ABERDEEN HARBOUR EXPANSION PROJECT

November 2015

Volume 3: Technical Appendices

APPENDIX 6-B HYDRODYNAMIC MODELLING AND COASTAL PROCESSES ASSESSMENT

FUGRO EMU LIMITED

ABERDEEN HARBOUR EXPANSION PROJECT

HYDRODYNAMIC MODELLING AND COASTAL PROCESSES ASSESSMENT

Report Reference. P1974_RN3859_Rev2

Issued 13 October 2015

Intertek
Exchange House
Liphook
Hants GU30 7DW
United Kingdom

Tel: +44 (0) 1428 727800
Fax: +44 (0) 1428 727122

E-mail: energy.water.info@intertek.com
Web Site: www.intertek.com

DOCUMENT RELEASE FORM

Title:	ABERDEEN HARBOUR EXPANSION PROJECT HYDRODYNAMIC MODELLING AND COASTAL PROCESSES ASSESSMENT
Client:	FUGRO EMU LIMITED
Report Reference:	P1974_RN3859_REV2
Date of Issue:	13 October 2015

		Hard Copy	***Digital***
Distribution:	FUGRO EMU LIMITED	No: -	.PDF
	Intertek Energy & Water consultancy services	No: -	.PDF
Prepared By:	Ashley Silk, Yan Wu		

Project Manager:	Authoriser:
[redacted]	p.p. [redacted]
Alasdair Fraser	Chris Mooij

Rev No	***Date***	***Reason***	***Author***	***Checker***	***Authoriser***
Rev 0	31/07/2015	Original	ASI/YW	AGF	CPM
Rev 1	15/09/2015	Client feedback	ASI/YW	AGF	CPM
Rev 2	13/10/2015	Client feedback	ASI	AGF	CPM

COPY NUMBER: (applies to hard copies only)

Intertek Energy & Water consultancy services is the trading name of Metoc Ltd, a member of the Intertek group of companies

SUMMARY

Aberdeen Harbour Board (AHB) has proposed the design and construction of a new harbour facility at Nigg Bay, immediately south of the existing harbour. The purpose of the new facility is to complement and expand the capabilities of the existing harbour, accommodate larger vessels, retain existing custom, and attract increased numbers of vessels and vessel types to Aberdeen.

The new harbour development shall include but is not limited to:

- Dredging the existing bay to accommodate vessels up to 9 m draft with additional dredge depth of 10.5 m to the east quay and entrance channel;
- Construction of new North and South breakwaters to form the harbour;
- Provision of approximately 1,500 m of new quays and associated support infrastructure. The quay will be constructed with solid quay wall construction and suspended decks over open revetment;
- Construction of areas for development by others to facilitate the provision of fuel, bulk commodities and potable water;
- Land reclamation principally through using materials recovered from dredging operations and local sources, where possible;
- Provision of ancillary accommodation for the facility;
- Off-site highway works to the extent necessary to access the facility and to satisfy statutory obligations; and
- Diversions and enabling works necessary to permit the development.

This development will potentially affect the hydrodynamic, spectral wave and sediment regimes in and around the development area. These impacts are required to be assessed as part of an Environmental Impact Assessment (EIA) being carried out by Fugro EMU Ltd (Fugro), and are reported within this document. Effects may range from the near-field (within 1 km of the development) and the far-field (greater than 1 km from the development), with short to long term changes. The assessment has considered timescales up to 85 years.

The assessment used the existing Aberdeen Coastal Model (ACM), which had been calibrated, validated, and was accepted as being fit for purpose by Scottish Environment Protection Agency (SEPA) for use in water quality assessments based on hydrodynamic

(HD) and spectral wave (SW) applications. The ACM was updated using recent data, which provided the increased resolution in Nigg Bay required for the coastal process and water quality assessments. The previously accepted standards of model performance were maintained during the upgrade, achieving compliance with the Foundation for Water Research 1993 guidelines. The sediment transport module was used to provide a full assessment of the coastal processes. This allowed the baseline environmental conditions to be determined, against which the effects of the proposed development have been assessed.

The key conclusions of this assessment are as follows:

Increases in maximum water level inside the harbour during extreme conditions are approximately 11 mm. South of the development, the maximum water level is expected to slightly decrease as a result of flow blockage by the breakwater. Current flow is expected to change within the harbour, with the breakwaters preventing the formation of eddy currents which are present under baseline conditions. Current speeds inside the development are predicted to reduce, with a maximum change of approximately -0.4 m/s. Far-field changes to the maximum water level and current speed are ±3 mm and ±0.15 m/s respectively.

The significant wave height within the development area will be reduced for all environmental conditions to less than 0.5 m, from a previous maximum height of 8.5 m. Reductions are present throughout the harbour area. Increases in significant wave height, ranging from 0.2 m to 1.0 m, are limited to off-shore of the breakwaters and represent a minor change. Predicted far-field changes to the wave climate are small, ±0.2 m.

Far-field sediment transport regime will only experience minimal changes from the development, due to the sediment transport pathways remaining unaltered. Within the near-field, there will be larger changes due to the effects on the hydrodynamic regime. Large eddy currents will no longer form within the bay, due to the breakwater arms blocking the current and wave action, producing low current speeds. As a result of weak wave action and small current in the harbour, fine sediments brought into the harbour from the local streams and washed off from the coast would likely be deposited in the harbour.

Changes during future climate conditions are generally predicted to be of a slightly greater magnitude than during current climate scenarios, covering a similar spatial extent. Therefore the effect of the development on the coastal processes is predicted to remain constant in the future, with any changes remaining confined to the immediate development area.

The proposed Aberdeen Harbour expansion will not cause large changes to the far-field hydrodynamic regime, wave climate and sediment transport regime. Conditions within the Harbour (including Nigg Bay Site of Special Scientific Interest) will be calmer, with reduced wave heights and current speeds. Sediment transport pathways are removed from the bay, which will result in a greater accumulation of fine sediments brought into the harbour area. No changes are predicted at Aberdeen Ballroom Bathing Water, Cove Site of Special Scientific Interest, River Dee Special Area of Conservation, and Ythan Estuary and Sands of Forvie draft Special Protection Area.

CONTENTS

TABLES

FIGURES

ABBREVIATIONS

ACM	Aberdeen Coastal Model
AHB	Aberdeen Harbour Board
BW	Bathing Water
CSO	Combined Sewer Overflow
DIA	Drainage Impact Assessment
EIA	Environmental Impact Assessment
ES	Environmental Statement
FWR	Foundation for Water Research
FRA	Flood Risk Assessment
HD	Hydrodynamic
HDM	Hydrodynamic Modelling
HW	High Water
Intertek	Intertek Energy and Water Consultancy Services
LSO	Long Sea Outfall
MSL	Mean Sea Level
PT	Particle Tracking
SAC	Special Area of Conservation
SEPA	Scottish Environment Protection Agency
SPA	Special Protection Area
SSSI	Site of Special Scientific Interest
ST	Sediment Transport
SW	Spectral Wave
WFDA	Water Framework Directive Assessment
WQ	Water Quality

1 INTRODUCTION

1.1 PROJECT BACKGROUND

Aberdeen Harbour Board has proposed the design and construction of a new harbour facility at Nigg Bay, immediately south of the existing harbour. The purpose of the new facility is to complement and expand the capabilities of the existing harbour, accommodate larger vessels, retain existing custom, and attract increased numbers of vessels and vessel types to Aberdeen.

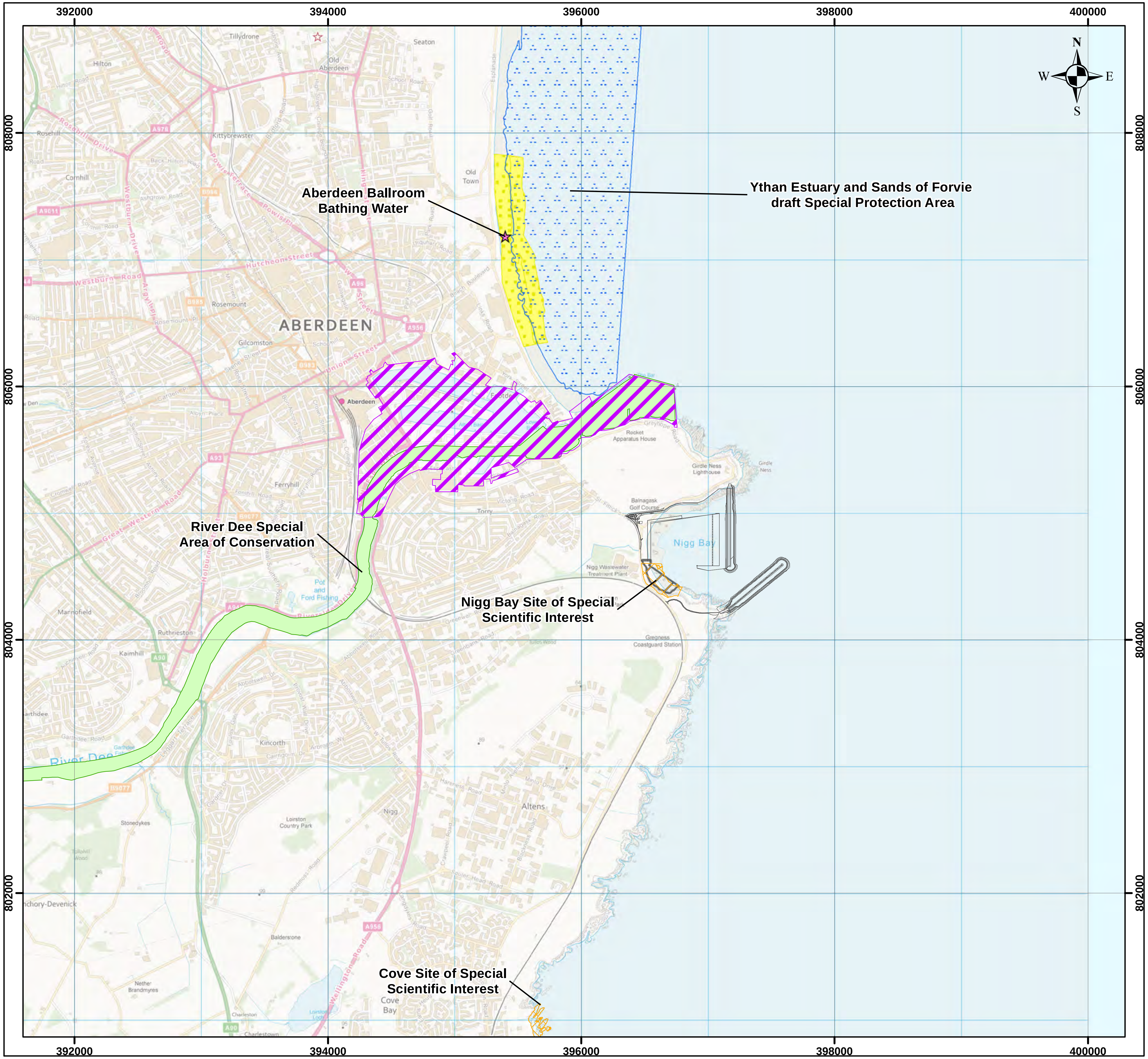
The new harbour development shall include but is not limited to:

- Dredging the existing bay to accommodate vessels up to 9 m draft with additional dredge depth of 10.5 m to the east quay and entrance channel;
- Construction of new North and South breakwaters to form the harbour;
- Provision of approximately 1,500 m of new quays and associated support infrastructure. The quay will be constructed with solid quay wall construction and suspended decks over open revetment;
- Construction of areas for development by others to facilitate the provision of fuel, bulk commodities and potable water;
- Land reclamation principally through using materials recovered from dredging operations and local sources, where possible;
- Provision of ancillary accommodation for the facility;
- Off-site highway works to the extent necessary to access the facility and to satisfy statutory obligations; and
- Diversions and enabling works necessary to permit the development.

The current proposed option for the Aberdeen Harbour Expansion Project is shown in Figure 1-1. The option is considered an indicative plan and may change prior to the final development. For this reason, the technical assessments and resulting EIA/ES have adopted a Rochdale Envelope approach for assessing impacts. This approach will make realistic assumptions about the development, but will tend towards conservatism (in terms of potential impacts) where there is presently uncertainty regarding the precise details of the project. The proposed layout is shown in Figure 1-2 with the data extraction locations used in this report indicated.

ABERDEEN HARBOUR EXPANSION PROJECT

Figure 1-1: Geographic overview of the area of interest



Legend

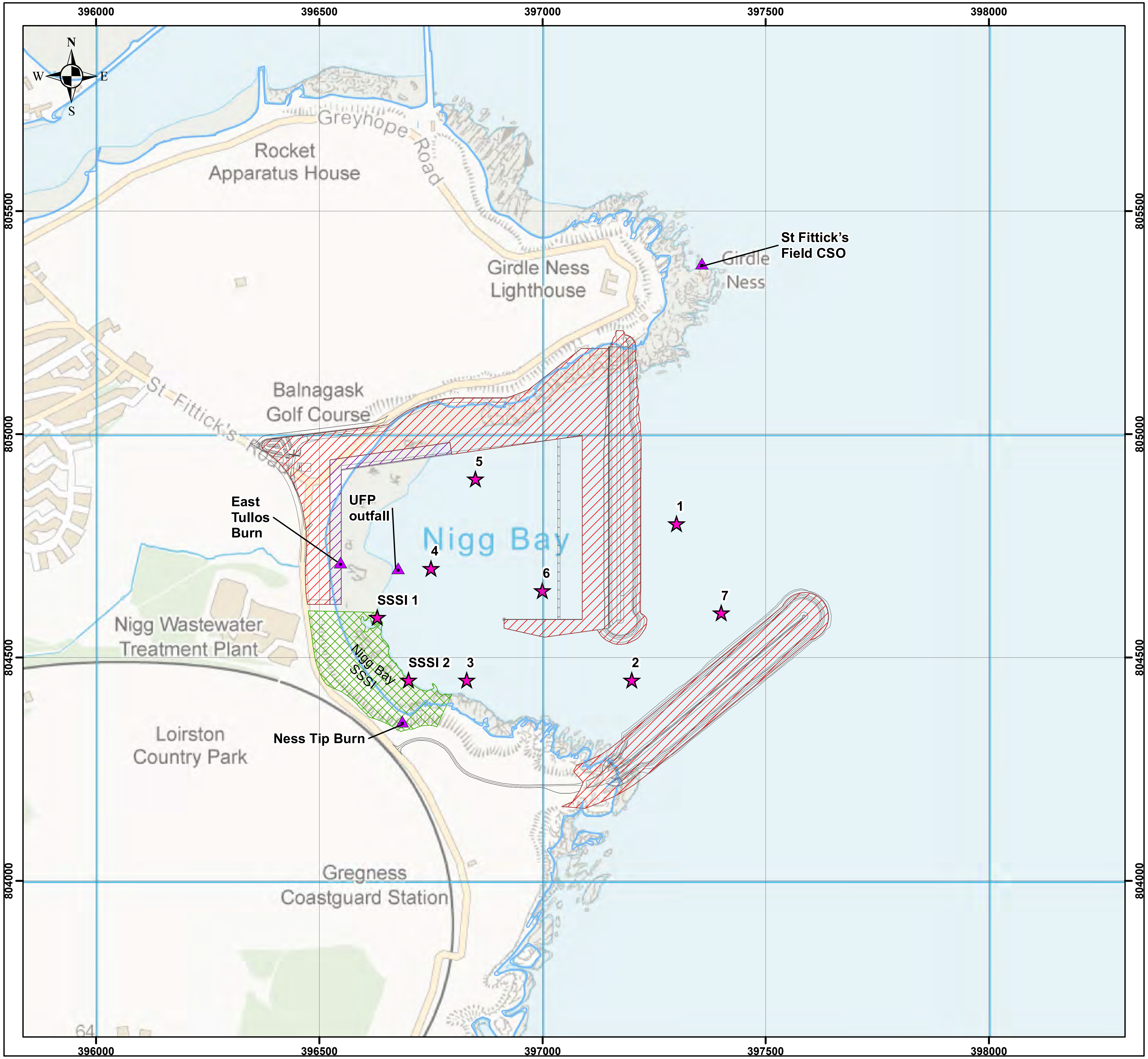
- Aberdeen Harbour Expansion Project area
- Existing Aberdeen Harbour Area
- Special Area of Conservation
- Site of Special Scientific Interest
- Draft Special Protection Area
- Bathing Water Monitoring Location
- Aberdeen Ballroom Bathing Water

NOTE: Not to be used for Navigation

Date	Monday, September 7, 2015 09:48:11
Projection	British_National_Grid
Spheroid	Airy_1830
Datum	D_OSGB_1936
Data Source	OSOD, SNH, JNCC, SEPA
File Reference	J:\P1974\Mxd\Method_Statement\ Geographical_Overview.mxd
Created By	Emma Langley
Reviewed By	Ian Charlton
Approved By	Kevin McGovern

Valued Quality. Delivered.

km
0 0.2 0.4 0.8 1.2 1.6



Contains Ordnance Survey data © Crown copyright and database right 2013

ABERDEEN HARBOUR EXPANSION PROJECT

Figure 1-2: Extraction Locations

Legend

- Model extraction locations
- Discharge Location
- Aberdeen Harbour Expansion Project
- Suspended Deck Structure
- Site of Special Scientific Interest

NOTE: Not to be used for Navigation

Date	Thursday, September 10, 2015 17:26:32
Projection	British_National_Grid
Spheroid	Airy_1830
Datum	D_OSGB_1936
Data Source	OSOD, FUGRO
File Reference	J:\P1974\Mxd\ WQ_Extraction_Locations_v4.mxd
Created By	Ian Charlton
Reviewed By	Emma Langley
Approved By	Paul Taylor

Valued Quality. Delivered.

0 100 200 300 400 m

1.2 Scope of Work

Fugro appointed Intertek Energy and Water Consultancy Services (Intertek) to undertake a range of technical assessments to inform the relevant chapters of the ES. The assessment of potential impacts on designated sites will be addressed fully by the EIA and reported in the ES. With this in mind, the following designated sites in the immediate vicinity of the proposed development are identified:

- Nigg Bay Site of Special Scientific Interest (SSSI);
- Cove SSSI;
- River Dee Special Area of Conservation (SAC);
- Ythan Estuary and Sands of Forvie draft Special Protection Area (SPA); and
- Aberdeen Ballroom Bathing Water (BW).

These sites are indicated on Figure 1-1.

1.3 Method

A Method Statement was prepared by Intertek and agreed with Fugro (Intertek, 2015). This statement was issued as a stand-alone report in April 2015, and was then forwarded to all relevant stakeholders (Aberdeen City Council, Marine Scotland, the Scottish Environment Protection Agency (SEPA) and Scottish Natural Heritage) for review.

The agreed approach is summarised as follows:

- Existing hydrodynamic (HD) and spectral wave (SW) models covering the Development and surrounding area would be updated, calibrated and validated. These models comprise part of the Aberdeen Coastal Model (ACM).
- A bespoke sand transport (ST) model covering the development during the operational phase and surrounding region would be developed. This comprises part of the ACM. This would be constructed using the same software as the HD and SW models.

The ACM would be used to assess the following using a full mean spring-neap tidal cycle:

- Baseline conditions (an understanding of the hydrodynamic and wave and sedimentological regimes as they are now);
- Short-term impacts on suspended sediment concentrations during the construction phase (from the dredging operations);
- Post-construction impacts from the development, and
- The possible implications of climate change to the impacts predicted by the hydrodynamic and wave assessment.

Following the submission of the Method Statement, and subsequent responses from stakeholders, the project team discussed and agreed in more detail the different scenarios to be included in the assessment. It was agreed to adopt a realistic ‘worst case’ scenario for the proposed development, where details were not yet known. This is in line with the ‘Rochdale Envelope’ approach as outlined by the Infrastructure Planning Commission. The key numerical model that was used in the assessment was the ACM. This model has been used to assess a range of conditions covering water levels, currents, waves, water quality and sediment transport / coastal processes.

1.4 PURPOSE OF REPORT

This report has been prepared by Intertek on behalf of Fugro. It sets out the construction, calibration and validation of the ACM, and the method and results of the hydrodynamic, spectral wave and sediment regime assessments.

2 MODEL DEVELOPMENT

2.1 BASELINE MODEL

The existing ACM has been updated and refined for the impact assessment of the proposed Aberdeen Harbour Expansion Project. A range of technical assessments, i.e. the HDM assessment, and elements of the FRA and WFDA assessments, were undertaken using a combination of HD, SW, water quality (WQ) and sediment transport (ST) models.

The ACM was constructed for water quality assessments in the Aberdeen area. The calibrated and validated model was accepted as fit for this purpose by SEPA. For the purposes of the Aberdeen Harbour Expansion Project assessment, the model has been updated with the latest bathymetry data available from AHB. Furthermore, the spatial resolution of the model in the Nigg Bay area has been refined so as to accurately represent the local environment and the proposed harbour structures for the model with the development in place.

The ACM was built to comply with relevant modelling guidelines and standards, and the modifications to the model for this assessment also comply with these guidelines and standards. Relevant documents include:

- The Foundation for Water Research (FWR) 'Framework for Marine and Estuarine Model Specification in the UK' (FWR, 1993).
- SEPA's 'Supporting Guidance WAT SG 11 – Modelling Coastal and Transitional Discharges', which includes 'SEPA Standards for Models' (SEPA, 2013).

The guidelines distinguish between models of coastal and estuarine waters. The general guidelines adopted for hydrodynamic modelling of coastal waters are:

1) Modelled current speeds should be within ± 0.1 ms^{-1} or ± 10 – 20% of observed speeds.

2) Modelled directions should be within ± 10° of observed directions.

3) Modelled water levels should be within ± 0.1 m or 10% of observed spring tidal ranges, and 15% of observed neap tidal ranges.

4) Model phase should generally be within 30 minutes of observed values for both currents and elevations, and there should be a sound relationship between the phasing of currents and elevations.

5) Ideally, these conditions should be satisfied for 90% of position/time combinations evaluated.

For estuarine waters the guidelines are:

1) Modelled current speeds should be within ± 0.2 ms^{-1} or ± 10 – 20% of observed speeds.

2) Modelled directions should be within ± 20° of observed directions.

3) Modelled levels should be within ± 0.1 m of observed ranges at the estuary mouth, and within ± 0.3 m at the estuary head. Alternatively, modelled levels should be within ± 15% of observed spring tidal ranges, and within ± 20% of observed neap tidal ranges.

4) Ideally, these conditions should be satisfied for 90% of position/time combinations evaluated.

Although tidal phase is not expressly covered by the FWR guidelines, Intertek stipulates that model phase should generally be within 30 minutes of observed values for both currents and elevations, and that there should be a sound relationship between the phasing of currents and elevations. It should be noted, however, that in the context of Intertek's typical approach to water quality modelling, phase errors alone are not deemed to be a significant source of long term error. This is because equal weighting is placed on pollutant discharges occurring at different stages of the tide, and the absolute time of discharge is not a factor. Nevertheless, accurate phasing gives confidence that a hydrodynamic model is performing well.

These guidelines provide a good basis for assessing model performance, but experience has shown that they can sometimes be too prescriptive, and visual reality checks are always required. Under certain conditions, models can meet the statistical calibration standards but appear to perform poorly; conversely, seemingly accurate models can fall short of the guidelines. Other factors may also affect how well a model can meet these guidelines, e.g.:

- In areas of low current velocities the standards are either too easily achieved (if the 'absolute' criteria of ± 0.2 ms-1 is applied), or are too difficult to achieve (if the 'relative' criteria of ± 20% of observed speeds is applied).
- It is generally very difficult to meet the current direction standard of ± 10°, particularly in coarse grid models or where instruments and measuring techniques cannot resolve direction to this level of accuracy. A directional range of ± 30° is considered more appropriate and has been used previously in Scotland without detriment to model performance.

In such cases the standards alone cannot be used when assessing the performance of the model, and it is necessary for experienced modellers/oceanographers to offer a critical assessment of model performance taking all the available information into account.

The model has been used to assess a range of conditions covering water levels, currents, waves, sediment transport / coastal processes, and water quality.

