PORT OF **WEIPA**

APPENDIX E

Predictive bathymetric model

PORT & COASTAL SOLUTIONS

Port of Weipa: Sustainable Sediment Management Assessment

Bathymetric Model

Report No. P007_R07F1

NORTH QUEENSLAND BULK PORTS CORPORATION

Technical Report
February 2020

PORT & COASTAL
SOLUTIONS

Port of Weipa: Sustainable Sediment Management Assessment

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North Queensland Bulk Ports Corporation Ltd

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Executive Summary

North Queensland Bulk Ports Corporation (NQBP) and Rio Tinto Alcan (RTA) commissioned Port and Coastal Solutions (PCS) who, along with its sub-consultants Water Modelling Solutions and DAMCO Consulting, are undertaking a series of studies to understand whether sedimentation can be managed at the Port of Weipa and at Amrun Port, to avoid or reduce the need for maintenance dredging. These studies form part of NQBP/RTA's long-term Sustainable Sediment Management (SSM) assessment at the Ports, which aims to answer the questions regulators have regarding ongoing maintenance dredging.

Aim: The aim of this study was to develop an interactive predictive sedimentation model for the Port of Weipa. This model will allow future sedimentation predictions to be made for the dredged areas of the Port, which will allow NQBP to understand future maintenance dredging requirements.

Sedimentation Update: Sedimentation rates for the dredged areas of the Port have been updated to include findings from an analysis of bathymetric data collected following the 2018/2019 wet season, which included a number of cyclonic events and a tropical low. It is important to note that the sedimentation over this year (2018-19) in the whole South Channel was more than double that over any other year since the South Channel was enlarged (in 2006). It is not expected that such an extreme event will occur more than once every ~ten years (and is likely to be less frequent).

Predictive Bathymetric Model: A predictive bathymetric model was developed using typical annual and extreme event sedimentation rates, based on volumes calculated from bathymetric changes between surveys undertaken between 2006 and February 2019. Limitations have been accounted for within the bathymetric model to estimate the potential uncertainty associated with the sedimentation volume predictions. Annual sedimentation volume calculations for typical conditions are based on using the 95% confidence interval as a statistic to estimate the uncertainty or limitation that can be place on the sedimentation rate data. For tropical cyclones and years with worst case sedimentation there were insufficient data available to calculate the confidence interval and so the value was set at 0.5 which means that the sedimentation could be 25% more or less than the predictions.

The predictive model has been developed using Microsoft Excel software. The model has been specifically designed for the Port of Weipa, ensuring that user inputs and model outputs are tailored to provide the relevant information required to assist NQBP determine its future dredging requirements.

Future Sediment Management: The bathymetric model has been used to develop an example dredging strategy, providing annual sedimentation depths and volumes that can be used to inform and develop a dredging strategy for the desired number of years by summing the preferred number of years with typical conditions, typical conditions including a tropical cyclone event and typical conditions including worst case sedimentation (i.e. years with two severe tropical cyclones and a tropical low).

The bathymetric model has also been used to estimate future sediment management requirements at the Port of Weipa over the next 10 years. The total sedimentation volume above design depth over the next 10 years for the Port of Weipa is predicted to be in the order of 9.5 million m^3, with the majority of this (approximately 99%) in the South Channel region, specifically the South Channel Mid and South Channel Mid Outer areas (75%).

1. Introduction

North Queensland Bulk Ports Corporation (NQBP) and Rio Tinto Alcan (RTA) commissioned Port and Coastal Solutions (PCS) who, along with its sub-consultants Water Modelling Solutions and DAMCO Consulting, are undertaking a series of studies to understand whether sedimentation can be managed at the Port of Weipa and at Amrun Port to avoid or reduce the need for maintenance dredging. These studies form part of NQBP/RTA's long-term Sustainable Sediment Management (SSM) assessment at the Ports, which aims to answer the questions regulators have regarding ongoing maintenance dredging. The various studies being undertaken by PCS as part of the SSM assessment are as follows:

- Bathymetric Analysis: the aim of this study is to analyse historic bathymetric data, quantify previous bathymetric changes at the ports and define the natural processes which have caused the changes;
- Sediment Budget: the aim of this study is to understand the sediment transport processes which naturally occur at the Ports. This includes understanding the source of the sediment, sediment transport pathways, processes controlling the sediment transport and the development of a quantitative sediment budget;
- Bathymetric Model: the aim of this study is to develop interactive predictive sedimentation models for the two Ports. These models will allow future sedimentation predictions to be made for the dredged areas of the Ports which will allow NQBP/RTA to understand future maintenance dredging requirements at the Ports; and
- Engineered and Technical Solutions: the aim of this study is to assess the availability, practicality and feasibility of engineered or technical solutions that could be implemented to reduce sedimentation in the dredged areas of the Ports. The results from this study will then be used to determine whether there are feasible solutions to avoid or reduce the need for maintenance dredging at the Ports.

1.1. Project Background

NQBP undertakes regular maintenance dredging of the channels and berths at the Port of Weipa to ensure there is sufficient depth for vessels to safely travel to and from the berths (further detail of the historic maintenance dredging is provided in Section 1.2). The sediment that has historically been removed by maintenance dredging, has been relocated to an offshore dredge material placement area (DMPA) located in Albatross Bay (Figure 2).

NQBP has current State and Commonwealth approvals to support maintenance dredging and at-sea placement of the dredged sediment at the Port of Weipa. The current 10-year permit was issued in 2010. Since then, the process to obtain new long-term sea dumping permits in Queensland has become more onerous.

In 2016, a Maintenance Dredging Strategy (MDS) was developed for the ports that are situated within the Great Barrier Reef World Heritage Area (GBRWHA) (DTMR, 2016). This MDS (which supports the wider Reef 2015 Plan) provides a framework for the sustainable, leading practise management of maintenance dredging in the GBR (Figure 1). It is a requirement of the MDS that each Port within the GBRWHA develops Long-term Maintenance Dredging Management Plans (LMDMPs). Such LMDMPs are aimed at creating a framework for continual improvement in environmental performance. DTMR have provided guidelines to assist in the development of the LMDMPs (DTMR, 2018). The guidelines note that they should include, among 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.

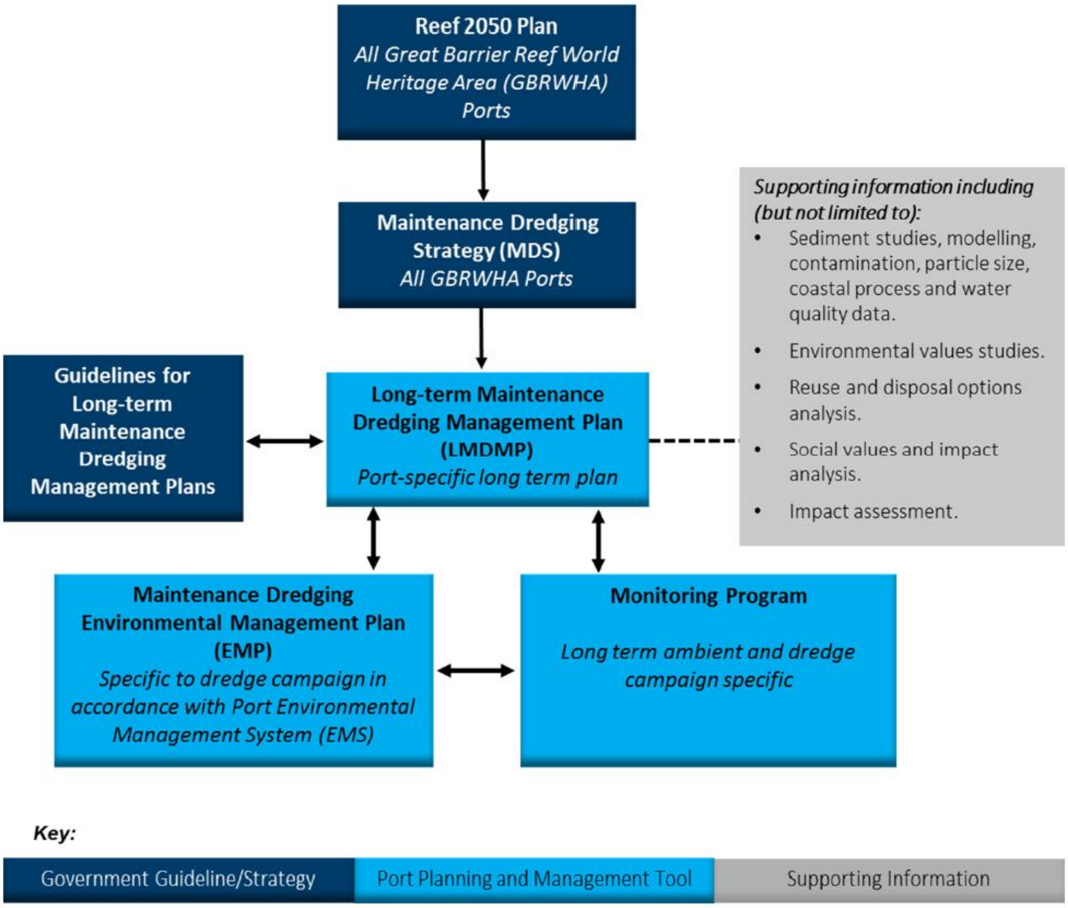


Figure 1. Planning and implementation mechanisms for maintenance dredging of ports Queensland wide (DTMR, 2018).

The requirement to investigate whether sedimentation at ports can be managed to avoid or reduce the need for maintenance dredging is derived from the London Protocol, which forms the basis for Australia's Sea Dumping Act 1981. Based on this, the environmental regulators are particularly focused on the following questions:

1. Can sedimentation be managed at the Port to avoid or reduce the need for maintenance dredging?
   - Where do sediments accumulate in the Port and at what volumes and rates?
   - What causes sedimentation in the Port?
   - Does sedimentation at the Port pose a risk to port operations and safety?
   - Why does the Port need to undertake maintenance dredging?
2. If maintenance dredging must occur, has there been a comprehensive assessment of whether the material can be beneficially reused?
3. If no beneficial reuse options are available, what would be the most suitable and feasible disposal or placement options?
4. Has a comparative analysis of options been undertaken, which considers human health, social values, environmental impacts and disproportionate costs?

To answer these questions, NQBP developed a framework as part of the SSM assessment at the Port of Hay Point. This framework was subsequently used to inform the framework which has been adopted at the Port of Weipa and Amrun Port as well as the framework developed for the MDS, demonstrating that NQBP have been proactive at developing sound long-term maintenance dredging strategies. The studies included as part of the work currently being undertaken by PCS are aimed at answering the questions posed under point 1. Separate studies will be undertaken by NQBP/RTA to answer the other three questions. The findings from all these SSM studies will feed into the development of new LMDMPs at the Ports of Weipa and Amrun.

1.2. Port of Weipa

The Port of Weipa is located in the Gulf of Carpentaria, on the north-west coast of the Cape York Peninsula in Northern Queensland. The Port is within Albatross Bay, a large embayment, with the wharves and berths located in the Embley River (Figure 2 and Figure 3).

In the 2016/17 financial year, the Port of Weipa handled approximately 36 million tonnes of commodities, including bauxite (>95%), fuel, cattle and general cargo. Rio Tinto Alcan (RTA) currently operates most of the port facilities for the export of bauxite (aluminium ore) from the nearby RTA mine.

The Port of Weipa consists of:

- a main shipping channel in Albatross Bay called South Channel (Figure 2); and
- an Inner Harbour which is within the Embley River and consists of four shipping berths (Lorim Point East and West, Humbug Wharf and Evans Landing) and the Approach and Departure Channels (Figure 3).

Several capital dredging campaigns have been undertaken at the Port of Weipa since the early 1960's, with the most recent capital works undertaken in 2012:

- 1961-63: the South Channel was first dredged across the inner half of Albatross Bay, with the natural South Channel being deepened to a depth of 8.2 m below Low Water Datum (approximately equivalent to the Lowest Astronomical Tide (LAT));
- 1980's: the South Channel was deepened and extended to a length of 14.5 km;
- 2006: the South Channel was widened and deepened (GHD, 2005). Due to variable sedimentation within the South Channel the design depth[1] was increased from the uniform depth of -12.2 m LAT in some areas (see Figure 4 for depths following capital dredging) and due to the deepening, the channel also had to be widened to ensure the batter slopes were stable; and
- 2012: the South Channel was extended by 2.4 km with a design depth of -12.2 m LAT (PaCE, 2011).

The Port has approximately 622 hectares of channels, swing basins and berths where depths are maintained by maintenance dredging. NQBP currently has a 10-year Sea Dumping Permit for the Port of Weipa which allows for an average of 1,200,000 m^3 of sediment to be removed by maintenance dredging per annum. This allowance includes a contingency for events such as cyclones, and so this maximum volume is not normally realised on an annual basis. Since 2002 maintenance dredging at the Port has been undertaken annually by the Trailing Suction Hopper Dredger (TSHD) Brisbane, with volumes ranging from approximately 300,000 m^3 to 980,000 m^3 (the high volume of 980,000 m^3 dredged in 2002 was due to the fact that no dredging had been undertaken in 2001). Prior to 2002, maintenance dredging was typically undertaken every two years. The majority of the historic maintenance dredging at the Port of Weipa was undertaken towards the western end of the South Channel, with

[1] the 'design depth' or 'dredge depth' is the depth that engineers have selected as being suitable for the safe and efficient operation of the Port at all tidal levels with natural sedimentation also factored in. The 'declared depth' is the depth designated by the harbour master and reflects the maximum depth for safe navigation, which in some places can also correspond to the shallowest depth within the area.

limited maintenance dredging occurring in the Inner Harbour. A summary of the historic dredging works at Weipa is provided in Table 1. The average volumes of dredged material removed from 2012 to 2016 are detailed in Table 2.

The fact that the Port requires annual maintenance dredging indicates that regular (substantial) sedimentation occurs. In addition to the regular sedimentation, it has also been observed that extreme events such as tropical cyclones (TCs) can result in significant increases in the sedimentation and therefore increased maintenance dredging requirements at the Port. TCs occur in the Gulf of Carpentaria in most years. Based on analysis of historical TCs, it follows that the Weipa region is influenced by TCs on average every other year, although the magnitude of this influence can vary significantly. To reduce the risk of increased sedimentation from a TC resulting in operational or safety issues at the Port, the maintenance dredging has typically been scheduled immediately after the wet season (when TCs occur) and the design depths have been adjusted over time based on the variable sedimentation which occurs in the Port (Figure 4 and Figure 5). In addition, a Dynamic Under Keel Clearance (DUKC®) system, which was developed by OMC International, is in operation at the Port of Weipa to provide real-time navigational aid to ensure safe vessel navigation and to help optimise port operations.

Table 1. Historic in-situ dredging volumes at the Port of Weipa (Advisian, 2018).

