GIPPSLAND LAKES OCEAN ACCESS

Review of dredge design

APPENDIX F

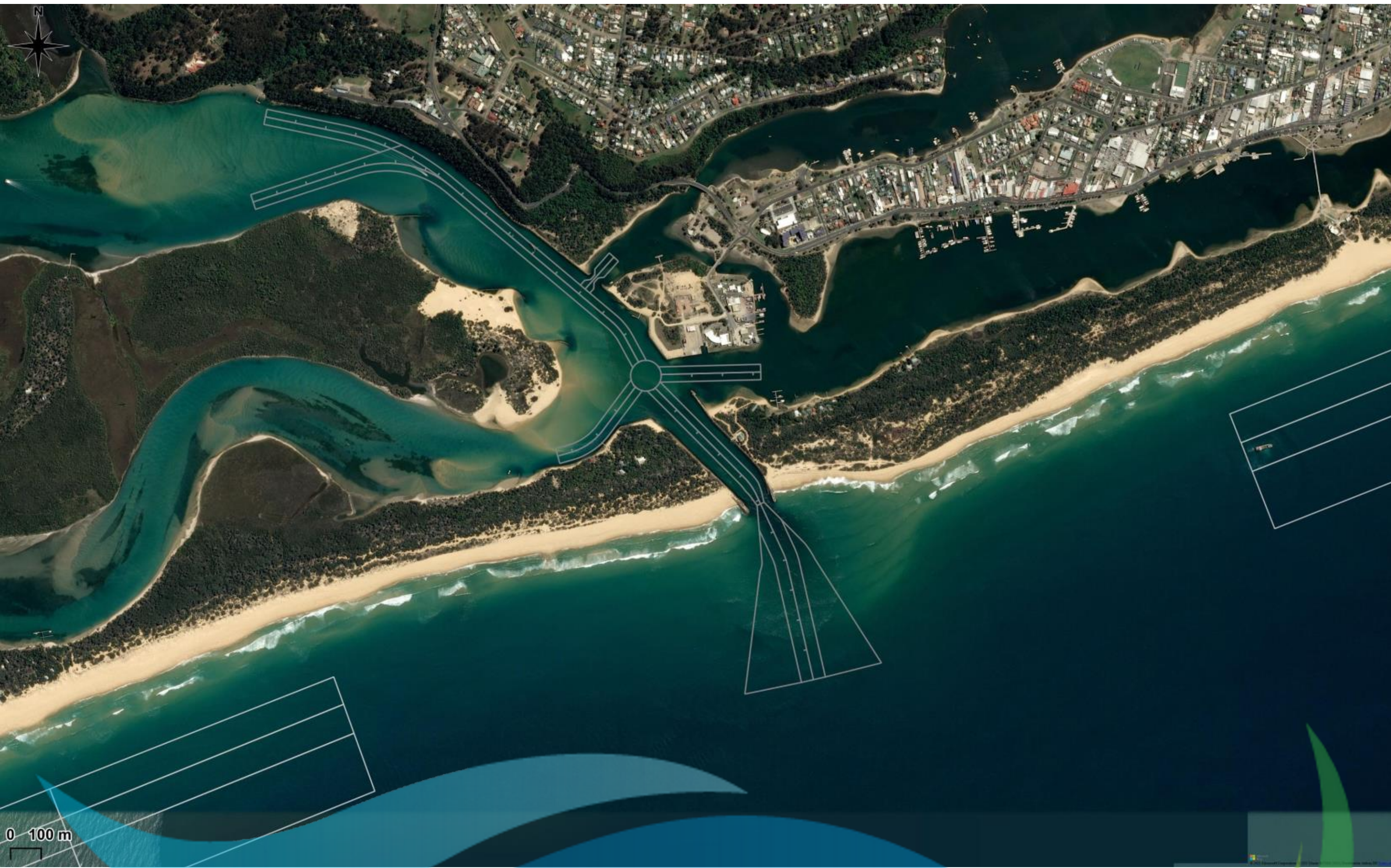
Supporting technical and environmental studies

PORT & COASTAL SOLUTIONS

Gippsland Lakes Ocean Access Program

Dredge Design

Version 0.2



Gippsland Ports
Technical Report
December 2021

Gippsland Lakes Ocean Access Program

Dredge Design

Version 0.2

December 2021

P043_R03v02

Gippsland Ports Ref. 27/965

Version	Details	Authorised By	Date
0.1	Draft	Andy Symonds	15/10/2021
0.2	Final	Andy Symonds	01/12/2021

Document Authorisation		Signature	Date
Project Manager	Andy Symonds		01/12/2021
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Executive Summary

Gippsland Ports (GP) commissioned Port and Coastal Solutions (PCS) to undertake multiple studies to support the future long-term Commonwealth and State dredging permits and consents at the Port of Gippsland Lakes (the Port). These will ensure the long-term continuity of the Gippsland Lakes Ocean Access (GLOA) Program (2023-33).

Aim: The aim of this study is to review the existing dredge design at the Port as well as modified dredge design options and assess potential impacts of both the existing and modified designs.

Bathymetric Analysis: As part of this assessment analysis of hydrographic survey data and satellite imagery has been undertaken to understand the morphology and changes over time in areas adjacent to the dredged regions of the Port. The analysis found the following:

- the shallow shoal between Reeve Channel and the northern end of the Narrows has grown in easterly and southerly directions;
- there has been an easterly migration of the shallow shoal adjacent to the south-eastern corner of Rigby Island, with the 2021 data showing that the edge of the shoal almost reaching the western end of Hopetoun Channel;
- the bathymetry to the west of Hopetoun Channel has remained relatively stable;
- sedimentation associated with the migration/growth of the natural bar offshore of the Entrance Channel has the potential to influence depths within the dredged Bar further offshore at the eastern side of the Bar (approximately 450 m from start of the Entrance Channel) compared to the western side of the Bar (approximately 200 m from start of the Entrance Channel); and
- there is the potential for a shallow sand bar to form directly offshore of the western training wall which can result in direct sedimentation into the narrowest section of the Bar Channel.

Options: Modified dredge designs were developed in collaboration with GP to provide a range of realistic potential alternative options which could be assessed as well as the existing dredge design of the Bar and Inner Channels. The dredge design options which were considered included seven options for the Bar (including the existing scenario) and three options for the Inner Channels (including the existing scenario). In addition, a scenario with the Bar not dredged was also considered as part of the assessment to help understand the potential impacts of the existing wedge shape design of the Bar.

Dredge Design: The assessment has included a review of previous relevant studies, an analogues assessment to gain information from similar relevant case studies, bathymetric analysis, hydrodynamic and wave modelling and longshore transport calculations. The assessment has found the following regarding the existing wedge shape dredge design of the Bar:

- it was not successful in maintaining a clear navigable channel between annual maintenance dredging programs, with more than 2 m of sedimentation occurring throughout the width of the channel eight months after an annual dredge program;
- predicted changes to the wave conditions along the beaches adjacent to the training walls were found to alter the longshore transport rates so that there would have been less build-up of sand adjacent to the two training walls, thereby indirectly improving the effectiveness of training walls;
- the dredge design was only predicted to result in localised changes to the hydrodynamics, with the design unlikely to result in much reduction to sand ingress into

the entrance channel except as a result of the small reduction in longshore transport towards the training walls predicted; and

- there was predicted to be a large increase (17.1% to 22.9%) in wave energy at both training walls during a 1 in 1 year wave event as a result of the existing dredge design. Although the east training wall has experienced slumping while the west training wall has not, the relative increase in wave energy predicted at both training walls could have resulted in an increase in damage to the structures. However, this is unlikely to have been the only cause of the damage at the eastern training wall, it is likely that the main reason for the damage is related to the age of the structure.

A summary of the findings from the numerical modelling of the modified dredge design options is provided below:

- the hydrodynamic modelling predicted that the modified dredge design options would not result in a measurable change to the water level either in the Entrance Channel or within the Inner Channels. In addition, the modified options were not predicted to result in a measurable change to the flow volumes either into or out of the Entrance Channel;
- the modified dredge design options would only result in localised increases in current speed where the bathymetry has changed relative to the existing case and in the immediate adjacent areas. Typically, the modelling showed that shallowing the depths resulted in localised increases in current speed while deepening the depths resulted in localised decreases;
- the hydrodynamic modelling predicted that the modified dredge design options would not result in changes to the current speeds within the Entrance Channel or the tidal prism which flows into and out of Gippsland Lakes through the Entrance Channel;
- localised increases in wave height during typical wave conditions were predicted to occur over the Bar due to the modified dredge design options for the Bar relative to the existing case, while during larger wave events the options were predicted to result in a reduction in wave heights in the Bar and inshore of the Bar;
- most of the modified dredge design options for the Bar were predicted to result in a reduction in annual wave energy at the two training walls and the adjacent two beaches. In addition, all of the modified dredge design options for the Bar were predicted to result in reductions in wave energy at the training walls during a 1 in 1 year wave event compared to the existing dredge design; and
- the modified dredge design options for the Bar were predicted to increase the net westerly longshore transport rates at the East Beach and most of the options were predicted to result in a reduction in transport at the West Beach. Therefore, the results indicate that the modified dredge design options for the Bar could potentially result in an increase in sand adjacent to the training walls compared to the existing case which could result in the training walls becoming less effective.

Recommendations: Based on the findings of the assessment, none of the dredge design options for the Bar were found to be preferred compared to the existing dredge design, with the existing design predicted to be the most effective in terms of providing a time buffer for sand bar formation and effectiveness of limiting build-up of sand at the training walls. However, all of the options result in a significant reduction in wave energy at the training walls during a 1 in 1 year wave event compared to the existing case. The results also indicated that there would be increased risk to navigation if the dredge design depth was reduced from -5.5 m CD to -4.5 m CD over the Bar as sedimentation of more than 2 m can occur during a large wave event. As a result, it is recommended that the depth remains at -5.5 m CD over the Bar. Alternative modifications to the existing dredge design of the Bar have been recommended to further optimise the existing dredge design based on the findings of this assessment. These modifications include reducing the width of the offshore end of the Bar and extending the dredge area to the north-west to try and reduce sedimentation in the Bar

Channel close to the western training wall. These modifications have the potential to maintain the benefits of the existing dredge design while also potentially reducing the risk of the Bar Channel becoming unnavigable and reducing sand ingress into the Entrance Channel.

The assessment did not identify any issues associated with the option of minor widening of the Entrance Channel, Cunninghame Arm and the Narrows and as a result the option was considered to be feasible. The option was predicted to increase future maintenance dredging in the order of 30,000 m^3/yr. The option of allowing the northern 20 m of Hopetoun Channel to naturally infill over time and only maintaining the southern 30 m width of the channel was also found to be feasible and it was predicted that this option could result in a reduction in maintenance dredging volumes of 10,000 to 15,000 m^3/yr. It is recommended that further assessment of this option should be undertaken by GP to confirm that reducing the width of the channel would not have navigational implications or result in restrictions for future maintenance dredging operations within the channel.

1. Introduction

Gippsland Ports (GP) commissioned Port and Coastal Solutions (PCS) to undertake a number of studies to support the future long-term Commonwealth and State dredging permits and consents at the Port of Gippsland Lakes (the Port). These will ensure the long-term continuity of the Gippsland Lakes Ocean Access (GLOA) Program (2023-33). The scope of the work being undertaken by PCS is as follows:

- Task 1: to undertake a bathymetric analysis of the dredged areas and Dredged Material Grounds (DMGs);
- Task 2: to review the current beneficial reuse of dredged sand practises at the Port and assess potential alternative options; and
- Task 3: to review the existing dredge design at the Port and assess any potential impacts.

This report relates to Task 3, reviewing the existing dredge design and assessing any potential impacts. Separate reports have been prepared for the other two tasks, reported in PCS (2021a; and 2021b).

1.1. Project Overview

As part of the GLOA program, GP has obtained State and Commonwealth Approvals to enable the program to be delivered in an environmentally compliant and sustainable manner. While some of the approvals are perpetual, two are due to expire in October 2023 (Sea Dumping Permit and Coastal Management Act consent). Therefore, a tailored Sustainable Sediment Management (SSM) assessment framework is being adopted for the GLOA Program (2023-33) to support these future approvals as this framework is considered to represent the port industry best practice.

GP had discerned the need to further improve their understanding of the interactions between maintenance dredging operations (including at sea placement of dredged material) and the local and regional environment, in order to identify best environmental and operational outcomes and ensure the ongoing sustainability of these operations. The SSM assessment will therefore be focused on determining the following:

- an understanding of port-specific sedimentation conditions and processes;
- consideration of management approaches;
- an assessment of beneficial reuse options; and
- long-term dredging requirements based on sedimentation rates, port safety and port efficiency needs.

Maintenance dredging at the Port is conducted to provide and deliver reliable ocean access to the Gippsland Lakes. Maintenance dredging has been undertaken at the Port for over 130 years with various different techniques adopted in the Inner Channels and the Bar. Between 2008 and 2016 annual maintenance dredging was undertaken at the Bar and Entrance Channel using a split Trailing Suction Hopper Dredge (TSHD) and since October 2017 ongoing maintenance dredging has been undertaken in this area using the bottom-door opening TSHD *Tommy Norton*, procured by GP. Dredging in the Inner Channels has generally been ongoing using a Cutter Suction Dredge (CSD).

1.2. Port of Gippsland Lakes

The Port of Gippsland Lakes is located in East Gippsland, Victoria. The Port waters cover approximately 420 km^2 and extend from Sale in the west to Lakes Entrance in the east and include Lake Wellington, Lake Victoria and Lake King. A permanent man-made ocean access was opened at Lakes Entrance in 1889 to provide navigable passage between the

Gippsland Lakes and the Bass Strait which has contributed significantly to the region since this time.

The dredged areas of the Port can be split into three main zones. The extents of these zones are shown in Figure 1 and are described below along with details of the current maintenance dredging practises undertaken:

- Bar: extends approximately 600 m offshore of the entrance to the Port. The maintained areas consist of a central channel with a width of 80 m which runs through the centre of the region as well as wedges located to the west and east of the channel which extend the dredged area to a width of 450 m at the seaward end of the channel. The total area of the channel and the wedges is 145,000 m^2. The wedge-shape Bar dredge design was initially recommended as it could potentially provide the following benefits:
  - to increase the time before sedimentation impacts the Bar Channel so that it remained navigable between annual dredging programs;
  - reduce the volume of sand being transported into the Entrance Channel; and
  - refract the waves to limit build-up of sand near the training walls and therefore enable the training walls to act as sediment traps.

  Prior to 2017, when annual maintenance dredging campaigns were undertaken, sand traps up to 3 m deeper than the main channel were also sometimes dredged in the wedges to provide additional sedimentation buffer prior to sedimentation influencing the central channel. Since October 2017 maintenance dredging has been undertaken ongoing year round by GP's TSHD *Tommy Norton* and prior to then annual maintenance dredging by a contracted TSHD had been undertaken since 2008;
- Entrance Channel and Swing Basin: the central channel in the Bar connects to the Entrance Channel adjacent to the seaward limit of the training walls and the Entrance Channel and extends to the north-west to the circular Swing Basin. The Entrance Channel is 25 m wide where it connects to the Bar channel (due to restrictions from the adjacent training walls) and then widens to a width of 50 m for the majority of its length. The Swing Basin has a radius of 50 m and connects the Entrance Channel to three of the Inner Channels (the Narrows, Hopetoun Channel and Cunninghame Arm). The total area of the Entrance Channel and Swing Basin is 33,000 m^2. As with the Bar, ongoing year round maintenance dredging by the TSHD *Tommy Norton* has been undertaken in the Entrance Channel and Swing Basin since 2017 (and prior to this annual maintenance dredging by TSHD, with some minor CSD dredging in the Swing Basin); and
- Inner Channels: the Inner Channels extend to the north, south-west and east from the Swing Basin. In total there are approximately 2.75 km of channels all at a width of 50 m (except for the North Arm which is 40 m wide with a narrow 15 m wide entrance). The Inner Channels are shown in Figure 1 and include Hopetoun Channel, Cunninghame Arm, North Arm, the Narrows and Reeve Channel. The total area of the Inner Channels is 141,000 m^2. The Inner Channels have historically been maintained by year round ongoing maintenance dredging using a CSD. The dredging is currently undertaken by the CSD *Kalimna*, although the TSHD *Tommy Norton* undertakes dredging in areas of the Inner Channels where it can access to help support the CSD *Kalimna*.

Details of the depths required for navigation and the target depths for maintenance dredging (to allow for sedimentation) for the different areas of the Port are provided in Table 1.

Table 1. Navigation and Dredge depths in the Port.

Location	Navigation Depth (m CD)	Dredge Depth (m CD)
Bar	3.5	5.5
Entrance Channel	3.5	4.5
Swing Basin	3.5	4.5
Cunninghame Arm	3.5	4.5
The Narrows	3.0	4.0
Hopetoun Channel	3.0	4.0

The placement of dredged sediment has varied depending on whether it was dredged by a CSD or TSHD, details are provided below:

- TSHD Placement: since 2008 a TSHD has maintained the Bar, Entrance Channel and Swing Basin and the resultant sediment has been placed at two DMGs, located 1.5 km to the west and east of the Bar. The DMGs are both 2 km in length and 400 m in width and orientated so their longest side is parallel with the shoreline (Figure 1). They each contain 160 individual placement cells (four rows, A to D, and 40 columns) so that placement can be varied over time. The selection of which DMG should be used for the placement of sediment has historically been determined mainly based on the wave conditions so that the relocation correlates with the natural longshore transport (i.e. if the natural longshore transport at the time would have been to the west then the West DMG would have been used so that sediment would be transported away from the dredged area). The locations of the two DMGs are aimed to provide an offshore source of sand which over time will be transported onshore to help nourish the adjacent beaches. Prior to 2008 sediment dredged from the bar was sidecast a short distance (in the order of 40 m) to the west or east, but it was determined that this approach could not keep up with sedimentation because of how quickly the sediment was being transported back into the dredged areas; and
- CSD Placement: a Sand Transfer System (STS) was setup at the Port in 2001 which allows the CSD to connect up to a number of transfer pipelines when dredging from where the dredged sediment is pumped to one of two nearshore beach discharge points, either located 1 km to the west or east of the Bar (see Figure 2 and Image 1). The discharge points are located in the nearshore wave breaking zone so that the sand goes back into the active sediment system as a form of beneficial reuse.

Historical maintenance dredging volumes and placement volumes for the Port are shown in Table 2. Historically the largest volume of dredging has been at the Bar, with approximately 1.7 million m^3 dredged between 2011 and 2020. In contrast, the volume of sediment removed from the Entrance Channel and Swing Basin over the same period is almost an order of magnitude lower, with less than 200,000 m^3 removed from this area. Since the TSHD *Tommy Norton* has been undertaking ongoing maintenance dredging at the Bar (October 2017), the annual volume of sediment removed from the Bar has been very similar to the annual volume of sediment removed from the Inner Channels.

Between 2008 and 2016 the majority of the sediment dredged by the TSHD was placed at the West DMG, but from 2017 onwards all the sediment has been placed at the East DMG. The main reason that more sediment has historically been placed at the West DMG compared to the East DMG is because the placement location was determined based on the wave conditions. When the wave conditions were expected to result in longshore transport to the west, the West DMG was selected, and when the wave conditions were expected to result in longshore transport to the east, the East DMG was selected. The shoreline alignment means that the dominant waves from the south-east and east south-east result in a westerly longshore transport, and as a result the majority of sediment was placed at the West DMG. The offshore placement at the DMGs also takes into account the volume of sediment discharged through the STS to the beach outfalls to try and ensure that the annual net transport of around 100,000 m^3 to the west at Lakes Entrance is maintained (GHD, 2013). Based on the bathymetric surveys a much larger volume of placed sediment was found to still be present at the West DMG compared to the East DMG and the eastern STS beach discharge outfall was no longer operational and so it was decided that from when GP procured the TSHD *Tommy Norton* (October 2017), sediment should be placed at the East DMG until the volume of sediment remaining in the West DMG naturally reduced over time. From 2021 onwards it is planned for sand to be placed at both DMGs.

Table 2. Maintenance dredge volumes and DMG placement volumes at the Port of Gippsland Lakes.

Year	Volume (m^3)[1]			DMG Placement	
	Bar	Entrance[2]	Inner Channels	West	East
2008	309,456	80,104	166,624	272,782	282,016
2009	227,165	12,193	1,183	147,311	93,230
2010	156,550	6,162	2,027	97,593	67,146
2011	355,579	23,197	417	379,175	0
2012	228,910	1,356	132,194	214,251	30,315
2013	162,539	10,141	135,182	173,892	0
2014	160,786	16,269	118,562	179,774	1,158
2015	149,735	4,063	158,824	96,330	60,459
2016	198,435	2,333	176,330	198,911	1,857
2017	43,585	2,013	165,233	0	45,598
2018	132,966	45,668	135,585	0	184,401
2019	108,909	49,551	102,432	0	172,271
2020	152,600	34,667	132,962	0	210,787
Total	**1,694,044**	**189,240**	**1,257,304[3]**	**1,705,474**	**1,007,785**

[1] the volume shown represents the volume reported by the dredge vessel as the transported volumes. Based on previous comparison by GP it was estimated that the in-hopper volume for the TSHD is approximately 16% more than the in-situ volume due to bulking and sand infill into the dredged areas prior to post dredge survey.
[2] this includes the Entrance Channel and the Swing Basin.
[3] the majority of the sediment dredged from the Inner Channels region was pumped to the nearshore beach discharge points using the STS.

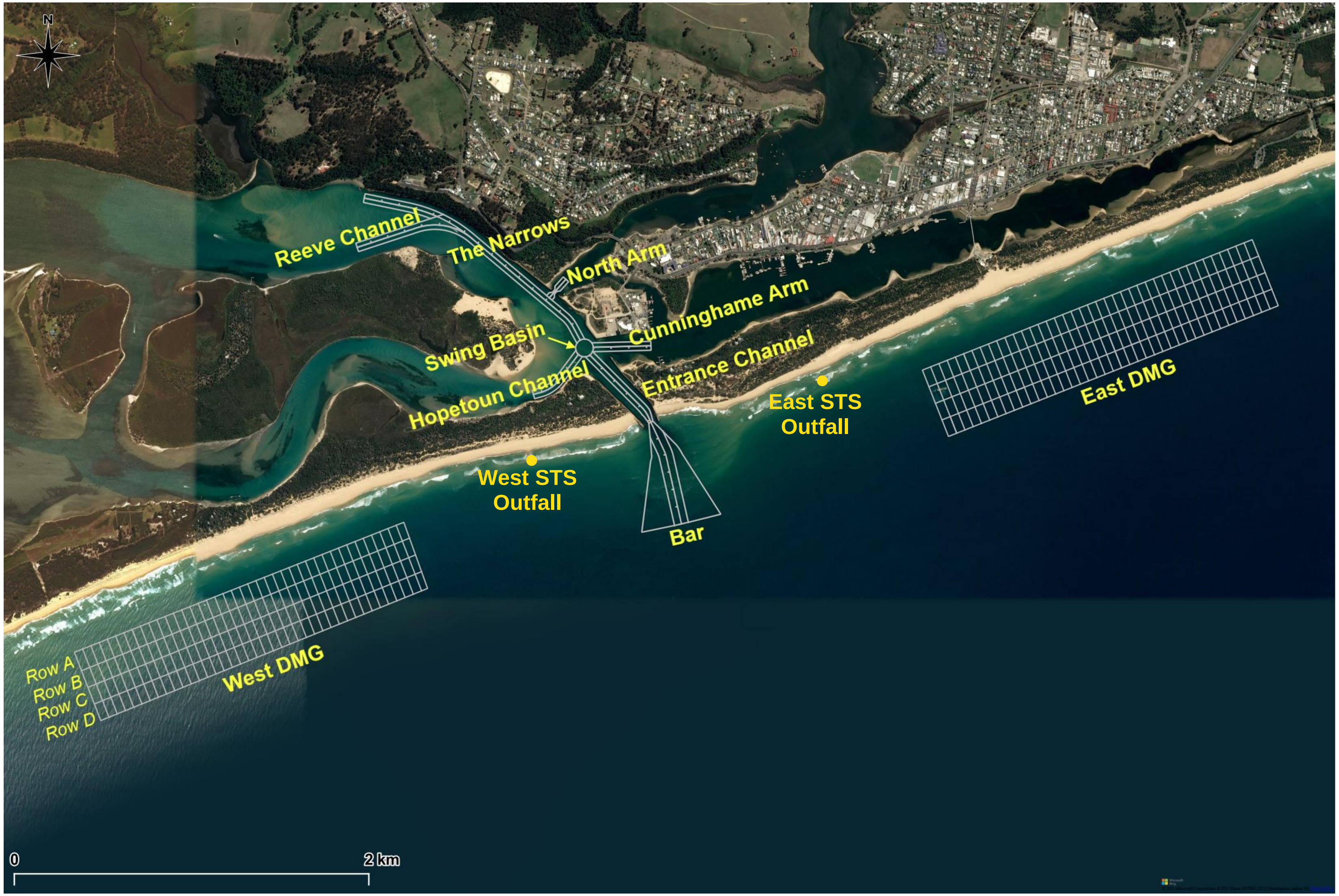

Figure 1. Port of Gippsland Lakes dredged areas and DMGs.

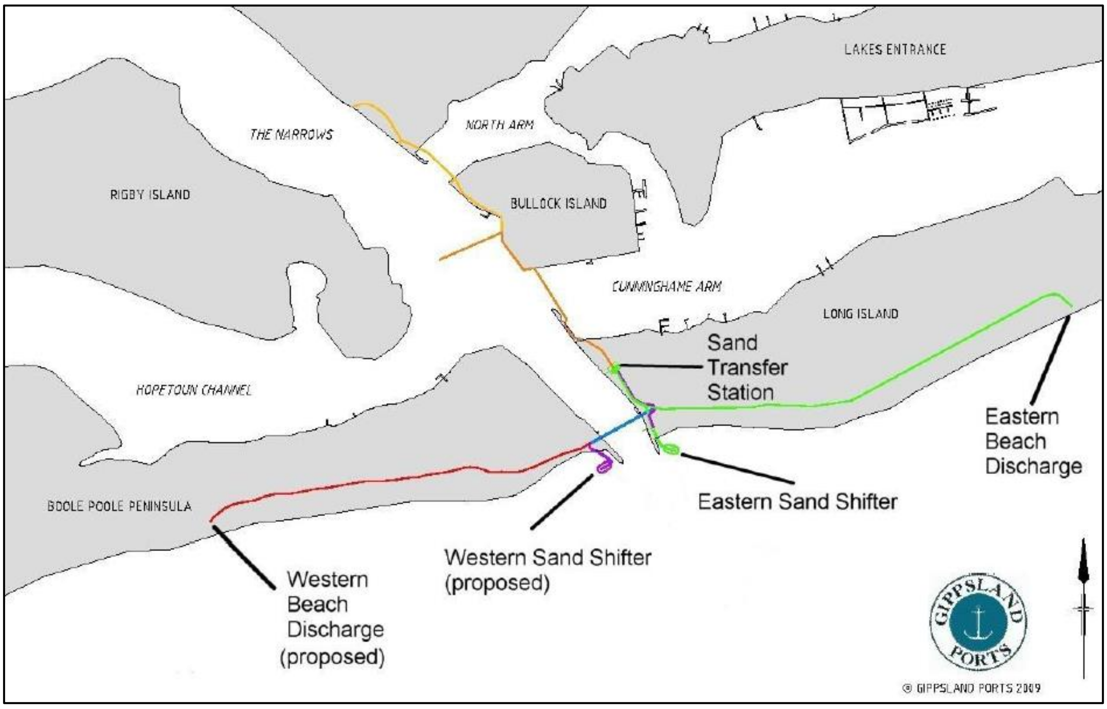

Figure 2. **Elements of the Port of Gippsland Lakes Sand Transfer System (Gippsland Ports, 2015).** *Note: the Western Beach Discharge is now operational and the trial Sand Shifters are removed.*

Image 1. **East (left) and East (right) nearshore outfall (source: Gippsland Ports).**

1.3. Report Structure

The report herein is set out as follows:

- a summary of the relevant findings from the bathymetric analysis component of the SSM Project as well as some additional is given in **Section 2**;
- an assessment of the various dredge design options is provided in **Section 3**;
- a discussion of the results from the dredge design assessment is provided along with recommendations in **Section 4**; and
- a summary of key findings is provided in **Section 5**.

Unless stated otherwise, levels are reported to Chart Datum (CD) which is the equivalent to Lowest Astronomical Tide (LAT) at Lakes Entrance. Volumes presented throughout are in-situ cubic metres.

Wind and wave directions are reported as the direction the wind and waves are coming from in degrees clockwise from True North. Current and longshore drift directions are reported as the direction the current/transport is going to in degrees clockwise from True North.

2. Bathymetric Analysis

This section provides a summary of the relevant findings from the bathymetric analysis component of the SSM Project (PCS, 2021a). This includes the analysis of relevant metocean data as well as bathymetric changes which have occurred in the dredged areas of the Port and aspects of the sediment transport understanding which are relevant to this assessment.

Additional bathymetric analysis which has been undertaken as part of this assessment is also presented which includes an assessment of bathymetric changes in areas adjacent to the dredged areas of the Port to better understand any ongoing morphological changes.

2.1. Metocean Data

Current data are recorded at a site along the eastern training wall within the Entrance Channel by GP. As part of the bathymetric analysis the current data were analysed to show annual flow speed exceedance. The analysis found that there was a higher occurrence of faster flows in 2016 than during other years and comparably slower flows in 2011 and 2012. For example, more than 22% of recorded flows from 2016 exceeded 1.5 m/s, compared to 12% of flows in 2011 and 19% of flows from the period 2010-2020. To examine these changes further and to identify whether they are likely to be a result of natural variability in tidal forcing conditions or from dredge related changes to the bathymetry, additional analysis of the flow data has been undertaken as part of this assessment.

To help visualise the annual variability in the flow data the percentiles have been presented using box and whisker plots for the period pre September 2017 (when annual maintenance dredging was undertaken) and post September 2017 (when ongoing dredging was undertaken) (Figure 3). The plot shows that prior to September 2017, from year to year there was typically more variability in current speeds though the Entrance Channel while after this time there was less variability in the current speeds.

Water level data have also been measured by GP at the site within the Entrance Channel along the eastern training wall (i.e. not within the Bar where dredging was regularly undertaken). A percentile analysis of these data has been undertaken and a similar box and whisker plot to the current speed plot is presented in Figure 4. The plot shows that the water levels have experienced a similar annual variability to the current speeds. It is therefore considered likely that the variability in water levels and current speed are a result of natural variations in metocean conditions and not due to changes in bathymetry resulting from dredging (Figure 4). The numerical modelling being undertaken as part of this study will be used to confirm if this is the case (see Section 3.3.1).

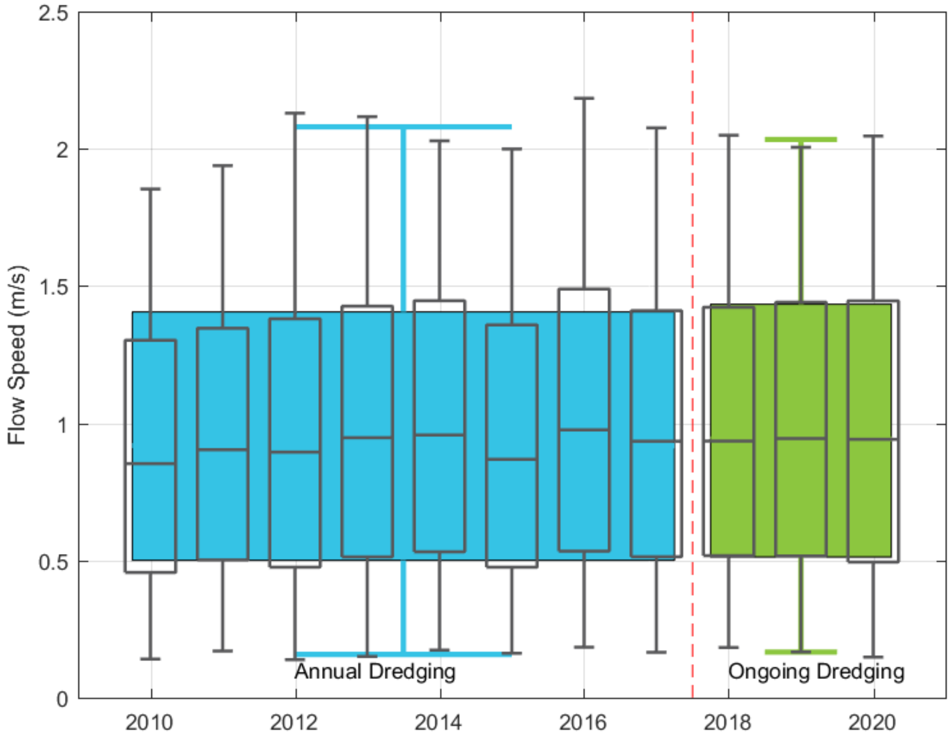

Figure 3. Box and Whisker Plots of Annual Flow Speed Data, with boxes showing 25th, 50th and 75th percentile and whiskers showing 1st and 99th percentiles.

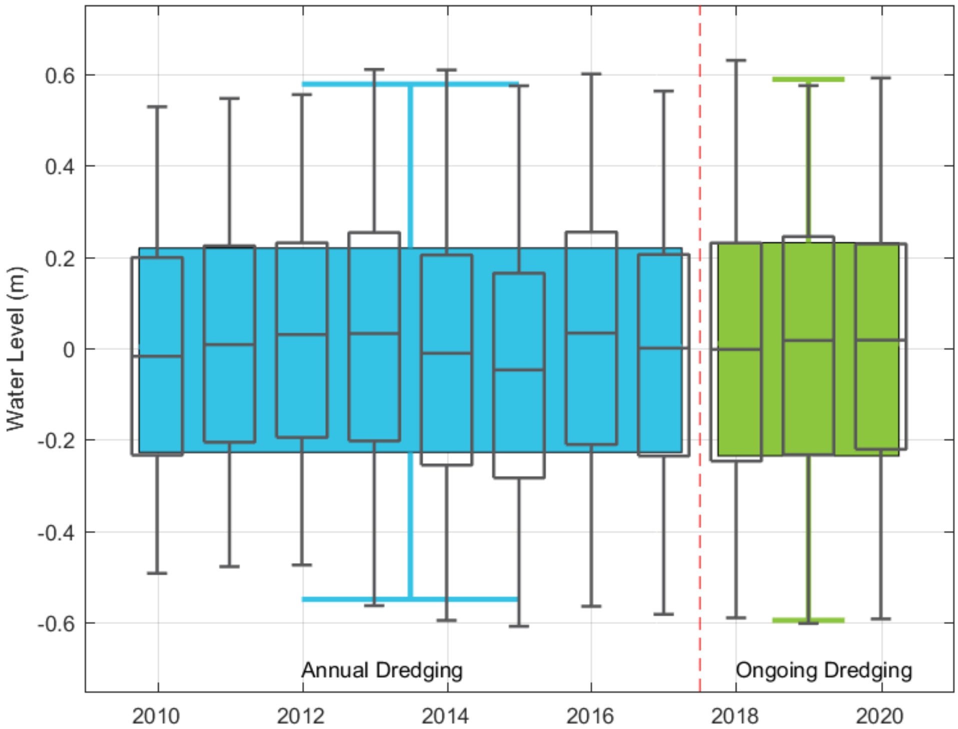

Figure 4. Box and Whisker Plots of Annual Water Level Data at Lakes Entrance, with boxes showing 25th, 50th and 75th percentile and whiskers showing 1st and 99th percentiles.

2.2. Bathymetric Changes, Dredged Areas

Monthly hydrographic survey data of the Bar and Entrance Channel between December 2014 and December 2020 and monthly survey data of the Inner Channels between December 2016 and November 2020 were analysed as part of the previous bathymetric analysis (PCS, 2021a). As discussed in Section 1.2, from 2011 to 2017 annual maintenance dredging campaigns were undertaken to manage sedimentation in the Bar and Entrance Channel and since October 2017 year round maintenance dredging has been undertaken using the TSHD *Tommy Norton*. As a result, the bathymetric analysis results can be used to help understand how the dredge design performs during annual dredging. A summary of the results from the bathymetric analysis are presented in the following sections for the Bar and the Inner Channels.

2.2.1. Bar, Entrance Channel and Swing Basin

To provide an indication of the natural bathymetry of the Bar, Entrance Channel and Swing Basin without dredging, the bathymetry between annual maintenance dredging programs and after one year of sedimentation is shown in Figure 5. The plot shows the following:

- there is a naturally deep area of the channel where the Bar joins the Entrance Channel with depths of more than 10 m below CD. This is due to the constriction in this location resulting from the channel training walls and subsequent acceleration of tidal flows;
- the offshore end of the Bar is naturally deep (around 7.5 m below CD) and results from the bathymetric analysis have shown that minimal changes occur in this area; and
- the Bar is a relatively uniform depth across the whole area, with slightly shallower depths at the sides of the Bar compared to the centre of the Bar, with depths of 3.5 to 4 m below CD across the entire width of the Bar. It is expected that the morphology of the Bar would remain the same but that further shallowing would occur if sedimentation continued for more than a year.

The depth of the Bar relative to the design depth after one year of sedimentation is shown in Figure 6. The plot shows that the depths are between 1 and 2 m above the design depth across a width of up to 300 m of the Bar. The depth of the Bar Channel within 100 m of the Entrance Channel is typically at least 1 m below the design depth, although there is a shallow area 2 m above the design depth along the western side of the Bar Channel.

Historical sedimentation rates at the Bar during annual maintenance dredging have been variable, but with sedimentation of between 1 and 2 m per year typically occurring across a width of up to 300 m of the Bar (Figure 7). Sedimentation has typically been highest along the eastern side of the Bar wedge, with sedimentation of more than 2 m across most of this side of the Bar. The changes in bathymetry over time along the centre of the Bar Channel are shown in Figure 8 from October 2016 to March 2018. The plot shows that over a year with no dredging sedimentation had resulted in a length of around 300 m of the Bar Channel being above the design depth, with around half of this length being above design depths after six months. The March 2018 bathymetry shows that the TSHD *Tommy Norton* returned the depths across the length of the Bar Channel to -5 m (CD) (0.5 m above the design depth).

The sedimentation which occurred in the different areas of the Bar was quantified over the three years when annual maintenance dredging was undertaken (Table 3). The results show that sedimentation in the West and East Wedges represent between 70 and 80% of the total sedimentation, with sedimentation in the Bar Channel representing the remaining 20 to 30%. The results also show that there can be significant interannual variability in the sedimentation rates, with the total sedimentation in the Bar being more than 2.5 times higher in 2016 compared to in 2017. The variability in sedimentation was found to be related to the wave conditions, with 2017 experiencing relatively calm wave conditions and 2016 experiencing the most energetic conditions of the three years. Based on the results from the analysis of the sedimentation over the three years the average seasonal and annual sedimentation for the different areas of the Bar was estimated (Table 4). The average annual sedimentation for the

Bar Channel (with the majority of this predicted to be above design depth) is estimated to be just under 60,000 m^3, while the average annual sedimentation for the two wedges is predicted to be around 135,000 m^3. This shows that the ongoing maintenance dredging predicted to be required in the future for the wedges is more than double that for the Bar Channel. As the wedges were initially designed to provide additional capacity so the Bar Channel depths were maintained between annual dredging programs, now that year round dredging is undertaken it could be possible to reduce the size of the wedges. The potential for this will be further investigated in Section 3.

Table 3. Positive change in volume for the Bar, Entrance Channel and Swing Basin regions for the three years when annual maintenance dredging was undertaken (PCS, 2021a).

Region	Annual Increase in Volume (m^3/yr)		
	2015	2016	2017
Entrance Channel	24,202	28,184	19,059
Swing Basin	3,401	7,179	3,306
Wedge West	40,211	56,711	34,537
Wedge East	63,663	100,841	37,097
Bar Channel	42,642	77,123	19,393
Total	**174,119**	**270,038**	**113,392**
Bar Total	*146,516*	*234,676*	*91,027*

Table 4. Predicted average seasonal and annual sedimentation rates for the Bar (PCS, 2021a).

Region	Total Sedimentation (m^3)				
	Summer	Autumn	Winter	Spring	*Annual*
Bar Inner Channel	0	5,555	0	6,699	*12,253*
Bar Mid/Outer Channel	5,632	12,006	15,387	13,399	*46,424*
Wedge West	8,163	12,408	17,553	18,367	*56,492*
Wedge East	29,012	22,054	11,205	15,218	*77,489*

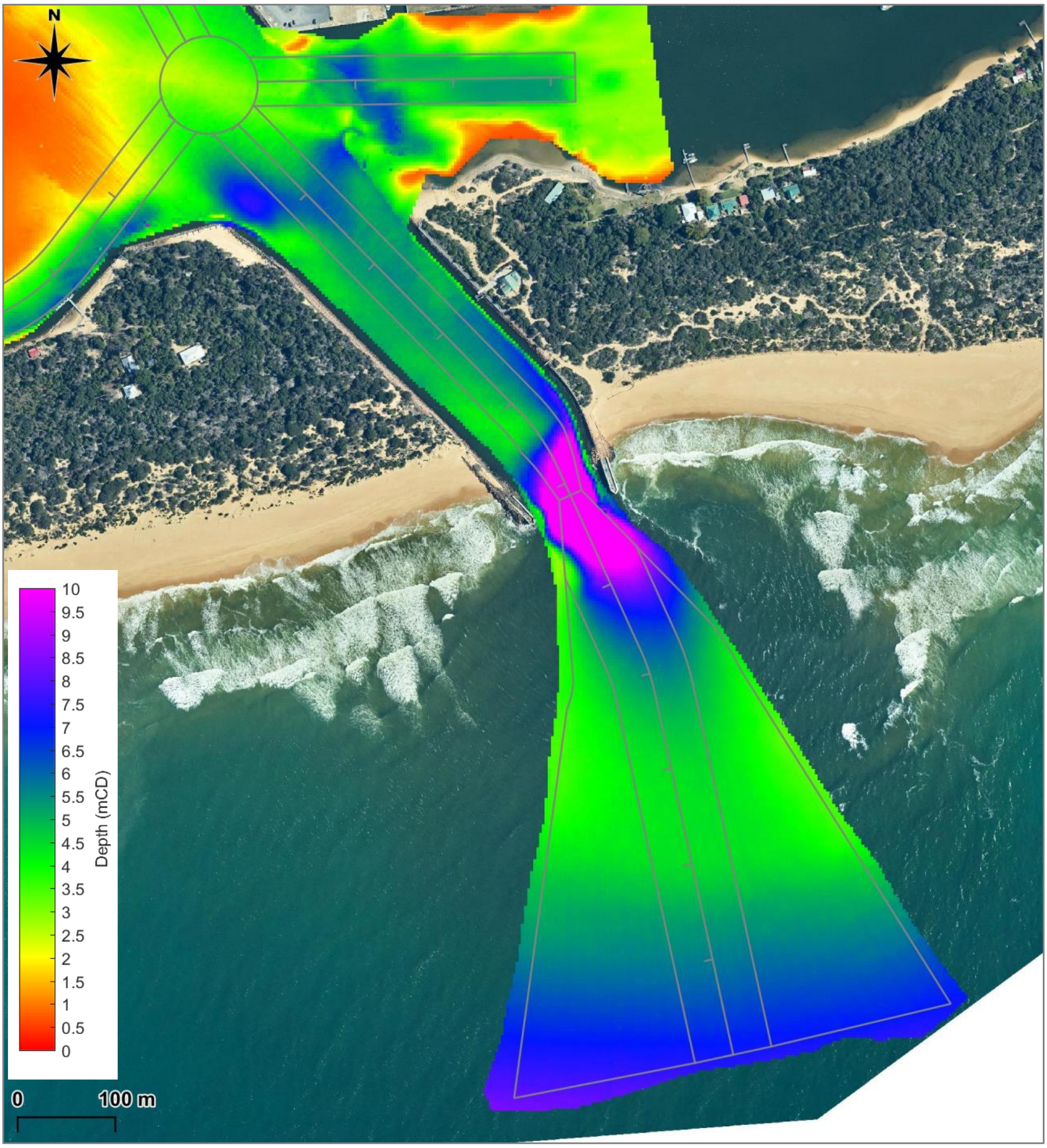

Figure 5. **Bathymetry of the Bar and Entrance Channel one year after maintenance dredging (September 2017) (PCS, 2021a).**

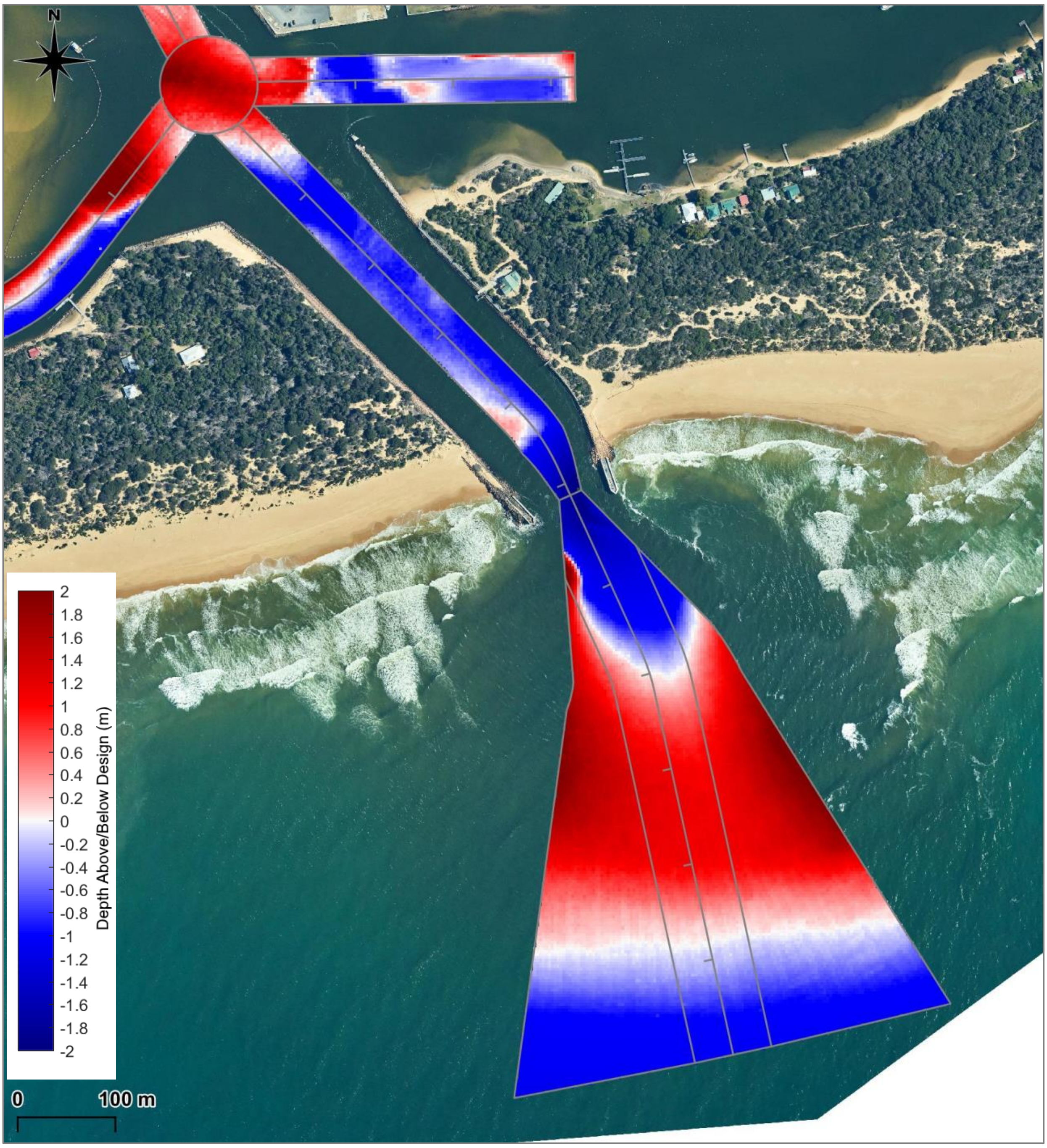

Figure 6. Depth relative to design depths for the Bar and Entrance Channel one year after maintenance dredging (September 2017) (PCS, 2021a). *Note: blue is below design depth, red is above design depth.*

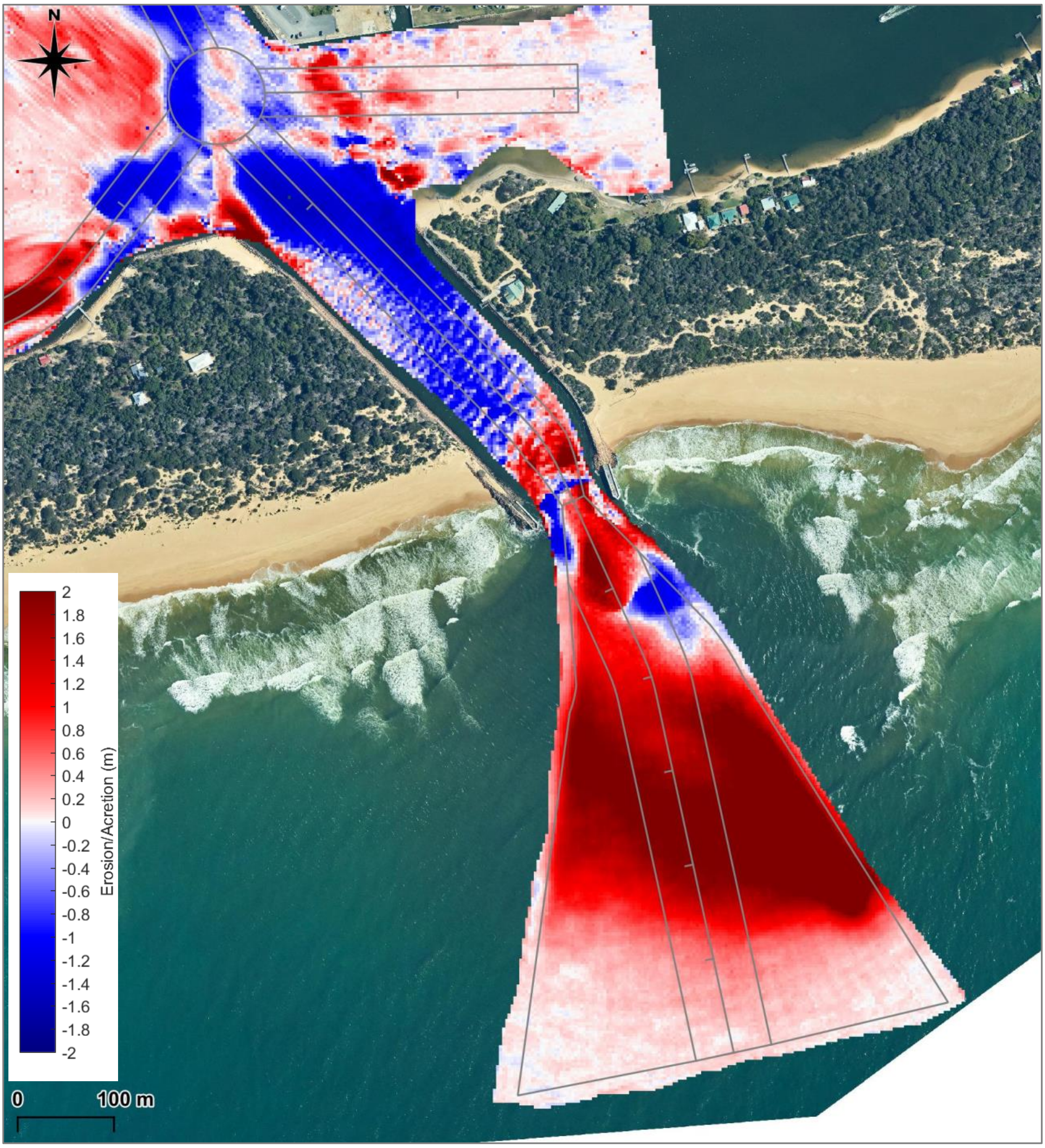

Figure 7. Example sedimentation depths in the Bar and Entrance Channel over 8 months (between December 2015 and August 2016) (PCS, 2021a).

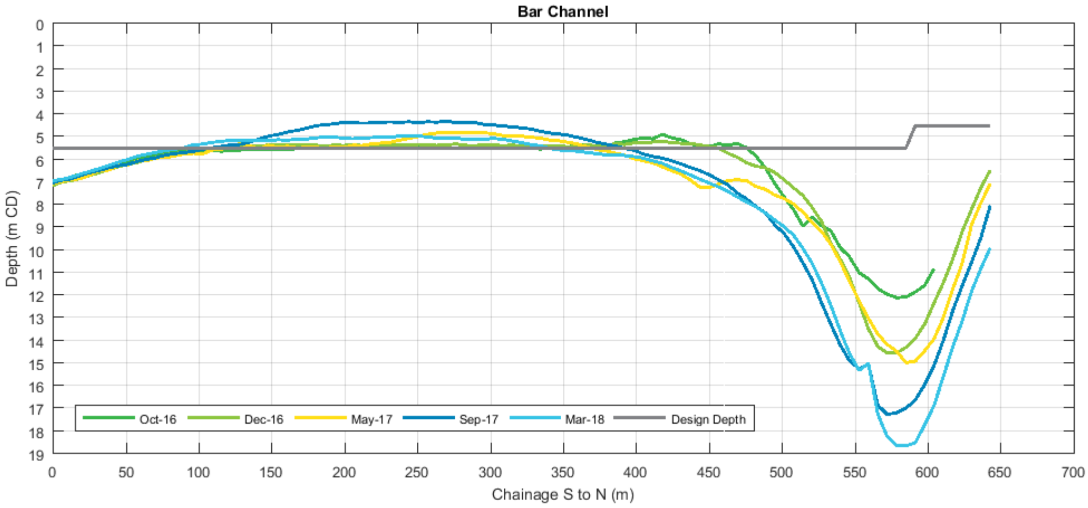

Figure 8. Long section through the centre of the Bar Channel showing the change in bathymetry from October 2016 to March 2018 (PCS, 2021a). *Note: 0 m chainage represents the offshore end of the Bar and 600 m chainage the start of the Entrance Channel.*

2.2.2. Inner Channels

The Inner Channels have historically been maintained by year round ongoing maintenance dredging using a CSD. Despite year round maintenance dredging occurring over the four year analysis period, it was still possible to estimate the sedimentation which occurred. The majority of the Inner Channels area is relatively shallow and when the depths are compared to the design depths it can be seen that large areas are either just below, at or above design depths (Figure 9 and Figure 10). This suggests that most sedimentation which occurs in the Inner Channels is likely to be above design depth.

The annual sedimentation which occurred in the Inner Channels was calculated for each of the four years analysed by summing all of the positive monthly changes each year (Figure 11). The results showed that regular ongoing sedimentation had occurred in the following areas:

- the majority of the Hopetoun Channel, where annual sedimentation rates of 4 m can occur. Higher sedimentation tends to occur along the northern half of the channel;
- the 100 m length of the Cunninghame Arm closest to the Swing Basin where between 2 and 4 m of sedimentation can occur over a year;
- the 100 m length of the Narrows closest to the Swing Basin where between 2 and 4 m of sedimentation can occur over a year; and
- the mid section of the Narrows, south of the confluence between the Narrows and Reeve Channel, where up to 2 m of sedimentation can occur over a year.

The monthly results from the bathymetric analysis were used to calculate the annual positive increase in volume for each region of the Inner Channels, with the total annual sedimentation varying from approximately 180,000 to 210,000 m^3/yr (Table 5). The results show that the variation in the annual sedimentation rates is relatively small, suggesting that the sedimentation over this period was mainly driven by regular tidal forcing as opposed to extreme events (e.g. high discharge flows during flood events). However, it is important to note that the period from 2017 to the end of 2020 was relatively calm with no major flood events and no large wave events or large surges.

Comparison of the average annual sedimentation in the areas where maintenance dredging has been undertaken over the four years (Hopetoun Channel, Cunninghame Arm, the

Narrows and Reeve Channel) to the annual average volume of sediment removed by maintenance dredging (193,000 m³/yr of sedimentation compared to 134,000 m³/yr dredged) shows that there has been more sedimentation than sediment removed by maintenance dredging by approximately 60,000 m³/yr. This deficit in the volume dredged explains why some areas of the Inner Channels were above design depth in November 2020 despite ongoing maintenance dredging being undertaken (i.e. design depths have not been achieved in all of the Inner Channels).

The analysis has shown that some of the channels where natural depths were below design depth have experienced sedimentation meaning that the majority of the channels are now close to design depth. This means that future maintenance dredging requirements are likely to increase as future sedimentation in most areas of the Inner Channels will result in depths above design depth. The total sedimentation which has historically required maintenance dredging in all the Inner Channels has ranged from 140,000 to 170,000 m³/yr. This volume could increase to between 180,000 to 210,000 m³/yr if ongoing sedimentation in areas below design depth result in depths reaching design depth.

Details of the historic annual sedimentation for the various designated Inner Channels is provided below:

- Hopetoun Channel: consistent ongoing sedimentation above design depth of 25,000 to 50,000 m³/yr. The sedimentation is throughout the entire channel, but highest along the northern side;
- Cunninghame Arm: sedimentation of around 10,000 to 15,000 m³/yr regularly occurs in the 100 m stretch of the channel adjacent to the Swing Basin;
- North Arm: regular sedimentation in the order of 5,000 m³/yr occurs;
- Narrows Channel: the total sedimentation which could require maintenance dredging in the Narrows ranges from around 80,000 to 120,000 m³/yr. However, approximately 40,000 m³/yr of this is not currently above design depth (although with ongoing sedimentation below design depth this could change in the future) or is subsequently naturally eroded; and
- Reeve Channel: the total sedimentation in Reeve Channel has been fairly consistent, with approximately 20,000 m³/yr being deposited.

As part of the bathymetric analysis the annual sedimentation which occurred in the wedge between the designated Reeve Channel and the northern end of the Narrows was also calculated to approximately 45,000 m³/yr.

Table 5. Positive change in volume for the Inner Channels region from 2017 to 2020.

Region	Annual Increase in Volume (m³/yr)				
	2017	2018	2019	2020	*Average*
Cunninghame Arm	13,485	18,005	10,888	10,790	*13,292*
Hopetoun Channel	46,101	47,367	39,753	33,946	*41,792*
North Arm	5,608	6,615	5,916	6,465	*6,151*
Narrows	119,491	112,912	105,072	107,093	*111,141*
Reeve Channel	21,860	22,746	20,223	19,261	*21,023*
Total	**206,545**	**207,645**	**181,852**	**177,555**	***193,399***

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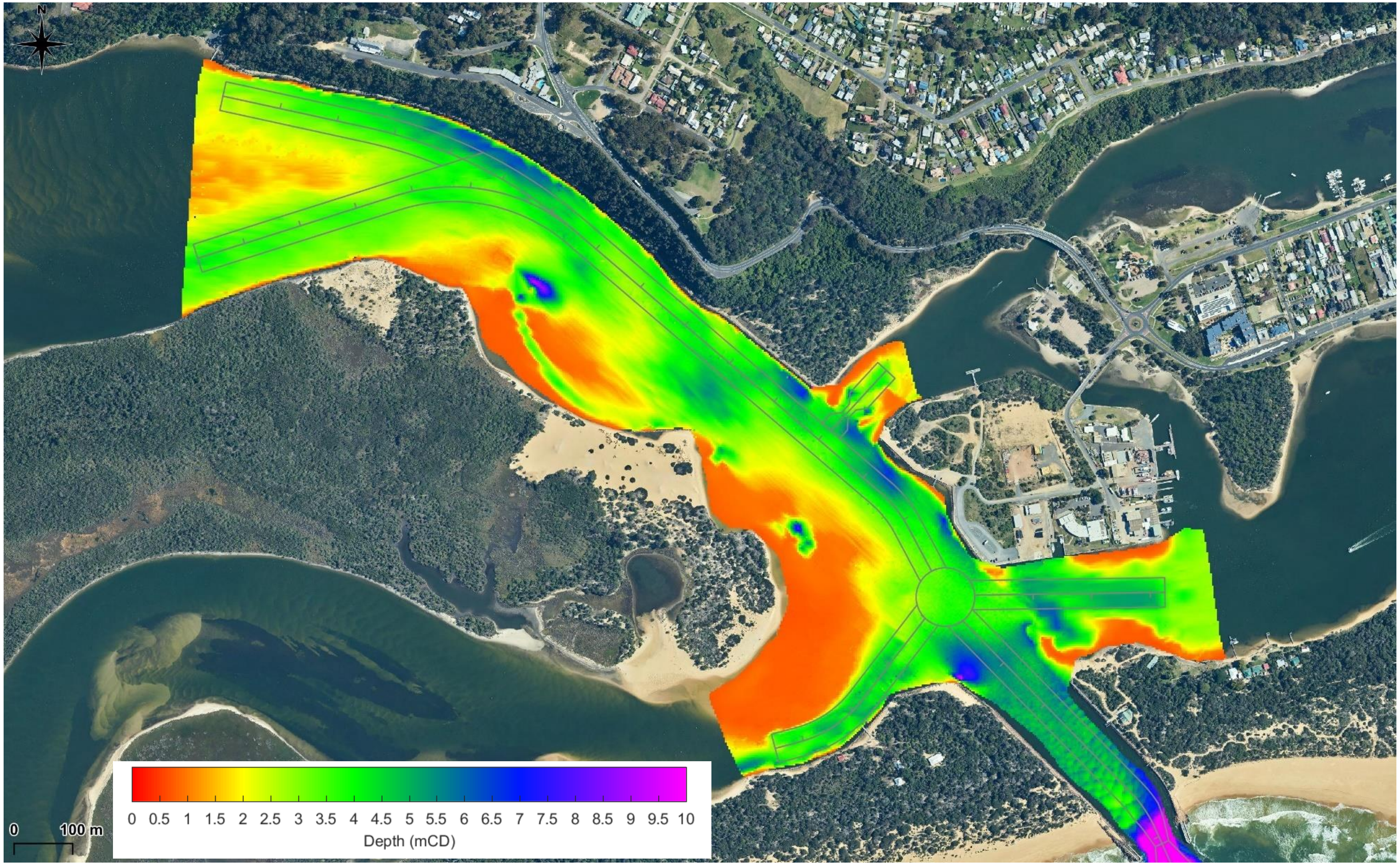

Figure 9. Bathymetry of the Inner Channels in November 2020 (PCS, 2021a).