The model uses the MIKE21 modelling software. This is an industry-standard modelling package that is used throughout the world. The software is made up of numerous modules that are designed to address different physical processes, either alone or in combination. Areas of application are wide-ranging and, with reference to the Aberdeen Harbour Expansion Project assessment, include:

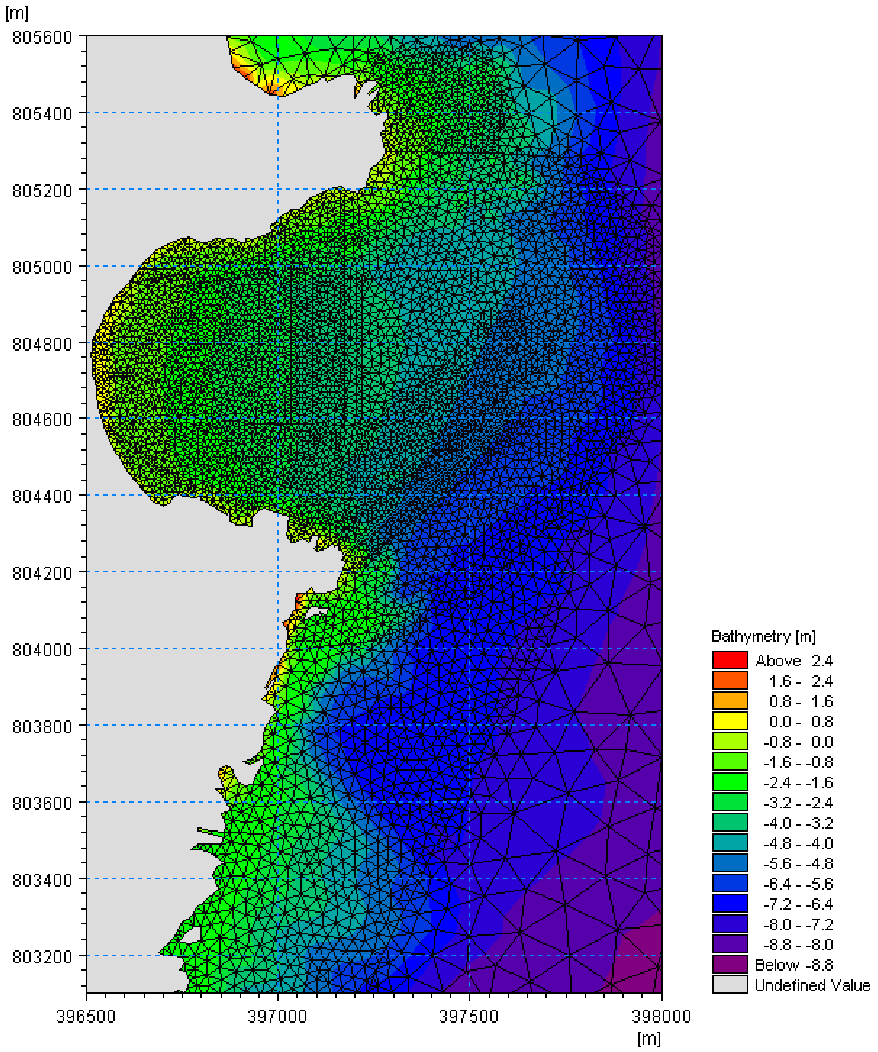
- Hydrodynamics (water levels and currents);
- Waves;
- Sediment transport and coastal processes;
- Coastal flooding; and
- Water quality.

The ACM has been updated using bathymetric data collected in a recent bathymetric survey (Arch Henderson, 2015) undertaken on behalf of Fugro; to better define the seabed within Nigg Bay. Where new data were unavailable, the original model bathymetry has been used. The unstructured model grid has been refined within the development area to increase model resolution. Resolution has also been increased around local sites of importance, e.g. Nigg LSO and St. Fittick's CSO. The original ACM was calibrated and validated with a constant Manning number of 30 $m^{1/3}s^{-1}$, which has also been used in the updated model.

During the refinement process, the proposed expansion plans were incorporated into the model grid generation process, and the model elements were manipulated to enable the development to be added to the baseline model grid to form the model with the development in place without altering the grid structure. Maintaining the grid structure in both the baseline model and the model with the development in place allows for a more accurate impact assessment to be made, as this removes the differences induced by the model grid when two different model grid structures are used.

The grid has a spatial resolution varying from approximately 30 m in the area of interest to approximately 3000 m in the offshore part of the model domain. A total of 15,700 triangular elements are used in the model which covers an area of 1,696 km^2 encompassing Nigg Bay, Aberdeen Harbour, and the rivers Dee and Don to their tidal limits. The model grid and bathymetry of the baseline model at Nigg Bay are shown in Figure 2-1. Vertical datum for the model is mean sea level (MSL).

Figure 2-1: Baseline model grid and bathymetry at the Aberdeen Harbour Expansion



To ensure the ACM maintained its originally approved performance following the update, the model was validated against the historic data used in the original model development. The updated model was validated against current speed, current direction and water level (Appendix A). The data used for calibration and validation of the ACM, covering a period from 30 June 2009 to 1 September 2009, were repredicted using the tidal constituents to remove any short term meteorological effects and provide a clearer tidal signal. Model results are depth averaged. Field data are provided for both depth averaged and non-depth averaged formats. The calibration and validations locations used in the model development are shown in Figure A-1. Model validation results show that the updated model has retained its original model performance, producing the same degree of good fit to the field data (speed, direction and water level) as the originally approved model.

> Model performance has been retained in the updated Aberdeen Coastal Model to produce the same good degree of fit as the originally approved model which was well calibrated and validated against appropriate field data. The updated model is therefore considered fit for the purpose of undertaking hydrodynamic, wave and coastal processes assessments.

The updated ACM has also been validated against field data collected at two locations within Nigg Bay between 20 February 2015 and 6 April 2015. Data from these two locations showed a weak tidal signal and therefore could not be repredicted, resulting in short term meteorological effects remaining in the comparison against the model results.

Figure A-2 to Figure A-5 show comparisons of model predicted current (speed and direction) and field data. The results from the eastern survey location (Figure A-5) show that the model varies by approximately 15-20 degrees to the observed current direction. Receipt of subsequent field data covering the full survey period shows a change in the observed values of approximately 15 degrees (from approximately 175 to 190 degrees) from the 7 April until the end of the survey period on 11 June. The current directions observed in the later portion of the field data are in line with the model results, as shown in Figure A-6 to Figure A-7 and are believed to be more representative than the period used for all sites. Despite the field data from the western survey location showing a weak tidal signal, the current speed and directions predicted by the model produce a good fit and show that the model is able to accurately reproduce the tidal signal within Nigg Bay.

> The ACM has been validated against field data specifically from the development area and has been demonstrated to produce a good fit. The ACM is therefore considered fit for the purpose of undertaking hydrodynamic, wave and coastal processes assessments.

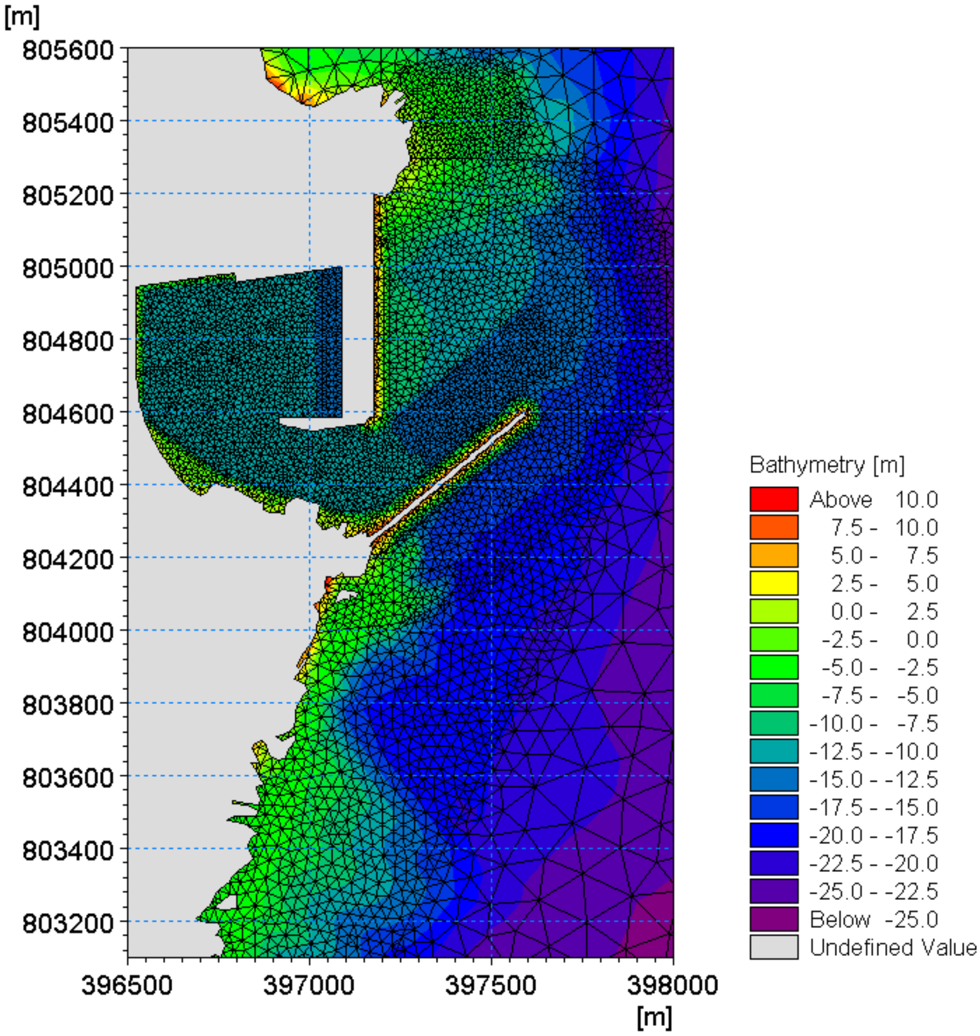
2.2 Operational Phase Model

Consistency in the model grid structure between the baseline model and the model with development in place was maintained by constructing the baseline model grid with the outline of the development included in the grid generation process. This enabled the area occupied by the development to be removed from the baseline grid, thus ensuring that where the two grids coincide, the elements are identical so that any differences resulting from any grid mismatch are removed.

The bathymetry of the operational model was updated to meet the proposed dredging depths as detailed in the development plan. The bathymetry at the breakwaters has been represented as sloping from the top of the breakwaters to the seabed. The gradient of the slope is controlled by the top of the structure and the seabed. The north-west corner of the quay side contains a suspended deck. Under this structure, rock armour will be installed. This has been included using the same method as the breakwaters.

The grid of the operational model is shown in Figure 2-2.

Figure 2-2: ACM showing operational phase grid and bathymetry



2.2.1 Construction Phase Model

The construction phase model version represents the development at the mid-point in the construction. This is required to check the environmental impacts of the construction process.

The construction phase grid was produced using the same method as the development grid, with the areas occupied by the partially complete breakwaters. Bathymetry has been changed where the breakwaters will be (to represent the completed groundworks) and the slopes detailed in the 'with development' grid have also been applied.

3 HYDRODYNAMIC MODELLING

The hydrodynamic (HD) modelling assessment covers modelling of water levels, tidal currents, wave processes, wave induced littoral currents and sediment dynamics. The HD model predicts water levels and tidal current speeds and directions, and the spectral wave (SW) model predicts the wave processes. These are used in combination with the sediment transport (ST) model to assess sediment dynamics, and the particle tracking (PT) model to assess sediment plumes and water quality impacts.

3.1 HD Model Scenarios

Three HD model scenarios are modelled to represent a range of different environmental conditions (i.e. currents and water levels): the average condition, a typical storm condition, and an extreme condition. All three HD scenarios have been run for both the baseline and operational phase configurations. In addition, the average condition has also been run for the construction phase.

The HD scenarios have been selected to represent: normal (average) conditions; a 1 in 1 year storm condition; and a 1 in 200 year extreme condition. For conservatism, the 1 in 200 year condition will assume a 1 in 200 year river flow combined with a 1 in 200 year water level event (storm surge plus high tide), although in reality it is physically unlikely that these two extreme events would coincide.

The 1 in 200 year water level represents a combination of storm surge level and a high (spring) tide. The method for calculating the total water level is based on SEPA technical guidance for undertaking strategic Flood Risk Assessment (SEPA, 2012). This draws on technical and practical guidance on coastal flood boundaries published by the Environment Agency and supported by (amongst others) SEPA and the Scottish Government (Environment Agency, 2011a; 2011b). The HD model scenarios undertaken are shown in Table 3-1.

Table 3-1: Modelled HD Scenarios

Environmental scenario	Tidal Conditions	Fluvial Discharge	Storm Surge Level
Average	Mean spring-neap tidal cycle	Mean	No storm surge event
Storm	Mean spring	High fluvial discharge (10-percentile)	No storm surge event
Extreme	High spring	1:200 year discharge event	1:200 year storm surge event

3.2 SW Model Scenarios

A discrete number of wave conditions have been defined along the offshore boundaries of the SW model, through analysis of the UK Met Office ReMap model data. These wave conditions have been run through the SW model in order to provide predictions of the wave climate in Nigg Bay and its surrounding area.

Modelled wave conditions represent average conditions, annual maximum conditions and extreme conditions. A tidal water level equivalent to high water

(HW) on a mean spring tide has been applied in each scenario. In addition, for the sediment transport scenarios, the SW model has been run in conjunction with the HD model to simulate the littoral currents and the ST regime.

Based on the location and exposure of Nigg Bay, three key wave directions, i.e. northeast, east and southeast, have been assessed. Table 3-2 provides a summary of model scenarios for the wave modelling.

Table 3-2: SW model environmental scenarios

Environmental scenario	Return period (years)	Fluvial Discharge	Incident directions
Average	Annual mean (50 %ile)	Mean	45^0, 90^0, 135^0
Annual	1:1	Mean	45^0, 90^0, 135^0
Extreme	1:200	1:200 year discharge event	45^0, 90^0, 135^0

The above wave conditions selected to represent the baseline have also been modelled for the operational phase configuration, to enable a relative assessment of the impacts on the wave climate

3.3 ST Model Scenarios

The coastal processes assessment draws on output from the sediment transport model. The baseline sediment transport model is used to establish the existing sediment transport regime.

The sediment transport model has been run for the set of hydrodynamic and wave conditions that represent the typical (average) hydrodynamic regime and wave climate. These model results have been used to derive sediment transport rates, by weighting the model results based on their frequency of occurrence. Sediment erosion and deposition patterns and sediment transport pathways have been determined.

As sediment transport in the coastal waters is strongly dependent on the amplitude of the waves, four wave conditions from each direction are included in the sediment transport modelling, i.e. 50%ile, 90%ile, 97%ile and 99%ile waves. Wave conditions used in the model are derived through analysis of the UK Met Office ReMap model data. Extreme significant wave height values were calculated by fitting a three-parameter Weibull function to the cumulative frequency of observed significant wave heights. Results of this process were then evaluated against Fenton’s limit. Table 3-3 gives a summary of wave conditions used in the sediment transport modelling. Their frequencies of occurrence are given in Table 3-4, which provides the weighting factor for deriving the net sediment transport.

Table 3-3: Modelled wave conditions derived from ReMap model data

Mean Wave Direction (degree)		0	45	90	135	180	225	270	315
50 %ile	Hs (m)	0.96	0.86	1.09	1.00	1.01	0.85	0.82	0.87
	Tp (s)	6.75	6.75	7.00	6.00	5.00	5.25	3.50	3.50
95 %ile	Hs (m)	2.20	2.01	2.68	2.62	2.21	1.73	1.72	1.77
	Tp (s)	8.75	9.00	9.25	7.75	6.75	6.75	4.50	4.75
97 %ile	Hs (m)	3.09	2.98	3.88	3.65	3.03	2.30	2.18	2.30
	Tp (s)	9.50	9.25	10.25	8.75	7.50	7.50	5.25	5.25
99 %ile	Hs (m)	3.81	3.83	4.73	4.53	3.69	2.73	2.65	2.86
	Tp (s)	9.75	9.50	10.50	9.25	8.25	8.00	5.50	5.75

Table 3-4: Spectral wave frequency of occurrence

Wave Direction (degree)	Frequency of Occurrence (percentage of time)
0	17.79
45	18.70
90	13.49
135	18.15
180	22.65
225	5.26
270	1.32
315	2.65

The sediment grain size distribution used in the model was determined using field data obtained by Centre for Marine and Coastal Studies and Soil Engineering Geoservices at locations within Nigg Bay. Sediment data from the Centre for Marine and Coastal Studies consist of three samples analysed using laser sizing conducted on 4 February 2015. Data from Soil Engineering Geoservices were collected in 2013 and consist of 50 boreholes and 18 trial pits. Results from depths greater than 0.50 m were not used in the calculation as they would not be representative of the surface sediments.

Analysis showed that distributions of the particulate material are not significantly different across the site, with a small range of grain sizes dominating the distribution. Therefore a representative grain size for the whole site has been applied to the model. Results from the sediment grain distribution analysis are shown in Table 3-5.

Table 3-5: Nigg Bay sediment grain size distribution

Sediment Category	Mean Grain Size (mm)	Settling Velocity (m/s)	Volume (%)
Very Coarse Gravel	47.75	1.4171	1.75
Coarse Gravel	24.00	1.0560	2.81
Medium Gravel	11.94	0.7968	2.91
Fine Gravel	5.93	0.5548	2.28
Very Coarse Gravel	3.00	0.3494	5.15
Very Coarse Sand	1.50	0.2030	4.05
Coarse Sand	0.75	0.1031	7.94
Medium Sand	0.38	0.0471	17.82
Fine Sand	0.19	0.0179	42.81
Very Fine Sand	0.09	0.0054	5.52
Mud	0.03	0.0007	6.45

In addition, sediment plume modelling has been undertaken using a Particle Tracking (PT) model driven by output from the HD model. The PT model has been used to assess impacts resulting from the existing maintenance dredging of the Aberdeen Harbour and the capital dredging of the Aberdeen Harbour Expansion Project. The dredging modelling results are reported separately.

3.4 Future Conditions (Climate Change) Scenarios

The quantified changes to hydrodynamic, wave and coastal processes due to the project have been assessed under present climatic conditions (i.e. with no sea level rise or increased storminess). Under a future climate scenario, the quantified changes due to the project are likely to be different to the changes under present climatic conditions.

For the assessment of changes to the hydrodynamic, wave and coastal processes under a different climate in the future, the UK Climate Projection 2009 (UKCP09) predictions of sea-level rise and increased storminess have been applied to the baseline scenario. Storm surge levels are obtained from the Environment Agency (Environment Agency, 2011a).

A time horizon of 85 years from 2015 has been used to determine the level of climate change. This has been selected as it is the longest period available from the UKCP09 projections.

The climate changes applied are summarised in Table 3-6.

Table 3-6: Future (changing) climate projections applied

Parameter	Baseline Condition (2015)	Future Condition (2100)
Sea-level rise (m)	0	+ 0.306 m
Wave height (m)	X	1.1x
Storm surge (m)	X	+ 3.17 m

4 BASELINE CONDITIONS

The baseline represents the present environmental conditions and provides the reference point for assessing changes caused by the Aberdeen Harbour Expansion Project to the environment.

4.1 HYDRODYNAMIC REGIME

The numerical model has been run to predict baseline hydrodynamic conditions around the area of the Aberdeen Harbour Expansion Project and beyond.

4.1.1 Water Level

Nigg Bay is subject to a meso tidal range (spring tidal range is between 2 m and 4 m), with a mean spring tidal range of 3.7 m and a mean neap tidal range of 1.8 m (Aberdeen). The highest astronomical tidal range can reach 4.8 m (Aberdeen).

Model results indicate that water levels in Nigg Bay are not significantly different from the water level recorded at Aberdeen.

4.1.2 Tidal Current

Figure B-1 shows the peak flood and ebb tidal current predicted under mean spring tide conditions for the baseline. Peak tidal currents under mean neap tide conditions are presented in Figure B-2. Plots in two different spatial scales are given in the figures, to show tidal current in a large extent beyond the development area and detailed current patterns around the development area (Nigg Bay).

Model results indicate that current speeds experience a large variation across the development area due to the presence of the headlands, with speeds up to about 0.6 m/s on both the flooding and ebbing spring tides in the outer bay and 0.1 m/s or lower in the inner bay. On both flooding and ebbing neap tides current speeds in the outer bay are approximately 0.4 m/s and less than 0.1m/s in the inner bay.

Current speeds are more uniform offshore, with speeds of 0.5 m/s on both flooding and ebbing spring tides and 0.4 m/s on both flooding and ebbing neap tides.

A large eddy forms within Nigg Bay as a result of the shear flow around the headlands, the direction of which varies with the tides (clockwise on flood tides, and counter-clockwise on ebb tides). Current strengths are greater on flood tides than ebbing tides, under both spring and neap conditions.

Figure B-3 shows the predicted tidal residual currents under mean spring tide conditions, for the baseline. Tidal residual currents under mean neap tide conditions are presented in Figure B-4.

From the model results given in the figures, it can be seen that tidal residual currents are small in the area with straight coastline, but increase significantly around the headland to the north of Nigg Bay. Tidal residual currents around the headland can be as strong as 0.4 m/s under mean spring tide conditions and 0.2 m/s under mean neap tide conditions, with a clockwise circulation of residual current being established in the outer area of Nigg Bay.

Modelled storm conditions show the same tidal regime as during the average scenario shown in Figure B-1 to Figure B-4. Differences between the scenarios (detailed in Table 3-1) are limited to increased river flow and coverage of a mean spring tide. Due to the identical nature of the results the average condition results can be used for the assessment of storm conditions.

4.1.3 Extreme Sea Level

Estimated extreme sea levels (the combination of astronomical tidal level and storm surge non-tidal component) are published in Coastal flood boundary conditions for UK mainland and islands (Environment Agency, 2011a). Sea levels during 1 in 200 year events at Nigg Bay are on average + 2.923 m MSL (with a range of ± 2mm), and at Aberdeen Ballroom BW are + 2.936 m MSL.

4.1.4 Future Climate

Maximum sea levels during future climate conditions (modelled during surge conditions on a high spring tide) are on average +3.229 m MSL. The range predicted for maximum sea level is ± 2 mm, the same as under current climate conditions. The maximum predicted sea level at Aberdeen Ballroom BW is + 3.242 m MSL.

4.2 WAVE CLIMATE

Wave climates within Nigg Bay are influenced by wave shoaling and refraction effects as waves propagate into inshore shallow water where more wave energy is dissipated due to wave breaking and friction on the seabed. Wave climates in Nigg Bay are also influenced by the sheltering effect of headlands.

The SW component of the ACM has been used to model the baseline wave climate. Average wave (mean), annual wave (1:1 year) and extreme wave (1:200 years) from three key directions are modelled to establish the baseline conditions. Offshore wave conditions (wave conditions at the model open boundary) are derived from UK Met Office ReMap model data (35 years: 1980-2014). Table 4-1 provides the offshore wave conditions used in the model.

Table 4-1: Offshore wave conditions from ReMap model data

Environmental Scenario	Wave Direction (deg)	Significant Wave Height (m)	Wave Period (s)
Average	45	0.86	6.8
	90	1.03	7.0
	135	1.00	6.0
Annual	45	5.86	11.0
	90	6.88	11.3
	135	6.62	11.1
Extreme	45	8.89	13.6
	90	10.45	13.9
	135	9.93	13.6

Figure B-5 to Figure B-7 show the model predicted significant wave height and wave propagation directions under the average (mean) conditions, annual conditions (1:1 year return period), and extreme conditions (1:200 year return period). Waves from three key directions are presented in the figures.

Model results in the figures indicate that the wave climate across the development area is highly variable, with large spatial variations in the significant wave height. Under north-easterly waves, the incident wave height is greatly reduced in the north part of the bay, as a result of the sheltering effects of the headland. The area in the south part of the bay is sheltered from the south-easterly waves, with wave heights greatly reduced in the lee of the headland. The bay is more open to the easterly waves, with higher wave heights predicted at the top of the bay under the average wave condition compared to waves from other directions. The wave height within the bay is largely governed by the local water depth under the storm and extreme wave conditions as more wave energy is dissipated on the seabed and the wave height is limited by the local water depth.

4.2.1 Future Climate

Offshore wave conditions during the modelled future climate conditions will be stormier with increased significant wave height. These changes are shown in Table 4-2. Results show greater significant wave heights offshore and within Nigg Bay, with average increases in significant wave height of 4.5 %. However the same distribution of significant wave height is produced within Nigg Bay and along the coastline across all wave directions, demonstrating that wave height remains controlled by local water depth during future conditions. Due to the close similarities between future and current climate results plots for this condition have not been included.

Table 4-2: Offshore wave conditions during future climate scenario

Environmental Scenario	Wave Direction (deg)	Significant Wave Height (m)	Wave Period (s)
Future Climate	45	9.78	13.6
	90	11.49	13.9
	135	10.92	13.6

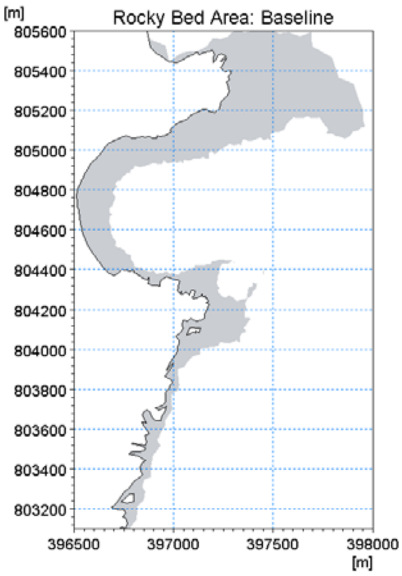
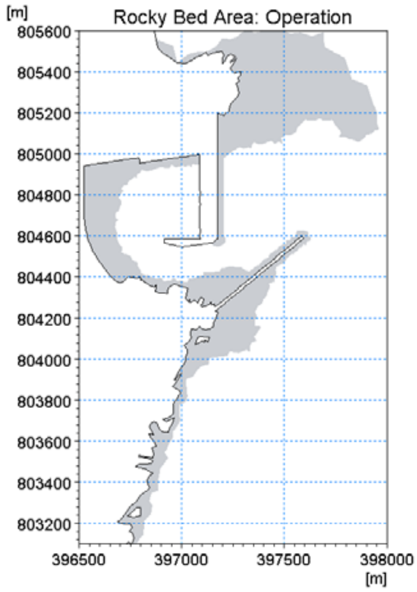
4.3 SEDIMENT REGIME

4.3.1 Seabed Sediment

Geophysical surveys undertaken by Caledonian Geotech (Caledonian Geotech, 2012), on 10 August 2012 to 23 August 2012, highlighted variations in sediment depths across Nigg Bay. Along the coastline, extending east-wards at both headlands, the seabed is rocky. The inner Nigg Bay area is sandy, with areas of sand waves identified. Sediment grain size distribution data collected by Soil Engineering Geoservices, using grab samples and boreholes, and Centre for Marine and Coastal Studies demonstrated a reasonably uniform distribution across the area and agreement on the extent of coarser areas. Coarser (cobble) sediment and rocky areas have the same sediment transport characteristics, and will not provide sediment for erosion except under the most extreme conditions. These areas have been combined in the sediment transport modelling.