Year	Type of dredging	Volume of in-situ material removed (m^3)
2002	Maintenance	976,585
2003	Maintenance	463,513
2004	Maintenance	621,650
2005	Maintenance	803,098
2006	Capital and Maintenance	2,976,868
2007	Maintenance	711,000
2008	Maintenance	774,100
2009	Maintenance	553,457
2010	Maintenance	832,779
2011	Maintenance	470,820
2012	Capital and Maintenance	927,057
2013	Maintenance	644,525
2014	Maintenance	394,523
2015	Maintenance	368,384
2016	Maintenance	504,071
2017	Maintenance	297,301
2018	Maintenance	591,875

Table 2. Typical maintenance dredging volume estimates, declared depths, design depths and estimated footprints for the different dredged areas at the Port of Weipa (Advisian, 2018).

Port Area	Volume Estimate (m^3)	Declared Depth (m below LAT)	Design Depth[1] (m below LAT)	Footprint (ha)
South Channel	465,000	11.1	12.1 to 14.1	256
Approach Channel	24,000	7.3	7.3	272.5
Departure Channel	12,000	11.1	11.1 to 11.8	138.3
Evans Landing	500	9.4	9.4	0.5
Humbug	500	9.5	9.5	0.86
Lorim Point	500	12.3	12.3	2.45
Tug Berth	500	9.0	9.0[2]	2.12

[1] in some areas the design depth is variable due to natural variability in the sedimentation which occurs. The design depths are shown in Figure 4 and Figure 5.

[2] although the design depth at the Lorim Point Tug Berths is -9 m LAT it has not been dredged to that depth (currently around -5 m LAT) and due to the existing depths, the TSHD Brisbane is not able to dredge this area and so bed levelling has been used to maintain the depths to -5 m LAT.

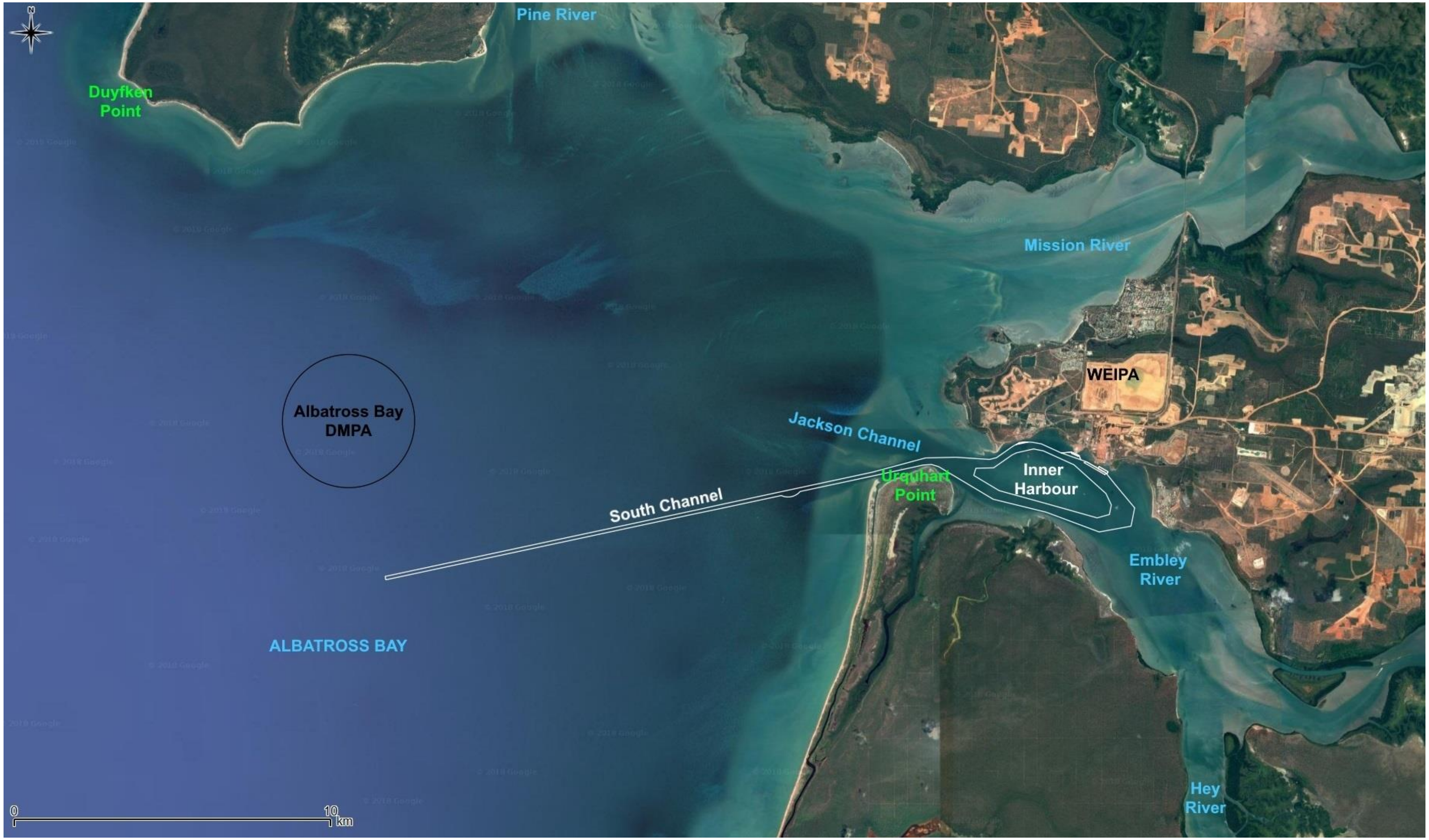


Figure 2. Location of the Port of Weipa.

Figure 3. Close up of the Port of Weipa Inner Harbour area and berths.

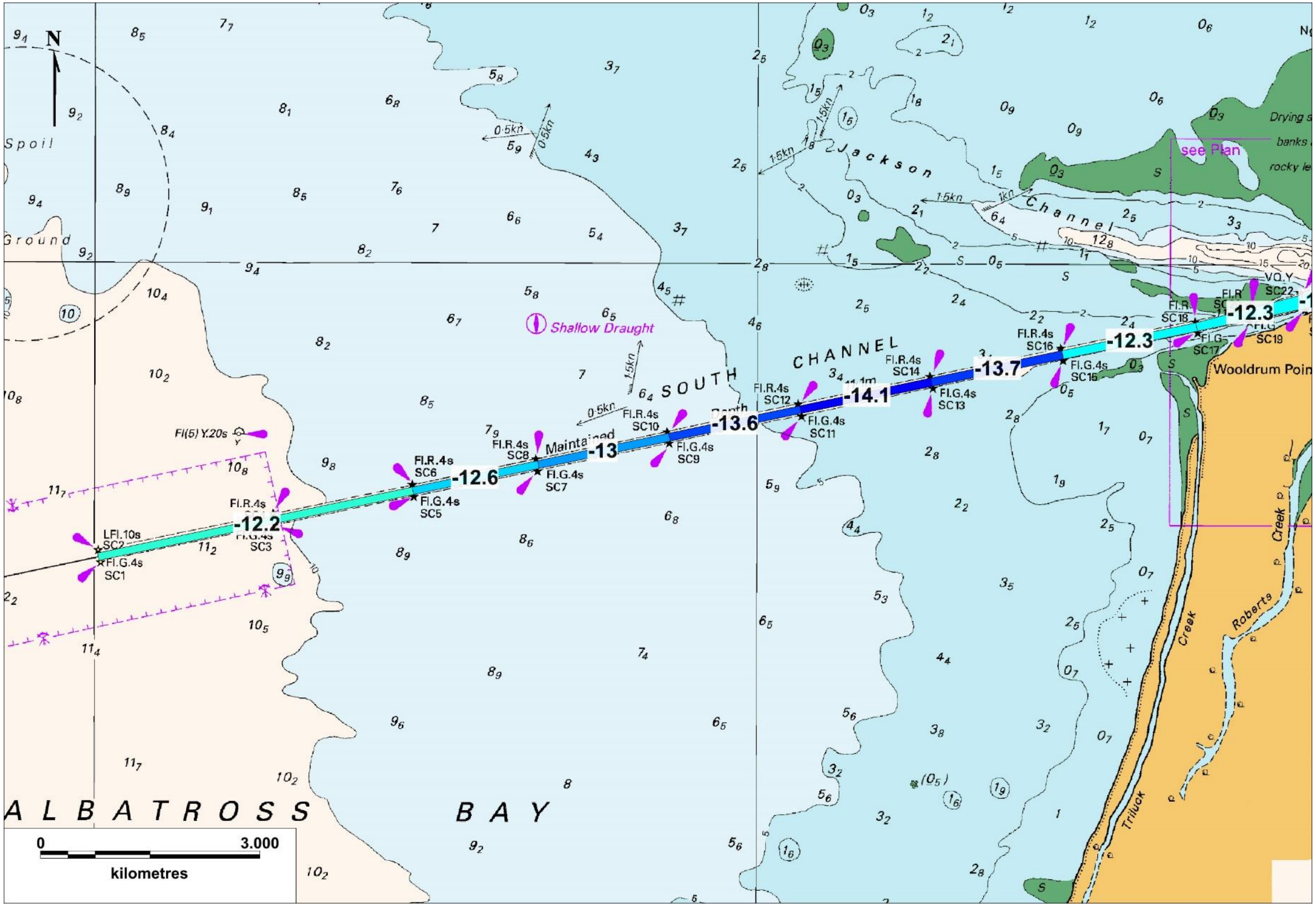


Figure 4. Variable design depths (m LAT) in the Port of Weipa South Channel.

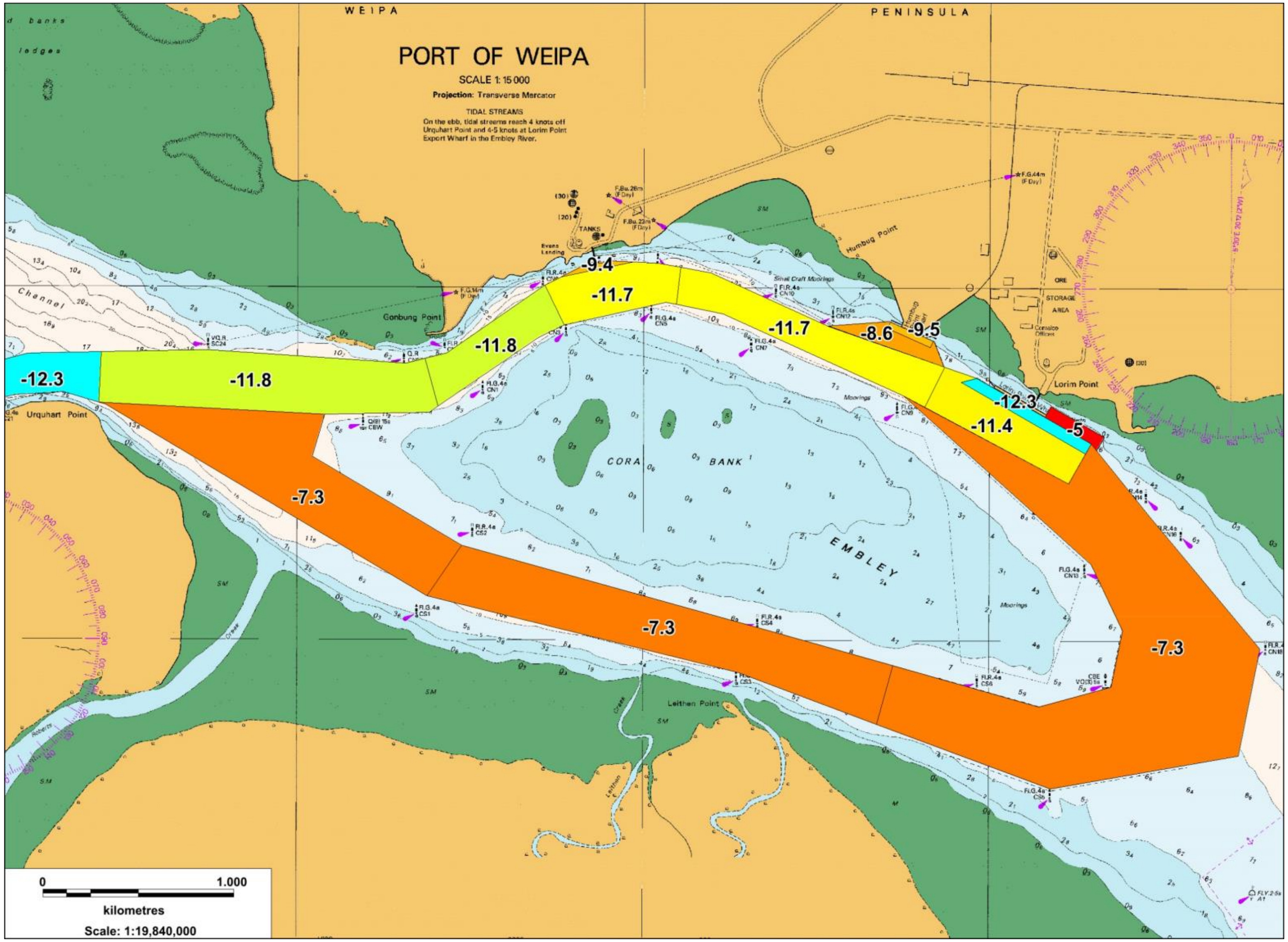


Figure 5. Variable design depths (m LAT) in the Port of Weipa Inner Harbour and berths.

1.3. Report Structure

This report for the Bathymetric Model at the Port of Weipa is set out as follows:

- an introduction to the study is provided in Section 1;
- an update to the bathymetric analysis undertaken by PCS (2018a) is provided in Section 2, this is to calculate the sedimentation which occurred over the 2018-19 wet season;
- details of the predictive bathymetric model for the Port of Weipa are provided in Section 3;
- instructions on how to use the predictive bathymetric model are given in Section 4, and
- a summary of the key components of the report are given in Section 5.

Unless stated otherwise, levels are reported to Lowest Astronomical Tide (LAT). At the Port of Weipa, zero metres LAT is equal to Chart Datum (CD). Volumes presented throughout are *in-situ* cubic metres.

1.4. Glossary

For the purpose of this report the following definitions have been adopted:

Tropical Cyclone (TC): A TC is defined as a non-frontal low pressure system of synoptic scale developing over warm waters and has gale force winds (sustained winds of 63 km/h or greater and gusts in excess of 90 km/h) near the centre. The severity of a tropical cyclone is described in terms of categories ranging from 1 (weakest) to 5 (strongest) related to the maximum mean wind speed, (BOM, 2019a). TC's classed as category 3 or above are defined as being severe. TCs occur intermittently within the Queensland region, however they generally form from lows within the monsoon trough between November and April.

Typical Tropical Cyclone (typical TC): The impact of a TC can vary, some can cause erosion in areas, while others can result in accretion. For the purpose of this study a typical TC has been defined as a single cyclone which is sufficiently large enough to directly influence the region, resulting in increased sedimentation within the specified dredge areas of the Port. Note: Typical TC's influence the region every two to five years.