Figure 10. Depth relative to design depths for the Inner Channels in November 2020 (PCS, 2021a). *Note: blue is below design depth, red is above design depth.*

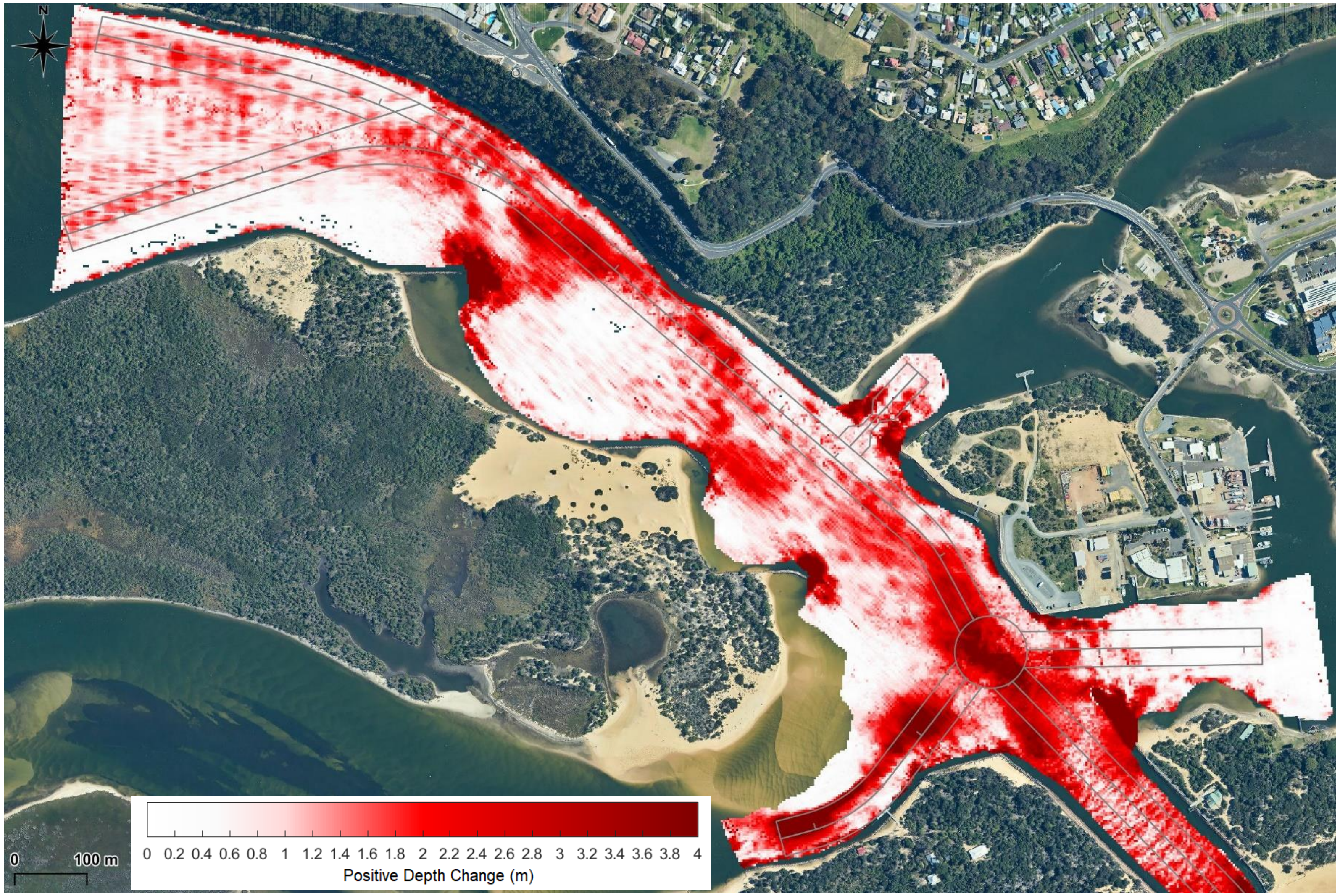

Figure 11. **Cumulative positive change in depth for the Inner Channels region during the 2017 calendar year (PCS, 2021a).**

2.3. Bathymetric Changes, Other Areas

To help understand the bathymetric changes within the dredged areas of the Port and any local impacts they could have it is important to also consider the bathymetry adjacent to the dredged areas of the Port. Hydrographic surveys undertaken by GP cover some of these adjacent areas, however many of these areas are not surveyed regularly if at all (e.g. shallow sandy shoals to the north and south of Rigby Island and bars which build up to the west and east of the entrance) and understanding the development or natural migration of these features could help in planning future dredge designs at the Port. For example, if a shallow shoal is migrating through a dredged area this could result in very high sedimentation rates for a period of time, followed by much lower sedimentation rates as the feature migrates beyond the dredged area. In addition, if the bars either side of the entrance channel have remained relatively stable over the last five years then the existing sediment management approach is likely to continue to be effective, but if the bars have been gradually accreting then at some point additional sediment management will be required. It is therefore important to consider longer-term morphological changes during dredge design and sediment management planning as it can help to optimise for the future.

Changes to the bathymetry in areas adjacent to the dredged areas has been investigated using hydrographic survey data provided by GP (Section 2.3.1). To extend the coverage of the data to some of the shallower areas not covered by the hydrographic surveys, we have also used satellite derived bathymetry from analysis of Sentinel-2 imagery (Section 2.3.2).

2.3.1. Lakes Surveys

Available hydrographic survey data were provided by GP for this assessment. The surveys covered the areas adjacent to the Inner Channels, but did not cover any areas adjacent to the Bar. Survey datasets were provided for the following periods:

- pre-2018: made up of surveys from various years to create a full dataset to cover all of the Gippsland Lakes. The dataset covered the full extent of the channels to the west of Hopetoun Channel and Reeve Channel;
- 2018: included the channel to the west of Reeve Channel;
- 2019: included the channel to the west of Hopetoun Channel; and
- 2020: covered the full extent of the channels to the west of Hopetoun Channel and Reeve Channel.

Interpolated bathymetry based on the pre-2018 and 2020 survey data are shown for the area around Rigby Island in Figure 12 and Figure 13 and the difference in bathymetry between the two is shown in Figure 14. The plots show the following:

- the shallow shoal off the south-eastern corner of Rigby Island has migrated to the east over the time between the two surveys, resulting in localised shallowing along the northern half of the western end of Hopetoun Channel in October 2020. The October 2020 bathymetry shows that following the migration of the shoal there were no further shallow shoals located directly to the west of Hopetoun Channel, suggesting there could be a reduction in future sedimentation at this end of Hopetoun Channel until a new shoal forms;
- the deeper bathymetry immediately to the west of Hopetoun Channel has remained relatively stable between the two surveys, with the closest shallow shoal (excluding the shoal attached to the south-eastern corner of Rigby Island) remaining approximately 200 m from the western end of Hopetoun Channel;
- the large shoal located between Reeve Channel and the northern end of the Narrows has shallowed in the triangular region between the two channels, while the area of the shoal located to the west of the channels has deepened slightly. The difference plot shows that the south-western edge of the shoal (located to the west of the two channels) has

shallowed, this is a result of the shoal migrating approximately 30 m to the south into the natural channel; and

- the natural channel around Reeve Channel has widened, with erosion occurring along the northern bank of Rigby Island.

To further understand the changes in bathymetry adjacent to Hopetoun Channel, Reeve Channel and the northern end of the Narrows, the bathymetry has been plotted for multiple survey years along the three transects shown in Figure 15. The transects are shown in Figure 16 to Figure 18 and the key findings summarised below:

- SE Rigby Island: the bathymetry along the southern-eastern corner of Rigby Island, approximately 50 m to the north of the northern edge of Hopetoun Channel, has remained relatively stable and in December 2020 it was deeper than most surveys over the previous five years along the north-eastern two thirds of the transect, but has been shallowing slightly along the western 100 m of the transect. This indicates that sedimentation along the majority of the northern edge of Hopetoun Channel is not expected to increase significantly in the future, although it is possible that it could increase along the western 100 m;
- W Hopetoun: the bathymetry has not changed significantly with the shallow shoal location remaining approximately the same. The 120 m of the transect closest to Hopetoun Channel has deepened by around 0.5 m on average, while the deeper section of the channel shallowed from -6.5 m to -4 m CD. As the bathymetry within 150 m of the western end of Hopetoun Channel was deeper than the channel dredge design depth of -4.0 m CD, the localised shallowing which had occurred is not expected to result in any future sedimentation in Hopetoun Channel; and
- Reeve Shoal: the transect shows that there has been localised areas of erosion and sedimentation between the pre-2018 and January 2020 bathymetric surveys. The bathymetry over the last 200 m of the transect (the western end) is very similar between the two years, while the bathymetry along the eastern end has shallowed by around 1 m suggesting that the shallower section of the shoal has advanced in an eastern direction by approximately 100 m. The western end of the shoal not changing while the eastern end has advanced suggests that the shoal is growing as opposed to migrating.

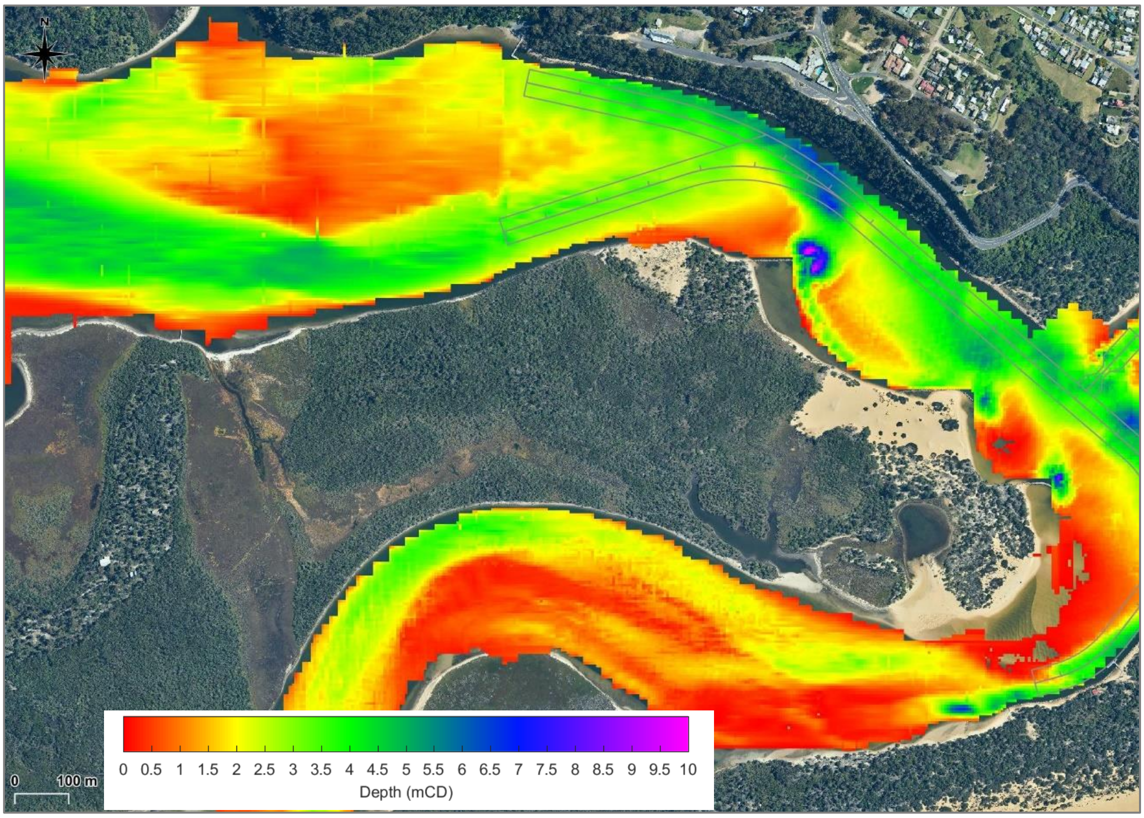

Figure 12. Bathymetry around Rigby Island from the pre-2018 dataset.

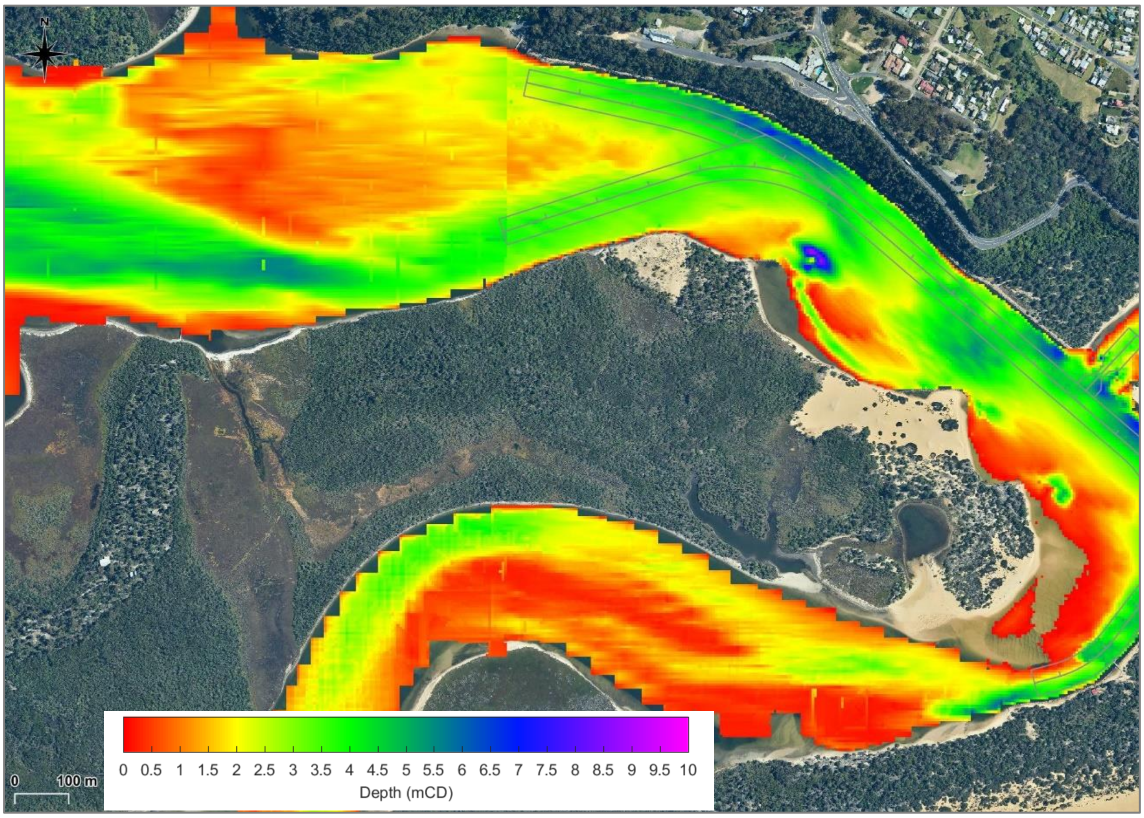

Figure 13. Bathymetry around Rigby Island from the October 2020 survey.

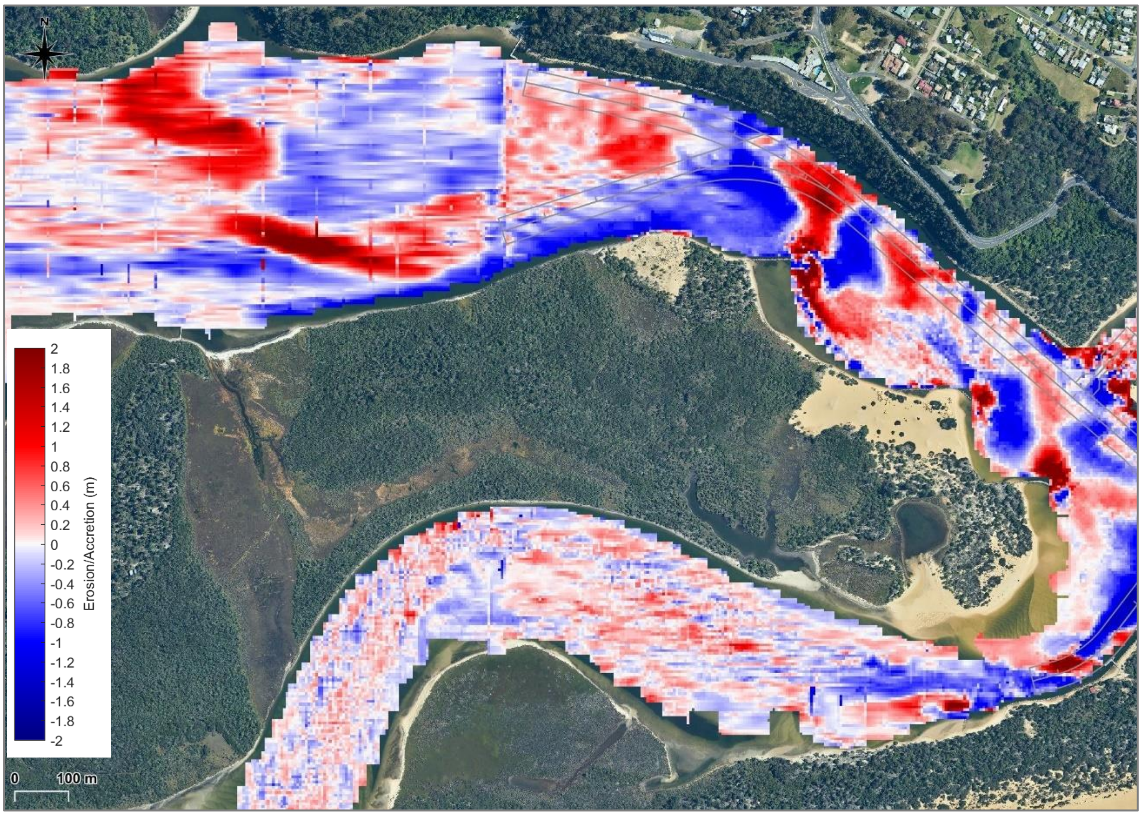

Figure 14. Difference in bathymetry around Rigby Island between the 2020 data and the pre-2018 dataset. *Note: positive change represents sedimentation, negative erosion.*

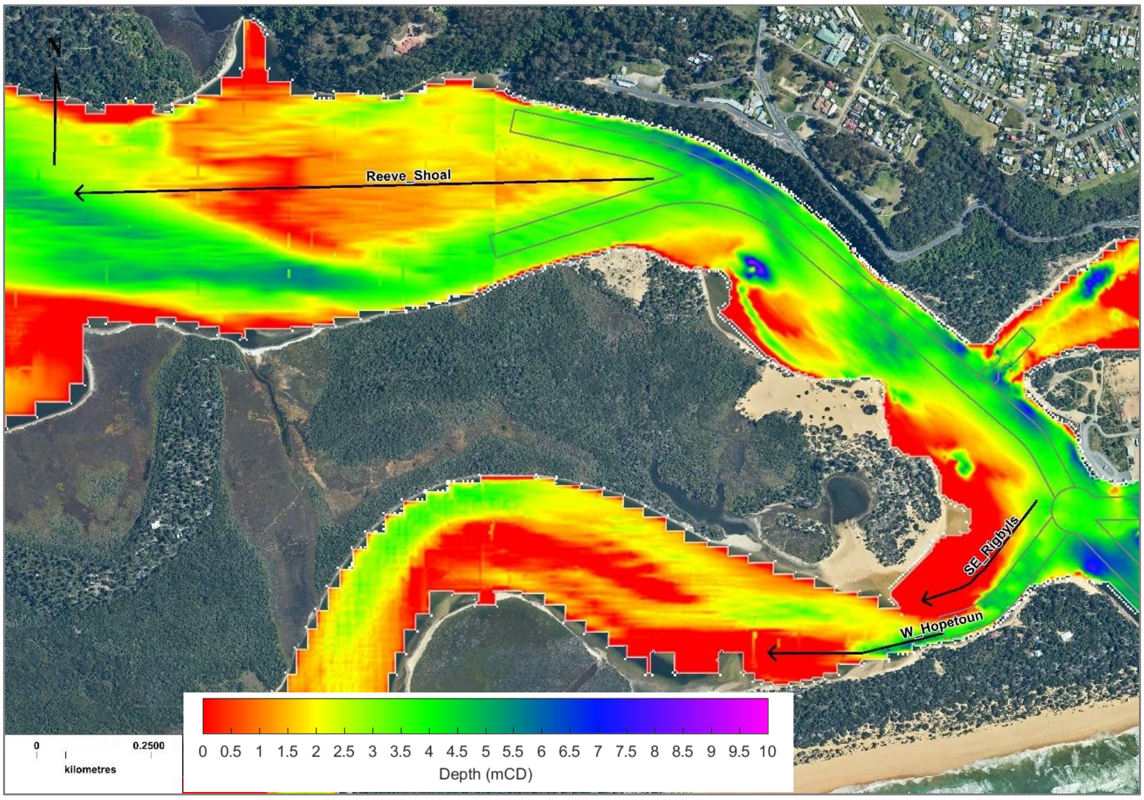

Figure 15. Location of transects relative to October 2020 bathymetry.

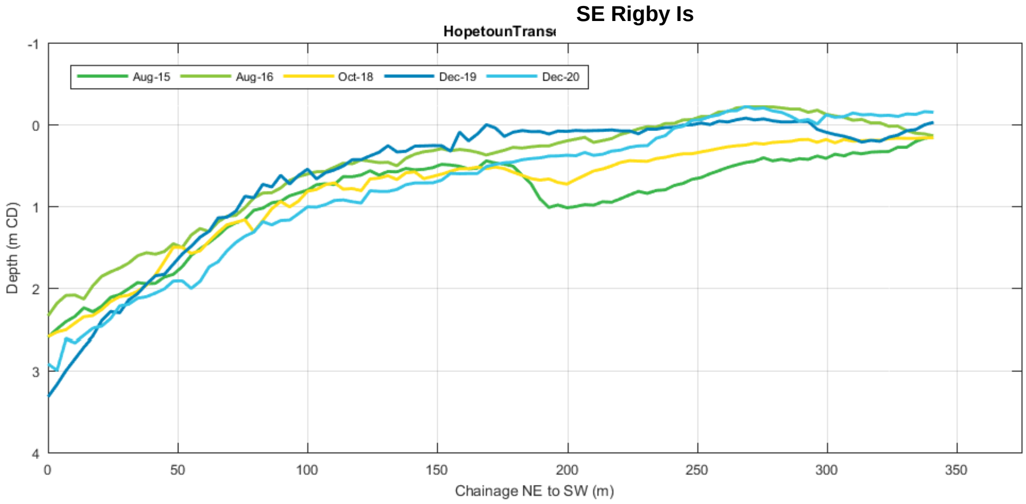

Figure 16. Transect along SE Rigby Island showing change in bathymetry from August 2015 to December 2020.

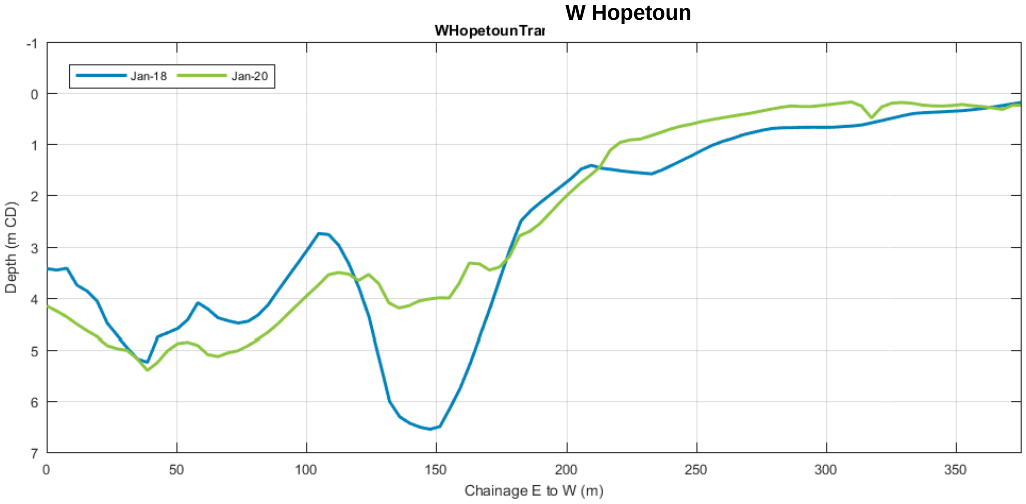

Figure 17. Transect along W Hopetoun showing change in bathymetry from pre-2018 to January 2020.

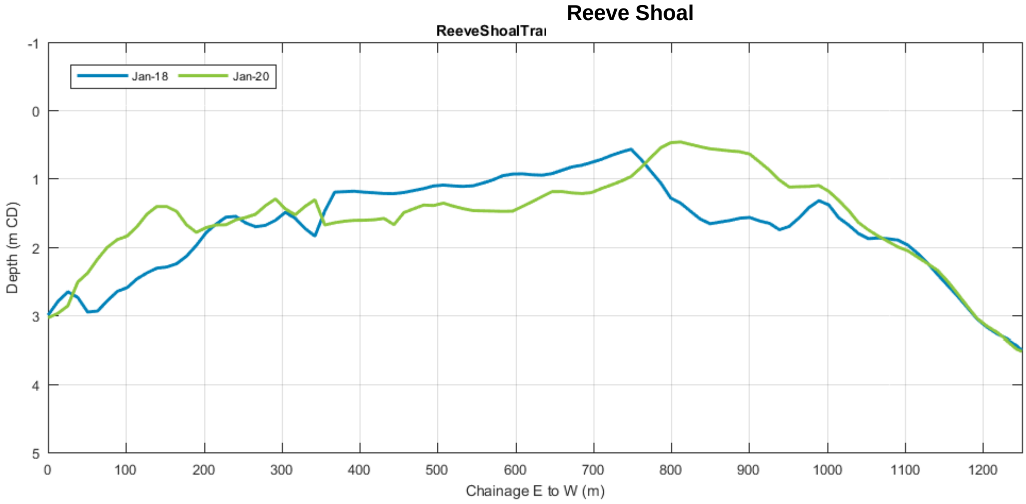

Figure 18. Transect along Reeve Shoal showing change in bathymetry from pre-2018 to January 2020.

2.3.2. Satellite Derived Bathymetry

Imagery from the Sentinel-2 satellite has been downloaded and processed to derive annual satellite derived bathymetry (SDB) datasets to further investigate changes occurring in a number of infrequently surveyed areas of interest between 2017 and 2021. The main areas include the sandy shoals to the north and south of Rigby Island and the natural bar formation to the east and west of the dredged Bar (Figure 19). The SDB of the areas to the north and south of Rigby Island will be used to determine whether the changes identified from the pre 2018 and the 2020 hydrographic survey are representative of typical ongoing changes. The SDB of the natural bar formation will be used to better understand how the bathymetry in this area changes over time.

Suitable satellite imagery (during periods of low cloud cover) has been sourced for each year between 2017 and 2021 and processed to derive bathymetry. The following imagery was used:

- 9th March 2017 10:12 AEST;
- 17th February 2018 10:10 AEST;
- 13th February 2019 09:56 AEST;
- 27th February 2020 10:11 AEST; and
- 15th March 2021 10:02 AEST.

The true colour satellite imagery for these dates is shown for the region in Figure 20 to Figure 24.

For consistency across all images, the Level-1C (top of the atmosphere) products were downloaded (Level-2A imagery corrected for atmospheric effects are only available post December 2018) and were processed to Level-2A using the ACOLITE processor developed by the Royal Belgian Institute of Natural Sciences (RBINS) (Vanhellemont and Ruddick, 2016). The ACOLITE processor was developed to correct imagery for atmospheric effects specifically over water and has been widely used in SDB studies (for example Caballero and Stumpf (2019) and Caballero and Stumpf (2020)) and was found to perform well in an assessment of different atmospheric correction methods (Ilori *et al.*, 2019).

The bathymetry was derived using the ratio model of log-transformed bands as developed by Stumpf *et al.*, (2003). The ratio model makes use of the reflectance of the blue (490 nm), green (560 nm) and red (664 nm) bands for each satellite image corrected for atmospheric effects, with the log transform accounting for the exponential decrease in light with depth. Comparisons of the ratio of blue to green bands (pSDBgreen) and blue to red bands (pSDBred) against survey data are then used to define linear fits so that SDBgreen and SDBred can be derived. In this instance, comparisons of pSDBgreen against survey data were found to have high degrees of scatter and low levels of correlation. It is possible that this could be because the atmospheric corrections applied to the imagery were derived for over water, while the study area is located more inland where different atmospheric corrections may be more applicable. This study therefore focusses on the use of pSDBred within the Lakes area, which given the shallower areas of interest is not considered to pose a limitation on the derived bathymetry.

Figure 19. Main areas of interest for analysis of bathymetric changes using satellite derived bathymetry.

Figure 20. True colour image from Sentinel 2 on 9th March 2017 10:1 2 AEST.

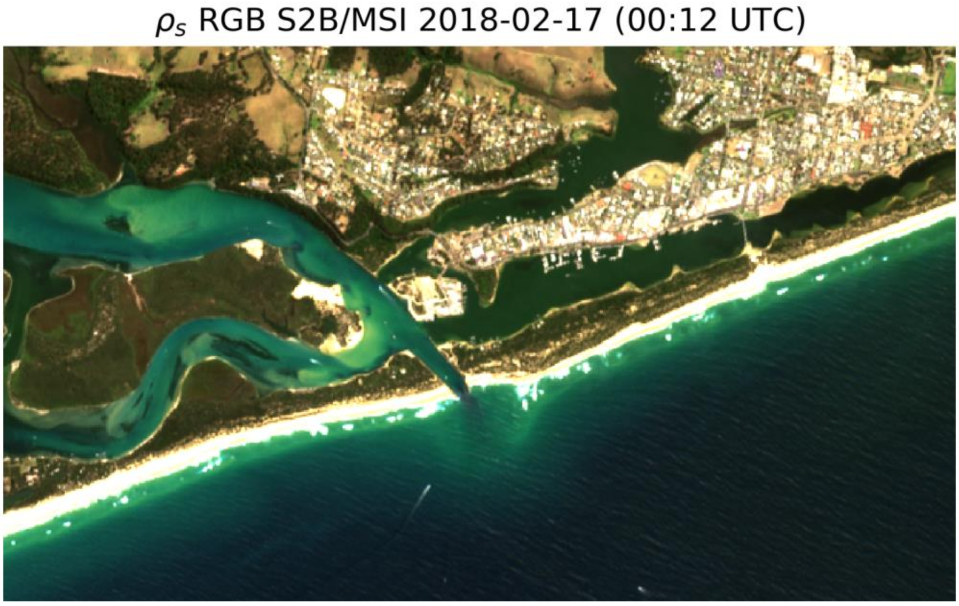

Figure 21. True colour image from Sentinel 2 on 7th February 2018 10:10 AEST.

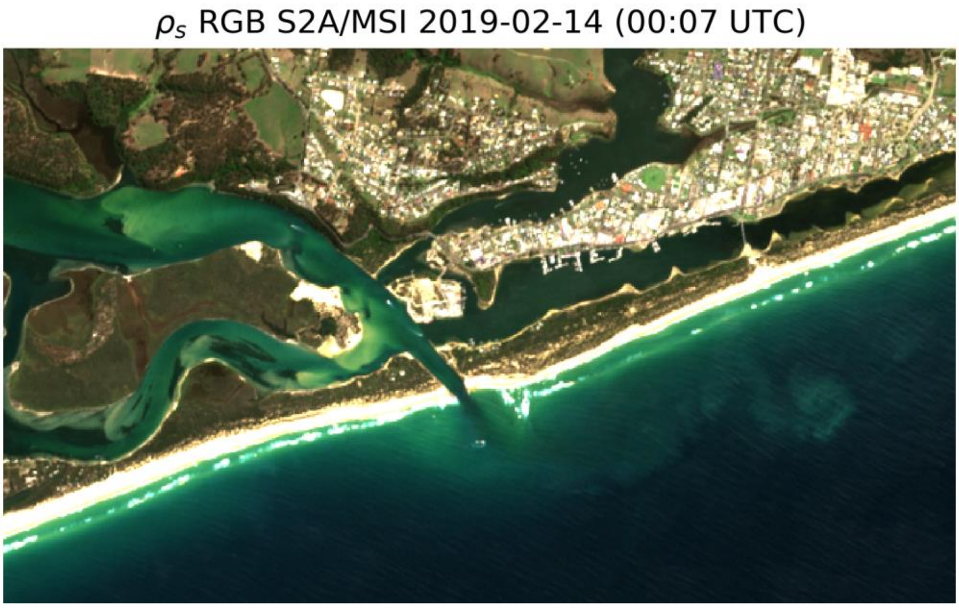

Figure 22. True colour image from Sentinel 2 on 13th February 2019 09:56 AEST.

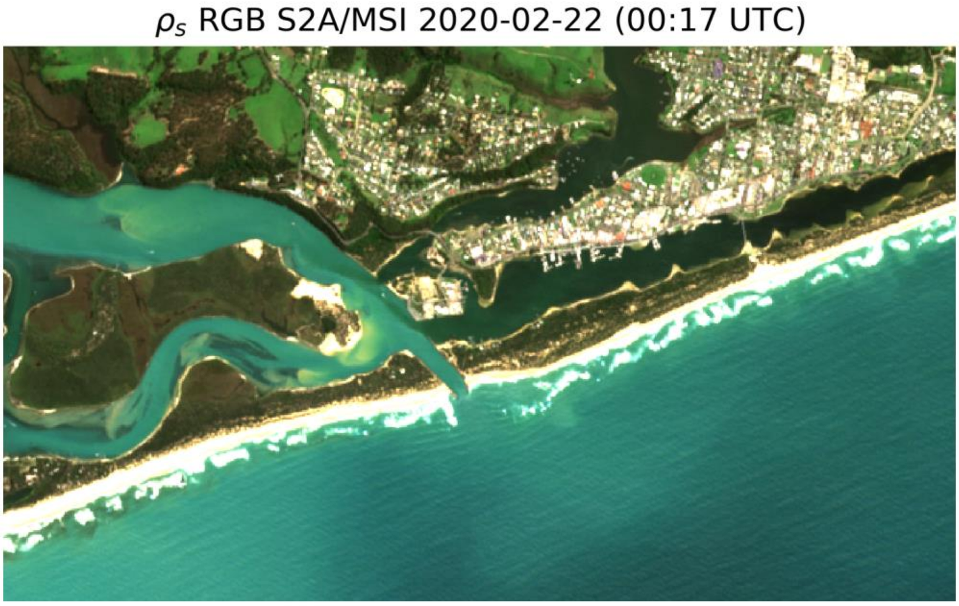

Figure 23. True colour image from Sentinel 2 on 22nd February 2020 10:11 AEST.

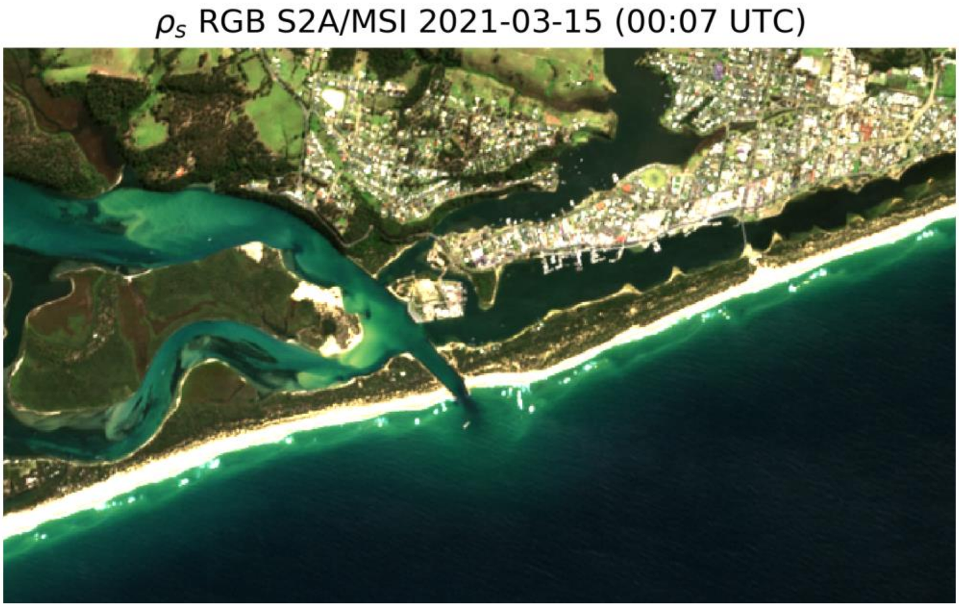

Figure 24. True colour image from Sentinel 2 on 15th March 2021 10:02 AEST.

SDB based on the Sentinel 2 images for 2017 to 2021 are shown for the area around Rigby Island in Figure 25 to Figure 29. As noted, the SDB is most accurate in the shallower depths (0 to 2 m) and is likely to underestimate the deeper depths. Despite this limitation the plots can still be used to understand how the shallow shoals have changed over time. The change in bathymetry between the 2021 and 2018 plots has also been calculated and is presented in Figure 30. The plots show the following:

- overall there is a good agreement between the depths from the SDB and from the hydrographic surveys in the shallower areas (see Figure 12 and Figure 13) providing confidence in the SDB;
- the eastward migration of the shallow shoal off the south-eastern corner of Rigby Island and subsequent localised shallowing along the northern half of the western end of Hopetoun Chanel identified from the pre 2018 and 2020 hydrographic survey data appears to be part of an ongoing trend. This shoal shows an easterly migration between 2019 and 2021, with the edge of the shoal almost reaching the western end of Hopetoun Channel in the 2021 data. The change in bathymetry between 2018 and 2021 indicates that the shoal directly to the north of the western end of Hopetoun Channel has shallowed by just under 0.5 m, this ties in well with the 2018 and 2020 hydrographic survey data shown in Figure 16;
- the area to the west of the Hopetoun Channel which was identified as being relatively stable between pre 2018 and 2020 from the hydrographic survey data is also shown to have remained relatively stable in the SDB data. However, although the shallow shoal located approximately 200 m to the west of the western end of Hopetoun Channel appears to have remained stable between 2017 and 2020, the 2021 data suggests that it might have migrated closer to Hopetoun Channel;
- the sedimentation occurring on the large shoal located between Reeve Channel and the northern end of the Narrows appears to have increased between 2017 and 2021, this also agrees with the findings based on the hydrographic survey data; and
- the widening of the natural channel around Reeve Channel (and to the west of Reeve Channel) and erosion along the northern edge of Rigby Island is part of an ongoing trend. The shallow shoal to the north of Reeve Channel appears to be migrating/growing in a southerly direction and this is resulting in the natural deeper channel also migrating to the south which is causing erosion of the northern shoreline of Rigby Island.

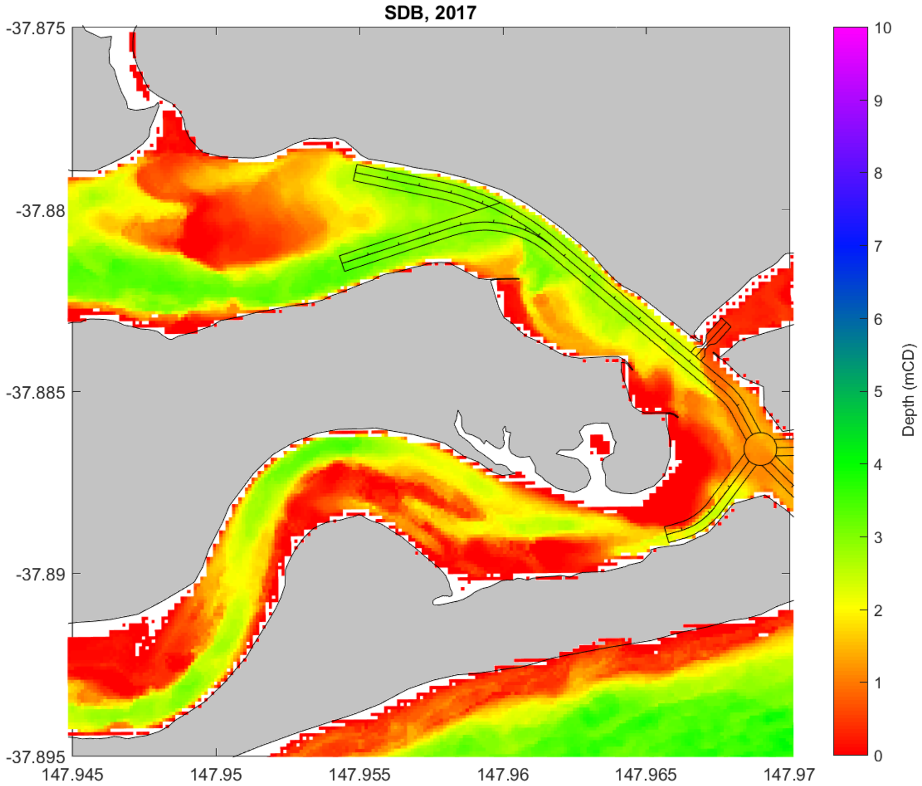

Figure 25. SDB of the Inner Channels in 2017 (Sentinel 2 image from 9th March 2017).

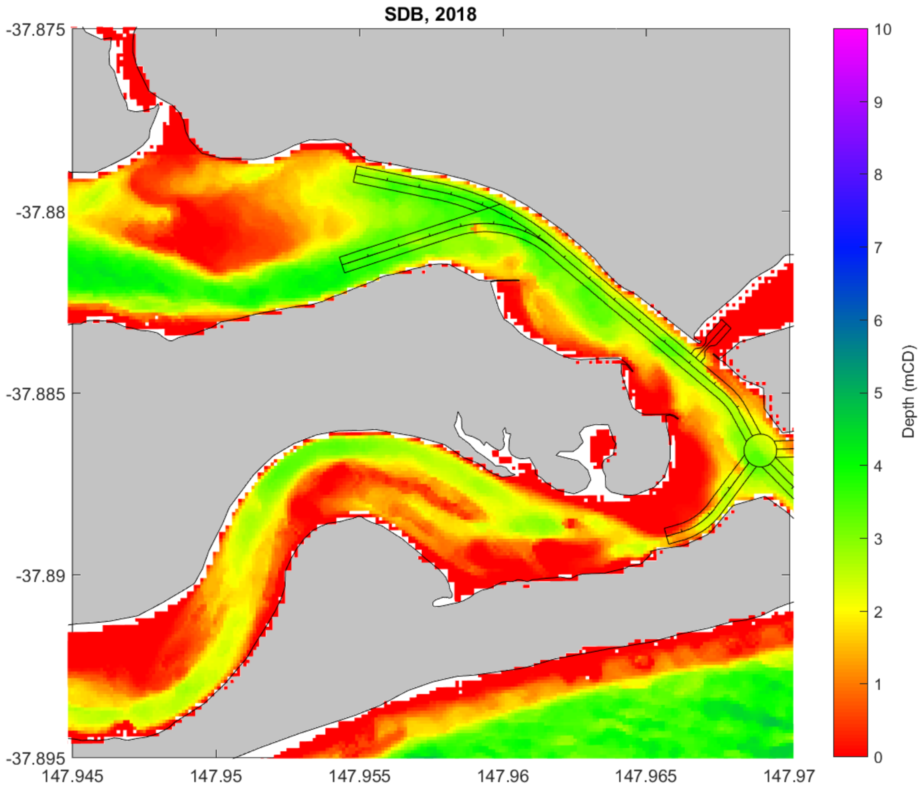

Figure 26. SDB of the Inner Channels in 2018 (Sentinel 2 image from 17th February 2018).

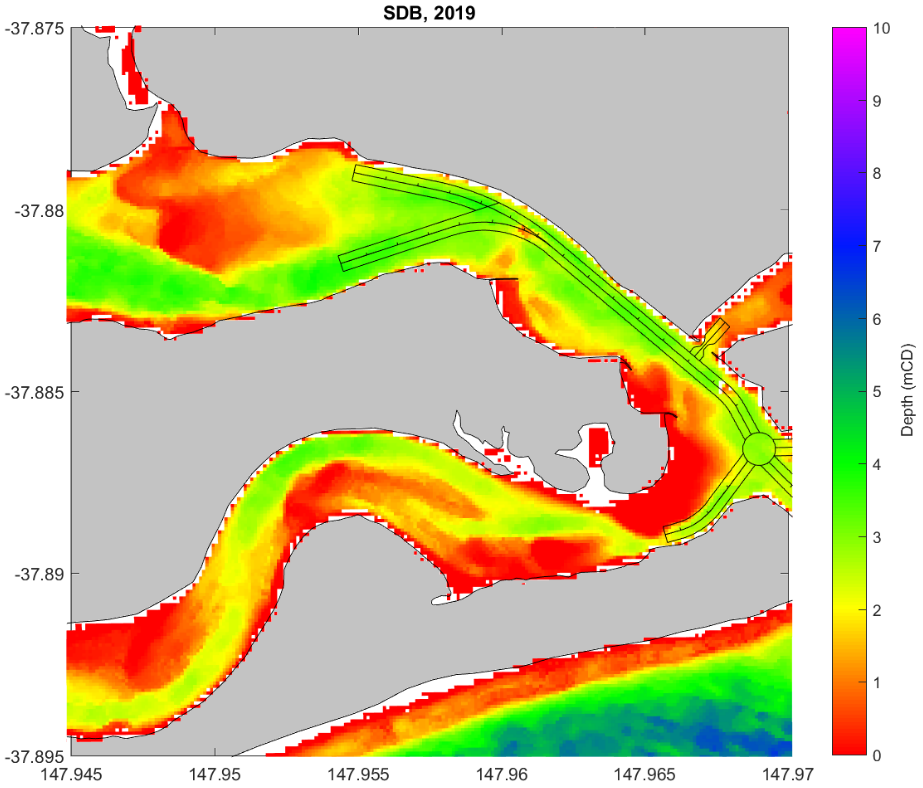

Figure 27. SDB of the Inner Channels in 2019 (Sentinel 2 image from 13th February 2019).

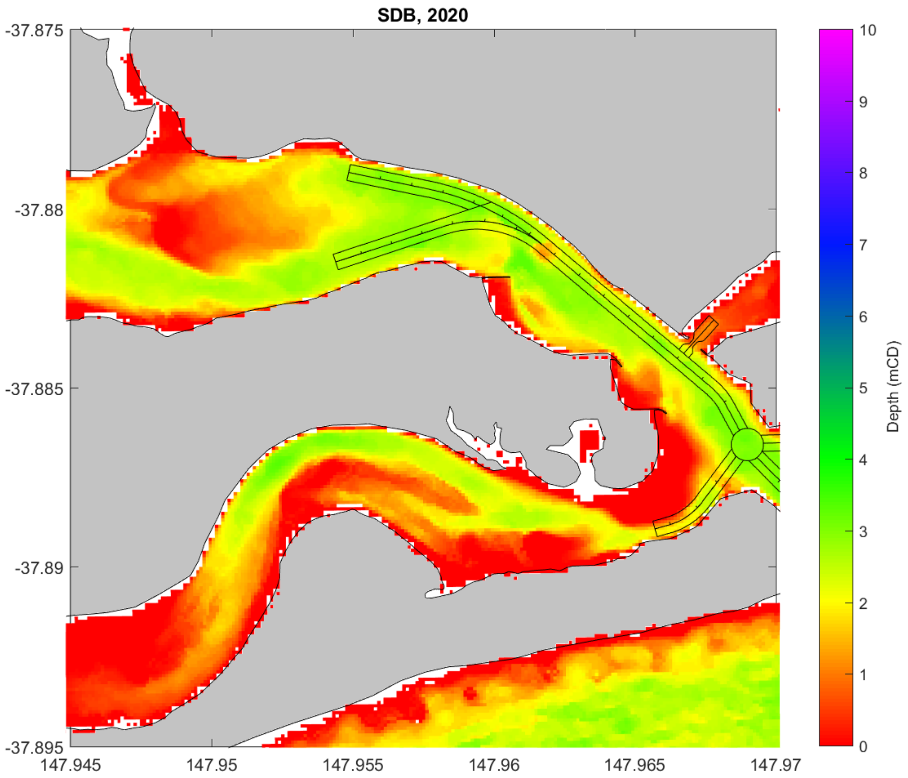

Figure 28. SDB of the Inner Channels in 2020 (Sentinel 2 image from 22nd February 2020).

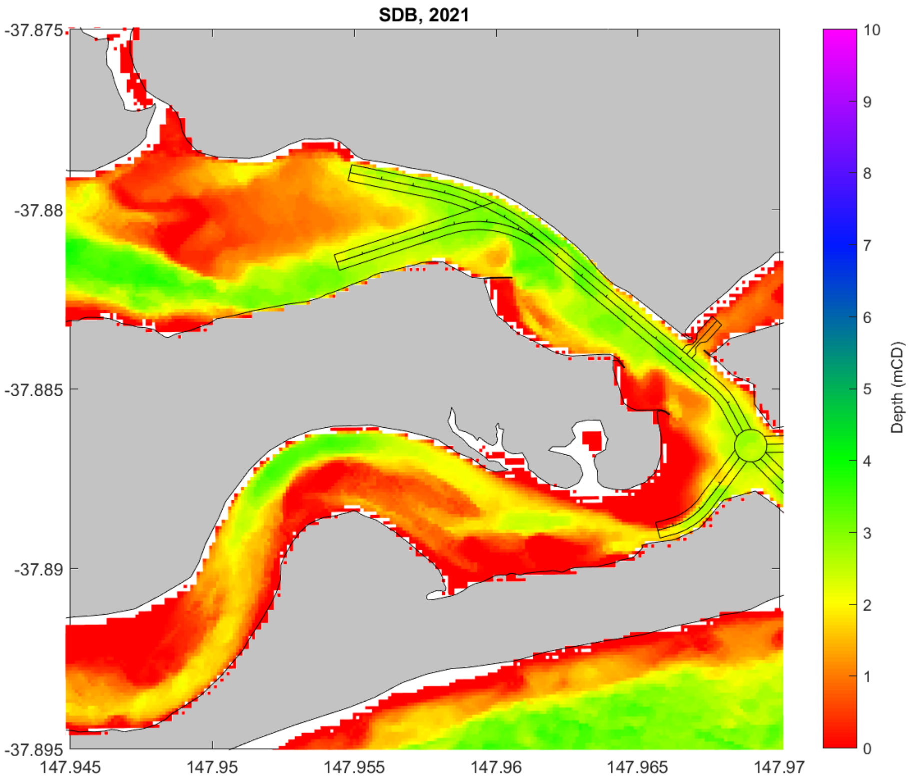

Figure 29. SDB of the Inner Channels in 2021 (Sentinel 2 image from 15th March 2021).

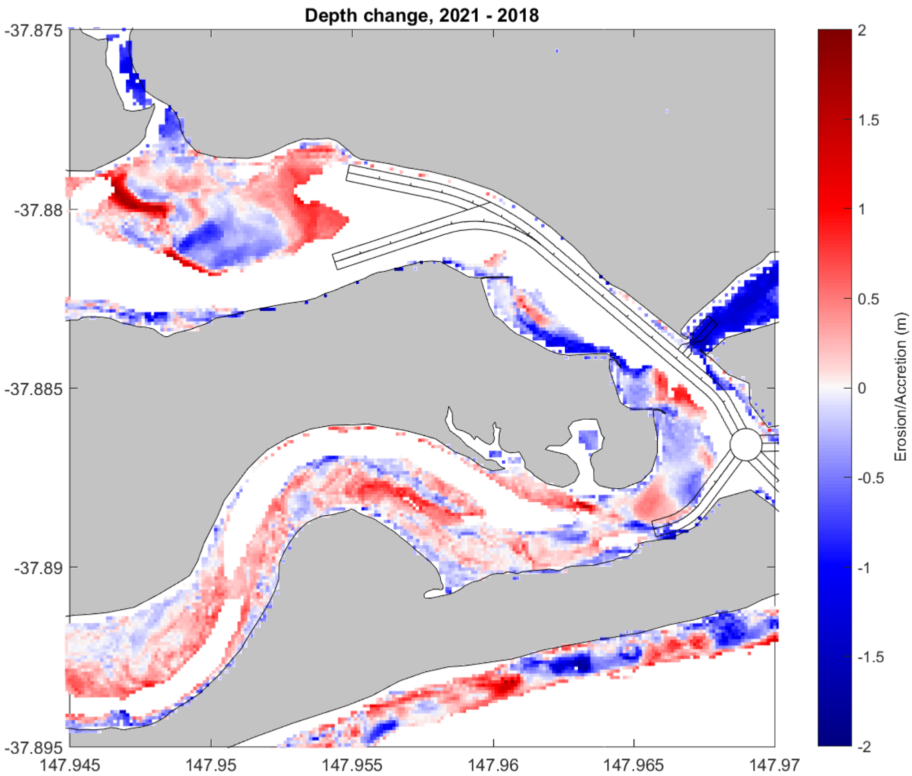

Figure 30. Difference in bathymetry around Rigby Island between the 2021 SDB and the 2018 SDB dataset. *Note: positive change represents sedimentation, negative erosion.*

The SDB for the natural bar adjacent to the dredged Bar was found to be less reliable than the SDB within the Lake due to additional constraints such as wave action and reduced water clarity. As a result, meaningful SDB could only be processed for 2018 to 2021 and the resultant depths should only be used to provide a qualitative indication of the bar morphology (i.e. the absolute depths shown in the images should not be compared between images). The SDB based on the Sentinel 2 images for 2018 to 2021 are shown for the area around the dredged Bar in Figure 31 to Figure 34. The plots show that:

- the natural bar on the eastern side of the entrance forms where the coastline orientation changes, approximately 400 m to the east of the eastern training wall, rather than adjacent to the eastern training wall. In addition, the eastern side of the natural bar consistently extends further offshore compared to the western side by 30% to 50%. As a result, sedimentation associated with the migration/growth of the natural bar has the potential to influence depths within the dredged Bar further offshore at the eastern side of the Bar (approximately mid way along the middle section of the Bar, 450 m from start of the Entrance Channel) compared to the western side of the Bar (approximately where the first kink in the Bar wedge occurs, 200 m from start of the Entrance Channel); and
- there is the potential for a shallow sand bar to form directly offshore of the western training wall which can result in direct sedimentation into the narrowest section of the Bar Channel. There appears to be less potential of this occurring adjacent to the eastern training wall, this is likely to be related to the shoreline orientation, training wall orientation and the fact that the natural bar has formed further offshore on this side.

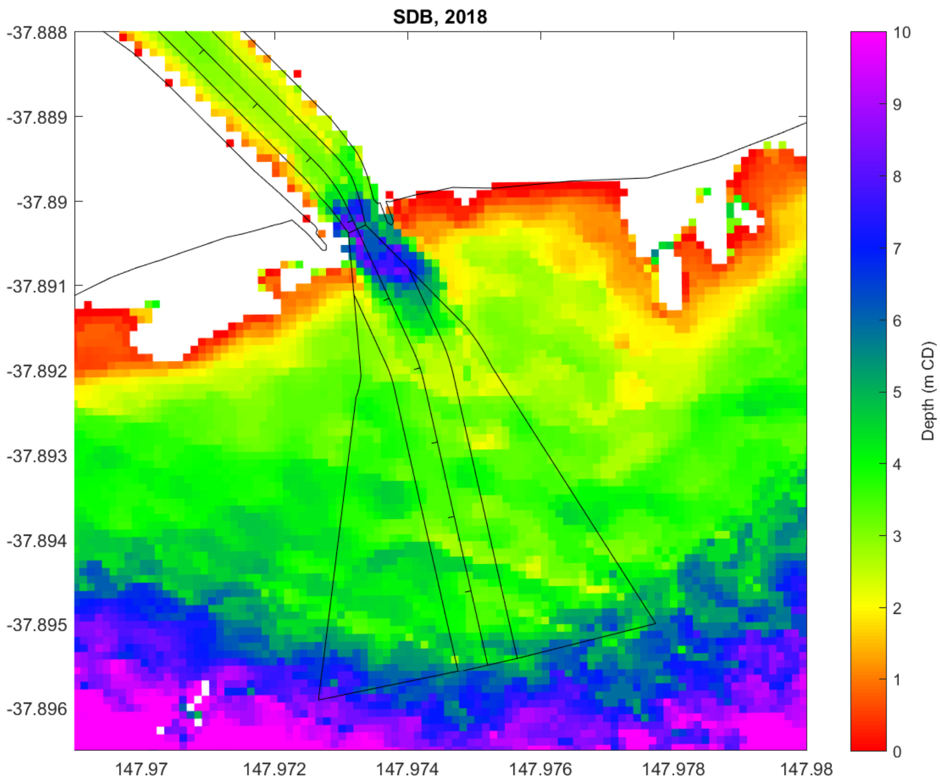

Figure 31. SDB of the Bar region in 2018 (Sentinel 2 image from 17th February 2018).

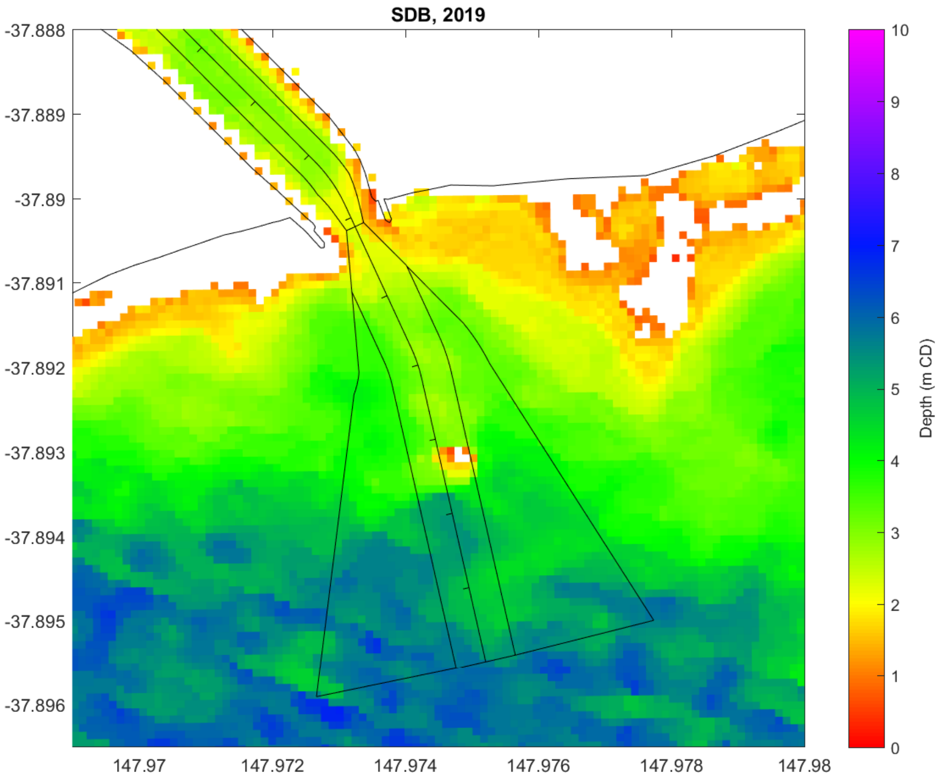

Figure 32. SDB of the Bar region in 2019 (Sentinel 2 image from 13th February 2019).