Figure 4-1 shows the distribution of rocky (grey) and sandy (white) areas that have been applied in the model. Rocky areas do not provide sediment for erosion, but sediment can be deposited (and subsequently moved) at these locations. Sediment grain size distributions showed mean grain sizes of fine to medium sand (0.125 mm to 0.500 mm) across the area. Uniform sediment values of medium sand (0.375 mm) were applied across the area, with the sediment grading covering the range of grain sizes. During the operational phase, breakwater slopes have been assigned rock characteristics.

Figure 4-1: Seabed sediment distribution

<table>
<tr><th>Baseline Sediment Distribution</th><th>Operational Sediment Distribution</th></tr>
<tr><td>
</td><td>
</td></tr>
</table>

4.3.2 Sediment Transport and Pathway

Sediment transport is driven by the combined effects of tidal current and wave action, with the sediment pathways governed by the residual current as a result of asymmetry between flood and ebb tides. Sediment pathways are also determined by wave conditions as a result of littoral transport driven by wave breaking and alongshore current.

The sediment transport (ST) component of the ACM has been used to model sediment transport under the baseline conditions. As wave conditions significantly influence alongshore sediment transport, four wave conditions from each direction (8 direction sectors, no wave is applied for directions of 225^{o}, 270^{o}, and 315^{o}), i.e. 50%ile, 90%ile, 97%ile and 99%ile waves, have been modelled, so a better estimation on net sediment transport can be derived. A summary of the wave and wind conditions applied in the sediment transport modelling are shown in Table 3-3.

Sediment transport pathways are presented for the three key directions under the 90%ile wave condition only as the direction of the sediment transport is not significantly changed by the wave height. Figure B-8 shows sediment transport pathways under the three key wave directions. The vectors in this figure have been included to show the sediment transport direction and magnitude within Nigg Bay and the offshore area.

Both north-easterly and easterly waves produce a southerly movement of sediment outside of Nigg Bay. However, north-easterly waves produce a clockwise circular movement of sediment within the bay, while the easterly waves transport sediment into the top of bay at both the north and south shores of the bay.

South-easterly waves produce a northerly sediment transport movement, with areas of increased load along the coastline south of Nigg Bay and both headlands. South-easterly waves cause an anti-clockwise circular movement of sediment within the bay.

The net sediment transport is calculated by weighting the 64 model results (4 wave conditions x 8 directions x 2 tides) according to their frequency and is shown in Figure B-9. The model results indicate the net sediment transport pathway outside of Nigg Bay is from south to north along the coast. There is a net movement of sediment into the top of the bay at both the north and south shores of the bay, and a clockwise circular movement of sediment is established to the east of the bay.

5 OPERATIONAL PHASE CONDITIONS

This section provides a detailed assessment of the proposed development on the hydrodynamics, waves and coastal processes. The discussion is divided into changes to the hydrodynamic regime, changes to the wave climate, and changes to the sediment regime. Finally, the assessment of potential changes due to the future (or changing) climate are discussed.

The scenarios used for the assessment were modelled for both the baseline and the 'with development' configuration, and the results compared to identify any differences. The baseline results were subtracted from the 'with-development' results, so that positive changes indicate an increase (e.g. in current speed) due to the development, and negative changes show a decrease.

It should be noted, all numerical models represent numerical approximations to real world physical processes and are subject to errors and uncertainties, although the model has been demonstrated to perform well when compared to field data, and meet the guideline standards set out in the Foundation for Water Research (FWR) document 'A Framework for Marine and Estuarine Model Specification in the UK'.

Model predicted impacts of the development are presented in two scales, to show the near-field impacts (small extent to show the impacts local to the development) and far-field impacts (large extent to show the impacts further away from the development).

5.1 Hydrodynamics

Changes to the hydrodynamic regime have been modelled over three environmental scenarios as detailed in Table 3-1. Average conditions represent the mean hydrodynamic regime, covering tidal currents and river flow. Changes during the HD storm conditions are limited to increases in river flow, to assess changes to coastal processes and sediment movement. Extreme HD conditions include the effects of surge levels during high spring tide and extreme (1:200 year) river flow.

5.1.1 Water Level

5.1.1.1 Average Condition

Figure C-1 shows the model predicted changes of maximum water level under mean spring tide conditions. Plots in two different spatial scales are given in the figures, to show changes in a large extent beyond the development area and detailed changes around the development area.

Far-Field

Model results given in the figures indicate that the proposed development will not cause any large changes to far-field maximum water levels during the operational phase.

Near-field

Model results show that maximum changes in the maximum water level under mean spring tide conditions are less than 10 mm. Within the harbour the maximum water level shows an increase by an average of 4 mm (ranging from 3 to 5 mm) over an area of approximately 400 m x 250 m. Smaller areas within the navigation channel are predicted to increase by up to 4 mm, with a localised maximum increase of 8 mm. The eastern end of the southern breakwater shows an increase of 3 mm.

South of the development, the maximum water level of an area (approximately 750 m x 700 m) is predicted to decrease by up to 10 mm, with an average reduction of 6 mm. This area represents where the flow on the flood tide is blocked by the southern breakwater, resulting in flow bypassing this area, and producing lower water levels.

Table 5-1 shows the changes at the 10 specified locations, see Figure 1-2. Maximum changes of +4 mm are predicted at location six, with other locations experiencing average changes of +3 mm, including at Nigg Bay SSSI. The predicted near-field changes of (up to) 10 mm are approximately 0.27 % of the mean spring tidal range of 3.7 m.

Table 5-1: Change in maximum water level under average condition

Location	Baseline (m)	Operational (m)	Difference (m)
1	1.653	1.653	0.000
2	1.654	1.657	0.003
3	1.656	1.658	0.003
4	1.656	1.659	0.003
5	1.656	1.659	0.003
6	1.655	1.659	0.004
7	1.653	1.654	0.001
BW_1	1.662	1.662	-0.001
SSSI_1	1.656	1.659	0.003
SSSI_2	1.656	1.659	0.003

5.1.1.2 Storm Condition

Far-Field

Model results indicate that the proposed development will produce equivalent changes during annual conditions as during average conditions, and will not cause any large changes to far-field maximum water level during the operational phase.

Near-field

Predicted changes to the near-field water elevations are the same as those during average conditions presented in section 5.1.1.1, with the extracted results shown in Table 5-2. Due to the impact of the development being identical to the average conditions, plots have not been included (Figure C-1should be used for reference), and the results will not be discussed further.

Table 5-2: Change in maximum water level under storm condition

Location	Baseline (m)	Operational (m)	Difference (m)
1	1.653	1.653	0.000
2	1.654	1.657	0.003
3	1.656	1.658	0.003
4	1.656	1.659	0.003
5	1.656	1.659	0.003
6	1.655	1.659	0.004
7	1.653	1.654	0.001
BW_1	1.663	1.662	-0.001
SSSI_1	1.656	1.659	0.003
SSSI_2	1.656	1.659	0.003

5.1.1.3 Extreme Condition

Figure C-2 shows the model predicted changes of maximum water levels under storm surge conditions. Plots in two different spatial scales are given in the figures to show changes in a large extent beyond the development area and detailed changes around the development area.

Far-field

Model results given in the figure indicate that the proposed development will not cause any large changes to far-field maximum water level during the operational phase.

Near-field

Increases in water elevation are predicted within the harbour of up to +11 mm (0.30% of spring tidal range), with an average change of +8 mm. Nigg Bay SSSI will be subject to a water level increase of 7 mm.

Increases within the navigation channel range from 6 mm to 8 mm, along with average increases of 4 mm east of the development area. Maximum water levels around the southern breakwater will increase by up to 9 mm. South of the development, an area (800 m x 1000 m) is predicted to experience decreases in maximum water levels ranging from -4 mm to -10 mm.

Table 5-3 provides a summary of the changes in water elevations during the operational phase.

Table 5-3: Change in maximum water level under extreme condition

Location	Baseline (m)	Operational (m)	Difference (m)
1	2.920	2.924	0.004
2	2.921	2.929	0.008
3	2.924	2.931	0.007
4	2.924	2.932	0.007
5	2.924	2.932	0.008
6	2.922	2.932	0.01
7	2.920	2.926	0.006
BW_1	2.936	2.935	-0.001
SSSI_1	2.924	2.932	0.007
SSSI_2	2.924	2.932	0.007

5.1.1.4 Future (Changing Climate) Conditions

Figure D-1 shows the model predicted changes in maximum water level under extreme conditions, with climate change taken into account. Plots in two different spatial scales are given in the figure, to show changes in a large extent beyond the development area and detailed changes around the development area.

Far-field

Model results given in the figure indicate that the proposed development will not cause any large changes to maximum water levels in the far-field during the operational phase.

Near-field

Model results show that the maximum increase in water levels under future extreme conditions is less than 10 mm. Within the harbour maximum water levels increase by an average of 5 mm, with a maximum increase of 8 mm. Increases are predicted to the north (up to Girdle Ness). South of the development, reductions in water level are predicted over an 850 m x 1200 m area, with maximum changes of -12 mm. Maximum water levels at Nigg Bay SSSI increase by 5 mm, and there is no impact at Aberdeen Ballroom BW. Results from this scenario are shown in Table 5-4.

Table 5-4: Future climate scenario water level changes

Location	Baseline (m)	Operational (m)	Difference (m)
1	3.227	3.230	0.003
2	3.228	3.235	0.007
3	3.231	3.236	0.005
4	3.231	3.236	0.005
5	3.231	3.236	0.006
6	3.229	3.236	0.008
7	3.227	3.232	0.005
BW_1	3.242	3.242	-0.001
SSSI_1	3.231	3.236	0.005
SSSI_2	3.231	3.236	0.005

5.1.2 Current

5.1.2.1 Average Condition

Figure C-3 shows the model predicted changes in mean tidal current speed. Plots in two different spatial scales are given in the figures to show changes in a large extent beyond the development area and detailed changes around the development area. Changes in the maximum tidal current speed are presented in Figure C-4.

Comparisons of the current speed and direction are shown in Figure C-5, presented as vector plots. In the plot, black arrows represent current speed and direction under the baseline, and red arrows represent the conditions during the operational phase. Contours in the plots are based on the current speed with the development in place.

Changes in the tidal residual current speed are shown in Figure C-7, and Figure C-8 gives vector plots to show the changes in flow patterns.

Far-field

Figure C-4 shows the model predicted changes of maximum current speeds over a large extent. Model results given in the figures indicate that the proposed development will not cause any large changes to far-field tidal currents during the operational phase.

Near-field

Near-field changes to current speeds are greatest at the southern breakwater, with a maximum reduction of 0.40 m/s during both spring and neap tides (Figure C-3 and Figure C-4). Within the harbour, average reductions of -0.10 m/s are shown on both tides. Current speed reductions at Nigg Bay SSSI range from -0.04 to -0.01 m/s (Table 5-5).

The navigation channel shows different reductions depending on the tide. Spring tides show changes up to -0.50 m/s, compared to -0.30 m/s on neap tides. South of the southern breakwater an area approximately 400 m x 650 m shows average reductions of -0.20 m/s, with a maximum decrease of -0.65 m/s during spring and neap tides. East of the southern breakwater a north-south trending area (approximately 400 m x 700 m on spring tides) is predicted to increase maximum current speeds by 0.05 m/s, resulting in maximum speeds locally exceeding 1.0 m/s. On spring tides, a smaller area (150 m x 200 m) south of the development is also predicted to increase in speed by 0.10 m/s.

Table 5-5: Average scenario current speed extraction results

Location	Baseline (m/s)	Operational (m/s)	Difference (m/s)	Difference (%)
1	0.330	0.197	-0.133	-40.39
2	0.306	0.039	-0.267	-87.13
3	0.103	0.024	-0.079	-76.80
4	0.092	0.022	-0.070	-75.65
5	0.110	0.010	-0.100	-90.71
6	0.181	0.011	-0.170	-93.77
7	0.453	0.166	-0.287	-63.25
BW_1	0.099	0.100	0.001	0.78
SSSI_1	0.048	0.009	-0.039	-81.09
SSSI_2	0.043	0.032	-0.011	-25.38

The current field within the development area is predicted to change as eddy currents formed in Nigg Bay under the baseline will disappear when the development is in place (Figure C-5). On flood tides the current direction is predicted to diverge from the baseline scenario around the breakwaters. The northern breakwater produces eddies along the outer wall, resulting in the reversal of current directions (180^0). The southern breakwater increases the easterly component of flow, changing directions by up to 40^0. This influence extends 600 m north of the breakwater and up to 500 m east. South of the development the current direction is also reversed (180^0) from baseline conditions due to the presence of eddy currents. Approximately 1000 m south of the development, the current direction returns to baseline conditions, with flow direction (and magnitude) unchanged.

Ebb tides are predicted to be affected up to 200 m south of the development area, with divergence occurring around the southern breakwater, where the eastward component of flow increases with the changes up to 45^0. Flow immediately north of the southern breakwater approaches baseline conditions for 200 m before diverging, with an increase in the westerly flow component of up to 90^0. Flow along the northern breakwater is predicted to develop eddy currents that reverse the flow direction.

Changes to the current direction cover a similar spatial extent on both spring and neap tides, with a greater magnitude of change during spring tides. Resulting conditions within the harbour are similar under all tidal conditions.

South of the development, average increases of 0.05 m/s are predicted for the tidal residual current (Figure C-7). Impact magnitudes are comparable on both spring and neap tides, with a larger spatial extent on spring tides. Spring tides produce increases in residual currents following a south-west to north-east trend. Increases are greatest south of the development, averaging 0.06 m/s, with changes from 0.02 m/s to 0.17 m/s. Decreases occur around the inner harbour and northern breakwater, with the greatest change -0.16 m/s (at St. Fittick's point), and average changes of -0.03 m/s within the harbour. Changes on neap tides demonstrate a similar distribution and magnitude. The maximum predicted changes during neap tides are +0.16 m/s (at the end of the southern breakwater) and -0.13 m/s (at St. Fittick's point). Average residual current results are at the data extraction locations are provided in Table 5-6.

Table 5-6: Average scenario residual current extraction results

Location	Baseline (m/s)	Operational (m/s)	Difference (m/s)	Difference (%)
1	0.074	0.055	-0.020	-26.21
2	0.057	0.006	-0.051	-88.81
3	0.004	0.003	-0.001	-35.87
4	0.008	0.011	0.003	35.29
5	0.023	0.008	-0.015	-65.66
6	0.045	0.006	-0.038	-85.59
7	0.046	0.044	-0.002	-5.39
BW_1	0.005	0.003	-0.002	-34.07
SSSI_1	0.004	0.001	-0.003	-71.28
SSSI_2	0.003	0.003	-0.001	-20.93

5.1.2.2 Storm Conditions

Far-field

Model results indicate that the proposed development will not cause any large changes to far-field tidal currents during the operational phase.

Near-field

Changes to near-field current speeds during storm conditions, are the same as during the average conditions scenario shown in Figure C-6.

Table 5-7 provides the results from the extraction locations, demonstrating the similarity between the scenario results. As the impacts are the same as the average scenario, they will not be discussed further.

Table 5-7: Storm scenario current speed extraction results

Location	Baseline (m/s)	Operational (m/s)	Difference (m/s)	Difference (%)
1	0.330	0.197	-0.133	-40.42
2	0.307	0.039	-0.267	-87.18
3	0.103	0.024	-0.079	-76.72
4	0.092	0.023	-0.069	-75.40
5	0.110	0.010	-0.100	-90.53
6	0.181	0.011	-0.170	-93.68
7	0.453	0.166	-0.286	-63.25
BW_1	0.099	0.100	0.001	0.78
SSSI_1	0.048	0.009	-0.039	-81.48
SSSI_2	0.043	0.030	-0.013	-29.98

Residual tidal currents during storm conditions shown in Table 5-8 are predicted to produce the same changes (in terms of magnitude and spatial distribution) as during the average environmental conditions.

Table 5-8: Storm scenario residual current extraction results

Location	Baseline (m/s)	Operational (m/s)	Difference (m/s)	Difference (%)
1	0.074	0.056	-0.019	-25.22
2	0.057	0.006	-0.051	-88.69
3	0.004	0.003	-0.001	-33.29
4	0.008	0.011	0.003	40.11
5	0.023	0.008	-0.015	-64.84
6	0.045	0.007	-0.038	-85.3
7	0.046	0.044	-0.002	-4.54
BW_1	0.005	0.004	-0.002	-32.55
SSSI_1	0.003	0.001	-0.002	-71.35
SSSI_2	0.003	0.002	-0.001	-30.38

5.2 WAVE CLIMATE

Changes to the wave climate due to the development have been modelled using the ACM SW model. The plots show the predicted changes to significant wave height due to the development on both the local scale (near-field) and regional scale (far-field). The environmental scenarios discussed in this section are detailed in Table 3-2.

5.2.1 Significant wave height

Figure C-10 shows the model predicted significant wave height and wave propagation directions during the operation phase, under the average (mean) conditions. Changes in significant wave height under the average conditions, as a result of the development, are presented in Figure C-11. Model results for waves from three key directions are presented in the figures with two different spatial scales, to show wave conditions or changes in a large extent beyond the development area and detailed wave conditions or changes around the development area. Model results for the 1 in 1 year waves are given in Figure C-12 and Figure C-13 and for the 1 in 200 year wave the results are shown in Figure C-14 and Figure C-15.

Far-field

Model results given in the figures indicate that the proposed development will not cause any large changes to far-field wave climate during the operational phase.

Near-field

From the model results presented in the figures it can be seen that the significant wave height is greatly reduced inside the harbour as a result of sheltering effects provided by the two breakwaters. Table 5-9 provides a summary of the changes to the significant wave height at the key locations. Significant wave heights during average conditions are predicted to decrease within the harbour. The north-easterly wave is the only direction where the wave height is not reduced within the navigation channel, producing significant wave heights of ~3.0 m at the harbour entrance. Reductions of -0.2 m to -0.9 m are predicted along the southern and northern breakwaters across all scenarios.

Table 5-9: Changes in significant wave height

Scenario	Average			Annual			Extreme		
Location	45^0	90^0	135^0	45^0	90^0	135^0	45^0	90^0	135^0
1	0.010	-0.019	-0.443	0.075	-0.329	-2.207	0.129	-0.328	-2.271
2	-0.099	-0.730	-0.755	-1.494	-4.373	-4.489	-2.693	-5.684	-6.399
3	-0.499	-0.622	-0.224	-2.739	-2.874	-2.028	-2.866	-2.962	-2.681
4	-0.442	-0.988	-0.517	-3.328	-3.992	-3.654	-4.028	-4.352	-4.172
5	-0.296	-0.922	-0.798	-2.486	-4.489	-4.514	-3.915	-4.954	-5.057
6	-0.643	-0.982	-0.728	-4.318	-5.429	-4.630	-5.771	-6.124	-5.693
7	-0.018	-0.459	-0.707	-0.660	-3.294	-4.197	-1.441	-4.634	-6.090
BW_1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SSSI_1	-0.454	-0.903	-0.331	-2.374	-2.553	-2.414	-2.554	-2.761	-2.716
SSSI_2	-0.475	-0.584	-0.162	-2.026	-1.996	-1.636	-1.956	-1.998	-1.958

Significant wave heights under annual conditions are predicted to decrease within the harbour, ranging from 4.4 m to 5.7 m (on 90^0 and 135^0 waves respectfully). Significant wave heights in the navigation channel show average reductions of approximately 4 m. Increases during north-easterly waves are only predicted at the end of the southern breakwater and along the northern breakwater, with maximum increases of 0.3 m. Easterly and south-easterly waves are predicted to increase significant wave heights along the southern breakwater.

Extreme wave conditions predict maximum decreases of 6.6 m within the harbour, with the navigation channel experiencing decreases up to 8.8 m and a minimum change of -1.8 m. The northern breakwater produces increases of 0.5 m over an area of 30 m x 300 m during north-easterly waves, decreasing to 50 m x 40 m on 135^0 waves. Increases offshore of the southern breakwater of 0.2 m to 1.0 m are predicted.

It should be noted that reduction of significant wave height may be over predicted as wave diffraction is only partially accounted for in the model software.

5.2.2 Peak Wave Period

Far-field

Model results indicate that the proposed development will not cause any large changes to far-field wave period during the operational phase.

Near-field

Small changes in the peak wave periods as a result of the development are predicted, with no significant difference among the average, annual and extreme waves. Table 5-10 provides a summary of the predicted changes at key locations.

Table 5-10: Changes to peak wave period during the operational phase

Scenario	Average			Annual			Extreme		
Location	45^0	90^0	135^0	45^0	90^0	135^0	45^0	90^0	135^0
1	0.005	-0.004	0.004	0.000	-0.015	0.032	0.003	-0.027	0.011
2	-0.087	0.030	0.121	-0.100	-0.001	0.111	-0.085	-0.017	0.075
3	-0.024	-0.049	-0.051	-0.067	-0.058	0.013	-0.076	-0.048	0.005
4	0.070	0.032	-0.051	-0.005	0.029	0.131	-0.025	0.039	0.111
5	0.069	0.032	-0.051	0.036	0.126	0.234	0.009	0.128	0.192
6	0.069	0.032	-0.051	0.244	0.405	0.233	0.150	0.302	0.320
7	-0.028	-0.015	0.043	-0.059	-0.029	0.070	-0.059	-0.034	0.057
BW_1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SSSI_1	-0.033	-0.026	0.026	-0.063	-0.055	0.028	-0.069	-0.042	0.019
SSSI_2	-0.035	-0.049	-0.081	-0.061	-0.052	0.015	-0.072	-0.045	0.006

5.2.3 Future (Changing Climate) Conditions

Figure D-2 shows the model predicted changes in significant wave height under future extreme conditions, with climate change taken into account.

Far-field

Model results indicate that the proposed development will not cause large changes to far-field wave climate during the operational phase.

Near-field

From the model results presented in the figure it can be seen that significant wave heights are greatly reduced inside the harbour as a result of sheltering effects provided by the two breakwaters. Increases in significant wave height are predicted in front of the breakwaters, with a maximum increase of approximately 0.8 m predicted.

Table 5-11 provides a summary of the changes to the significant wave height at the key locations.

Table 5-11: Changes in key wave properties during future climate scenario

Parameter	Significant Wave Height (m)			Peak Wave Period (s)		
Location	45^0	90^0	135^0	45^0	90^0	135^0
1	0.140	-0.334	-2.257	0.003	-0.028	0.009
2	-2.850	-5.860	-6.677	-0.086	-0.020	0.076
3	-2.955	-3.073	-2.779	-0.079	-0.050	0.002
4	-4.187	-4.525	-4.342	-0.028	0.037	0.107
5	-4.103	-5.130	-5.241	0.007	0.129	0.187
6	-5.989	-6.316	-5.894	0.142	0.301	0.314
7	-1.521	-4.781	-6.339	-0.057	-0.034	0.057
BW_1	0.000	0.000	0.000	0.000	0.000	0.000
SSSI_1	-2.704	-2.929	-2.868	-0.075	-0.046	0.014
SSSI_2	-2.054	-2.104	-2.034	-0.074	-0.047	0.002

5.3 SEDIMENT REGIME

Figure C-16 shows the model predicted sediment transport pathways during the operational phase. Model results are presented for the three key directions under the 90%ile wave condition which shows the general trend of sediment transport directions.

Figure C-17 shows net sediment transport pathways for both the baseline and operational phase, from which changes in the net sediment transport can be understood.

Figure C-18 shows sediment deposition and erosion patterns for both the baseline and operational phase. Changes in sediment deposition and erosion pattern can be identified by comparing baseline and operational phase results presented in the figure.

Far-field

Model results given in the figures indicate that the proposed development will not cause any large changes the sediment transport pathway and sediment deposition and erosion patterns in far-field during the operational phase.

Near-field

Sediment transport pathways outside the development area are not greatly affected by the development (Figure C-16). Both north-easterly and easterly waves still produce a southerly movement of sediment outside of Nigg Bay, and south-easterly waves cause a northerly sediment transport. Inside the development area, sediment transport pathways are largely affected by the development, with minimal sediment movement within the harbour as wave action is greatly reduced by the presence of the breakwaters. All wave directions predict a reduction in the flux within the harbour. Sediment may be driven to the navigation channel along the northern breakwater by wave action under some wave conditions.

Similar to the sediment transport pathway under a specific wave condition, the net sediment transport pathway (calculated by weighting results according to wave condition frequency) outside the development area is not greatly affected by the development (Figure C-17). However, sediment movement to Nigg Bay has been largely stopped as a result of protection provided by the breakwaters.