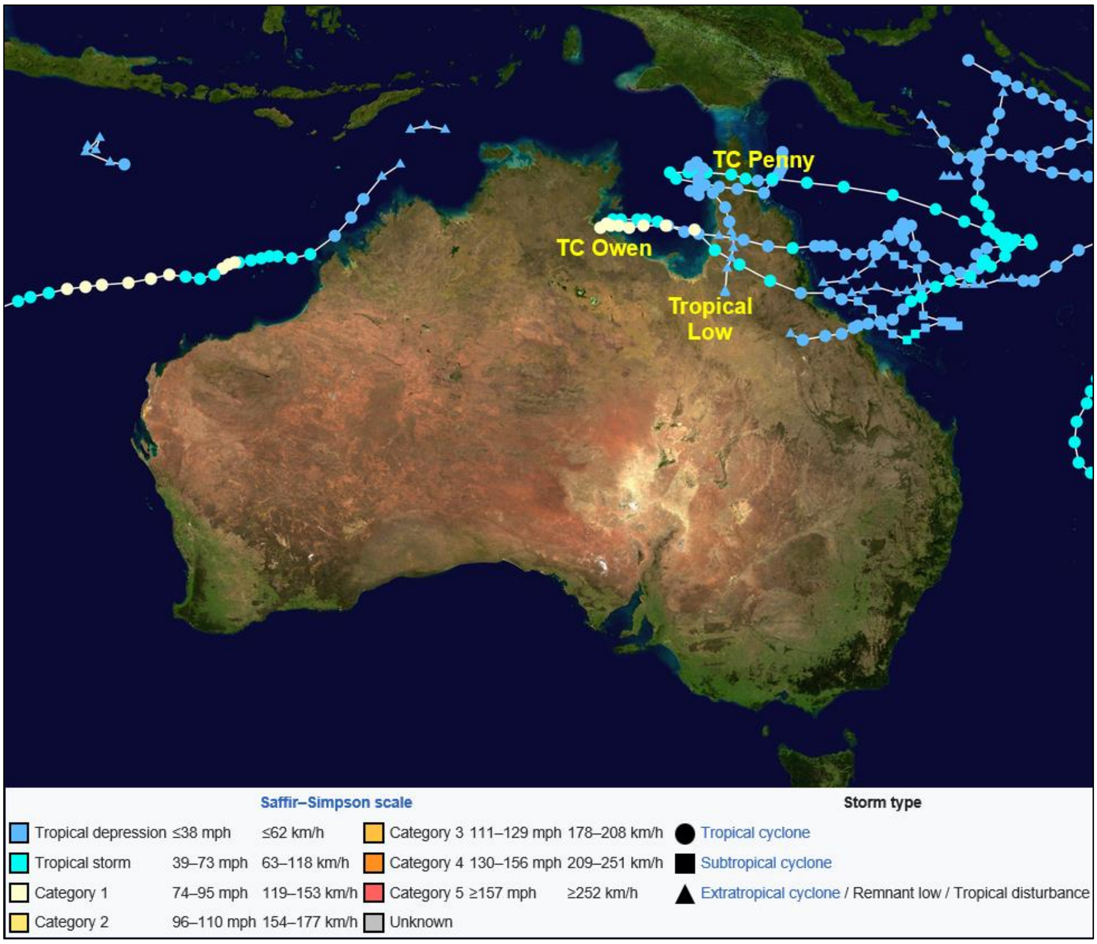
Tropical Low: A Tropical Low is defined as a tropical depression or low pressure system which has a lower intensity (lower average wind speed and higher atmospheric pressure) than a Category 1 TC. For example, on the Beaufort wind scale low pressure systems average wind speeds of less than 62 km/h range in definition from gale to calm conditions (BOM, 2019b). Note: Tropical Low 13U, which is discussed within this report, had sustained winds of 55 km/h, classifying the low pressure system as 'near gale' on the Beaufort scale (one class down from a Category 1 TC) (Wikipedia, 2019).

Worst case sedimentation year: For the purpose of this study a year with worst case sedimentation includes two severe tropical cyclones and one tropical low all directly influencing the region. Note: Only one worst case sedimentation year has occurred in the region over the period considered as part of this assessment (2003 - 2019) and based on this it is assumed that they could occur every 10 - 20 years. A year with worst case sedimentation is differentiated from a typical TC as this year has multiple events in addition to natural sedimentation.

2. Sedimentation Update

During the 2018 to 2019 wet season, a number of cyclonic and tropical low events influenced the Gulf of Carpentaria (Figure 6). This included TC Owen in early December 2018 and TC Penny at the end of December 2018 and early January 2019. Both of these cyclones made landfall twice along the Cape York peninsula, they initially crossed in a westerly direction before turning around in the Gulf of Carpentaria and crossing again in an easterly direction. TC Penny made landfall close to Weipa when it crossed in an easterly direction, resulting in the largest waves (up to ~3.5 m) of the 2018-19 wet season, although the Tropical Low in January/February 2019 resulted in the longest duration of increased wave heights (Figure 7).

The weather events in the 2018-19 wet season resulted in the significant wave heights (H_s) exceeding 2 m for more than double the duration of any other year since 2009 (= the year when the Albatross Bay wave rider buoy (WRB) was installed by the Department of Environment and Science (DES) of the Queensland Government) (Figure 8). This threshold was identified as a potential indicator of sedimentation volumes in the dredged areas (specifically the South Channel) of the Port of Weipa (PCS, 2018a). Given the potential for high sedimentation during the 2018-19 wet season, an additional bathymetric analysis was undertaken as part of this assessment so that the sedimentation that occurred over the 2018-19 wet season could be included in the bathymetric model. This section provides details of the results of that additional bathymetric analysis.



Note: the colour of the symbols represents the maximum sustained wind speeds as categorised in the Saffir-Simpson Hurricane scale and the shape represents the type of storm.

Figure 6. Summary of the 2018-19 Australian region cyclone season (up to the start of March 2019) (Wikipedia, 2019).

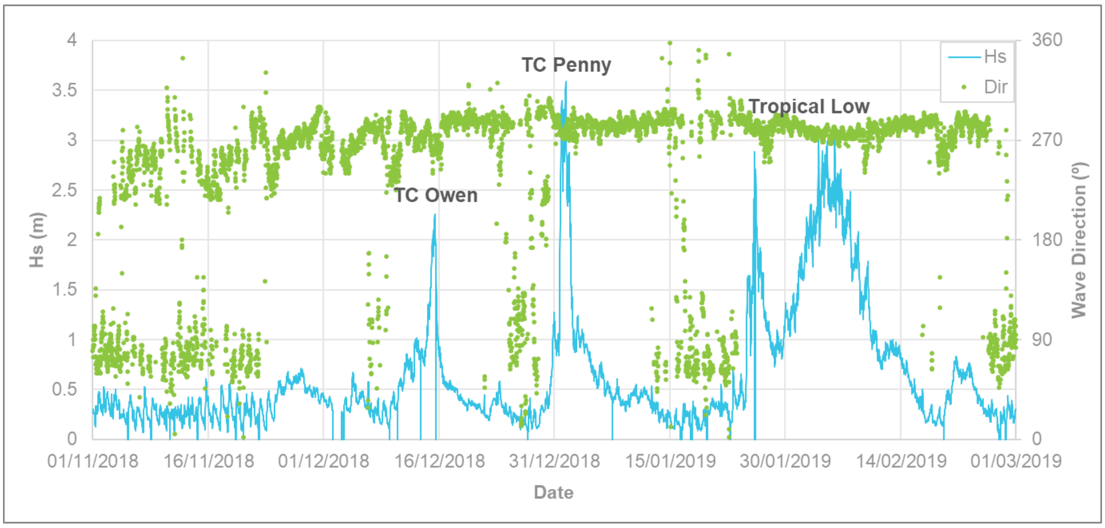


Figure 7. Significant wave height and direction during the 2018-19 wet season measured at the Albatross Bay WRB (wave data from DES).

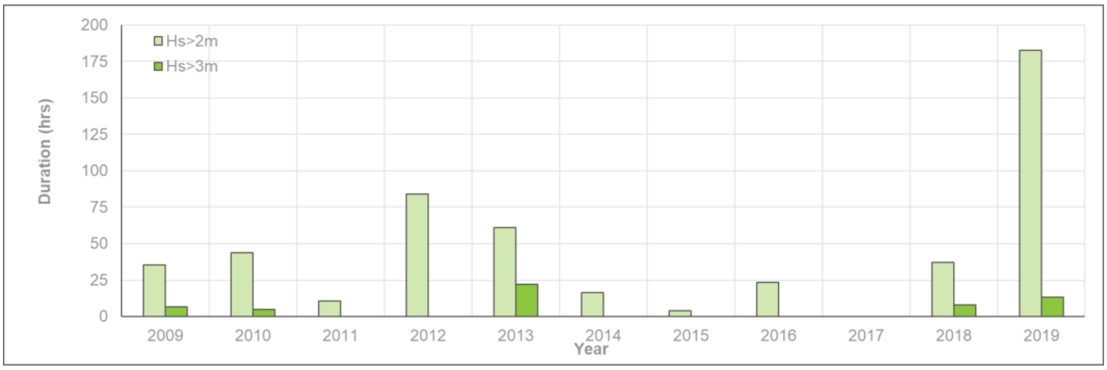


Figure 8. Duration of hours H_s > 2 m and 3 m from 2009 to 2019.

2.1. Bathymetric Analysis

The following hydrographic surveys of the South Channel of the Port of Weipa have been analysed as part of this assessment:

- 6th May 2018 post dredge; and
- 19th February 2019 post tropical low.

As with the previous bathymetric analysis undertaken for the Port of Weipa SSM Project (PCS, 2018a), the hydrographic survey data were used to create high resolution (3 m) gridded Digital Elevation Models (DEMs). The DEMs were created using an inverse distance weighting interpolation method (PitneyBowes, 2009) with a search radius of 20 m. The DEMs were analysed and processed to determine how the bathymetry has changed between 2018 and 2019.

2.2. Results

The difference between the bathymetry in February 2019 and May 2018 (i.e. the sedimentation which occurred in the South Channel) is shown in Figure 9 and the difference between the February 2019 bathymetry and the design and declared depths are shown in Figure 10 and Figure 11, respectively. The plots show that significant sedimentation has occurred in the South Channel between SC2 and SC16 over this period, with the highest sedimentation (up to 2 m) having occurred between beacons SC8 and SC14. The sedimentation has resulted in the depths being more than 1 m shallower than the design depths for the majority of the South Channel and 2 m shallower between Beacons SC10 and SC14 (Figure 10). Despite the extensive sedimentation which has occurred, the majority of the bathymetry in the South Channel has remained below the declared depth of -11.1 m LAT, due to the sedimentation allowance created by the difference between the design and declared depths (up to 3 m in places). There are some locations along the edge of the channel where the sedimentation has resulted in the bathymetry exceeding the declared depth, these are mainly along the northern side of the channel between beacons SC8 and SC14.

A long section through the centre of the South Channel shows the change in bathymetry between May 2018 and February 2019 along with the sedimentation allowance provided by the variable design depth (i.e. the difference between the declared depth and the design depth) (Figure 12). The plot shows how the sedimentation has resulted in the bathymetry along the South Channel in February 2019 being a gradual curve between beacons SC2 and SC16, with the peak of the curve located between beacons SC8 and SC10. The reason for this curve is thought to be related to the complex relationship between the following processes which influence sedimentation within the South Channel:

- trapping efficiency of the channel: the trapping efficiency increases as the difference in depth between the channel and the adjacent natural seabed increases. As such, the highest trapping efficiency in the South Channel occurs to the east of Beacon SC10 as the post maintenance dredging depth is less than -13 m LAT and the seabed is less than -6 m LAT;
- wave exposure: the wave conditions will vary significantly along the South Channel which will also influence the potential for sedimentation. Larger waves will occur at the western end of the channel and the waves will reduce in size with distance east along the channel due to wave propagation and breaking. Larger waves will act to limit sediment deposition as the waves will regularly resuspend any deposited sediment, while sediment deposition can occur with smaller waves when they do not impose sufficient force on the seabed; and
- tidal current speeds: high tidal current speeds can regularly resuspend fine-grained sediment from the seabed, thereby preventing net sedimentation from occurring. In contrast, low tidal current speeds will encourage regular sedimentation and allow a net build-up of sediment on the seabed. The tidal currents in the South Channel increase towards the mouth of the Embley River, these current speeds limit sedimentation to the east of Beacon SC16, while the current speeds reduce to the west of this Beacon, allowing sedimentation to occur.

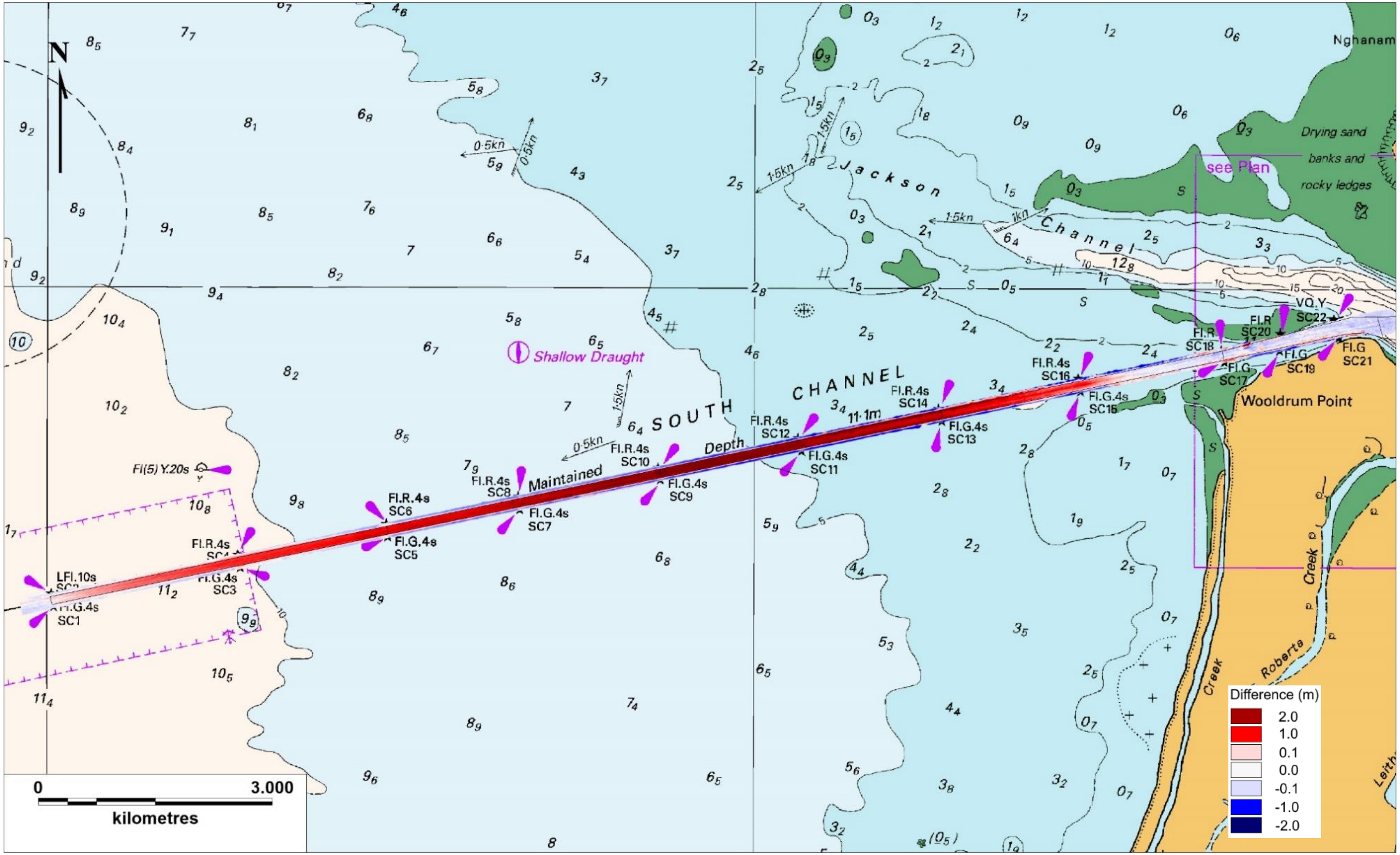


Figure 9. Bathymetric change in the South Channel of the Port of Weipa from May 2018 to February 2019, showing erosion in blue and accretion in red.