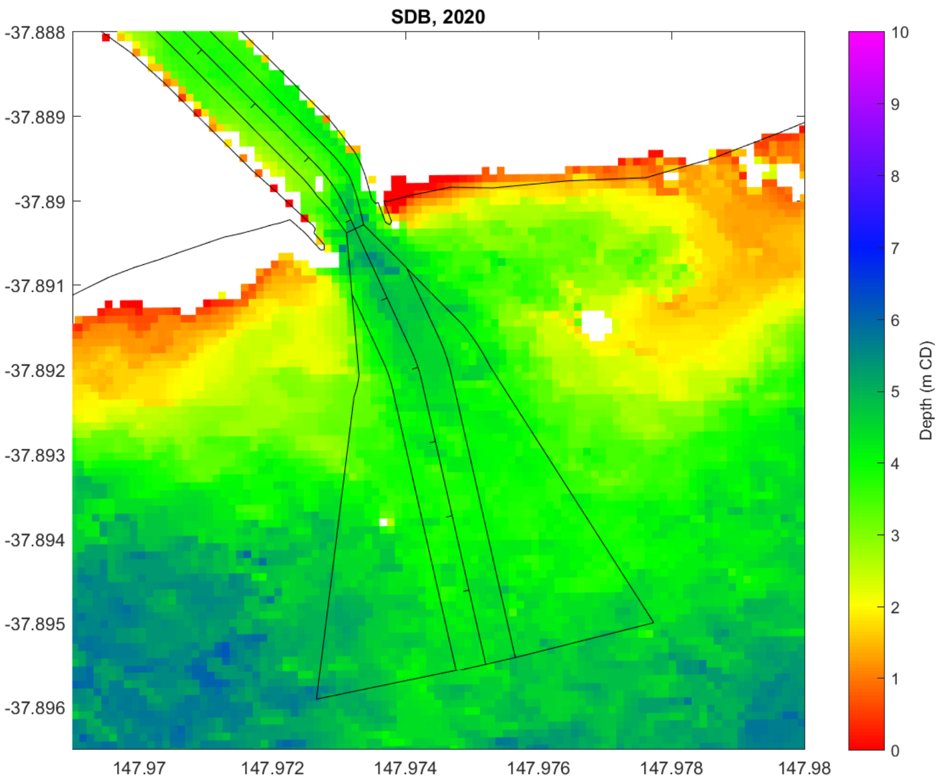

Figure 33. SDB of the Bar region in 2020 (Sentinel 2 image from 22nd February 2020).

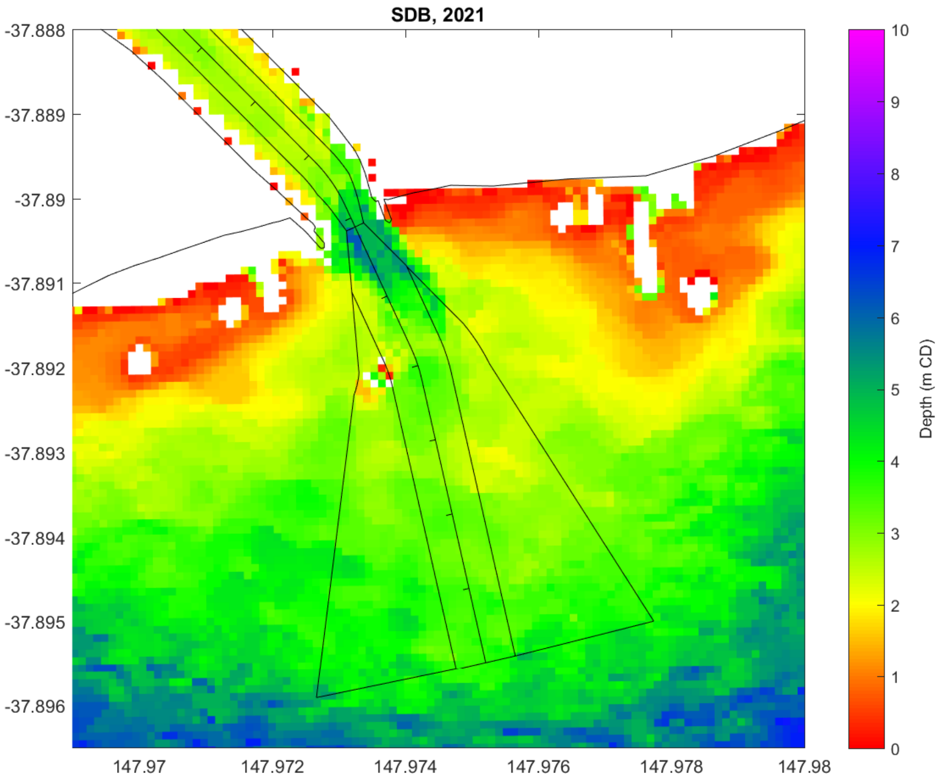

Figure 34. SDB of the Bar region in 2021 (Sentinel 2 image from 15th March 2021).

3. Dredge Design

The dredge design assessment is aimed at assessing the performance of the current dredge design of the Bar and Inner Channels as well as assessing potential alternative dredge designs. The assessment includes an analogues assessment, numerical modelling and further bathymetric analysis as well as consideration of the previous findings from the bathymetric and metocean data analysis.

3.1. Analogues Assessment

It can be beneficial to understand the dredge design adopted at other locations with a similar river entrance and bar configuration to help optimise the design at Lakes Entrance. Although the training of rivers entrances has been widely undertaken within Australia to improve navigation, only one analogue where regular maintenance dredging of the bar is required has been identified, which is the Tweed River entrance. A meeting with relevant personnel related to the sediment management at the Tweed River entrance was held as part of this study to better understand what management measures are implemented. Relevant details from the meeting related to this analogue are provided below:

- the Tweed River has a 150 m wide trained entrance (Lakes Entrance is 85 m) and ongoing maintenance dredging is required at the ebb bar (peak is located approximately 400 m offshore of the seaward end of the training walls/breakwaters which is similar to Lakes Entrance);
- there is a sand bypassing jetty located on the beach immediately to the south of the Tweed River entrance, which pumps sand across the Tweed River to discharge points located to the north of the entrance as part of a Sand Transfer System (STS). The sand which is pumped has been transported as longshore drift towards the Tweed River and without being intercepted by the STS would likely have been transported and deposited on the ebb bar at the river entrance;
- the STS is not able to relocate all of the sand transported by longshore transport and so some of the sand is deposited on the ebb bar at the Tweed River entrance. Over the last 10 years between 320,000 and 550,000 m^3/yr has been pumped through the STS (Tweed Sand Bypassing, 2021). It has been estimated that the STS captures approximately 70% of the longshore transport and the remaining 30% is transported to the bar. The ongoing sedimentation which occurs in this area is typically managed through annual maintenance dredging programs where a TSHD relocates between 100,000 and 150,000 m^3 of sediment to beneficial reuse sites located to the north and south of the Tweed River (Figure 35);
- the target depth of the dredging at the bar is -6 m CD, which is only 0.5 m deeper than Lakes Entrance. However, unlike at Lakes Entrance the maintenance dredging for the Tweed River entrance is undertaken by an external dredge contractor and so the volume of sediment dredged each year is dependent on the available budget meaning it is not always possible to achieve the target depth;
- the dredge area for the Tweed River Entrance bar is a wedge shape which is similar to Lakes Entrance except that for the Tweed River the wedge is wider. The wedge shape was designed in consideration of the fact that maintenance dredging is undertaken annually during a single campaign (lasting one to two months dependent on metocean conditions) and so the dredging is required to ensure sufficient depth is available for safe navigation between the annual programs. A number of different dredge configurations have been tested within the dredge area, with the preferred approach being dredging to a single depth and widening the dredge area as much as possible; and
- no impacts to the training walls, the flood tide delta or the tidal elevations within the estuary have been observed as a result of the dredging of the Tweed River bar. Modelling of the wave refraction and potential impact on surfing at the adjacent beaches is planned in the future, but to date no work has been undertaken.

Figure 35. Oblique aerial image showing the TSHD Albatros dredging the Tweed River entrance bar (Dutch Dredging, 2021).

Although the Tweed River STS has been a very effective approach to manage the majority of the longshore transport which reaches the southern side of the Tweed River, this approach is not considered to be suitable for Lakes Entrance. The longshore transport in the Tweed River region is in a northerly direction for the majority of the time, with transport in a southerly direction only occurring for a small amount of time. This means that the formation of the bar typically occurs due to longshore transport at the southern side of the Tweed River building up adjacent to the training wall and then the bar advancing beyond the training wall in a northerly direction. In contrast, at Lakes Entrance although there is a net dominant westerly longshore transport, the waves which result in easterly longshore transport occur for approximately a third of the time each year as well meaning that relatively high longshore transport rates can occur both to the west and the east. This would mean that the process of transferring sand from one side of the entrance to the other would not be as effective at Lakes Entrance as it as at the Tweed River.

The fact that the Tweed River dredge design is a wider wedge than at Lakes Entrance allows increased buffer to ensure that the entrance remains navigable between the annual dredge programs. This is required at the Tweed River entrance as the strong dominance in a northerly longshore transport means that the net longshore transport rates are higher than at Lakes Entrance. In addition, since 2017 GP has had the TSHD *Tommy Norton* and have been able to undertake ongoing maintenance dredging rather than annual campaigns meaning that a wider dredge design is not required.

It is interesting to note that no impacts to the training walls, the flood tide delta (within the estuary) or the tidal elevations within the estuary have been noted as a result of the dredging of the bar at the Tweed River. Due to the similarities between the two locations, it would also be expected that no impacts would have occurred at Lakes Entrance due to dredging of the Bar.

3.2. Dredge Design Options

The wedge-shaped Bar dredge design was originally adopted in 2008 to provide sufficient buffer between annual maintenance dredging so that the Bar Channel remained navigable. In addition, the design was also noted as having the potential to refract waves, help to keep the training walls clear of sand and to limit the transport of sand into the Entrance Channel.

A number of modifications to the existing dredge design have been considered as part of this assessment. The modifications were developed in collaboration with GP to provide a range of realistic potential alternative options to the existing dredge design of the Bar and Inner Channels. The dredge design options being considered include seven options for the Bar (including the existing scenario) and three options for the Inner Channels (including the existing scenario), the options are detailed below:

- Option A1 (existing Bar and Inner Channel case): wedges and Bar Channel dredged to -5.5 m CD (-6.26 m MSL) and the Inner Channels based on the December 2020 bathymetric survey. This option is considered to represent the existing approved dredge design and is what was adopted when annual maintenance dredging was undertaken by GP (Figure 36);
- Option A2: wedges and Bar Channel dredged to -4.5 m CD (-5.26 m MSL). This option along with Option B is representative of what the Bar is currently dredged to as year round maintenance dredging is undertaken by GP (Figure 37);
- Option B: Bar Channel dredged to -5.5 m CD (-6.26 m MSL) and wedges dredged to -4.5 m CD (-5.26 m MSL) (Figure 38);
- Option C: Bar Channel and east wedge dredged to -5.5 m CD (-6.26 m MSL), west wedge returned to natural depths (Figure 39);
- Option D: Bar Channel and west wedge dredged to -5.5 m CD (-6.26 m MSL), east wedge returned to natural depths (Figure 40);
- Option E1: Bar Channel dredged to -5.5 m CD (-6.26 m MSL) and wedges returned to natural depths (Figure 41);
- Option E2: Bar Channel widened to 160 m and dredged to -5.5 CD (-6.26 MSL), remaining parts of wedges returned to natural depths (Figure 42);
- Option IC01: Bar channel and wedges dredged to -5.5 m CD (-6.26 m MSL) and Inner Channel including minor widening of the Entrance Channel (-4.5 m CD), Cunninghame Arm (-4.5 m CD) and the Narrows (-4.0 m CD) in the areas of the channel adjacent to the Swing Basin and an extension to the Cunninghame Arm channel along the east side of Bullock Island (-4.5 m CD) (Figure 43); and
- Option IC02: Bar channel and wedges dredged to -5.5 m CD (-6.26 m MSL) and Hopetoun Channel width reduced from 50 m wide to 30 m wide, with the northern boundary of the channel shifted 20 m to the south (Figure 44).

Figure 36. Option A1 dredge design.

Figure 37. Option A2 dredge design.

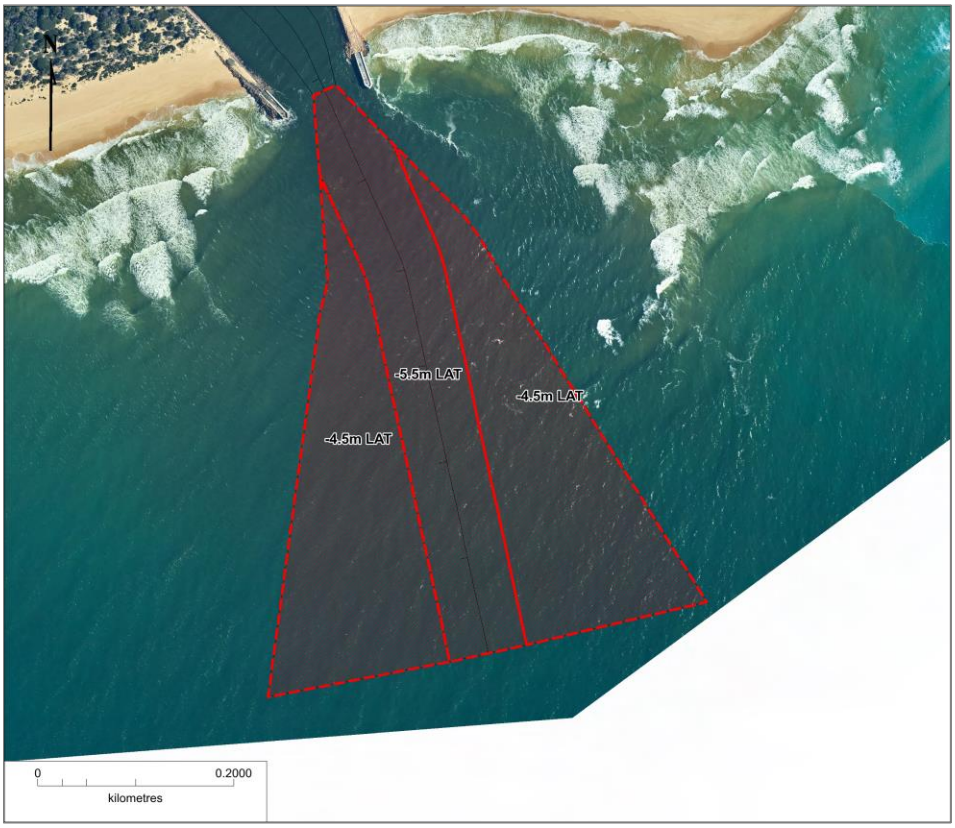

Figure 38. Option B dredge design.

Figure 39. Option C dredge design.

Figure 40. Option D dredge design.

Figure 41. Option E1 dredge design.

Figure 42. Option E2 dredge design.

Figure 43. Option IC01 dredge design.

Figure 44. Option IC02 dredge design.

3.3. Numerical Modelling

To assess any impacts to hydrodynamics or waves resulting from the existing and alternative dredge designs for the Bar and Inner Channels, both hydrodynamic and spectral wave modelling has been undertaken. Hydrodynamic and spectral wave models of the Lakes Entrance region have been developed and calibrated for this assessment, further detail on the setup and calibration of the models is provided in Appendix A.

Wave modelling of the existing dredge design for the Bar was never undertaken numerically or physically and so the potential impact of the wedge dredge design on wave refraction is unknown. An assessment of the impacts to hydrodynamics of the existing approved dredge design of the Bar was previously undertaken to support the current Sea Dumping Permit (Water Technology, 2013). The previous modelling assessed potential impacts to hydrodynamics and sediment transport processes of proposed revisions to the dredged design of the Bar. The modelling predicted negligible impacts to the hydrodynamics within the entrance to Gippsland Lakes for the different dredge design scenarios considered.

For this assessment, the hydrodynamic and spectral wave modelling has modelled a scenario with the Bar not dredged, referred to in the following sections as the 'base' case. The model bathymetry for the base case was based on the bathymetric survey of the Bar from September 2017 which was 12 months after previous maintenance dredging was undertaken and so can be considered to be representative of a natural bar configuration.

For all options, the model bathymetry for the dredged areas of the Port was based on the bathymetry from the most recent hydrographic surveys collected in December 2020 and then the bathymetry of the Bar area or the Inner Channels region was changed for the various options being modelled as noted in Section 3.2.

3.3.1. Hydrodynamic Modelling

The hydrodynamic model was setup to model all nine of the dredge design options detailed in Section 3.2 as well as the base case over a 15 day spring neap cycle. The water level and flow discharge results from the model have been processed to show the following:

- box and whisker plots of the percentiles for the water level in the Entrance Channel and at Bullock Island over the 15 day spring neap cycle (Figure 45 and Figure 46); and
- box and whisker plots of the percentiles for the discharge through the Entrance Channel over the 15 day spring neap cycle (Figure 47).

The water level box and whisker plots show that the different Bar and Inner Channel dredge designs modelled are not predicted to result in a measurable change to the water level either in the Entrance Channel (Lakes Entrance site) or within the Inner Channels (Bullock Island). In addition, the modelled dredge designs of the Bar and Inner Channels are not predicted to result in a measurable change to the discharge either into or out of the Entrance Channel (Lakes Entrance transect). These results provide further evidence in addition to the previous finding from the analysis of measured current speed and water level data, that the annual variability was a result of natural variations in metocean conditions and not due to changes in bathymetry resulting from dredging.

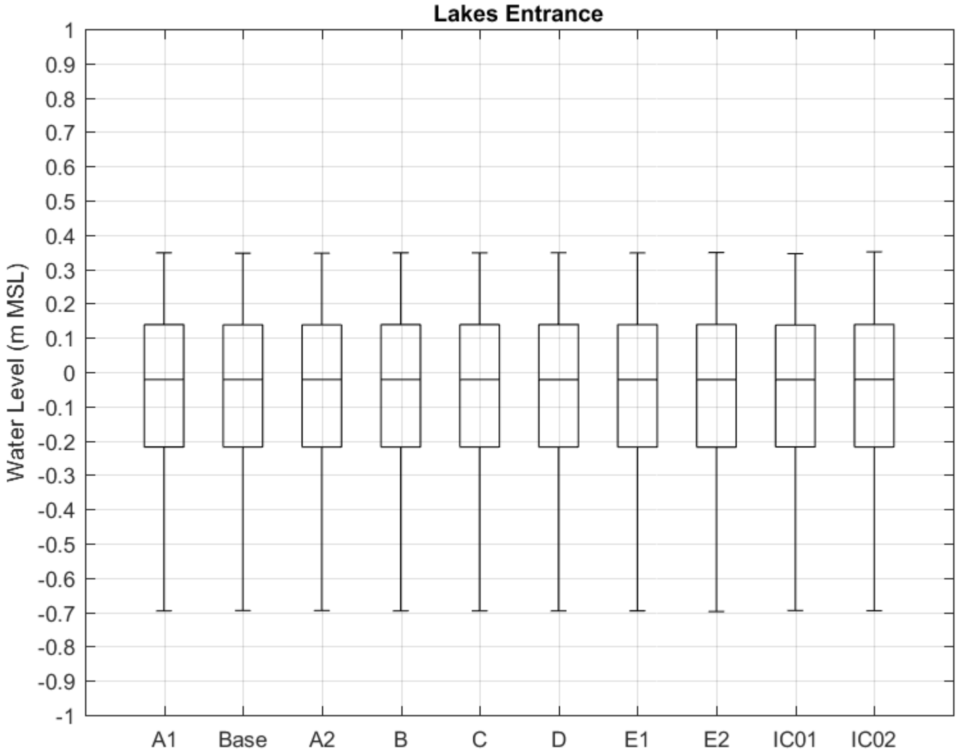

Figure 45. Box and whisker plot of water levels at the Lakes Entrance site over the 15 day model simulation for the various scenarios modelled. *Note: the boxes are represented by the 25th, 50th and 75th percentiles, while the whiskers represent the 1st and 99th percentiles.*

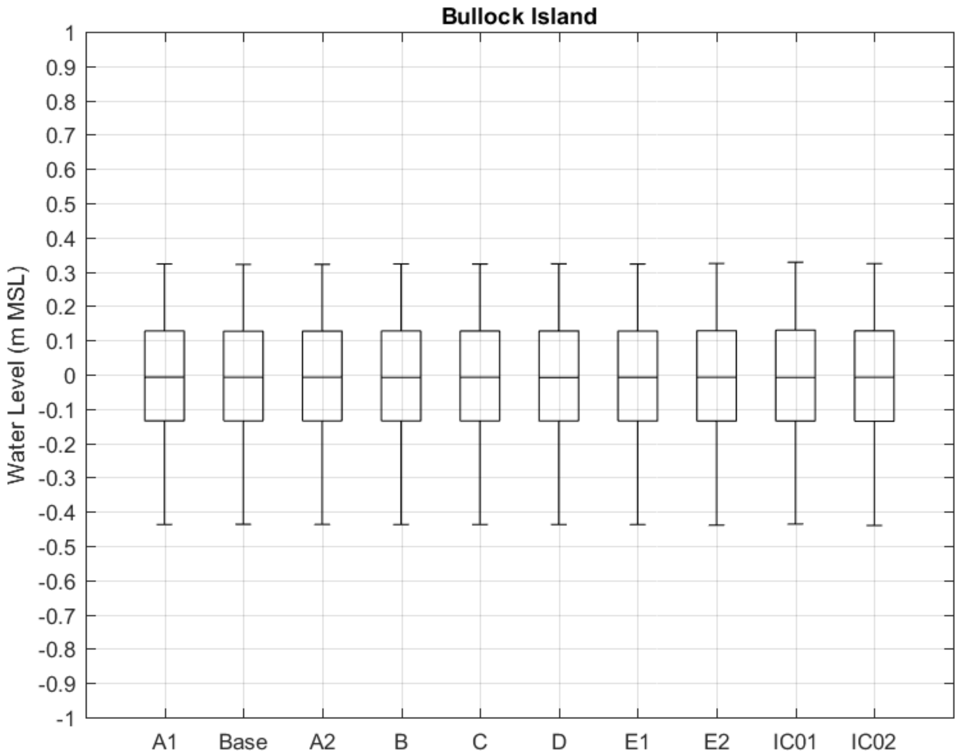

Figure 46. Box and whisker plot of water levels at the Bullock Island site over the 15 day model simulation for the various scenarios modelled. *Note: the boxes are represented by the 25th, 50th and 75th percentiles, while the whiskers represent the 1st and 99th percentiles.*

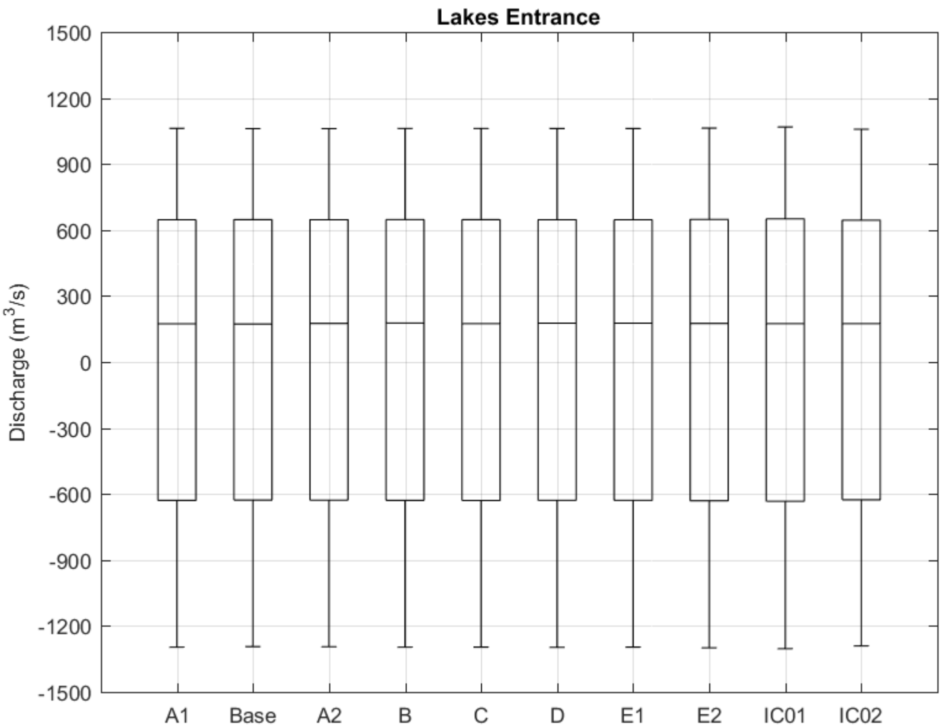

Figure 47. Box and whisker plot of discharge through the Entrance Channel (across the red dashed line at Lakes Entrance shown in Figure 50) over the 15 day model simulation for the various scenarios modelled. *Note: the boxes are represented by the 25th, 50th and 75th percentiles, while the whiskers represent the 1st and 99th percentiles.*

Map plots showing the current speed and current vectors at the time of peak flood and peak ebb during a spring tide are shown for the A1 and Base cases in Figure 48 and Figure 49, respectively (plots for all options are provided in Appendix B). The plots show that the current speeds are lower during the peak flood stage of the tide compared to the peak ebb stage of the tide. Comparison between the predicted currents for the A1 and Base cases shows very little difference during the flood stage of the tide. During the ebb stage of the tide the predicted currents are very similar in the Inner Channels and Entrance Channel, with some localised increases in current speed in the Bar for the Base case relative to the A1 case due to the shallower depths in the Base case. The differences in current speed at the peak flood and peak ebb stages of the tide during a spring tide have been calculated for the dredge design options compared to the existing A1 case, with an increase in current speed showing that the design option has higher current speeds than the A1 case and vice versa for a reduction in current speed. The plots showed little to no change for any of the Bar dredge options during the peak flood stage of the tide and so example plots for just the peak ebb stage of the tide are shown in Figure 50 to Figure 55 for some of the Bar dredge options. The plots show the following:

- most of the options result in localised increases in current speed over the Bar and adjacent areas due to areas of the Bar bathymetry in the option being shallower than the existing A1 case (with no options having a deeper Bar Channel and wedges than existing). The predicted increases in flow speed are up to 0.25 m/s, but are typically less than 0.15 m/s;
- some of the options also result in small localised reductions in flow speed of up to 0.1 m/s over the Bar due to slight changes in the current direction. The only exception to this is option E2, where deepening a 160 m wide Bar Channel to -5.5 m CD and returning the remainder of the wedges to natural depths results in a localised increase in flow speed of up to 0.15 m/s in the west wedge and Bar Channel and a reduction in flow speed of up to 0.15 m/s at the seaward end of the east wedge, extending offshore; and
- none of the Bar dredge options are predicted to result in any changes to the current speed in the Entrance Channel or Inner Channels.

The modelled difference in current speed for the Inner Channel dredge options predicts some changes during both the peak flood and peak ebb stages of the tide and so results from both stages are presented for the two Inner Channel dredge design options in Figure 56 and Figure 57. The plots show the following:

- IC01: the model predicts that this dredge design option would result in localised reductions in current speed of up to 0.25 m/s in the deepened areas and adjacent to them during both the peak flood and peak ebb stages of the tide. During the peak ebb stage of the tide the option is also predicted to result in an increase in current speed of up to 0.15 m/s along the eastern training wall in the Entrance Channel. The increase is not predicted to extend into the designated Entrance Channel and is only localised along the eastern training wall; and
- IC02: the model predicts that this dredge design option would result in localised increases in current speed of up to 0.2 m/s within Hopetoun Channel and adjacent to it to the north and south. The increases in current speed are a result of the shallowing of the northern 20 m of Hopetoun Channel (returning it to approximate natural depths), meaning flow speeds need to increase to allow the same volume of water to flow through the channel as for the existing A1 case during both the flood and ebb stages of the tide. The model results also predict a small localised area with a reduction in current speed of less than 0.15 m/s to the west of the western end of Hopetoun Channel.

Plots showing the difference in current speed at the peak flood and peak ebb stages of the tide during a spring tide relative to the existing A1 case, are shown for all the dredge design options in Appendix B.

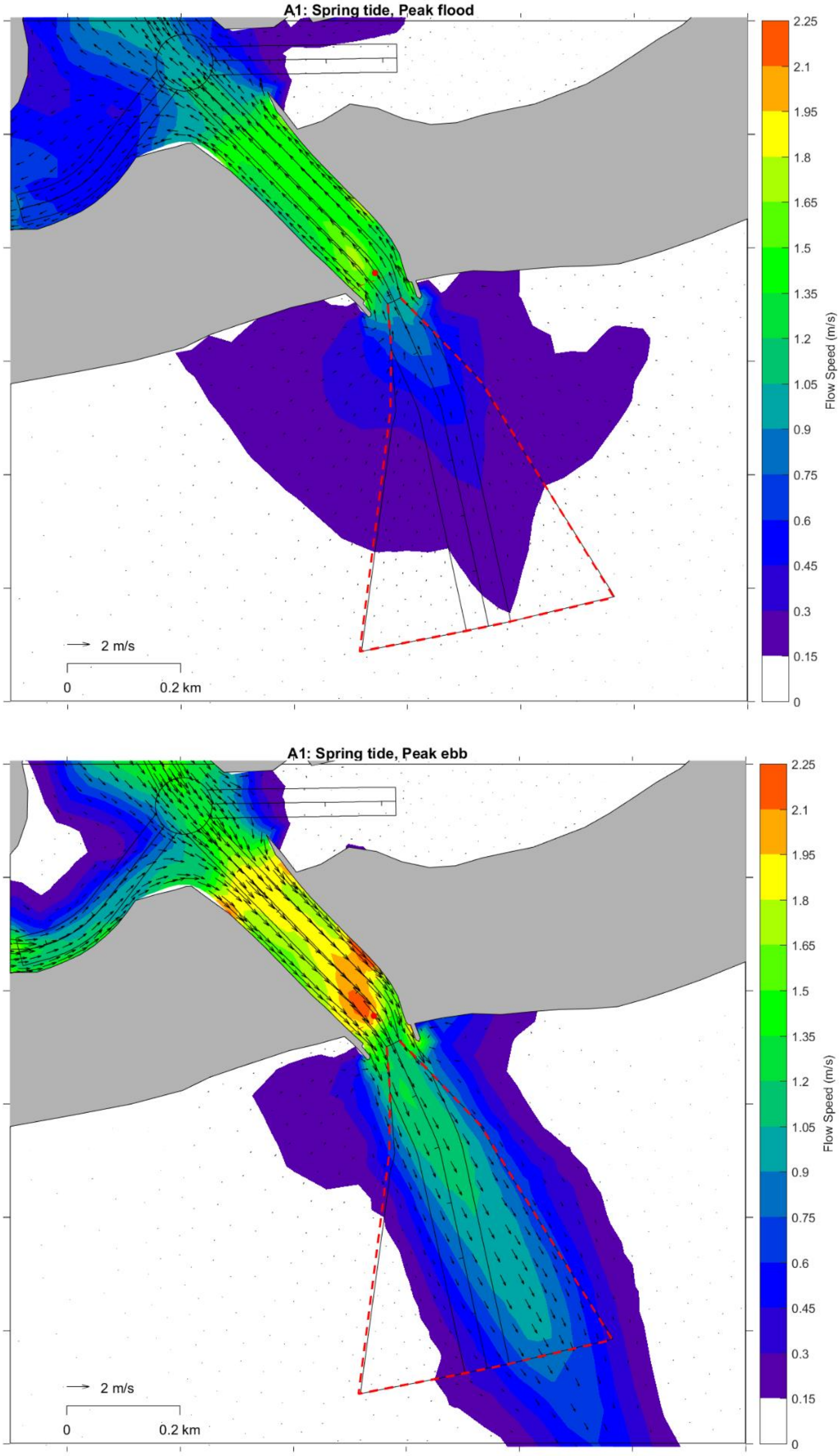

Figure 48. Current speed and vectors at the peak flood (top) and ebb (bottom) stages of the tide for the A1 option (existing case).

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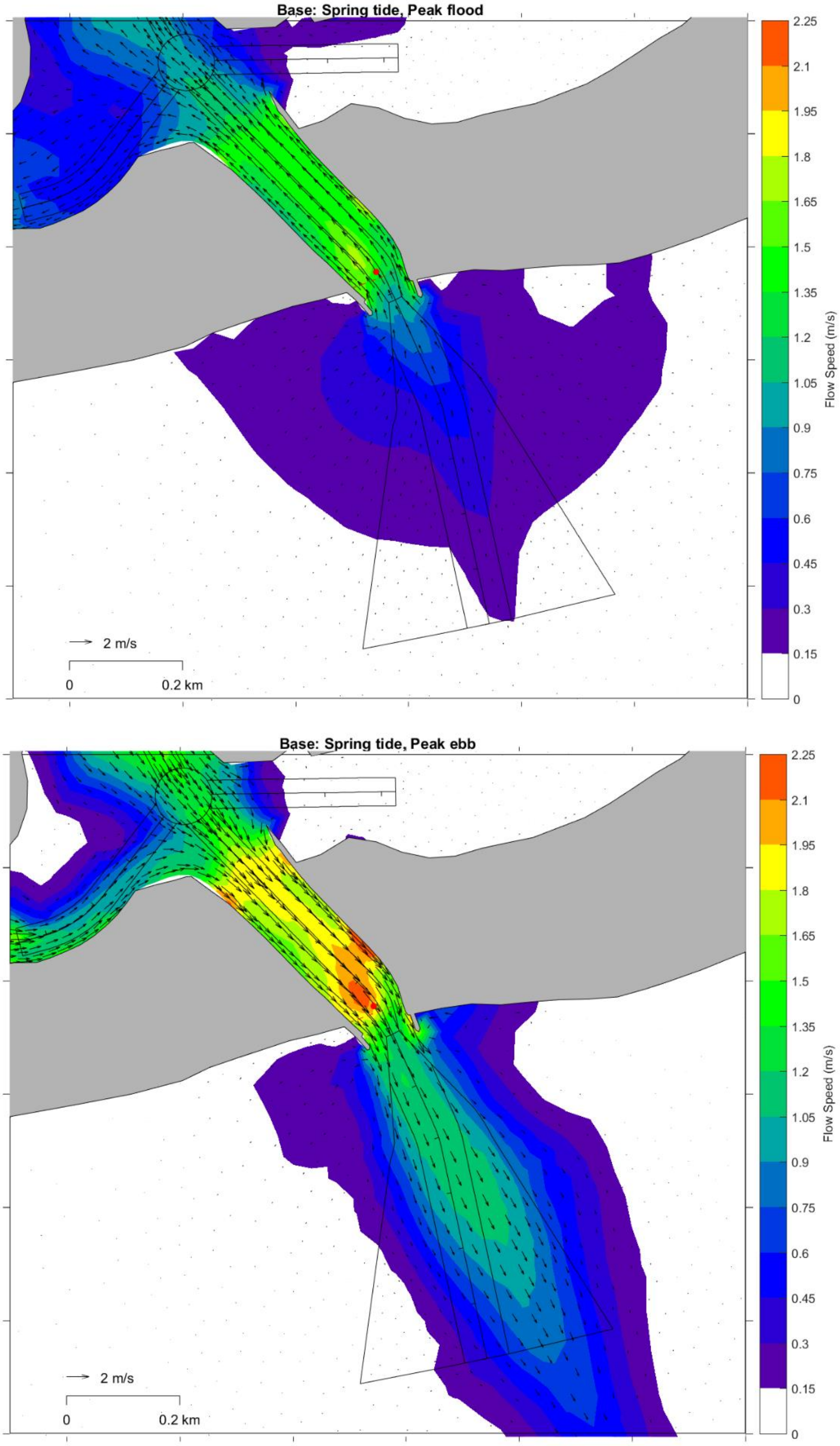

Figure 49. Current speed and vectors at the peak flood (top) and ebb (bottom) stages of the tide for the Base option (no dredging of the Bar).

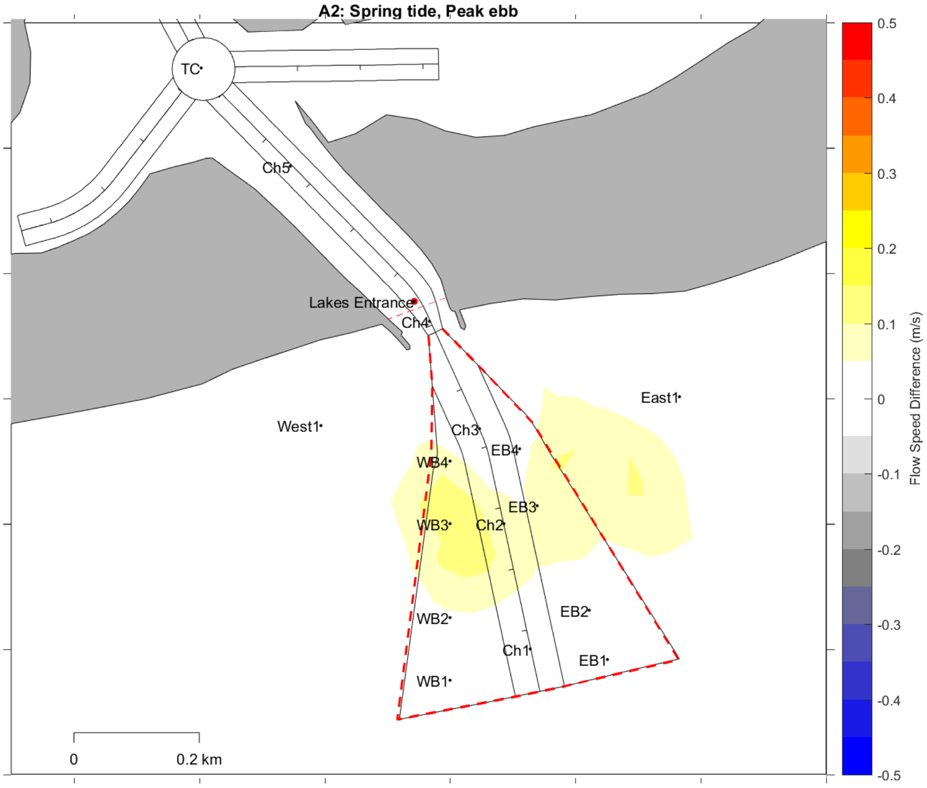

Figure 50. Difference in current speed between options A1 and A2 at peak ebb.

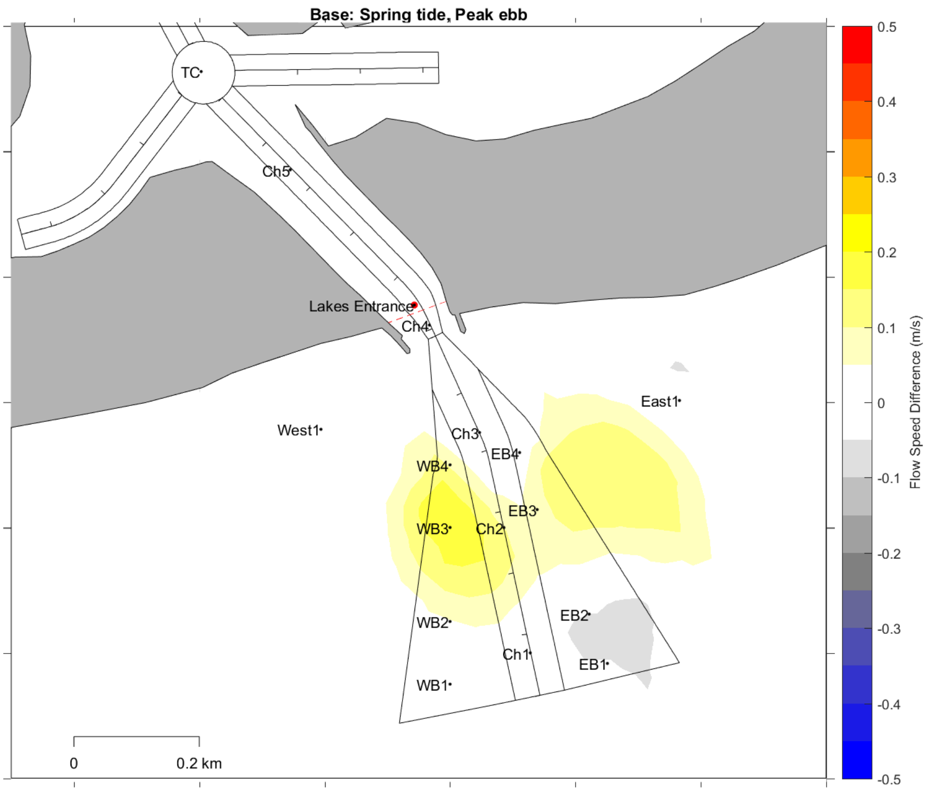

Figure 51. Difference in current speed between options A1 and Base at peak ebb.

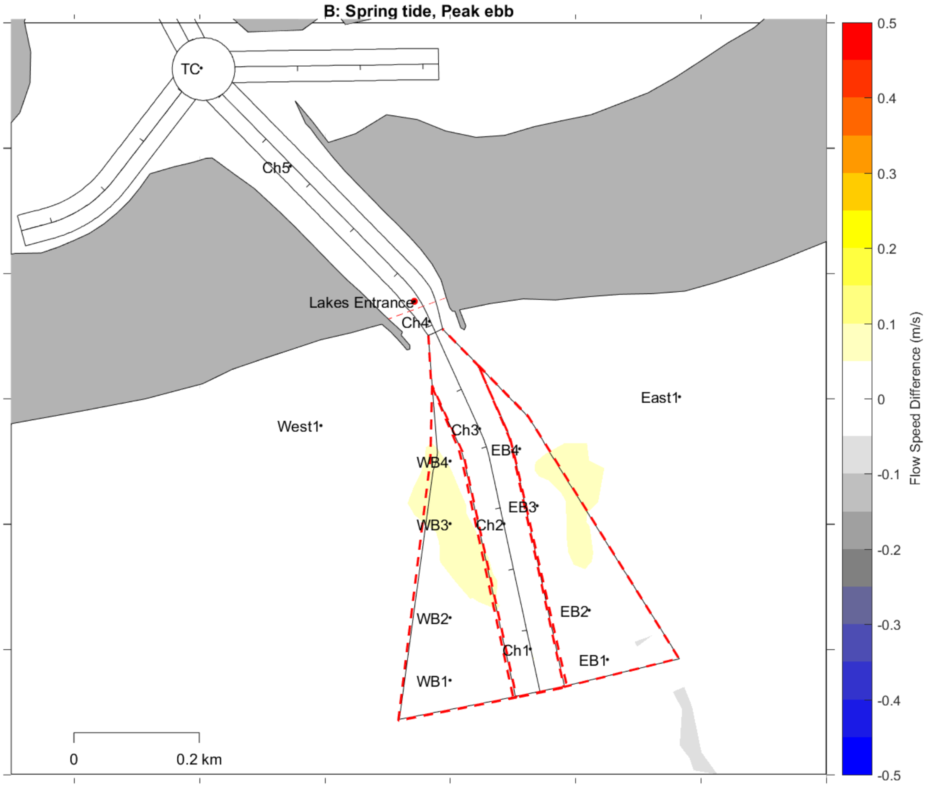

Figure 52. Difference in current speed between options A1 and B at peak ebb.

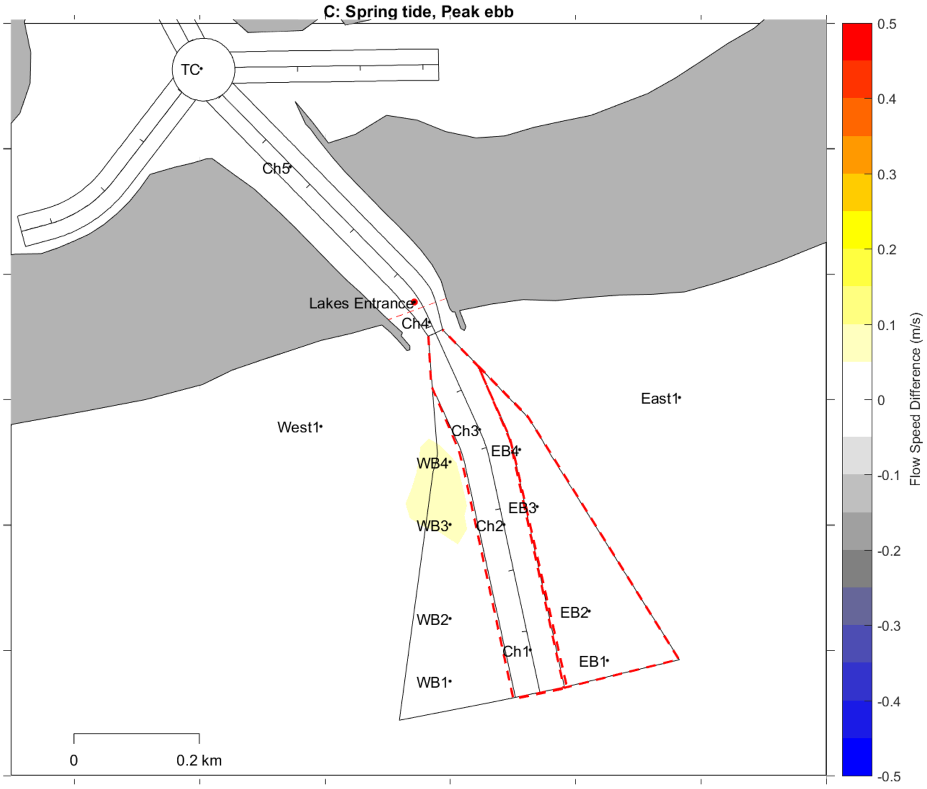

Figure 53. Difference in current speed between options A1 and C at peak ebb.

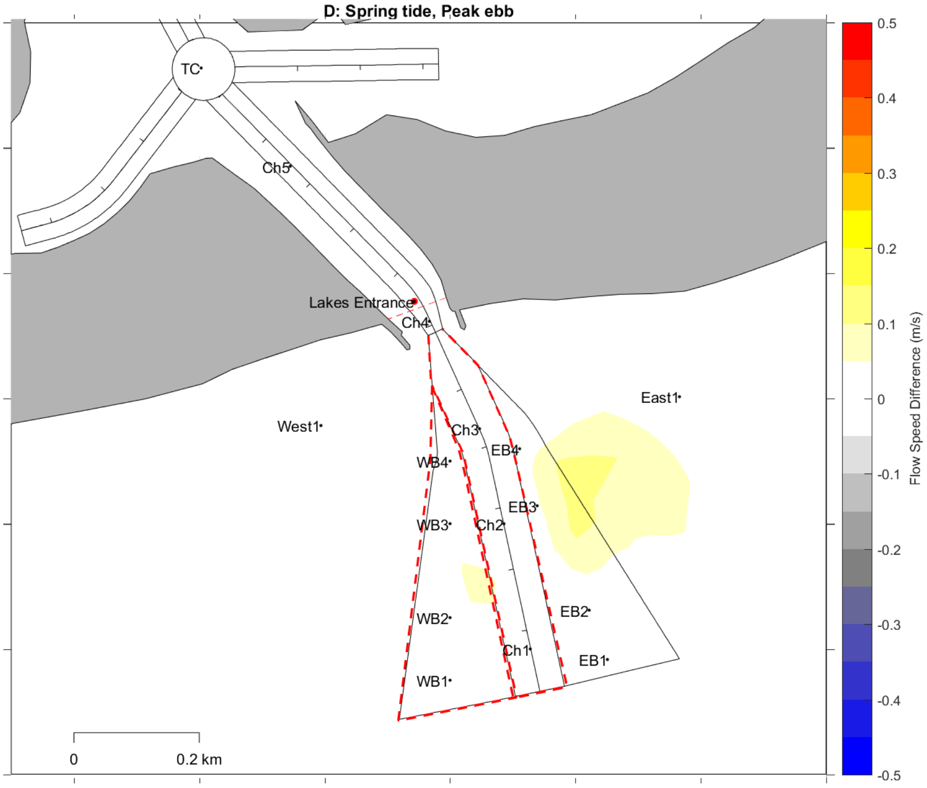

Figure 54. Difference in current speed between options A1 and D at peak ebb.

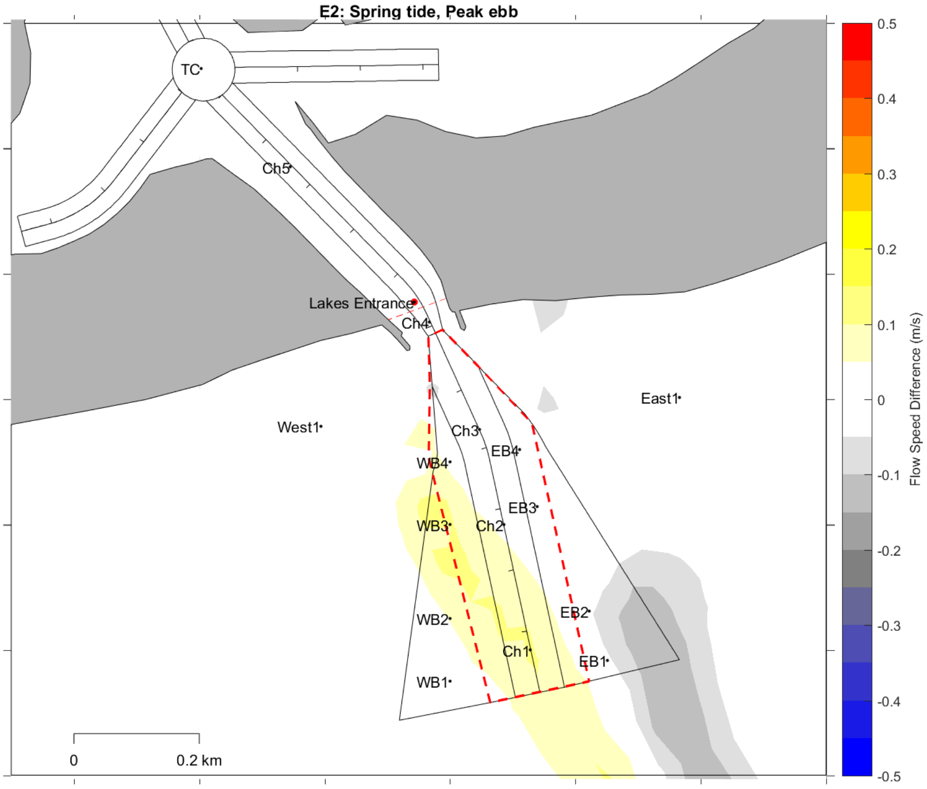

Figure 55. Difference in current speed between options A1 and E2 at peak ebb.

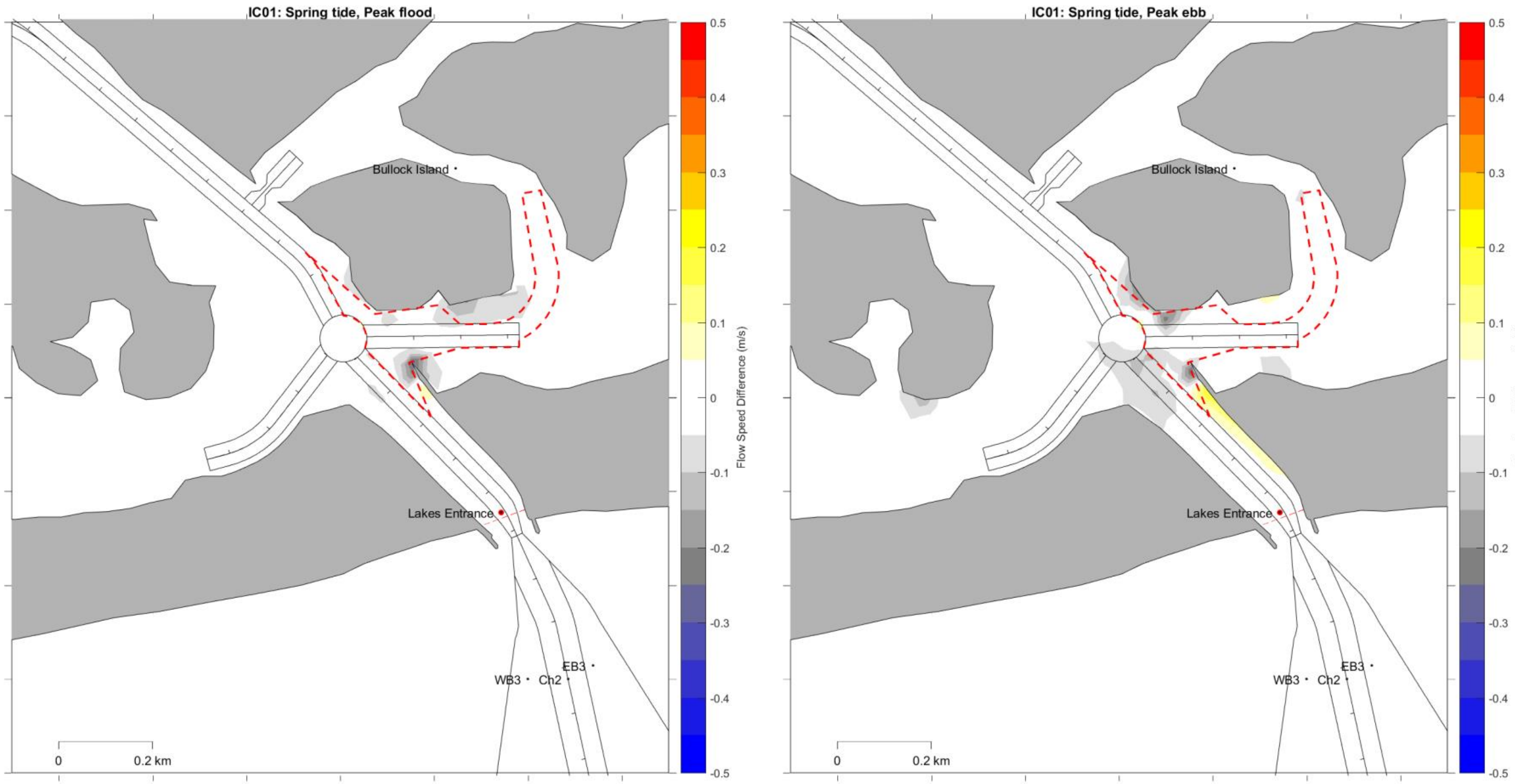

Figure 56. Difference in current speed between options A1 and IC01 at peak flood (left) and peak ebb (right).

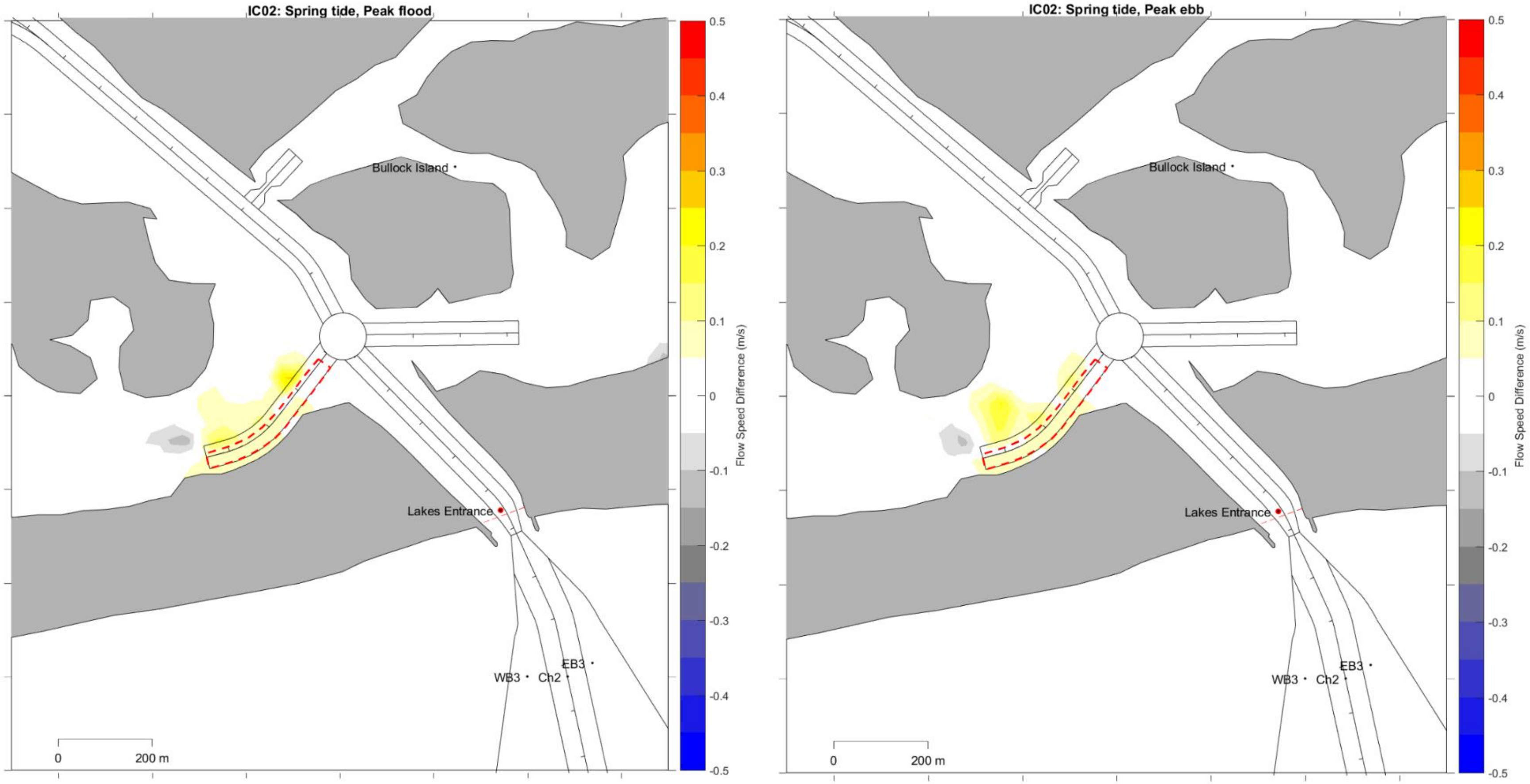

Figure 57. Difference in current speed between options A1 and IC02 at peak flood (left) and peak ebb (right).

To provide a current speed comparison between the different dredge design options being considered, box and whisker plots which give a percentile representation of the current speeds over a 15 day spring neap cycle are shown for all the dredge design options at four different locations in Figure 58 to Figure 61. The plots also include a dashed red line which provides an indication of the current speed required to mobilise medium sized sand[1] (0.4 m/s). As with the map plots, the box and whisker plots show that the dredge design options only influence the current speeds locally in the area where the depth differs relative to the existing A1 case. The plots show the following:

- the only location where the current speeds are consistently below the threshold to mobilise medium sand is in the western wedge of the Bar, with higher speeds occurring in the Bar Channel and eastern wedge suggesting more potential for sediment transport and resultant sedimentation in these areas;
- the Base case is predicted to result in the highest current speeds within the Bar (Ch2, EB3 and WB3), with the A2 dredge design resulting in the next highest current speeds. The other dredge design options result in variable increases in current speed within the Bar relative to the existing A1 case depending on how much shallower the different areas of the Bar are compared to the existing A1 case;
- tidal current speeds in the Entrance Channel are similar for all of the dredge design options. The only dredge design option which results in a small change to the tidal currents is the IC02 dredge design which is predicted to result in a slight reduction in current speed in the order of 0.01 to 0.02 m/s; and
- the tidal current speed changes indicate that the dredge design options have the potential to result in localised changes to the sediment transport within the Bar, with most of the options having the potential to result in a localised increase in sediment transport. In contrast, within the Entrance Channel the dredge design options considered are unlikely to result in any changes to the sediment transport.

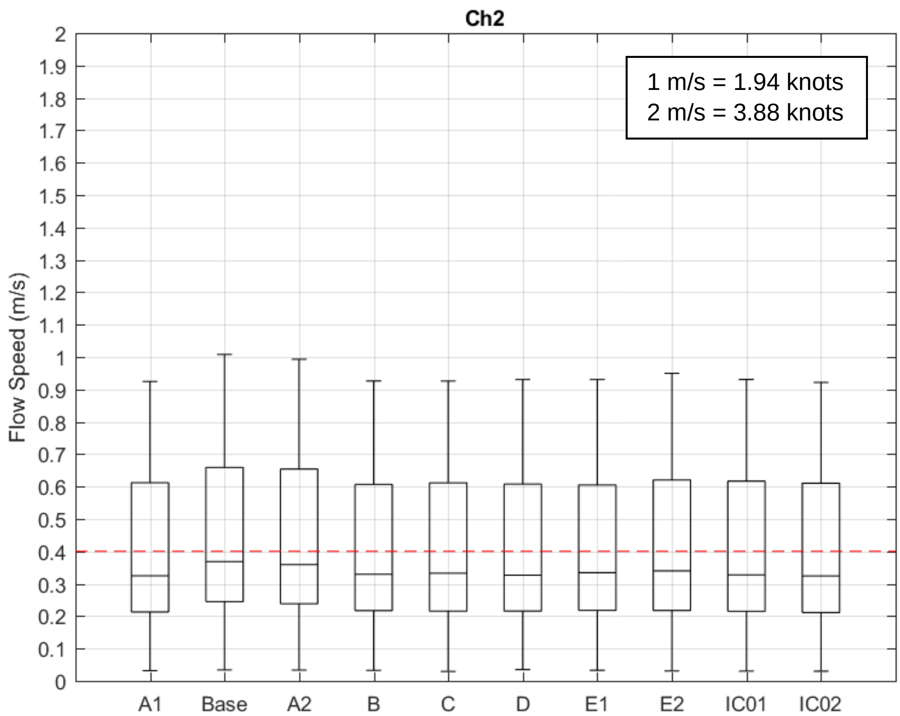

Figure 58. Box and whisker plot of current speed at the Ch2 site over the 15 day model simulation for the various scenarios modelled. *Note: the boxes are represented by the 25th, 50th and 75th percentiles, while the whiskers represent the 1st and 99th percentiles.*

[1]Based on formula in Van Rijn (1984), broadly applicable to medium sand in water depths of 4.5 m to 5.5 m.