Sediment deposition and erosion patterns in Nigg Bay will be altered as a result of the development. Under the baseline condition (first plot in Figure C-18), areas of deposition and erosion as a result of continuously reworked seabed by the actions of waves and currents, can be seen. However, with the development in place there would be very little movement of sediment within the harbour due to the reduced wave action and current (second plot in Figure C-18). As a result of weak wave action and small current in the harbour, fine sediments brought into the harbour from the local streams and washed off from the coast would likely to be deposited in the harbour.

Outside of the proposed Aberdeen Harbour Expansion Project sediment transport pathways are largely unchanged during the operational phase, except within the vicinity of the breakwaters. Figure C-16 shows sediment transport directions are deflected by the structure, with the largest changes shown around the southern breakwater. The same pattern is shown in Figure C-17 where the largest increase in net load occurs at this location due to the increase in current speed.

Figure C-18 shows the deposition and erosion patterns during the operational phase are unchanged outside the proposed harbour, with the exception of the area around the breakwaters. Erosion can be seen to increase along the northern breakwater and at the end of southern breakwater where sediment is available for erosion. Deposition is increased south of the southern breakwater due to the sheltering effects of this structure producing lower energy conditions. Sediment deposition can also be seen along the edge of navigation.

Deposition and erosion patterns in areas where rock has been modelled (as shown in Figure 4-1) should be assessed carefully as these locations will affect the erosion and deposition patterns produced, with the outline of the rocky area shown in Figure C-18. In these areas sediment deposition will occur during low energy events, but will not be eroded during high energy conditions (as no sediment is available). Previous figures indicate an increase in sediment transport at the end of the southern breakwater, which is related to an increase in current speed and sediment flux at this location. However, as the rock armour has been included in the model there is no sediment available for erosion at this location, and as a result no decrease in bed level during high energy conditions. Sediment is deposited along the breakwaters during some wave conditions due to the reduced water depth, which produces an increase in bed level. This process is also present along the coastline south of Nigg Bay.

It should be noted that sediment modelling is very challenging with large uncertainty and a wide band of acceptable error in the underlying methods. Model results presented here provide indicative sediment transport pathways and sediment deposition and erosion patterns, and should not be used to derive long-term deposition and erosion rates.

5.4 SEDIMENT PLUME MODELLING

Modelling of the maintenance dredging operations at Aberdeen Harbour Expansion Project has been undertaken using the PT module of the ACM. This work is reported separately.

6 CONSTRUCTION PHASE CONDITONS

Hydrodynamics under the construction phase have been modelled to provide the flow field to drive the particle tracking model for dredging plume modelling. These model results are also used to assess the changes in hydrodynamics caused by the development during the construction phase, from which changes on sediment transport can be interpreted.

6.1 HYDRODYNAMICS

Figure E-1 presents vector plots showing the changes in tidal current field from the baseline during the construction phase. In the plots black arrows represent current speed and direction during the baseline condition, and red arrows represent the construction phase. Contours in the plots are based on the current speed during the construction phase.

Changes and differences in the tidal residual current are shown in Figure E-2 (showing changes from the baseline). In the plots, black arrows represent residual current speed and direction during the baseline condition, and red arrows represent the residual current flow field under the construction phase. Contours in the plots are based on the residual current speed during the construction phase.

Far-field

Model results given in the figures indicate that the proposed development will not cause any large changes to tidal currents in the far-field during the construction phase.

Near-field

In the near-field, localised changes in current direction are dependent on the tidal phase. On flood tide current directions around the south of the development slightly diverge to the south, while ebbing tidal current directions slightly diverge to the east around the south of the development and to the north around the north of the development. In general, current flow patterns remain similar to the baseline both inside and outside the bay apart from area close to the breakwater arms. A slight reduction in current is predicted in Nigg Bay during the construction phase.

6.2 SEDIMENT REGIME

Model results presented above indicate that the current flow pattern remains similar to the baseline both inside and outside the bay apart from a slight reduction of current inside the bay. Therefore, it is unlikely that the sediment regime during the construction phase would be greatly different from the baseline condition. A reduction of current in the bay may result in slightly higher deposition of fine sediments in the bay. Sediment plume modelling of construction activities such as dredging are reported separately.

7 CONCLUSIONS

The existing Aberdeen Coastal Model has been updated and refined for the impact assessment of the proposed Aberdeen Harbour Expansion Project. This assessment included hydrodynamics, wave climate, sediment regimes, and consequently the effect on coastal processes. The refined model has been applied to both the baseline conditions and conditions with the development in place, to assess the effects of the development during the operational phase. Hydrodynamics during the construction phase have also been modelled, to identify any changes in the current flow field that result during the construction phase. From this assessment, the impact on the sediment regime during the construction phase can be understood.

Both near-field and far-field impacts due to the development have been assessed. Effects on the hydrodynamic regime and wave climate that may result from the potential changes to the climate in the future have also been considered. From the model results, a number of conclusions can be made. Conclusions from this assessment are presented below.

7.1 Operational Phase

7.1.1 Hydrodynamics

Water Level

The proposed development will not cause any large changes to maximum water levels in the far-field during the operational phase.

In the near-field, local to the development, the maximum water level increases inside the harbour are approximately 11 mm for the extreme condition. South of the development, a slight decrease in the maximum water level is expected as a result of flow blockage by the breakwater.

Current

The proposed development will not cause any large changes to tidal current in the far-field during the operational phase.

In the near-field local to the development, the current flow field is predicted to change as eddy currents formed in the bay under the baseline scenario will disappear when the development is in place. On flood tides the current direction is predicted to diverge from the baseline scenario around the breakwaters, with eddy formation along the outer wall of the northern breakwater. On ebb tides, the current is predicted to be diverged eastward along the outer wall of the southern breakwater.

In the operational phase, the current speed inside the development area is reduced due to the presence of the breakwaters, with a maximum reduction of approximately -0.4 m/s predicted. The tidal residual current is reduced in the development area, but increased around the outer walls of the breakwaters, with a maximum increase of 0.15 m/s predicted south of the southern breakwater.

Changes to the current direction cover a similar spatial extent on both spring and neap tides, with a greater magnitude of change during spring tides.

7.1.2 Wave Climate

The proposed development will not cause any large changes to the wave climate in the far-field during the operational phase.

In the near-field local to the development, the wave climate has been impacted by the proposed harbour. The significant wave height inside the development area is predicted to experience large reductions as a result of the additional protection afforded by the breakwaters. Immediately outwith the harbour, a slight increase in significant wave height is predicted in front of the breakwaters.

7.1.3 Sediment Transport and Pathway

The proposed development will not cause any large changes to sediment transport in the far-field during the operational phase. In the near-field local to the development, changes in sediment transport are predicted.

Sediment transport pathways outside the development area are not greatly affected by the development. Both north-easterly and easterly waves still produce a southerly movement of sediment outside of Nigg Bay, and south-easterly waves cause a northerly sediment transport. Inside the proposed harbour, sediment transport pathways are affected by the development, with no large sediment movement predicted within the harbour as wave action is greatly reduced by the presence of the breakwaters.

Similar to the sediment transport pathway under a specific wave condition, the net sediment transport pathway outside the development area is not significantly affected by the development. However, sediment movement to Nigg Bay is largely stopped as a result of protection provided by the breakwaters.

Sediment deposition and erosion patterns in Nigg Bay will be affected by the development. Under the baseline condition, areas of deposition and erosion can be seen, as a result of continuous seabed rework by the actions of waves and currents. However, with the development in place there would be very little movement of sediment within the harbour due to the reduced wave action and current.

Under the development scenario, as a result of weak wave action and small currents in the harbour, fine sediments brought into the harbour from the local streams and washed off from the coast would be likely to be deposited in the harbour.

7.2 Future (Changing Climate) Impacts

Future climate change is projected to result in a mean sea level rise. This scenario represents extreme events with an increase of mean sea level taken into account.

Water Level

The proposed development will not cause any large changes to maximum water level in the far-field during the operational phase.

Similar to the conditions without considering future climate change, in the near-field, the development will cause an increase of maximum water levels inside the harbour and a slight decrease in the maximum water level to the south of the development. The magnitude of impact is similar to that without considering climate change, although a larger spatial extent is predicted to be impacted when the future climate change is included.

Wave Climate

The proposed development will not cause any large changes to wave climate in far-field during the operational phase.

In the near-field the wave climate has been affected. The significant wave height inside the development area is greatly reduced as a result of the protection afforded by the breakwaters. A slight increase in wave height is predicted at the front of the breakwaters. The magnitude of change caused by the development is similar to that without considering climate change.

7.3 Construction Phase

Hydrodynamic conditions during this phase will be constantly changing due to the evolving nature of the development. The assessment made here covers a single arrangement present during this phase, representing half the length of both breakwaters in place and completed groundworks.

7.3.1 Hydrodynamics

The proposed development will not cause any large changes to the current flow field in the far-field during the construction phase.

In the near-field, localised changes in current direction are predicted. On flood tides current directions around the south of the development slightly diverge to the south, while ebbing tidal current directions slightly diverge to east around the south and north of the development. In general, current flow patterns remain similar to the baseline both inside and outside the bay apart from the area local to the breakwater arms. A slight reduction in current speed is predicted in Nigg Bay during the construction phase.

7.3.2 Sediment Transport and Pathway

The proposed development will not cause any large changes to sediment transport in far-field during the construction phase.

In the near-field, the effects on the sediment regime will change throughout the construction phase. During the initial period it is unlikely that the sediment transport regime would be greatly different from the baseline condition, as it is predicted that current flow pattern remains similar to the baseline both inside and outside the bay. As the construction phase progresses a reduction of current speeds in Nigg Bay may temporarily result in slightly higher deposition of fine sediments while sediment continues to be transported into the Harbour area. The volume of sediment being transported into the Nigg Bay will decrease during the breakwater construction until they are fully constructed and operational phase conditions are established.

8 REFERENCES

Arch Henderson, 2015. Topographic and Hydrographic Survey Data: 121106. April 2015.

BODC, 2015. UK National Tide Gauge Network. Measured data for Aberdeen 1930 – 2015. Available at <http://www.bodc.ac.uk/data/online_delivery/ntslf/>. Accessed 15 April 2015

Caledonian Geotech, 2012. Geophysical and Bathymetry Surveys Aberdeen. CG-1048-RPT-01. November 2012.

Defra, 2009. UK Climate Projections 2009. Available at <http://ukclimateprojections.metoffice.gov.uk/>. Accessed 5 June 2015.

Environment Agency, 2011a. Coastal flood boundary conditions for UK mainland and islands. TR2 – Design sea levels. February 2011.

Environment Agency, 2011b. Coastal flood boundary conditions for UK mainland and islands. TR4 – Practical guidance design sea levels. February 2011.

FWR, 1993. A Framework for Marine and Estuarine Model Specification in the UK. March 1993.

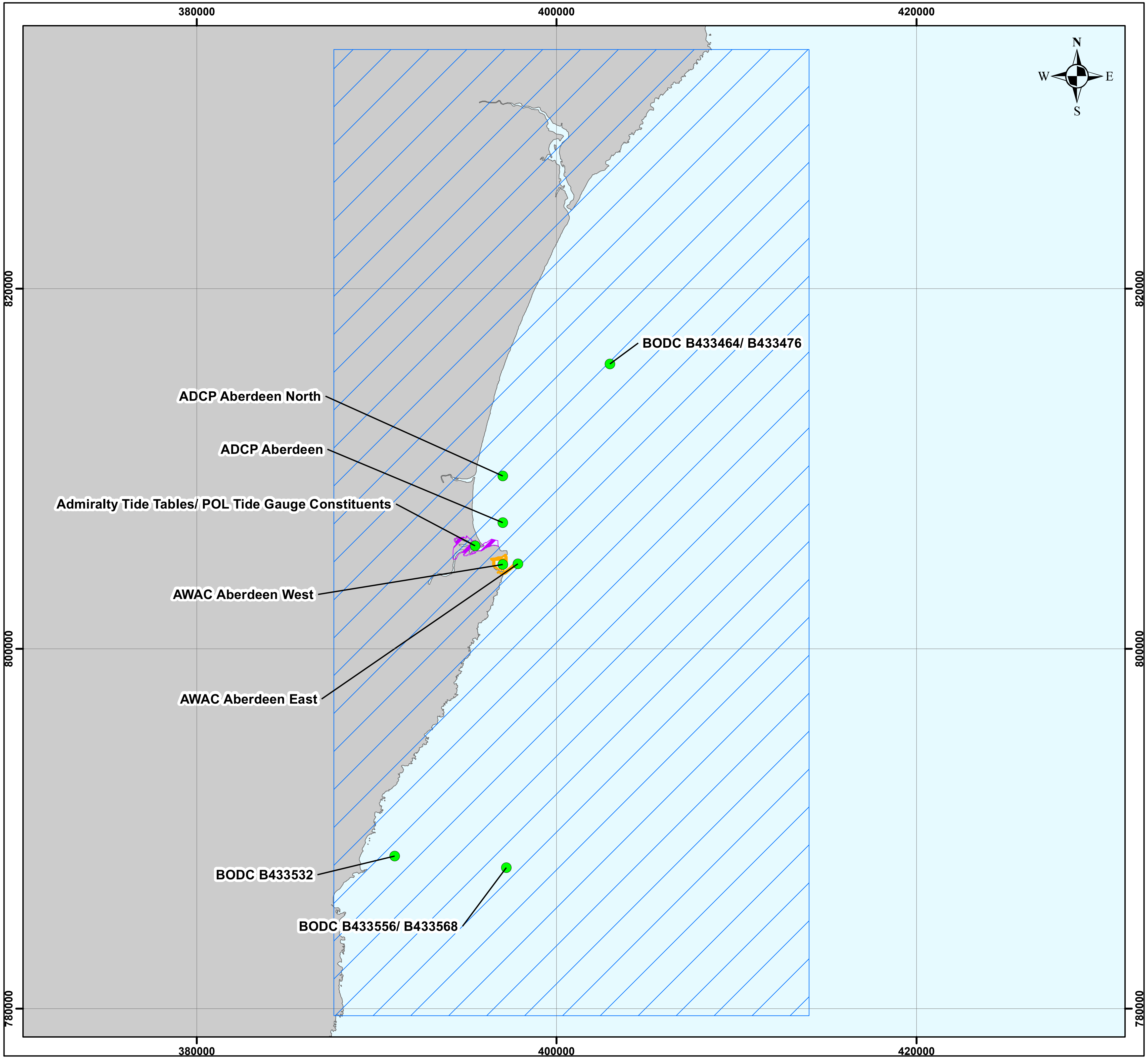
Intertek, 2015. Aberdeen Harbour Expansion at Nigg Bay – Method Statement. Report P1974B_R3789_Rev0. 24 April 2015

Metoc plc, 2010. Aberdeen Flexible Mesh Model – Calibration and Validation. Metoc plc on behalf of Scottish Water. Report P1048D_RN2389, Rev 1. 23 July 2010.

SEPA, 2012. Strategic Flood Risk Assessment – SEPA technical guidance to support Development Planning. Version 1, 25 June 2012

Soil Engineering Geoservices, 2013. Ground Intestigation Report for Bay of Nigg Harbour Development Aberdeen. TA7148. December, 2013.

Appendix A HD Model Validation

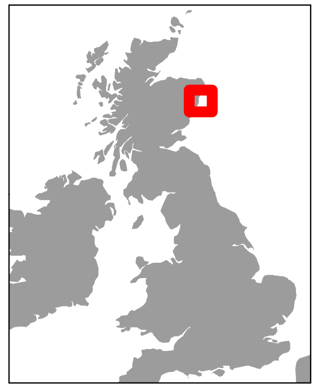


ABERDEEN HARBOUR EXPANSION PROJECT

Figure A-1. Plot title: Aberdeen Coastal Model calibration and validation locations.

Legend

- Tide Gauges
- Aberdeen Harbour Expansion
- Model Domain
- Existing Aberdeen Harbour Area



NOTE: Not to be used for Navigation

Date	Wednesday, August 26, 2015 14:22:29
Projection	British_National_Grid
Spheroid	Airy_1830
Datum	D_OSGB_1936
Data Source	OSOD, SNH, JNCC, SEPA
File Reference	J:\P1974\Mxd\Method_Statement\ Coastal_Model_Cal_Val_Locs.mxd
Created By	Emma Langley
Reviewed By	Ian Charlton
Approved By	Kevin McGovern

FUGRO

Intertek
Valued Quality. Delivered.

km 0 2 4 6 8 10

A.1 Validation Period: 2015 Survey

Figure A-2: Model validation for speed at the western location

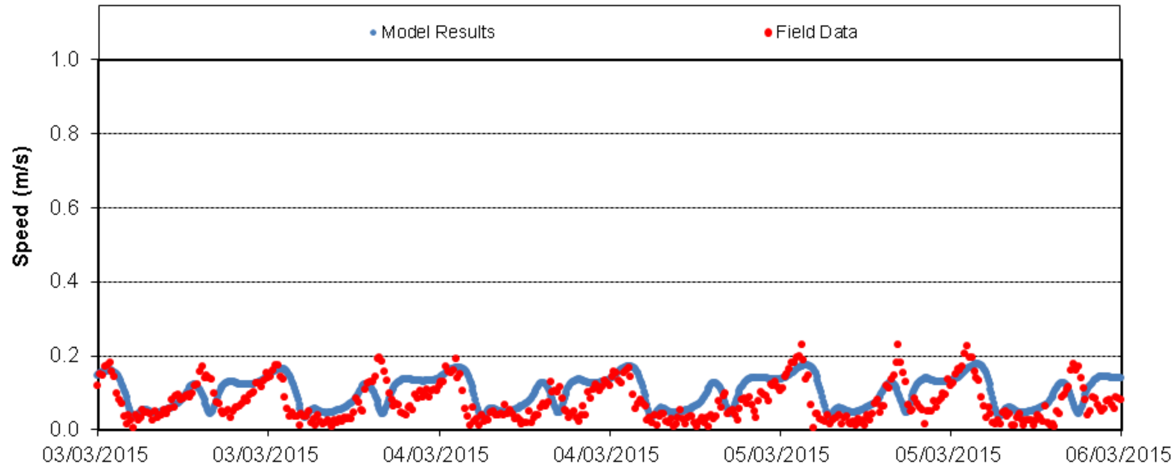


Figure A-3: Model validation for direction at the western location

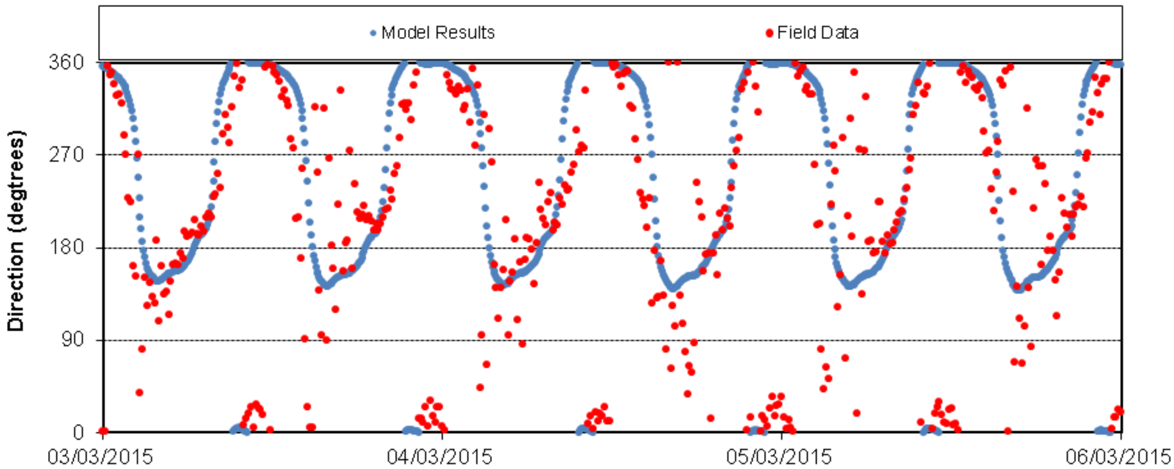


Figure A-4: Model validation for speed at the eastern location

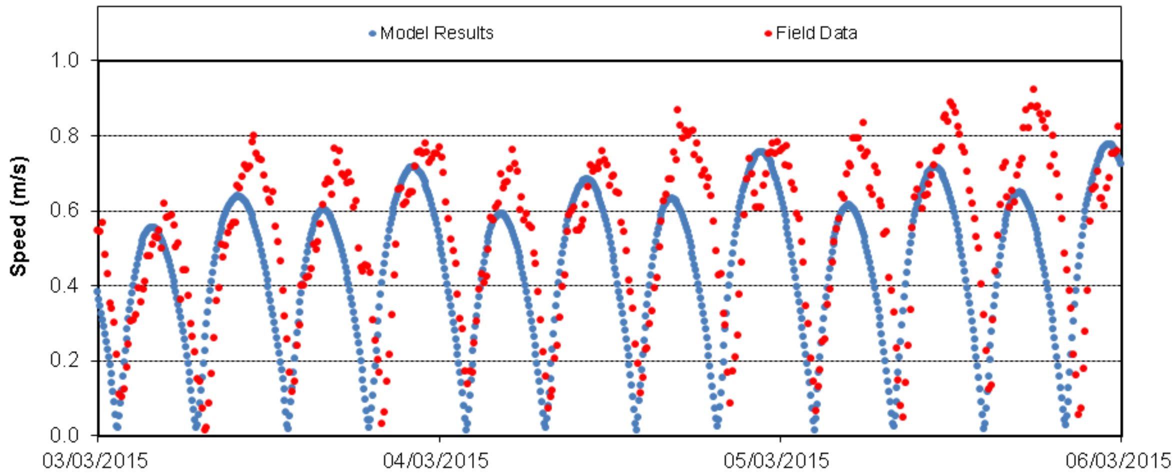


Figure A-5: Model validation for direction at the eastern location

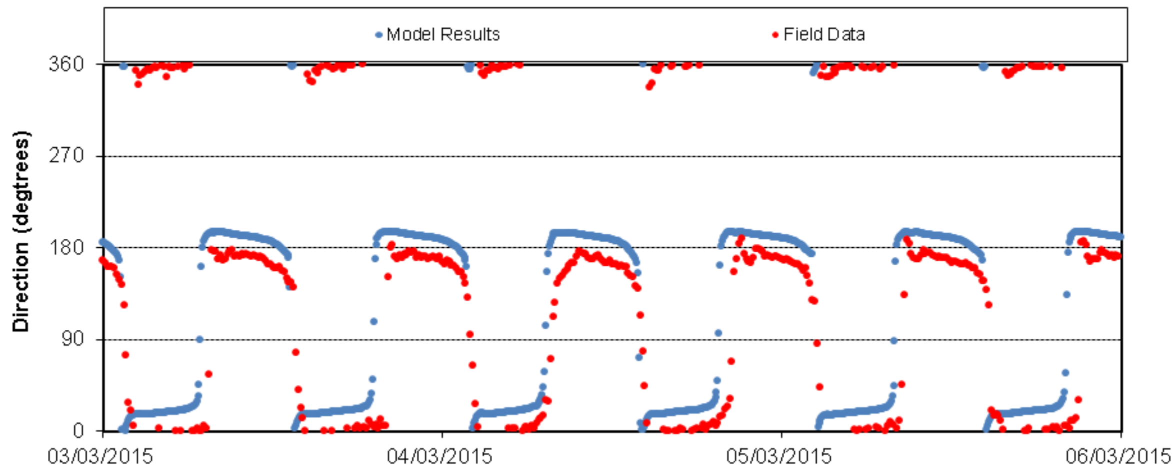


Figure A-6: Model validation for speed at the eastern location later in field survey period