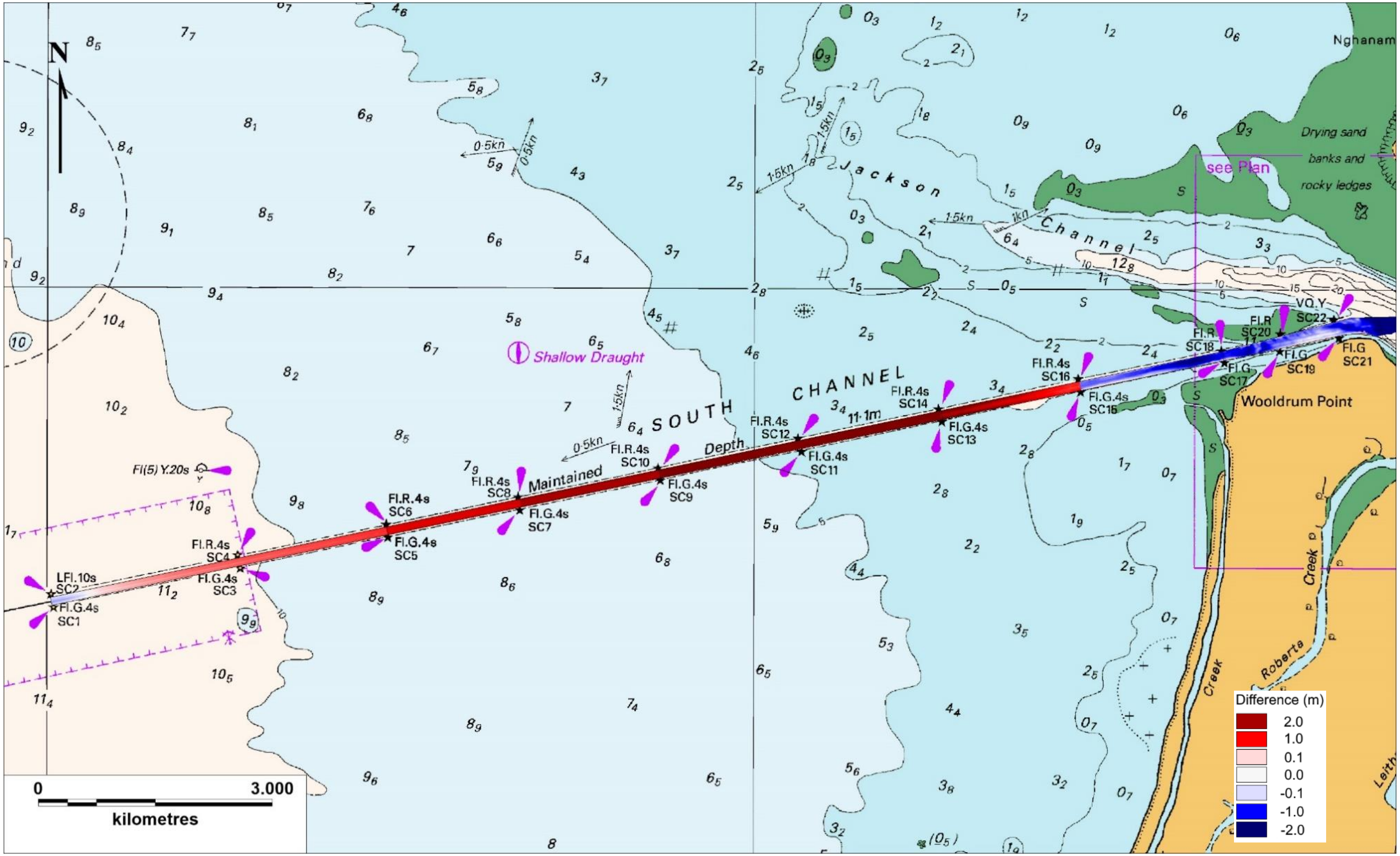
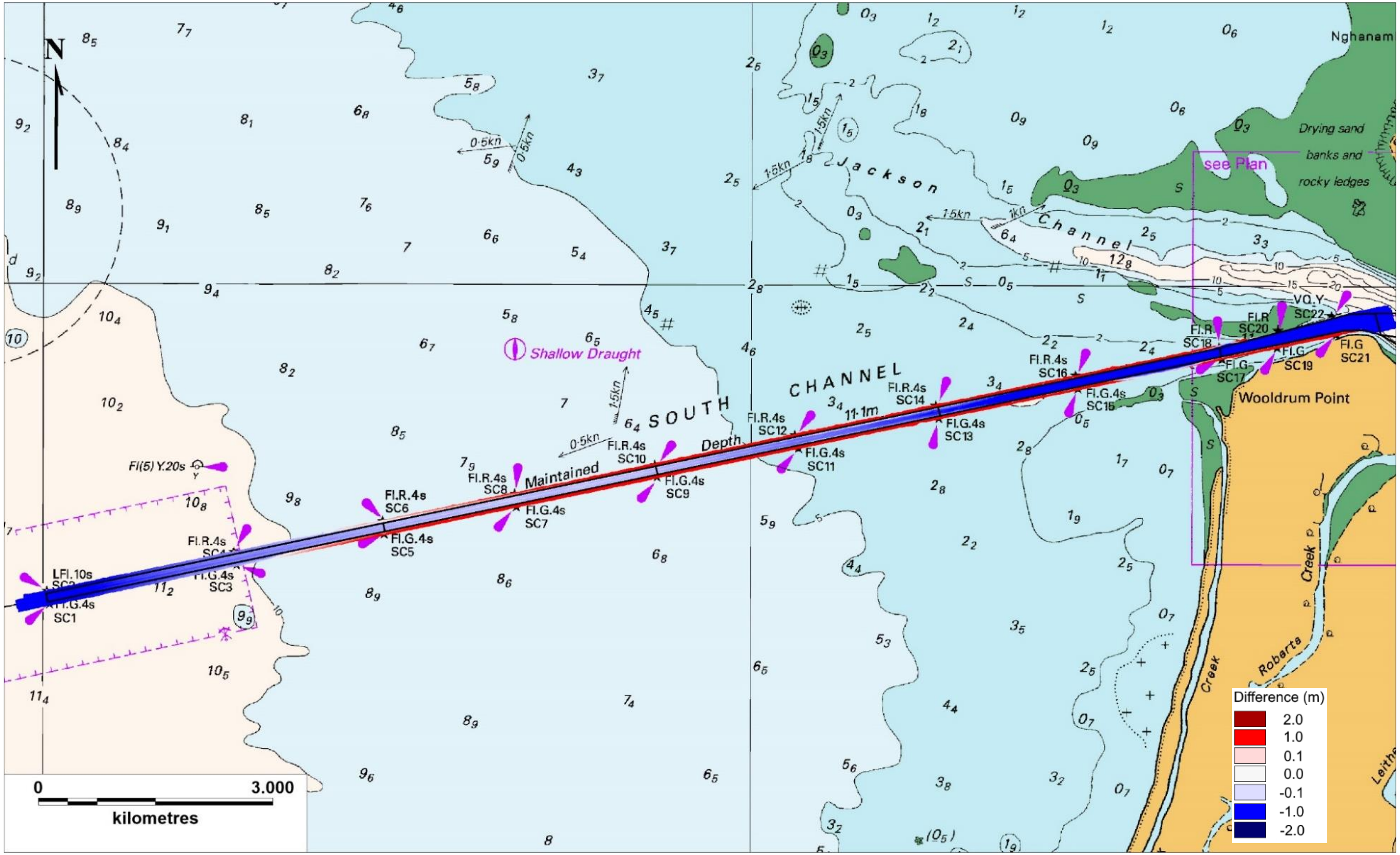


Figure 10. Depth above (red) and below (blue) design depths for the February 2019 post tropical low survey for the South Channel.



Note: The channel and separate volume calculation regions are outlined in black.

Figure 11. Depth above (red) and below (blue) declared depth for the February 2019 post tropical low survey for the South Channel.

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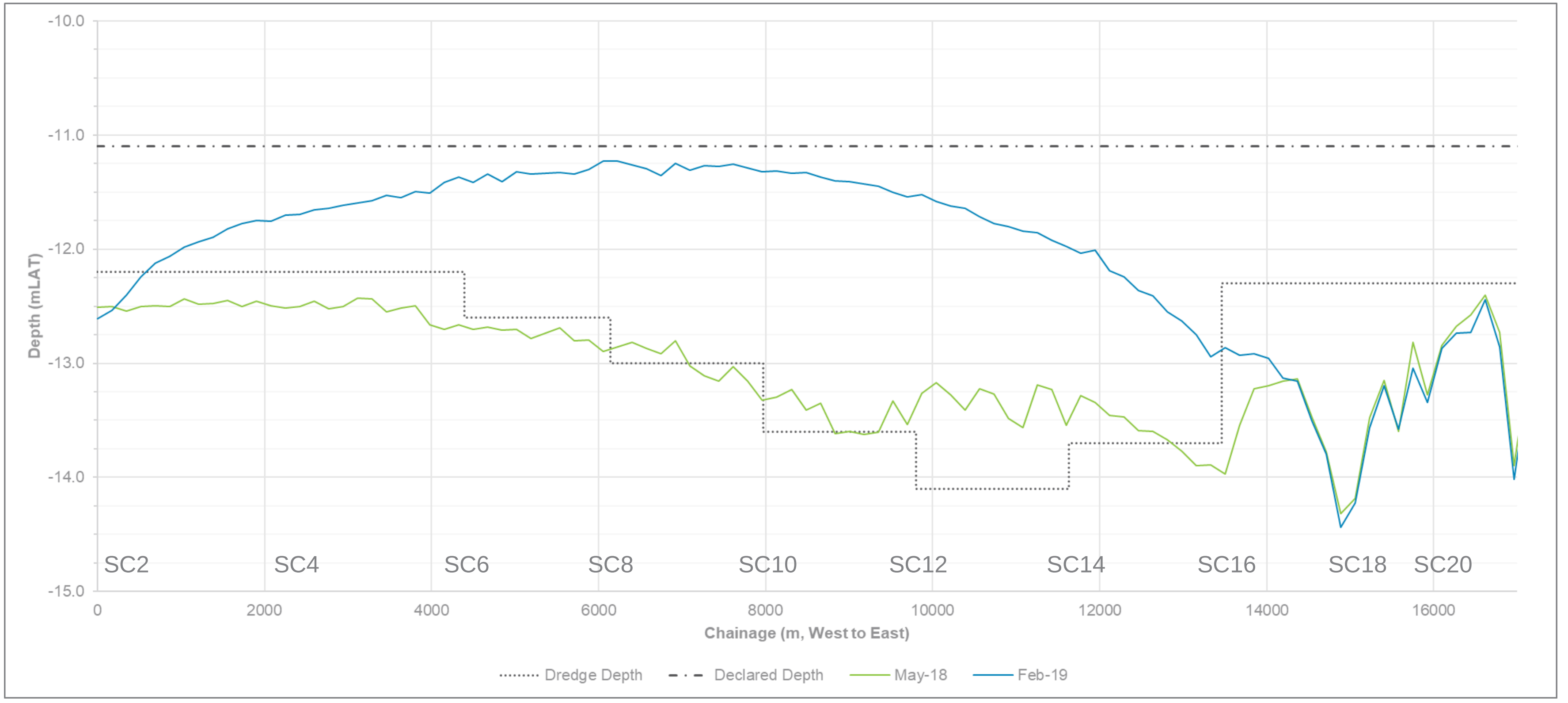


Note: the channel beacon names are shown above the x-axis.

Figure 12. Long Section along the centre of the South Channel showing the May 2018 and February 2019 bathymetry along with the design and declared depths for the South Channel.

A volumetric analysis of the bathymetric data has been undertaken and is detailed in Table 3. The table shows that in total almost 1.9 Mm^3 of sediment was deposited in the South Channel between May 2018 and February 2019. Due to the sedimentation the volume of sediment above the design depths in the South Channel was just over 2 Mm^3, while the volume of sediment above the declared depth was less than 10,000 m^3.

Table 3. Volumetric analysis results for the February 2019 bathymetric survey.