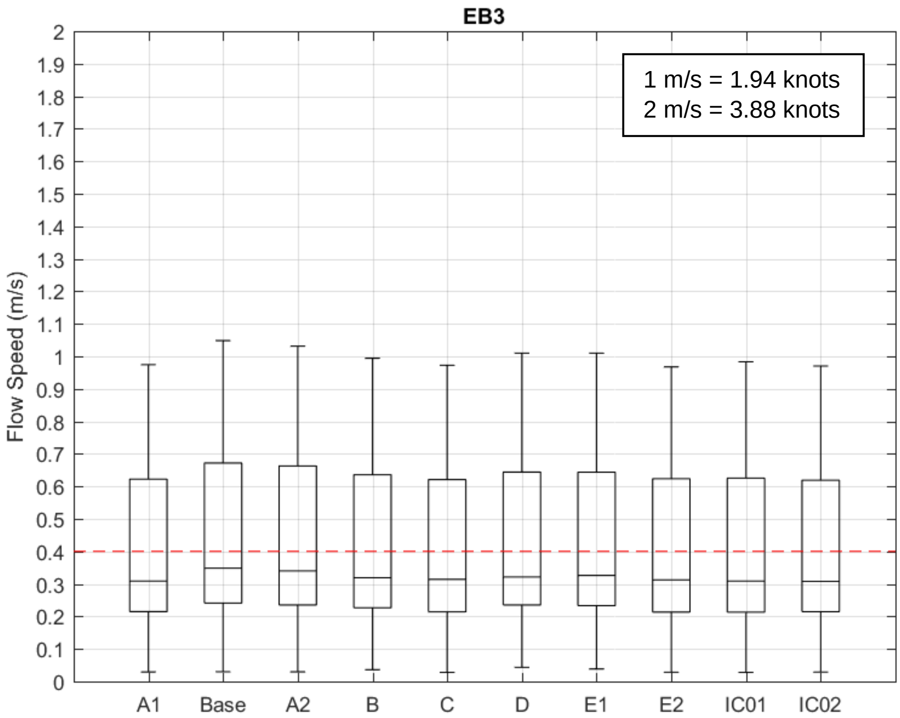

Figure 59. Box and whisker plot of current speed at the EB3 site over the 15 day model simulation for the various scenarios modelled. *Note: the boxes are represented by the 25th, 50th and 75th percentiles, while the whiskers represent the 1st and 99th percentiles.*

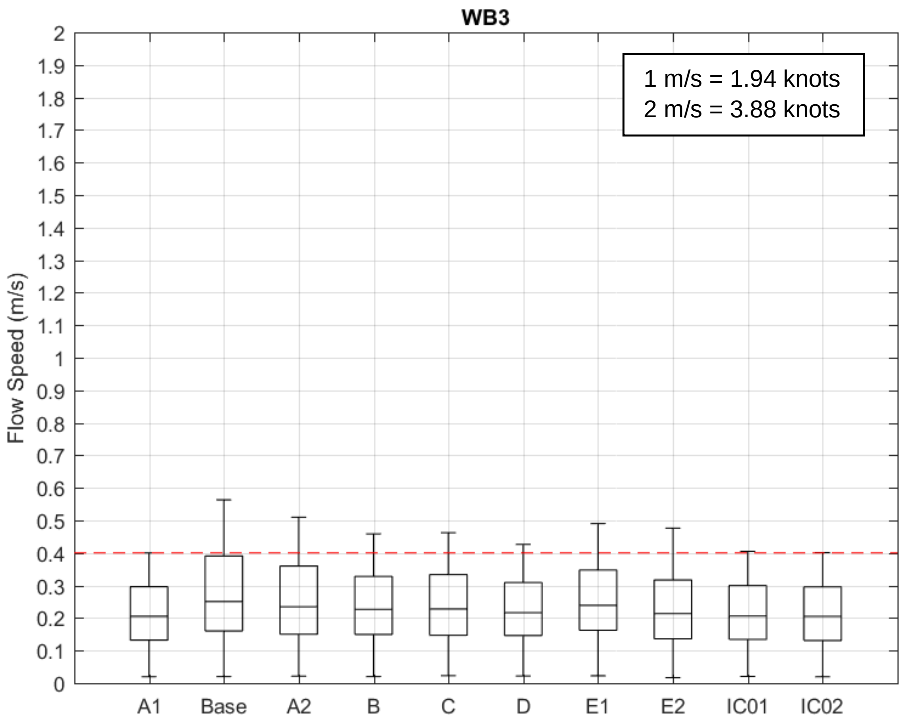

Figure 60. Box and whisker plot of current speed at the WB3 site over the 15 day model simulation for the various scenarios modelled. *Note: the boxes are represented by the 25th, 50th and 75th percentiles, while the whiskers represent the 1st and 99th percentiles.*

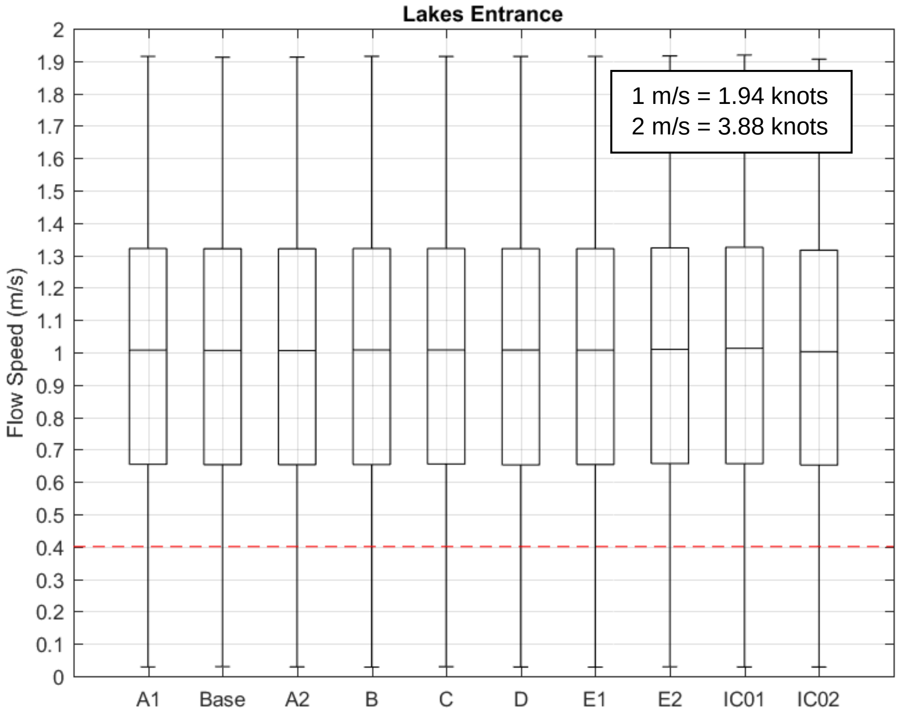

Figure 61. Box and whisker plot of current speed at the Lakes Entrance site over the 15 day model simulation for the various scenarios modelled. *Note: the boxes are represented by the 25th, 50th and 75th percentiles, while the whiskers represent the 1st and 99th percentiles.*

3.3.2. Spectral Wave Modelling

The spectral wave model was setup to model the seven dredge design options for the Bar as detailed in Section 3.2 as well as the Base Bar case. The Inner Channel options were not modelled as the dredge areas are not exposed to waves. The wave model was setup to simulate the following six discrete wave conditions:

- Typical southerly wave: H_s = 1.15 m, T_p = 7.2 seconds;
- Typical south-easterly wave: H_s = 0.9 m, T_p = 10.0 seconds;
- Typical east south-easterly wave: H_s = 0.9 m, T_p = 8.8 seconds;
- 10 in 1 year southerly wave: H_s = 2.38 m, T_p = 8.2 seconds;
- 10 in 1 year south-easterly wave: H_s = 2.42 m, T_p = 10.4 seconds;
- 1 in 1 year south-easterly wave: H_s = 3.81 m, T_p = 11.4 seconds.

These wave conditions can be considered to represent the range of wave conditions which occur during a typical year. The spatial variation in significant wave height (H_s) for these six wave conditions are shown for the existing A1 case in Figure 62. The difference in H_s between the dredge design option and the existing A1 case have been calculated for all the wave conditions and all the options. Results for a range of the dredge design options are shown in Figure 63 to Figure 65 and plots for all options are provided in Appendix C. The spatial difference plots show the following:

- for the typical wave conditions the shallower depths in the Bar for the dredge design options being considered result in a localised increase in H_s within and directly adjacent to the Bar, with the largest increase predicted due to the Base case as this has the largest difference in depth relative to the existing A1 case. The reason for these increases is due to increased wave shoaling over the shallower areas of the Bar which results in a reduction in the wavelength (i.e. waves are closer together) and an increase in wave height;

- for the larger wave events (10 in 1 and 1 in 1 year events) the shallower depths in the Bar for the dredge design options being considered result in a reduction in H_s both within the Bar and inshore of the Bar extending within the Entrance Channel and along the beaches to the west and east of the entrance channel. The reason for the reduction in H_s is due to wave breaking occurring over the areas of the Bar which are shallower in the options than the depth in the existing case (-5.5 m CD) as wave breaking for these wave conditions will start to occur in water depths of 3 to 5 m. The largest reductions are focused within the Bar for the Base case (as this has the largest difference in depth relative to the existing case), with reductions of up to 0.5 m for the 1 in 1 year event. Reductions of up to 0.25 m occur at the seaward ends of the training walls and up to 0.15 m occur at the beaches. This indicates that the initial deepening of the wedge shape of the Bar could have resulted in an increase in wave height at the seaward ends of the entrance training walls of up to 0.25 m for a 1 in 1 year event and up to 0.15 m along the beaches for the same event;
- the locations of any increases or decreases vary depending on the dredge design and specifically, on where the design is shallower than the existing A1 case. For example, for dredge design option C, where the Bar Channel and eastern side of the wedge is dredged to -5.5 m CD, but the western side of the wedge is returned to natural depths, the changes are mainly focused around the western wedge; and
- overall, the results suggest that the beach directly to the east of the Entrance Channel is more likely to experience a change in wave height due to a change in the dredge design of the Bar. The changes in wave height of more than 0.05 m are not predicted to extend to the shoreline of the beach directly to the west of the Entrance Channel.

The relative change in H_s for each wave condition and each dredge design option is shown at some of the model output locations in Figure 66 to Figure 68 and summarised for the Beach and Training Wall locations in Table 6. Again, the results show the existing A1 case consistently results in the largest wave heights for the less frequent wave events and the smallest wave heights for the typical wave conditions. In addition, the results also show that the Base option with no dredging results in the largest change relative to the existing A1 case with a maximum reduction of 0.25 m at the East Training Wall, with the other options falling somewhere between the two. The results show the following relating to the other dredge design options:

- dredge design option E1 consistently results in the lowest wave heights at the West Beach, East Beach and the seaward ends of both training walls;
- dredge design options C and D result in similar wave heights to the existing A1 case either to the east or west of the Entrance Channel and then reduced wave heights the other side. For example, for option C which involves deepening of the eastern side of the wedge and the Bar Channel the H_s is similar to the existing A1 case at the East Beach (EBeach) and East Training Wall (ETW) but with a lower H_s than the existing case at the two sites to the west of the Entrance Channel;
- the A2 and B dredge design options result in fairly similar wave heights, with an H_s approximately mid-way between the A1 case and the Base no dredging case. With the current year round maintenance dredging which GP undertake, options A2 and B are closest to the maintained depths on the Bar, while the A1 case represents the dredge depths when a single annual dredging campaign was undertaken. Therefore, the results show that wave heights for larger wave events are lower at the training walls and beaches with the current year round maintenance dredging compared to the previous once a year dredging; and
- the dredge design option E2 results in wave heights closer to the existing A1 case at the two Training Wall sites. At the two beach output points the dredge design options E1 and E2 are predicted to have a similar H_s, which is lower than the existing A1 case. This

suggests that the shape of the wedges influences the focussing of wave energy which can change the resultant wave heights at the adjacent beaches. The width of the dredged Bar Channel can also influence the wave heights at the training walls during larger wave events, but has less of an influence on the wave conditions at the adjacent beaches.

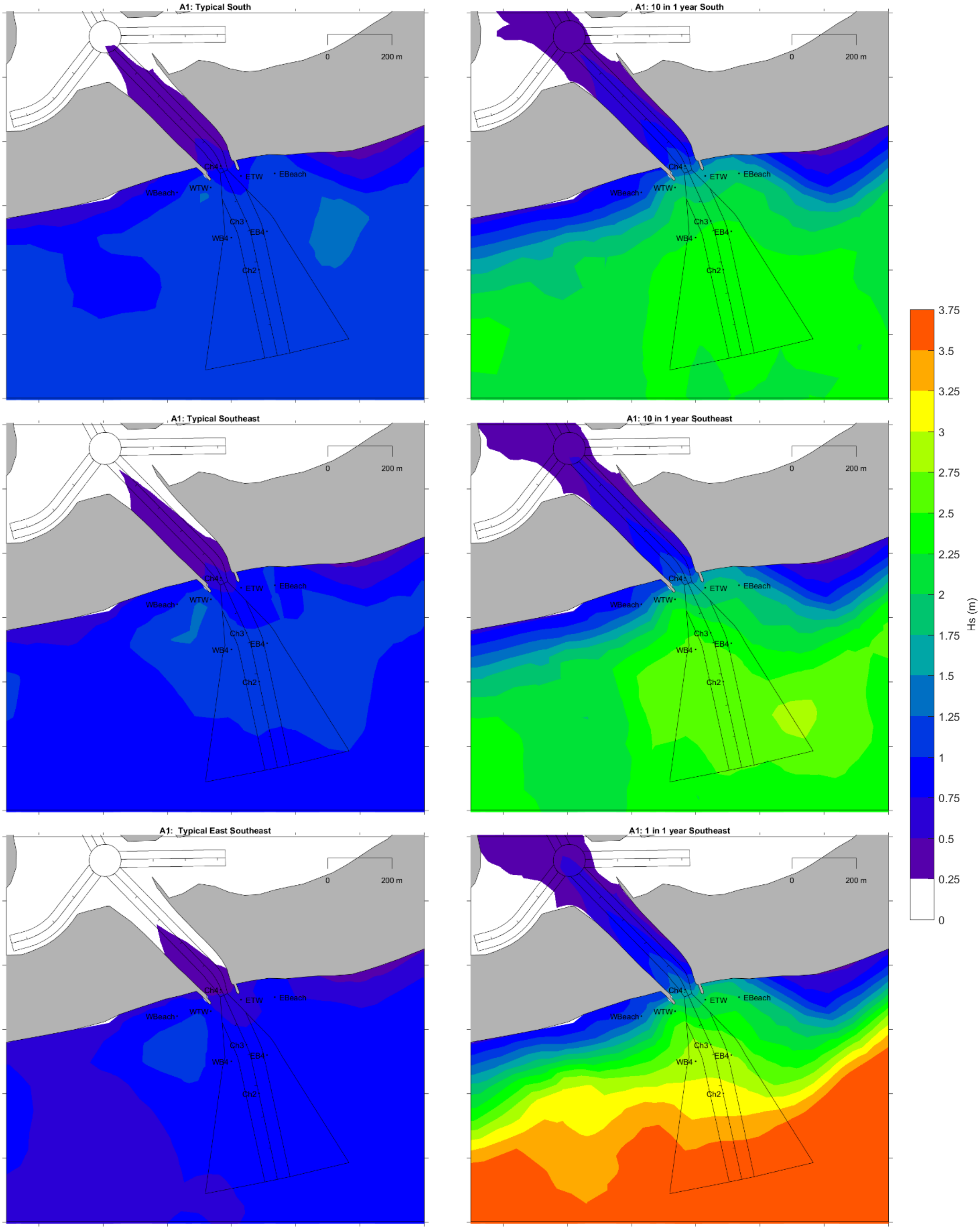

Figure 62. **Spatial maps of H_s for the existing A1 case for the range of wave conditions modelled.**

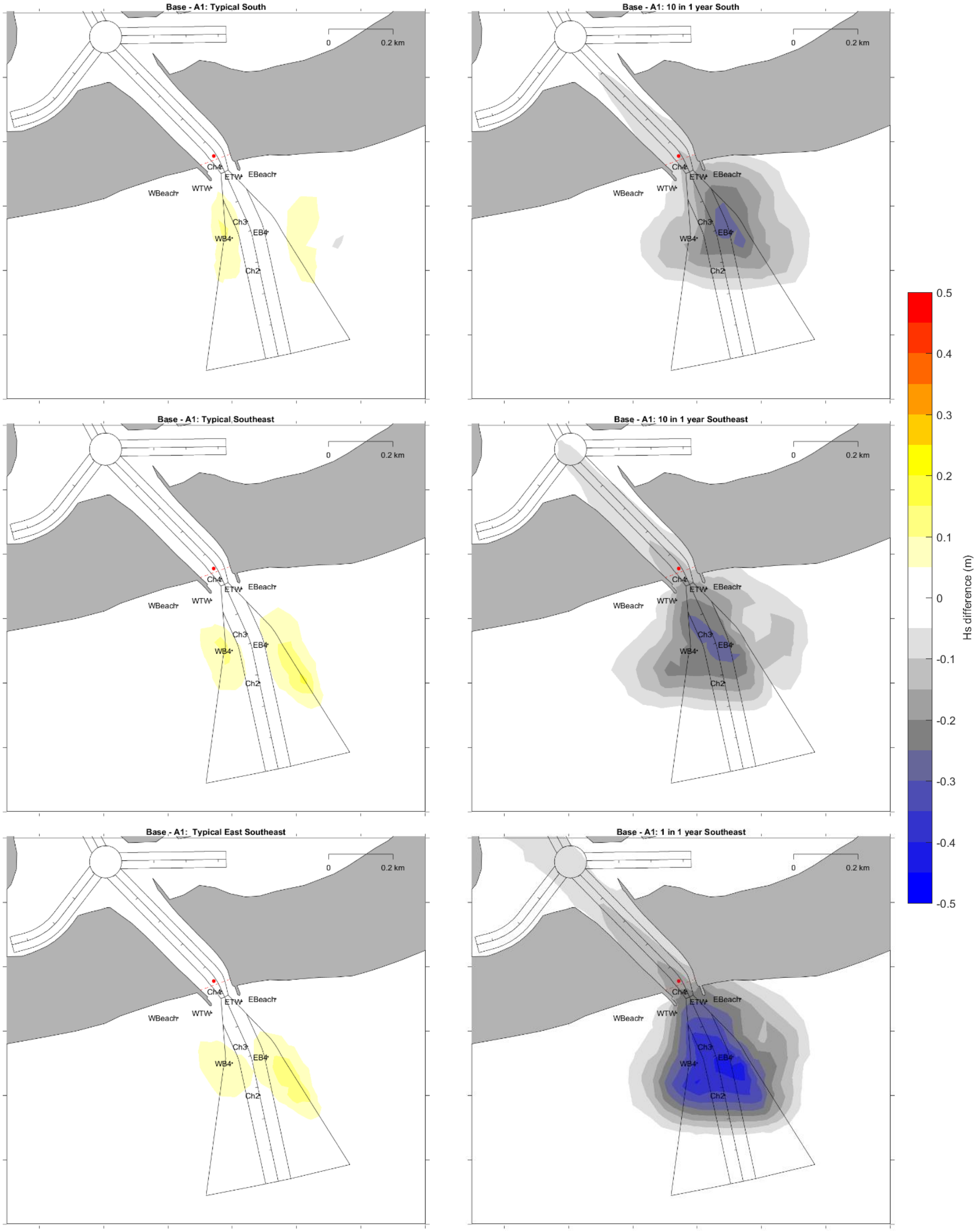

Figure 63. Spatial maps showing the change in H_s relative to the existing A1 case for the Base case for the range of wave conditions modelled.

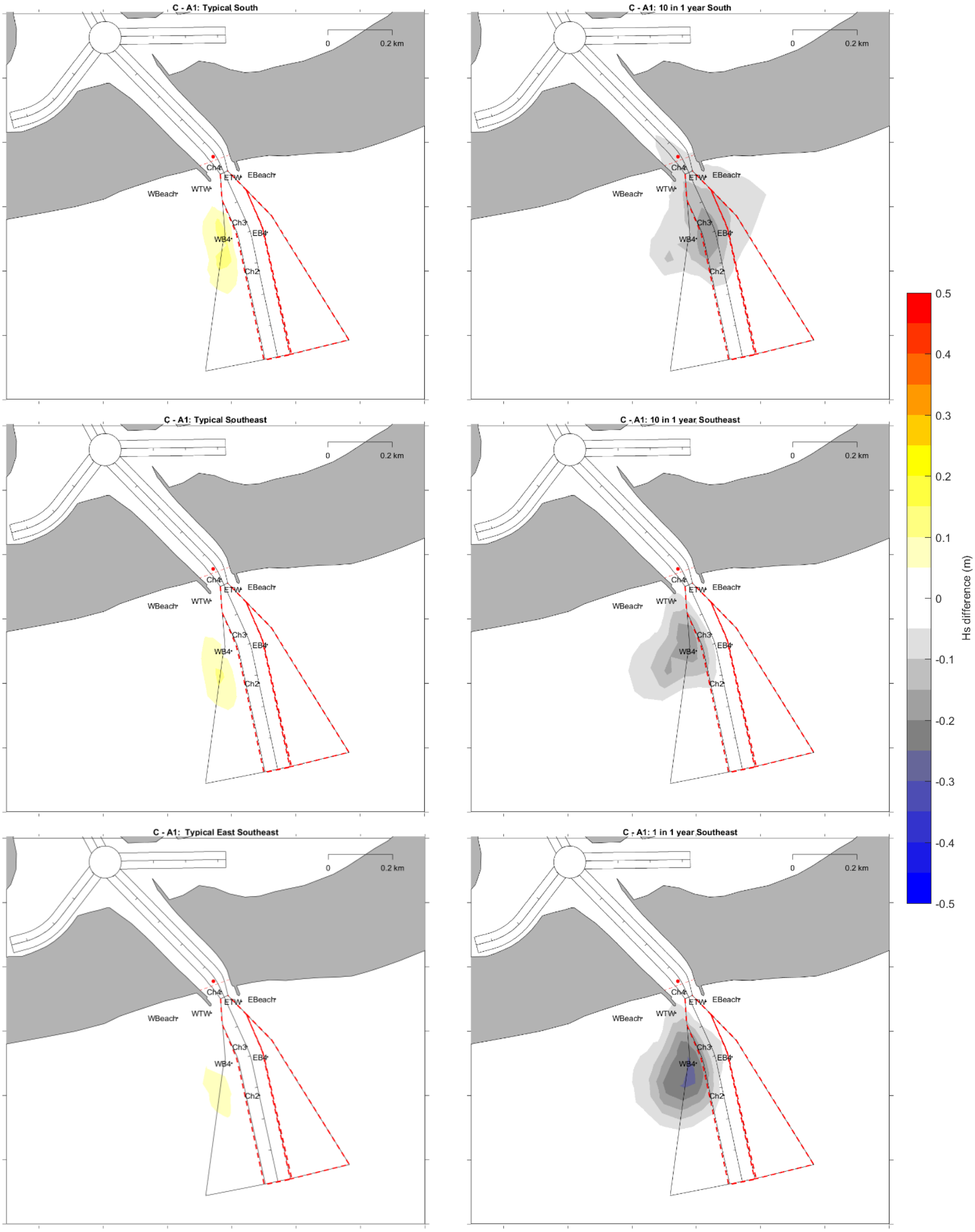

Figure 64. Spatial maps showing the change in H_s relative to the existing A1 case for the C case for the range of wave conditions modelled.

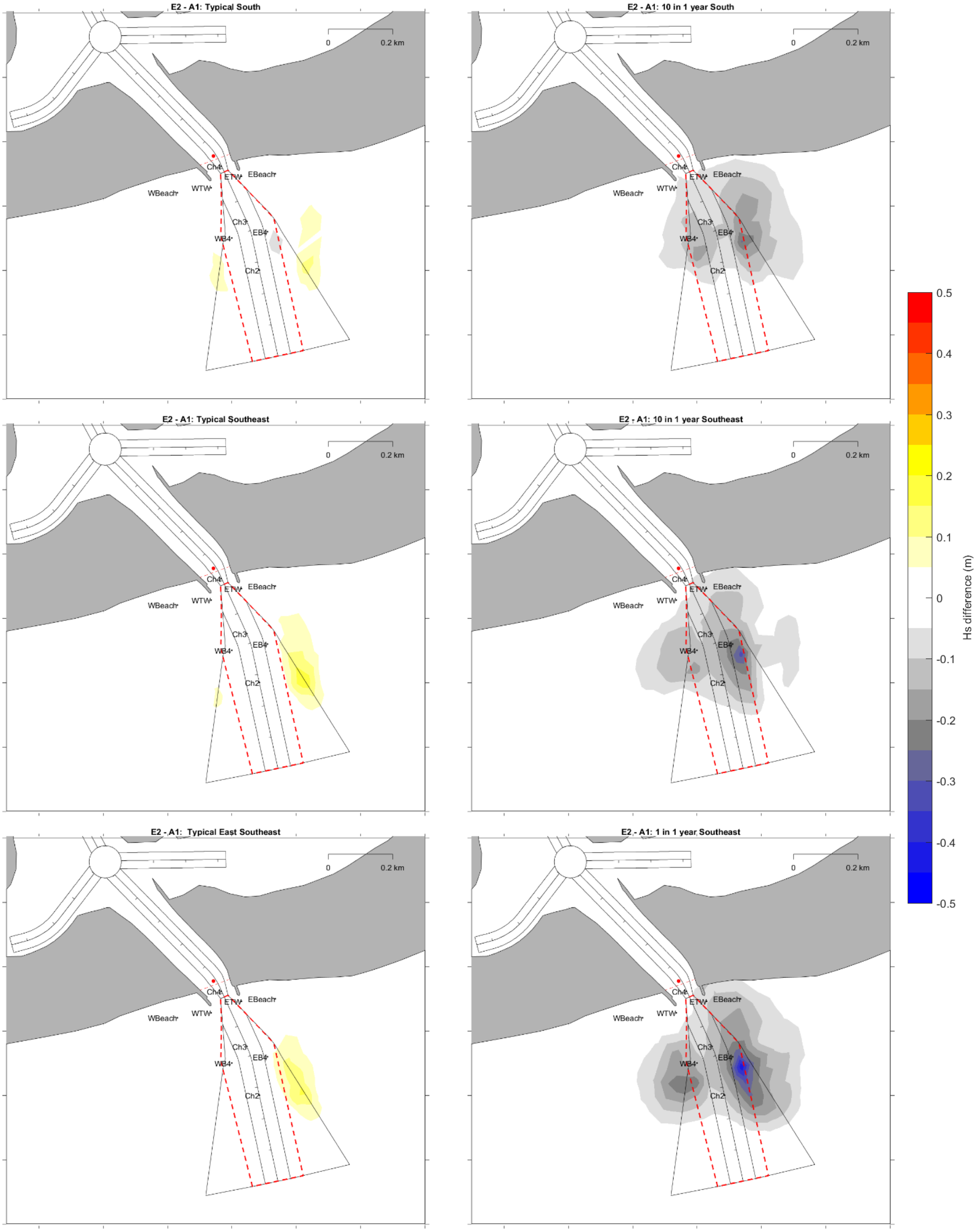

Figure 65. Spatial maps showing the change in H_s relative to the existing A1 case for the E2 case for the range of wave conditions modelled.

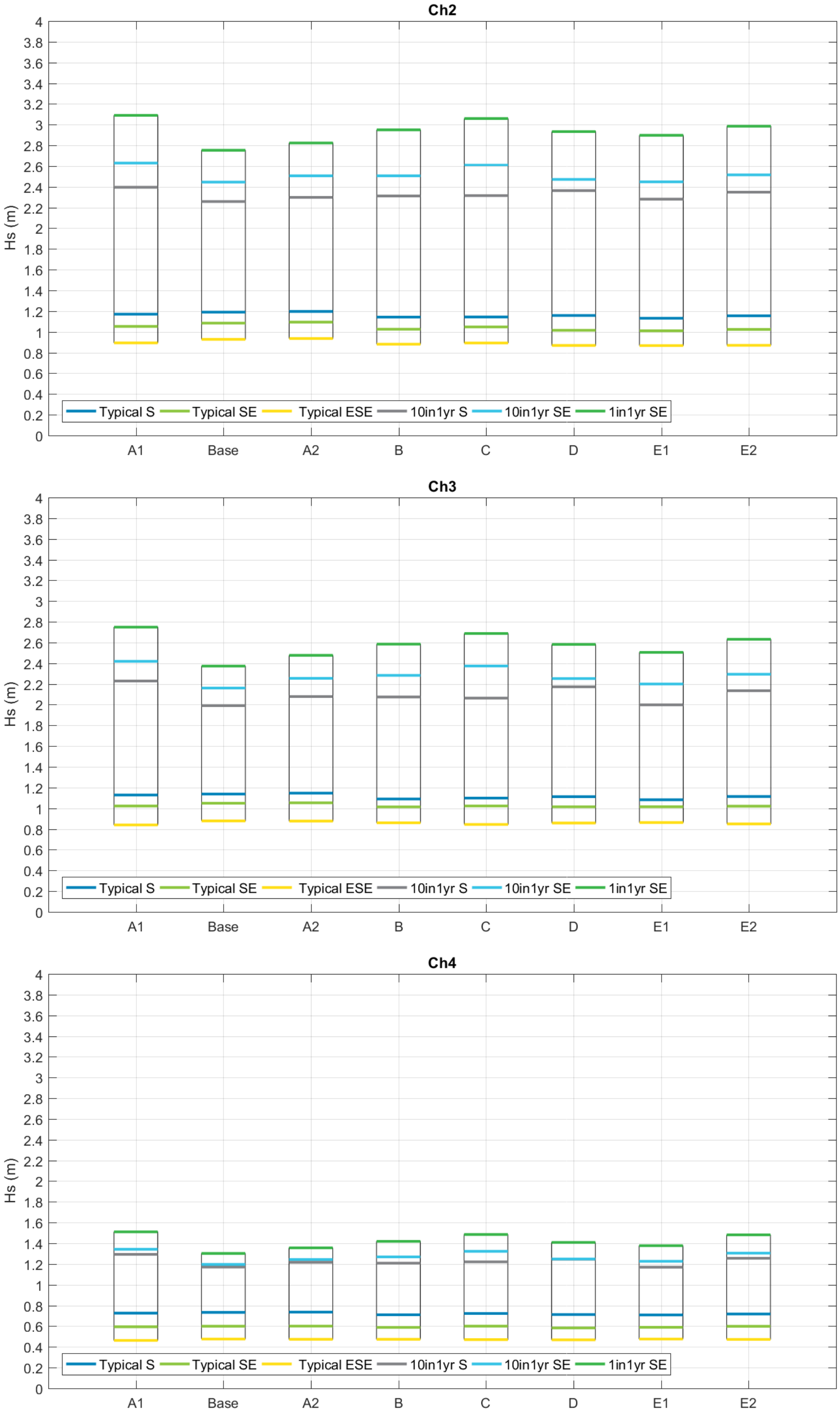

Figure 66. Box plots showing the H_s for all wave conditions and all dredge design options at Ch2 (top), Ch3 (middle) and Ch4 (bottom).

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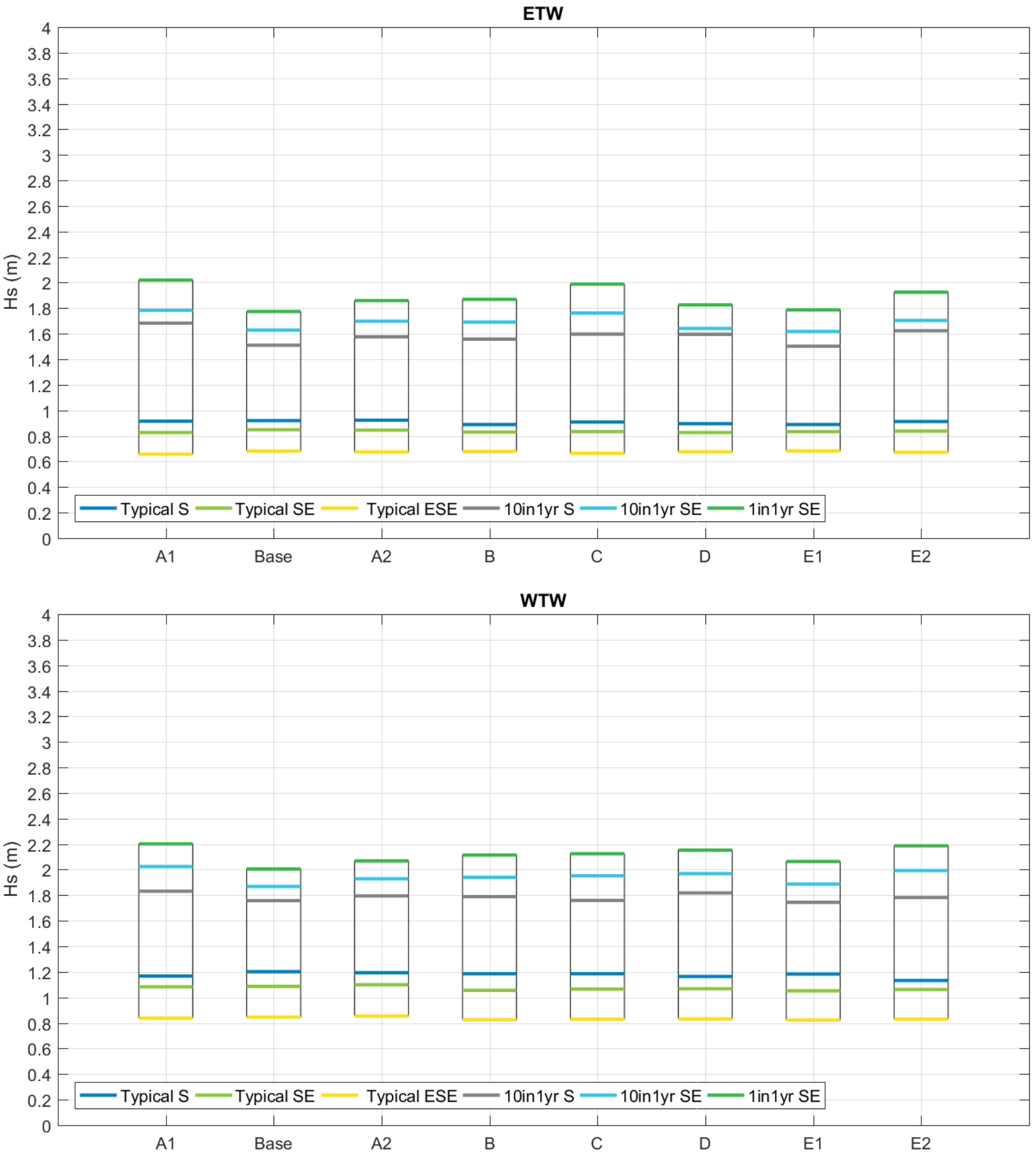

Figure 67. Box plots showing the H_s for all wave conditions and all dredge design options at ETW (top) and WTW (bottom).

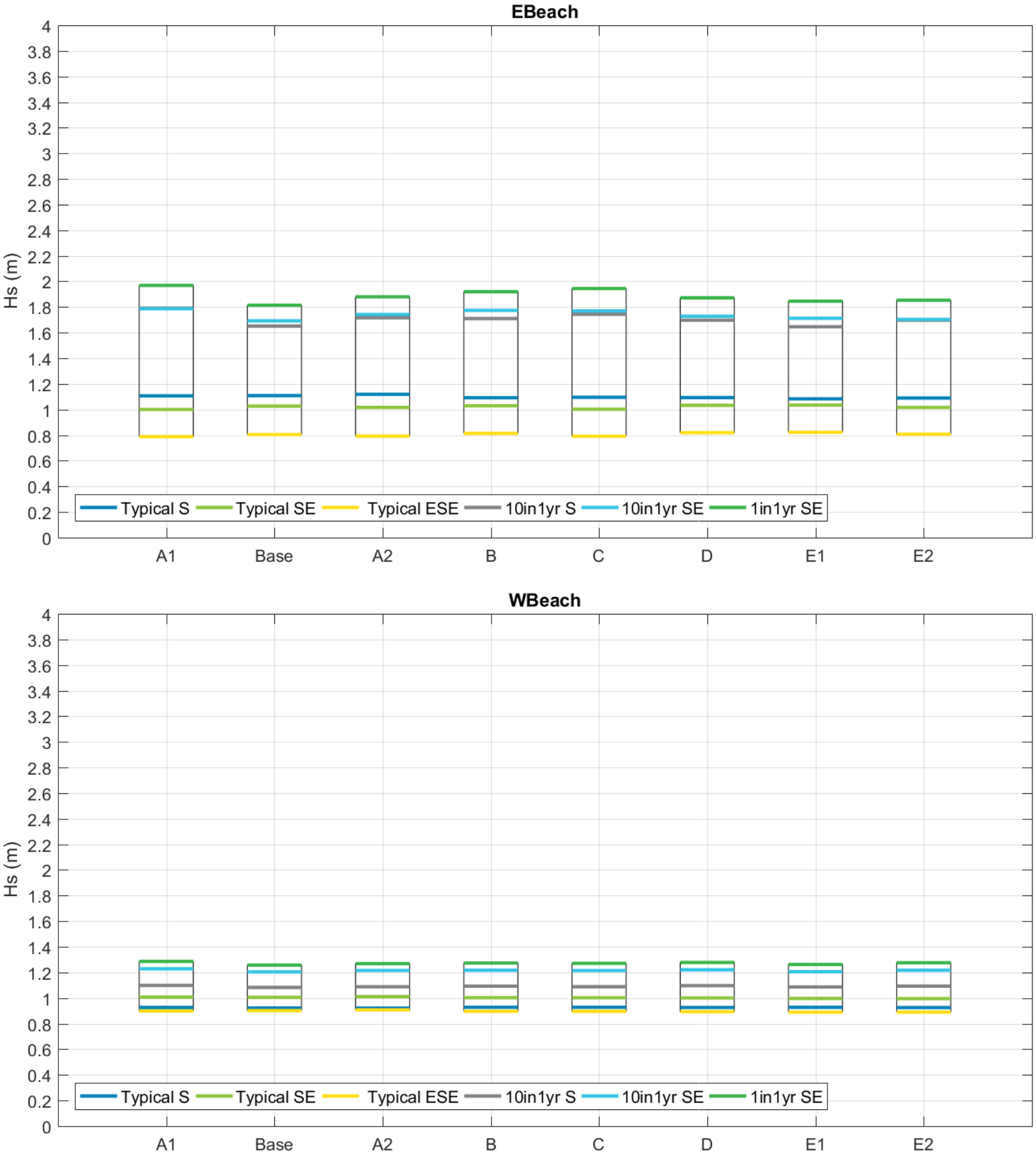

Figure 68. **Box plots showing the H_s for all wave conditions and all dredge design options at EBeach (top) and WBeach (bottom).**

Table 6. Predicted significant wave height for the different wave conditions and different dredge design options at four model output locations.

Region	H_s (m)					
	Typical S	Typical SE	Typical ESE	10 in1 yr S	10 in 1 yr SE	1 in 1 yr SE
East Training Wall (ETW)						
A1	0.92	0.83	0.66	1.68	1.78	2.02
Base	0.92	0.85	0.68	1.51	1.63	1.77
A2	0.92	0.85	0.67	1.58	1.70	1.86
B	0.89	0.83	0.68	1.56	1.69	1.87
C	0.91	0.83	0.66	1.60	1.76	1.99
D	0.90	0.83	0.68	1.60	1.64	1.83
E1	0.89	0.83	0.68	1.50	1.62	1.79
E2	0.91	0.84	0.67	1.62	1.70	1.93
West Training Wall (WTW)						
A1	1.17	1.08	0.84	1.83	2.02	2.20
Base	1.20	1.09	0.85	1.76	1.87	2.01
A2	1.19	1.10	0.85	1.79	1.93	2.07
B	1.19	1.06	0.83	1.79	1.94	2.11
C	1.19	1.07	0.83	1.76	1.95	2.13
D	1.16	1.07	0.83	1.82	1.97	2.15
E1	1.18	1.05	0.82	1.74	1.89	2.06
E2	1.13	1.06	0.83	1.78	1.99	2.19
East Beach (EBeach)						
A1	1.11	1.00	0.79	1.79	1.79	1.97
Base	1.11	1.03	0.80	1.65	1.69	1.81
A2	1.12	1.02	0.79	1.72	1.74	1.88
B	1.09	1.03	0.81	1.71	1.77	1.92
C	1.10	1.00	0.79	1.74	1.77	1.94
D	1.09	1.03	0.82	1.70	1.73	1.87
E1	1.08	1.03	0.82	1.65	1.71	1.85
E2	1.09	1.02	0.81	1.70	1.70	1.85
West Beach (WBeach)						
A1	0.93	1.01	0.90	1.10	1.23	1.29
Base	0.92	1.01	0.90	1.08	1.20	1.26
A2	0.92	1.01	0.91	1.09	1.22	1.27
B	0.93	1.00	0.90	1.09	1.22	1.27
C	0.93	1.00	0.90	1.09	1.21	1.27
D	0.93	1.00	0.89	1.10	1.22	1.28
E1	0.93	1.00	0.89	1.09	1.21	1.26
E2	0.93	1.00	0.89	1.09	1.22	1.28

As well as influencing the wave height, the change in bathymetry of the Bar due to the different dredge design options also has the potential to change the wave direction. Plots showing wave vectors have been created for the dredge design options, with the plots also showing the wave vectors for the existing A1 case to show any changes. Plots for the 10 in 1 year wave events from the south and south-east are shown for some of the options (as these cases showed the potential for changes to wave conditions inshore of the Bar) in Figure 69 to Figure 71 and plots for all wave conditions and all options are provided in Appendix C. The plots show the following:

- relatively large changes in wave direction of up to around 20º are predicted to occur immediately to the east and west of the Bar, but most changes of direction within the Bar and inshore of the Bar are significantly less than this; and
- changes in wave direction can occur inshore of the Bar, but by the time the waves either reach the shoreline or the seaward end of the training walls or the Entrance Channel their direction is very similar to the existing case wave direction. This is due to increased refraction of waves on the inshore side of the Bar resulting in waves reaching the shoreline at a similar direction regardless of the bathymetry in the Bar.

The relative change in wave direction for each wave condition and each dredge design option is shown at some of the model output locations in Figure 72 to Figure 74 and summarised for the Beach and Training Wall locations in Table 7. The results show that within the Bar Channel and at the training walls and adjacent beaches the dredge design options only result in small changes to the wave direction relative to the existing A1 case. The results also show:

- at the training walls the wave directions are predicted to change by up to 1º during typical wave conditions and by up to 2º during larger wave events;
- at the beaches the wave directions are predicted to change by up to 2º during typical wave conditions and by up to 3º during larger wave events; and
- the relative changes in wave direction vary depending on the configuration of the dredge design, the wave condition and the model output location. For example, dredge design C which has the same depth as the existing A1 case for the Bar Channel and eastern wedge, but shallower natural depths in the western wedge are predicted to result in similar wave directions to the A1 case at the sites to the east of the Entrance Channel, but slight changes at the sites to the west. For dredge design E1, where only the Bar Channel is dredged so the wedges are shallower than the A1 case there are changes in wave direction both sides of the Entrance Channel.

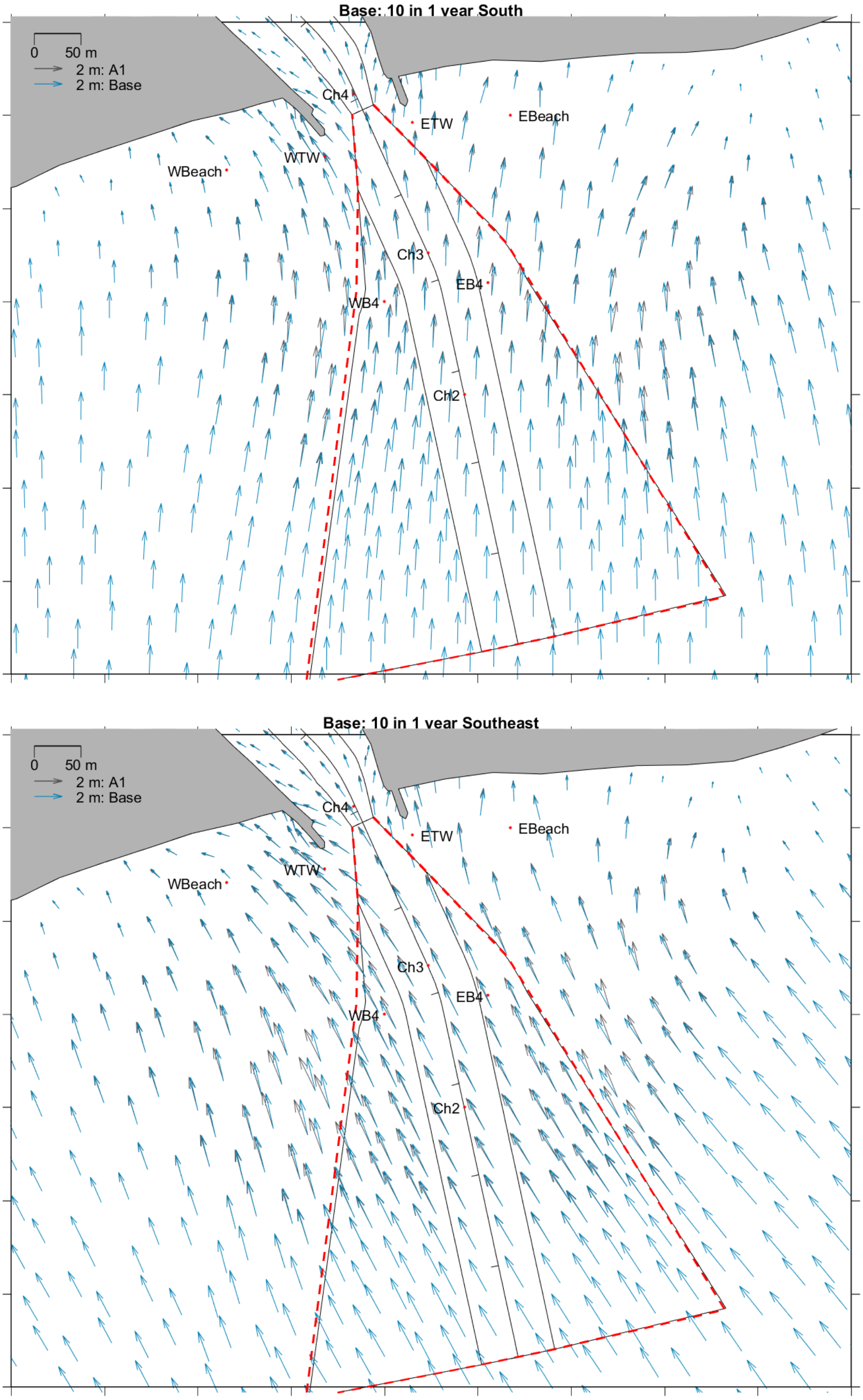

Figure 69. Spatial maps showing wave vectors for the Base case relative to the existing A1 case for the 10 in 1 year south and south-east wave conditions.

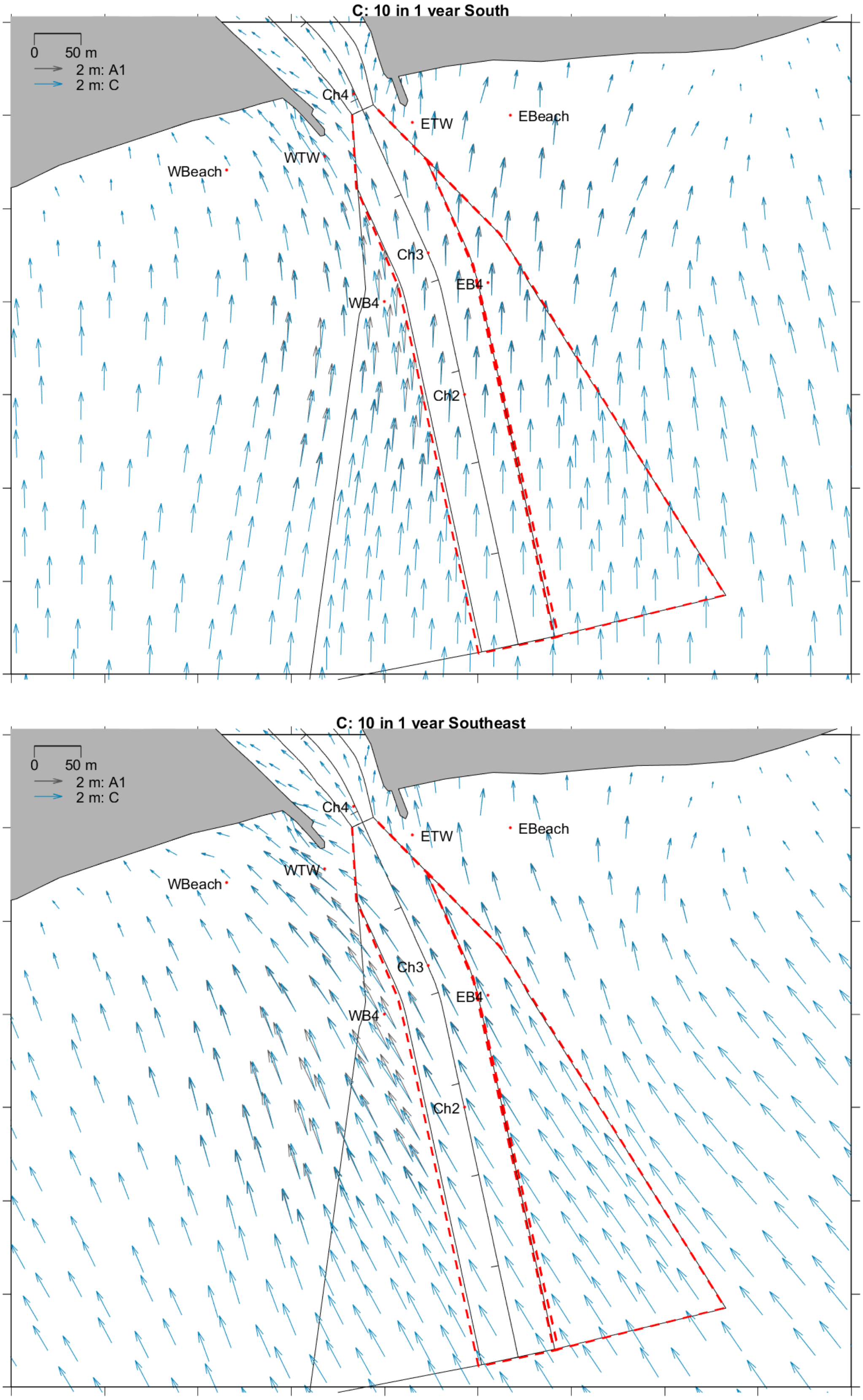

Figure 70. Spatial maps showing wave vectors for the C case relative to the existing C case for the 10 in 1 year south and south-east wave conditions.

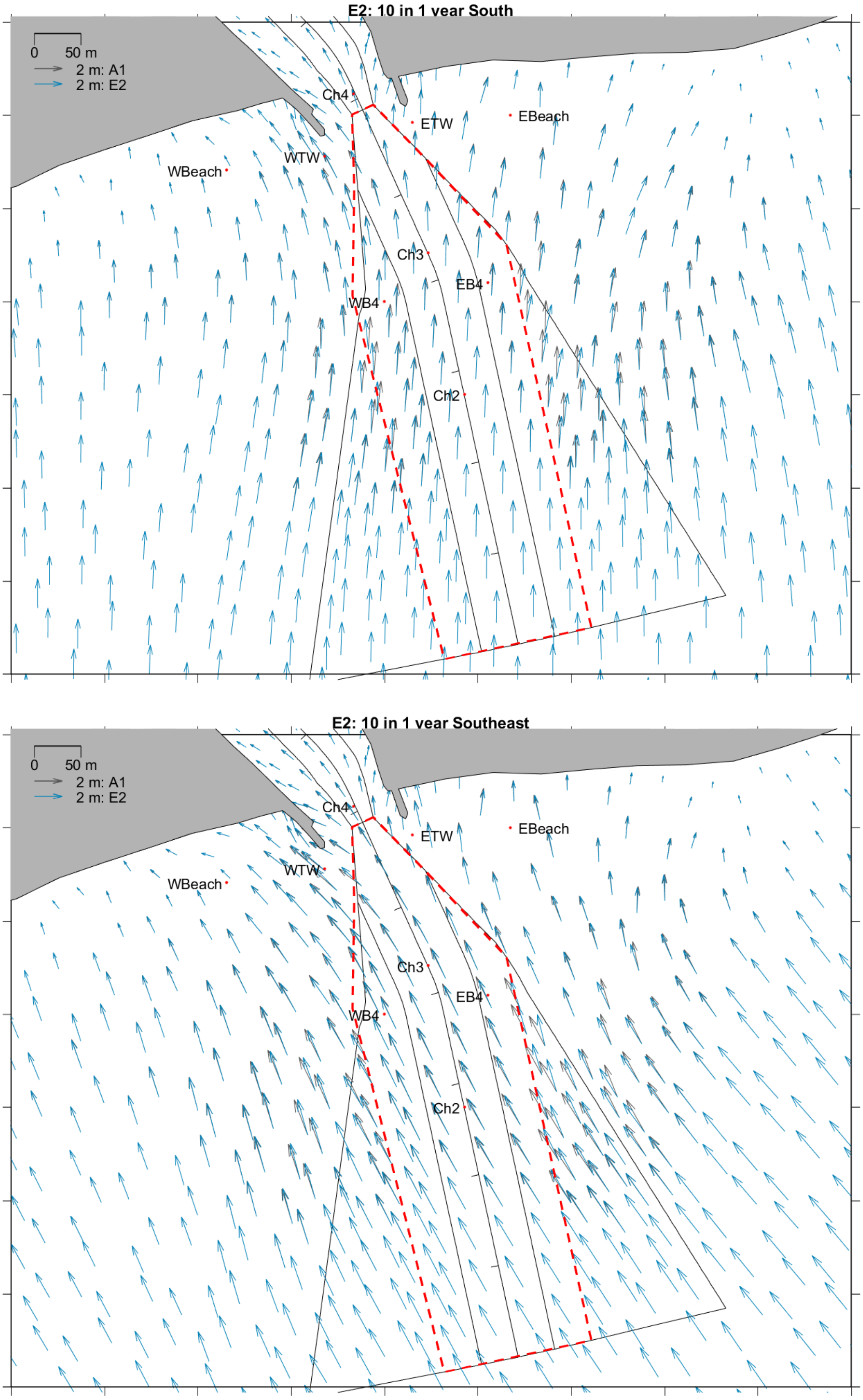

Figure 71. Spatial maps showing wave vectors for the E2 case relative to the existing E2 case for the 10 in 1 year south and south-east wave conditions.

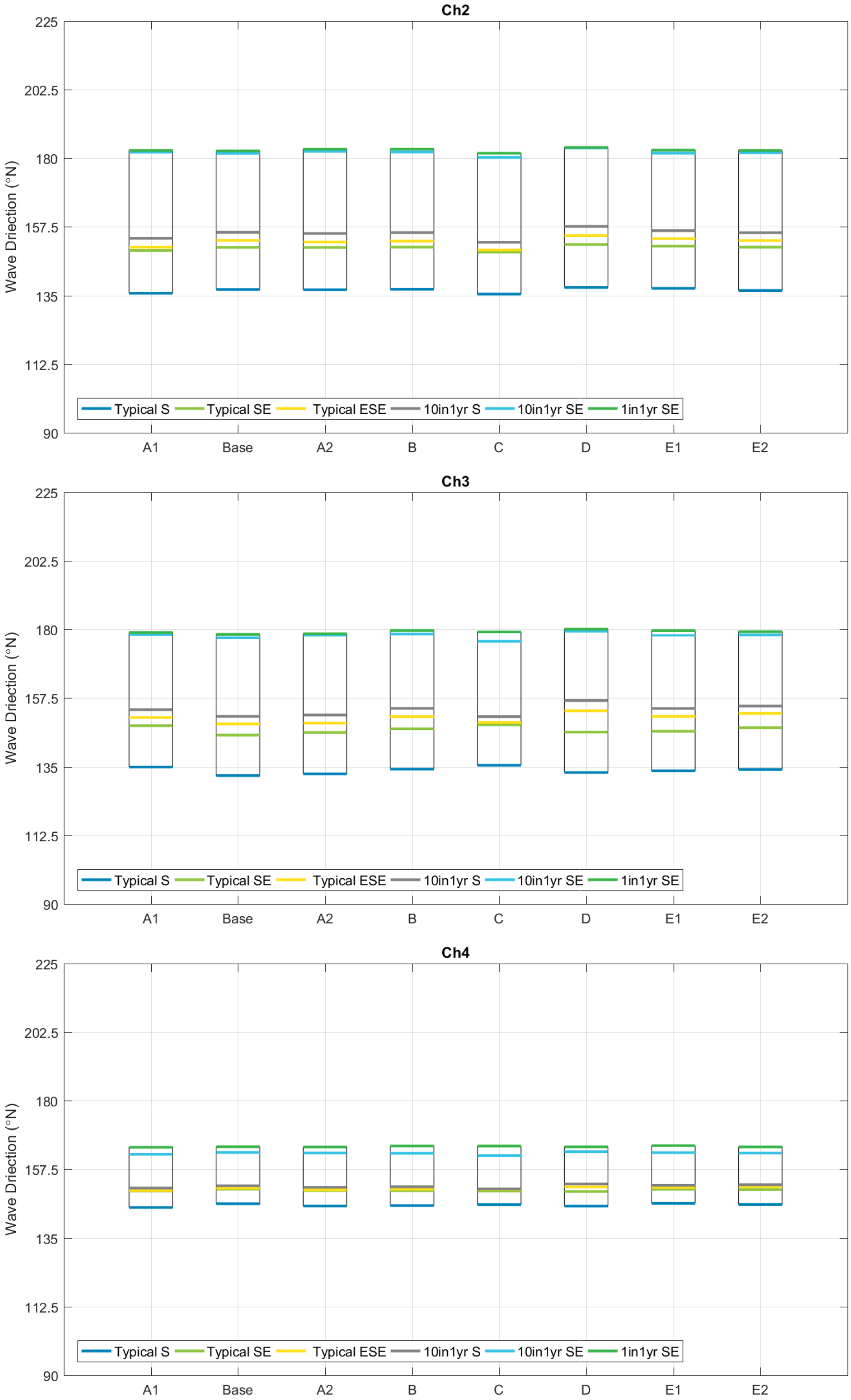

Figure 72. **Box plots showing the wave direction for all wave conditions and all dredge design options at Ch2 (top), Ch3 (middle) and Ch4 (bottom).**

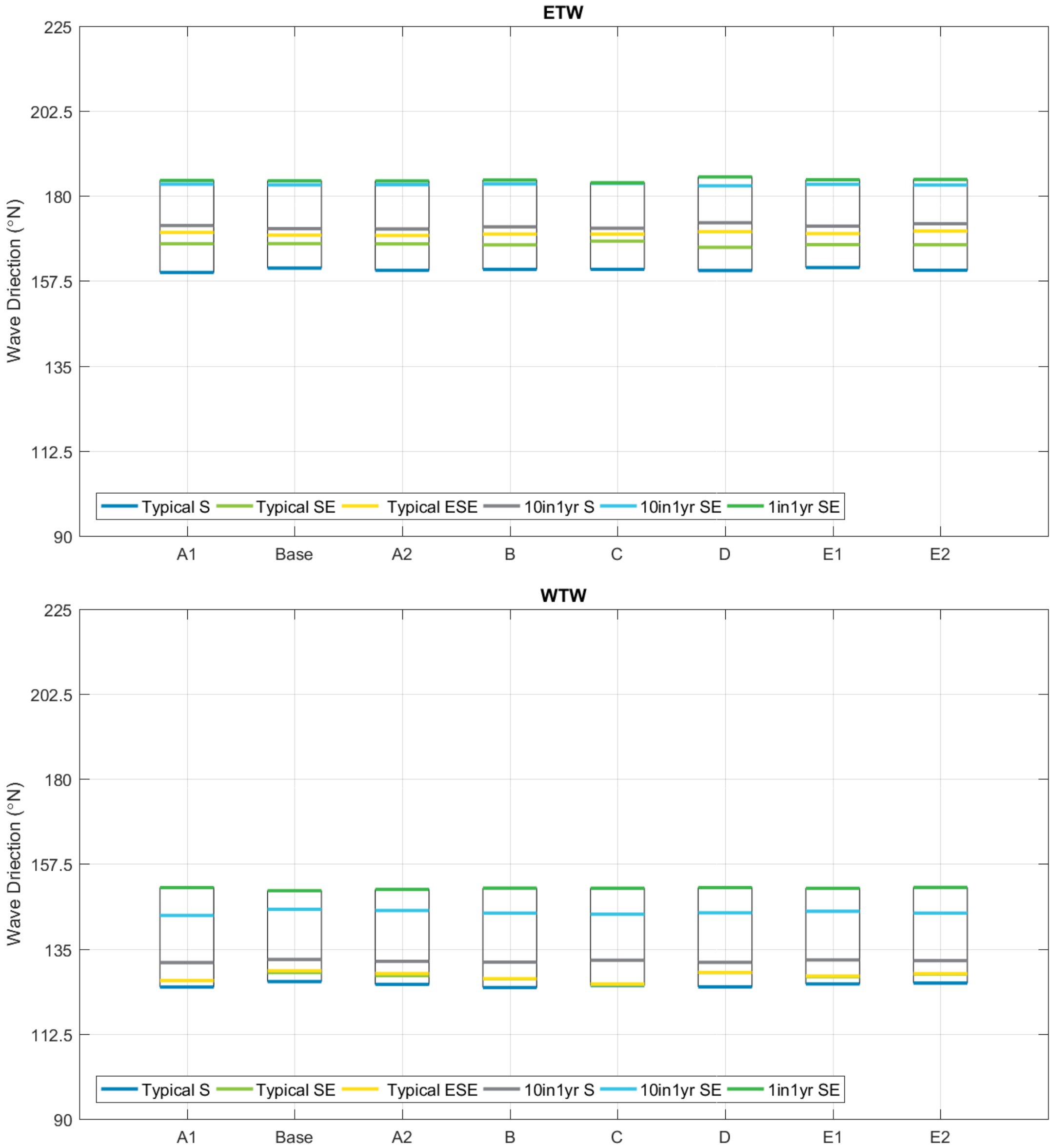

Figure 73. Box plots showing the wave direction for all wave conditions and all dredge design options at ETW (top) and WTW (bottom).