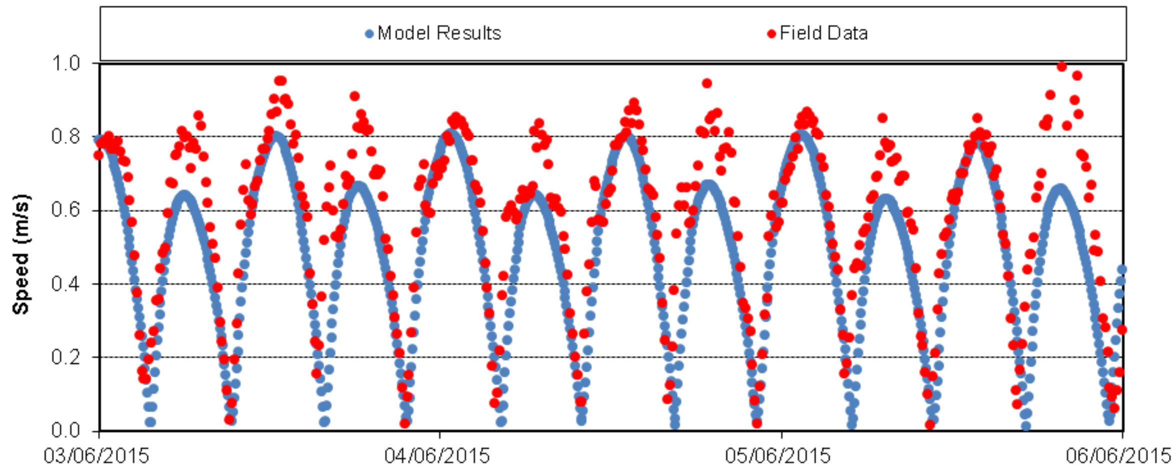
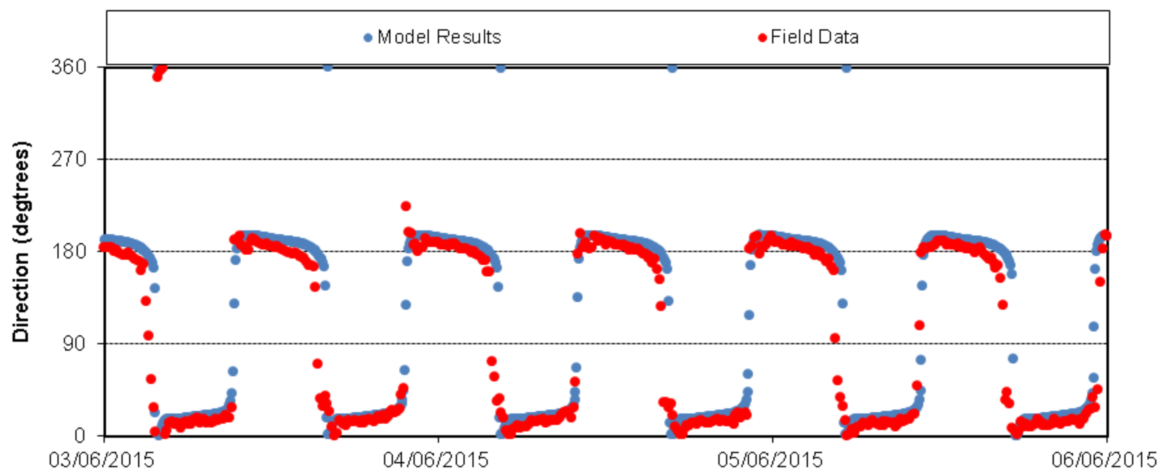


Figure A-7: Model validation for direction at the eastern location later in field survey period



A.2 Original ACM Calibration Period

Figure A-8: Model validation for speed at BODC433464 on a spring tide

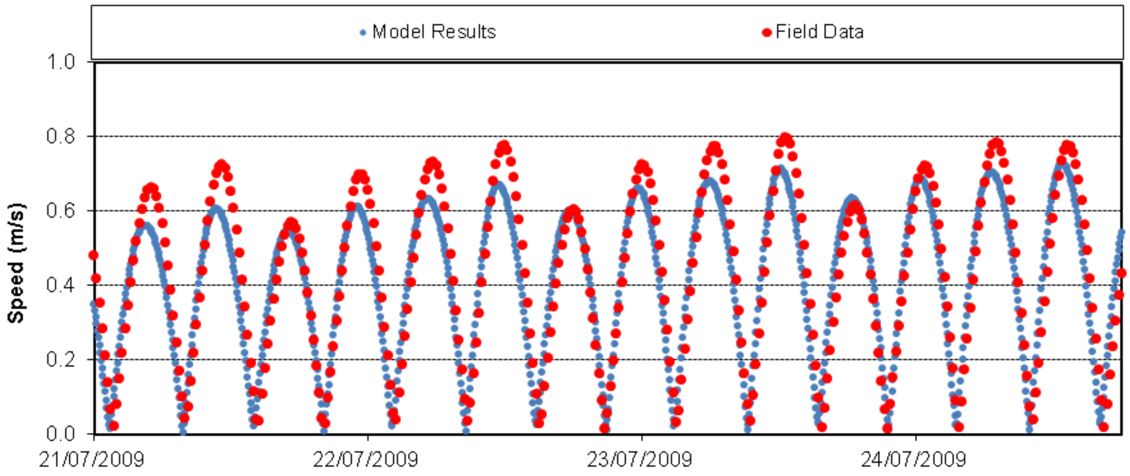


Figure A-9: Model validation for direction at BODC433464 on a spring tide

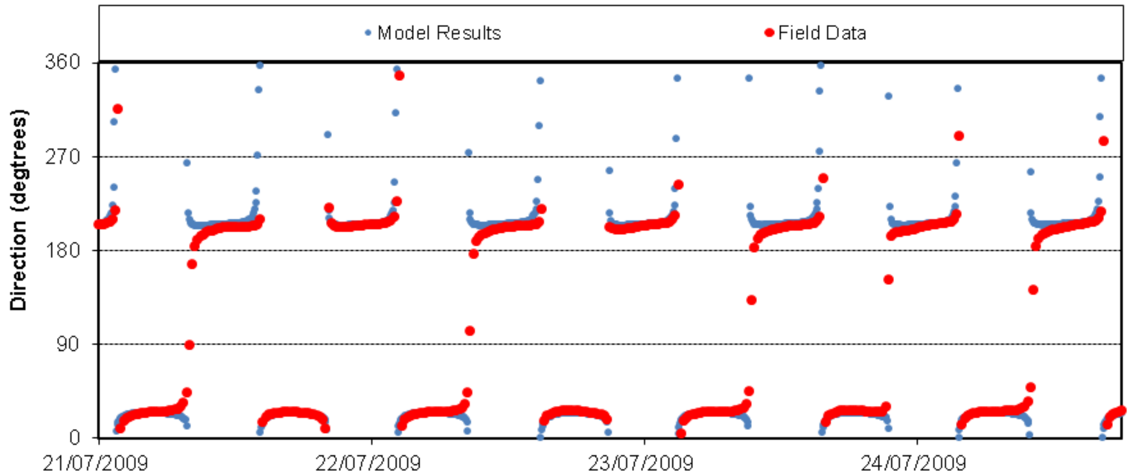


Figure A-10: Model validation for speed at BODC433476 on a spring tide

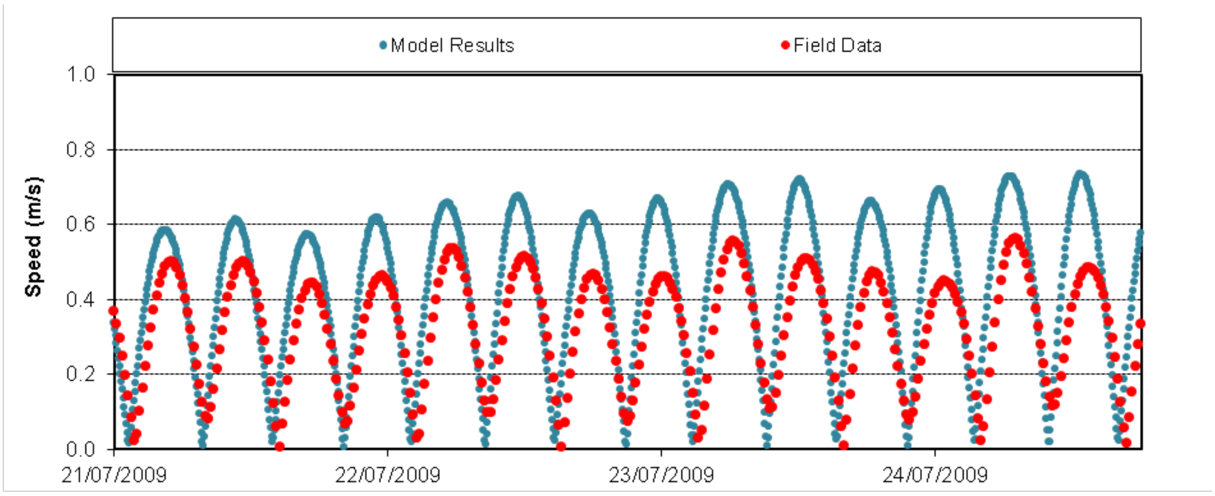


Figure A-11: Model validation for direction at BODC433476 on a spring tide

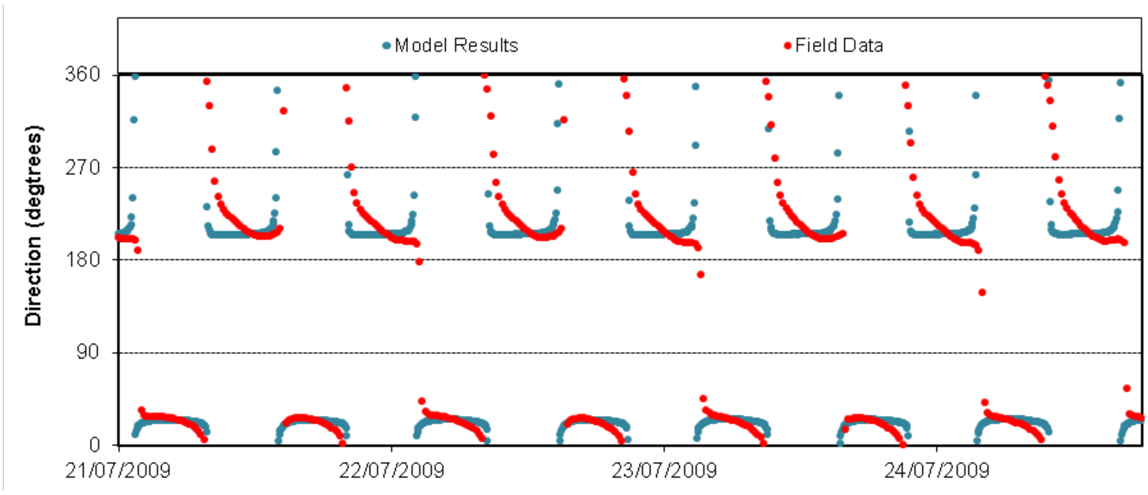


Figure A-12: Depth averaged model validation for speed at BODC433464/433476 on a spring tide

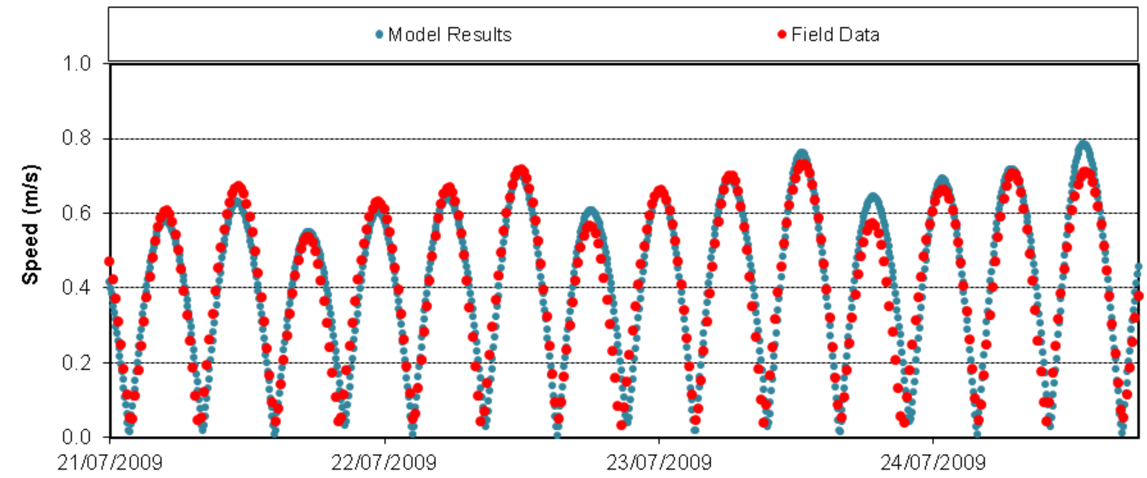


Figure A-13: Depth averaged model validation for direction at BODC433464/433476 on a spring tide

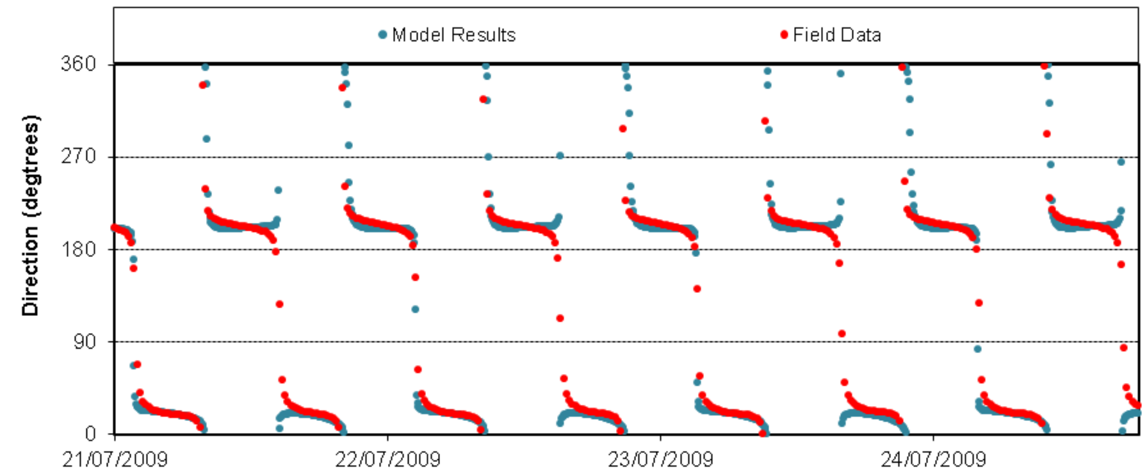


Figure A-14: Model validation for speed at BODC433556 on a spring tide on a spring tide

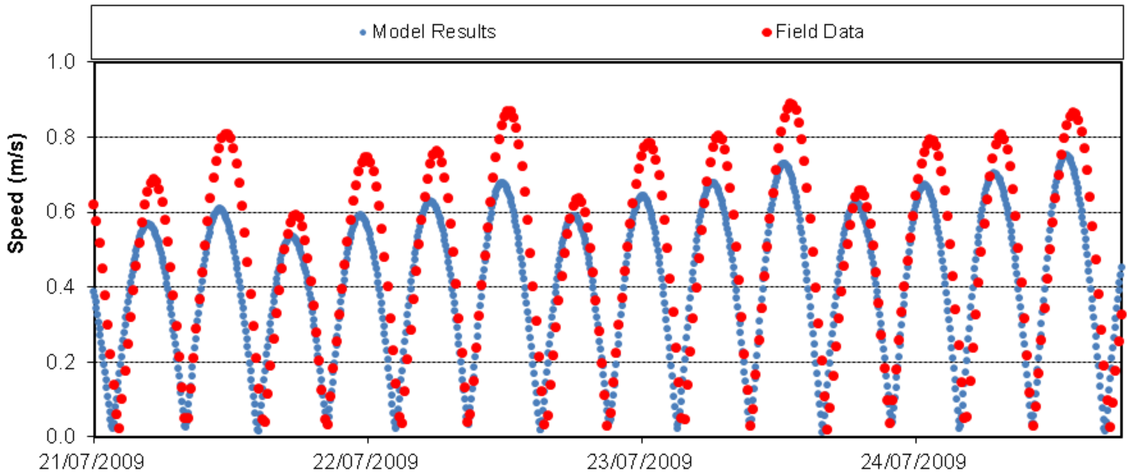


Figure A-15: Model validation for direction at BODC433556 on a spring tide on a spring tide

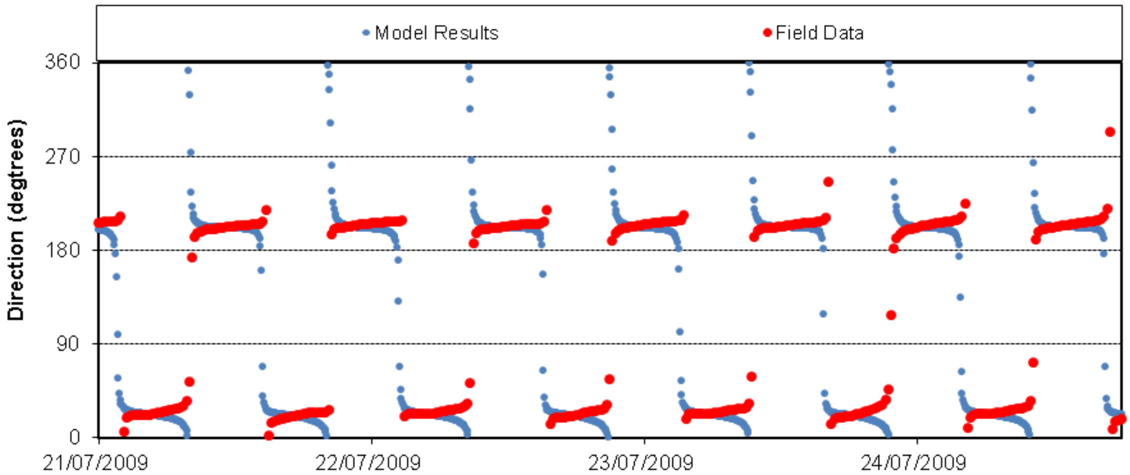


Figure A-16: Model validation for speed at BODC433568 on a spring tide

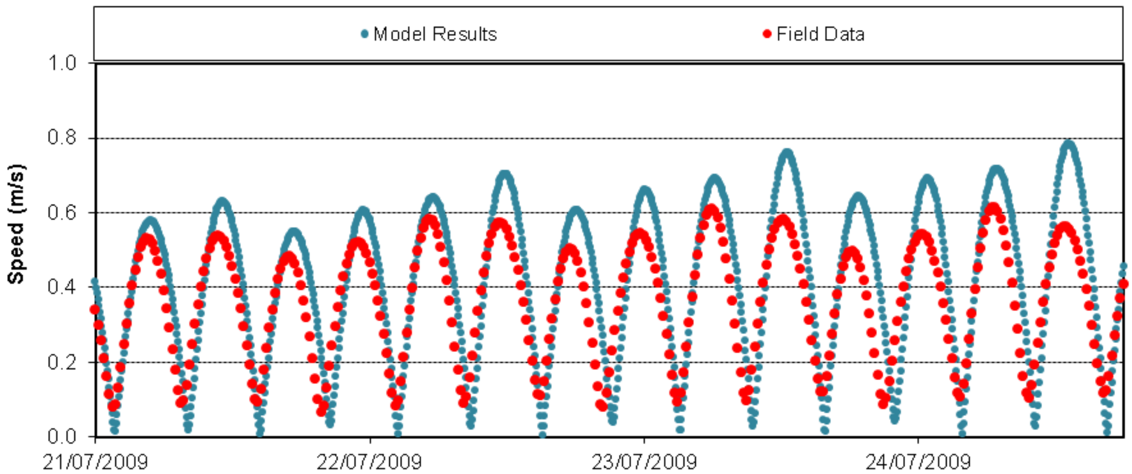


Figure A-17: Model validation for direction at BODC433568 on a spring tide

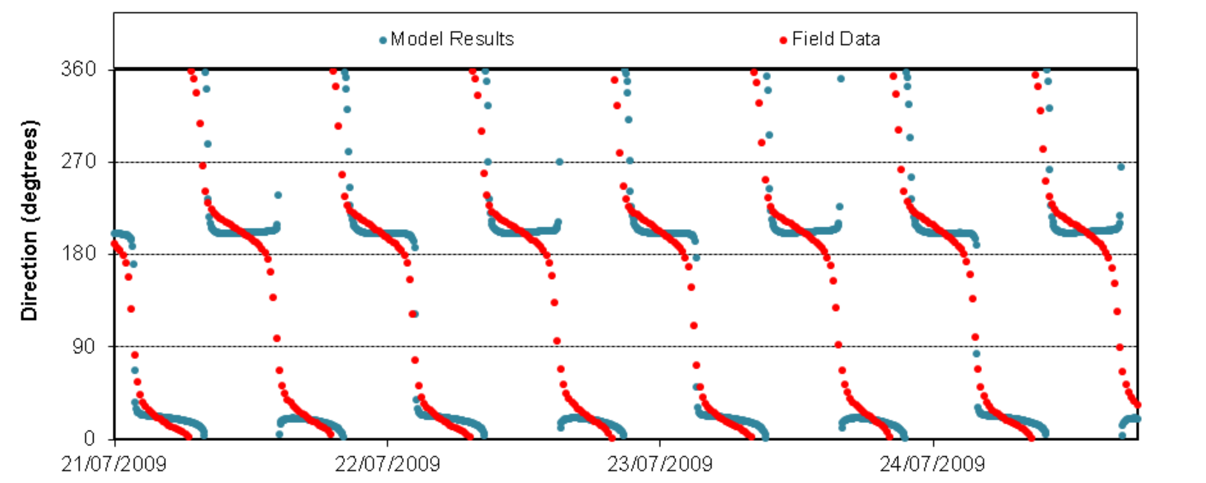


Figure A-18: Depth averaged model validation for speed at BODC433556/433568 on a spring tide

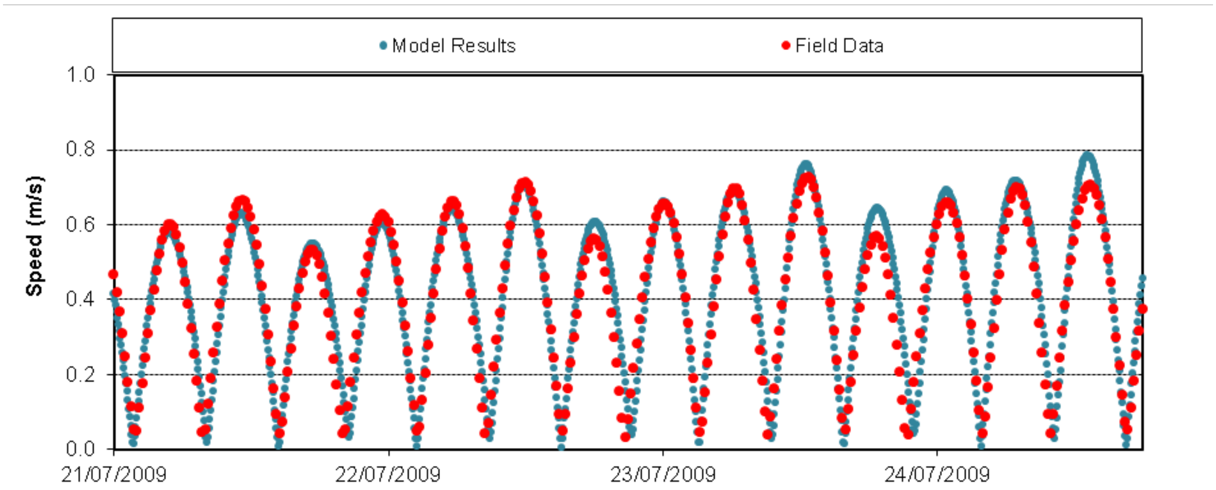


Figure A-19: Depth averaged model validation for direction at BODC433556/433568 on a spring tide