Area	2018-19 Sedimentation (m^3)	2019 Volume above design depth (m^3)	2019 Volume above declared depth (m^3)
S Channel Outer	327,212	228,462	27
S Channel Mid Outer	560,680	564,010	964
S Channel Mid	740,977	945,761	8,156
S Channel Mid Inner	245,144	305,919	192
S Channel Inner	11,824	3,235	21
S Channel Total	**1,885,838**	**2,047,388**	**9,360**

When the February 2019 sedimentation volume is compared to the historic volumes over the last 10 years (since 2009 when the Albatross Bay WRB was installed) it is more than three times higher (Figure 13)[2]. It was previously noted by PCS (2018b) that there was a relationship between sedimentation in the South Channel and the number of hours that the Albatross Bay WRB H_s was more than 2 m. Figure 13 and Figure 14 show that with the 2019 sedimentation data also included there is still a clear correlation. This relationship suggests that for each hour the H_s exceeds 2 m there will be in the order of 8,000 m^3 of sedimentation in the South Channel and each year regardless of wave conditions approximately 115,000 m^3 of sedimentation is expected. Based on these relationships the total sedimentation over the 2018-19 period was estimated to be 1,715,000 m^3 (approximately 90% of the measured sedimentation). The relationships can also be used to estimate the sedimentation that occurred for each extreme event over the 2018-19 wet season, to determine their relative contribution to the total annual sedimentation:

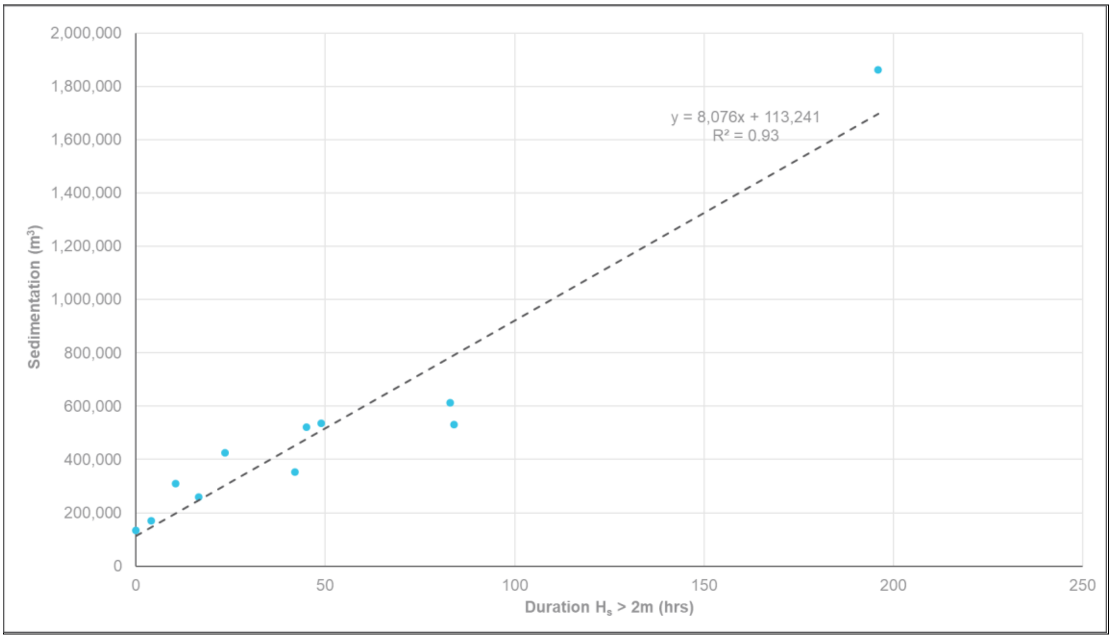
- TC Owen (early December 2018): 50,000 m^3 of sedimentation (3% of total annual sedimentation);
- TC Penny (end December 2018 and early January 2019): 370,000 m^3 (22% of total annual sedimentation); and
- Tropical Low 13U (end January to early February 2019): 1,180,000 m^3 (69% of total annual sedimentation).

The 2019 sedimentation rates will be incorporated into the predictive bathymetric model as a worst case year where multiple cyclonic and tropical low events result in a long duration of large waves in the Weipa region[3]. It is important to note that the sedimentation over this year in the whole South Channel was more than double that over any other year since the South Channel was enlarged (in 2006) and therefore such an event is not expected to occur more than once every ten years (and is likely to be less frequent).

[2] the second highest annual sedimentation within the South Channel since the 2006 channel enlargement was in 2008 when approximately 840,000 m^3 was deposited, this was primarily due to TC Helen.

[3] the worst-case year sedimentation for South Channel Inner has been taken from 2010, as 2019 showed no net sedimentation in this region and 2010 resulted in the largest net sedimentation since 2006.

Figure 13. Total annual sedimentation in the South Channel (bottom) along with the hours that wave heights were exceeded each year at the Albatross Bay WRB (top).



Note: to represent the increased sedimentation when H_s > 3 m the durations were doubled. This was to account for the non-linear relationship between H_s and SSC (see PCS (2018b)).

Figure 14. Updated correlation between wave conditions and sedimentation in the South Channel including the 2018 to 2019 sedimentation.

2.3. Sedimentation Summary

Following the February 2019 bathymetric survey, severe TC Trevor impacted the Weipa region in March 2019 and resulted in additional sedimentation in the South Channel. The bathymetric survey was not analysed as part of this assessment, but based on analysis of surveys undertaken between 28th March and 9th April 2019 by the Australian Hydrographic Surveys (AHS), the total volume above the design depth in the South Channel increased from 2.0 Mm^3 in February 2019 to 2.4 Mm^3 in April 2019. This relative increase in sedimentation was factored into the final bathymetric model, with the sedimentation volumes included in Table 4 and Table 5 which provide a summary of the annual sedimentation at the Port of Weipa.

The data presented for the South Channel region shows the net change in bathymetry, while the data for the Inner Harbour and berth regions shows sedimentation above design depth. This is because the sedimentation in the South Channel is relatively uniform over each area, while in the Inner Harbour the sedimentation which influences navigation is very localised.

The values for the South Channel presented for the 2018 to 2019 period in Table 3 differ slightly from those presented in Table 4 and Table 5. Table 3 presents the sedimentation which occurred and ignores erosion (this only influences the values in South Channel Inner and South Channel Mid Inner), while the values in Table 4 and Table 5 present the net change in bathymetry (i.e. the values are influenced by both sedimentation and erosion), with periods of erosion being replaced with a zero value so that they do not influence the mean rate.

The data presented in Table 4 and Table 5 will be used within the predictive bathymetric model for the Port of Weipa.

Table 4. Sedimentation at the Port of Weipa from 2002 to 2018 (table 1 of 2).

Region	Area	Annual sedimentation rate (m³/year)								
		2006	2007	2008	2009	2010	2011	2012	2013	2014
South Channel	S Channel Outer	64,830	19,202	45,725	12,328	15,198	0	60,291	0	0
	S Channel Mid Outer	158,639	172,439	258,669	59,251	149,324	52,683	192,671	140,989	40,806
	S Channel Mid	339,480	329,345	439,226	177,182	223,942	129,216	198,663	328,021	84,348
	S Channel Mid Inner	50,315	87,913	56,324	0	76,684	18,417	33,921	46,141	0
	S Channel Inner	26,939	31,409	38,770	33,618	55,551	40,898	21,764	22,158	46,357
Inner Harbour	Approach 1	0	1	0	0	1	0	2	6	5
	Approach 2	9	0	0	66	13	72	94	4	0
	Approach 3	5,548	595	2,803	5,133	2,415	4,736	4,513	54	1,158
	Departure 1	3,558	0	0	0	2,556	736	0	0	29
	Departure 2	3,159	2,419	1,728	2,455	3,637	2,882	2,678	1,382	572
	Departure 3	4,781	0	3,528	0	1,532	2,193	503	0	674
Berths	Evans Landing	9	0	0	0	0	0	3	0	0
	Humbug Approach	19	4	16	0	21	3	58	17	16
	Lorim Berths	61	44	379	134	484	481	1,514	143	202
	Humbug Berth	133	5	29	13	0	217	236	0	71
	Lorim Tugs	796	0	0	0	214	21	0	0	0

Notes:

For areas within the South Channel, volumes were calculated to provide the net change in bathymetry.
For areas within the Inner Harbour and berths, volumes were calculated above design depth.

Table 5. Sedimentation at the Port of Weipa from 2002 to 2018 (table 2 of 2).

Region	Area	Annual sedimentation rate (m³/year)					Sedimentation rate (m³)		
		2015	2016	2017	2018	2019	Total Net	Mean	Max
South Channel	S Channel Outer	0	24,072	0	154,816	396,662	*793,123*	*30,497*	*396,662*
	S Channel Mid Outer	0	66,671	0	122,217	692,014	*2,106,373*	*108,797*	*692,014*
	S Channel Mid	63,795	223,368	0	184,677	899,436	*3,620,699*	*209,328*	*899,436*
	S Channel Mid Inner	0	44,085	0	29,455	348,203	*791,457*	*34,096*	*348,203*
	S Channel Inner	8,084	16,449	4,780	0	34,492	*377,615*	*26,675*	*55,551*
Inner Harbour	Approach 1	1	0	0	1		*16*	*1*	*6*
	Approach 2	0	89	0	50		*398*	*31*	*94*
	Approach 3	194	4,184	2,615	6,023		*39,972*	*3,075*	*6,023*
	Departure 1	136	0	62	34		*7,111*	*547*	*3,558*
	Departure 2	398	314	373	940		*22,936*	*1,764*	*3,637*
	Departure 3	675	1,062	0	1,530		*16,478*	*1,268*	*4,781*
Berths	Evans Landing	0	0	0	1		*14*	*1*	*9*
	Humbug Approach	24	102	1	51		*330*	*25*	*102*
	Lorim Berths	92	123	212	1,045		*4,914*	*378*	*1,514*
	Humbug Berth	316	457	39	314		*1,830*	*141*	*457*
	Lorim Tugs	0	0	0	0		*1,031*	*79*	*796*

Notes:

For areas within the South Channel, volumes were calculated to provide the net change in bathymetry.
For areas within the Inner Harbour and berths, volumes were calculated above design depth.

3. Predictive Model

The aim of this study is to develop an interactive predictive sedimentation model for the Port of Weipa. This model will allow future sedimentation predictions to be made for the dredged areas of the Port, which will allow NQBP to understand future maintenance dredging requirements.

3.1. Introduction

Based on the analysis reported in PCS (2018a), a predictive bathymetric model has been developed to predict future sedimentation within the maintained areas of the Port of Weipa, including the South Channel, Inner Harbour and Berths.

As part of the analysis, the areas of the Port with maintained depths were split into a number of sub-regions as shown in Figure 15 (for the South Channel) and Figure 16 (for the Inner Harbour and Berths). These include:

- South Channel
  - South Channel Outer,
  - South Channel Mid Outer,
  - South Channel Mid,
  - South Channel Mid Inner, and
  - South Channel Inner
- Inner Harbour
  - Approach 1,
  - Approach 2,
  - Approach 3,
  - Departure 1,
  - Departure 2, and
  - Departure 3.
- Berths
  - Evans Landing,
  - Humbug Approach,
  - Lorim Berths,
  - Humbug Berth, and
  - Lorim Tugs.

Volumetric changes were calculated for each of these areas as part of the previous bathymetric analysis study (PCS, 2018a).

The bathymetric analysis has shown that the majority of the historical sedimentation at the Port of Weipa has occurred in the South Channel and that limited sedimentation has occurred in the Inner Harbour. The sedimentation within the South Channel is variable, with higher rates of sedimentation occurring in the Mid and Mid Outer regions (PCS, 2018a).

The bathymetric model will be designed to predict future ongoing sedimentation in these areas. It will also have the ability to predict episodic future sedimentation in these areas due to tropical cyclones and years with multiple tropical cyclones and tropical lows (albeit to a low degree of accuracy due to limited data). The interactive model has been developed to provide a decision support tool to allow for strategic planning of future maintenance dredging activity at the Port of Weipa.

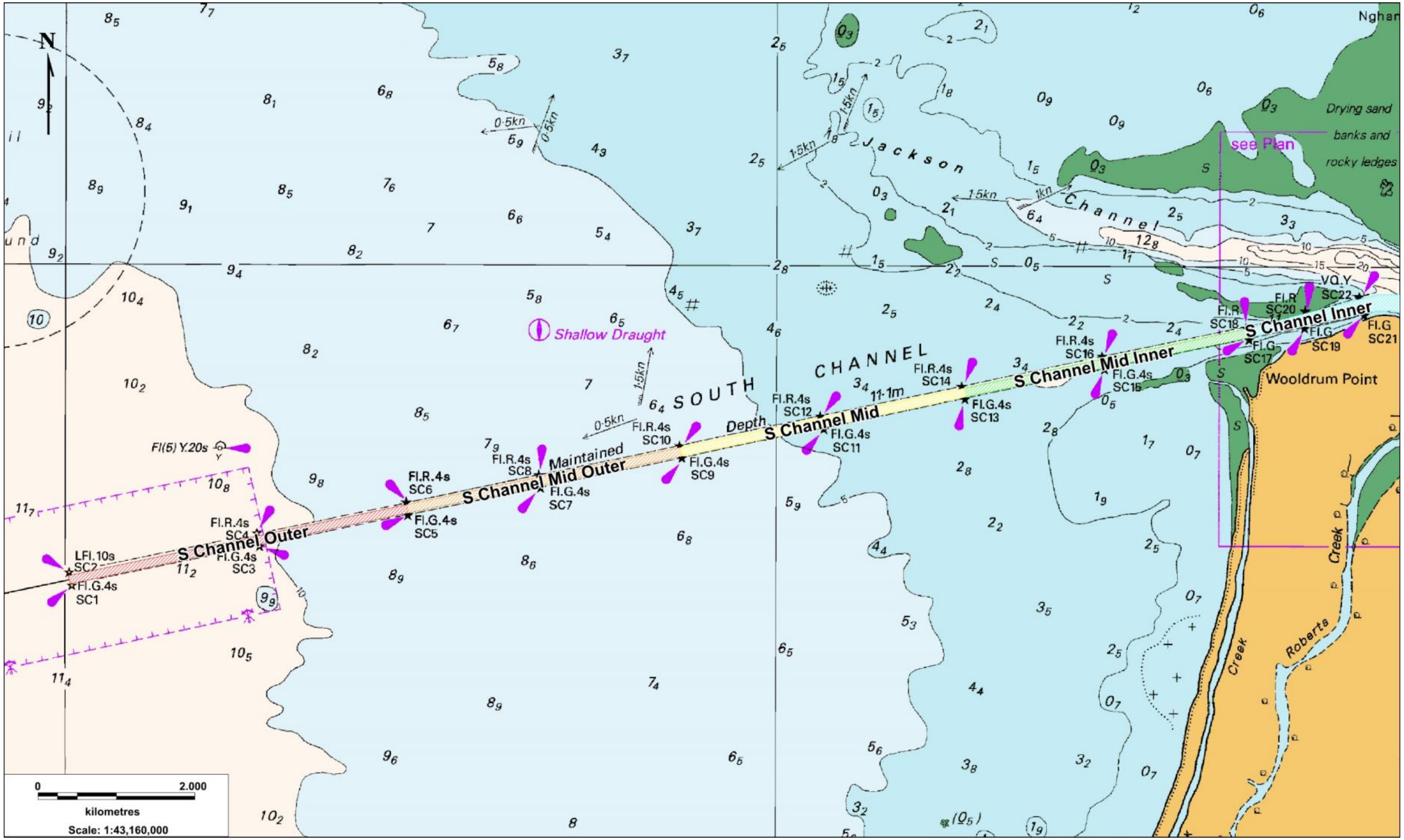


Figure 15. Sub-regions of the South Channel used in the bathymetric analysis.