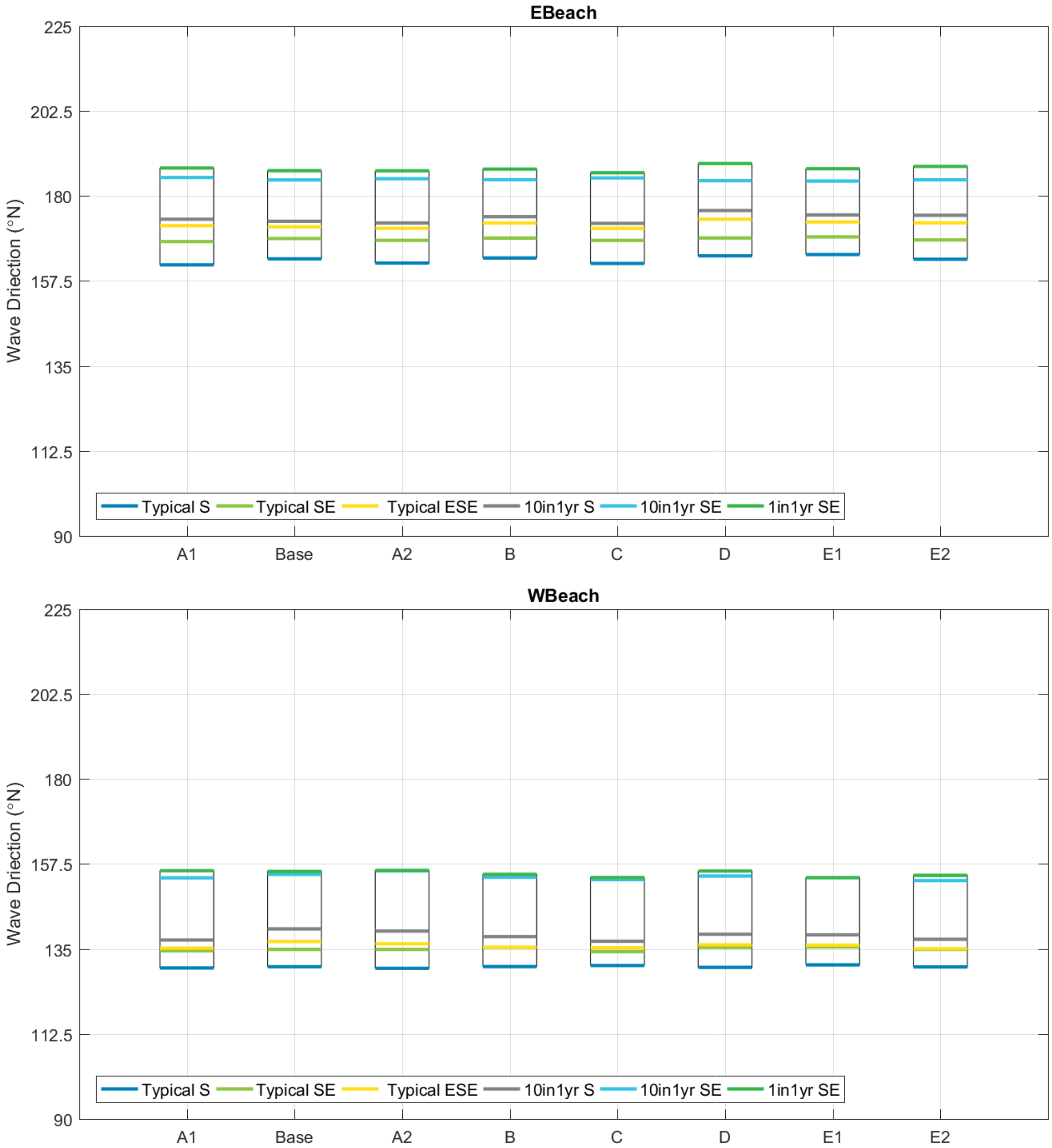

Figure 74. Box plots showing the wave direction for all wave conditions and all dredge design options at EBeach (top) and WBeach (bottom).

Table 7. Predicted wave direction for the different wave conditions and different dredge design options at four model output locations.

Region	Wave Direction (º)					
	Typical S	Typical SE	Typical ESE	10 in1 yr S	10 in 1 yr SE	1 in 1 yr SE
East Training Wall (ETW)						
A1	183	167	160	184	170	172
Base	183	167	161	184	170	171
A2	183	167	160	184	170	171
B	183	167	161	184	170	172
C	184	168	161	183	170	171
D	183	166	160	185	171	173
E1	183	167	161	184	170	172
E2	183	167	160	184	171	173
West Training Wall (WTW)						
A1	151	131	125	144	127	127
Base	150	132	126	146	129	129
A2	151	132	126	145	128	128
B	151	132	125	144	127	127
C	151	132	126	144	126	125
D	151	131	125	145	129	129
E1	151	132	126	145	128	128
E2	151	132	126	144	128	128
East Beach (EBeach)						
A1	185	168	162	187	172	174
Base	184	169	163	187	172	173
A2	185	168	162	187	171	173
B	184	169	164	187	173	175
C	185	168	162	186	171	173
D	184	169	164	189	174	176
E1	184	169	165	187	173	175
E2	184	168	163	188	173	175
West Beach (WBeach)						
A1	156	135	130	154	135	137
Base	155	135	130	156	137	140
A2	156	135	130	156	136	140
B	155	135	130	154	135	138
C	154	135	131	153	134	137
D	156	135	130	154	136	139
E1	154	136	131	154	136	139
E2	155	135	130	153	135	138

As wave direction changes have been predicted to be relatively small at the training wall and beach extraction sites, it is likely that any changes to wave conditions of sediment transport due to the dredge design options at the training walls or beaches would be a result of changes to wave height and wave period rather than wave direction. Therefore, results from the wave modelling have been used to estimate the annual wave energy (which is calculated based on H_s and T_p) at the training wall and beach output locations to provide an indication of the relative scale of changes to the wave conditions. The percent change in annual wave energy is presented for all the dredge design options relative to the existing A1 case in Table 8. The results show the following:

- the model predicts both increases and decreases in wave energy at the two beaches relative to the existing case, depending on the design option. Changes in annual wave energy of up to 1.5% are predicted at the two beaches, with a reduction in wave energy more likely at the West Beach and a slight increase more likely at the East Beach. The reason for both positive and negative changes in annual wave energy is because the options result in increases in H_s for some wave conditions and decreases in H_s for other wave conditions and when they are combined to estimate the annual wave energy this can result in some positive and some negative changes relative to the existing case;
- the results show that the majority of the options are predicted to result in a reduction in wave energy at the two training walls, with a reduction of up to 4.6% (option E1) predicted at the East Training Wall and up to 4.1% at the West Training Wall (option E2); and
- most of the dredge design options are predicted to predominantly result in a reduction in wave energy across the four sites. The only exception to this is dredge design A2, where the depth that the Bar Channel and wedges are dredged to is reduced from -5.5 m CD to -4.5 m CD, which is predicted to result in a relatively small (from 0.1% to 1.6%) increase in wave energy at all four sites. This is because it was the only dredge design option predicted to result in a small increase in H_s at the four sites for the typical south-east and typical east south-east wave conditions which occur most frequently during the year.

Table 8. Change in annual wave energy relative to the existing A1 case at the training walls and beaches.

Dredge Design	West Beach (%)	East Beach (%)	West Training Wall (%)	East Training Wall (%)
Base	-0.6	0.1	0.1	-1.3
A2	0.2	0.7	1.6	0.1
B	-0.5	1.1	-2.3	-3.3
C	-0.7	-1.0	-1.6	-0.8
D	-0.9	1.0	-2.1	-3.8
E1	-1.5	0.1	-3.6	-4.6
E2	-1.5	-1.1	-4.1	-0.6

It is likely that slumping and damage to the training walls would predominantly occur during large wave events, with typical wave conditions having minimal impact to the structures. Therefore, the difference in wave energy during a 1 in 1 year south-easterly wave event between the existing approved case and the modified dredge designs for the Bar has also been calculated at the two training walls (Table 9). The results predict that the existing case could have resulted in increases in wave energy during a 1 in 1 year wave event of 22.9% at the eastern training wall and 17.1% at the western training wall relative to the Base case. The results also show that all of the options are predicted to result in a reduction in wave energy at the training walls relative to the existing approved case, with the magnitude of the reduction being dependent on the relative different between the existing approved case and the dredge design option. The result predict that the current maintenance dredging practise, with year round dredging allowing the Bar depths to be maintained close to options A2 and B, results in a reduction in wave energy of around 15% at the eastern training wall and between 8 and 12% at west training wall relative to the A1 case which was adopted for annual maintenance dredging. Only maintaining the Bar Channel at design depths (option E1) is predicted to result in the largest reduction in wave energy at the training walls relative to the existing case out of all the modified dredge design options considered, with reductions in wave energy of 21.8% at the east training wall and 12.1% at the west training wall.

Table 9. Change in wave energy over a 1 in 1 year south-easterly wave event at the training walls relative to the existing case.

Dredge Design	West Training Wall (%)	East Training Wall (%)
Base	-17.1	-22.9
A2	-11.7	-15.2
B	-7.7	-14.4
C	-6.9	-3.1
D	-4.4	-18.3
E1	-12.1	-21.8
E2	-1.4	-9.2

3.3.3. Longshore Transport Predictions

Changes in the wave direction and wave energy at the beaches to the east and west of the Entrance Channel have the potential to result in localised changes to the longshore transport of sand which could influence whether sand accumulates adjacent to the training walls.

There are a number of different formulae available to calculate longshore transport. In this study, the Kamphuis (1991) method was adopted to calculate the wave driven longshore sediment transport as this method has been found to provide the most realistic longshore drift predictions (e.g. Wang *et al.* (2002) and Shanas and Kumar (2014)). The method uses the modelled wave conditions (H_s, T_p and direction) to provide a typical annual wave climate and assumes a medium sand grain size (400 µm), a typical beach slope of 0.03 and a coastline orientation representative of the shoreline directly adjacent to the wave model output locations to determine the longshore sediment transport rates. It is important to note that the calculated transport rates are potential transport rates which assume that there is an unlimited supply of sediment. If there is not sufficient sediment supply, then the actual transport rates which occur will be lower.

The predicted net longshore transport rates were in the order of 200,000 to 300,000 m^3/yr in a westerly direction. This corresponds well with the net longshore transport rates of around 200,000 m^3/yr in a westerly direction predicted for the area by O'Grady *et al.* (2019), but is higher than the net westerly transport of around 100,000 m^3/yr predicted by GHD (2013) . The similarity with the predictions by O'Grady *et al.* (2019) gives confidence that the way the annual wave climate has been represented based on the six modelled wave conditions is suitable and that the longshore transport calculations provide realistic values. The percentage difference in net westerly longshore transport between the dredge design options and the existing A1 case are shown in Table 10, with positive changes representing an increase and negative changes a reduction. The results show that the changes to the wave climate due to the different dredge design options are predicted to result in localised changes to longshore transport as follows:

- all of the options are predicted to result in an increase in net westerly longshore transport at the East Beach relative to the existing case, with changes ranging from 1% (option D) to 3.7% (option B); and

- all of the options except for option C are predicted to result in a reduction in net westerly longshore transport at the West Beach, with reductions ranging from 0.1% (options A2 and E2) to 3.0% (option D). Option C is predicted to result in an increase in net westerly longshore transport of 1.7%.

The changes in longshore transport at the two beaches are broadly in agreement with the changes in annual wave energy, with predominantly increases in wave energy at the East Beach and predominantly reductions in wave energy at the West Beach. The results therefore predict that the majority of the dredge design options have the potential to result in more sediment being transported towards the eastern training wall and less sediment transported away from the western training wall. Therefore, the options could potentially result in an increase in sand adjacent to the training walls compared to the existing case which could result in the training walls becoming less effective with more potential of sand bypassing them and being deposited straight into the Bar Channel. However, the predicted changes are relatively small and therefore any changes to sediment retention adjacent to the training walls is likely to be minor.

Table 10. Change in annual net westerly longshore transport relative to the existing A1 case at the East and West Beaches.

Dredge Design	West Beach (%)	East Beach (%)
Base	-0.5	2.7
A2	-0.1	2.7
B	-0.8	3.7
C	1.7	2.4
D	-3.0	1.0
E1	-1.3	3.3
E2	-0.1	1.3

3.4. Future Sedimentation

Further analysis of the historic bathymetric data has been undertaken to allow more detailed predictions of the future dredging requirements of the different dredge design options to be undertaken. As part of the additional analysis the monthly sedimentation which occurred when annual maintenance dredging programs were being undertaken between December 2014 and August 2016 was analysed for the following regions:

- within 40 m of the west and east sides of the Bar wedges (where sedimentation above design depth has historically occurred) as sedimentation rates in these regions adjacent to the natural bathymetry are likely to be the highest in the Bar region. The sedimentation in the remaining east and west halves of the Bar (where sedimentation above design depth has historically occurred) were also calculated to determine how much higher the sedimentation along the sides of the wedges has been;
- within the northern 20 m of Hopetoun Channel to determine how much of the sedimentation requiring maintenance dredging in Hopetoun Channel occurs in this part of the channel; and
- within the areas of the proposed Inner Channel expansion regions which are shallower than the proposed design depths.

The bathymetry in the Bar was also analysed to see if the sedimentation rate reduces once the depth has reduced from -5.5 m CD to -4.5 m CD. The analysis showed that there was limited correlation between the sedimentation rate and the depth of the Bar, with the sedimentation being dependent on the metocean conditions rather than on the local depth in the Bar. This finding indicates that the maintenance dredging requirement will be the same if the Bar (or areas of the Bar) is dredged to -5.5 m CD or -4.5 m CD.

Average monthly sedimentation rates were calculated for the different regions of the Bar where sedimentation above design depth can occur and these were divided by the spatial area of the regions to provide a standardised sedimentation rate for each region which can be adopted to predict future sedimentation for the different Bar dredge design options. The spatial area where sedimentation above design depth can occur was estimated to be 29,000 m^2 in the Bar Channel, 29,000 m^2 in the West Wedge and 34,000 m^2 in the East Wedge. The standardised monthly sedimentation rates are presented below:

- west 40 m of the Bar: 0.30 m^3/m^2/month;
- east 40 m of the Bar: 0.35 m^3/m^2/month;
- remaining western side of the Bar: 0.26 m^3/m^2/month; and
- remaining eastern side of the Bar: 0.29 m^3/m^2/month.

The standardised monthly sedimentation rates along with findings from the previous bathymetric analysis (see Section 2.2.1) have been used along with the footprint area of the dredge design where sedimentation above design depths is predicted to occur to predict the future average annual sedimentation rates for the dredge design options considered for the Bar:

- options A1, A2 and B: the historic bathymetric changes have shown that sedimentation rates do not vary when the depth in the Bar is -5.5 m CD or -4.5 m CD and so the predicted future average annual sedimentation for all three of these options is the same. Based on the findings from the previous bathymetric analysis and the results presented in Table 4, the future average annual sedimentation is predicted to be 193,000 m^3/yr (rounded to the nearest 1,000 m^3) (PCS, 2021a);
- option C: the sedimentation rate for the west 40 m of the Bar was applied to the Bar Channel and the sedimentation rates for the east 40 m and remaining eastern side of the Bar was applied for the eastern wedge. The future average annual sedimentation is predicted to be 169,000 m^3/yr;
- option D: the sedimentation rate for the east 40 m of the Bar was applied to the Bar Channel and the sedimentation rates for the west 40 m and remaining western side of the Bar was applied for the western wedge. The future average annual sedimentation is predicted to be 157,000 m^3/yr;
- option E1: the sedimentation rates for the east and west 40 m of the Bar was applied to represent the sedimentation in the Bar Channel. The future average annual sedimentation is predicted to be 89,000 m^3/yr; and
- option E2: the sedimentation rates for the east and west 40 m of the Bar was applied to represent the sedimentation in the 40 m wide area either side of the Bar Channel. To represent the sedimentation in the Bar Channel the average sedimentation rate over the remaining western and eastern sides of the Bar was adopted. The future average annual sedimentation is predicted to be 154,000 m^3/yr.

The monthly sedimentation rates in the proposed Inner Channel extension areas associated with dredge design option IC01 were calculated for the entire extension areas (as the monthly bathymetric surveys covered most of these areas) and for just the parts of the extension areas above design depth (i.e. where dredging would be required and therefore where future sedimentation is most likely). The average monthly sedimentation rates were then standardised to the spatial area that they represented, with rates ranging from 0.1 to 0.2 m^3/m^2/month. However, the sedimentation rates are likely to increase following dredging as deepening the bathymetry in these areas will reduce current speeds and increase the potential for sedimentation. To take this into account, the monthly standardised sedimentation rate for the Swing Basin (calculated to range from 0.2 to 0.3 m^3/m^2/month) was considered and the average sedimentation rate for the Swing Basin was adopted to provide an estimation of the future sedimentation rate in the Inner Channel extension areas where the bathymetry is currently shallower than the proposed dredge depth. Based on this, the future annual sedimentation requiring maintenance dredging for these areas is predicted to be in the order of 30,000 m^3/yr. For context, the annual sedimentation requiring maintenance dredging in the adjacent Cunninghame Arm was calculated to be between 10,000 and 15,000 m^3/yr (Section 2.2.2).

The analysis of sedimentation in Hopetoun Channel showed that approximately two thirds of the sedimentation requiring management occurred in the northern 20 m section of the channel. It is expected that the sedimentation in the remaining 30 m wide section of Hopetoun Channel would increase if the northern 20 m was no longer dredged, but due to a natural channel being present in this location and the adjacent rock training wall to the south of the natural channel preventing a southerly migration of the channel it is not expected that the increase in sedimentation would result in sedimentation rates as high as in the northern 20 m of the channel. However, it is not possible to accurately quantity what the increase in sedimentation in the 30 m wide channel would be. For this assessment it has been assumed that if the northern 20 m of Hopetoun Channel is no longer dredged then the total volume requiring maintenance dredging in Hopetoun Channel could reduce in the order of 30% to 40%. Based on the average annual sedimentation volume detailed in Table 5 this reduction would mean that the future annual maintenance dredging requirement in Hopetoun Channel for option IC02 would be 25,000 to 30,000 m^3/yr (i.e. a reduction of 10,000 to 15,000 m^3/yr).

3.5. Navigation

For the Bar area it is important to consider potential future dredge volumes but it is also important to understand the potential risks of sedimentation in the dredged areas of the Bar resulting in the Bar becoming unnavigable. As noted in Table 1, although the current dredge depth for the Bar is -5.5 m CD, the navigation depth is -3.5 m CD. Therefore, sedimentation of 2 m would result in navigation issues in the Bar if a dredge depth of -5.5 m CD was adopted and 1 m if a dredge depth of -4.5 m CD was adopted.

Changes to the bathymetry in the Bar relative to the existing dredge depth (-5.5 m CD) were reviewed over periods when large wave events occurred. Between January 2015 and May 2015 there were two large wave events, their wave conditions at the GP WRB are detailed below:

- the first in January was from the east south-east (direction = 110º), had a peak H_s of 4.33 m and a peak wave period (T_p) of 13.0 s; and
- the second in April was from the south-east (direction = 130º), had a peak H_s of 3.82 m and a T_p of 9.8 s.

The bathymetry relative to the dredge depth is shown for the surveys before and after these two wave events in Figure 75 and Figure 76 and transect along and across the Bar are shown in Figure 77 and Figure 78. The plots show the following:

- prior to the January 2015 wave event the majority of the Bar was below design depths. However, there were areas up to 1 m above design depth along both sides of the Bar and extending up to 90 m within the Bar from the eastern side. In addition, at the inner end of the Bar, close to the western training wall depths were more than 2 m above design depth extending up to 50 m from the side of the Bar and depths across half of the Bar Channel in this area were at least 1 m above design depths. Sedimentation in this area due to a shallow bar forming around the western training wall has occurred multiple times between 2016 and 2020 and as there is almost no wedge width present in this part of the Bar the sedimentation can influence navigation in the Bar Channel almost immediately. The development of a shallow bar in this location is also likely to result in increased transport of sand into the Entrance Channel under the influence of the strong tidal currents;
- during the January 2015 wave event the area where depths were 2 m above the dredge design depth on the west side of the Bar close to the training wall receded by more than

50 m, while along the east side of the east wedge an area 2 m above the design depth advanced by up to 50 m into the Bar and extended for a length of 200 m;

- during the April 2015 wave event the area where depths were 2 m above the design depth changed from extending 50 m into the Bar from the eastern side of the Bar to being close to 2 m above the design depth across the entire Bar. This wave event resulted in the bar formations on the east and west sides of the Bar connecting, resulting in areas 2 m above design depth extending across most of the Bar. The spatial plots show that along the eastern side of the Bar a distance of approximately 250 m is at least 2 m above design depth in the middle section of the Bar, while along the western side of the Bar a distance of approximately 70 m along the inner section of the Bar is at least 2 m above design depth; and
- the transects across the Bar can be used to show how far the sedimentation extended as a result of the wave events. The width of the Bar with navigable depths was reduced by around 40 m during the January 2015 wave event at the inner cross section. The April 2015 did not shallow to -3.5 m CD along most of the cross sections, but the width across the Bar that was below the -4.5 m CD contour (which can be considered as a proxy for the navigation depth if the dredge depth was set at -4.5 m CD) was reduced by this wave event by approximately 75 m at the inner cross section and by 125 m at the mid cross section.

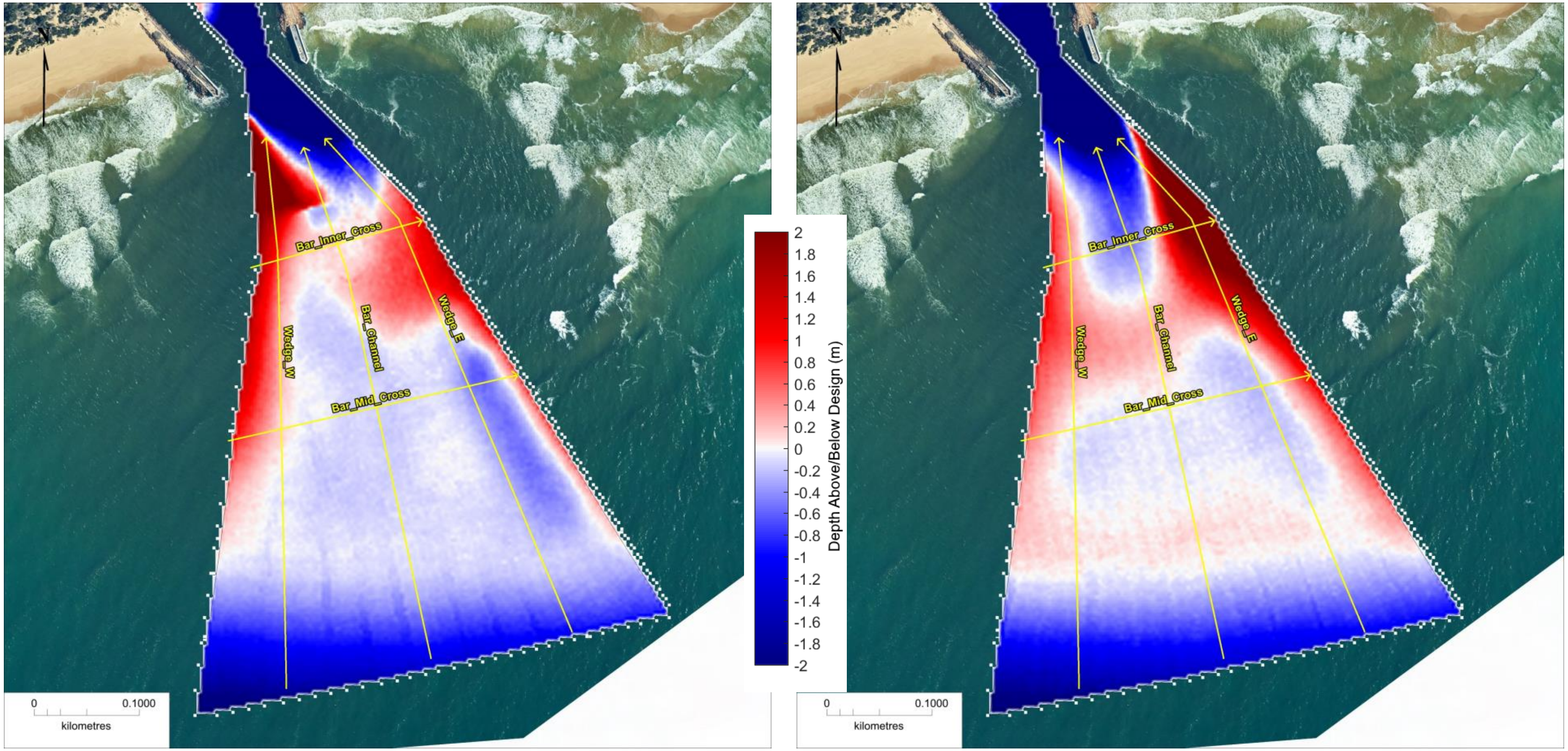

Figure 75. Depth of the Bar relative to design depth in January 2015 (left) and February 2015 (right), with transect locations shown in yellow.

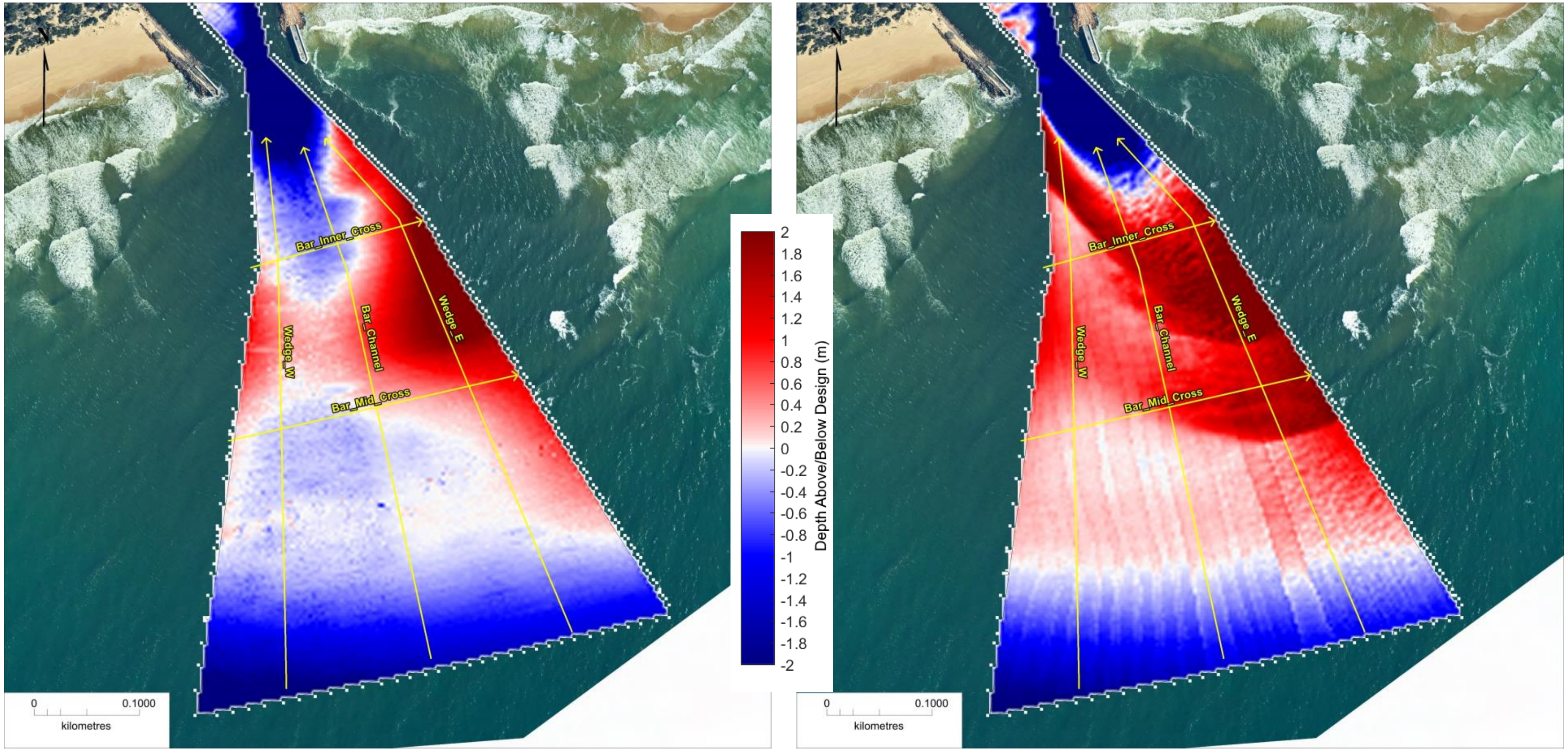

Figure 76. Depth of the Bar relative to design depth in April 2015 (left) and May 2015 (right), with transect locations shown in yellow.

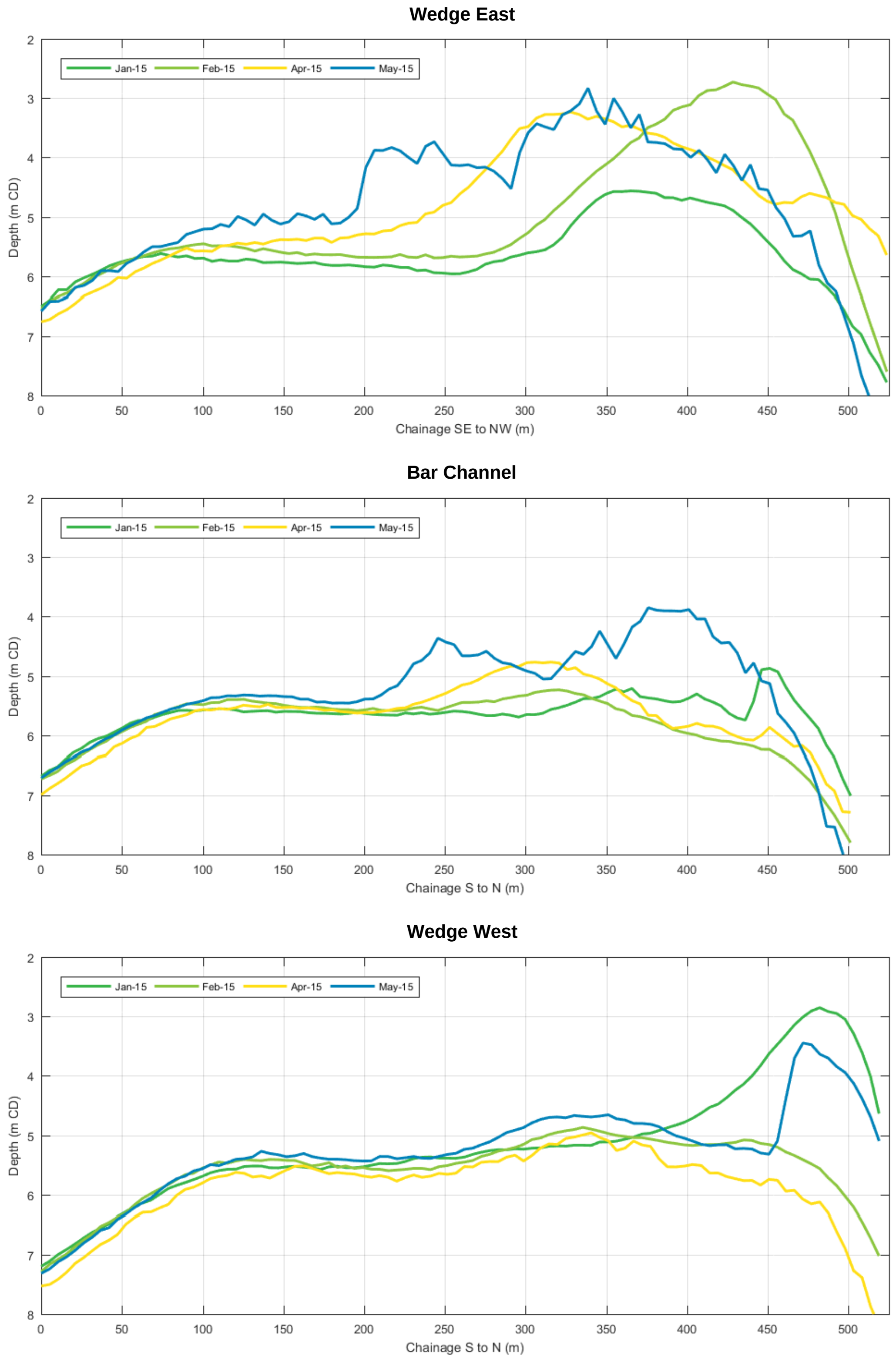

Figure 77. Transects along the Bar between January 2015 and May 2015.

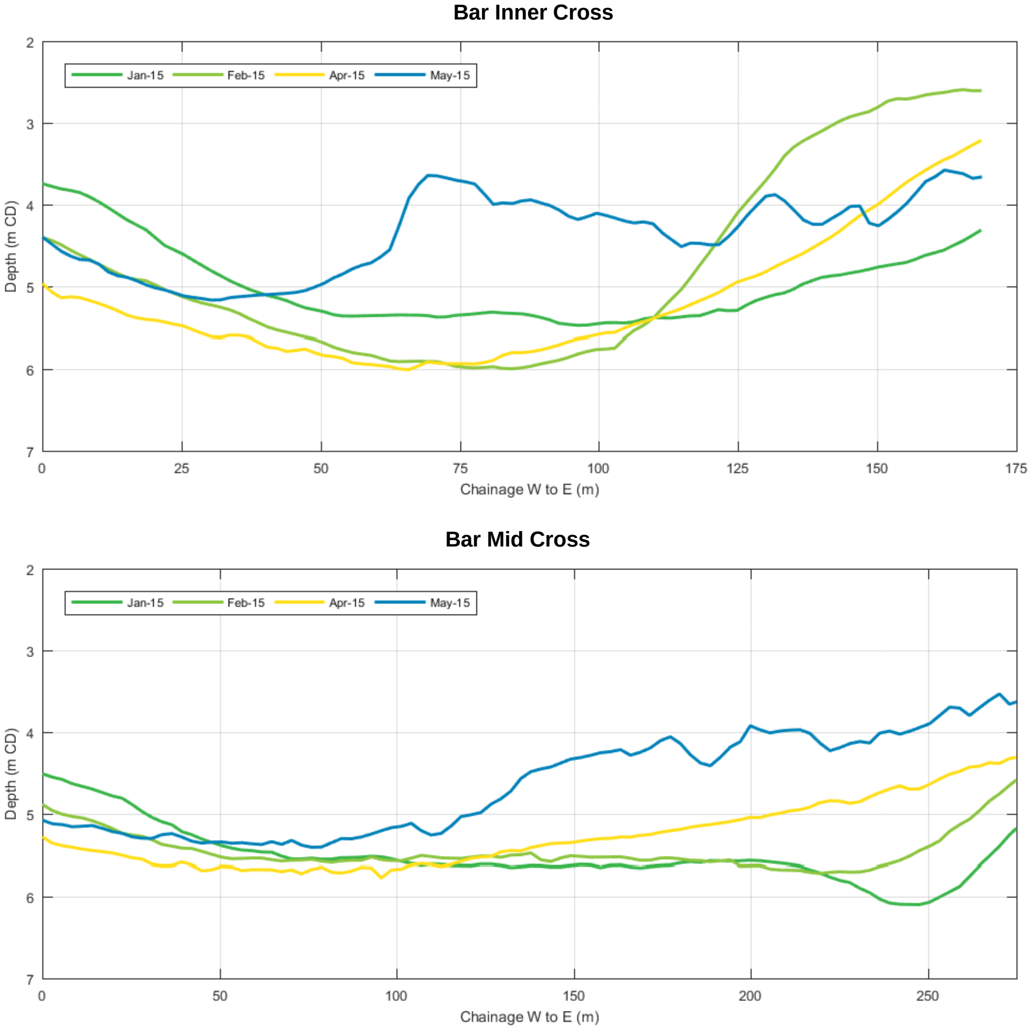

Figure 78. Transects across the Bar between January 2015 and May 2015.

Over the period that these wave events occurred there was no ongoing maintenance dredging of the Bar. This means that sediment which was transported into the Bar during the January 2015 wave event could have remained within the Bar for the subsequent April 2015 wave event and therefore resulted in increased sedimentation compared to what would have happened if ongoing maintenance dredging had occurred between the two events. However, other wave events during ongoing maintenance dredging have also resulted in sedimentation of more than 2 m above design depth extending up to 50 m within the Bar during a single wave event. The results have also shown that sedimentation of more than 1 m above the design depth can extend up to 75 m across the width of the Bar at the inner section and 125 m across the width of the Bar at the mid section.

Based on the results of the analysis there is a greater risk that navigation could be influenced for the dredge design options where the dredged width of the Bar has been reduced to less than 100 m (option E1) and where the design depth has been reduced to -4.5 m CD (option A2).

The analysis has shown that due to variations in the adjacent natural seabed morphology and wave climate, the distance from the inshore end of the Bar Channel to the offshore extent where the sedimentation can result in depths increasing to more 2 m above design depth varies between the eastern and western sides of the Bar. In May 2016 the Bar bathymetric survey also covered the adjacent natural bathymetry to the west and east of the Bar which provides a snapshot to help understand the natural bathymetry (Figure 79). The bathymetry shows that the natural bar on the east side of the dredged Bar is much shallower than the one to the west of the dredged Bar and extends further in an offshore direction. This is likely to be a result of the net westerly longshore transport combined with the shoreline alignment relative to the training walls at the entrance to Lakes Entrance. As a result, sedimentation above design depth is more likely to occur within the middle section of the Bar on the eastern side, with sedimentation of more than 2 m above design depth having occurred up to 450 m away from the inshore end of the Bar Channel. In contrast, sedimentation above design depth on the western side of the Bar is likely to occur in the inner section of the Bar, with sedimentation of more than 2 m above design depth typically occurring within 200 m of the inshore end of the Bar Channel, but occasionally occurring up to 350 m from the inshore end of the Bar Channel.

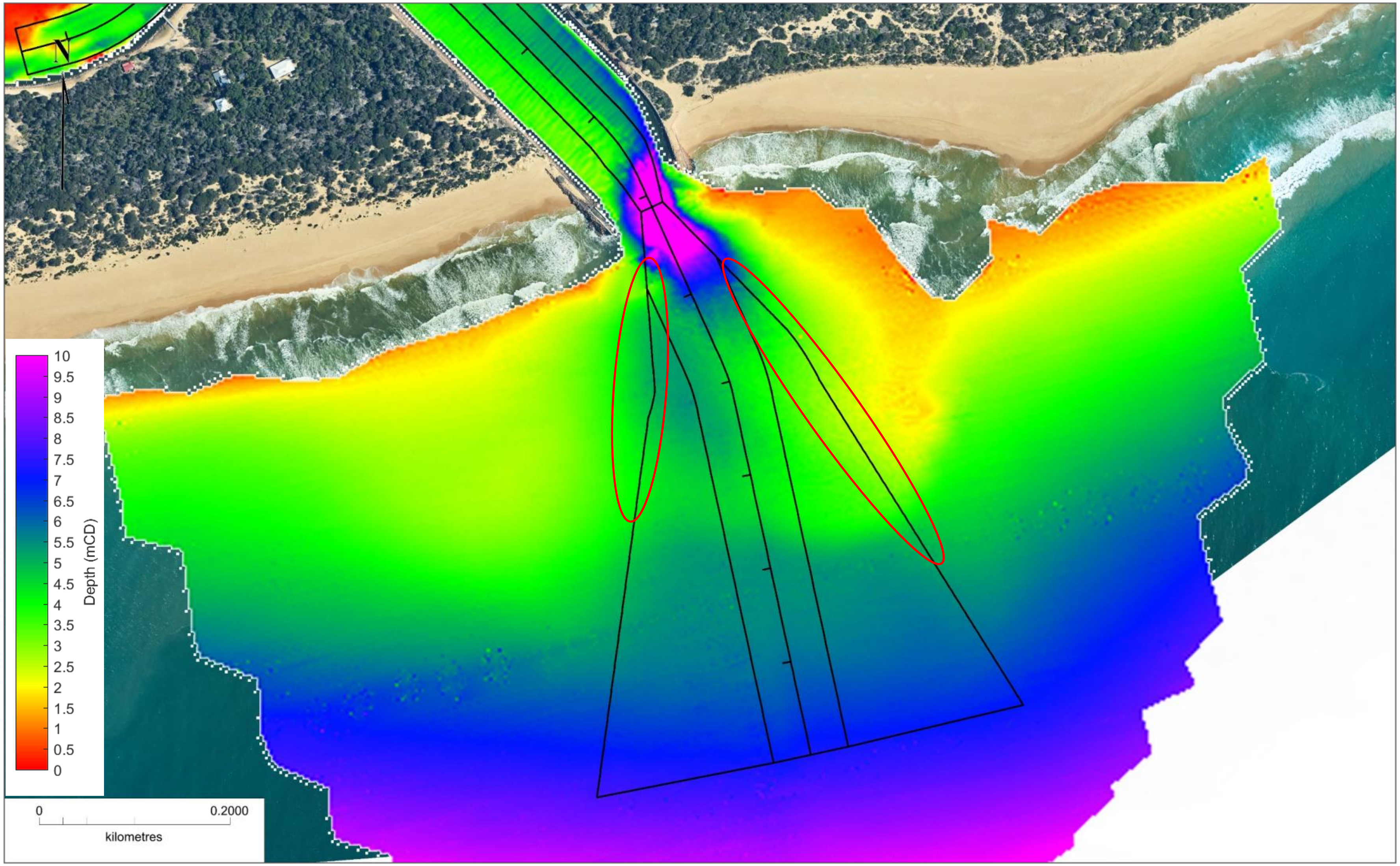

Figure 79. Bathymetry of the Bar dredge area and surrounding natural area to the east and west in May 2016.

4. Discussion

The results from the assessment have shown that the dredge design options are only predicted to result in localised changes to the wave conditions and hydrodynamics. The results have predicted some differences between the options, these are discussed below in terms of the key requirements for the dredge design option for the Bar and the Inner Channel.

4.1. Bar Dredge Design

The numerical modelling and bathymetric analysis undertaken provides information which can be used to assess the effectiveness of the existing wedge dredge design (option A1) relative to the three initial aims of the design (as detailed in Section 3.2). The results can also be used to assess whether the dredge design could have resulted in any potential impacts to the training walls:

- effectiveness of time buffer on sand bar formation: the bathymetric analysis has shown that sedimentation of more than 2 m occurred across the full width of the Bar eight months after the annual maintenance dredging program at the end of 2015. Therefore, the existing dredge design of the Bar wedge shape cannot be considered to have been completely successful at maintaining a navigable channel between annual maintenance dredging programs as significant navigational constraints will have occurred in the months before subsequent annual maintenance dredging programs. Based on the historical bathymetric data, the existing wedge shape dredge design would have been successful in maintaining a navigable channel (assuming a navigation depth -3.5 m CD) for around six months, but it is likely that some navigational constraints would have occurred between six and 12 months;
- effectiveness of wave refraction on removing sand from training walls: the wave modelling predicted that compared to the no dredging base case the existing dredge design resulted in a reduction in net westerly longshore transport of 2.7% at the east beach and an increase in net westerly longshore transport of 0.5% at the west beach. These predicted changes in longshore transport would have resulted in a reduction in sediment build-up adjacent to both training walls relative to the Base case, but the differences would have been small;
- effectiveness on reducing sand ingress to Inner Channels: the hydrodynamic modelling predicted that the existing dredge design did not influence the hydrodynamics in the Entrance Channel relative to the no dredging base case. The modelling also predicted that none of the dredge design options considered resulted in changes to the current speeds within the Entrance Channel or the tidal prism which flows into and out of Gippsland Lakes through the Entrance Channel; However, the reduction in net westerly longshore transport at the east beach and increase at the west beach would have resulted in less sand being transported around the training walls which could have resulted in a small reduction in sand ingress to the Inner Channels; and
- potential impacts to training walls: the wave modelling predicted that the annual wave energy at the seaward end of the eastern training wall was increased by 1.3% due to the existing approved dredge design relative to the no dredging base case. At the west training wall the existing approved dredge design was predicted to result in a small reduction in annual wave energy (0.1%) relative to the no dredging base case. However, it is likely that damage to the training walls would occur during large wave events and so the wave energy change was also calculated for a 1 in 1 year wave event. The results predicted that the existing approved dredge design resulted in an increase in wave energy of 22.9% at the eastern training wall and 17.1% at the western training wall. Although the east training wall has experienced slumping while the west training wall has not, the relative increase in wave energy predicted at both training walls due to the existing dredge design could have resulted in an increase in damage to the structures. However, this is unlikely to have been the only cause of the damage to the eastern

training wall, it is likely that the main reason for the damage is related to the age of the structures.

A summary of the differences between the dredge design options relating to the key requirements for the Bar dredge design is provided below:

- effectiveness of time buffer on sand bar formation: the numerical modelling has shown that any changes to the current speeds and wave conditions due to the options would be relatively small and localised. As a result, changes to the local metocean conditions due to the dredge design is not expected to influence the sedimentation which occurs within the Bar. Bathymetric analysis has shown that large wave events have the potential to result in shallowing of more than 2 m (i.e. the difference between existing dredge depth and the navigation depth) advancing into the Bar up to 50 m from the edge of the Bar and shallowing of more than 1 m (i.e. the difference between a -4.5 m CD dredge depth and the navigation depth) advancing into the Bar between 75 and 125 m. Based on this there is considered to be a higher risk of sand bar formation in the Bar resulting in impacts to navigation for options with a narrow channel (option E1) or a dredge design depth of -4.5 m CD (option A2);
- effectiveness of wave refraction on removing sand from training walls: all of the dredge design options are predicted to result in an increase in net westerly longshore transport at the beach to the east of the Entrance Channel relative to the existing case and most are predicted to result in a reduction at the beach to the west of the Entrance Channel. This would suggest that the options could potentially increase the risk of sand building up at the training walls. The exception to this is option C which is predicted to result in an increase in the net westerly longshore transport at the beach to the west of the Entrance Channel relative to the existing case, potentially reducing the risk of sand building up at this training wall. However, like all the other options, this option is still predicted to result in an increase in net westerly longshore transport at the beach to the east of the Entrance Channel, potentially increasing the risk of sand building up at this training wall. The differences in net westerly longshore transport between the dredge design options and the existing case are small (up to 3.7%) and the base no dredging case is predicted to result in changes of up to 2.7% meaning that the variation in transport caused by the options is close to the range which has been experienced historically. The largest predicted changes in net westerly longshore transport were for options B and E1, indicating that these options have the highest risk of increased sand retention at the training walls;
- effectiveness on reducing sand ingress to inner channels: the tidal current speeds which occur between the inner section of the Bar and the Entrance Channel have the potential to mobilise sand and transport it into the Entrance Channel during the flood stage of the tide. In addition, sand bars can form around the ends of the training walls (especially the western training wall) which can extend into the Entrance Channel, providing a source of sand which can be mobilised and transported in through the Entrance Channel by tidal currents during the flood stage of the tide. These two processes result in some sand being imported into the Entrance Channel and eventually the Inner Channels of the Port. The hydrodynamic modelling undertaken as part of this assessment has predicted that none of the options will result in a change in tidal currents at the inner section of the Bar adjacent to the Entrance Channel. As noted in the previous point, only option C is predicted to have the potential to reduce the risk of sand build-up at either of the training walls compared to the existing case, with the option predicted to reduce the risk of build-up at the western training wall, but increase the risk at the eastern training wall. Overall, the dredge design options are unlikely to change the sand ingress to the Inner Channels relative to the existing case, but there is small risk that they could increase the ingress due to the small changes in longshore drift that are predicted;
- potential impacts to training walls: the wave modelling undertaken as part of this assessment has predicted that the majority of the dredge design options considered would result in a reduction in annual wave energy at the heads of the training walls

compared to the existing case and that all of them would result in a reduction in wave energy during a 1 in 1 year wave event, indicating that if anything they would have a beneficial impact on the training walls. It is likely that any potential damage to the training walls would occur during large wave events and so the results from the 1 in 1 year wave event are considered the most applicable to compare the options. The highest reductions in wave energy at the training walls are predicted for option E1, with reductions in wave energy of 21.8% at the east training wall and 12.1% at the west training wall; and

- annual dredge volumes: the typical annual maintenance dredging volume is predicted to vary between some of the options, with volumes predicted to be similar to the existing case for options A2 and B. The typical annual maintenance dredging volume is predicted to be reduced by around 25,000 m^3/yr for option C, 35,000 m^3/yr for option D, 40,000 m^3/yr for option E2 and more than 90,000 m^3/yr for option E1 (a reduction of more than 50%).

4.1.1. Recommendations

This assessment has shown that none of the dredge design options are clearly preferred over the existing dredge design, with the existing case predicted to be the more effective in terms of providing a time buffer for sand bar formation and effectiveness of limiting build-up of sand at the training walls. However, all of the options result in a significant reduction in wave energy at the training walls during a 1 in 1 year wave event compared to the existing case. The results have also indicated that there would be an increased risk to navigation if the dredge design depth was reduced from -5.5 m CD to -4.5 m CD over the Bar and as a result it is recommended that the depth remains at -5.5 m CD as sedimentation of more than 2 m can occur during a large wave event. The results from the assessment indicate that the following modifications to the existing dredge design could help to further optimise the design:

- sedimentation along the inner 400 m of the east edge and inner 300 m of the west edge of the Bar has the potential to advance into the Bar Channel. Therefore, it is recommended that after these distances the dredge design follows the same alignment as the Bar Channel until it reaches the offshore end of the Bar (Figure 80). This would result in a reduction in width at the seaward end of the Bar of 108 m on the western side and 80 m on the eastern side, with a total width of the dredged area of the Bar reducing from 456 m to 268 m (although the offshore end of the Bar does not require maintenance dredging, so these distances are just for reference). Overall, this would result in a reduction in the Bar dredged area of 20%, but as much of this area does not require dredging the actual reduction in maintenance dredging volume would be smaller. This configuration is expected to perform similarly to the existing Bar in terms of wave refraction and longshore transport on the adjacent beaches, although if the option were to be adopted it is recommended that further numerical modelling should be undertaken to confirm the performance of the design in terms of wave refraction and longshore transport. In addition, the modelling could also be used to try and optimise the option to reduce wave energy reaching the training walls if this is considered a potential future concern; and
- sedimentation above design depth due to a shallow sand bar forming directly offshore of the western training wall has occurred regularly and can result in navigational issues as well as being a likely mechanism to increase sediment ingress into the Entrance Channel. The existing dredge design and all of the dredge design options considered are not able to reduce this potentially significant sedimentation mechanism. The risk to both navigation in the Bar Channel and sediment ingress to the Entrance Channel could be reduced by extending the Bar Channel to the west in this area and therefore providing additional buffer at this narrow section of the Bar (see hashed area in Figure 80). This polygon has an area of 6,500 m^2 and when combined with the reduced Bar area detailed in the previous point this would result in a reduction in the Bar dredged area of 15.5%. The polygon would not require maintenance dredging to the same depth as the remainder of the Bar as it would not need to be navigable, rather it would be aimed to

limit the development of a shallow bar which could extend into the Bar Channel. Based on this a dredge design depth of between -4 and -4.5 m CD is recommended. It is recommended that if GP consider the option to be feasible that further numerical modelling be undertaken to inform the final configuration and dredge depth.

It is possible that the optimised dredge design detailed above could be further optimised over time based on additional analysis of monthly bathymetric surveys and dredge volumes. Potentially the width of the optimised design could be further narrowed over time if it has been shown to be successful at keeping the Bar navigable during large wave events. In addition, the configuration of the additional dredge area close to the western training wall could also be further refined in the future, with the potential to optimise its shape, width or depth.

Analysis of historic bathymetric data of the Bar has shown that sedimentation above design depth typically occurs between 50 and 200 m of the Entrance Channel along the western side of the Bar and between 100 and 400 m of the Entrance Channel along the eastern side of the Bar. It is recommended that as long as there is no significant sedimentation within the Bar Channel, any sedimentation occurring along these areas of the Bar are prioritised in terms of ongoing maintenance dredging as over time they would be likely to result in sedimentation extending into the Bar Channel.

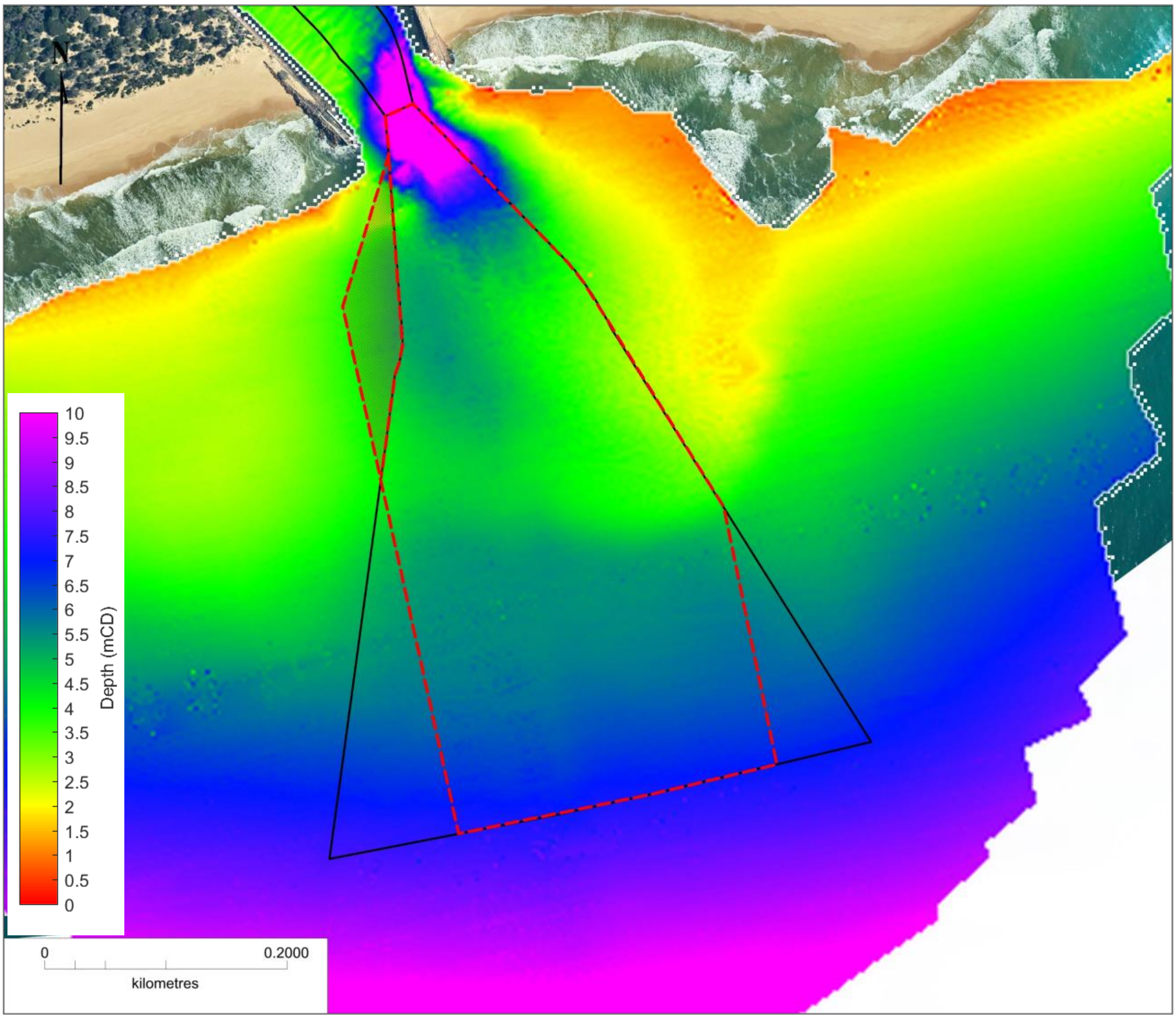

Figure 80. Proposed alternative dredge design (red dashed line), with the possible extension outside of the existing dredge design footprint shown by the shaded area.

4.2. Inner Channel Dredge Design

A summary of the proposed dredge design options relating to the key requirements for the Inner Channel dredge design is provided below:

- navigational access: the hydrodynamic modelling has predicted that any changes to hydrodynamics due to the two Inner Channel dredge design options would be in the form of localised changes in tidal currents. The deepening related to IC01 is predicted to result in localised reductions in tidal current speed, while the shallowing related to IC02 is predicted to result in localised increases in tidal current speed. Due to the localised nature of the changes, they are not expected to influence sedimentation elsewhere in the Inner Channels and the relative magnitude of the localised changes in current speed (up to ±0.15 m/s within the designated channels) are unlikely to influence navigation. The dredge design for option IC01 is aimed at improving navigation in the Inner Channels, acting to widen the Swing Basin and therefore enhance safe navigation. However, the narrowing of Hopetoun Channel from 50 m to 30 m could restrict navigation, this would need to be further assessed by GP based on the type, size and frequency that vessels use the channel;

- impacts to adjacent shorelines: both options are predicted to result in slight increases in current speed adjacent to the shoreline. For option IC01 during the ebb stage of the tide increases in current speed of up to 0.2 m/s are predicted adjacent to the eastern shoreline of the Entrance Channel (along the training wall), while for option IC02 during both stages of the tide increases in current speed of up to 0.1 m/s is predicted along the shoreline to the south of Hopetoun Channel (along the training wall at Boole Poole) and increases of up to 0.1 m/s almost extend to the south-eastern corner of Rigby Island. However, rock training walls are present in two of these locations and so the predicted increases in current speed are not expected to result in any localised erosion of the shoreline. The predicted increases close to the south-eastern corner of Rigby Island is due to the shallowing of the bathymetry in the northern 20 m of Hopetoun Channel resulting in slight acceleration of currents between the channel and Rigby Island. As these increases are predicted on both the flood and ebb stages of the tide they are not expected to result in a significant change to the sediment transport in the area and therefore are not likely to impact the shoreline. Localised reductions in current speed of up to 0.2 m/s are predicted adjacent to the Bullock Island shoreline (specifically around the south-western corner of the island), these reductions could promote an increase in sedimentation in these areas which could help to stabilise the shoreline;
- sand migration at the northern end of Rigby Island: neither of the options are predicted to result in any changes to the hydrodynamics at the northern end of Rigby Island and so would not influence the transport of sand which occurs in this area; and
- annual dredge volumes: a high level estimate of the future maintenance dredging requirement based on the two options considered has been undertaken. The annual increase in maintenance dredging was estimated to be in the order of 30,000 m^3/yr for option IC01, while option IC02 was predicted to result in a reduction in maintenance dredging in the order of 10,000 to 15,000 m^3/yr.

4.2.1. Recommendations

The results from this assessment have predicted that the only impacts resulting from the minor widening of the Entrance Channel, Cunninghame Arm and the Narrows would be a localised changes (predominantly reductions) in tidal currents. As a result, the option is considered to be feasible, although it is important to note that the option is predicted to increase future maintenance dredging in the order of 30,000 m^3/yr. The modelling also predicted that allowing the northern 20 m of Hopetoun Channel to naturally infill over time and only maintaining the southern 30 m width of the channel would only result in localised changes to the hydrodynamics and has the potential to result in a reduction in maintenance dredging volumes of 10,000 to 15,000 m^3/yr. This option is also considered to be feasible, but would require further consideration by GP to determine whether reducing the width of the channel would have navigational implications or would restrict future maintenance dredging operations within the channel.

