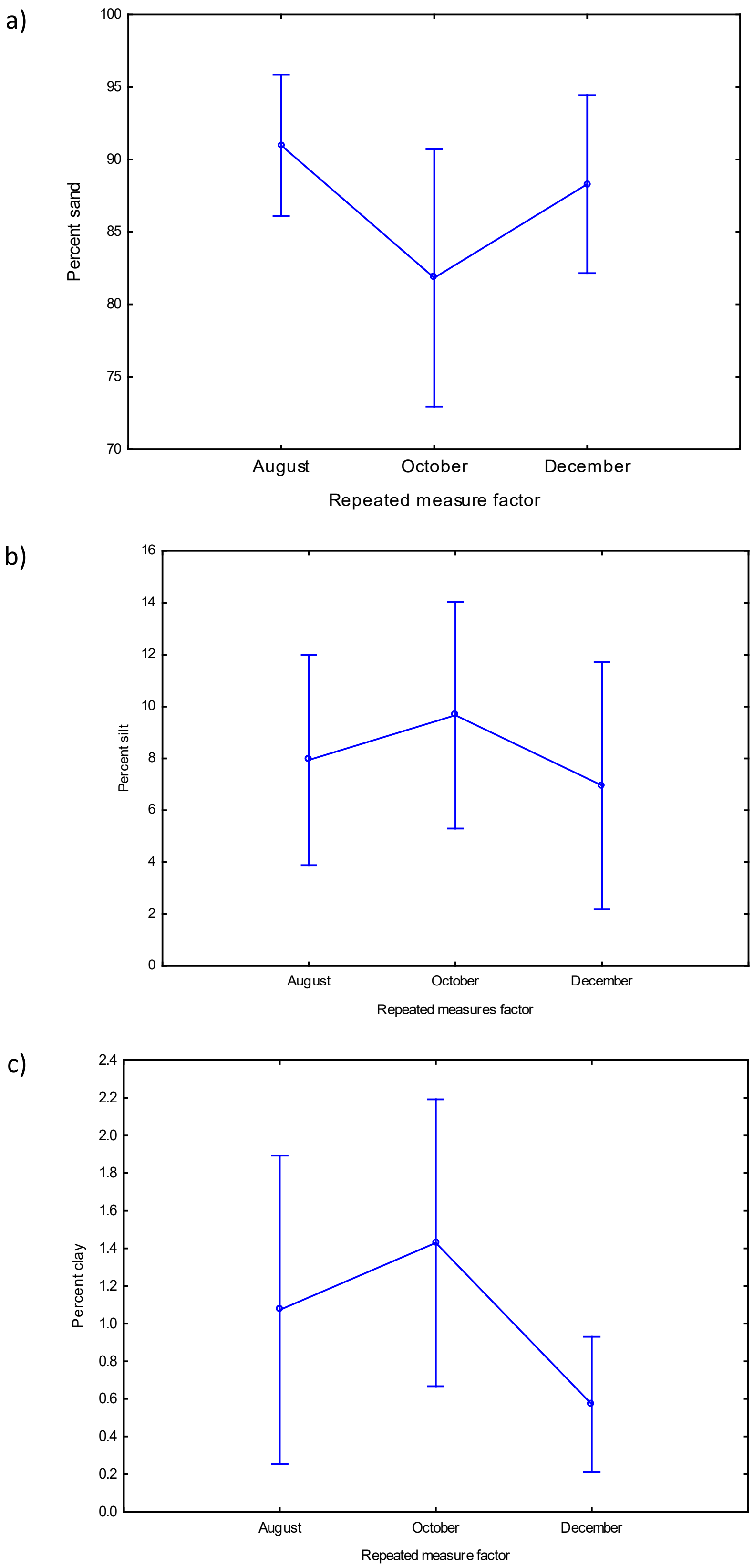


Figure 14 Change in the percentage (a) sand, (b) silt and (c) clay in sediment samples from the EBSDS in August (immediately pre- dredging disposal), October (immediately after dredge disposal cessation) and December (two months post dredge disposal). Bars denote 0.95 confidence intervals.

In terms of percent clay, there was also a significant difference between months ($F_{(2, 36)}$=3.30, p=0.048). There were no differences in percent clay between August (pre-dredging) and October (immediately post-dredging), but a significant decrease in percent clay in samples collected in December. There were no significant differences across months for percent silt Figure 14.