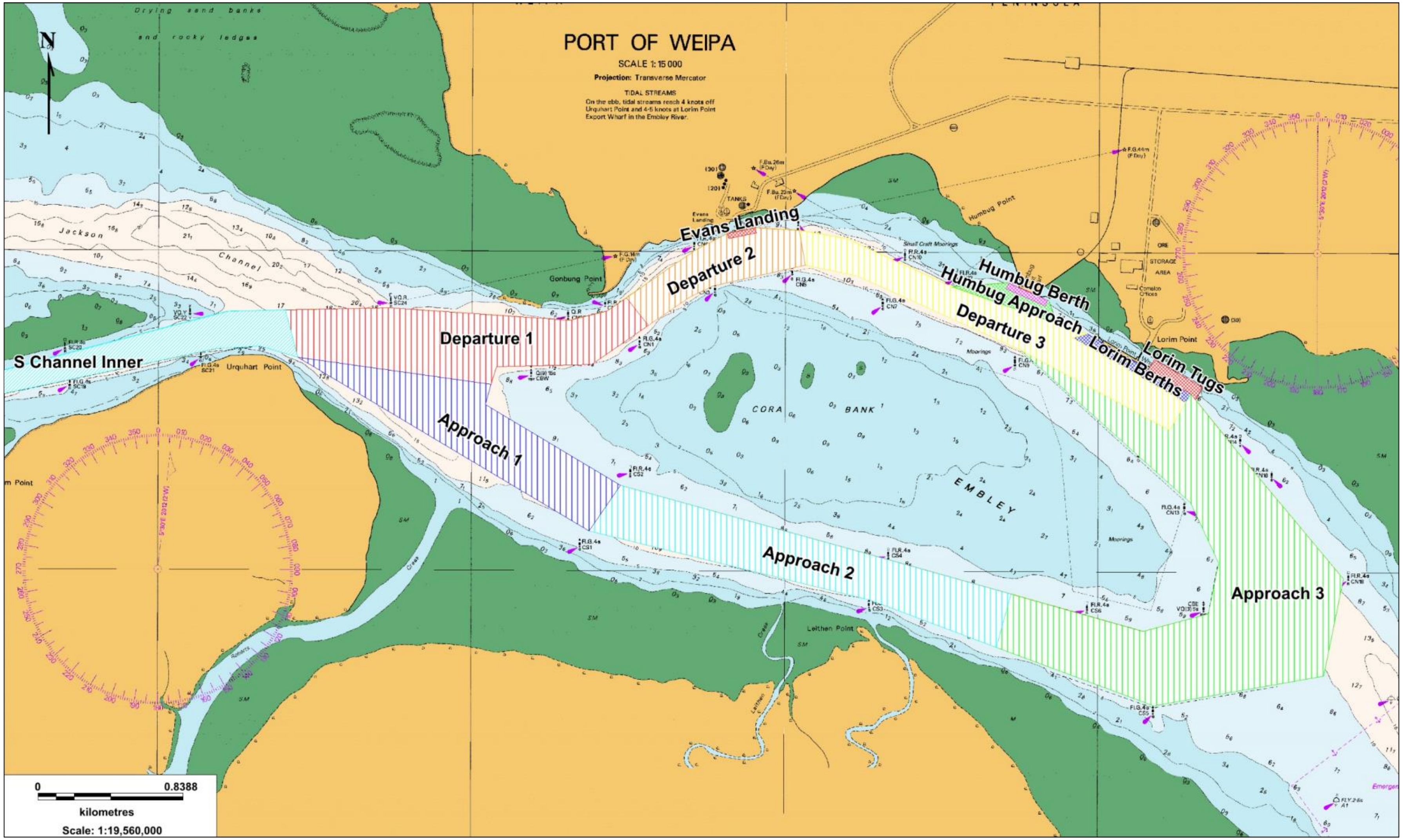


Figure 16. Berths and Sub-regions of the Inner Harbour used in the bathymetric analysis.

3.2. Development

The following section provides details on the development of the predictive model. The predictive capacity of this model would have to include future sedimentation rates and maintenance dredging requirements, the influence of tropical cyclones and tropical lows and a summary of annual sedimentation rates for the areas within the Port of Weipa.

3.2.1. Future sedimentation rates and maintenance dredging requirements

Analysis of the natural sedimentation/erosion which has occurred within the Port of Weipa each year was undertaken within the Bathymetric Analysis Report (PCS, 2018a). That analysis determined that the annual total change in bathymetry within the Port has been variable between 2003 to 2018, and resulted in the following (additional) observations:

- the maximum change was sedimentation of approximately 900,000 m^3 occurring between 2005-2006 and 2007-2008. The minimum change was erosion of approximately 300,000 m^3 that occurred between 2016-2017. The overall mean change between 2003 to 2018 has been sedimentation of approximately 360,000 m^3/year;
- the majority of the sedimentation in the dredge areas of the Port of Weipa occurred in the South Channel, with almost 5.8 M m^3 deposited in the channel between 2003 to 2018;
- there has been net sedimentation in all regions of the South Channel with the majority of the sedimentation occurring over an 8 km length of the 17 km long channel. This has been in the Mid region (between beacons SC10 and SC14) and Mid Outer region (between beacons SC6 and SC10) of the South Channel;
- the spatial distribution of the sedimentation in the Mid to Outer regions of the South Channel shows approximately even sedimentation on both sides of the channel, with either less sedimentation or net erosion in the centre of the channel due to the eroding effect of propeller wash. Within the Mid Inner and Inner regions of the South Channel, the spatial distribution is different, suggesting that the sedimentation here is due to different processes compared to the other regions of the South Channel;
- the majority of the Inner Harbour has been subject to net erosion between 2003 to 2018, with limited regions that were subject to net sedimentation (Approach 2, Approach 3 and the berths). The sedimentation in Approach 3 is clearly visible, with accretion occurring at the eastern end of Cora bank and along the southern edge of the channel. The accretion within the berths is predominantly along the side of the berth and at the ends of the berths as these areas will be less influenced by vessels propeller wash; and
- the sand waves at the northern and southern side of the channel at the Embley River mouth show areas of erosion and accretion as the sand waves migrated over time.

Following analysis of the 2018 and 2019 bathymetric surveys, the maximum change in sedimentation has been calculated to be significantly higher than previous years. Approximately 2.4 Mm^3 of sedimentation occurred between 2018 and 2019, as discussed previously in Section 2.3.

3.2.2. Influence of tropical cyclones

Tropical Cyclones (TCs) regularly form in the Gulf of Carpentaria during the wet season and have the potential to result in strong to gale force winds and large wave heights in the Weipa region. Between 1969 and 2018, a total of 21 TCs have passed within 100 km of the Port of Weipa and 45 TCs have passed within 200 km (BOM, 2019c). Due to the clockwise wind rotation of TCs in the southern hemisphere, combined with the location of Weipa in the Gulf of Carpentaria, it is typically TCs located south of Weipa that result in large waves and strong onshore winds in the vicinity of the Port of Weipa.

Recent TCs that have affected the Port include TC Penny (December 2018/January 2019), TC Owen (December 2018), TC Nora (March 2018), TC Oswald (January 2013), TC Olga (January 2010) and TC Charlotte (January 2009). Both TC Penny and TC Owen made landfall twice along the Cape York peninsula, they initially crossed in a westerly direction before turning around in the Gulf of Carpentaria and crossing again in an easterly direction. TC Penny made landfall close to Weipa when it crossed in an easterly direction, resulting in the largest waves of the 2018-19 wet season, although the Tropical Low in January/February 2019 resulted in the longest duration of increased wave heights.

The strong winds and large waves from TCs have the potential to result in substantial resuspension and a resultant transport of sediment from the seabed both within Albatross Bay and in the adjacent areas of the Gulf of Carpentaria. In addition to strong winds and large waves, TCs have the potential to create a storm surge (such as TC Oswald). The storm surge combined with the astronomical tidal level result in a peak storm tide water level (storm surge + astronomical tidal level) which can be higher than the highest astronomical tide level. The predictive bathymetric model assumes that these processes result in a more widespread resuspension of a thicker layer of bed sediment compared to 'normal' (typical) conditions. Accordingly, over the period following a cyclone this material has the potential to be transported around the Port and subsequently be deposited in the dredged areas.

It is estimated that TC Owen resulted in 50,000 m^3 of sedimentation; TC Penny 370,000 m^3; and the subsequent Tropical Low 13U (end January to early February 2019) in 1,180,000 m^3 within the South Channel region (see Section 2.2).

During a year with a single cyclone, the annual sedimentation volume within the South Channel Mid area could be in the order of 209,328 m^3, while during a year with worst case sedimentation (i.e. years with two severe tropical cyclones and one tropical low) it could be in the order of 740,977 m^3, which would be equivalent to approximately 1.7 m of sedimentation. Therefore, it is likely that the South Channel Mid area will need contingency dredging following a cyclonic event or multiple cyclonic events to return the area to its declared depth.

The predictive bathymetric model has been developed to enable the user to include the influence of TC's and years with worst case sedimentation within the Port. The option to include these within the chosen prediction period allows simulation of the requirement to remove sediment post TC's, to determine the potential impact this can have on the total maintenance dredging volume over a set number of years.

3.2.3. Annual sedimentation rates

Table 6 presents sedimentation rates for annual typical conditions, annual conditions including a typical TC[4] and annual conditions including worst case sedimentation conditions (i.e. years with two severe tropical cyclones and one tropical low), for the South Channel, Inner Harbour and berth regions and associated areas. The annual typical and typical TC sedimentation rates have been calculated using survey data collected between 2006 and 2018, while the worst case sedimentation conditions have been calculated using survey data collected between 2006 and 2019.

For South Channel values presented in Table 7 represent net sedimentation and when net erosion has occurred the sedimentation value has been set to zero. For the Inner Harbour and berth regions the values presented in Table 6 represent sedimentation above the design depth, as most of the areas within these regions are naturally below the design depth so the net sedimentation is not relevant in terms of future navigation. Sedimentation rates for the Inner Harbour and berth regions have been calculated using survey data collected between 2006 and 2018 as data for 2019 were not available for these areas at the time of the study. For all regions, the annual typical sedimentation has been calculated using the mean sedimentation between 2006 and 2018 (inclusive).

[4] the term 'typical TC' has been adopted to differentiate this from the 'worst case sedimentation'. The sedimentation for the Typical TC was calculated by subtracting the mean annual sedimentation from the maximum annual sedimentation (excluding the 2018-19 period which was used for the worst-case sedimentation).

Sedimentation associated with a typical TC was calculated by subtracting the annual typical sedimentation rate (i.e. the mean sedimentation) from the annual sedimentation from the year with a TC that increased the sedimentation the most. For the South Channel Outer area TC Monica was selected and for all other areas in the South Channel region TC Helen was used, being considered representative for what a cyclone could do in these respective regions. For the Inner Harbour and berth regions the typical TC sedimentation was calculated as the difference between the maximum and mean sedimentation from 2006 to 2018.

Sedimentation associated with a year with worst case sedimentation was calculated by subtracting the maximum sedimentation measured during surveys between 2006 and 2019 from the annual sedimentation rate. Note: For the South Channel maximum sedimentation calculations included the February 2019 survey. The February 2019 survey extent did not cover the Inner Harbour and berth regions, consequently, for these regions maximum sedimentation was calculated using surveys conducted between 2006 and 2018 (inclusive).

The sedimentation rates provided in Table 6 have been applied within the predictive bathymetric model for the Port of Weipa.

Table 6. Sedimentation rates at the Port of Weipa for typical and extreme conditions.

Region	Area	Sedimentation rate (m^3)		
		Annual typical	Typical TC	Worst case *
South Channel	S Channel Outer	30,497	34,333	366,165
	S Channel Mid Outer	108,797	149,872	583,217
	S Channel Mid	209,328	229,898	690,108
	S Channel Mid Inner	34,096	22,227	314,107
	S Channel Inner	26,675	12,094	28,875
Inner Harbour	Approach 1	-	-	-
	Approach 2	-	-	-
	Approach 3	3,075	2,948	2,948
	Departure 1	547	3,011	3,011
	Departure 2	1,764	1,872	1,872
	Departure 3	1,268	3,513	3,513
Berths	Evans Landing	-	-	-
	Humbug Approach	25	76	76
	Lorim Berths	378	1,136	1,136
	Humbug Berth	141	316	316
	Lorim Tugs	79	716	716

To calculate annual sedimentation rates for a typical TC, sedimentation rates for annual typical conditions are added to those for a typical TC event. For annual sedimentation rates including worst case sedimentation, annual sedimentation rates are added to the maximum sedimentation rates. Note: For the Inner Harbour and berth regions the typical TC and worst case sedimentation values presented are the same, as the maximum sedimentation rates have been used for both, as data from 2019 were not available for these regions. Annual sedimentation rates for a typical year, a year with a typical TC and a year with worst case sedimentation are provided in Table 7.

Table 7. Annual sedimentation rates at the Port of Weipa for typical, TC and worst case sedimentation years.

Region	Area	Annual sedimentation rate (m^3/year)		
		Annual typical	Typical TC	Worst case sedimentation
South Channel	S Channel Outer	30,497	64,830	396,662
	S Channel Mid Outer	108,797	258,669	692,014
	S Channel Mid	209,328	439,226	899,436
	S Channel Mid Inner	34,096	56,324	348,203
	S Channel Inner	26,675	38,770	55,550
Inner Harbour	Approach 1	-	-	-
	Approach 2	-	-	-
	Approach 3	3,075	6,023	6,023
	Departure 1	547	3,558	3,558
	Departure 2	1,764	3,637	3,637
	Departure 3	1,268	4,781	4,781
Berths	Evans Landing	-	-	-
	Humbug Approach	25	102	102
	Lorim Berths	378	1,514	1,514
	Humbug Berth	141	457	457
	Lorim Tugs	79	796	796

Notes:
Cells containing only an '-' indicate that there is no sedimentation above design depth.

3.2.3.1. Uncertainty in sedimentation rates

To represent the uncertainty associated with the annual sedimentation rates predicted by the bathymetric model the following approach has been adopted:

- Typical conditions: To estimate the uncertainty in sedimentation rates associated with typical conditions, 95% confidence intervals[5] were calculated for the areas where regular sedimentation has occurred (all areas within the three regions of the Port, excluding Approach 1 & 2 and Evans Landing). These confidence intervals are presented in Table 8. The 95% confidence interval represents the range of values (distributed equally above and below the mean value) that we can be 95% certain contains the true mean of the statistical population.

  The bathymetric model uses the 95% confidence interval calculated as a ratio of the annual typical sedimentation rate. Consequently, the closer the value to zero, the greater the confidence which can be placed in predictions for that area. Greater uncertainty can be associated with values closer to or greater than one. This limitation will be discussed further in Section 3.3.

- Tropical cyclone and years with worst case sedimentation: For years with extreme events the survey data showed that there is large variability in total sedimentation, particularly for years with tropical cyclones (PCS, 2018a). This variability in sedimentation is largely related to the wave conditions generated by the tropical cyclones, more specifically the

[5] Note: The 95% confidence interval represents the range of values that we are 95% certain contains the true mean of the population.

duration that the significant wave heights exceeded 2 m. Typically the longer the duration wave heights are exceeded 2 m, the higher the sedimentation rate. Consequently, for tropical cyclones and years with worst case sedimentation the confidence interval ratio (confidence error) has been set at 0.5. This constant value was selected to provide an indication of the error associated with more extreme events, given the difficulty in trying to isolate the direct impact of TCs on sedimentation rates. In the absence of a more complete dataset it was considered that the most appropriate way to provide an indication of the potential error in sedimentation rates associated with extreme events was to use an average 95% confidence interval value of 0.5. This average value was calculated using the 95% confidence interval value for all areas within the Port of Weipa during typical conditions[6].