5. Summary

This assessment has reviewed the existing dredge design at the Port as well as a number of modified dredge design options and assessed potential impacts of both the existing and modified designs. The modified dredge designs were developed in collaboration with GP to provide a range of realistic potential alternative options to the existing dredge design of the Bar and Inner Channels. The dredge design options which were considered included seven options for the Bar (including the existing scenario) and three options for the Inner Channels (including the existing scenario). In addition, a scenario with the Bar not dredged was also considered as part of the assessment to help understand the potential impacts of the existing wedge shape design of the Bar.

The assessment has included a review of previous relevant studies, an analogues assessment to gain information from similar relevant case studies, bathymetric analysis using bathymetric data from hydrographic surveys and from satellite imagery, hydrodynamic and wave modelling and longshore transport calculations.

The assessment has found the following regarding the existing wedge shape dredge design of the Bar:

- it was not successful in maintaining a clear navigable channel between annual maintenance dredging programs, with more than 2 m of sedimentation occurring throughout the width of the channel eight months after an annual dredge program;
- predicted changes to the wave conditions along the beaches adjacent to the training walls were found to alter the longshore transport rates so that there would have been less build-up of sand adjacent to the two training walls, thereby indirectly improving the effectiveness of training walls;
- the dredge design was only predicted to result in localised changes to the hydrodynamics, with the design unlikely to result in much reduction to sand ingress into the entrance channel except as a result of the small reduction in longshore transport towards the training walls predicted; and
- there was predicted to be a large increase (17.1% to 22.9%) in wave energy at both training walls during a 1 in 1 year wave event as a result of the existing dredge design. Although the east training wall has experienced slumping while the west training wall has not, the relative increase in wave energy predicted at both training walls could have resulted in an increase in damage to the structures. However, this is unlikely to have been the only cause of the damage at the eastern training wall, it is likely that the main reason for the damage is related to the age of the structure.

A summary of the findings from the numerical modelling of the modified dredge design options is provided below:

- the hydrodynamic modelling predicted that the modified dredge design options would not result in a measurable change to the water level either in the Entrance Channel or within the Inner Channels. In addition, the modified options were not predicted to result in a measurable change to the flow volumes either into or out of the Entrance Channel;
- the modified dredge design options would only result in localised increases in current speed where the bathymetry has changed relative to the existing case and in the immediate adjacent areas. Typically the modelling showed that shallowing the depths resulted in localised increases in current speed while deepening the depths resulted in localised decreases;
- the hydrodynamic modelling predicted that the modified dredge design options would not result in changes to the current speeds within the Entrance Channel or the tidal prism which flows into and out of Gippsland Lakes through the Entrance Channel;

- localised increases in wave height during typical wave conditions were predicted to occur over the Bar due to the modified dredge design options for the Bar relative to the existing case, while during larger wave events the options were predicted to result in a reduction in wave heights in the Bar and inshore of the Bar;
- most of the modified dredge design options for the Bar were predicted to result in a reduction in annual wave energy at the two training walls and the adjacent two beaches. In addition, all of the modified dredge design options for the Bar were predicted to result in reductions in wave energy at the training walls during a 1 in 1 year wave event compared to the existing dredge design; and
- the modified dredge design options for the Bar were predicted to increase the net westerly longshore transport rates at the East Beach and most of the options were predicted to result in a reduction in transport at the West Beach. Therefore, the results indicate that the modified dredge design options for the Bar could potentially result in an increase in sand adjacent to the training walls compared to the existing case which could result in the training walls becoming less effective.

Based on the findings of the assessment, none of the dredge design options for the Bar were found to be preferred compared to the existing dredge design, with the existing design predicted to be the most effective in terms of providing a time buffer for sand bar formation and effectiveness of limiting build-up of sand at the training walls. However, all of the options result in a significant reduction in wave energy at the training walls during a 1 in 1 year wave event compared to the existing case. The results have indicated that there would be an increased risk to navigation if the dredge design depth was reduced from -5.5 m CD to -4.5 m CD over the Bar and as a result it is recommended that the depth remains at -5.5 m CD as sedimentation of more than 2 m can occur during a large wave event. Alternative modifications to the existing dredge design of the Bar have been recommended to further optimise the existing dredge design based on the findings of this assessment. These modifications include reducing the width of the offshore end of the Bar and extending the dredge area to the north-west to try and reduce sedimentation in the Bar Channel close to the western training wall. These modifications have the potential to maintain the benefits of the existing dredge design while also potentially reducing the risk of the Bar Channel becoming unnavigable and reducing sand ingress into the Entrance Channel.

The numerical modelling of the Inner Channel options have predicted that the only hydrodynamic impacts resulting from the minor widening of the Entrance Channel, Cunninghame Arm and the Narrows would be a localised changes (predominantly reductions) in tidal currents. As a result, the option was considered to be feasible, although it is important to note that the option was predicted to increase future maintenance dredging in the order of 30,000 m^3/yr. The modelling also predicted that allowing the northern 20 m of Hopetoun Channel to naturally infill over time and only maintaining the southern 30 m width of the channel would only result in localised changes to the hydrodynamics and has the potential to result in a reduction in maintenance dredging volumes of 10,000 to 15,000 m^3/yr. This option was also considered to be feasible, but would require further consideration by GP to determine whether reducing the width of the channel would have navigational implications or would restrict future maintenance dredging operations within the channel.

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Appendices

Appendix A – Model Setup and Calibration

A.1. Introduction

This appendix provides details of the setup and calibration and validation of the hydrodynamic and spectral wave models developed as part of this dredge design assessment.

A.1.1 Model Setup

The numerical modelling has been undertaken using the MIKE software suite. The MIKE software has been developed by the Danish Hydraulics Institute (DHI) and is internationally recognised as state of the art and has been adopted by PCS, and others globally, in similar projects. The MIKE suite includes the necessary hydrodynamic and spectral wave modules which are required for this study, ensuring that all aspects of the study can be addressed.

A.1.1.1 Model Mesh

The flexible mesh (FM) version of MIKE has been adopted due to its ability to adjust the spatial resolution of the model mesh throughout the domain. This allows suitable model resolutions to be adopted throughout (i.e. higher resolution in areas of interest and lower resolution in the offshore areas away from areas of interest) which ensures model efficiency so that simulation times are not compromised by the model resolution.

The model mesh extends over the Gippsland Lakes including Lakes Wellington, King and Victoria and offshore of the Entrance Channel a distance of approximately 3.7 km, to water depths of around 45 m MSL (Figure A1).

The same mesh was used for the hydrodynamic and wave modelling, although for the wave model the depths inside Lakes Entrance were set to land values as the study focused on offshore swell waves at the Bar as opposed to locally generated wind waves within the Inner Channels.

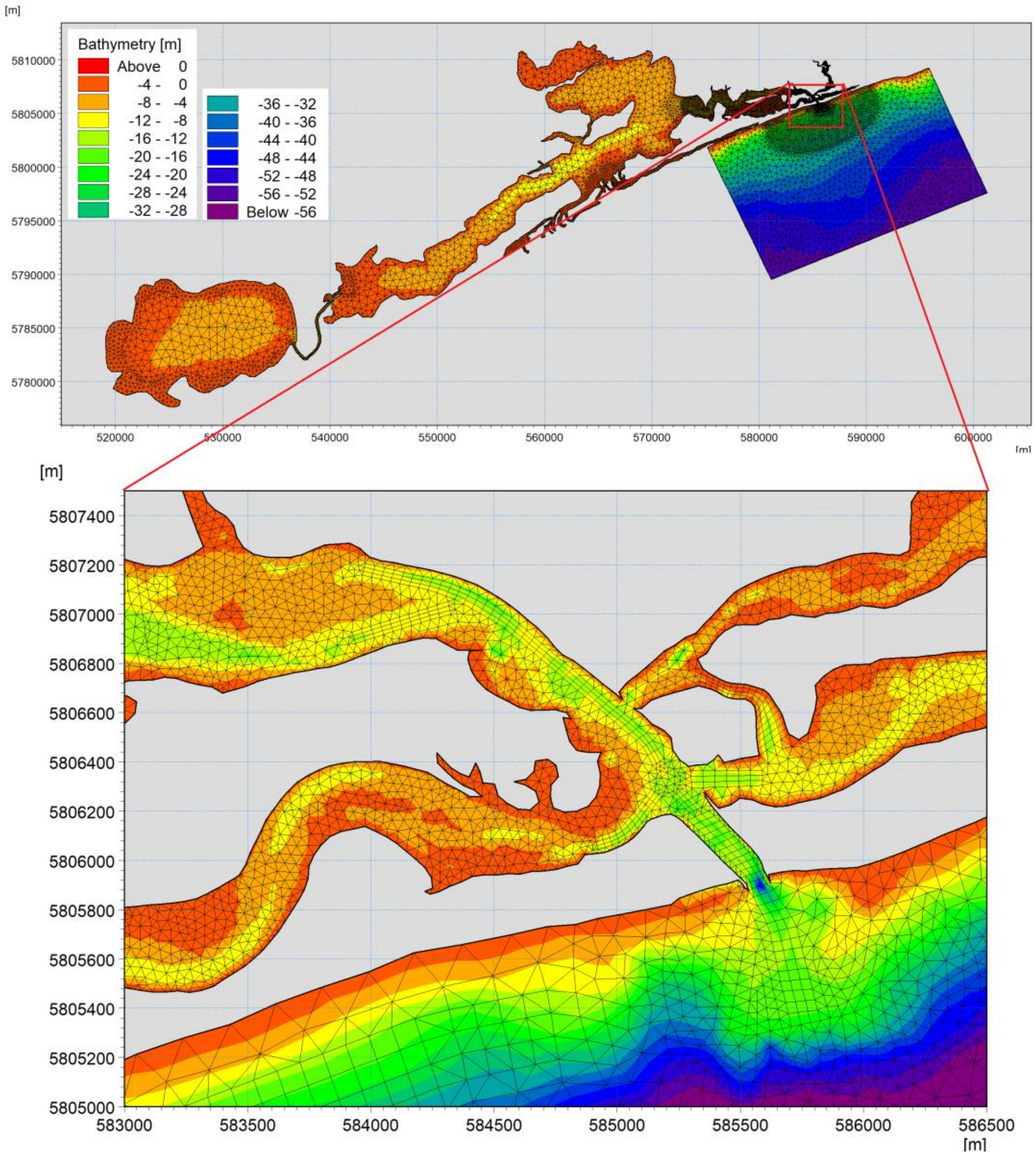

Figure A1. Model Mesh and bathymetry.

A.1.1.2 Bathymetry

The model bathymetry was developed using bathymetric surveys of the Bar, Entrance Channel, Inner Channels and other areas of the Lakes undertaken by GP. The model performance was calibrated for a period of ongoing dredging (representing the current dredge design) and validated for a period without the dredged Bar. Two different model bathymetries were therefore developed with the first based on the December 2020 survey data and the second based on the September 2017 survey data when the Bar had not been dredged for 12 months (Figure A1 and Figure A3, respectively).

For the offshore areas, the GP survey data for the DMG's was combined with the Geosciences Australia 'Australian Bathymetry and Topography Grid' (Whiteway, 2009), which combines available survey data to provide a gridded bathymetric dataset on a 9 arc second grid (equivalent to approximately 200 m x 250 m at Gippsland).

In addition, some SDB data from the 2020 Sentinel 2 image was included to represent the shallower areas which are not covered by the subtidal data surveys (see Section 2.3 for more details on the derivation of SDB data).

The same bathymetry was used for the hydrodynamic and wave modelling (although as noted above depths inside the Lakes were set to land values in the wave model).

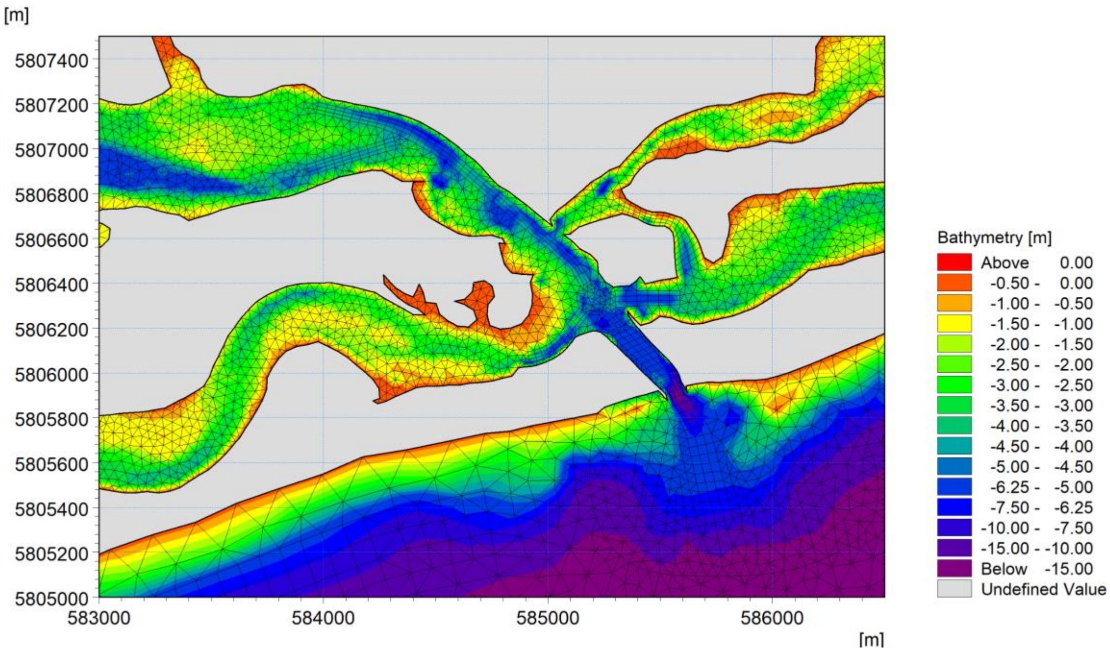

Figure A2. Model bathymetry for the current dredge design (2020).

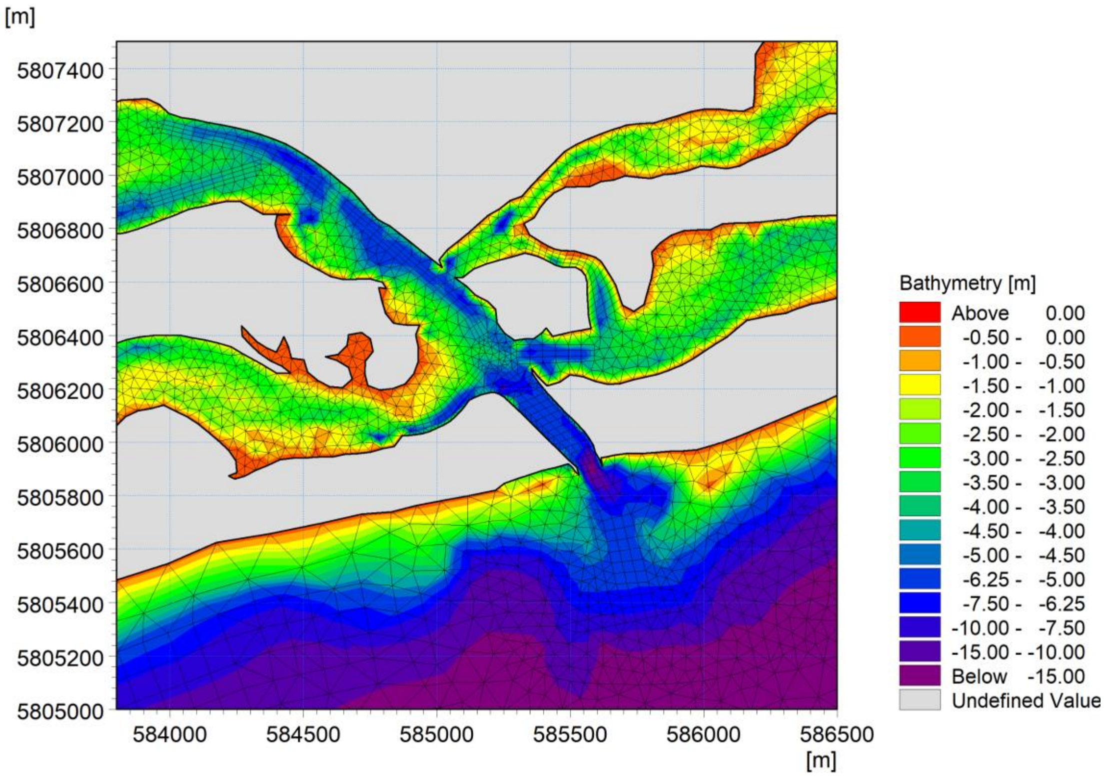

Figure A3. Model bathymetry for 2017.

A.1.2 Hydrodynamic Model

The MIKE21 FM hydrodynamic (HD) module has been used for the hydrodynamic modelling, this module was developed for applications within oceanographic, coastal and estuarine environments. The module is based on the numerical solution of the three-dimensional incompressible Reynolds averaged Navier-Stokes equations invoking the assumptions of Boussinesq and of hydrostatic pressure. The model consists of continuity, momentum, temperature, salinity and density equations and is closed by a turbulent closure scheme. The spatial discretization of the equations is performed using a cell-centred finite volume approach (DHI, 2017a).

Hydrodynamic boundary conditions for the offshore boundaries were modified based on measured water levels from the gauge at Lakes Entrance.

The hydrodynamic model bed resistance was defined as a Manning *M* number, this is equivalent to the inverse of the Manning *n* number which is a more commonly adopted bed resistance parameter. A single roughness value was applied throughout the domain, except along the offshore boundaries where a higher bed resistance value was applied to reduce the potential for any model instabilities as the tidal wave propagates along the open boundaries.

The models ability to accurately predict water levels and flows was assessed against observational data at Lakes Entrance. The models ability to predict water levels was also assessed against observational data at Bullock Island. The model was calibrated over a two week spring-neap tidal period in December 2020 and validated over a two week spring-neap tidal period in September 2017.

A.1.3 Wave Model

A spectral wave (SW) model was setup using the MIKE21 FM SW module. The MIKE21 FM SW module is a spectral wave model which has been developed for applications in offshore, coastal and port environments. The module simulates the growth, decay and transformation of wind-generated waves and swell in offshore and coastal areas. The model can include the following physical phenomena (DHI, 2017b):

- wave growth by the action of wind;
- non-linear wave-wave interaction;
- dissipation due to white-capping;
- dissipation due to bottom friction;
- dissipation due to depth-induced wave breaking;
- refraction and shoaling due to depth variations;
- wave-current interaction; and
- the effect of time-varying water depth and flooding and drying.

The SW model was setup to run using the same mesh as the hydrodynamic model. The model was driven by an offshore wave boundary based on wave conditions from the Gippsland WRB.

A.1.4 Model Calibration and Validation

A.1.4.1 Introduction

Model calibration is the process of specifying model parameters so that the model reproduces observed data to a suitable level of accuracy. Model validation is used to confirm that the calibrated model continues to consistently represent the natural processes to the required level of accuracy, in periods other than the calibration period, without any additional adjustment to the model parameters. The calibration and validation processes provide confidence in the model results and are essential to ensure the accurate representation of hydrodynamics, waves and sediment transport.

This section provides details of the calibration and validation undertaken for the hydrodynamic, spectral wave and sediment transport (natural and dredge plume) models adopted as part of this assessment.

A.1.4.2 Calibration and Validation Standards

To demonstrate that the HD model is capable of accurately representing the natural hydrodynamic conditions the model performance has been assessed against a set of standard guideline calibration standards based on Evans (1993). For combined coastal and estuarine waters such as at Gippsland, the following performance criteria are applicable:

- Modelled water levels (WL) should be within 15 – 20% of the tidal range over a spring neap tidal cycle, or within ± 0.1 – 0.3 m;
- Timing of high water (HW) and low water (LW) should be within 15 – 25 minutes;
- Modelled peak current speeds at the time of Peak Flood (PF) and Peak Ebb (PE) should be within 10 – 20% of measured speeds over a spring neap tidal cycle, or within ± 0.2 m/s; and
- Modelled peak flow directions at PE and PF should be within 10 – 15 degrees of measured directions over a spring neap tidal cycle.

Additional statistics have been considered to further quantify the model performance. These include:

- Root Mean Square (RMS) difference should be within ± 0.1 – 0.3 m for WL and within ± 0.3 m/s for flow speed; and
- Phasing difference should be within 15-25 minutes.

These additional statistics consider the model performance throughout the full tidal period and not just at the time of peaks. This can be particularly relevant in areas where the tidal signal departs significantly from the typical sinusoidal shape, such as occurs in the Gippsland region.

These standards provide a good basis for assessing model performance, but experience has shown that sometimes they can be too prescriptive and it is also necessary for visual checks to be undertaken. Under certain conditions, models can meet statistical calibration standards but appear to perform poorly. Conversely, seemingly accurate models can fall short of the guidelines. Consequently, a combination of both statistical calibration standards and visual checks has been used to ensure that the model can simulate the hydrodynamics.

To demonstrate that the SW model is capable of simulating the wave conditions, qualitative comparisons of measured and modelled wave height, wave period and wave direction have been undertaken. In addition, the correlation between modelled and measured wave heights has been calculated along with percentile wave height calculations.

A.1.4.3. Hydrodynamic Model

To ensure that the hydrodynamic model accurately represents the natural conditions within the study area, measured water levels and currents (speed and direction) have been compared against modelled predictions. The location of available data (referred to as calibration data) are shown in Figure A4.

Figure A4. Location of calibration data.

Modelled water levels and currents have been compared with the calibration data for the following periods:

- calibration period: a 15 day spring-neap cycle between 3rd October 2020 and 18th October 2020, when bathymetric conditions are representative of the current dredge design; and
- validation period: a 15 day spring-neap cycle between 3rd September 2017 and 18th September 2017, when bathymetric conditions are representative of a period of sustained natural sedimentation (i.e. a natural bar configuration).

A.1.4.4 Water Levels

Water level data are collected at the Lakes Entrance (Entrance Channel on Figure A4) and Bullock Island tide gauges by GP. Time series of measured and modelled water levels at Lakes Entrance and Bullock Island are shown in Figure A5 and Figure A6 for the calibration and validation period, respectively.

The plots demonstrate the complexity of the tidal signature in the study region with alternating periods of large semi-diurnal and small semi-diurnal tidal variations.

The time series plots demonstrate that overall, the model replicates the measured variations in water levels that occur, capturing the magnitude and timing of peak (HW and LW) levels as well as the complex shape of the tidal curve. During the calibration period the model has a slight tendency to under-predict the HW on some tides.

PCS (2021) noted that the measured tides at Bullock Island lag those at Lakes Entrance by approximately 5 minutes and have a tidal range of approximately 75% of the range at the Entrance, mainly as a result of the low water being elevated. A statistical comparison of modelled water levels at the two sites during the calibration and validation periods indicates that the model replicates these changes in tide between the two sites with the modelled tide at Bullock Island lagging that at Lakes Entrance by 8 minutes and with a tidal range of 65% of the range at the Entrance due to an increase in LW level. This provides confidence that the model is replicating the discharge into and out of the Entrance.

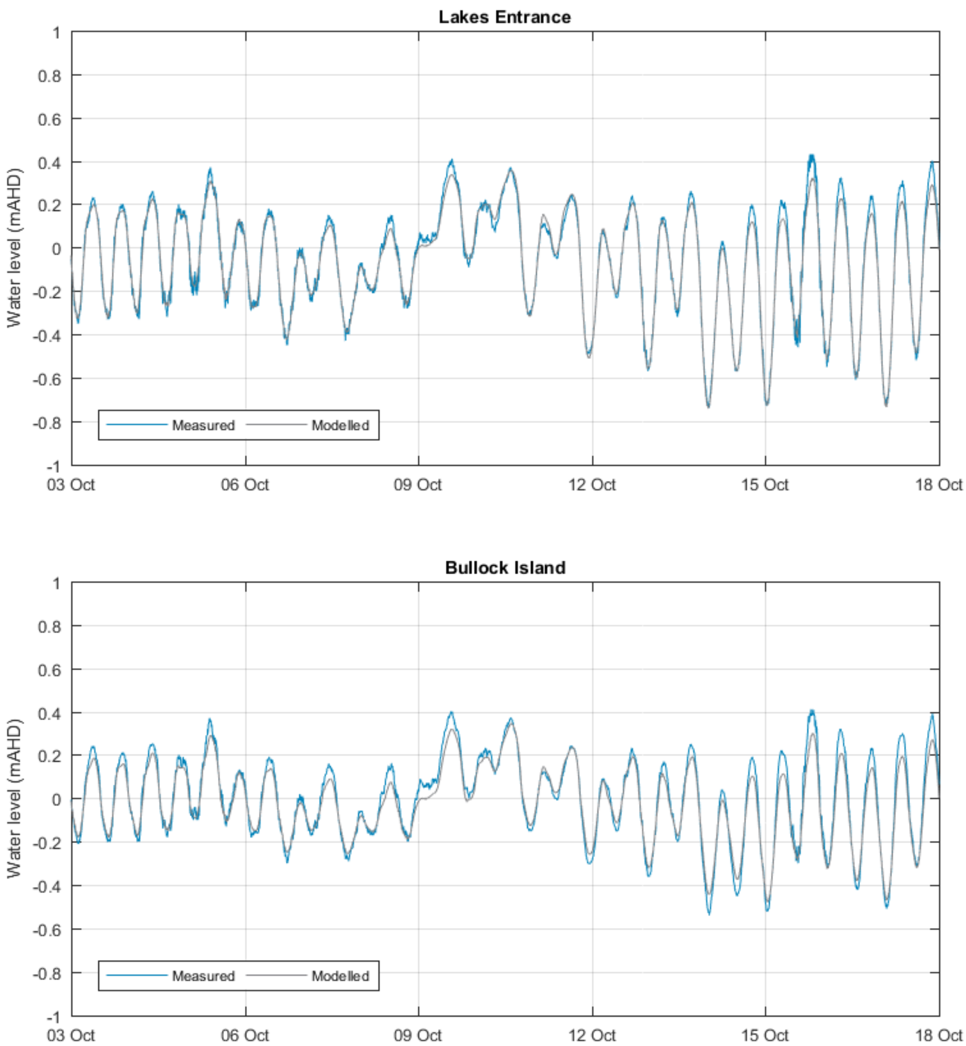

Figure A5. Modelled and measured water levels during the calibration period.

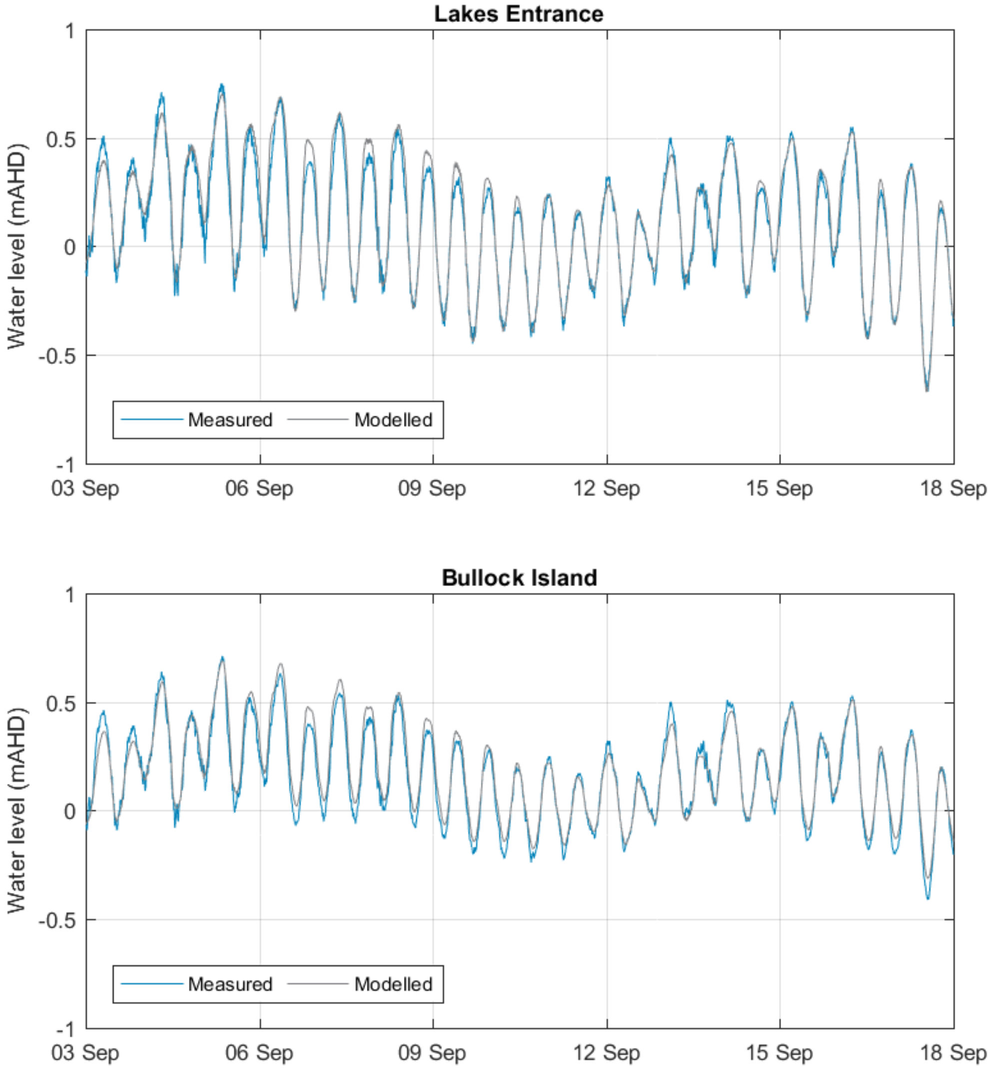

Figure A6. Modelled and measured water levels during the validation period.

To further assess the level of calibration achieved (and to ensure that the model performs within the calibration standards set out in Section A.1.4.2), a statistical analysis was undertaken to quantify the difference in elevation and timing between the modelled and measured water levels. The results of the statistical analysis are presented in Table A1. The table shows that the guideline standards are achieved for all statistics at both sites during both the calibration and validation periods.

Table A1. Statistics for comparison of modelled and measured water levels during the calibration and validation periods.

Site	WL difference (m)			WL difference (%)		Phase difference (minutes)		
	HW	LW	RMS	HW	LW	HW	LW	All
Current Dredge Design (calibration period)								
Lakes Entrance	-0.04	0.01	0.03	-7	2	9	4	1
Bullock Island	-0.05	0.02	0.04	-12	5	8	1	2
No Bar (validation period)								
Lakes Entrance	0.01	0.03	0.05	2	5	-7	3	1
Bullock Island	0	0.05	0.05	0	11	5	11	5
Notes: Differences are modelled minus predicted/measured so that positive values indicate that the model value is high/late relative to predicted/measured *Values in **blue** are above the calibration standard*								

A.1.4.5 Currents

Time series plots of the measured and modelled current speed and direction at the Lakes Entrance monitoring site are shown in Figure A7 and Figure A8 for the calibration and validation periods, respectively. The plots show that the model replicates the peaks in flows and the timing of the flow speed changes for the majority of tides. Furthermore, the model replicated the prolonged period of northward flows on the 9th of October (during the calibration period) and provides a reasonable representation of the flow alignment.

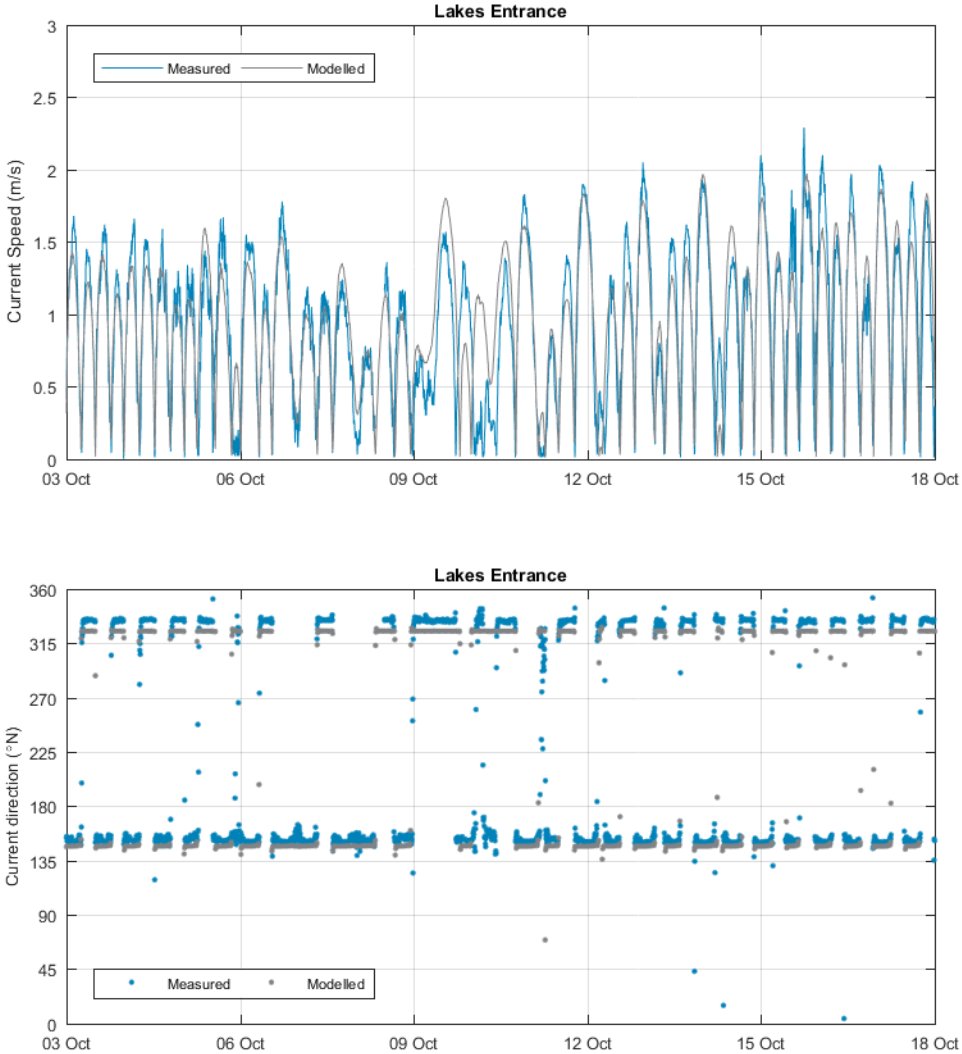

Figure A7. Modelled and measured currents at Lakes Entrance during the model calibration period.

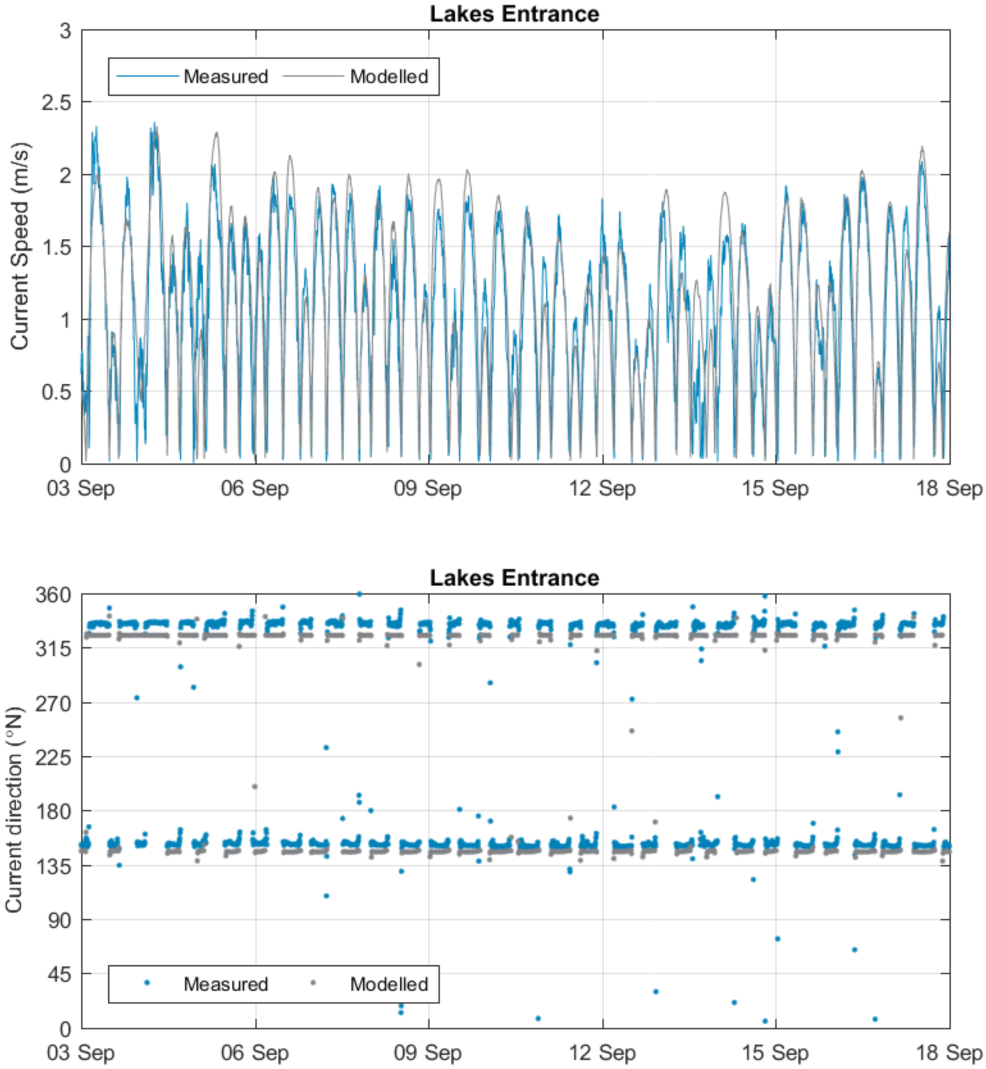

Figure A8. Modelled and measured flows at Lakes Entrance during the model validation period.

To further assess the level of calibration achieved (and to ensure that the model performs within the calibration standards set out in Section A.1.4.2), a statistical analysis was undertaken to quantify the difference in magnitude and phasing between the modelled and measured current speeds and directions. The results of the statistical analysis are presented in Table A2. The table shows that the guideline standards are achieved for all statistics during both the calibration and validation periods. The RMS error for the current speed during both periods is close to the guideline standard of 0.3 m/s, but comparison between the measured and modelled data shown in Figure A7 and Figure A8 gives confidence that the model is providing a good representation of the current speed and the high RMS is likely to be related to the natural variability in the current speeds and the fast flows.

Table A2. Statistics for comparison of modelled and measured currents during the calibration and validation periods.

Site	Speed difference (m/s)			Speed difference (%)		Direction difference (°)		Phase difference (minutes)
	PF	PE	RMS	PF	PE	PF	PE	All
Current Dredge Design (calibration period)								
Lakes Entrance	-0.01	-0.19	0.27	0	-9	-8	-4	-3
No Bar (validation period)								
Lakes Entrance	-0.04	-0.05	0.29	-2	-3	-10	-6	-2

Notes: Differences are modelled minus predicted/measured so that positive values indicate that the model value is high/late relative to predicted/measured

Values in bold are above the calibration standard

A.1.4.6. Wave Model

The wave model was set up to replicate the wave conditions at the Lakes Entrance Waverider Buoy (WRB) between January 2020 and January 2021. This year was selected as a period when both the wave energy from the south-east and the wave energy from the south-west were broadly representative of the long term mean conditions and as a period of high data return.

The model was also run for a large storm event from the east south-east (ESE) that occurred in May 2018, which was equivalent to a 1 in 10 year storm event to verify that it could accurately replicate more extreme storm conditions.

Time series plots of H_s, peak wave period (T_p) and mean wave direction are shown over 2020 in Figure A9. Further, a comparison of the modelled and measured wave conditions for a large storm event is shown in Figure A10. The plots show that the model provides a good representation of the measured wave height, period and direction at the WRB site throughout the model simulation periods, accurately replicating both typical and extreme conditions.

A quantitative assessment of the model calibration at the WRB site is provided in Table A3, with percentile statistics presented for both measured and modelled H_s for the 2020 run period. The statistics confirm that the modelled waves agree well with the measured data (to within 0.1 m or less). The correlation between the modelled and measured waves is also shown as a scatter plot in Figure A11 to Figure A12. The correlation coefficient (r^2) is 0.99 indicating a very good agreement between modelled and measured waves at the WRB. All plots and statistics presented confirm that the model accurately represents the wave conditions at the Lakes Entrance WRB for both typical and extreme wave conditions.

Table A3. Statistics for comparison of modelled and measured H_s for the 2020 model simulation

Percentile	Modelled H_s (m)	Measured H_s (m)
5th	0.49	0.55
10th	0.53	0.60
20th	0.64	0.69
50th	0.99	1.03
80th	1.54	1.55
90th	1.84	1.82
95th	2.07	2.09
99th	2.51	2.53

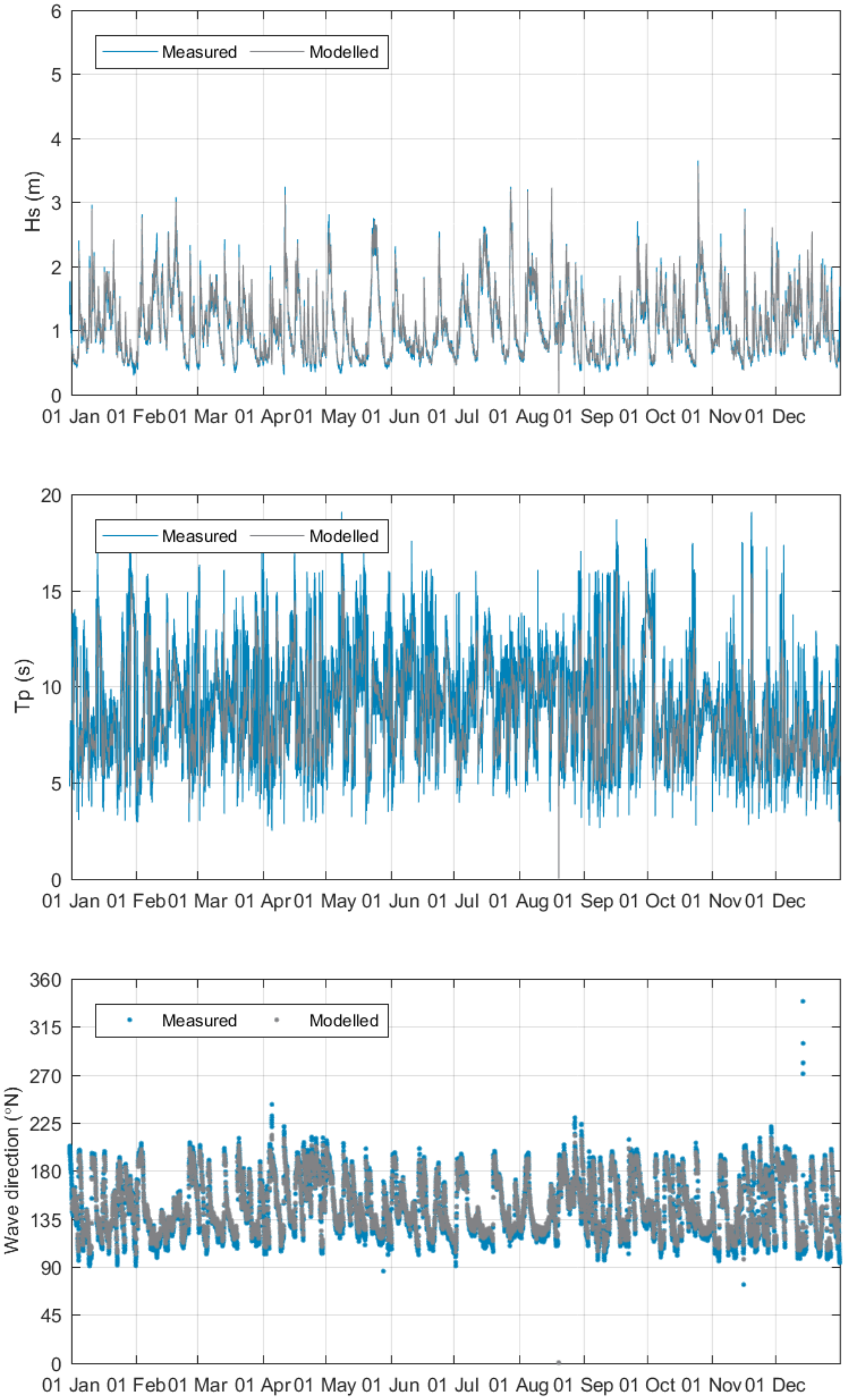

Figure A9. Time series of modelled and measured waves for the 2020 simulation showing H_s (upper), peak period (middle) and direction (lower).

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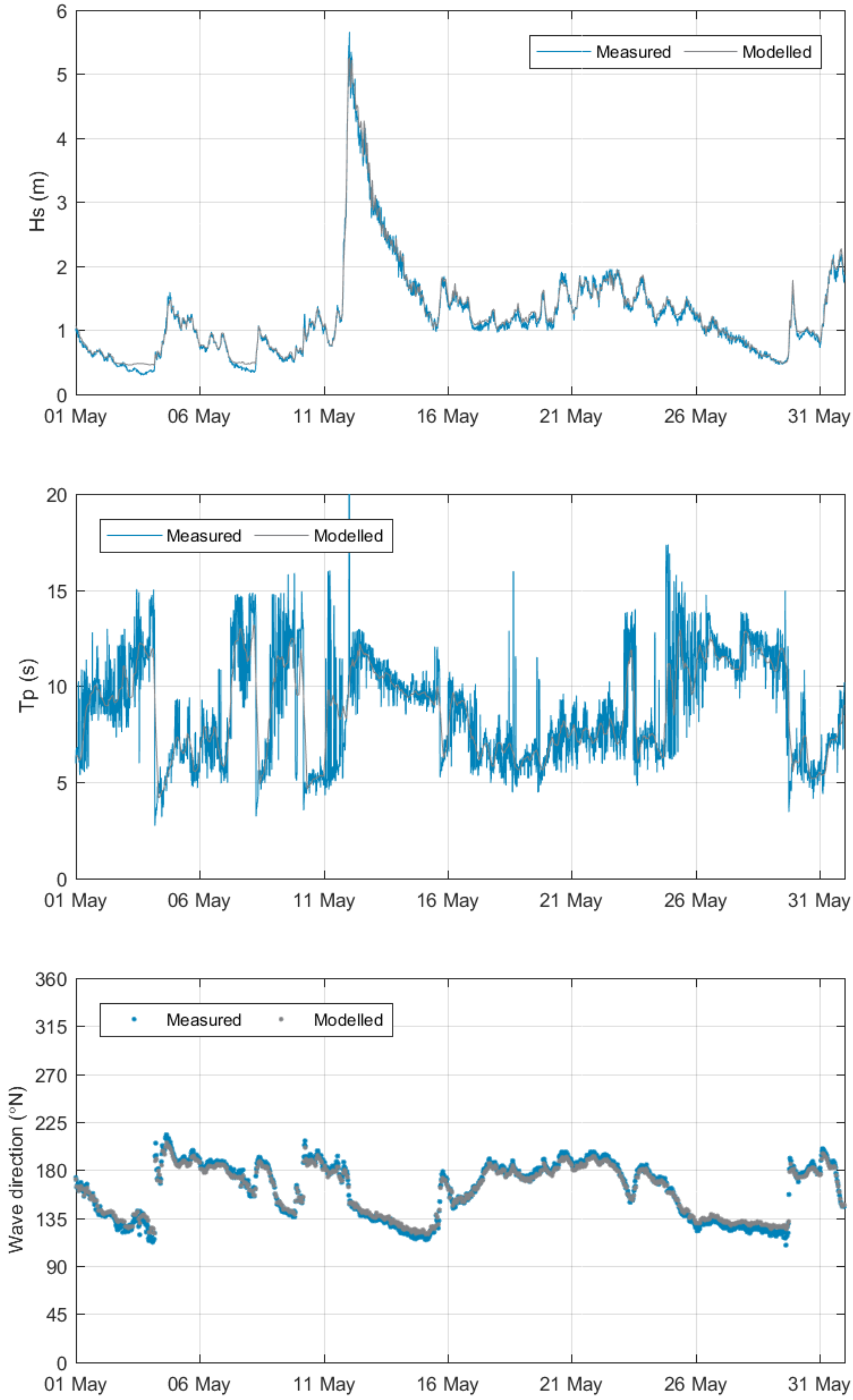

Figure A10. Time series of modelled and measured waves for a large storm showing H_s (upper), peak period (middle) and direction (lower).

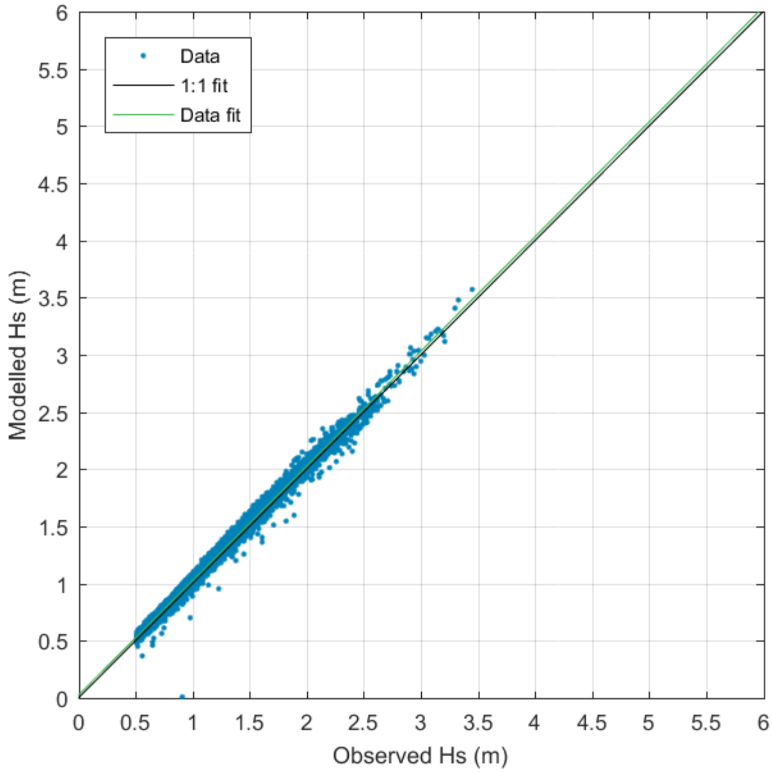

Figure A11. Comparison of modelled and measured H_s at the Lakes Entrance WRB in 2020.

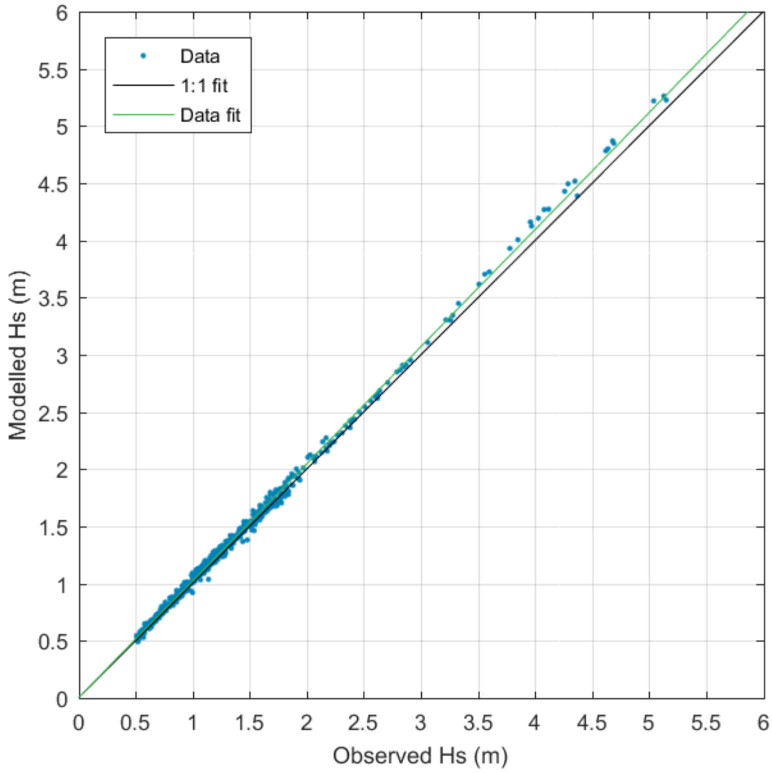

Figure A12. Comparison of modelled and measured H_s at the Lakes Entrance WRB during a large storm.

A.1.5. References

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Appendix B – Hydrodynamic Model Results

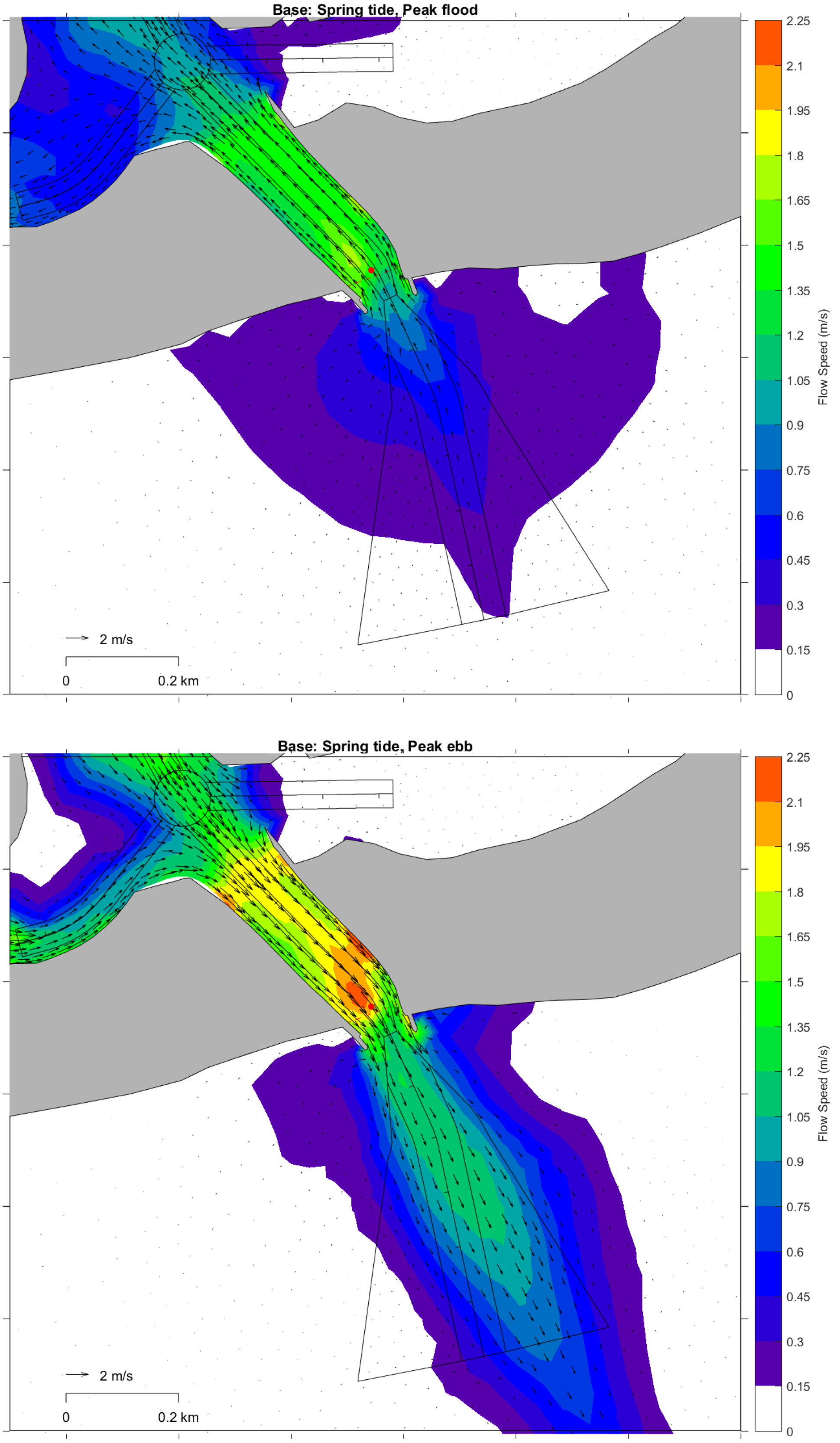


Figure B1. Current speed and vectors at the peak flood (top) and ebb (bottom) stages of the tide for the Base case.

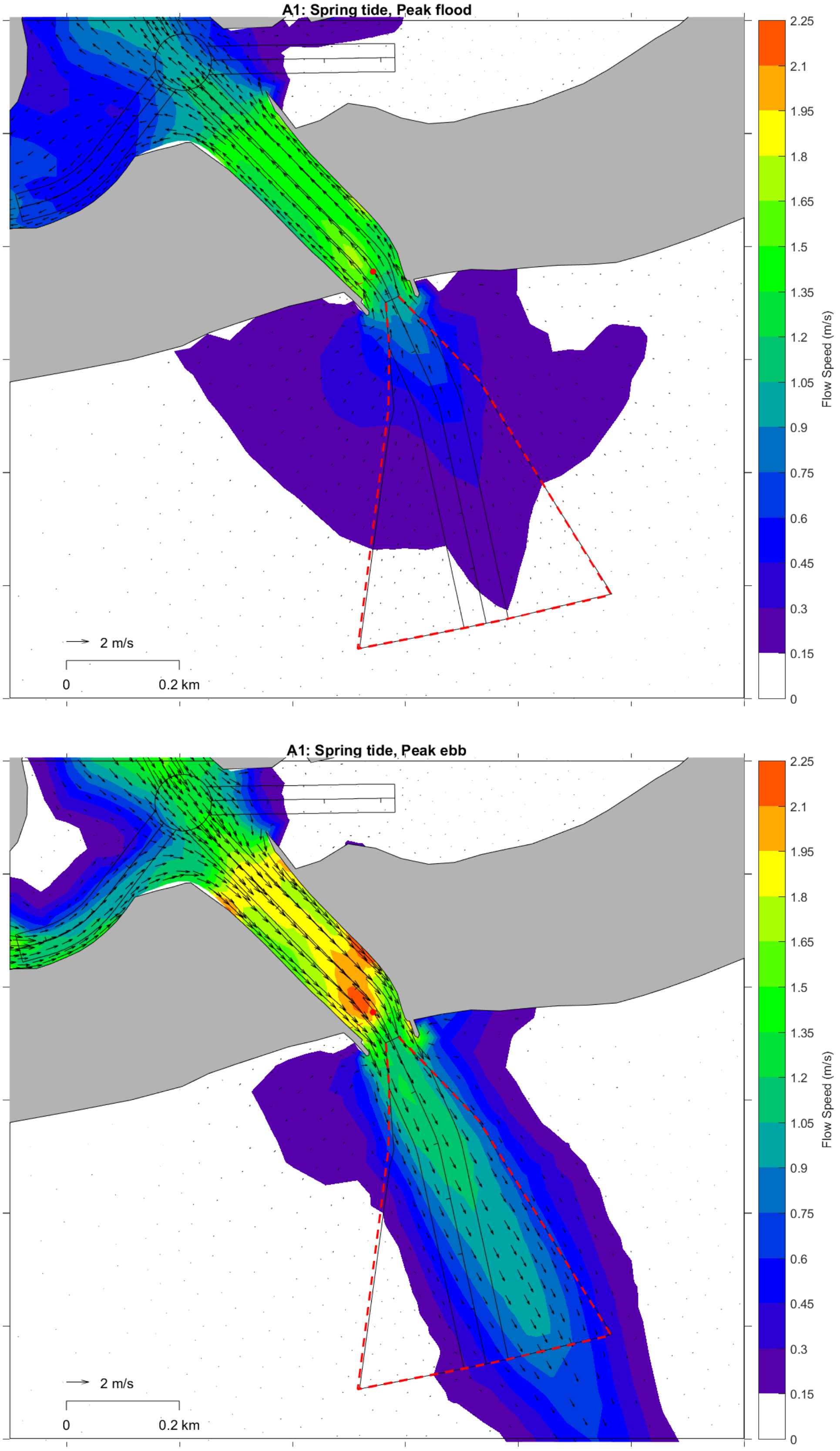


Figure B2. Current speed and vectors at the peak flood (top) and ebb (bottom) stages of the tide for Option A1.