A visual comparison of the sediment texture within the dredged channels from 2009, 2012 and 2017 sampling show (where sampling locations overlapped) that there was more fine-grained sediment in the channel in 2017 compared to 2009 and 2012. For example, sediment texture in the channel regions sampled in 2012 were primarily gravel, sand and gravelly sediment Figure 16. However in 2017, overlapping regions in the Golding Cutting were found to be sandy silt and silty sand. Jacobs Channel samples from 2017, post cutting of the channel, were high in silt and sandy silt, compared to a majority of sand and sand silt clay samples in 2009 in this area, prior to the channel being cut.

Differences in locations, sample timing and methods make statistical comparisons difficult, but Figure 16 highlights the potential temporal variation in sediments within the dredged channels. Whilst it is known that 2017 sampling occurred shortly after the annual maintenance dredging, more information on the timing of sampling in respect to dredging is required to make further interpretations of this data.

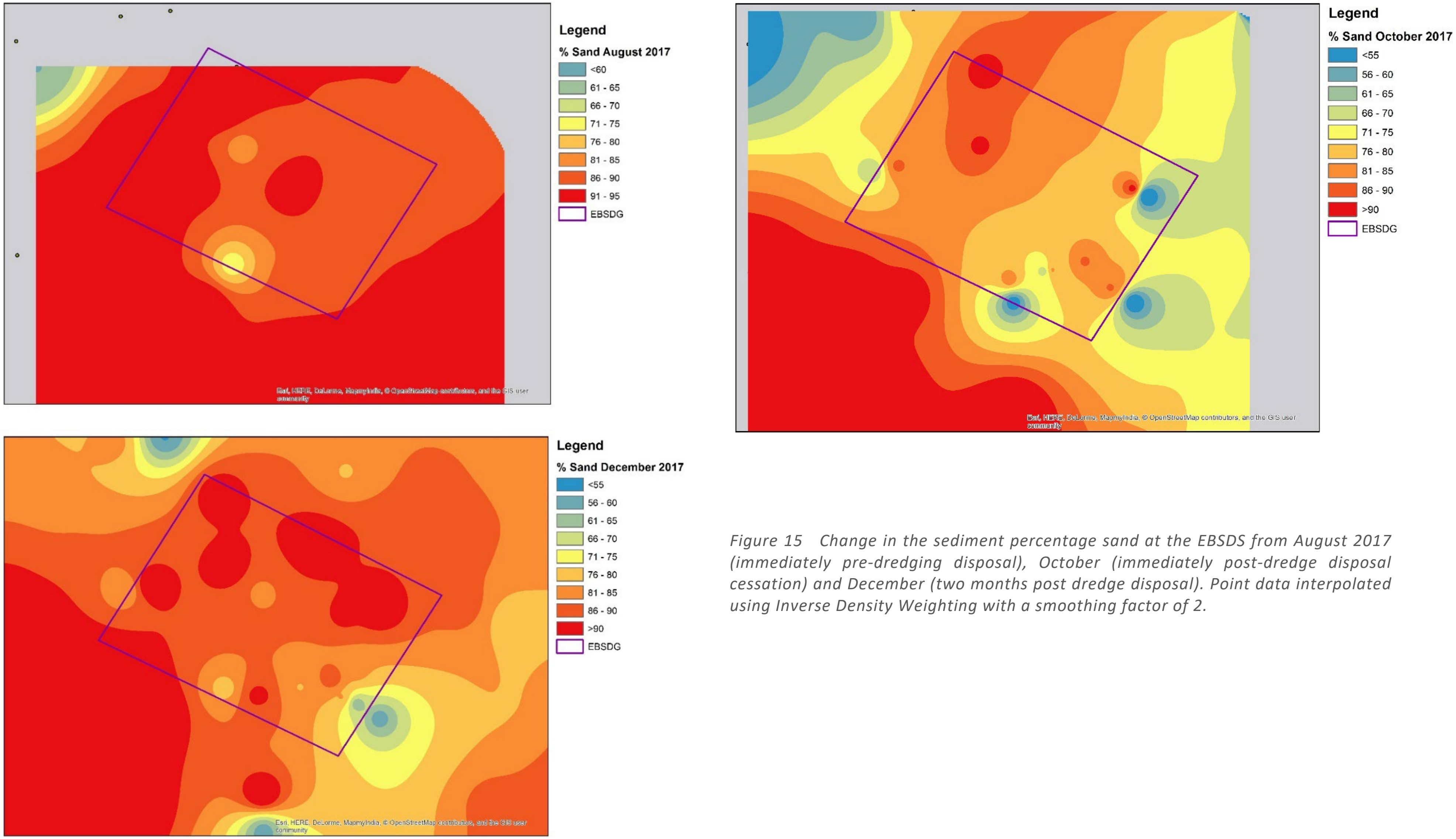
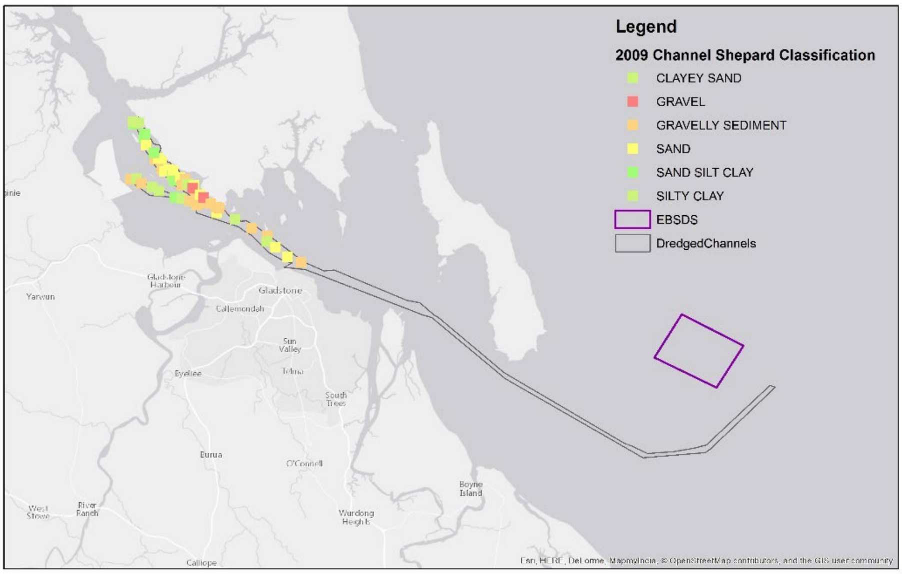
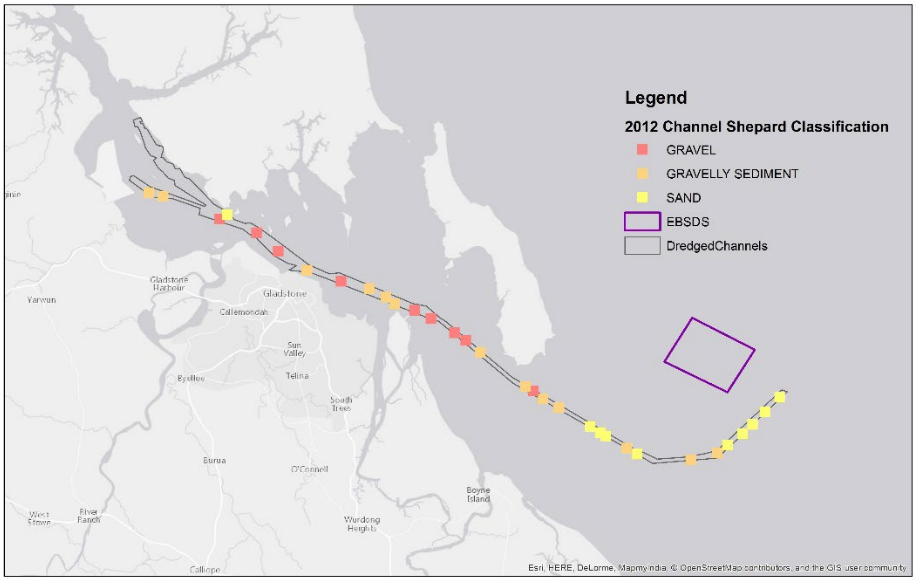


Figure 15 Change in the sediment percentage sand at the EBSDS from August 2017 (immediately pre-dredging disposal), October (immediately post-dredge disposal cessation) and December (two months post dredge disposal). Point data interpolated using Inverse Density Weighting with a smoothing factor of 2.