As an example, the mean sedimentation rate within the South Channel for typical tropical cyclones is around 450,000 m^3 (refer to Table 6). Using a mean 95% confidence interval value of 0.5 the predicted error in sedimentation rate is estimated to be around 110,000 m^3, indicating a sedimentation rate ranging between 340,000 m^3 (lower band) and 560,000 m^3 (upper band). The minimum sedimentation rate within the South Channel region calculated using data over tropical cyclones is between 280,000 m^3 (minimum) and 840,000 m^3 (maximum). Based on the variability in data this example shows that using a 95% confidence interval value of 0.5 appears reasonable, as the mean predicted sedimentation rate combined with the estimated error falls within the minimum and maximum sedimentation rate range for the South Channel region.

Table 8. Calculation of confidence intervals (error) for annual typical sedimentation conditions

Region	Area	Annual typical sedimentation rate (m³/year)	Standard deviation	95% Confidence interval	95% Confidence interval ratio
South Channel	S Channel Outer	30,497	43,910	23,869	0.78
	S Channel Mid Outer	108,797	78,827	42,850	0.39
	S Channel Mid	209,328	124,995	67,947	0.32
	S Channel Mid Inner	34,096	29,762	16,179	0.47
	S Channel Inner	26,675	16,649	9,050	0.34
Inner Harbour	Approach 1	-	-	-	-
	Approach 2	-	-	-	-
	Approach 3	3,075	2,103	1,143	0.37
	Departure 1	547	1,150	625	1.14
	Departure 2	1,764	1,176	639	0.36
	Departure 3	1,268	1,478	803	0.63
Berths	Evans Landing	-	-	-	-
	Humbug Approach	25	29	16	0.62
	Lorim Berths	378	437	237	0.63
	Humbug Berth	141	152	83	0.59
	Lorim Tugs	79	223	121	1.53

[6] Note: To provide a more representative estimate of the average 95% confidence interval value within the Port of Weipa, the Lorim Tugs berth area was excluded from this calculation due to the high variability in sedimentation at this location.

To enable the volumetric changes predicted for each area to be associated to a bed elevation change such that sedimentation can be related back to the design and/or declared depths, a representative existing bed elevation was defined for each area, as shown in Table 9.

The bathymetric model was developed to also allow planned maintenance dredging volumes to be included. Within the prediction period this allows simulation of the removal of sediment from the regions, so that the impact this has on the final maintenance requirement and bed elevations can be determined. In addition, a provision for TC's and worst case sedimentation years has also been made.

Table 9. Depths within the dredged areas at the Port of Weipa.

Region	Area	Depth (m LAT)		
		Design dredge depth *	Declared depth *	Current depth
South Channel	S Channel Outer	-12.2	-11.1	-11.7
	S Channel Mid Outer	-12.8	-11.1	-11.3
	S Channel Mid	-13.9	-11.1	-11.5
	S Channel Mid Inner	-13.0	-11.1	-12.7
	S Channel Inner	-12.3	-11.1	-13.2
Inner Harbour	Approach 1	-7.3	-7.3	-12.1
	Approach 2	-7.3	-7.3	-11.7
	Approach 3	-7.3	-7.3	-6.7
	Departure 1	-11.8	-11.1	-11.0
	Departure 2	-11.8	-11.1	-9.6
	Departure 3	-11.7	-11.1	-10.9
Berths	Evans Landing	-9.4	-9.4	-11.9
	Humbug Approach	-8.6	-8.6	-8.5
	Lorim Berths	-9.5	-9.5	-11.3
	Humbug Berth	-12.3	-12.3	-9.0
	Lorim Tugs	-5.0	-5.0	-2.6

** Note: The 'design' or 'dredge depth' is the depth that engineers have selected as suitable for the safe and efficient operation of the Port at all tidal levels with natural sedimentation between dredging programs also factored in. The 'declared depth' is the depth nominated by the Harbour Master and shown on navigational charts to represent the maximum legal and safe vessel draft for an area. The current depth within the South Channel is based on the average depth from the February 2019 and within the Inner Harbour and berth regions is based on the shallowest depth from the May 2018 survey.*

3.3. Model Limitations

It is useful to consider the limitations of the bathymetric model when it is applied for future sedimentation predictions.

When using the 95% confidence interval as a statistic to estimate the uncertainty or limitation which can be placed on a dataset the sample size is a major factor in determining the magnitude of the confidence interval, with smaller sample sizes resulting in larger intervals. As detailed in the previous section, when there were sufficient data available to calculate the potential error in sedimentation rate the 95% confidence intervals were calculated for typical conditions (years without tropical cyclones), using survey data collected between 2006 and 2018 for all regions within the Port of Weipa. These confidence intervals ranged in value between 0.32 for the South Mid Channel and 1.53 for Lorim Tugs for typical conditions. As additional sedimentation data becomes available the 95% confidence intervals are expected to gradually reduce and more confidence can be placed in the predictions from the bathymetric model, especially for areas which currently have values close to or greater than one.

Insufficient data were available to calculate reliable 95% confidence intervals for the sedimentation from tropical cyclones or years with worst case sedimentation (i.e. years with multiple tropical cyclones and tropical lows). In the absence of a more complete dataset, it was considered that the most appropriate way to provide an indication of the potential error in sedimentation rates associated with extreme events was to use an average 95% confidence interval value of 0.5, which was calculated using sedimentation rate data at the Port of Weipa during typical conditions. As more data becomes available the confidence interval value of 0.5 should be re-evaluated and if necessary adjusted to ensure it continues to provide a realistic representation of the predicted error in the sedimentation rate. Alternatively, when sufficient data are available it may be appropriate to adopt the same approach for calculating potential sedimentation rate error as used for typical conditions, by calculating the 95% confidence interval values.

The confidence intervals have been presented as error bars on the results plots in the bathymetric model relative to volume above design depth. The intervals have been calculated using the capped sedimentation volume predictions above design depth (see Section 4.2.3 for further details on the capping approach).

As new bathymetric data becomes available and is incorporated into the sedimentation predictions, the model results are expected to become more reliable and the confidence intervals are likely to reduce.

3.4. Model Updates

Improvements or adjustments can be made to the predictive bathymetric model as and when new bathymetric data becomes available. Updates to the bathymetric model will help to ensure it remains up to date and increase the level of confidence which can be placed in the model results (its predictions).

It is suggested that the model be updated annually as this will provide a number of benefits:

- allow regular validation of the model to ensure it is providing accurate predictions;
- ensure the model includes the most accurate sedimentation rates and the latest bathymetric survey elevations for future calculations;
- provide regular (annual) analysis of sedimentation during both typical and extreme conditions (if experienced) to help further our knowledge and understanding of the sediment transport and sedimentation processes; and
- enable the existing maintenance dredging requirement to be assessed and understood each year.

4. Model Use

The bathymetric model for the Port of Weipa has been developed to predict future sedimentation within the maintained areas of the Port. It is intended that this tool will allow NQBP to understand future maintenance dredging requirements.

This section of the report describes provides information about the how to use the model, in addition to an example dredging strategy and indication of future sediment management requirements within the Port.

4.1. Model software

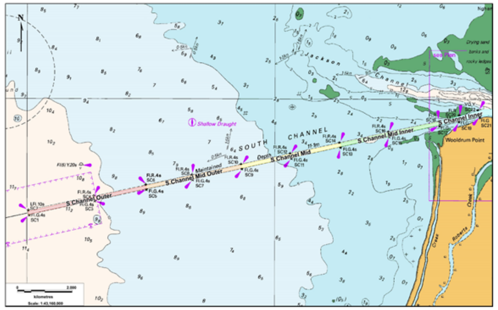
The predictive model has been developed using Microsoft (MS) Excel software (Microsoft Office 365, Excel Version 1902). MS Excel was selected to build the predictive model to allow ease of use, widespread availability and familiarity for users. The benefits of using this software also include:

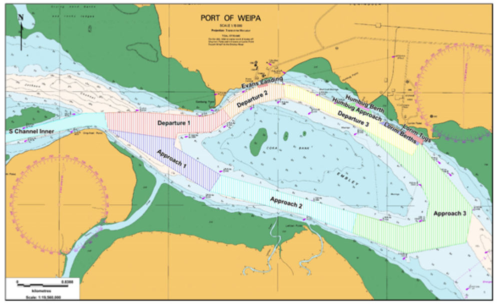
- Functionality, with the ability for the programmer to lock cells or worksheets within the spreadsheet to control user access, in addition to the ability to provide further security by adding password protection to spreadsheets if required by NQBP;
- No requirement for additional software installation, as MS Excel is typically installed on most business computers that run using a Windows operating system;
- Clear and familiar presentation of results which can be easily exported and incorporated within reports; and
- Straightforward refinement and updating of any components within the spreadsheet in the future.

An example of the model interface is shown in Figure 17 and Figure 18.

Port of Weipa Bathymetric Model

Port Layout





Version 1.1 February 2020

User Input - South Channel

Number of Years:		1
Planned Dredging (m³):	S Channel Outer	0
	S Channel Mid Outer	0
	S Channel Mid	0
	S Channel Mid Inner	0
	S Channel Inner	0
Extreme Events	Number of typical tropical cyclones	1
	Number of years with worst case sedimentation	0
Baseline Depth (m):	1 = Declared depth, 2 = Design depth 3 = Current depth (2018/2019)	2

User Input - Inner Harbour

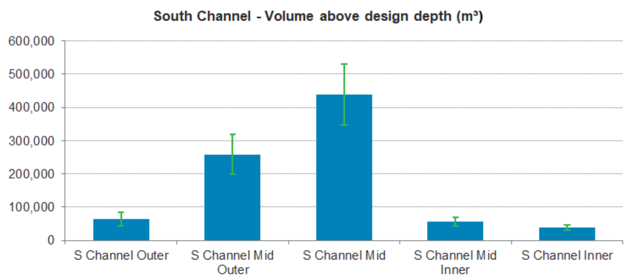
Number of Years:		1
Planned Dredging (m³):	Approach 1	0
	Approach 2	0
	Approach 3	0
	Departure 1	0
	Departure 2	0
	Departure 3	0
Extreme Events	Number of typical tropical cyclones	1
	Number of years with worst case sedimentation	0
Baseline Depth (m):	1 = Declared depth, 2 = Design depth 3 = Current depth (2018/2019)	2

Results - South Channel

Dredge Area	Depth relative to declared depth (m)	Depth relative to design depth (m)	Volume above design depth (m³)
South Channel Outer	-1.0	0.1	64,830
South Channel Mid Outer	-1.0	0.7	258,669
South Channel Mid	-1.7	1.0	439,226
South Channel Mid Inner	-1.8	0.1	56,324
South Channel Inner	-1.1	0.1	38,770

Results - Inner Harbour

Dredge Area	Depth relative to declared depth (m)	Depth relative to design depth (m)	Volume above design depth (m³)
Approach 1	0.0	0.0	0
Approach 2	0.0	0.0	0
Approach 3	0.5	0.5	6,023
Departure 1	-0.6	0.1	3,558
Departure 2	1.5	2.2	3,636
Departure 3	-0.1	0.5	4,781



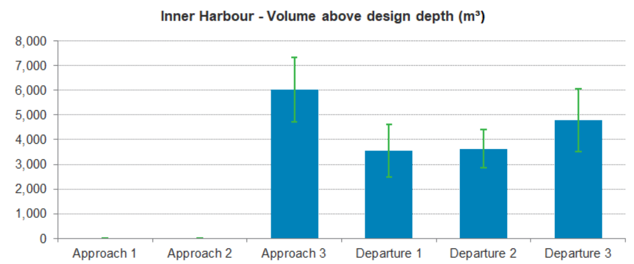


Figure 17. Bathymetric model interface for the Port of Weipa – Part 1

PORT & COASTAL SOLUTIONS

User Input - Berths

Number of Years:		1
Planned Dredging (m³):	Evans Landing	0
	Humbug Approach	0
	Lorim Berths	0
	Humbug Berth	0
	Lorim Tugs	0
Extreme Events	Number of typical tropical cyclones	1
	Number of years with worst case sedimentation	0
Baseline Depth (m):	1 = Declared depth, 2 = Design depth 3 = Current depth (2018-2019)	2

Notes

This model has been developed by Port and Coastal Solutions Pty Ltd to predict future sedimentation within the maintained areas of the Port of Weipa. It is intended that this tool will allow NQBP/RTA to understand future maintenance dredging requirements.

Model Use:

1. Enter user input data in the grey boxes to the left with blue text.

2. View the results in the green results box and bar chart below.

3. Additional results are tabulated under the 'Prediction Calculations' worksheet.

Note: There is typically a Tropical Cyclone (TC) every two to five years within the Port of Weipa region. A year with worst case sedimentation includes multiple TCs and tropical lows. Only one worst case sedimentation year has occurred in the region over the period considered as part of this assessment (2003 - 2019) and typically might occur every 10 - 20 years.

Results - Berths

Dredge Area	Depth relative to declared depth (m)	Depth relative to design depth (m)	Volume above design depth (m³)
Evans Landing	0.0	0.0	0
Humbug Approach	0.8	0.8	101
Lorim Berths	1.5	1.5	789
Humbug Berth	1.8	1.8	457
Lorim Tugs	0.2	0.2	795

Results:

Depth and volume calculations above design depth have been capped to take into consideration the surrounding ambient depths to provide a more realistic representation of sedimentation.

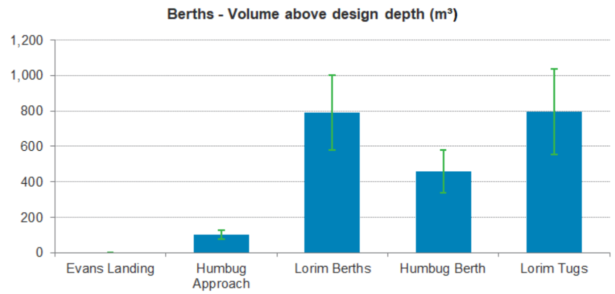


Figure 18. Bathymetric model interface for the Port of Weipa – Part 2

4.2. Model functionality

The model has been specifically designed for the Port of Weipa, ensuring that user inputs and model outputs are tailored to provide the relevant information required to assist NQBP determine its future dredging requirements. The model functionality is discussed below, providing an overview of the user input parameters and model outputs, in addition to the accompanying notes within the Port of Weipa bathymetric model worksheet.

The model provides notes on instructions for use, which include the following three steps:

Step 1: Enter user input data in the grey boxes to the left with blue text.

Step 2: View the results in the green results box and bar chart below.

Step 3: Additional results are tabulated under the 'Prediction Calculations' worksheet.

4.2.1. User input

Table 10 provides a list of the user input parameters and an associated description.