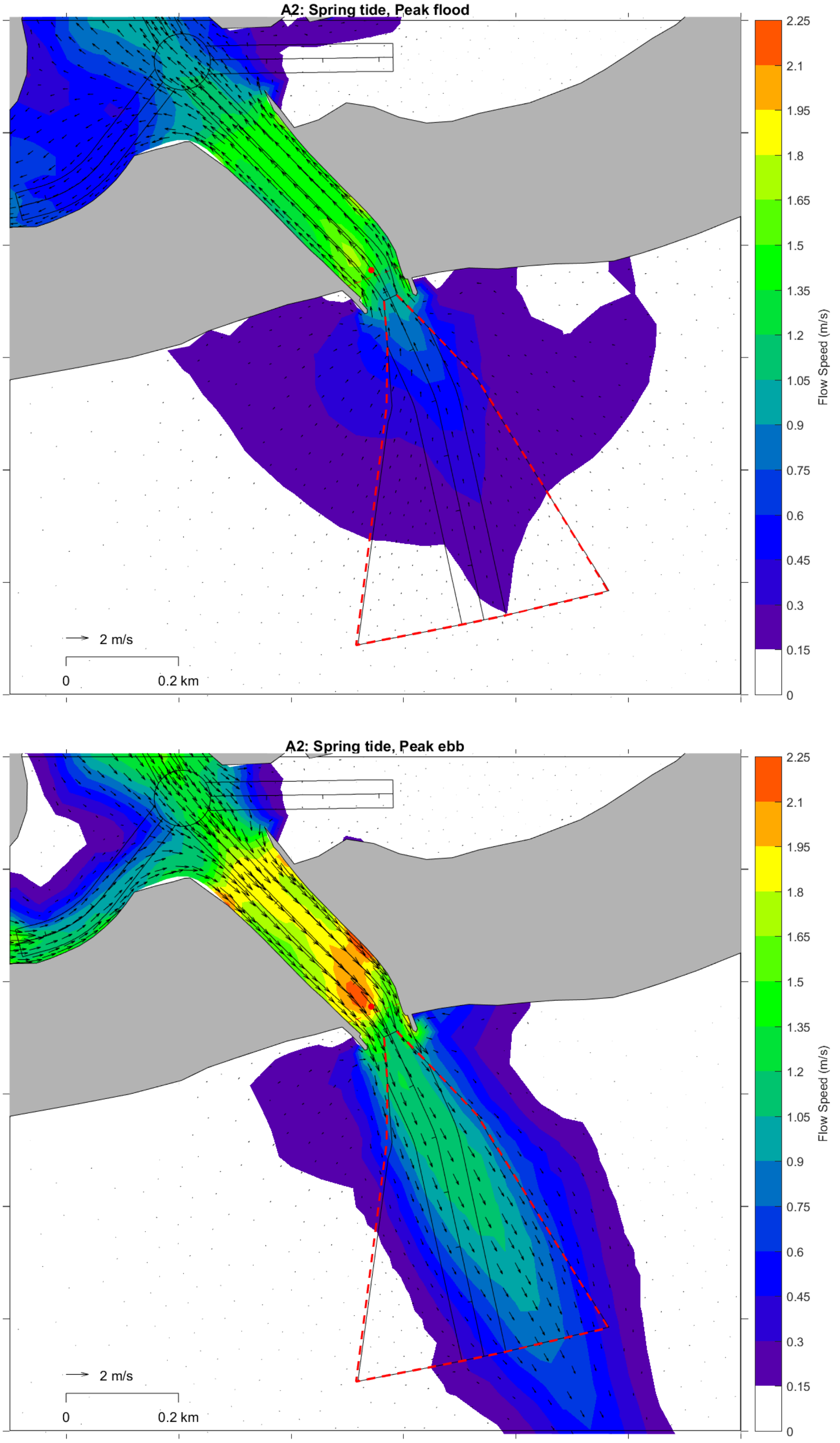


Figure B3. Current speed and vectors at the peak flood (top) and ebb (bottom) stages of the tide for Option A2.

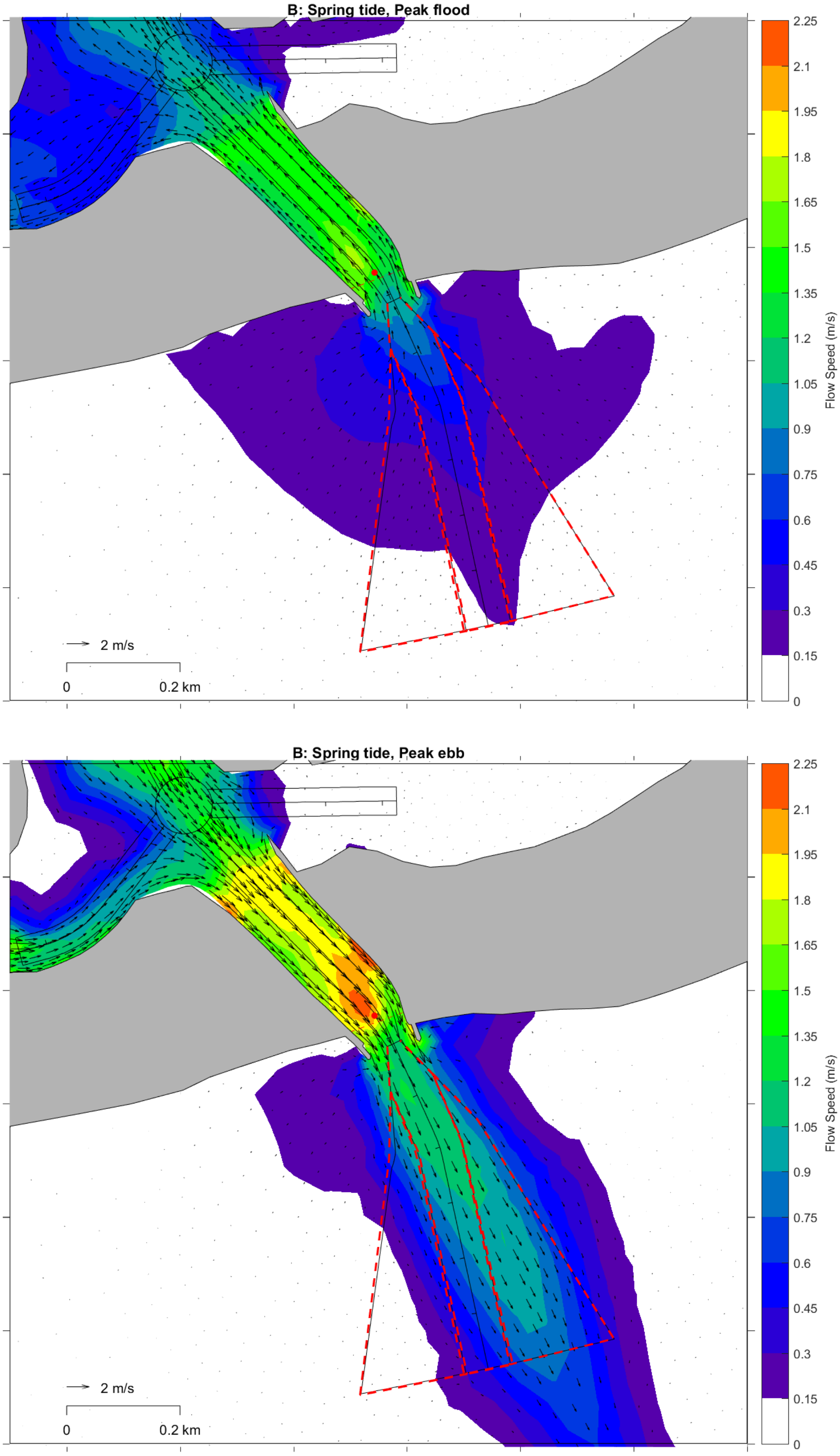


Figure B4. Current speed and vectors at the peak flood (top) and ebb (bottom) stages of the tide for Option B.

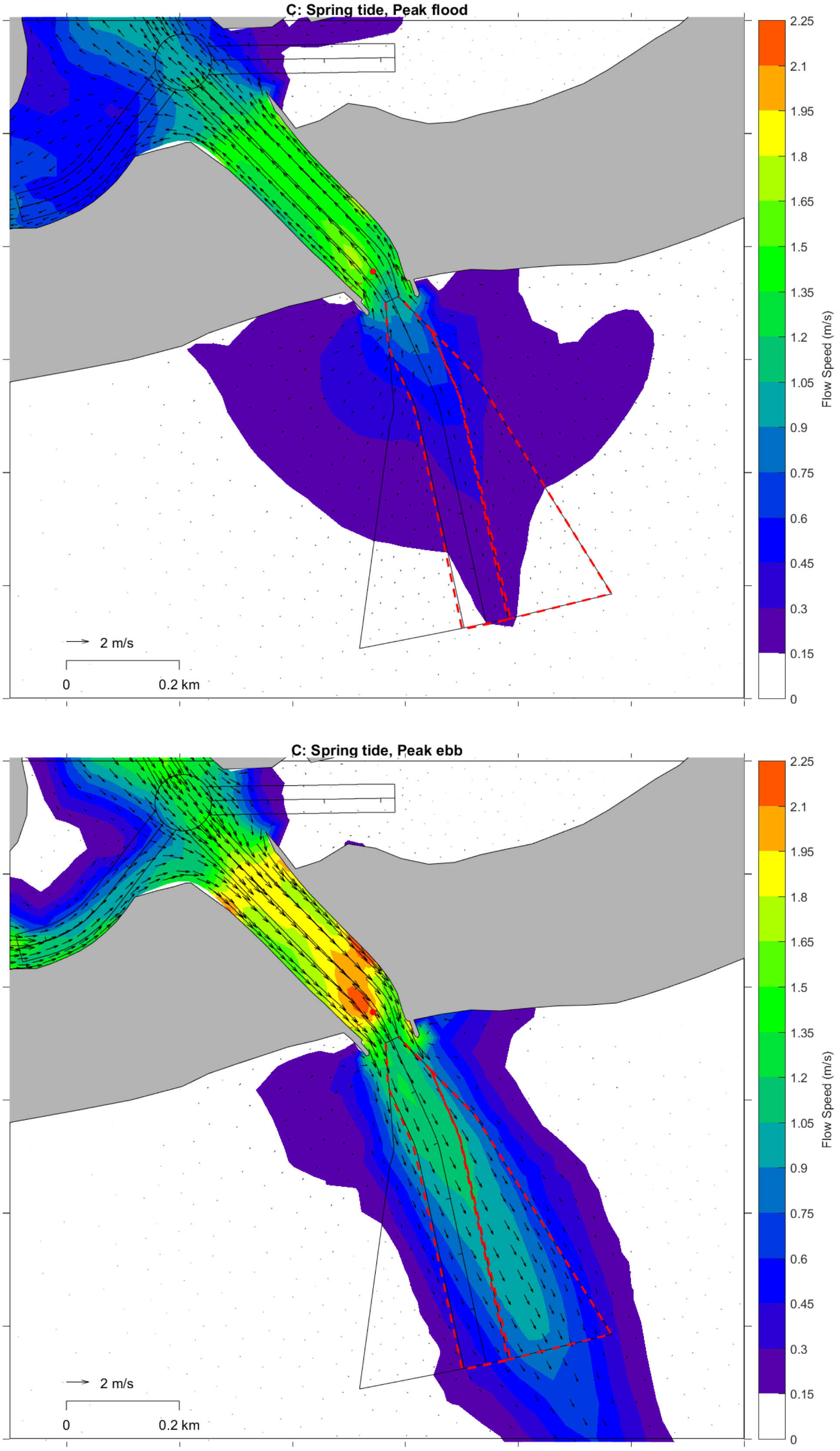


Figure B5. Current speed and vectors at the peak flood (top) and ebb (bottom) stages of the tide for Option C.

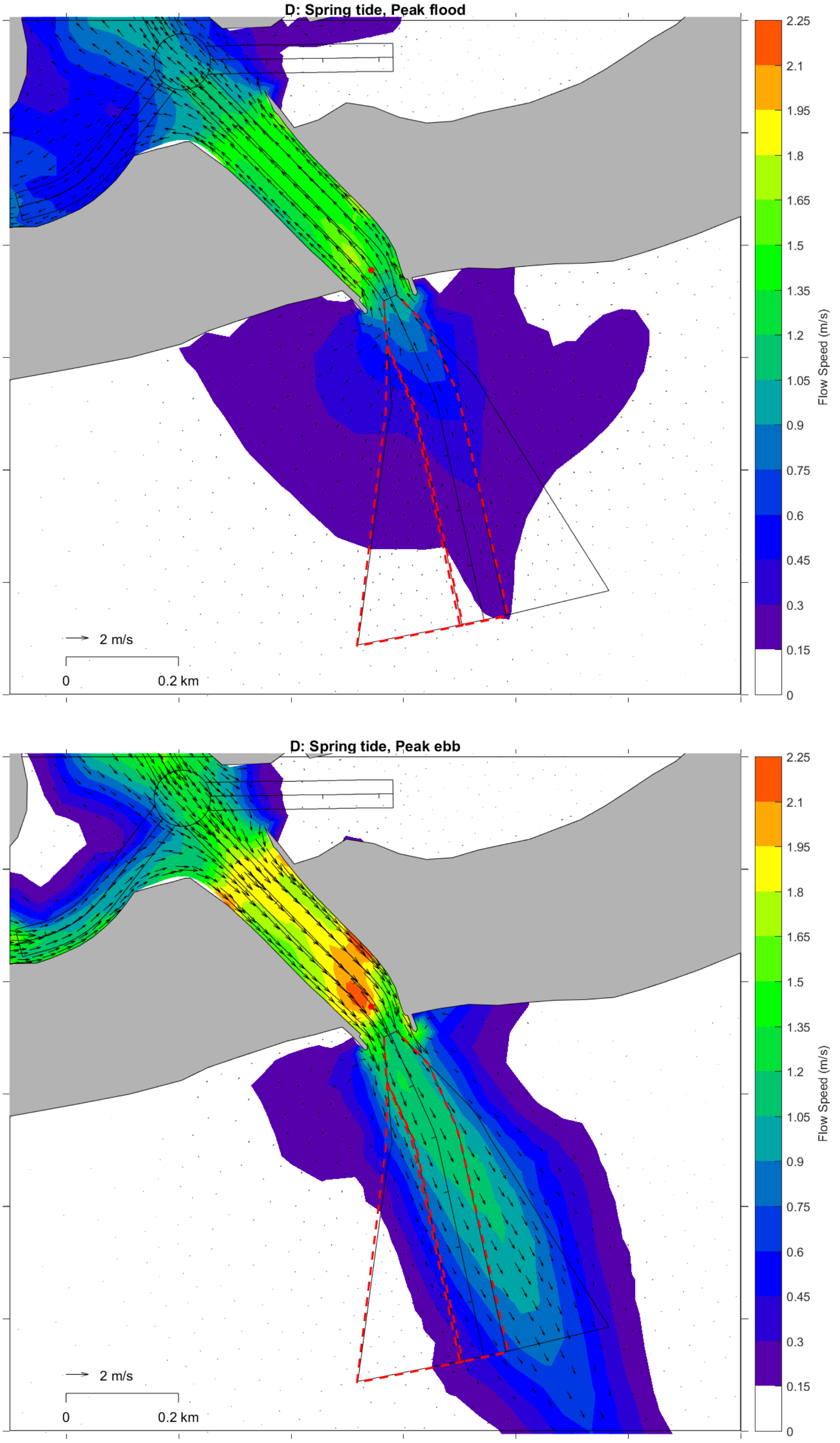


Figure B6. Current speed and vectors at the peak flood (top) and ebb (bottom) stages of the tide for Option D.

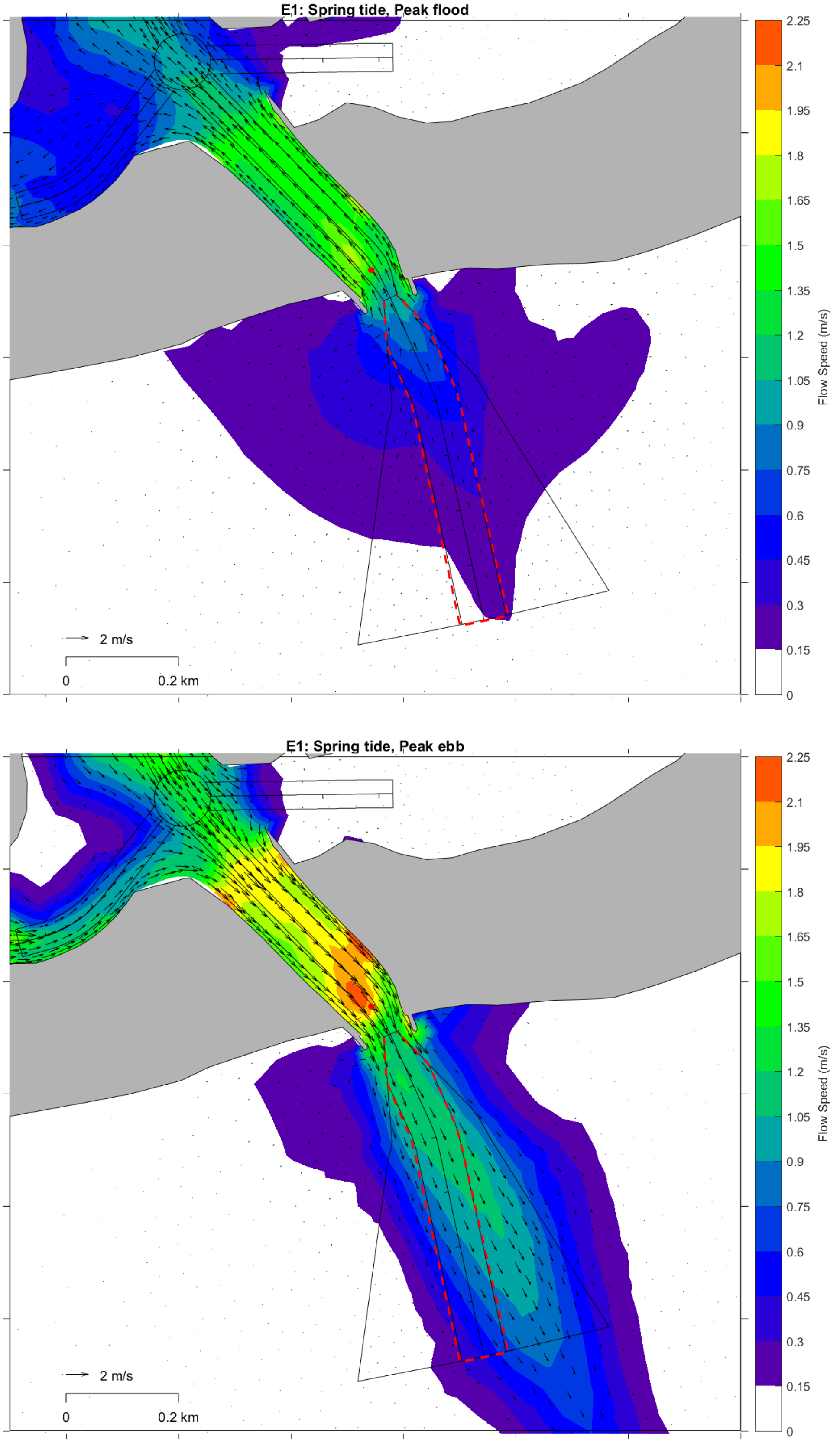


Figure B7. Current speed and vectors at the peak flood (top) and ebb (bottom) stages of the tide for Option E1.

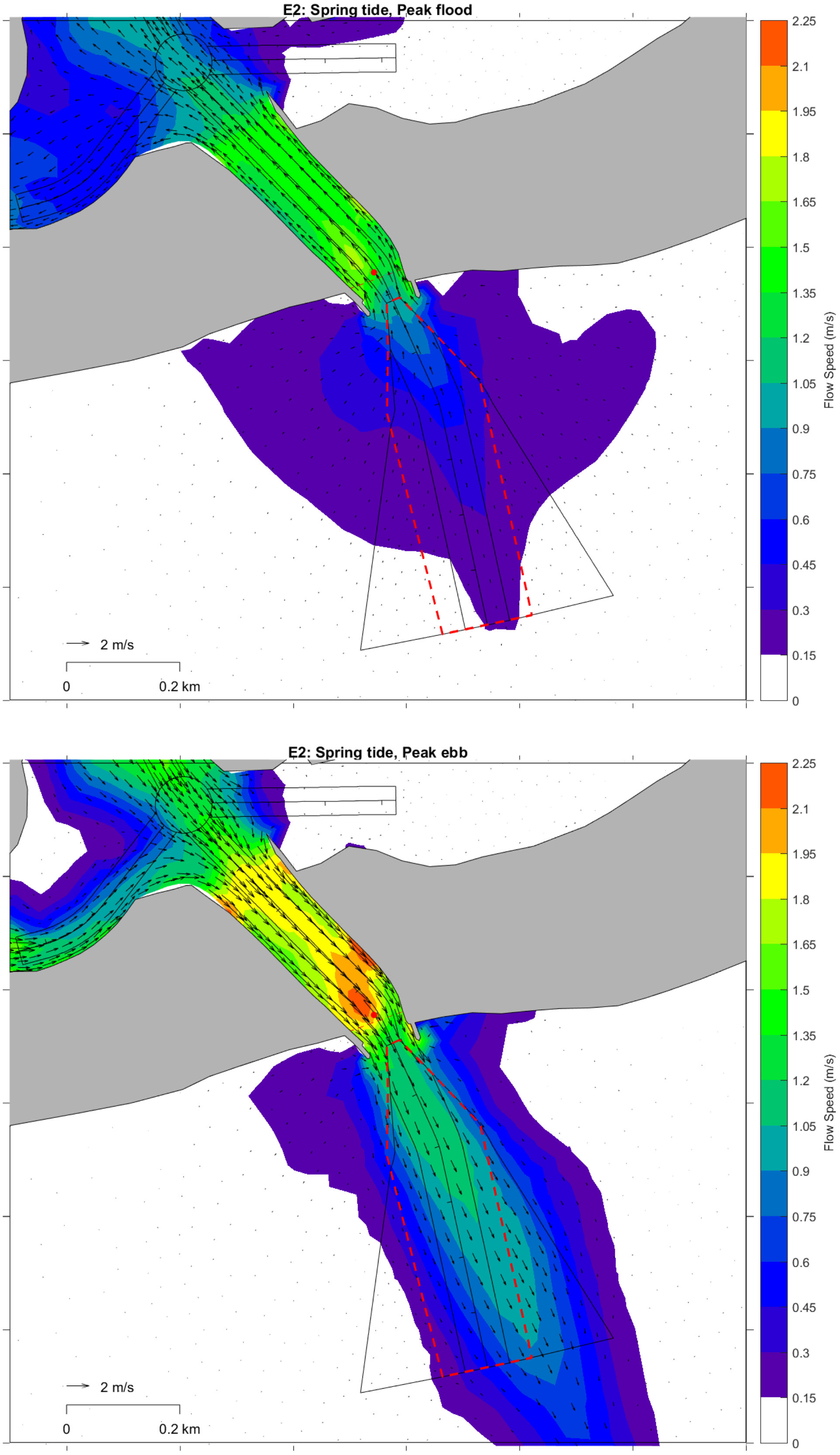


Figure B8. Current speed and vectors at the peak flood (top) and ebb (bottom) stages of the tide for Option E2.

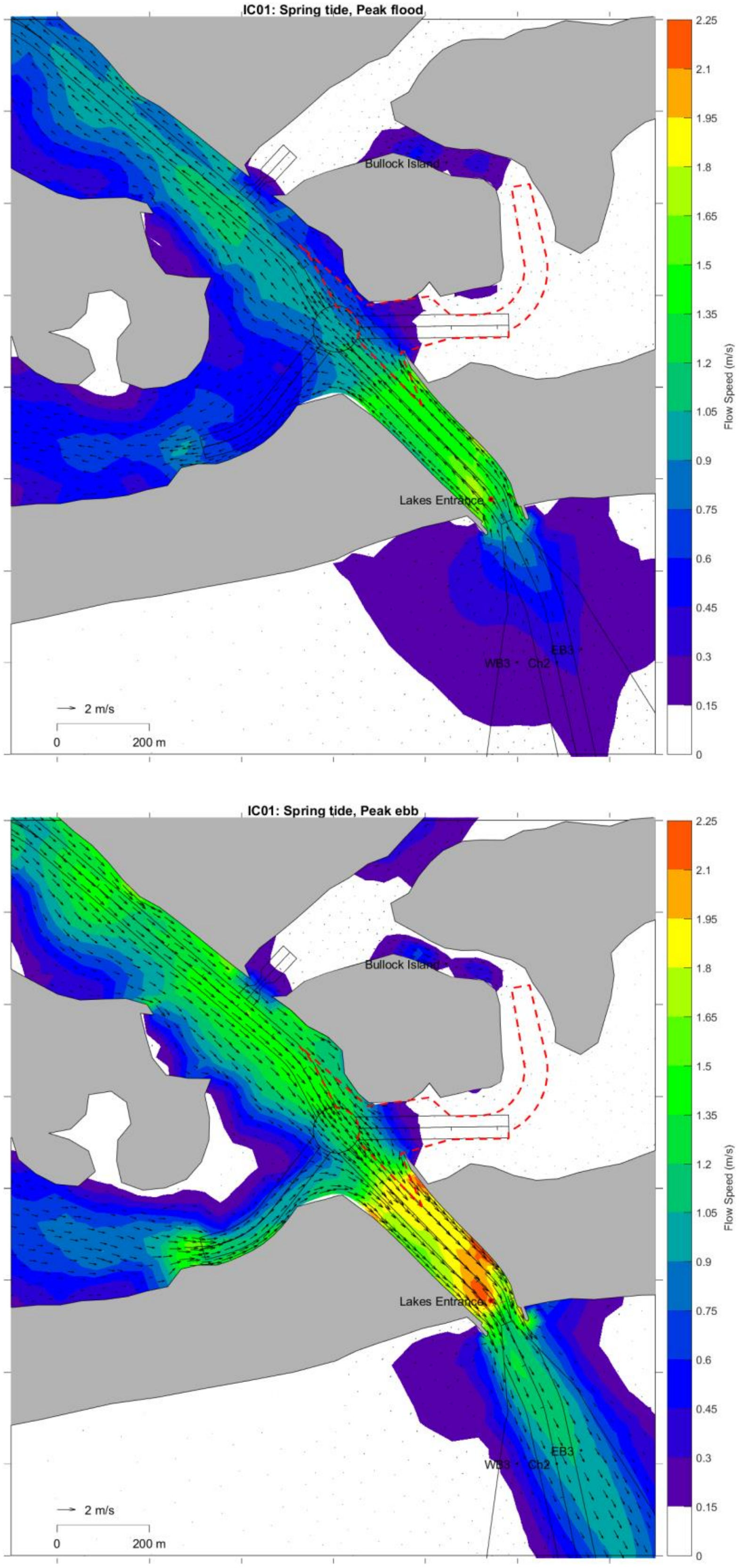
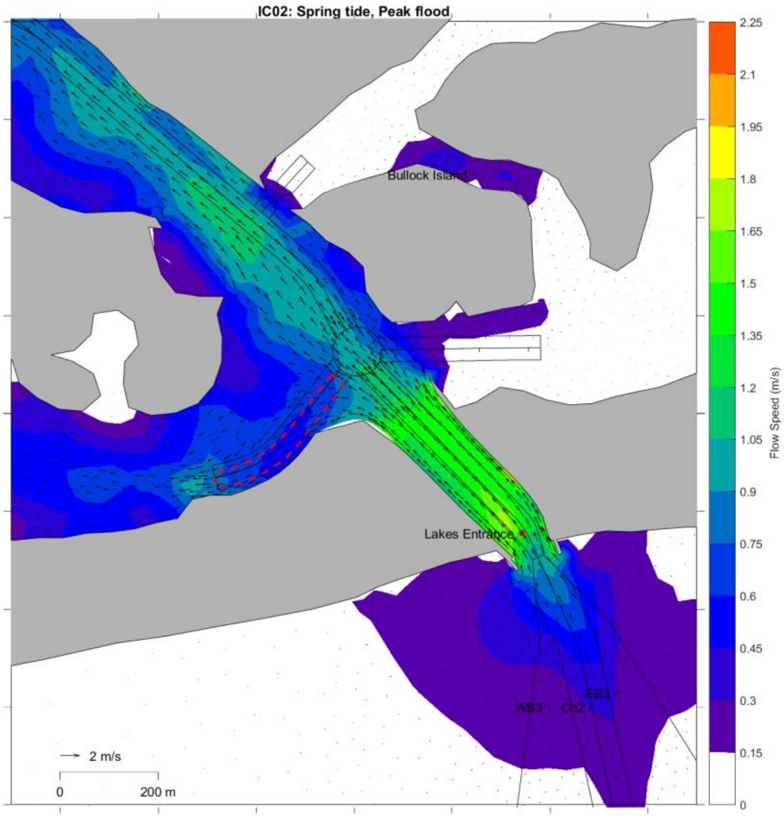


Figure B9. Current speed and vectors at the peak flood (top) and ebb (bottom) stages of the tide for Option IC01.



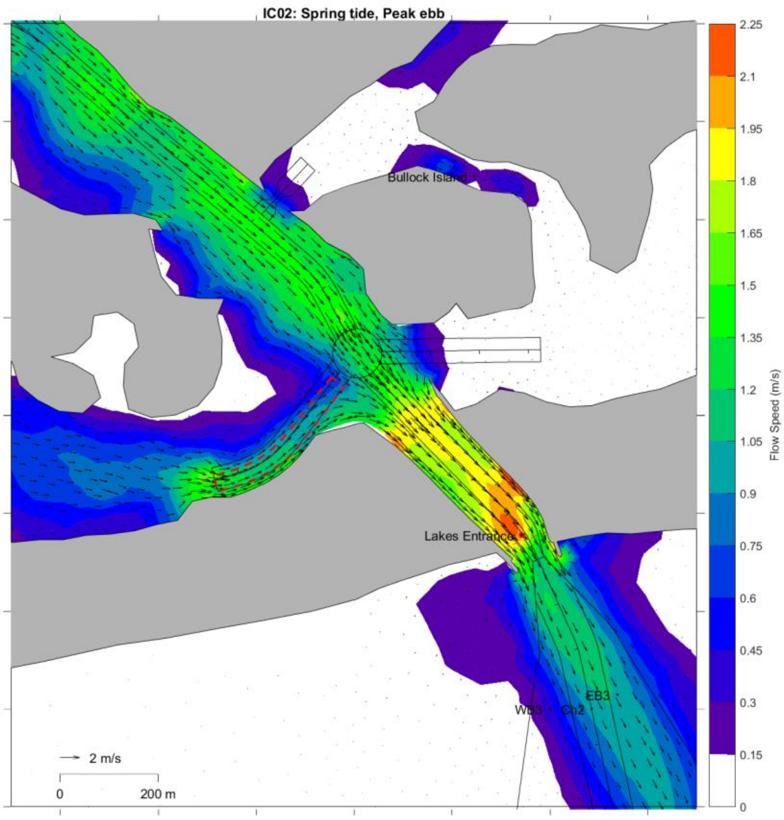


Figure B10. Current speed and vectors at the peak flood (top) and ebb (bottom) stages of the tide for Option IC02.

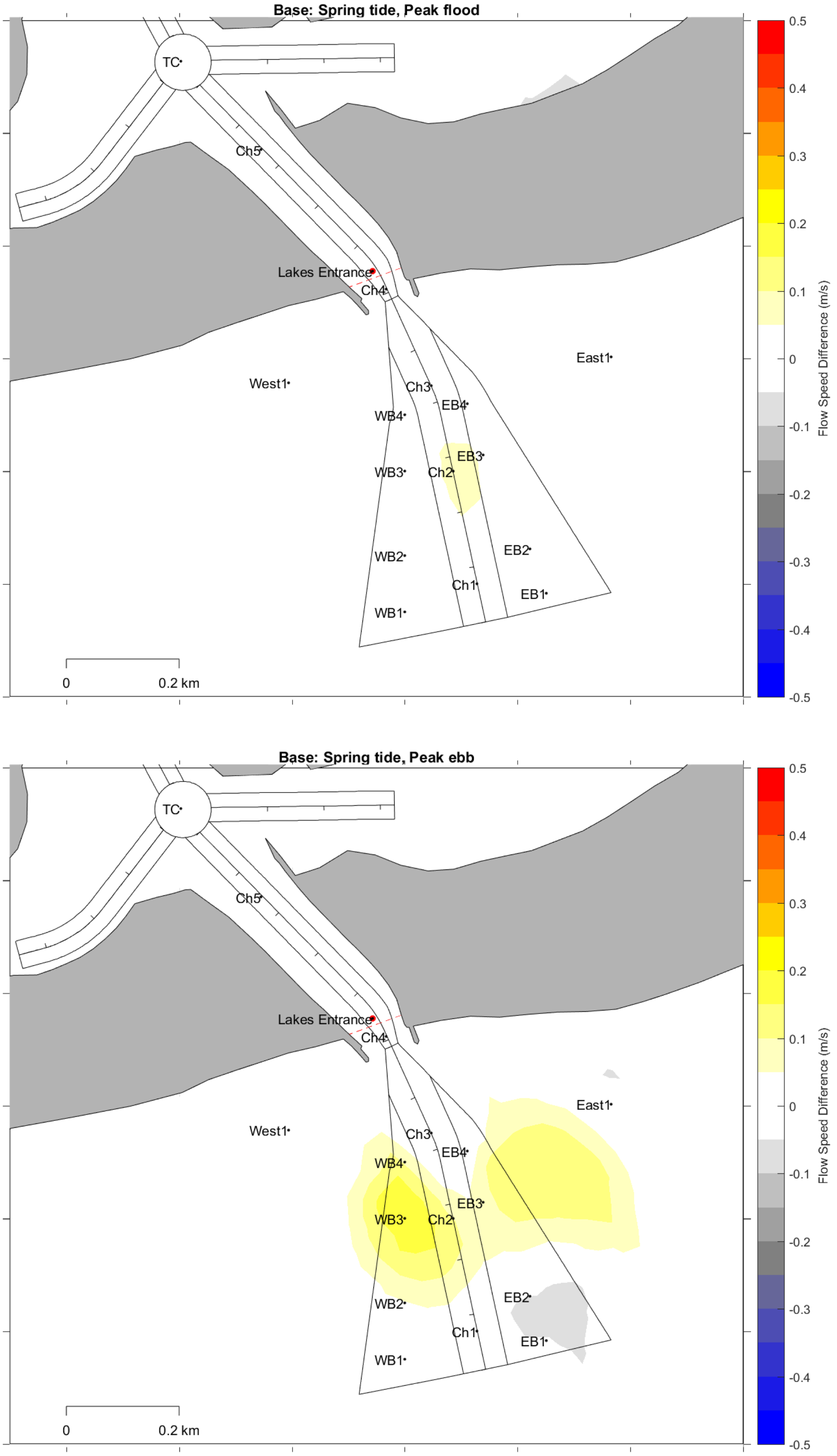
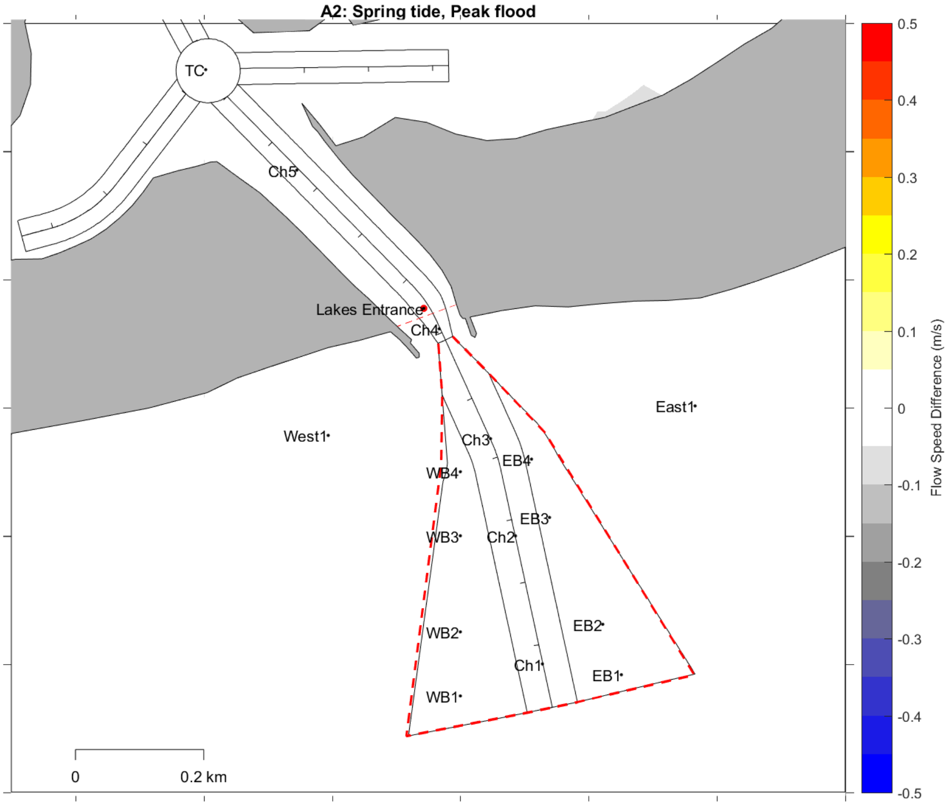


Figure B11. Difference in current speed between Option A1 and the base case at the peak flood (top) and ebb (bottom) stages of the tide.



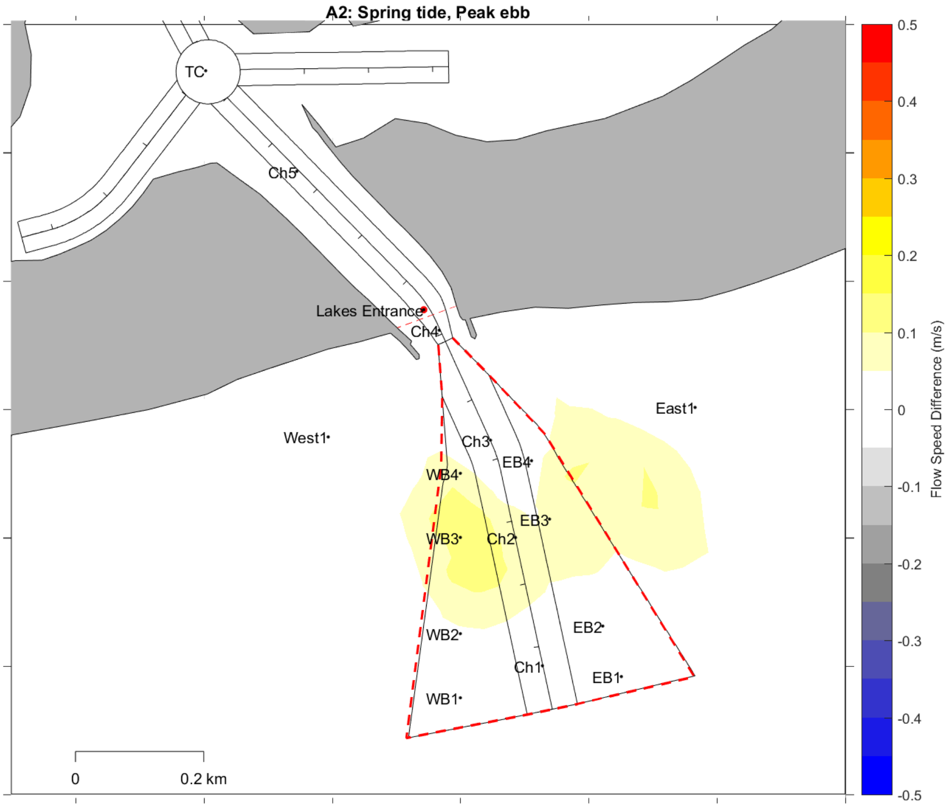
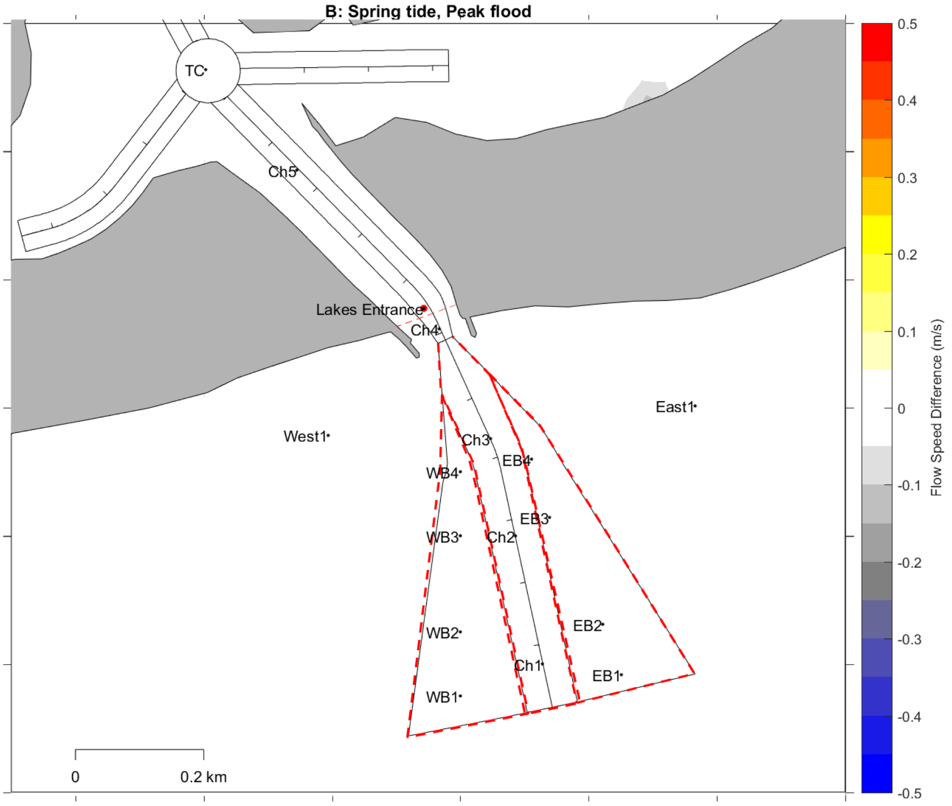


Figure B12. Difference in current speed between Options A1 and A2 at the peak flood (top) and ebb (bottom) stages of the tide.



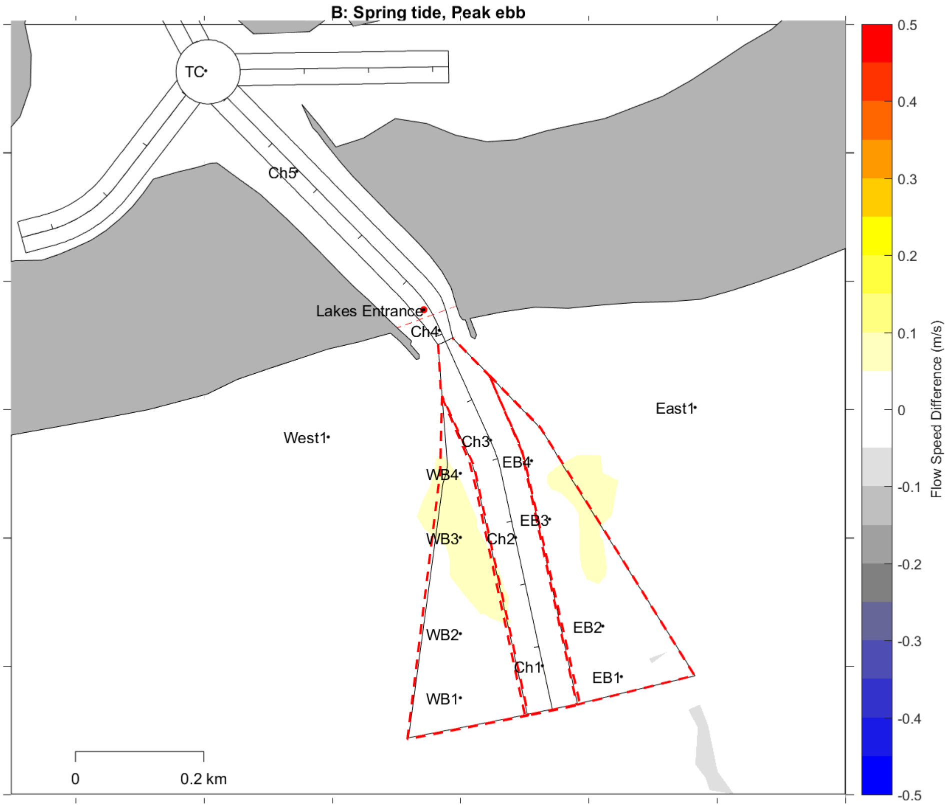


Figure B13. Difference in current speed between Options A1 and B at the peak flood (top) and ebb (bottom) stages of the tide.

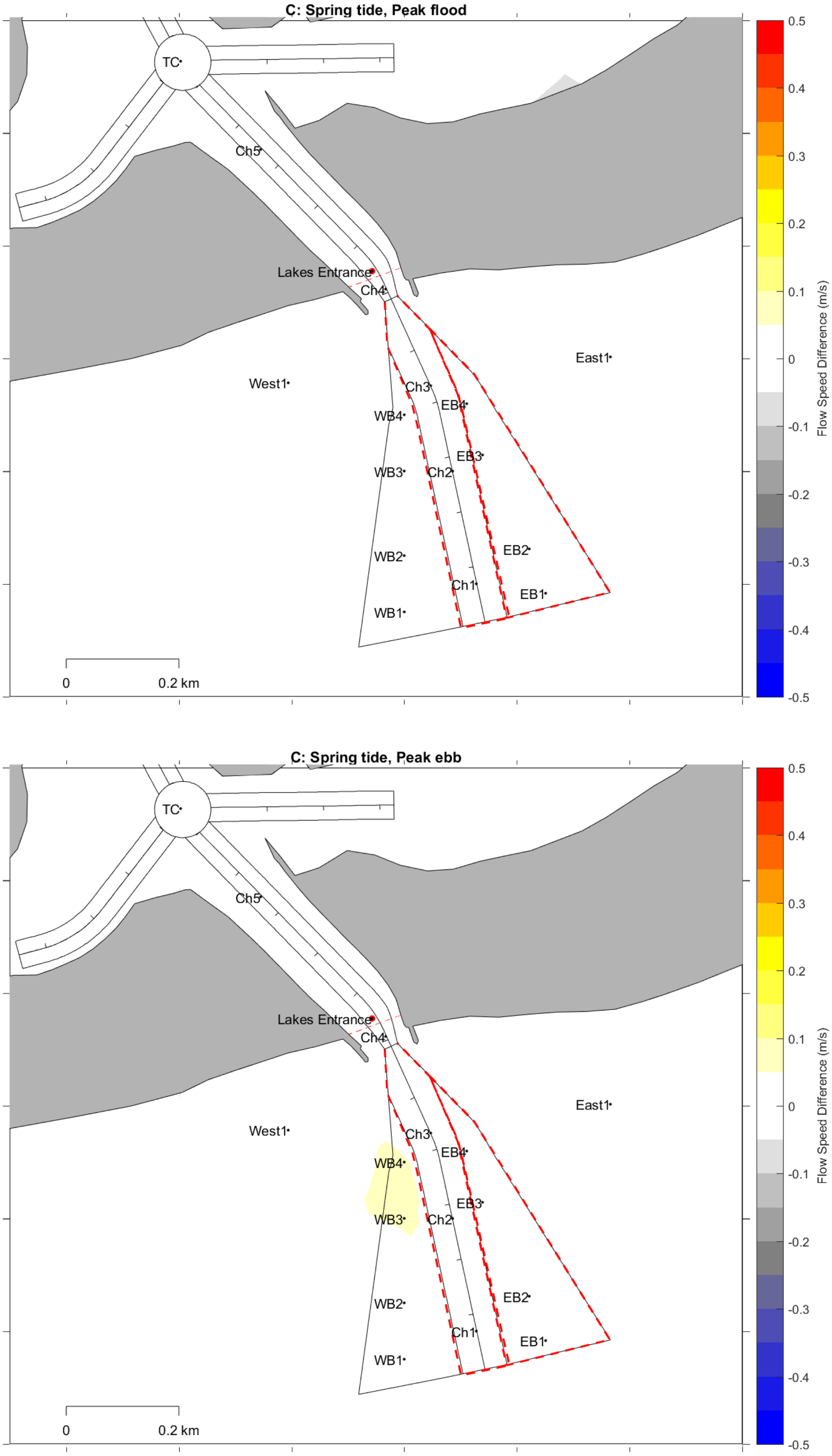


Figure B14. Difference in current speed between Options A1 and C at the peak flood (top) and ebb (bottom) stages of the tide.

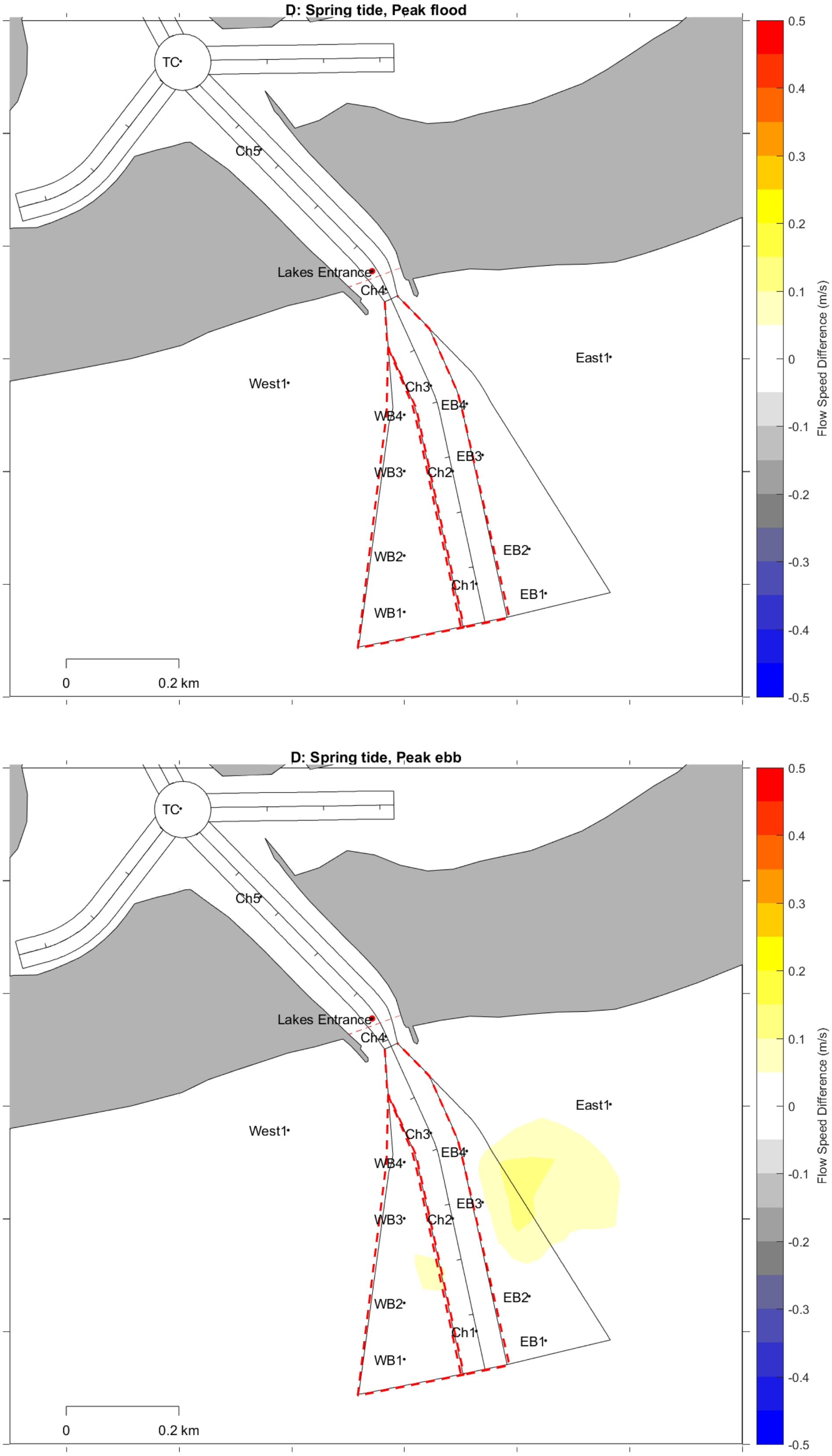
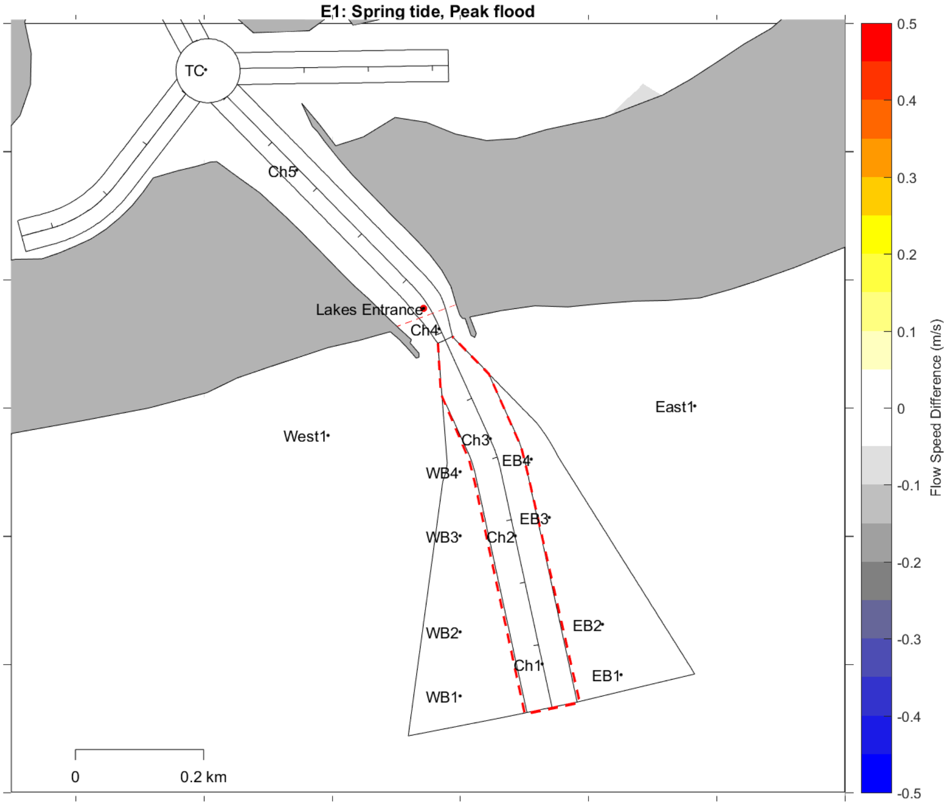


Figure B15. Difference in current speed between Options A1 and D at the peak flood (top) and ebb (bottom) stages of the tide.



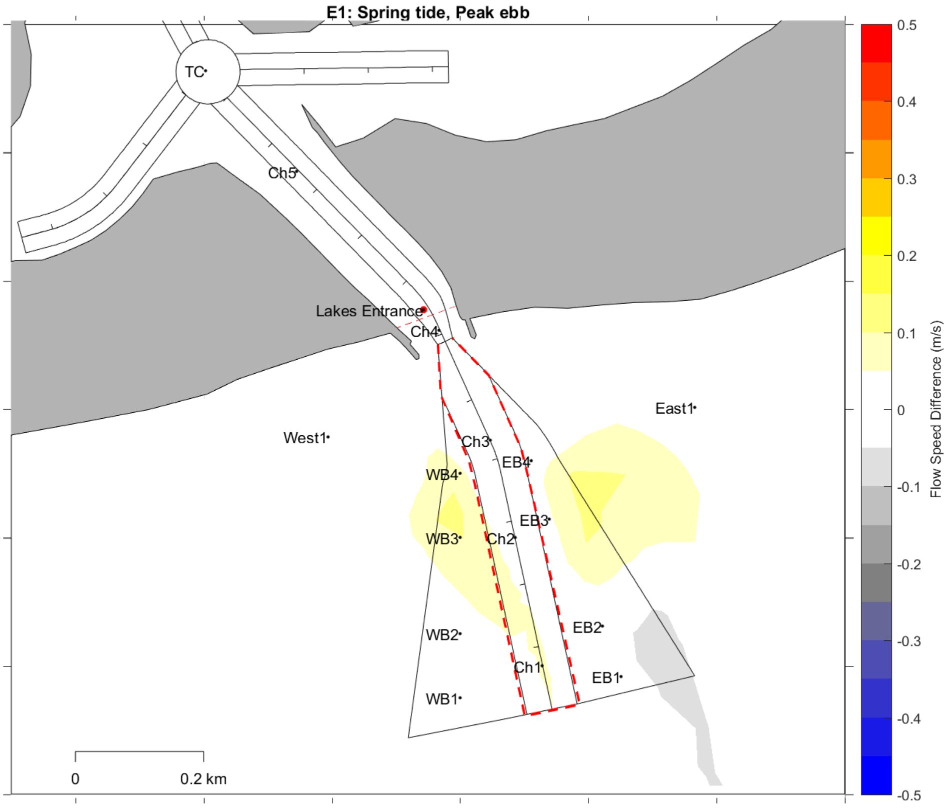


Figure B16. Difference in current speed between Options A1 and E1 at the peak flood (top) and ebb (bottom) stages of the tide.

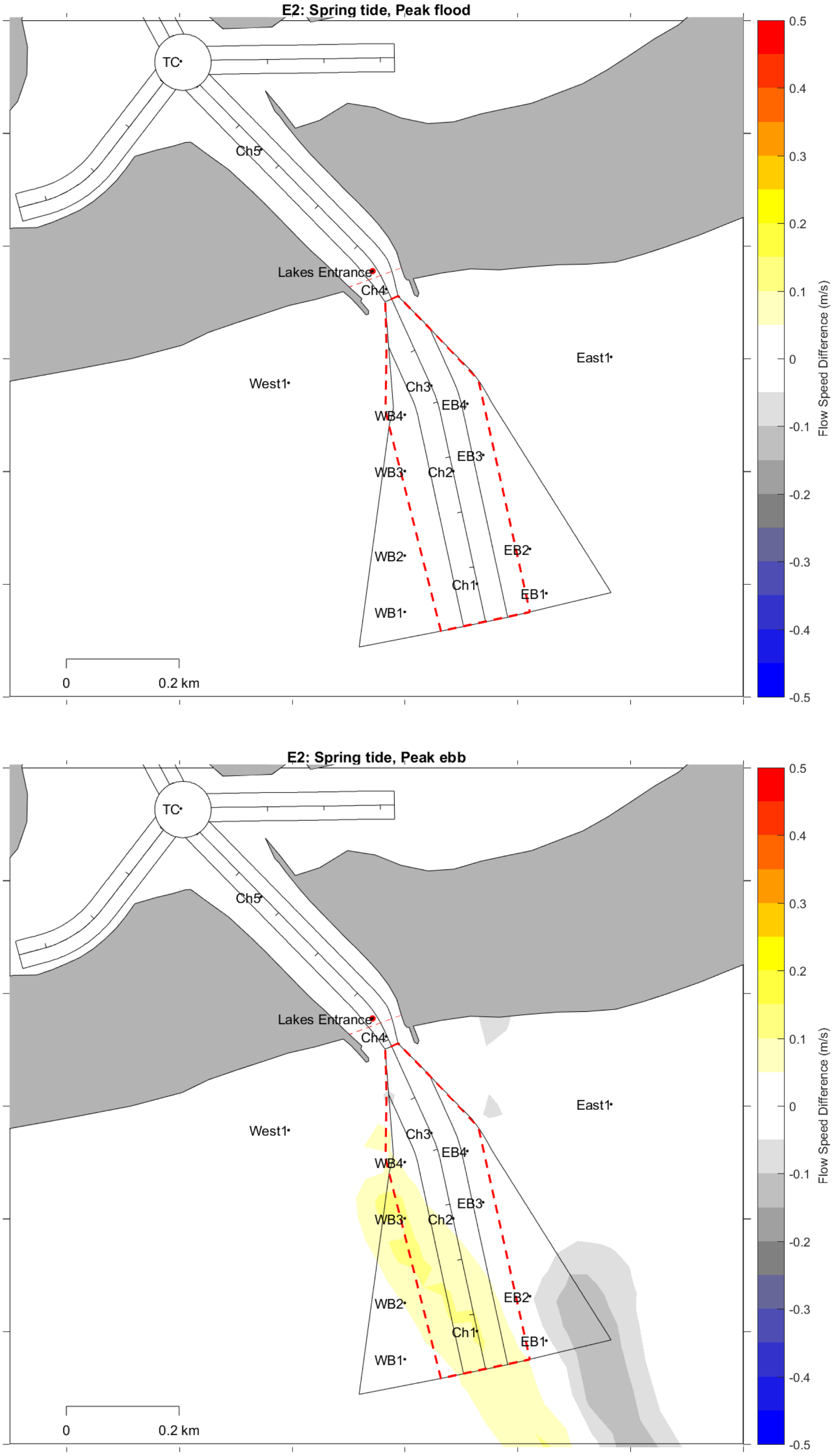
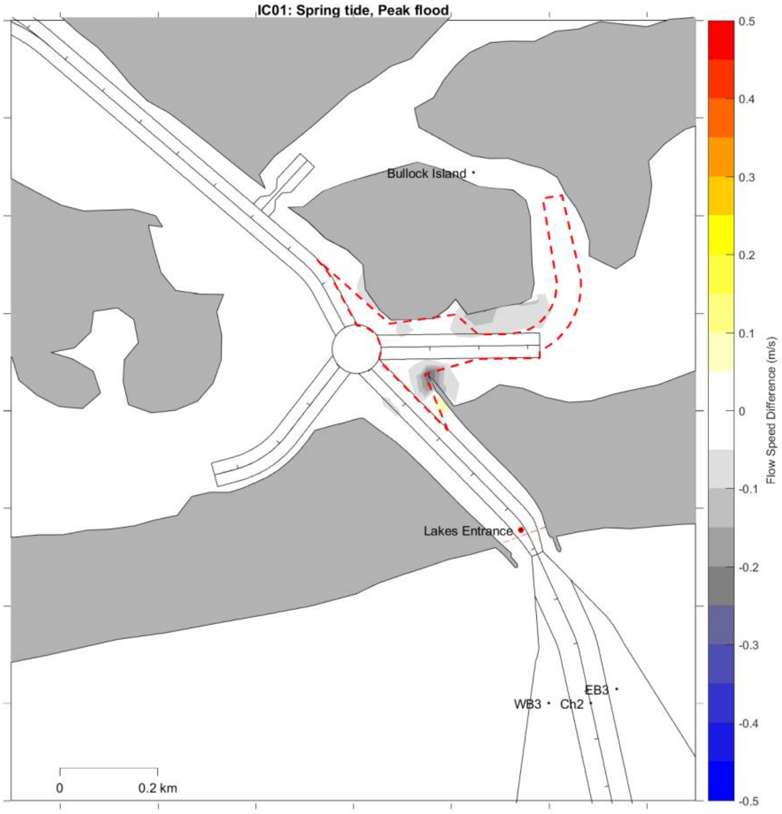


Figure B17. Difference in current speed between Options A1 and E2 at the peak flood (top) and ebb (bottom) stages of the tide.