Legend
2009 Channel Shepard Classification
CLAYEY SAND
GRAVEL
GRAVELLY SEDIMENT
SAND
SAND SILT CLAY
SILTY CLAY
EBSDS
DredgedChannels
Yarwun
Gladstone Harbour
Gladstone
Callemondah
Sun Valley
Byellee
Telina
South Trees
Burua
O'Connell
Boyne Island
West Stowe
River Ranch
Wurdong Heights
Calliope


Legend
2012 Channel Shepard Classification
GRAVEL
GRAVELLY SEDIMENT
SAND
EBSDS
DredgedChannels
Yarwun
Gladstone Harbour
Gladstone
Callemondah
Sun Valley
Byellee
Telina
South Trees
Burua
O'Connell
Boyne Island
West Stowe
River Ranch
Wurdong Heights
Calliope
Esri, HERE, DeLorme, Mapmyindia, © OpenStreetMap contributors, and the GIS user community

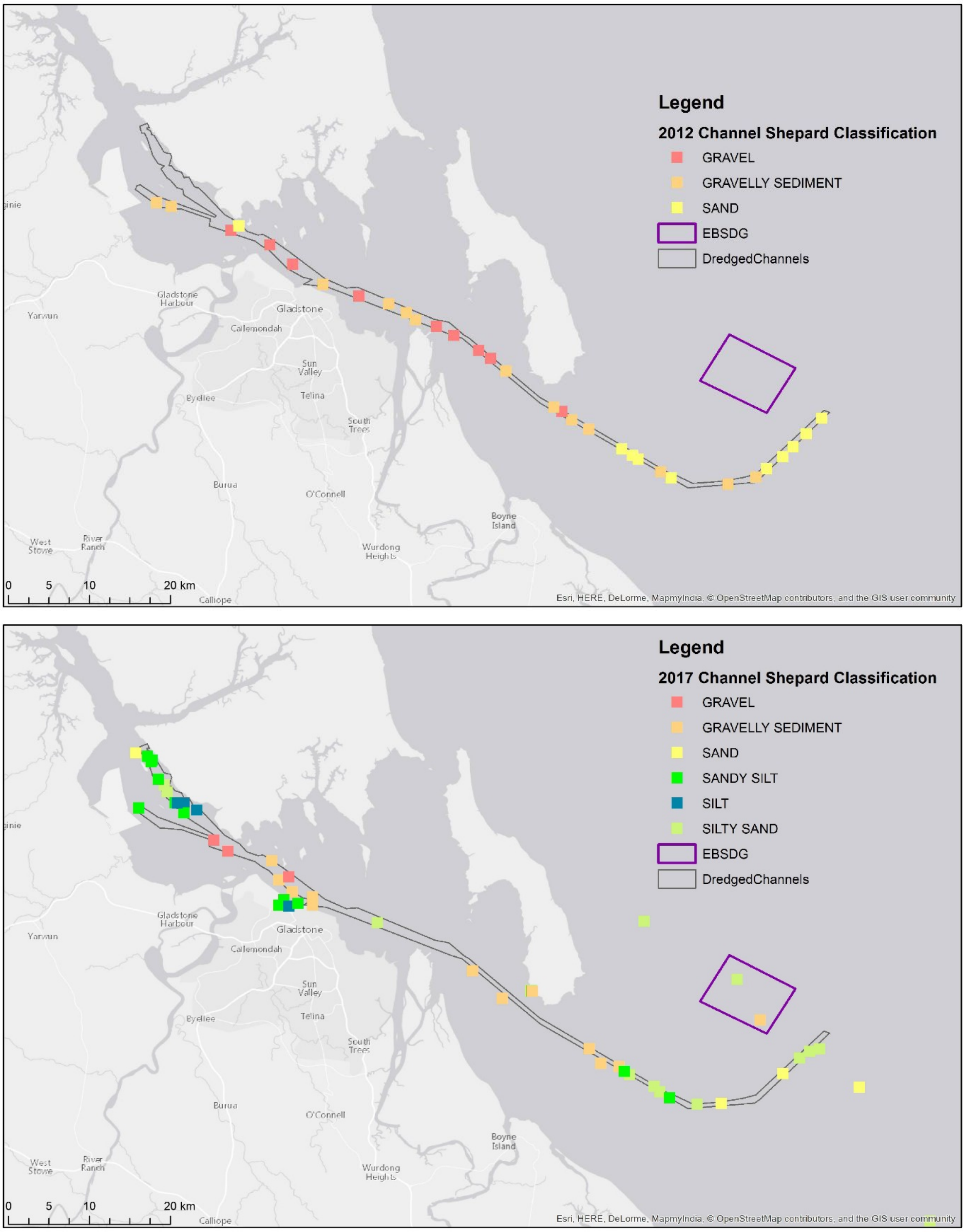


Figure 16 Comparison of dredged channel sediments in 2009, 2012 and 2017.

Discussion

The first aim of this study was to collate, review and map benthic sediment particle size data for Port Curtis and develop sediment texture maps of the Port Curtis seabed, with a focus on the EBSDS. Once existing data were collated additional samples were collected to provide a more comprehensive coverage and to resample areas such as the EBSDS where there is potential for significant change over time. In total 1171 samples were collated and supplemented by 358 new sediment samples. The new data collection focused on representative samples for areas with low historical sampling density including intertidal areas across a range of vegetation cover types, these were primarily in The Narrows and Grahams Creek and Outer Harbour and on the intertidal flats within the Middle and Inner Harbours. Whilst it is important to consider that differences in collection methods (for example coring versus grab sampling), sample processing and even data recording may influence the data included in the sediment texture map, it is still possible to utilise the collation to examine the broad patterns observed in the harbour and validate conceptual models. Detailed interpretations of sediment structure are not included in this report.