Table 10. User input parameters

Input Parameter	Description
Number of Years	This represents the number of years over which the model will predict sedimentation and controls the number of years with typical sedimentation that will be included in the model outputs.
Planned Dredging (m^3)	The user can input the individual in-situ volume of maintenance dredging (in m^3) that is proposed over the duration of the chosen model prediction calculation period for each of the following areas within the Port of Weipa (i) South Channel, (ii) Inner Harbour, (iii) Berths, (Note: These areas have been previously defined within the Bathymetric Analysis Report (PCS, 2018a) and are shown in Figure 2 and Figure 3).
Tropical Cyclones	The sedimentation resulting from extreme events is in addition to the typical sedimentation for that year (e.g. to predict the sedimentation for a year with a tropical cyclone the user will input Number of Years = 1 and Number of Tropical Cyclones = 1). TC's have been divided into two categories within the model to enable the user to differentiate between typical TC's and years with worst case sedimentation, providing a more representative indication of the variability in sedimentation which can be attributed to extreme events. The user can input the number of typical cyclones and number of years with worst case sedimentation which should be assumed. This option allows the user to test different frequencies and understand the potential impact of extreme events on sedimentation and therefore maintenance dredging requirements at the Port of Weipa. *Number of typical tropical cyclones* Typical TC's influence the Port of Weipa region every two to five years. *Number of years with worst case sedimentation* A year with worst case sedimentation includes multiple TCs and tropical lows. Only one worst case sedimentation year has occurred in the region over the period considered as part of this assessment (2003 - 2019) and based on this it is assumed that they could occur every 10 - 20 years.
Baseline Depth (m)	The user has the option to select one of three depths as the starting depth for the model prediction calculations. This can be specified by inputting either (1) Declared depth, (2) Design depth or (3) Current shallowest depth (2018/2019).

When the user inputs values into the various cells within the grey box of the model, the results tabulated in the green results box will automatically update to reflect the input values. An example of the user input parameters is shown in Figure 19.

User Input - South Channel

Number of Years:		1
Planned Dredging (m³):	S Channel Outer	0
	S Channel Mid Outer	0
	S Channel Mid	0
	S Channel Mid Inner	0
	S Channel Inner	0
Extreme Events	Number of typical tropical cyclones	0
	Number of years with worst case sedimentation	1
Baseline Depth (m):	1 = Declared depth, 2 = Design depth 3 = Current depth (2018/2019)	2

Figure 19. Example of bathymetric model user input

It is suggested that when using the model to determine future dredging requirements and to optimise dredging frequency, the model should initially be used to predict sedimentation without any dredging and then once the sedimentation is known the dredging should be included to calculate the requirement to either maintain declared depths or design depths.

4.2.2. Model outputs

The bathymetric model has two types of outputs, (i) tabulated results and (ii) graphical results. The user is able to export/capture the results using copy and paste or screen shot functions. Each output type is discussed in more details in the following sections.

4.2.3. Tabulated results

The Bathymetric Model calculates and tabulates three results for each dredge area defined within the Port, including 'Depth relative to declared depth (m)', 'Depth above design depth (m)' and 'Volume above design depth (m³). These results can be exported directly from MS Excel as either a table by selecting the data and using the copy (Ctrl c) and paste (Ctrl v) functions, or as an image using the print screen function (PrtScn) (shown in Figure 20).

Results - South Channel

Dredge Area	Depth relative to declared depth (m)	Depth relative to design depth (m)	Volume above design depth (m³)
South Channel Outer	-0.2	0.9	396,662
South Channel Mid Outer	0.1	1.8	692,014
South Channel Mid	-0.7	2.1	899,436
South Channel Mid Inner	-1.1	0.8	348,203
South Channel Inner	-1.0	0.2	55,550

Figure 20. Example of tabulated results.

It should be noted that the depth and volume calculations above design depth presented in the tabulated and graphical results have been capped to take into consideration the surrounding ambient depths, to provide a more realistic representation of sedimentation.

This 'capping' approach has been applied to prevent the results from showing ongoing sedimentation in areas where the sedimentation rate for an area within the Port is such that it would exceed the level of the surrounding bathymetry.

In the 'Predictions Calculations' worksheet the dredging volume calculations have assumed that any dredging activity occurs during the sediment accumulation period, as opposed to at the end of the period. Consequently, the dredging volume is subtracted from the uncapped sedimentation volume, as opposed to the capped sedimentation volume. In some cases, this can make it look like the dredging volume has not been applied to the capped volume above design depth calculations shown in the worksheet. However, this just means that the order in which the calculations have been undertaken will show that the dredging volume is applied prior to being capped by the level of the ambient bathymetry.

4.2.4. Graphical results

Results from the bathymetric model are also presented as a bar chart, showing the capped volume of sediment above the design depth with error bars to provide an indication of the confidence in predicted results. The error bars show the sedimentation error which includes errors in sedimentation rates associated with typical and extreme events, as discussed previously in Sections 3.2.3 and 3.3. These errors that have been discussed previously in Section 3.2.3.1. An example of the graphical output is shown in Figure 21. After running the model the results can be extracted from the graphical output using the print screen function on your keyboard (PrtScn).

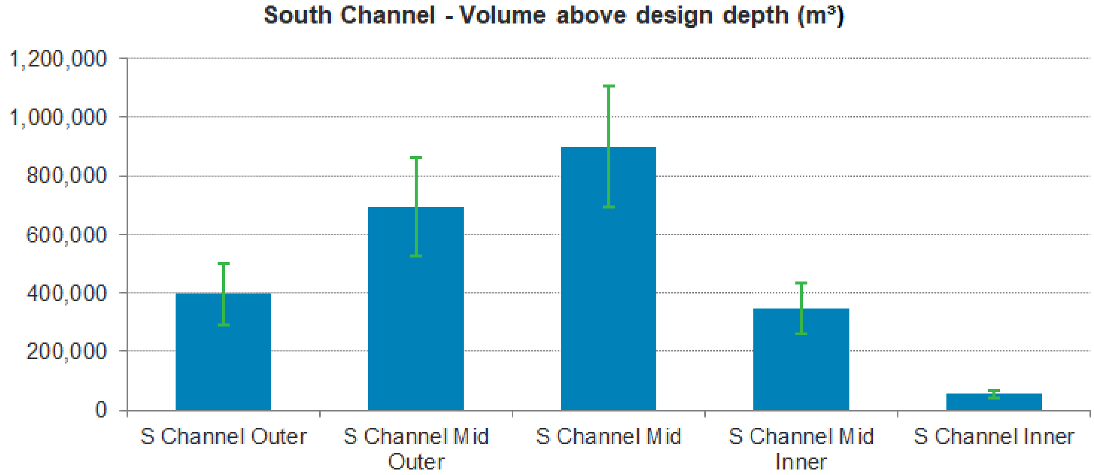


Figure 21. Example of graphical output

4.3. Example dredging strategy development

As the bathymetric model can predict future sedimentation volumes and depths, it can also be used to help develop and optimise future maintenance dredging/sediment management strategies. The following approach is suggested when developing these strategies:

1. Predict annual sedimentation depth and volume for typical conditions: Select option 2 'Design depth' for the baseline depth in the user input box and specify to run the model for a one year period with no TCs and no years with worst case sedimentation. Note down the depth and volume above design depth tabulated in the green results box for the areas of interest within the Port. For example: the South Channel Mid area has silted up by 0.5 m above the design depth, which is in the order of 200,000 m³.

2. Predict annual sedimentation and depth for a year with typical conditions including a typical TC: Select option 2 ‘Design depth’ for the baseline depth in the user input box and specify to run the model for a one year period including one TC and no years with worst case sedimentation. Under the Extreme Events heading input the number one in the box next to ‘Number of typical Tropical Cyclones’. Note down the depth and volume above design depth tabulated in the green results box for the areas of interest within the Port. For example: the South Channel Mid area has silted up by 1.0 m above the design depth, which is in the order of 450,000 m³.
3. Predict annual sedimentation and depth for a year with typical conditions including worst case sedimentation: Select option 2 ‘Design depth’ for the baseline depth in the user input box and specify to run the model for a one year period with no TCs and one year with worst case sedimentation. Under the Extreme Events heading input the number one in the box next to ‘Number of years with worst case sedimentation’. Note down the depth and volume above design depth tabulated in the green results box for the areas of interest within the Port. For example: the South Channel Mid area has silted up by 1.7 m above the design depth, which is in the order of 750,000 m³.

The results calculated from steps 1 to 3 have been tabulated in Table 11. These annual sedimentation depths and volumes can be used to develop a dredge strategy for the desired number of years by summing the preferred number of years with just typical conditions, typical conditions with one typical TC event (TC event) and typical conditions with worst case sedimentation (Worst case event). When adopting this approach, the frequency of these events should be taken into consideration to ensure that the dredge strategy is based on a realistic combination of conditions. As a reference, there has generally been a TC which has influenced sedimentation in the region every two to five years. A worst case sedimentation year has occurred once in the region over the period considered as part of this assessment (2003 - 2019) and so can be assumed to potentially occur every 10 - 20 years.

Table 11. Predicted annual sedimentation depths and volumes for typical conditions and extreme events.

Area	Annual sedimentation depth (m/year) *			Annual sedimentation volume above design depth (m³/year)		
	Typical conditions	TC event	Worst case event **	Typical conditions	TC event	Worst case event **
S Channel Outer	0.1	0.1	0.8	30,497	64,830	327,104
S Channel Mid Outer	0.3	0.7	1.5	108,797	258,669	560,680
S Channel Mid	0.5	1.0	1.7	209,328	439,226	740,977
S Channel Mid Inner	0.1	0.1	0.5	34,096	56,324	234,059
S Channel Inner	0.1	0.1	0.2	26,675	38,770	55,551
Approach 1	0.0	0.0	0.0	-	-	-
Approach 2	0.0	0.0	0.0	-	-	-
Approach 3	0.3	0.5	0.5	3,075	6,023	6,023
Departure 1	0.0	0.1	0.1	547	3,558	3,558
Departure 2	1.1	2.2	2.2	1,764	3,636	3,636
Departure 3	0.1	0.5	0.5	1,268	4,781	4,781
Evans Landing	0.0	0.0	0.0	-	-	-
Humbug Approach	0.2	0.8	0.8	25	101	101
Lorim Berths	0.7	1.5	1.5	378	789	789
Humbug Berth	0.6	1.8	1.8	141	457	457
Lorim Tugs	0.0	0.2	0.2	79	795	795

Notes:

** Depth relative to design depth. Assumes that either typical conditions, typical conditions including one typical TC event or typical conditions including one worst case event occurs,*

*** Worst case events are an abbreviation for a year with worst case sedimentation,*

Cells containing only an '-' indicate that there is no sedimentation above design depth, and

Results for the Inner Harbour and berths have the same sedimentation depths and volumes for a TC event and Worst case event as there is no data for a worst case event within these areas.

4.4. Future sediment management requirements

The bathymetric model has been used to estimate future sediment management requirements at the Port of Weipa over a 10 year period. The scenario includes typical sedimentation conditions in addition to the following:

- 1 year: one worst case sedimentation year (multiple TCs) included;
- 3 years: one worst case sedimentation year and one typical TC year included;
- 5 years: one worst case sedimentation year and two typical TC years included; and
- 10 years: two worst case sedimentation years and three typical TC years.

The sedimentation volumes calculated for this 10 year scenario are presented in Table 12. The calculations assume a starting bed elevation based on the design depth and assume that annual maintenance dredging occurs, returning the bed elevation back to the design depth each year.

The total sedimentation volume above design depth over 10 years for the Port of Weipa is predicted to be 9.5 million m³, which gives an indicative annual sedimentation volume of

954,000 m³. The sedimentation over 10 years in the Port of Weipa South Channel Mid area is estimated to be more than 4 million m³ with an annual average of 416,000 m³. As with the sedimentation predictions in Table 11, the cumulative sedimentation volumes in Table 12 do not include errors. These can be calculated using the bathymetric model and subsequently found tabulated under the 'Prediction Calculations' worksheet.

It should also be noted that the volume estimates provided in Table 12 present the uncapped sedimentation volumes above design depth as they assume that all areas are returned to design depths annually. This provides a more representative indication of projected dredge volumes for future sedimentation management requirements.

Table 12. Cumulative sedimentation volumes predicted for a 10 year period.

Region	Area	Volume above design depth (m³)				
		1 year	3 years	5 years	10 years	Annual average
South Channel	S Channel Outer	397,000	492,000	587,000	1,140,000	114,000
	S Channel Mid Outer	692,000	1,059,000	1,427,000	2,704,000	270,000
	S Channel Mid	899,000	1,548,000	2,197,000	4,163,000	416,000
	S Channel Mid Inner	348,000	439,000	529,000	1,036,000	104,000
	S Channel Inner	56,000	121,000	186,000	361,000	36,000
Inner Harbour	Approach 1	0	0	0	0	0
	Approach 2	0	0	0	0	0
	Approach 3	6,000	15,000	24,000	45,000	5,000
	Departure 1	4,000	8,000	12,000	21,000	2,000
	Departure 2	4,000	9,000	14,000	27,000	3,000
	Departure 3	5,000	11,000	17,000	30,000	3,000
Berths	Evans Landing	0	0	0	0	0
	Humbug Approach	100	200	400	600	100
	Lorim Berths	800	2,000	3,100	5,800	600
	Humbug Berth	500	1,100	1,700	3,000	300
	Lorim Tugs	800	1,700	2,500	4,400	400
	All areas within the Port of Weipa	**2,413,200**	**3,707,000**	**5,000,700**	**9,540,800**	**954,400**

Note: Predicted sedimentation volumes assume annual maintenance dredging/bed levelling and use design depth as the starting bed elevation. Values have been rounded to the nearest 1,000 or 100 m³ depending on the magnitude of the value.

It should further be noted that the values presented in Table 12 are taken directly from the bathymetric model and that realistically, especially when taking error into consideration, these predictions should not be interpreted as having such a detailed level of accuracy as the numbers may suggest.

5. Summary

This report has documented the process undertaken by PCS to develop a predictive bathymetric model for the Port of Weipa to allow future sedimentation predictions to be made for the dredged areas.

Sedimentation rates have been updated to include bathymetric data collected following the 2018/2019 wet season, which included a number of cyclonic events and a tropical low.

A predictive bathymetric model has been developed using typical annual and extreme event sedimentation rates, based on volumes calculated from bathymetric changes between surveys undertaken between 2006 and February 2019.

Limitations have been accounted for within the bathymetric model to estimate the potential uncertainty associated with the sedimentation volume predictions. Annual sedimentation volume calculations for typical conditions are based on using the 95% confidence interval as a statistic to estimate the uncertainty or limitation which can be place on the sedimentation rate data. For tropical cyclones and years with worst case sedimentation the confidence error has been set at 0.5 which means that the sedimentation could be 25% more or less than the predictions.

The predictive model has been developed using Microsoft Excel software. The model has been specifically designed for the Port of Weipa, ensuring that user inputs and model outputs are tailored to provide the relevant information required to assist NQBP determine its future dredging requirements.

The bathymetric model has been used to develop an example dredging strategy, which provides annual sedimentation depths and volumes that can be used to develop a dredge strategy for the desired number of years by summing the preferred number of years with typical conditions, typical conditions including a tropical cyclone event and typical conditions including worst case sedimentation.

The bathymetric model has also been used to estimate future sediment management requirements at the Port of Weipa over the next 10 years. The total sedimentation volume above design depth over the next 10 years for the Port of Weipa is predicted to be in the order of 9.5 million m^3, with the majority of this (approximately 99%) in the South Channel region, specifically the South Channel Mid and South Channel Mid Outer areas (75%).

6. References

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