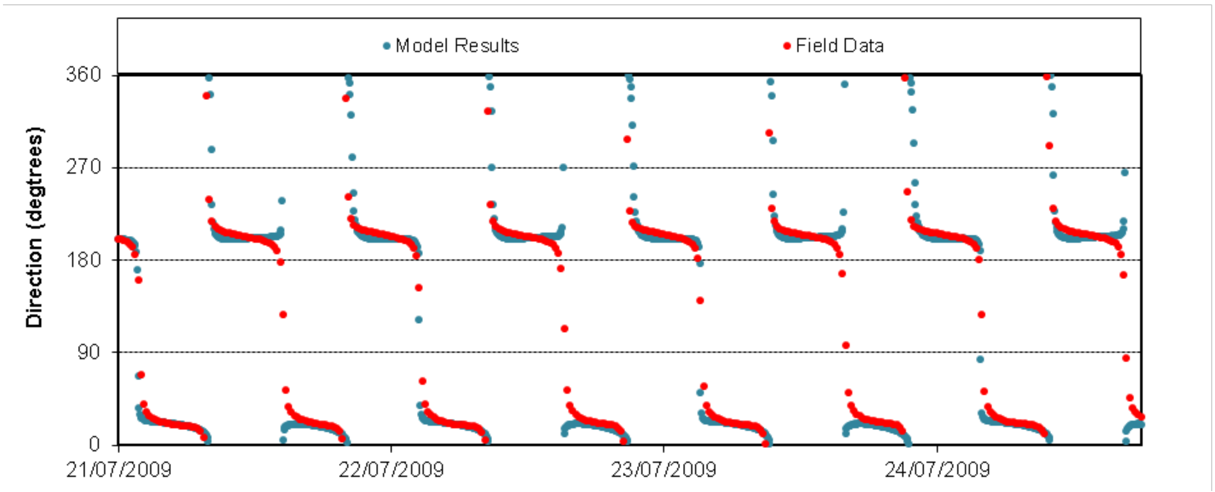


Figure A-20: Model validation for speed at BODC433532 on a spring tide

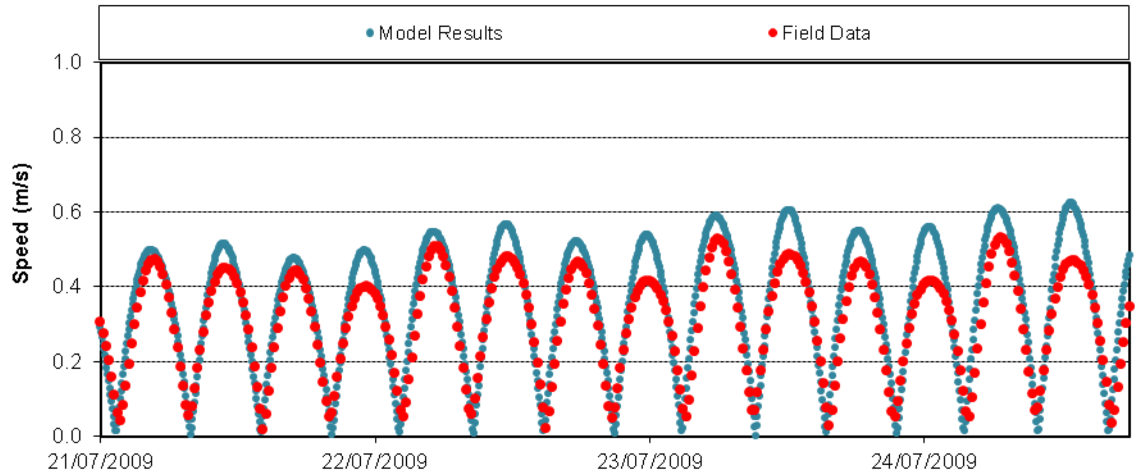


Figure A-21: Model validation for direction at BODC433532 on a spring tide

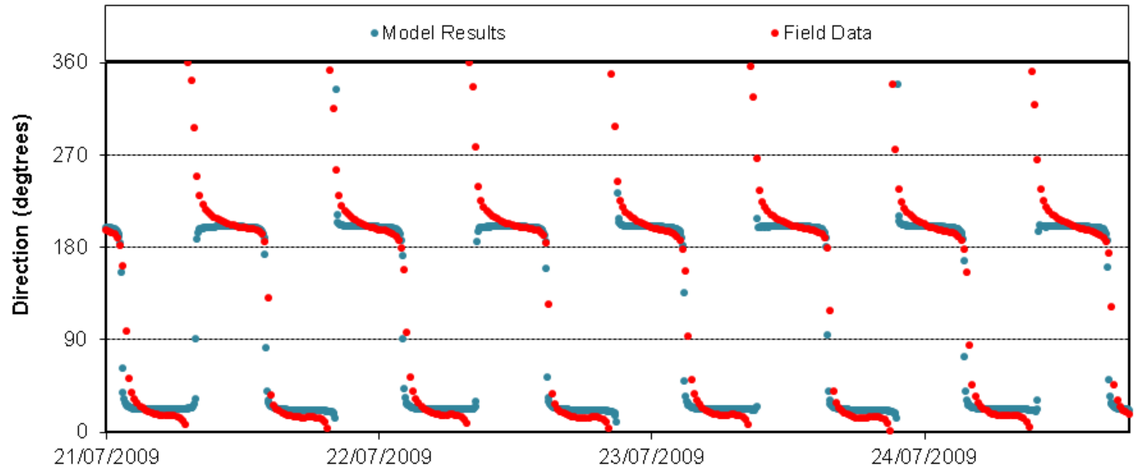


Figure A-22: Model validation for speed at Aberdeen North on a spring tide

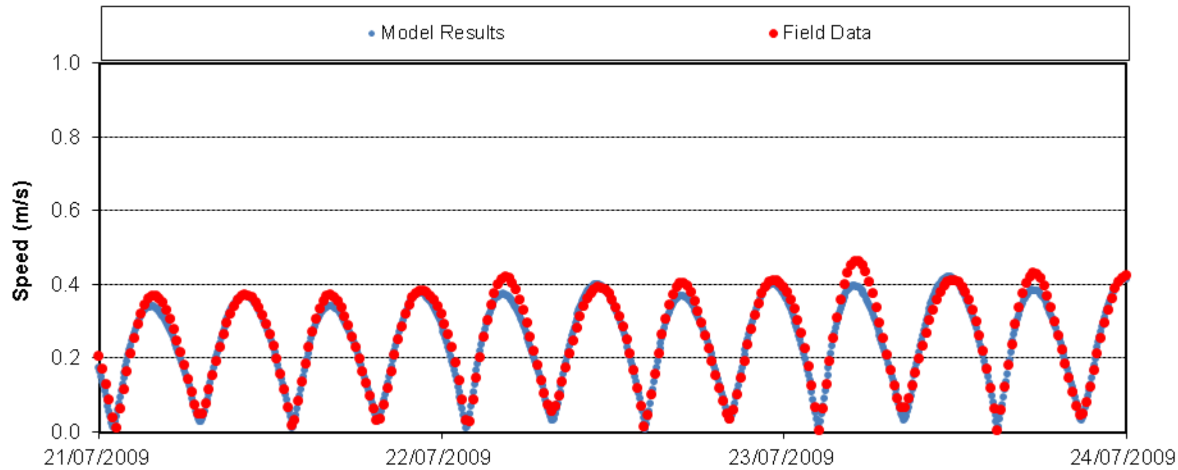


Figure A-23: Model validation for direction at Aberdeen North on a spring tide

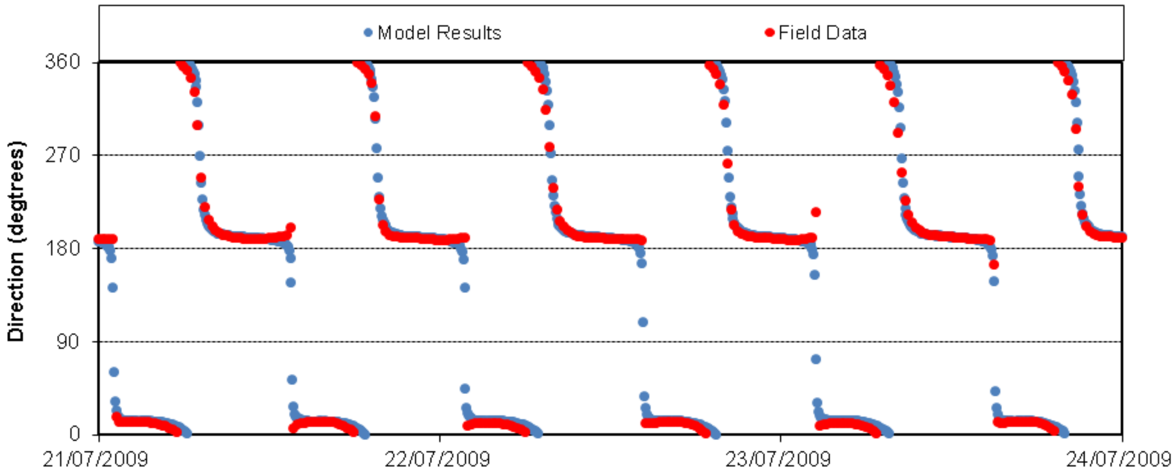


Figure A-24: Model validation for speed at Aberdeen on a spring tide

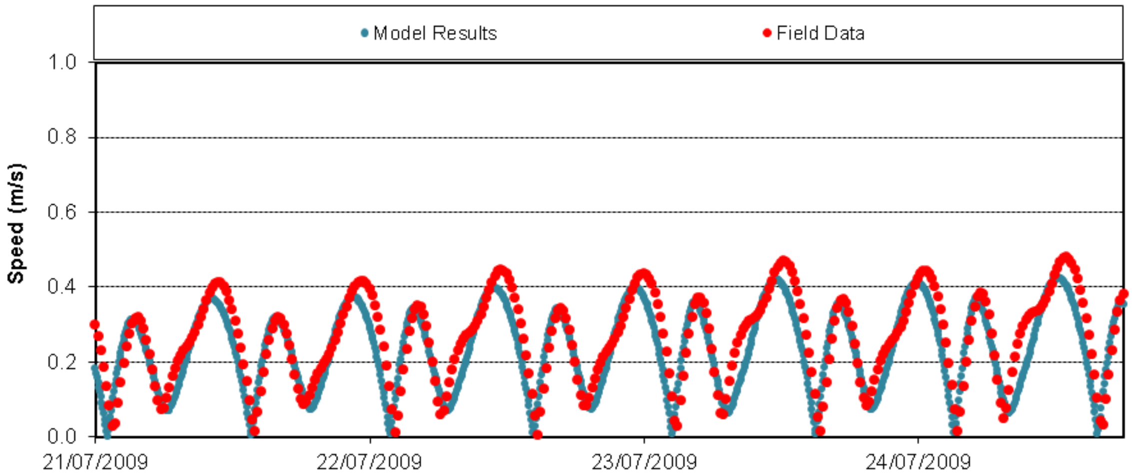


Figure A-25: Model validation for direction at Aberdeen on a spring tide

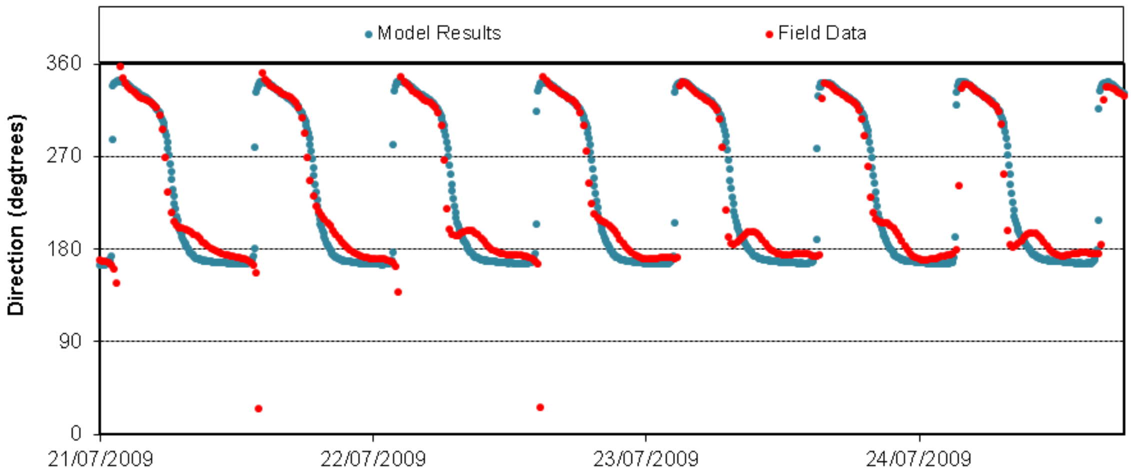


Figure A-26: Model validation for water level at Aberdeen on a spring tide

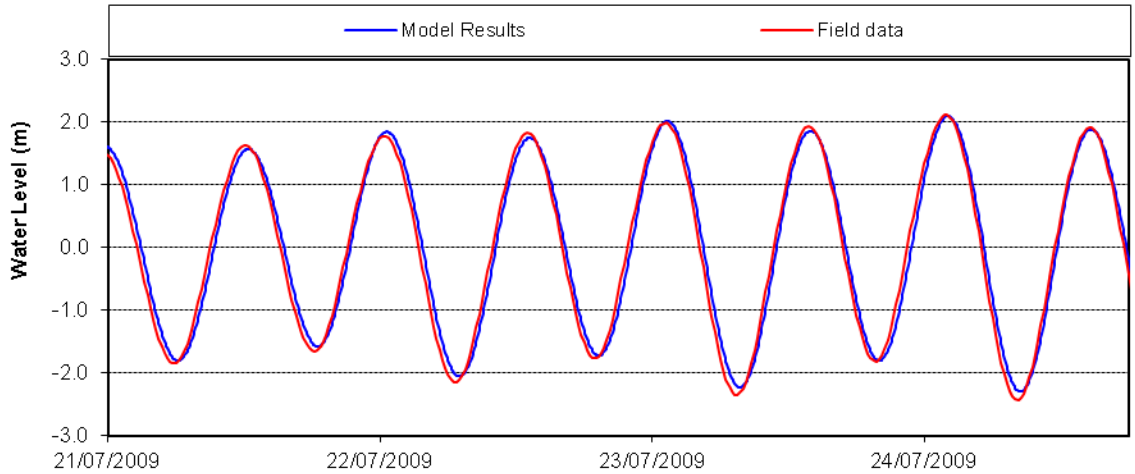


Figure A-27: Model validation for water level at Aberdeen North on a spring tide

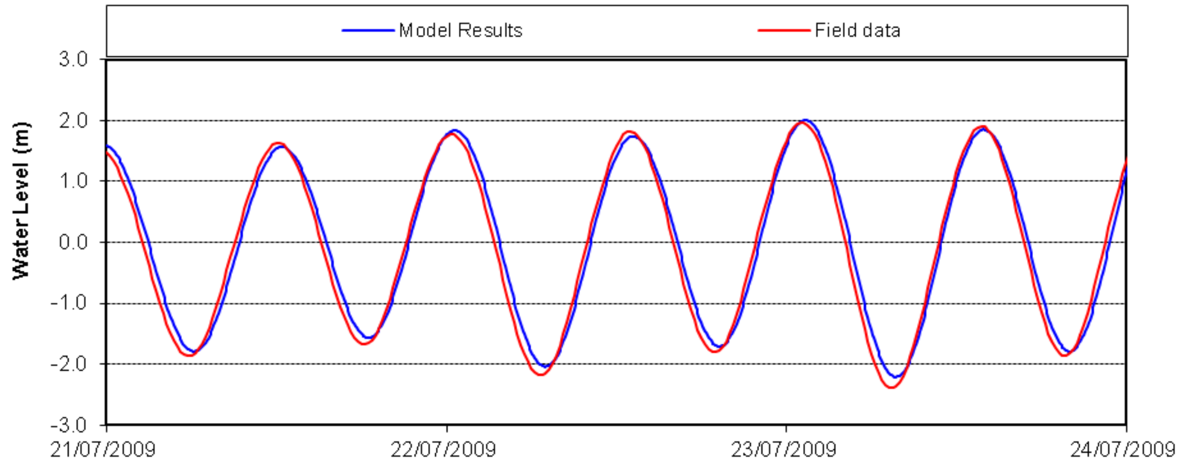


Figure A-28: Model validation for water level at Aberdeen Harbour POL on a spring tide

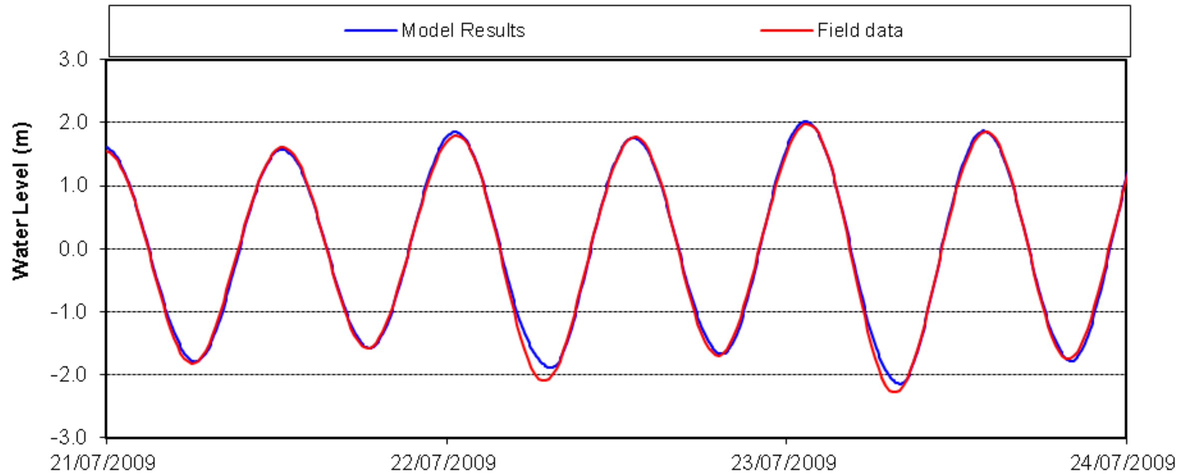
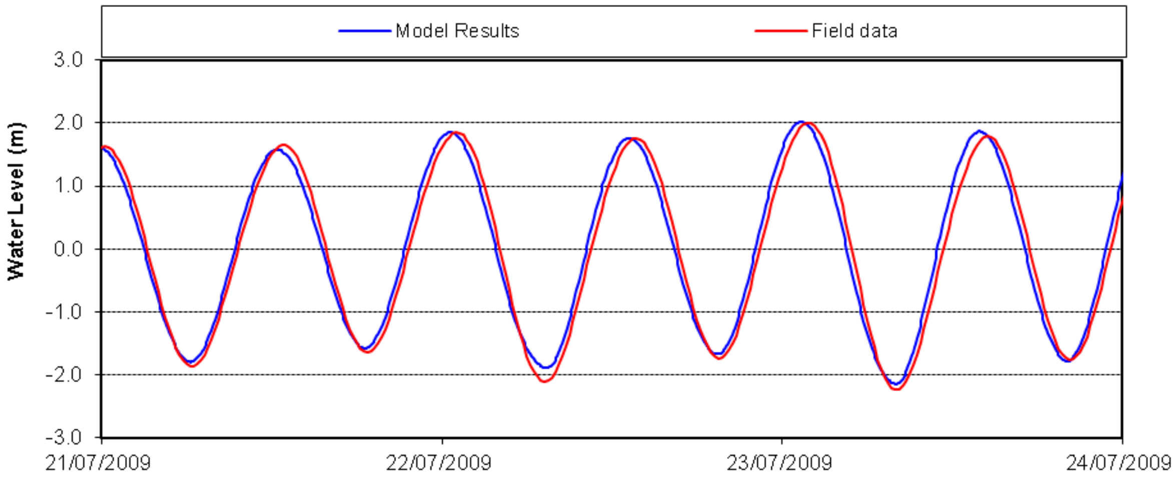


Figure A-29: Model validation for water level at Aberdeen Harbour Admiralty on a spring tide



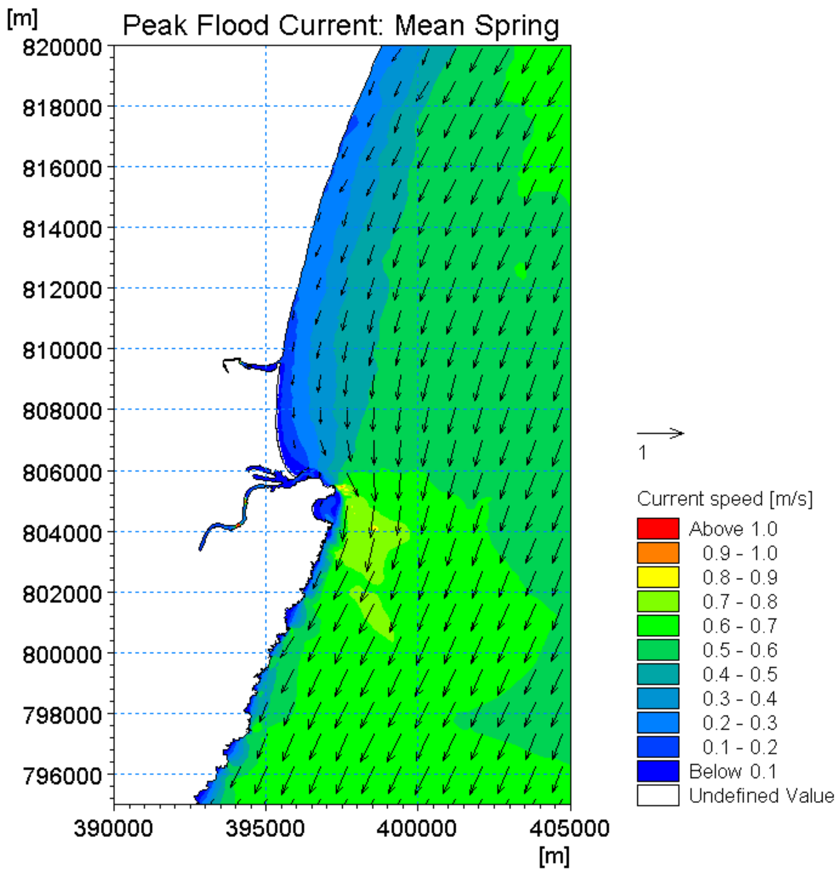
Appendix B Baseline Results

B.1 Hydrodynamics

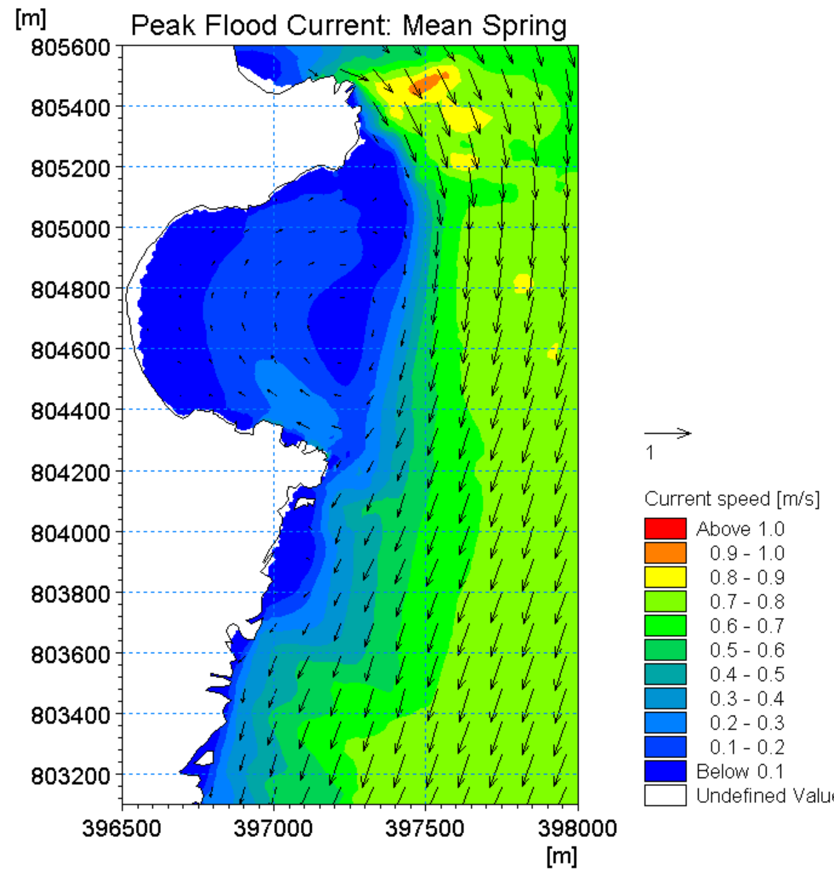
Figure B-1: Tidal current speed and direction on a mean spring tide