Sediment texture maps are being used to support the conceptual model development and the development of a quantitative sediment budget for the Port. The maps show that the sediment bed of Port Curtis consists of predominantly coarse lag deposits in the deeper channels along the estuary axis, while fine sediments have accumulated on peripheral shoals (Jackson et al. 2017). With distance from the mouth of any estuary there is likely to be a gradual decrease in the proportion of silt and clay fractions. Although the data support this general pattern within the Port Curtis estuarine complex (Figure 11), coarse sediments extend up into the Inner Harbour and Western Basin within the dredged channels, where flow velocities are greater. Conaghan (1966) suggested sands which do enter the harbour by drift are probably lost to the deeper channels, and that the nature of grain-size distributions suggest that the reworking and erosion of channel sediments is more important than the processes introducing sand through the channel entrances. The interpolated data did not properly capture the detailed changes occurring within the Channel areas of the Outer Harbour or the causes. The different focuses of specific surveys may bias temporal patterns when data from different sites are interpolated. For example, targeted sampling of areas where regular sedimentation occurs undertaken in 2017 may have resulted in the observed shift to finer sediments in the temporal comparison. In the Jacobs Channel region a shift from sand and sand silt clay samples in 2009, pre-dredging to silt and sandy silt in 2017 may be a result of changes in water depth (up to 10m) at sampling locations increasing siltation at the site. It may also be from the removal of old surface layers of sand and sand/silt/clay by the capital dredging leaving lower layers which were predominantly silt.

Examining the sediment texture point data (Figure 9) illustrates some channel areas are dominated by fine grained sediments, for example, the Golding Cutting just before the bend into Wild Cattle Cutting. It is proposed that finer sediments in this location may have been transported by tidal currents from the Mid to Inner Harbour regions, from sources such as the Calliope or Fitzroy Rivers, settling in this location due to the change in direction of the channel and subsequent reduction in flow velocity. It may also be a result of the resuspension of movement from large stores of fine-grained sediment within the Inner Harbour itself.