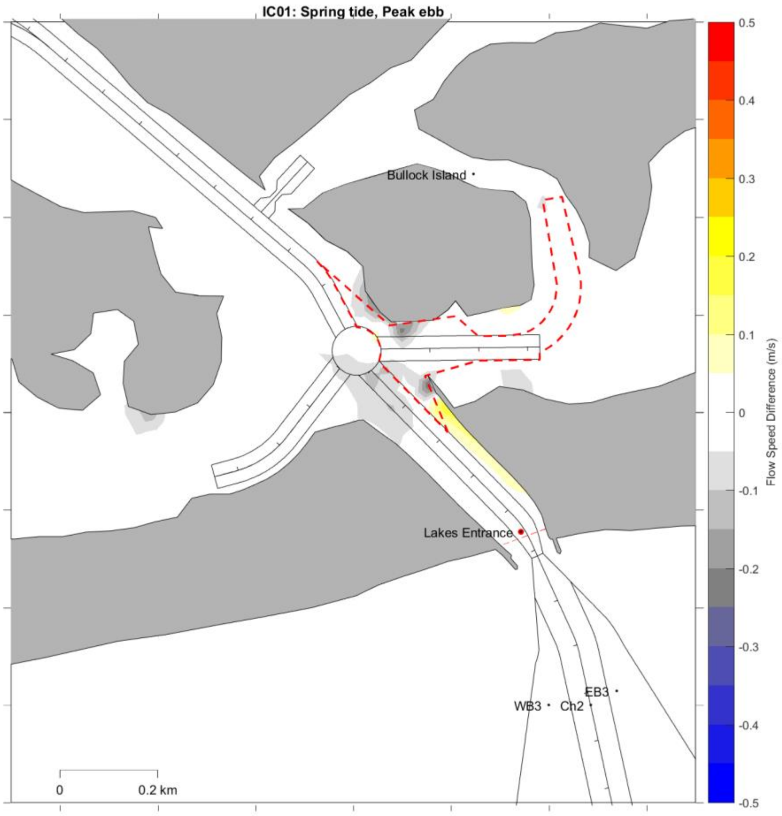


Figure B18. Difference in current speed between Options A1 and IC01 at the peak flood (top) and ebb (bottom) stages of the tide.

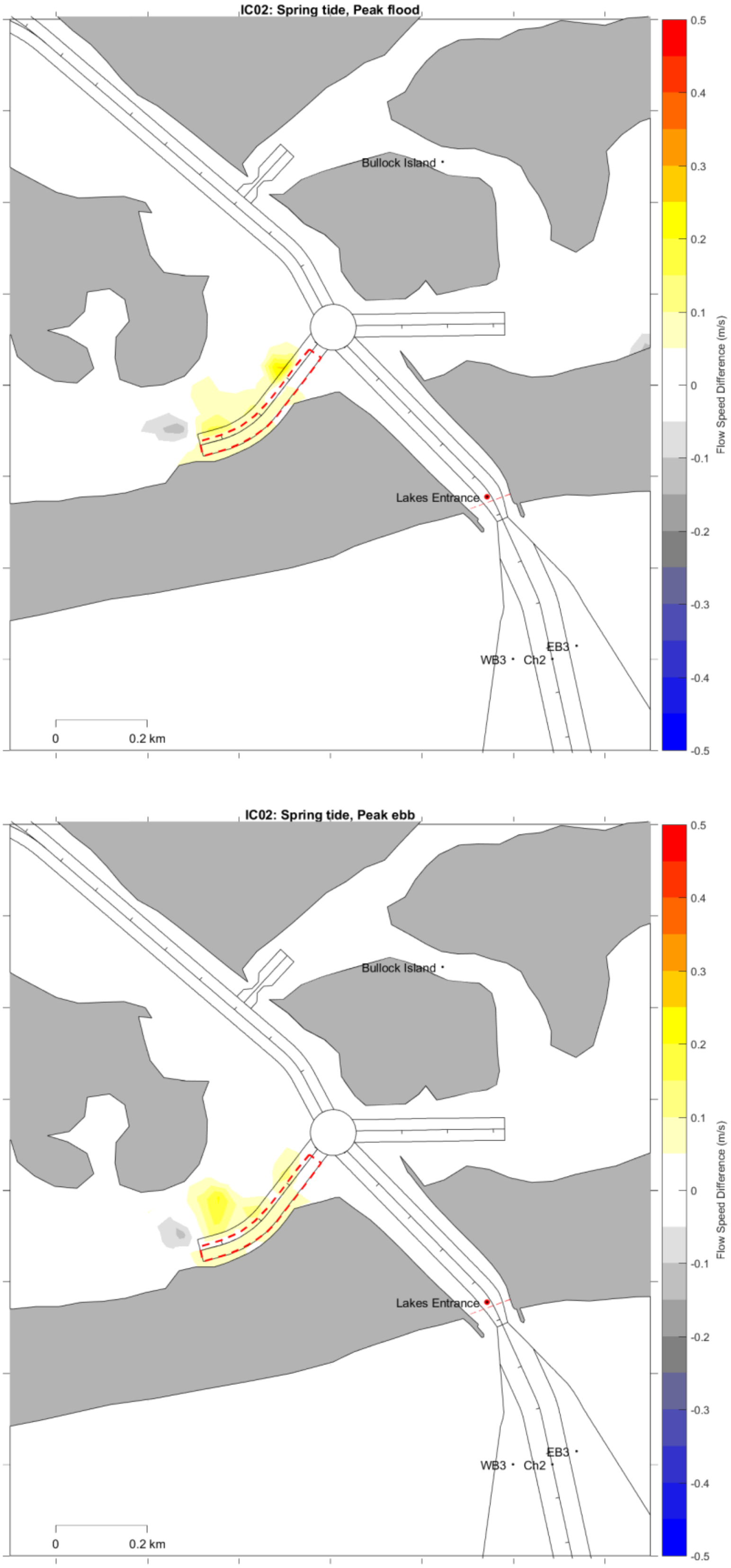


Figure B19. Difference in current speed between Options A1 and IC02 at the peak flood (top) and ebb (bottom) stages of the tide.

Appendix C – Wave Model Results

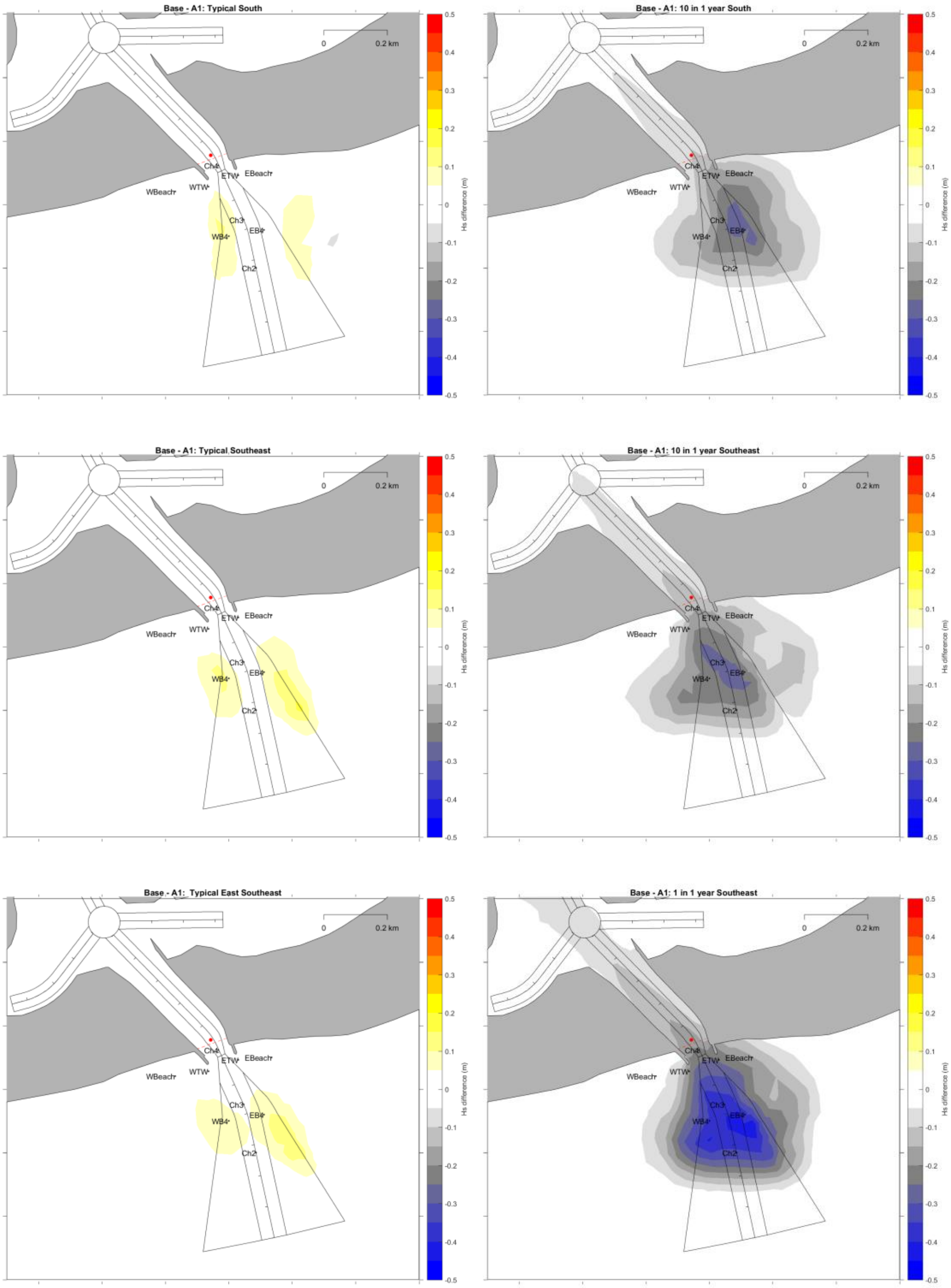


Figure C1. **Spatial maps showing the change in H_s relative to the existing A1 case for the Base case for the range of wave conditions modelled.**

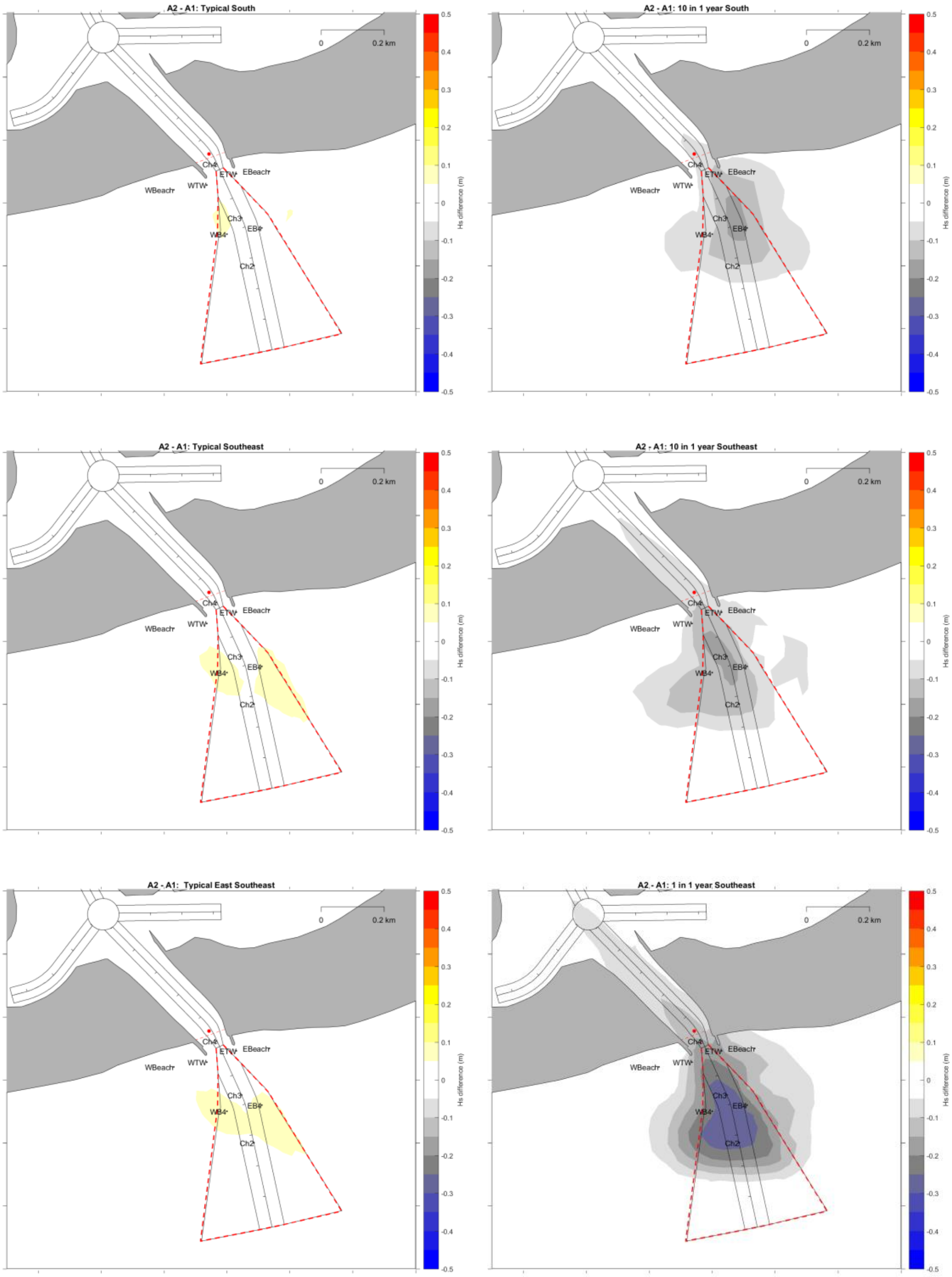


Figure C2. **Spatial maps showing the change in H_s relative to the existing A1 case for Option A2 for the range of wave conditions modelled.**

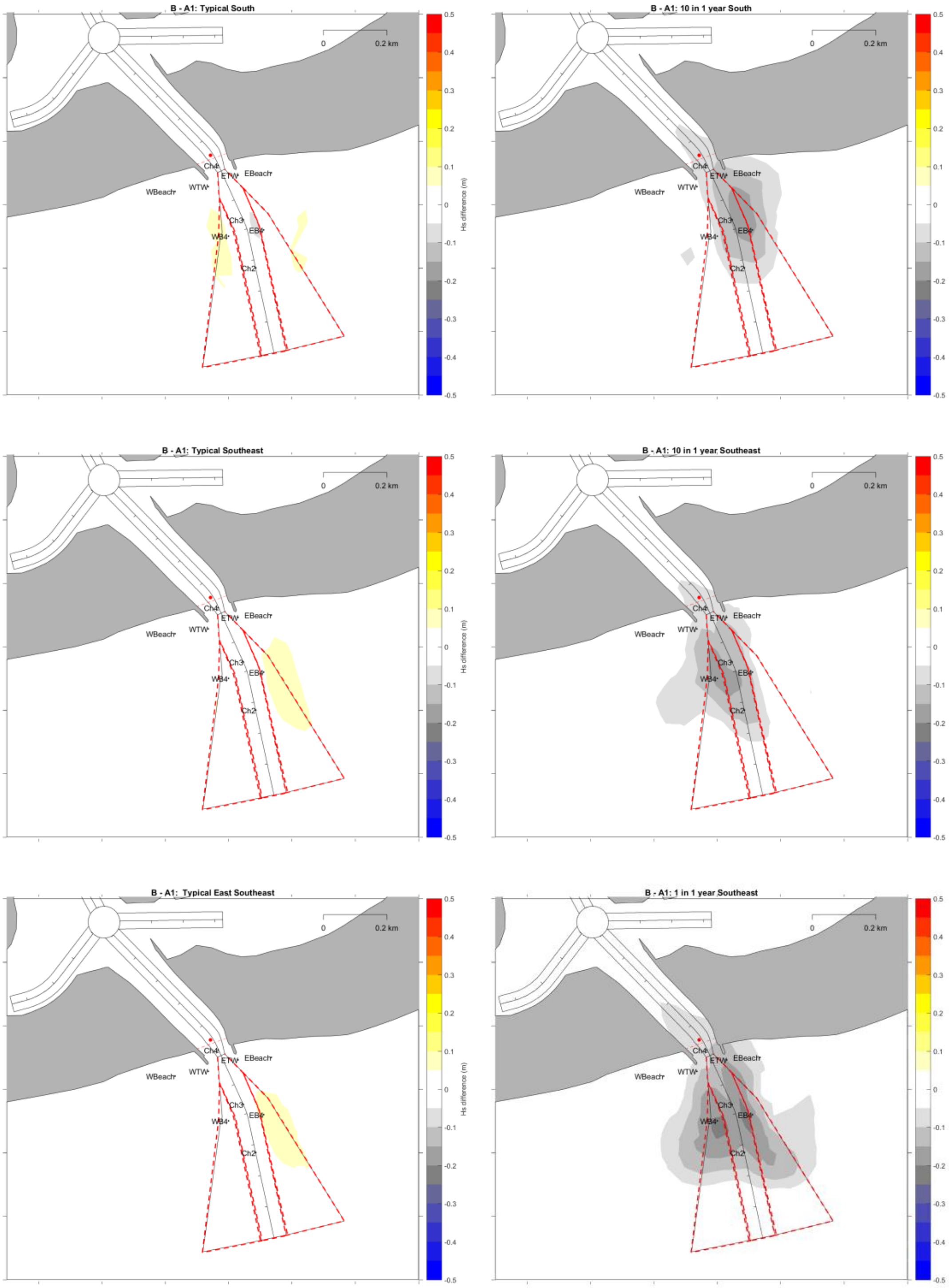


Figure C3. **Spatial maps showing the change in H_s relative to the existing A1 case for Option B for the range of wave conditions modelled.**

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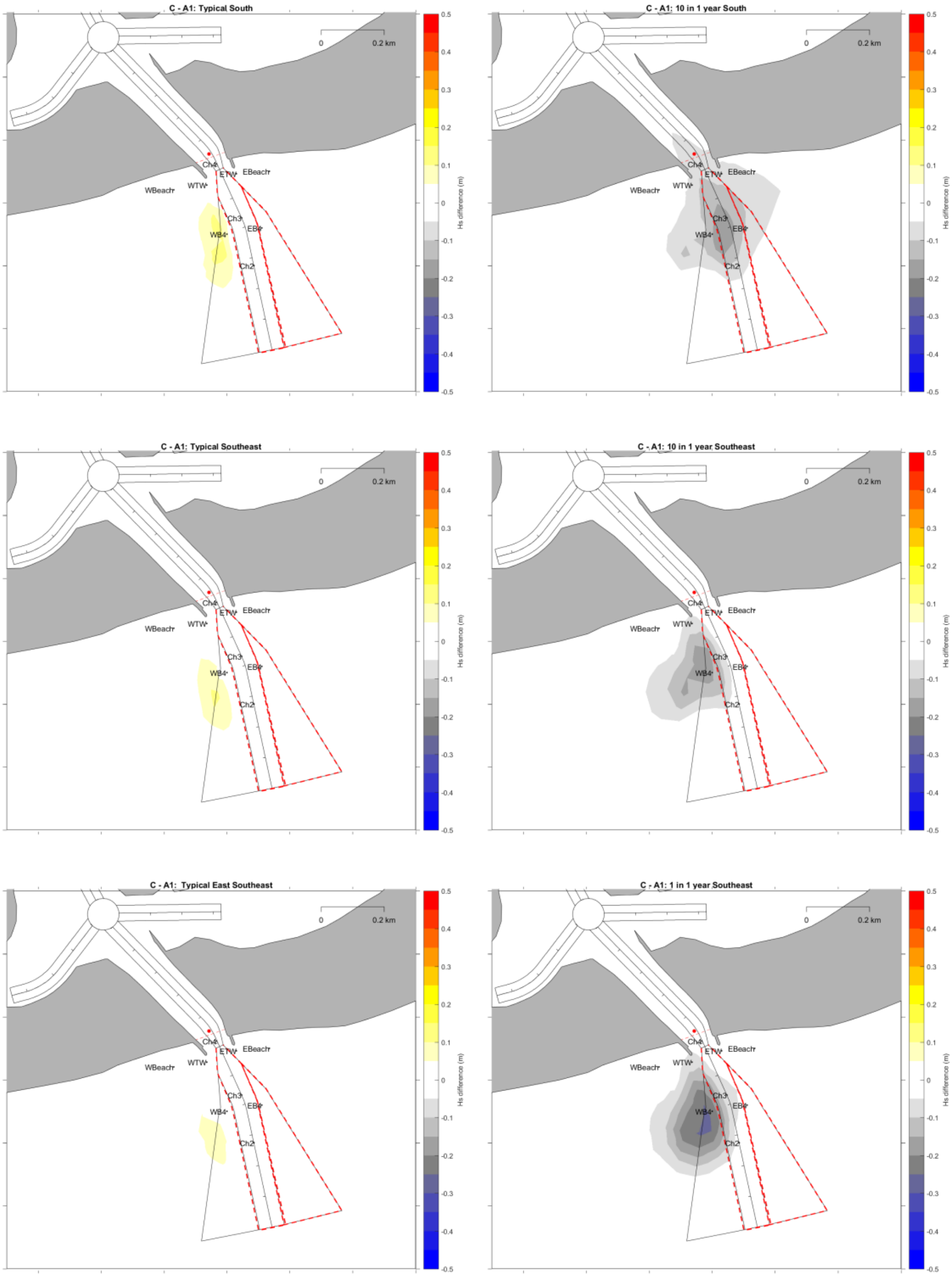

Figure C4. **Spatial maps showing the change in H_s relative to the existing A1 case for Option C for the range of wave conditions modelled.**

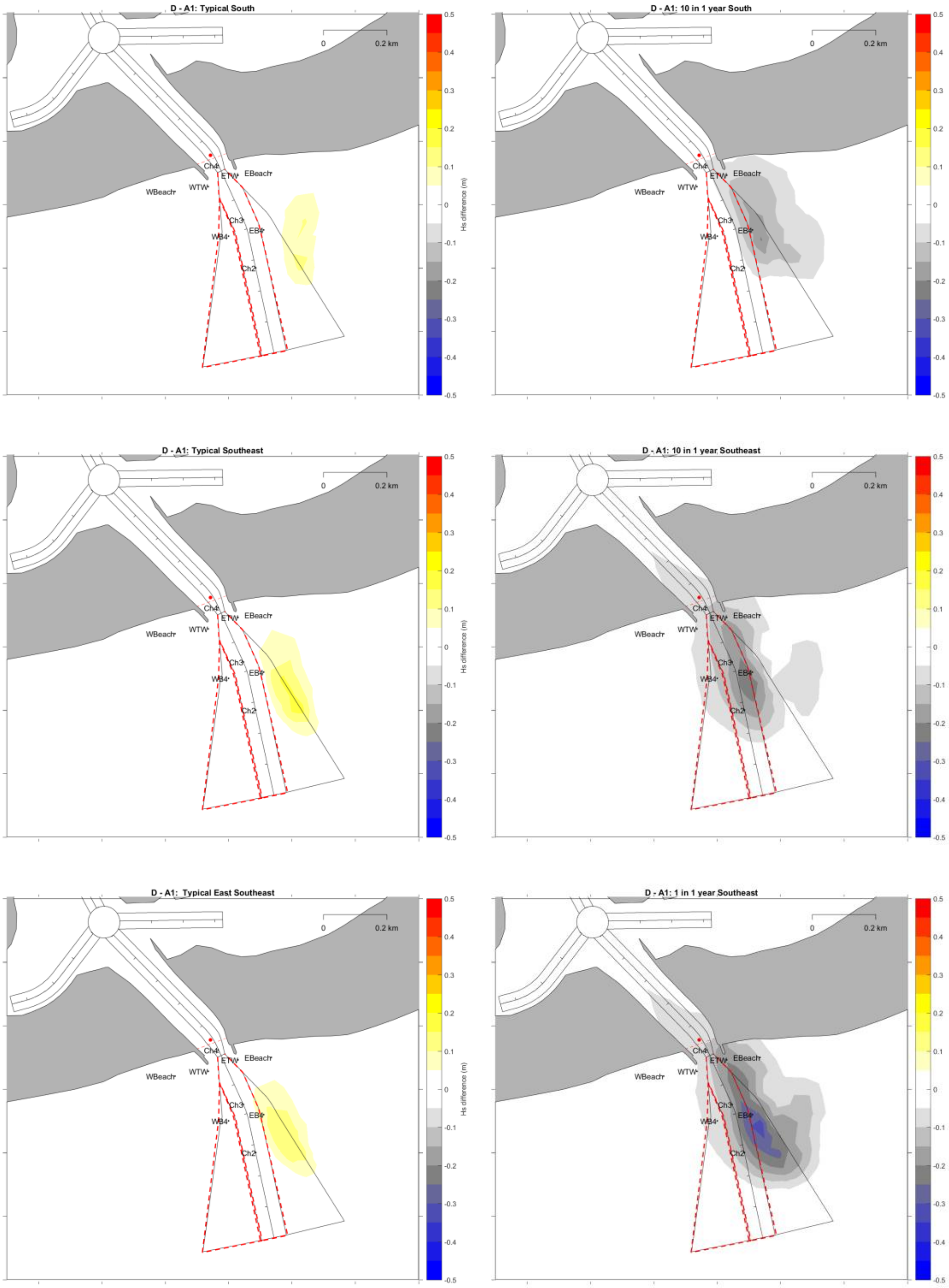

Figure C5. Spatial maps showing the change in H_s relative to the existing A1 case for Option D for the range of wave conditions modelled.

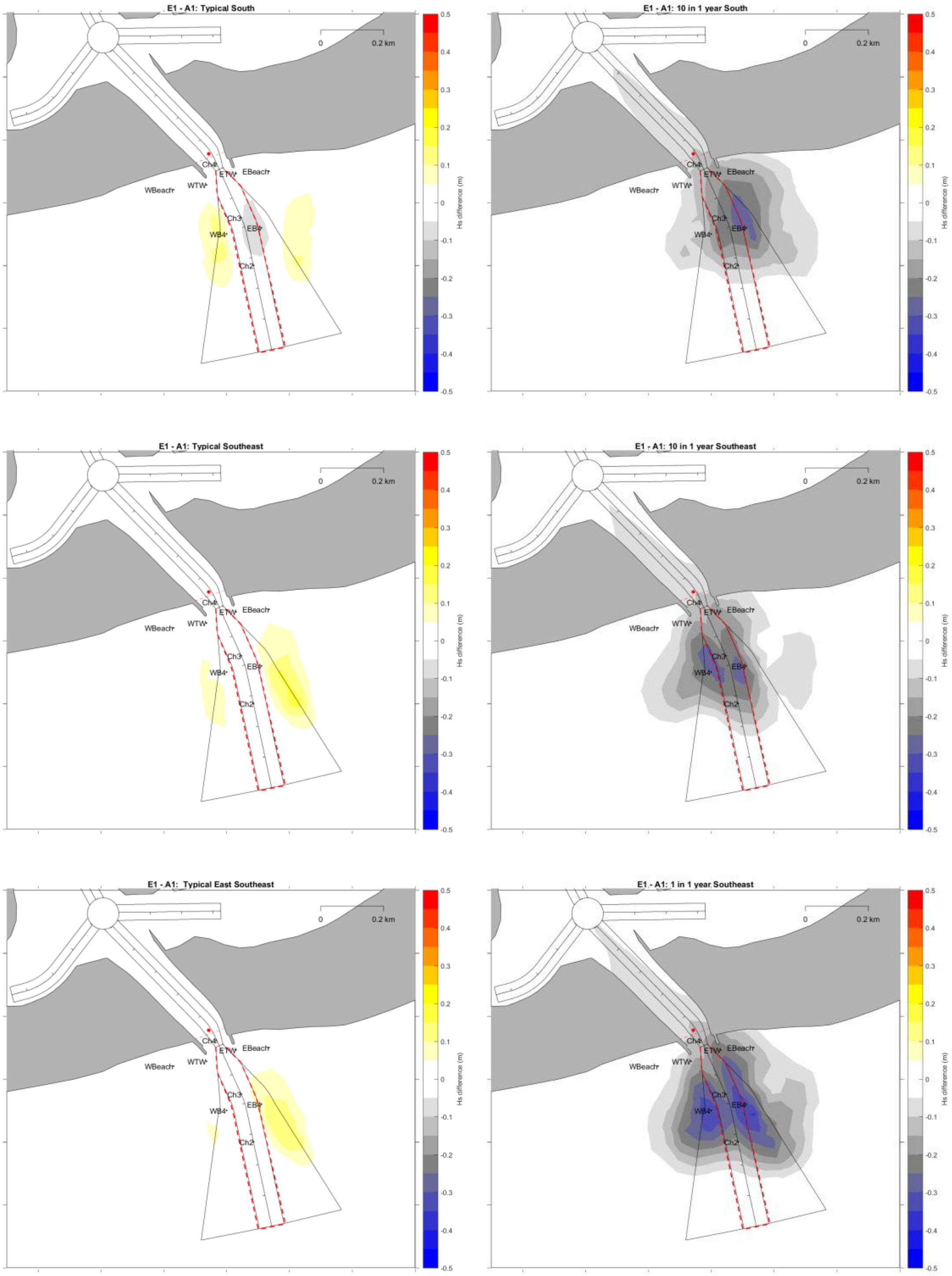

Figure C6. **Spatial maps showing the change in H_s relative to the existing A1 case for Option E1 for the range of wave conditions modelled.**

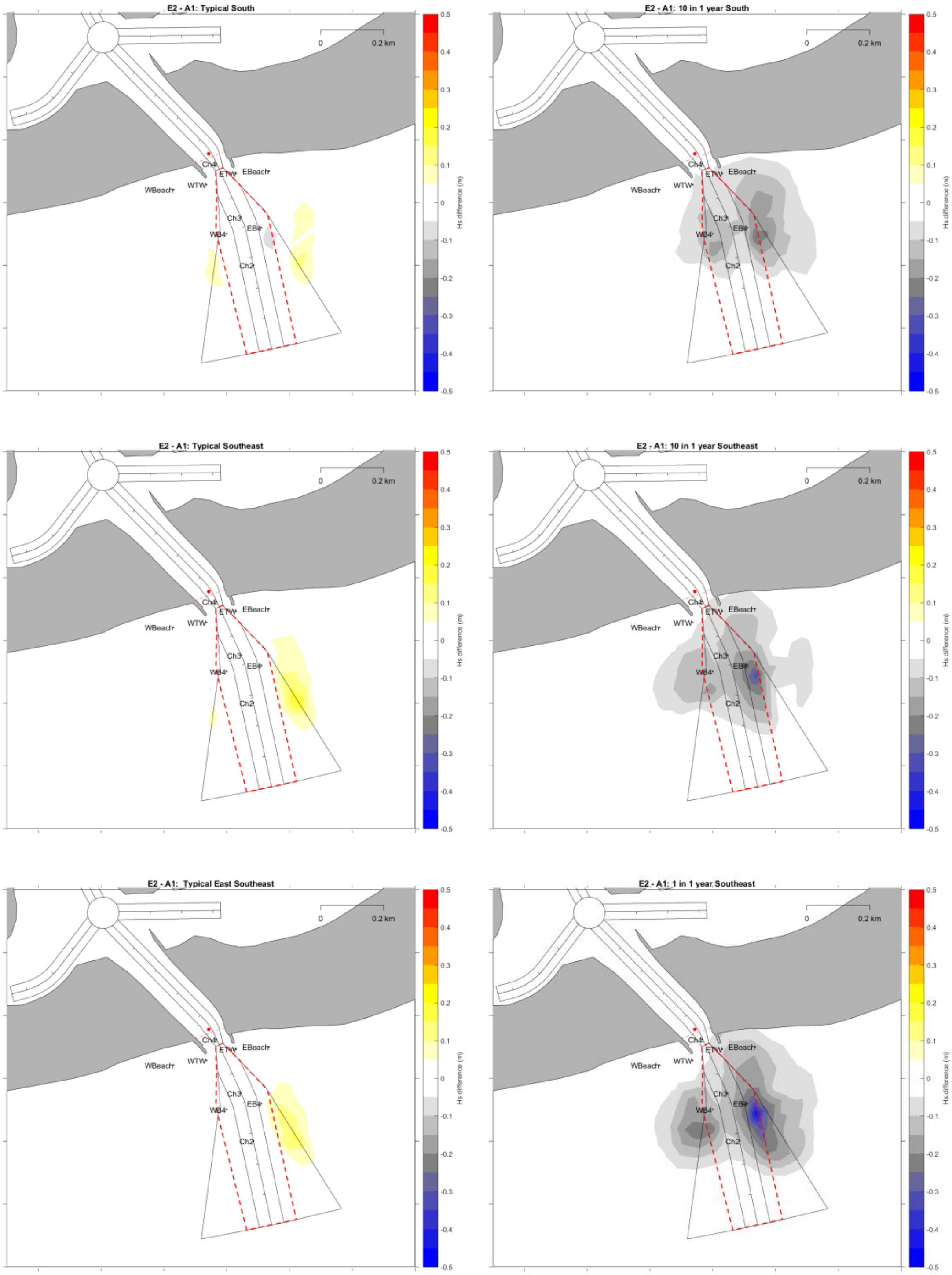

Figure C7. Spatial maps showing the change in H_s relative to the existing A1 case for Option E2 for the range of wave conditions modelled.

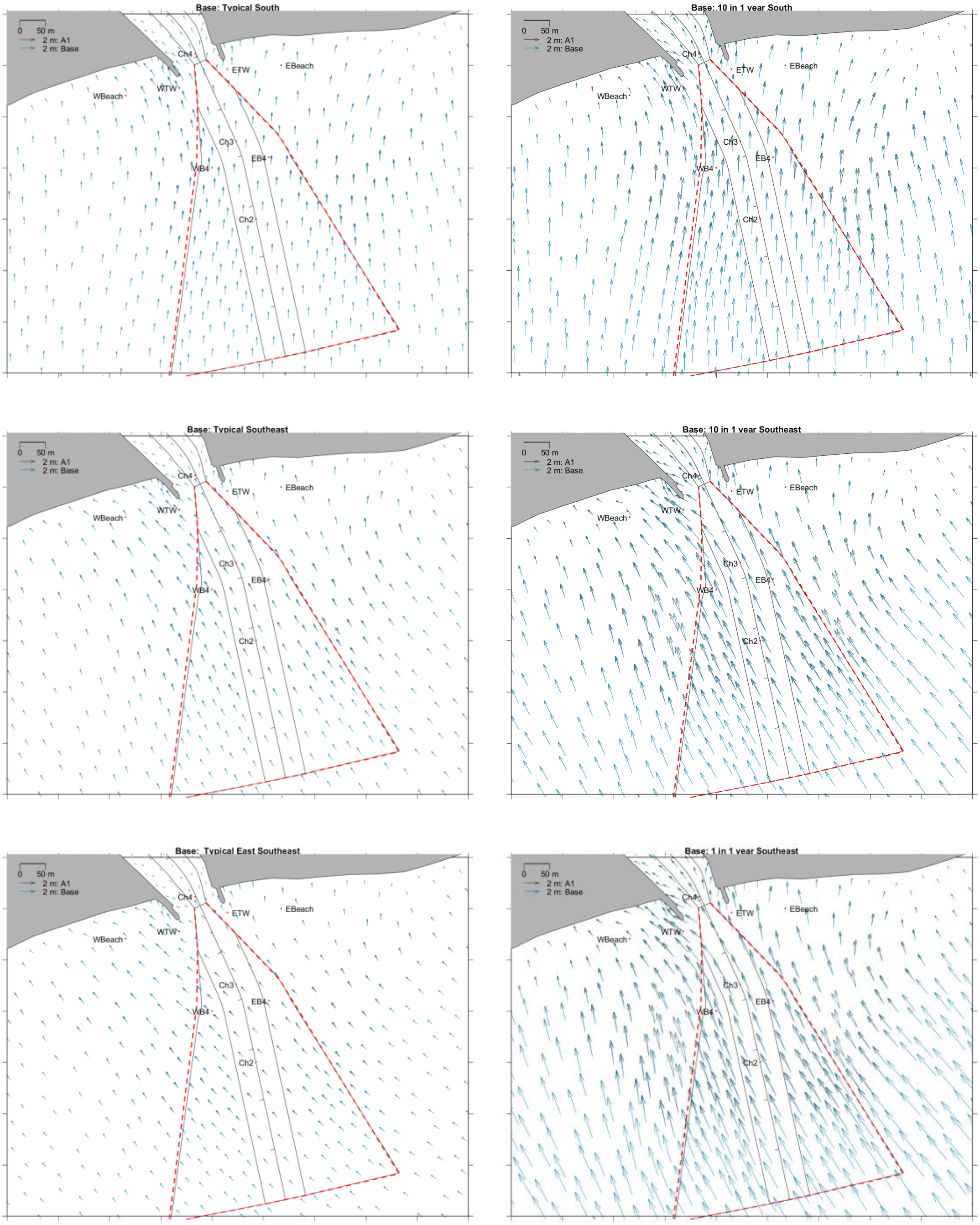

Figure C8. Spatial maps showing wave vectors for the Base case relative to the existing A1 case for the range of wave conditions modelled.

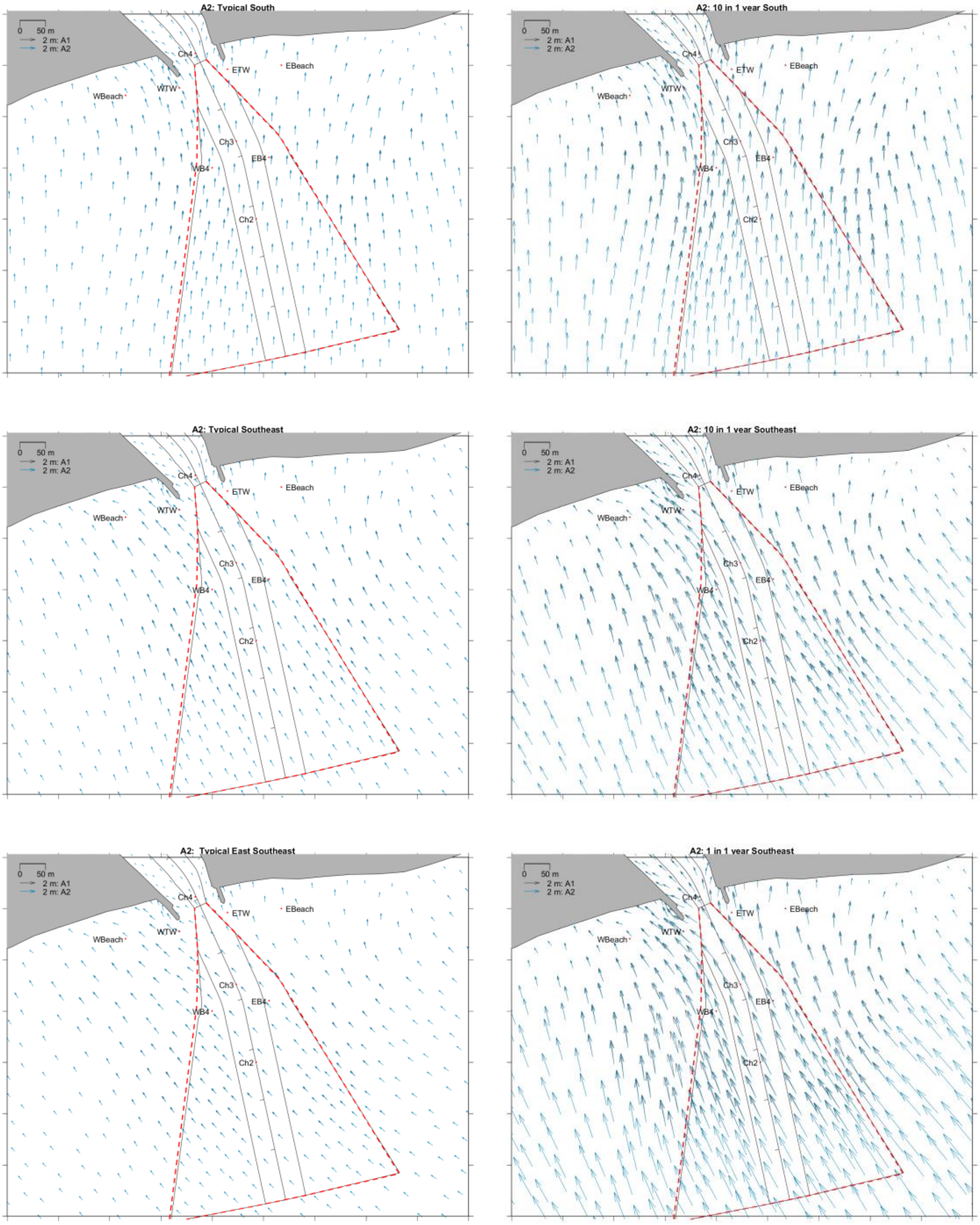

Figure C9. Spatial maps showing wave vectors for Option A2 relative to the existing A1 case for the range of wave conditions modelled.

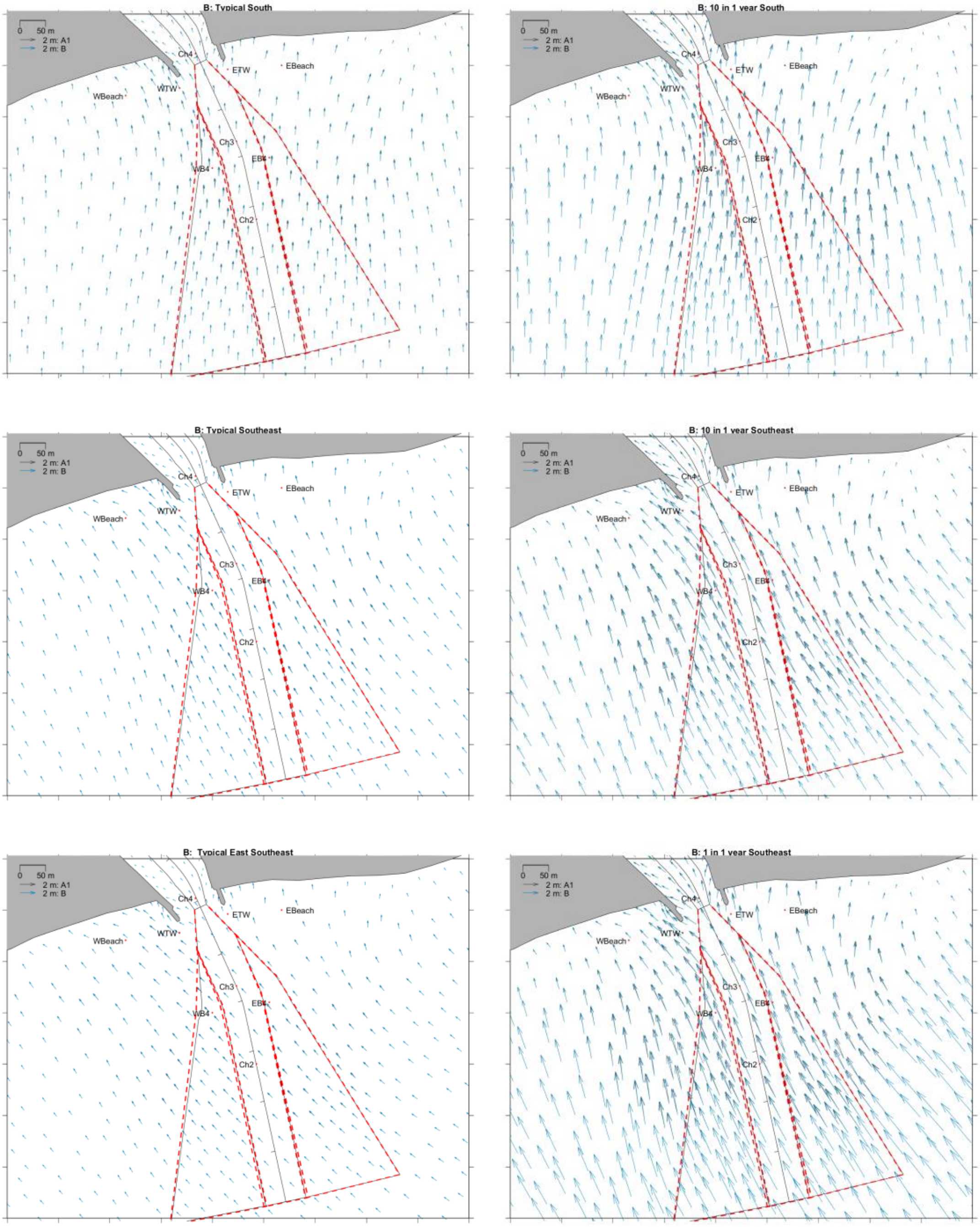

Figure C10. Spatial maps showing wave vectors for Option B relative to the existing A1 case for the range of wave conditions modelled.

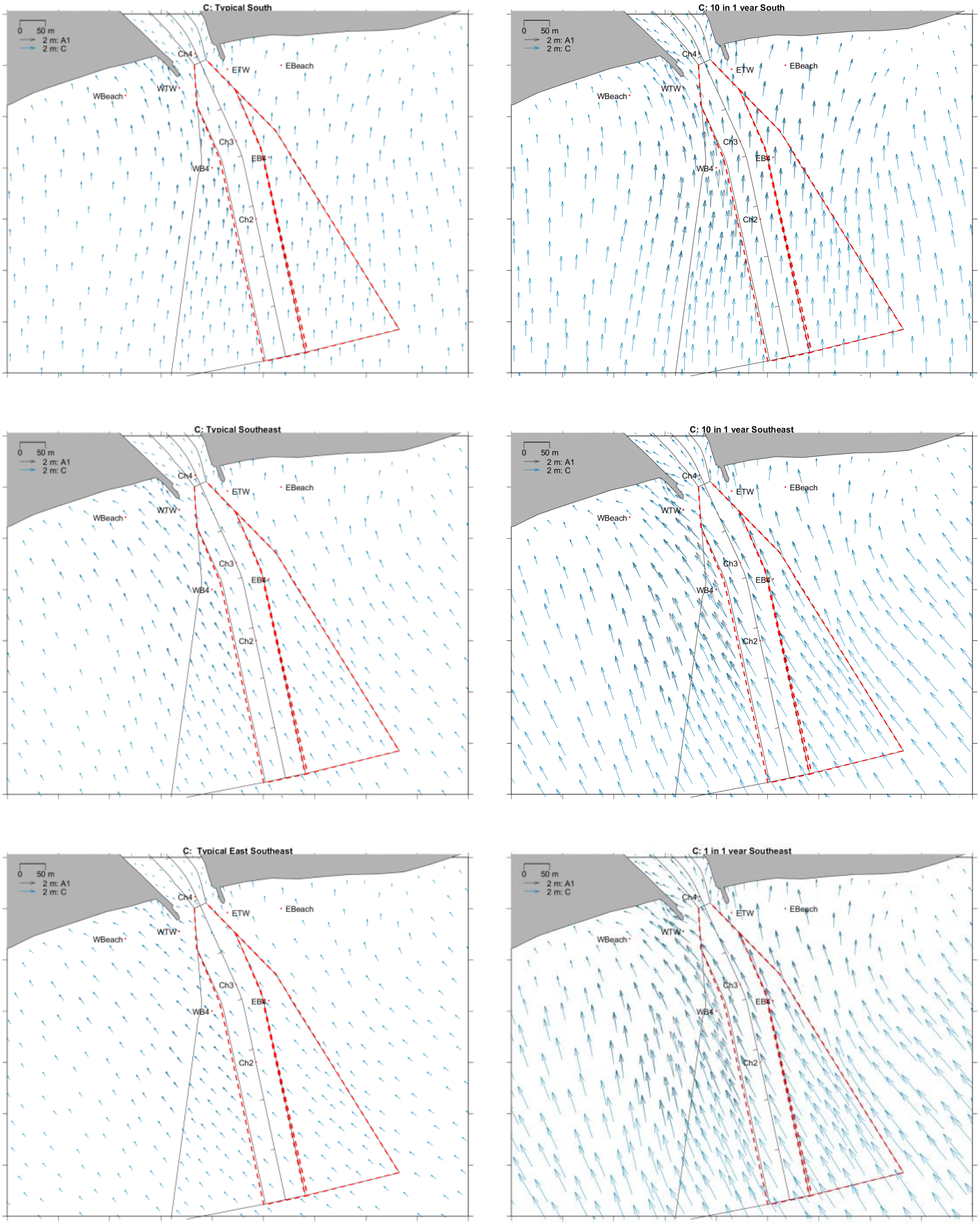

Figure C11. Spatial maps showing wave vectors for Option C relative to the existing A1 case for the range of wave conditions modelled.

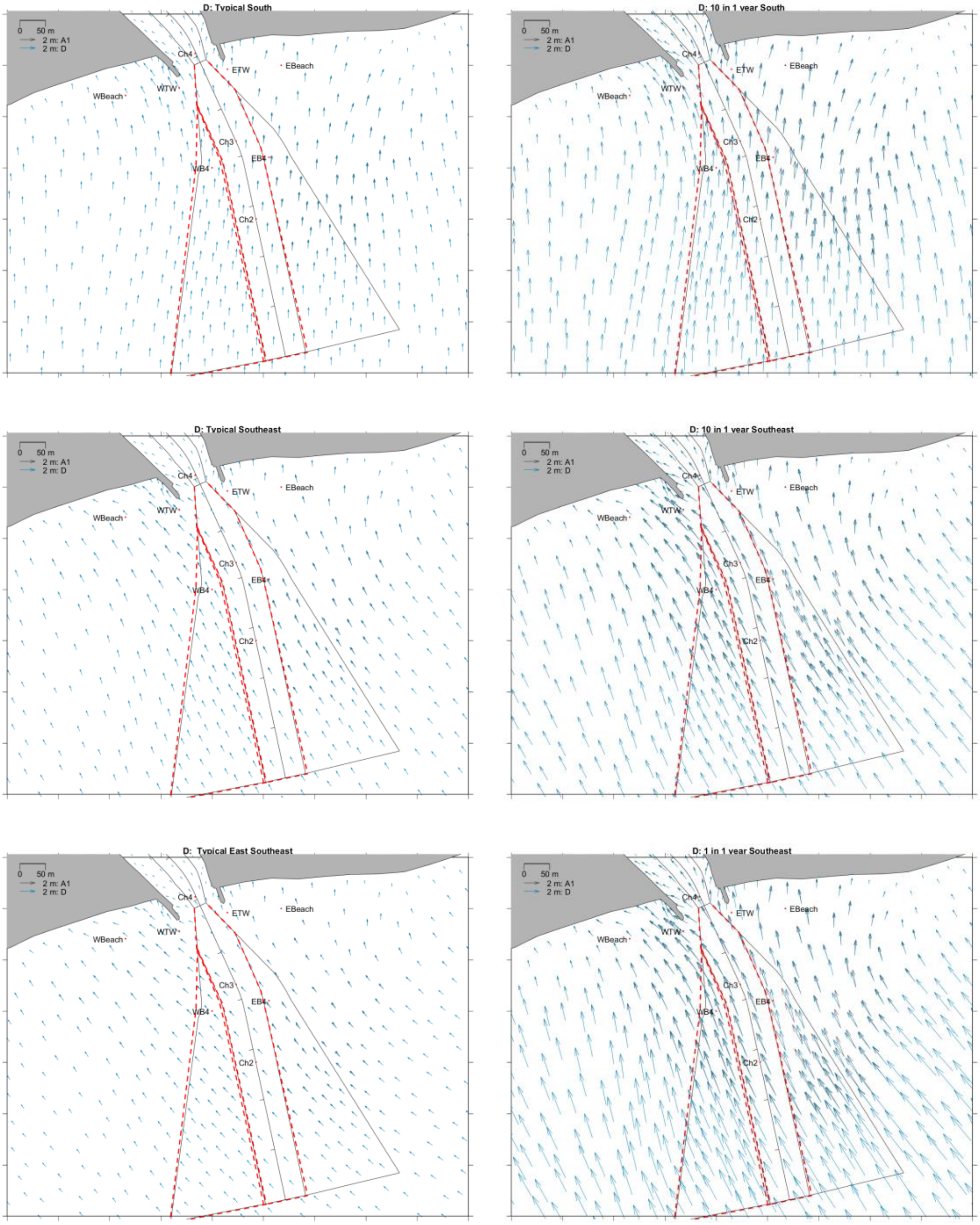

Figure C12. **Spatial maps showing wave vectors for Option D relative to the existing A1 case for the range of wave conditions modelled.**

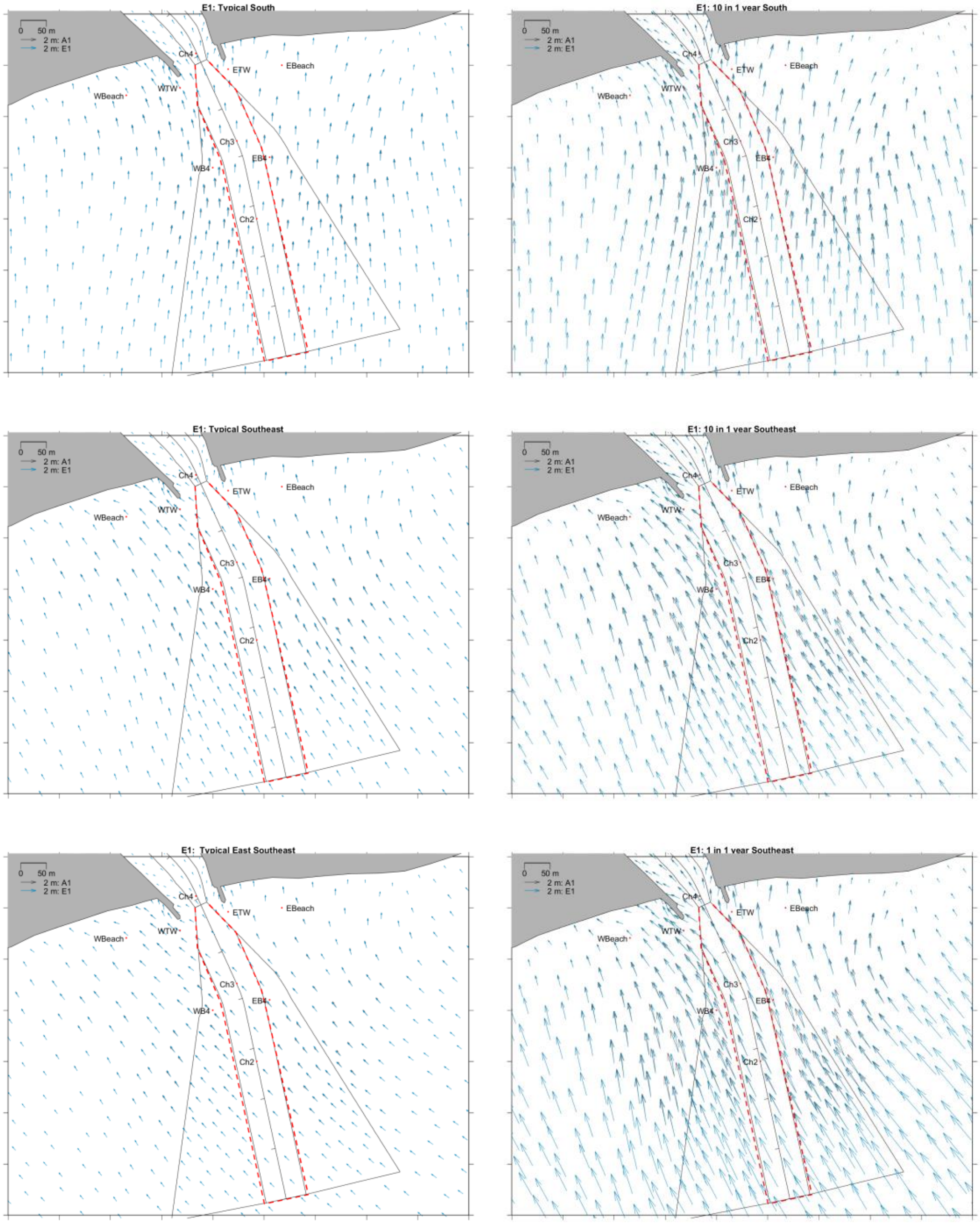

Figure C13. Spatial maps showing wave vectors for Option E1 relative to the existing A1 case for the range of wave conditions modelled.

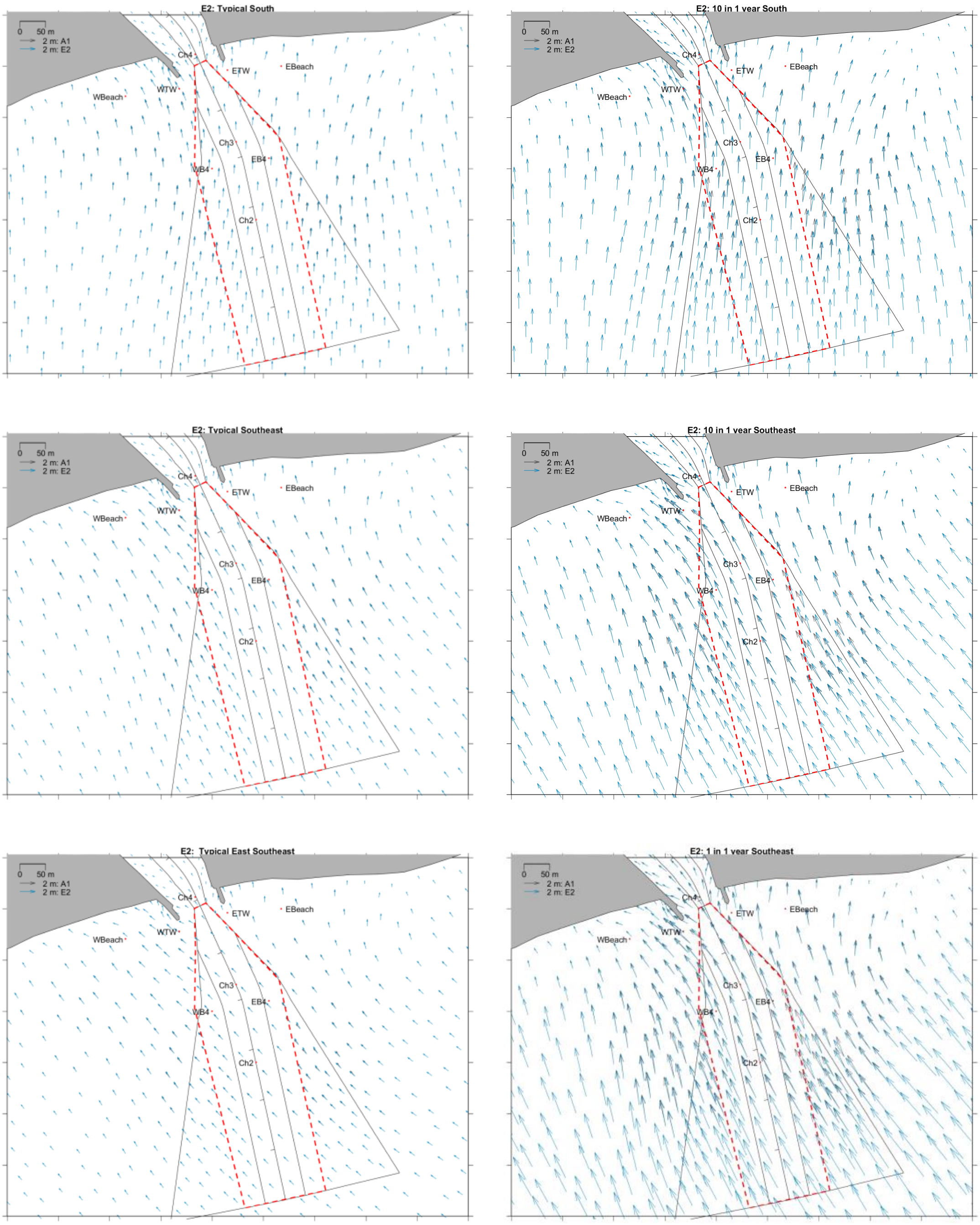

Figure C14. Spatial maps showing wave vectors for Option E2 relative to the existing A1 case for the range of wave conditions modelled.