Flood Tide

Over a Large Extent

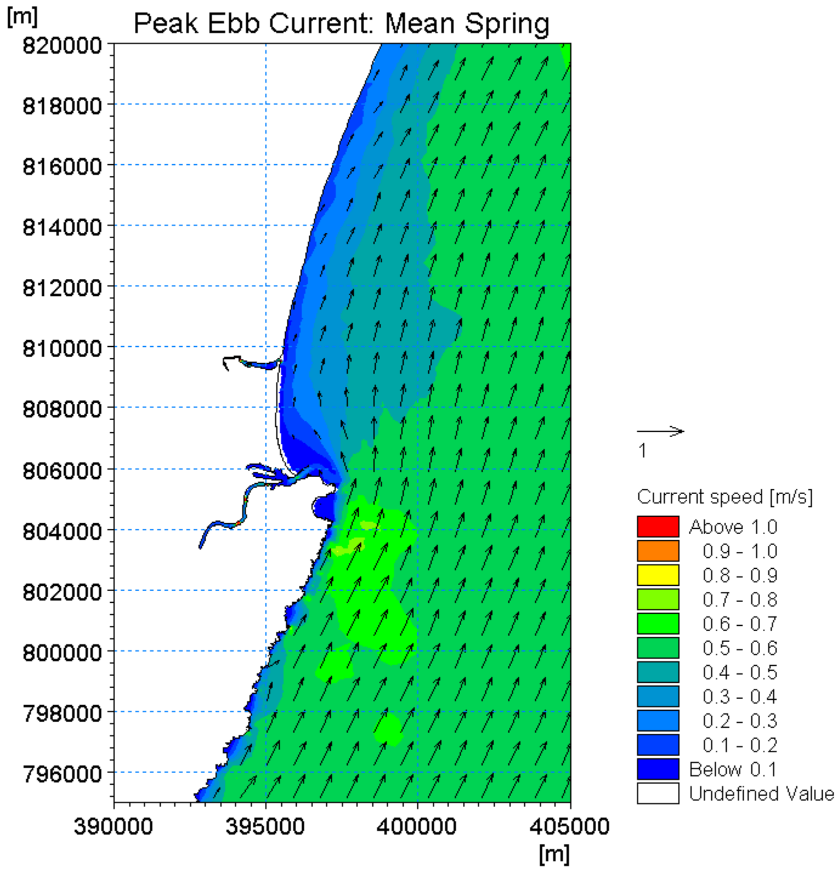


Local to the Development



Ebb Tide

Over a Large Extent



Local to the Development

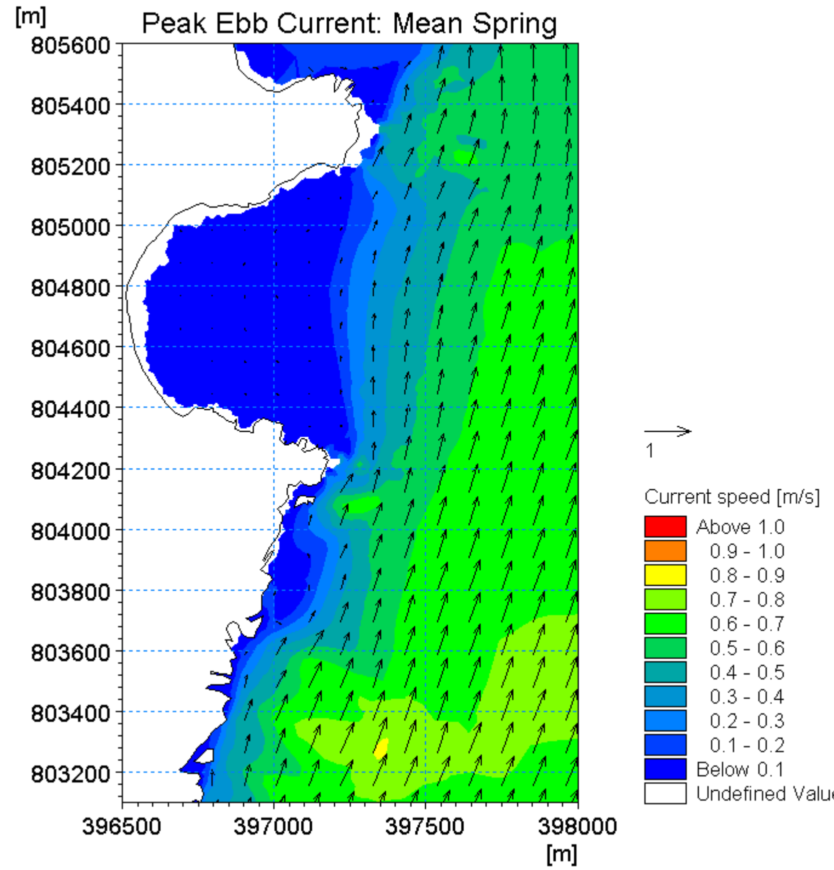
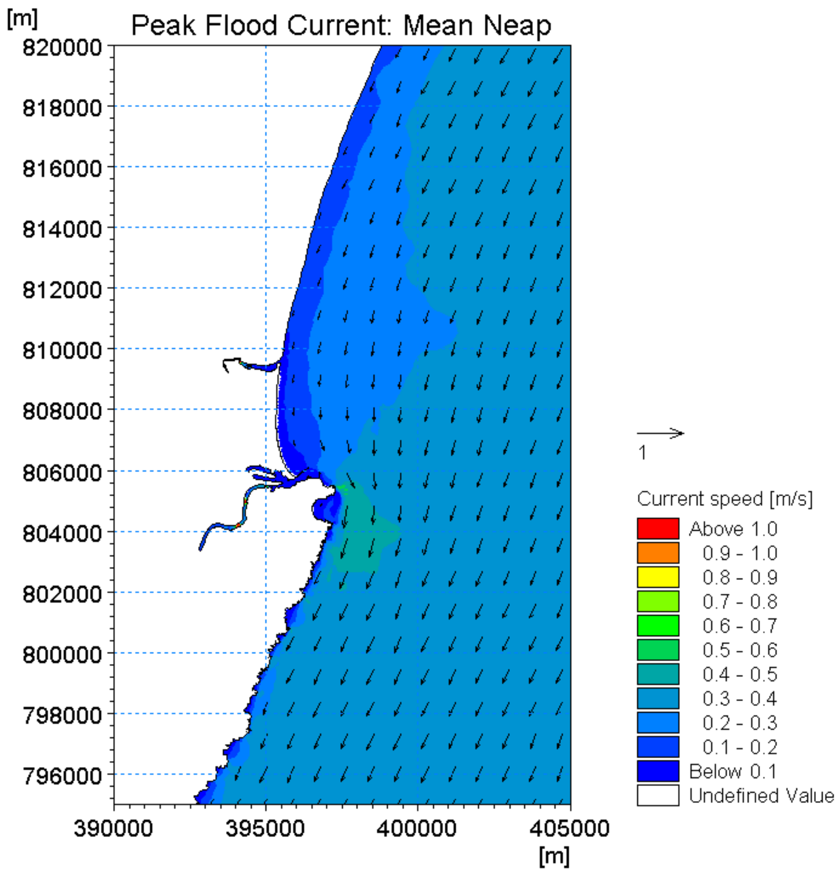


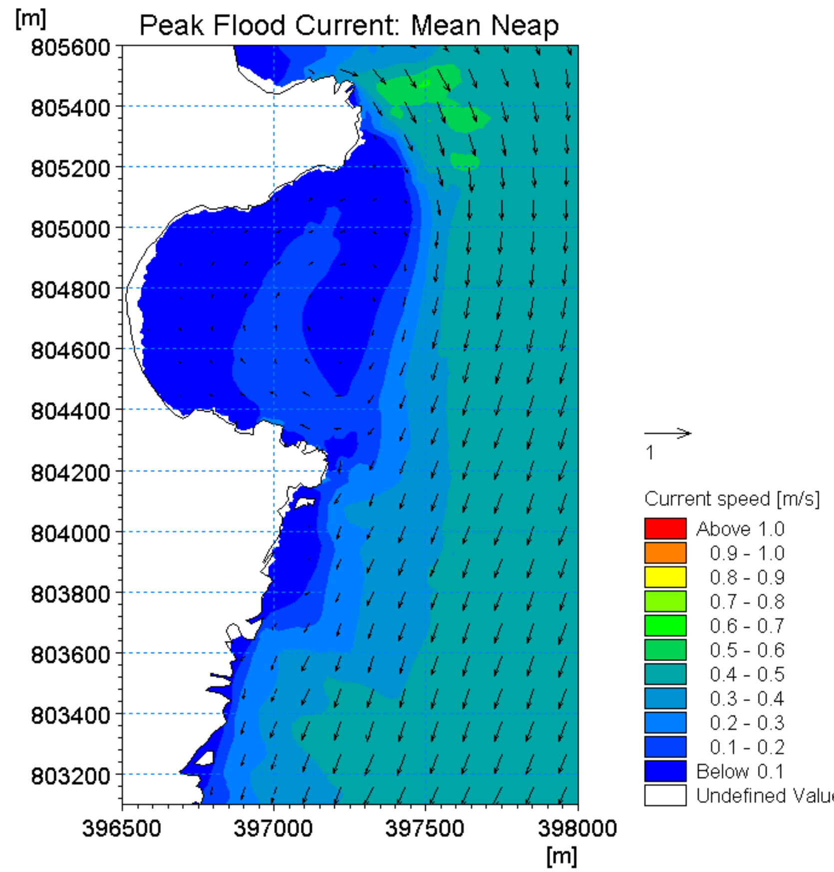
Figure B-2: Tidal current speed and direction on a mean neap tide: Baseline

Flood Tide

Over a Large Extent

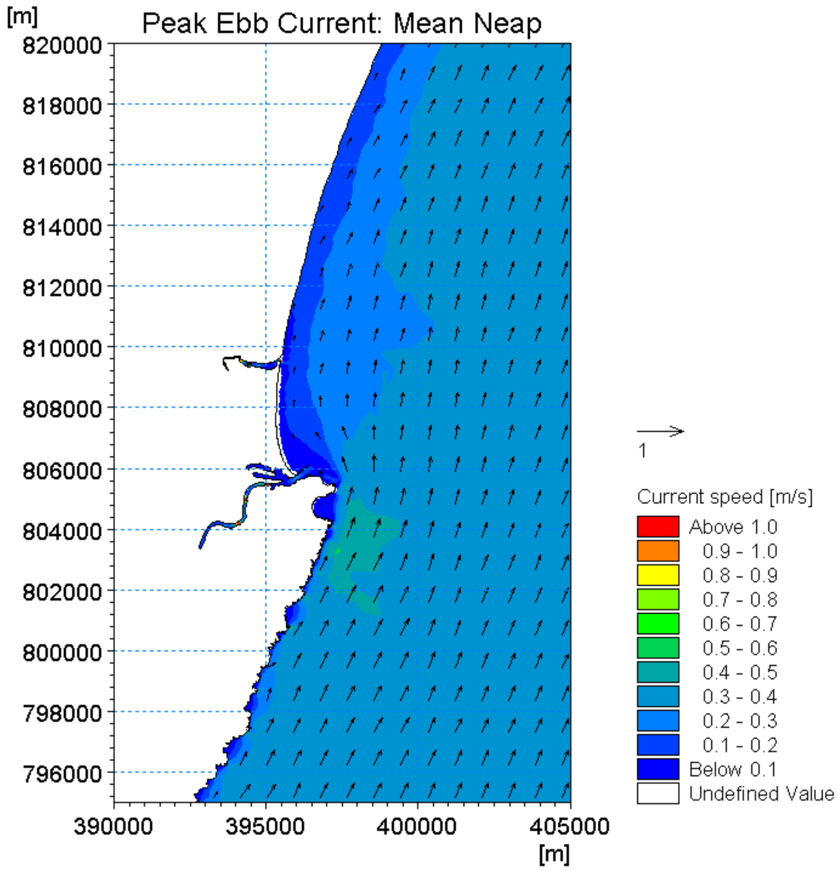


Local to the Development



Ebb Tide

Over a Large Extent



Local to the Development

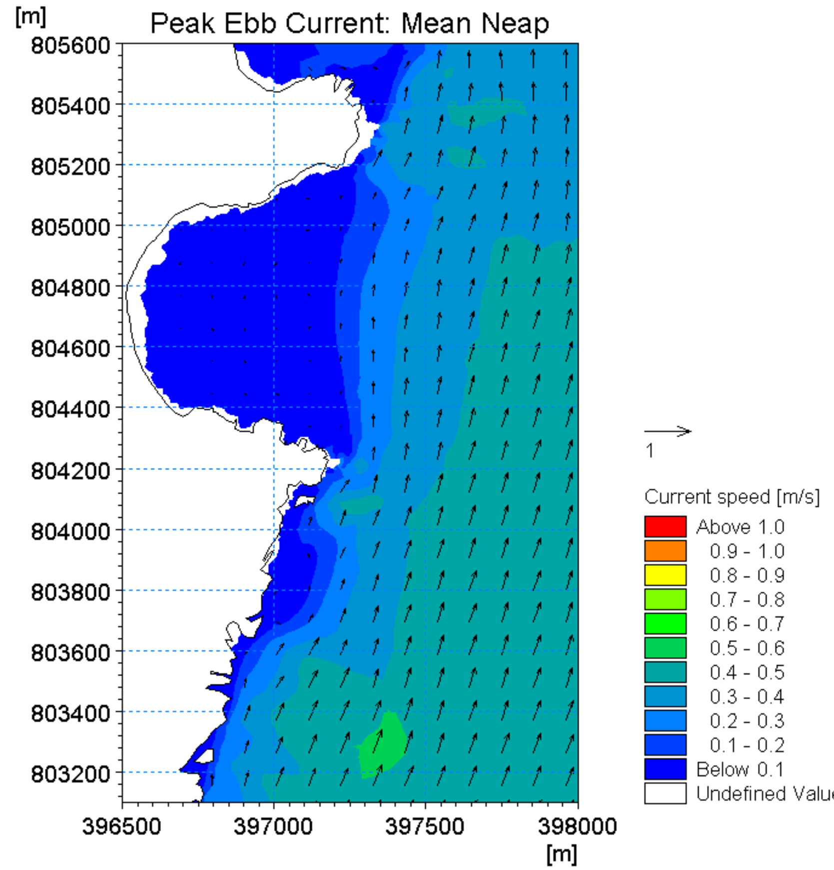
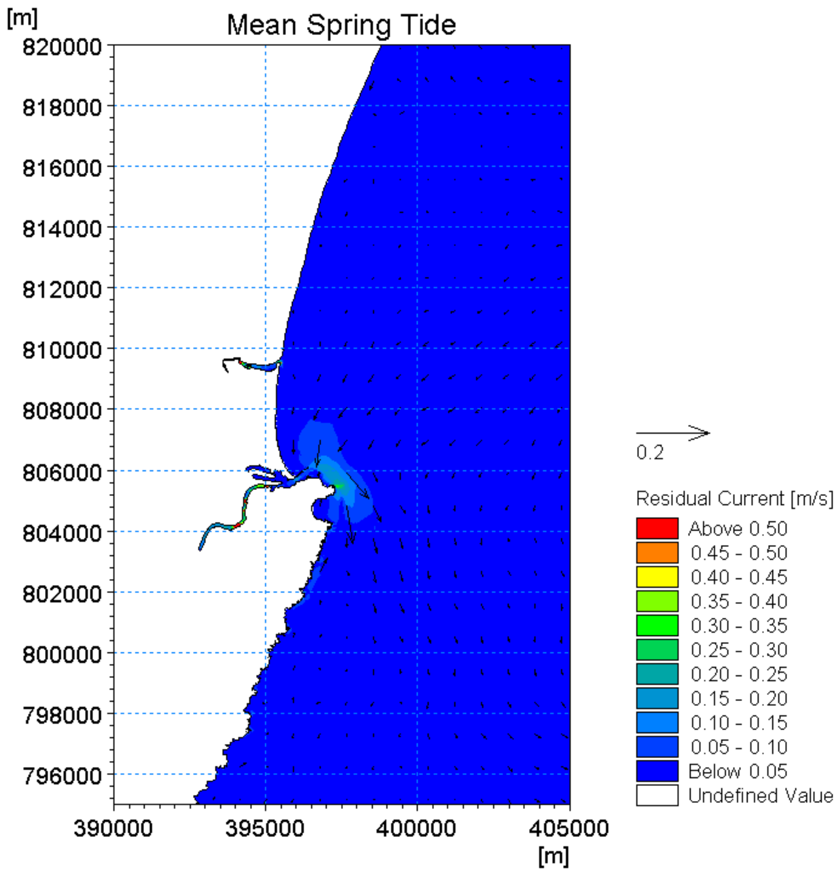


Figure B-3: Tidal residual current speed and direction on a mean spring tide: Baseline

Over a Large Extent



Local to the Development

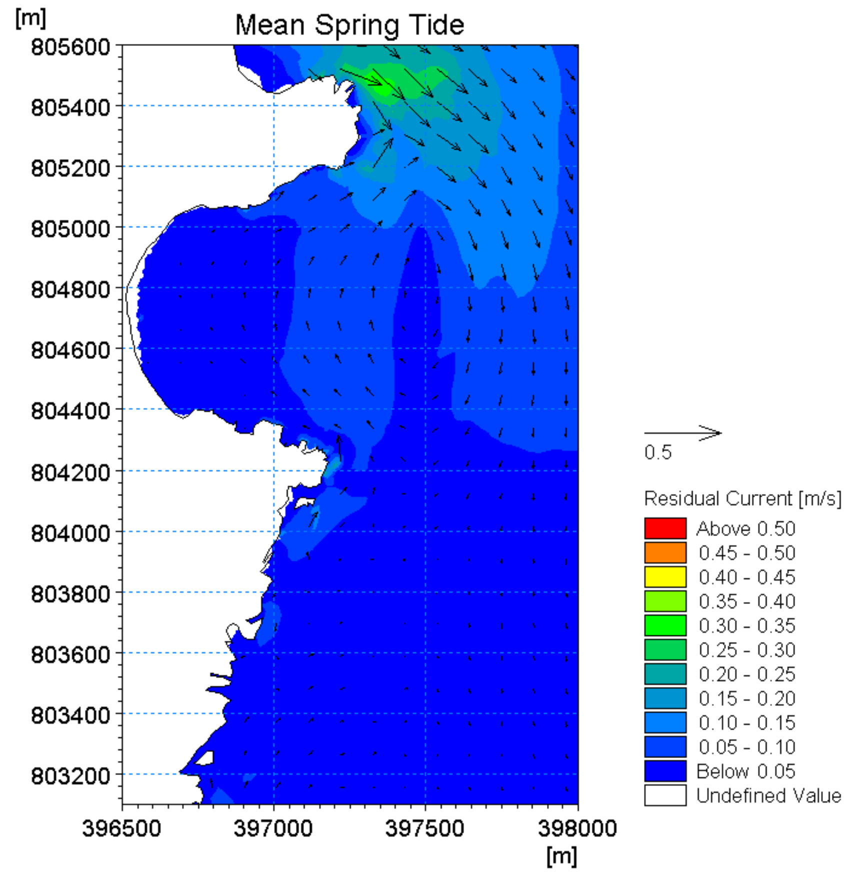
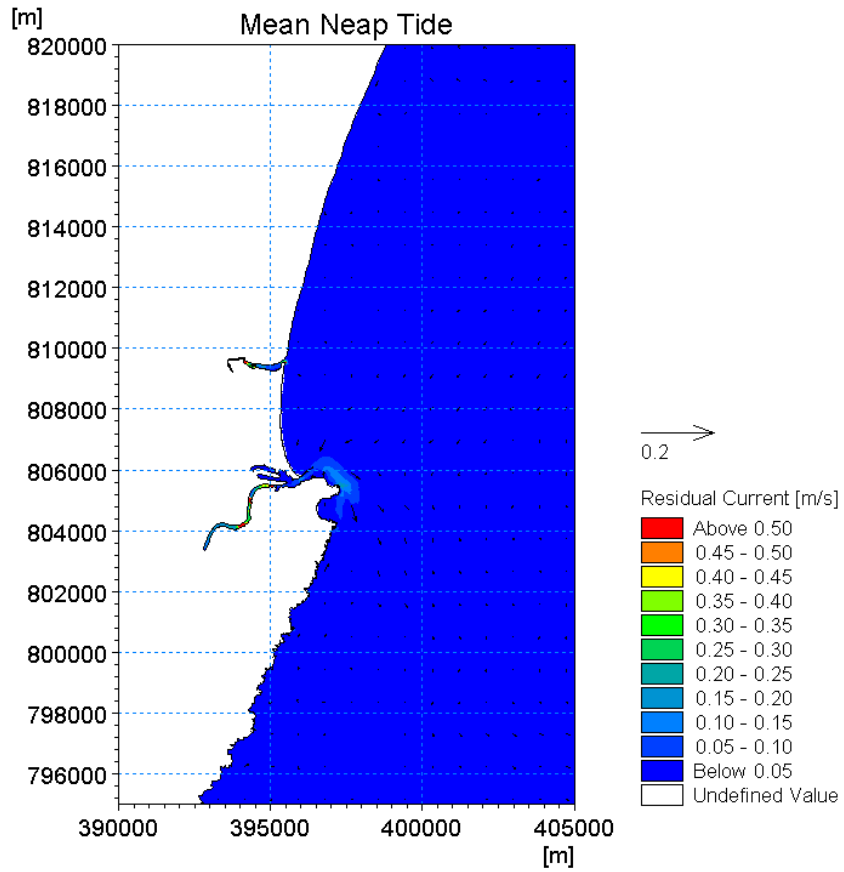
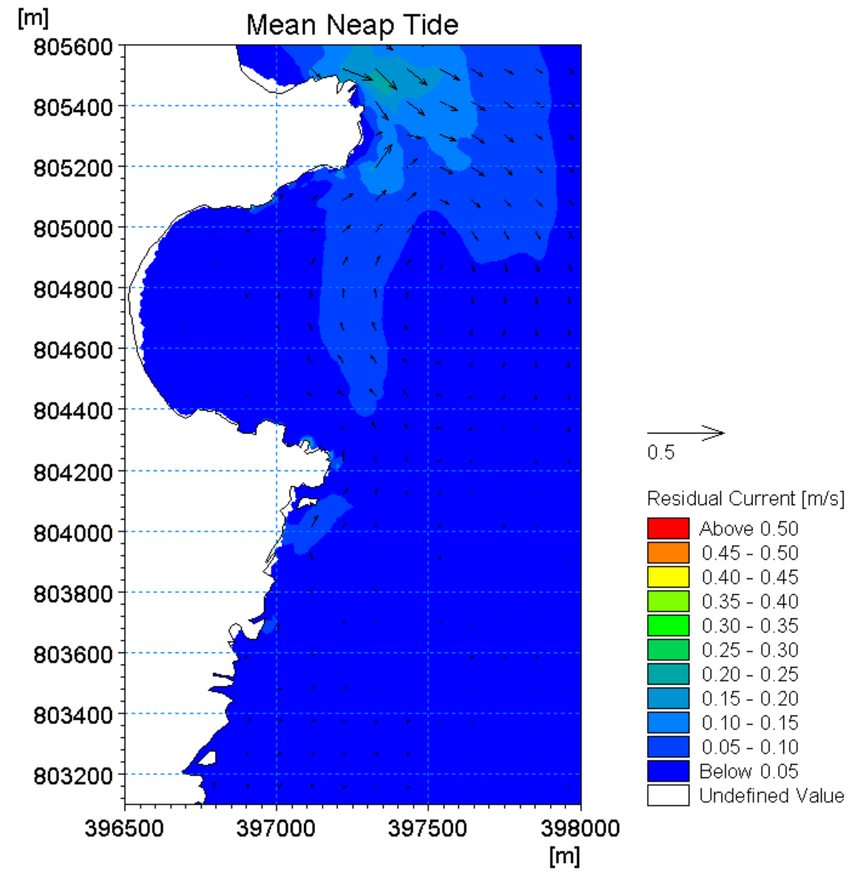


Figure B-4: Tidal residual current speed and direction on a mean neap tide: Baseline

Over a Large Extent



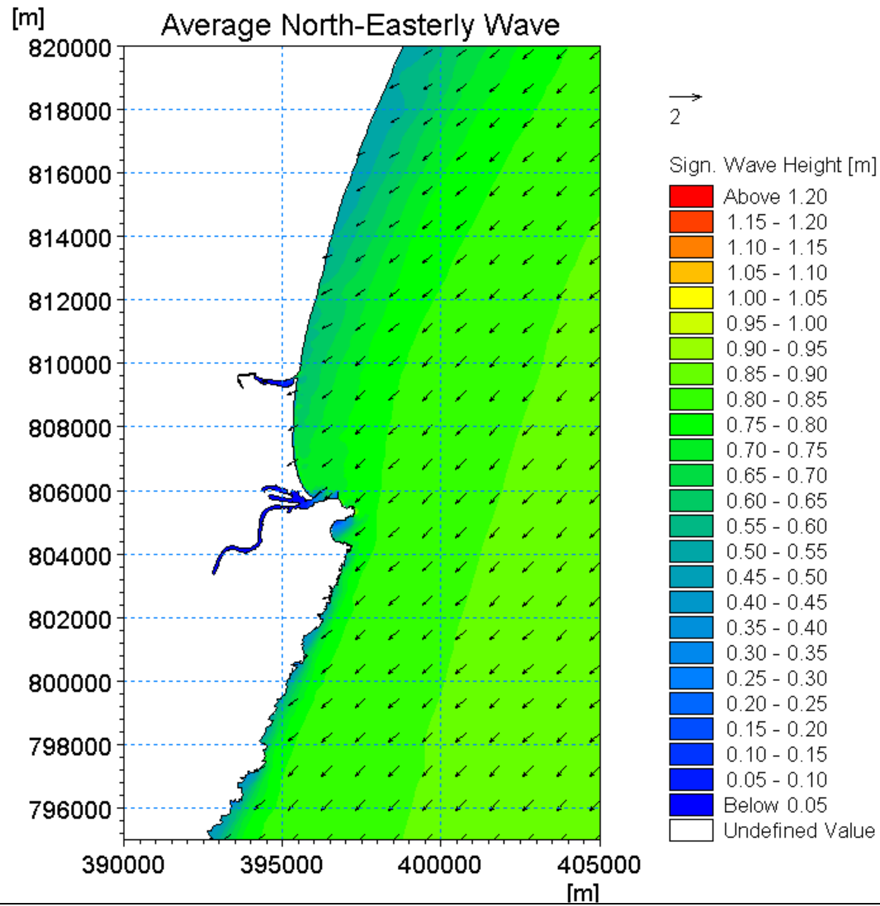
Local to the Development



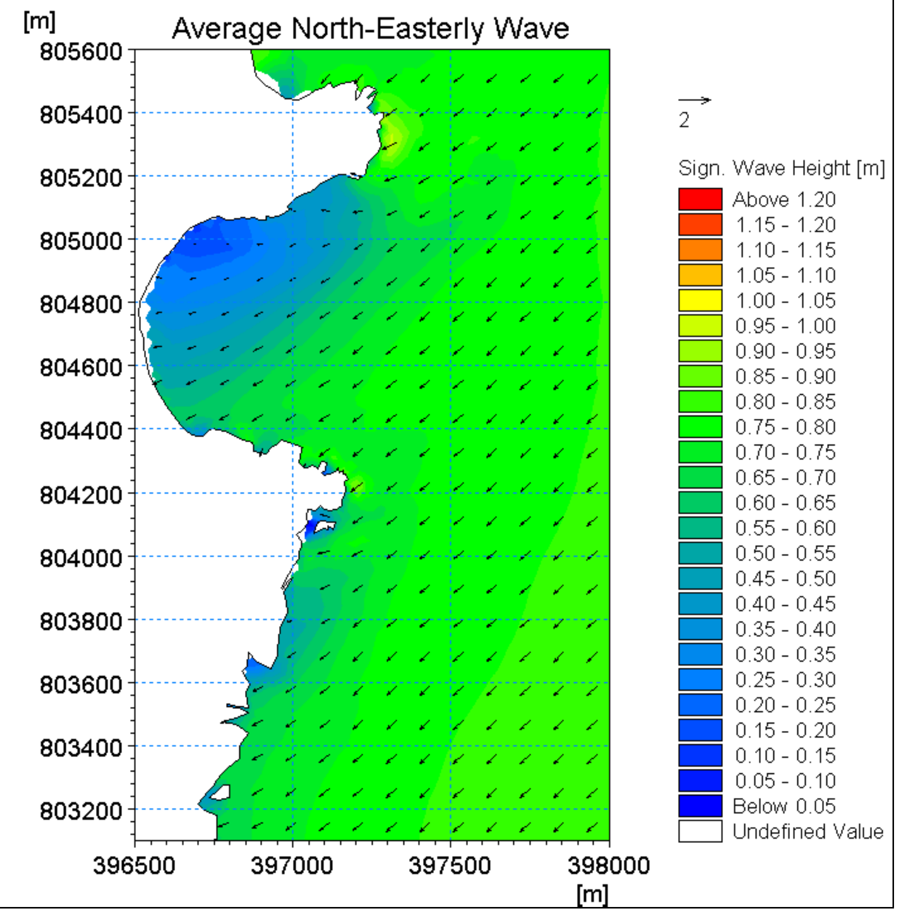
B.2 Wave Climate

Figure B-5: Significant wave height and wave propagation direction: Average Wave

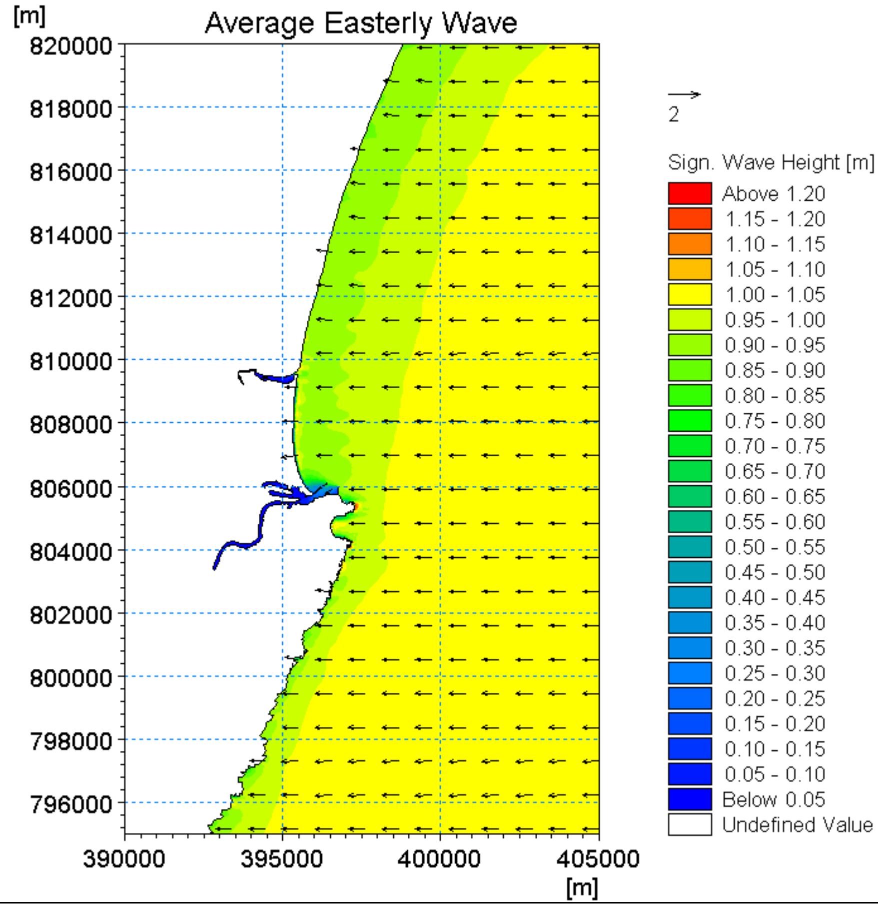
North-Easterly Wave: Over a Large Extent