Maintenance dredge material from the navigable channels in the Port of Gladstone is disposed of at the EBSDS in accordance with permits issued under the Australian *Environment Protection (Sea Dumping) Act 1981*(GPC 2014). East Banks was identified as a naturally occurring ebb bar which has formed offshore of the entrance to the estuary, an area of sediment accumulation due to the interaction of northwards moving longshore drift currents and tidal currents from the estuary meeting at the tip of Facing Island. Following decades of disposal at this site, the depth of the immediate surrounding area is now shallower. Analysis of the collated sediment data indicated that whilst finer material (silt and clays) are deposited at the site during dredging, the site is predominantly sandy, with areas of finer sediment deposited to the northwest and southeast of the site limits. One explanation for the observed spatial pattern (Figure 11b) is that the shoaling of the bank increases water flow velocities in this region resulting in resuspension of fine material which is moved predominantly northwest and southeast with tidal flow, as flow changes direction fine sediments are deposited in the lee of the shoal. Another explanation would be that the shallowing exposes the seabed to greater influence by wave action which, combined with the tidal currents, acts to resuspend and transport some of the fine-grained sediment present in the surface sediment. The data acquired as part of the current project during the 2017 dredge campaign suggests that fine sediment can be redistributed in this way within just a few tidal cycles Figure 15.

Recently collated data from the last 10 years were compared with a sediment layer resulting from the priming of the TUFLOW FV sediment transport model. Whilst there appears to be a general agreement in sediment particle size classes across the study region, drilling down and comparing point data to model values at specific points, showed some major inconsistencies. The greatest differences between model values and recorded data were observed in The Narrows, Western Basin Channels, Inner Harbour and Colosseum Inlet. Poor correlation between the model and sediment texture layer in the Western Basin dredged channels is likely a result of the continuously changing natural hydrodynamic conditions in these regions compared to others. The limited comparisons of sediment texture over time in the current model show how highly dynamic the estuarine complex of Port Curtis is. Various factors, natural and anthropogenic, drive these variations. Natural variability may include changing climate (cyclones, rainfall, waves, surges), variations in sediment supply and export, and, over longer periods, fluctuations in relative sea level. There are also natural and anthropogenic constraints that limit the movement of sediment, such as the underlying geology and human developments such as land reclamation, sea wall and wharf construction, canalisation of estuaries, and dredging of navigation channels. Similarly the model in this study was compared to data, which, whilst arguably recent, were taken from different times following different short term forcing factors (for example a rain event, dredging, king tides etc.) but were compared to a model run under representative, yet limited, conditions. The temporal variability in the data also suggest that any sediment texture map developed is likely to become less reliable over time.

The sediment texture map presented here can be used to help inform the sediment texture distribution adopted in future TUFLOW FV modelling of sediment dynamics, although some conceptualisation of the data will be required. In particular further interpretation of the data to understand short term conditions driving sediment distribution would allow the model and data to be more carefully matched and the identification of areas which show very little change over the years and which could potentially be locked into the model.

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Appendix 1 Collated data sources and number of records

Source report and data files	Count
Alquezar, R. and Small, K. (2006). Port Curtis Macrobenthic Monitoring Programme (Final report). Gladstone Port Authority November 1995 - November 2003. Centre for Environmental Management Faculty of Arts, Health and Sciences Central Queensland University, Gladstone, Qld.	**257**
CQPA sediment _KS Ent FP.xls	210
GPA Benthic November 2003 Ent FP.xls	15
GPA NOV 2002 Ent FP.xls	16
Macrobenthic April 2003 Ent FP.xls	16
Alquezar, R. and Small, K. (2006). Port Curtis Macrobenthic Monitoring Programme. Gladstone Port Authority November 1995 - November 2005. Centre for Environmental Management Faculty of Arts, Health and Sciences Central Queensland University, Gladstone, Qld.	**49**
Particle Size analysis FP.xls	8
QERL macrobenthic Nov2004 FP.xls	7
SPP Benthic November 2003 FP.xls	14
SPP November 2001 FP.xls	14
SPPD Seagrass NOV02 FP.xls	6
Arrow LNG Plant Supplementary Report to the EIS, Part B: Marine & Estuarine Ecology Report (2012)	**20**
Sediment particle size- Coffey Environments -Shell LNG -August 2012.xlsx	20
Arrow_Energy_Marine_Benthic_Fish_Mangroves_Report_DRAFT_Vers 3.docx	**20**
No associated file	20
Aurecon (2015), Port of Gladstone Gatcombe and Golding Cutting Channel Duplication Project Final Geotechnical Report. Aurecon Australasia Pty Ltd, Brisbane QLD, 287 pp.	**23**
POG GGCDP Final Geotechnical Report Rev 2.pdf	23
Aurecon (2016), Clinton Vessel Interaction Project Sampling and Analysis Plan Implementation Report. Aurecon Australasia Pty Ltd, Brisbane, 767 pp.	**21**
DOCSCQPA-#1284542v2CVIP_Report_CS15000152_Clinton_Channel_Sampling_and_Analysis_Plan_(SAP)_Implementation_Report_Final.PDF	21
BMT WBM (2012), Port of Gladstone Maintenance Dredging - SAP Implementation Report. BMT WBM Pty Ltd Level 8, 200 Creek Street Brisbane 4000 Queensland Australia PO Box 203 Spring Hill 4004, 351 pp.	**45**
Appendix A - Sediment Analysis Plans - Port of Gladstone Maintenance Dredging - SAP Implementation Report August 2012.pdf	45
BMT WBM (2014), Maintenance Dredging of the Western Basin Dredging and Disposal Project Footprint - Sediment Quality Report	**17**
Appendix A - Sediment Analysis Plans - Maintenance Dredging of the Western Basin Dredging and Disposal Project Footprint - Sediment Quality Report August 2014	17
Central Queensland Ports Authority (2005). 2004 Dredge Material Placement Site Monitoring (Draft). Centre for Environmental Management, Central Queensland University, Gladstone, QLD.	**102**
Sediment 2003_2005 Ent FP.xls	102
Coffey Environments Australia Pty Ltd (2011). Marine and estuarine ecology impact assessment Arrow LNG Plant.	**20**
Particle Size for Coffey Environment May 2010.xlsx	8
Sediment particle size, Coffey Calliope 2011.xls	12
GHD (2006), Report for Sediment Sampling for Sea Disposal of Maintenance Dredging Material Port of Gladstone. 244 pp.	**30**
ENV East Shores GHD (2006) Report for Sediment Sampling for Sea Disposal of Maintenance Dredging Material_ Port of Gladstone.PDF	30

Source report and data files	Count
Gladstone Ports Corporation (2009), Report for Western Basin Dredging and Disposal Project, Sediment Quality Assessment, 527 pp.	**63**
Appendix L - Sediment Quality Report.pdf	63
GPC Sediment budget project	**251**
RTK measurements	16
Dan_Spooner_Grab_Samples_Mastersizer_Analysis.xlsx	12
GPC Sediment budget project	67
No associated file	156
Port of Gladstone Maintenance Dredging Sampling and Analysis Plan	**65**
No associated file	65
Skillington_PCIMP_Seagrass_Bioindicator Study	**9**
No associated file	9
Smithers, S. (2016). REPORT ON TEXTURAL ANALYSES OF MARINE SEDIMENT SAMPLES SUBMITTED FOR ANALYSIS DECEMBER 2015.	**9**
No associated file	9
Worley Parsons resources & energy (2009), Australia Pacific LNG - Dredge Area Option 1B Sediment Characterisation Study. 380 pp.	**19**
Appendix A - Sediment Quality Report - Option 1b.pdf	19
Worley Parsons resources & energy (2009), Australia Pacific LNG - Dredge Area Option 2A Sediment Characterisation Study. 445 pp.	**48**
Appendix B - Sediment Quality Report - Option 2a.pdf	48
CQUniversity Centre for Environmental Management archive	**542**
April 16 Mangrove Sediments.xlsx	26
CQPA Mangrove Nov2004 FP	16
Mangrove data Oct 16 combined_Final.xlsx	26
Mangrove PSA data final 30-06-15.xlsx	26
Mangroves November 2003.xls	15
Mangroves September 2002.xls	17
October size fractions final.xlsx	26
Particle Size analysis FP	17
Particle Size Dec 07 FP	4
Particle Size for URS 2008 FP	24
Particle size nov05 FP.xls	16
PC Port-wide macrobenthos study sediment data Ent FP.xls	149
PCIMP historical Data.xlsx	134
Pelican_banks_seed_field_data_MASTER_EJ.xlsx	21
QERL mangrove Nov2004 FP	5
QERL seagrass Nov2004 FP	9
Wiggins Island April 2003 FP	4
Wiggins Island November 2003 FP	4
Wiggins SEPT01 FP	3
Grand Total	**1610**