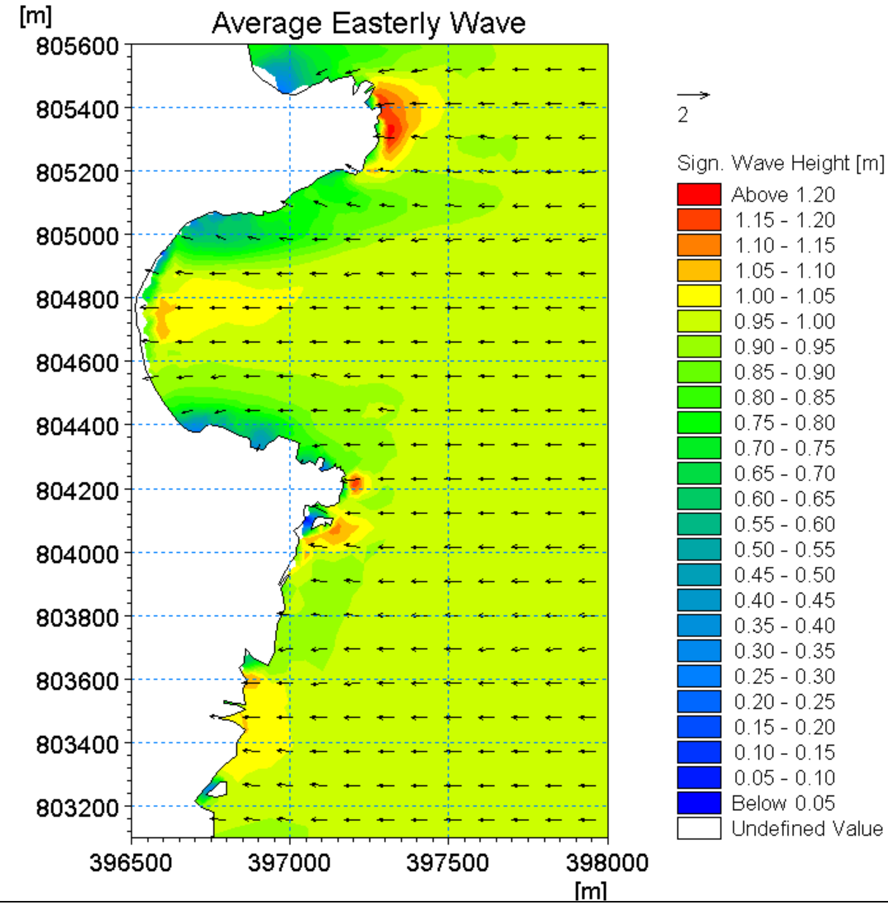
North-Easterly Wave: Local to the Development



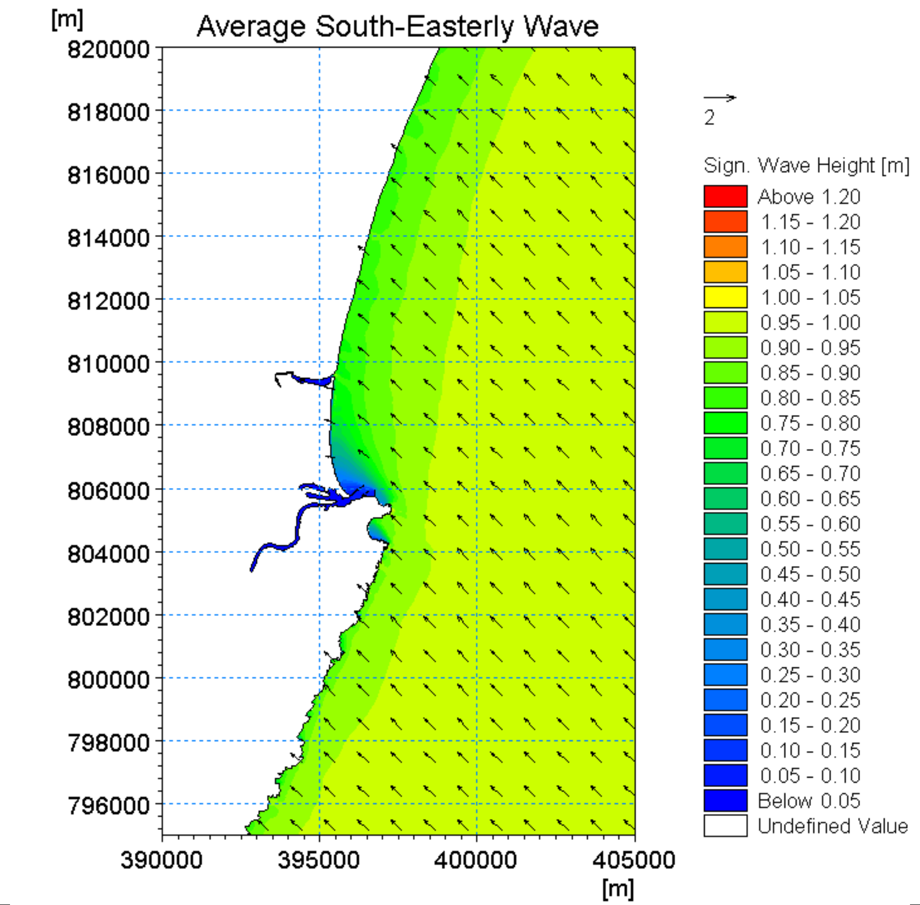
Easterly Wave: Over a Large Extent



Easterly Wave: Local to the Development



South-Easterly Wave: Over a Large Extent



South-Easterly Wave: Local to the Development

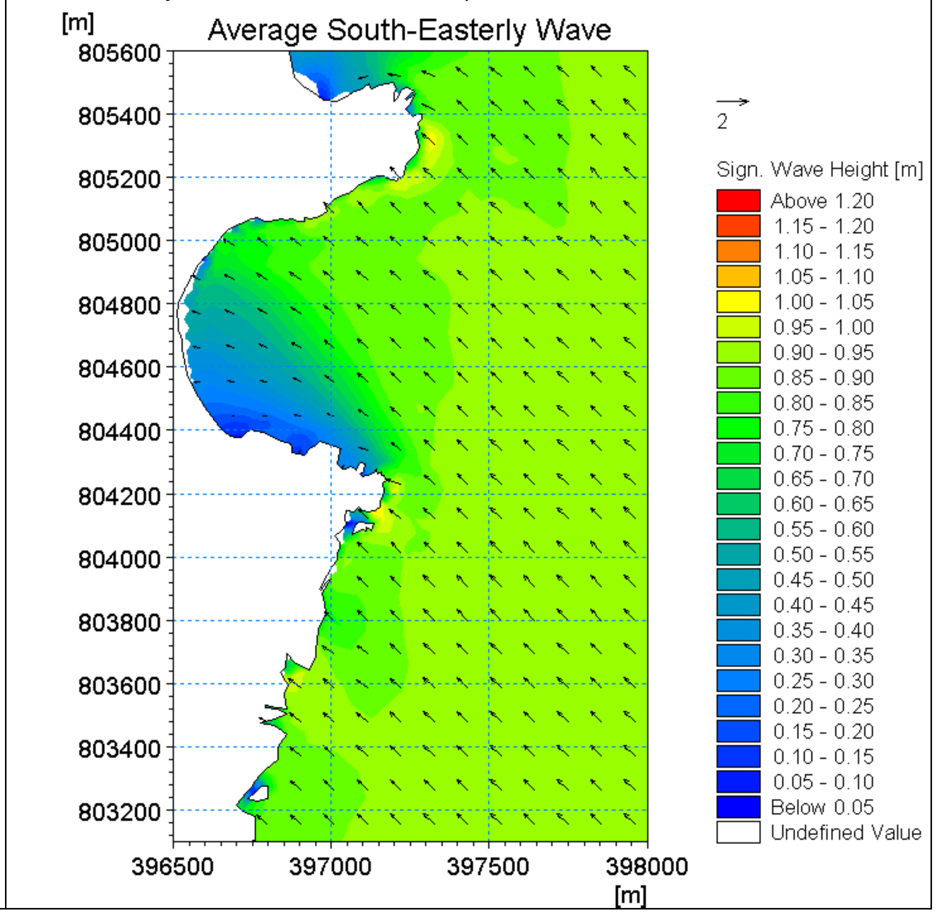
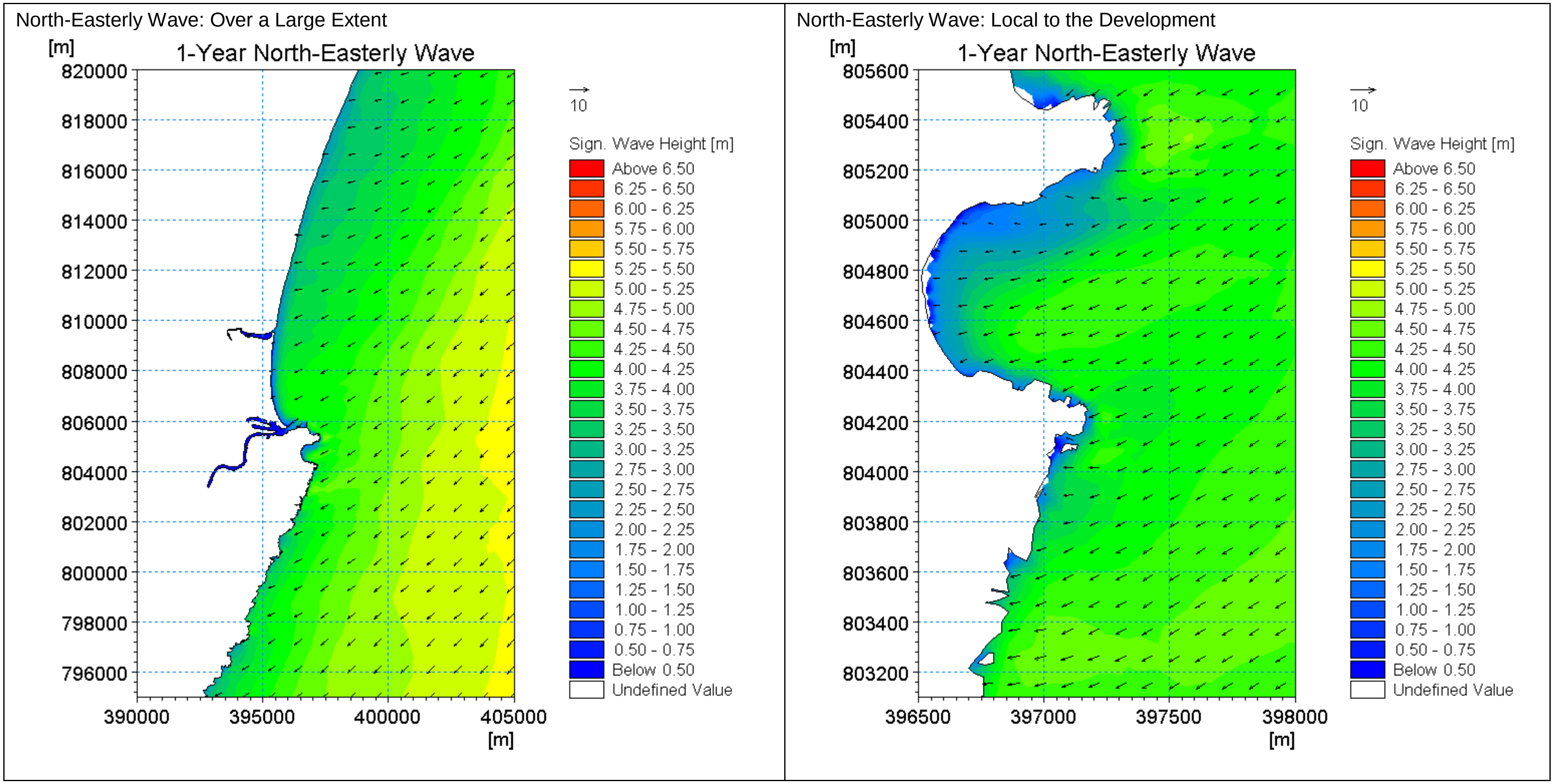
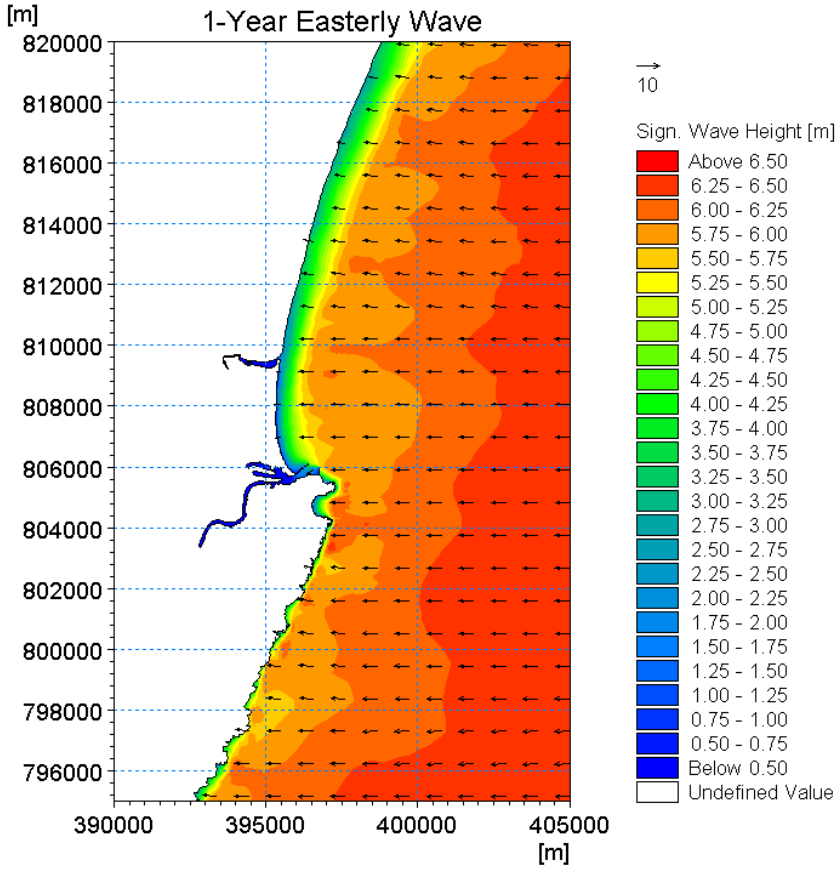


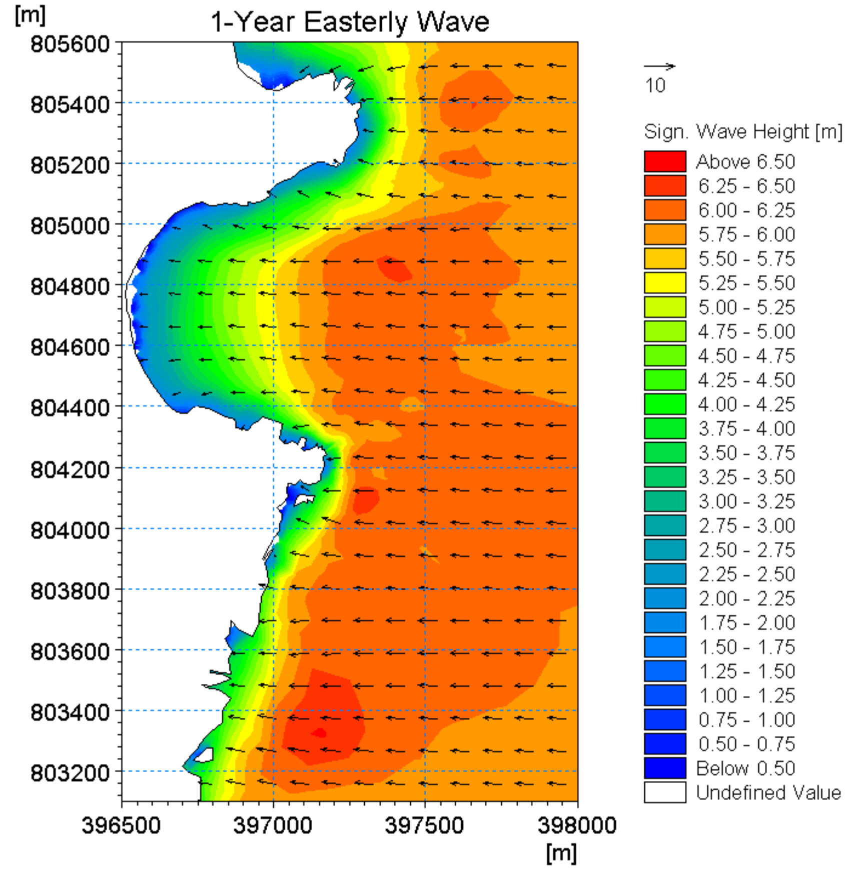
Figure B-6: Significant wave height and wave propagation direction: 1 in 1 Year Wave



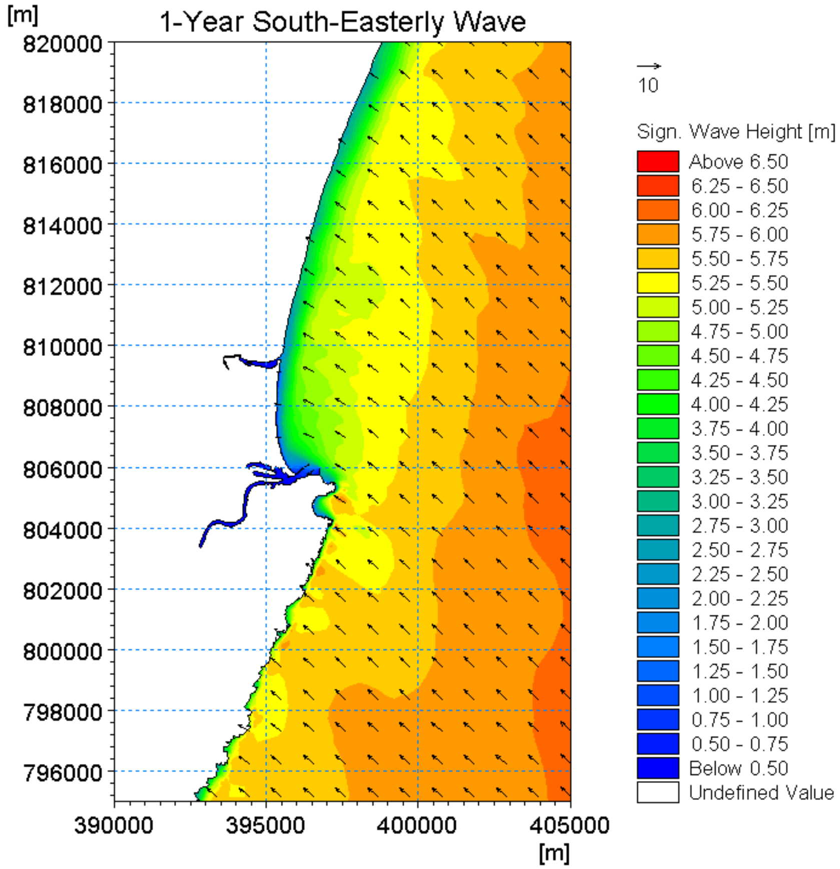
Easterly Wave: Over a Large Extent



Easterly Wave: Local to the Development



South-Easterly Wave: Over a Large Extent



South-Easterly Wave: Local to the Development

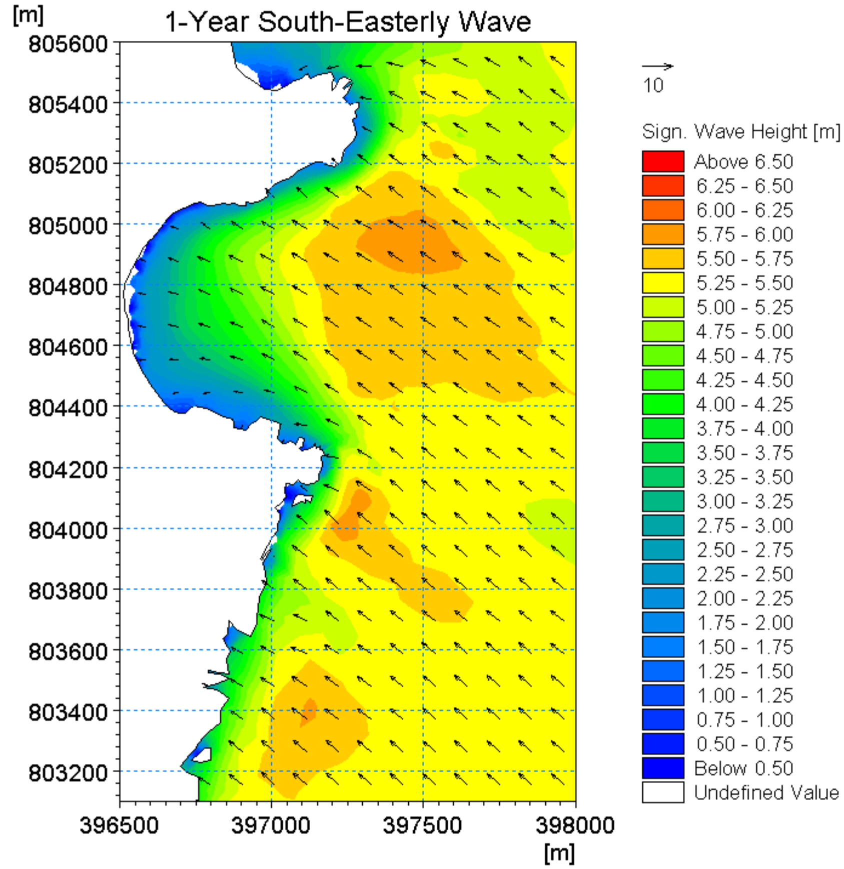
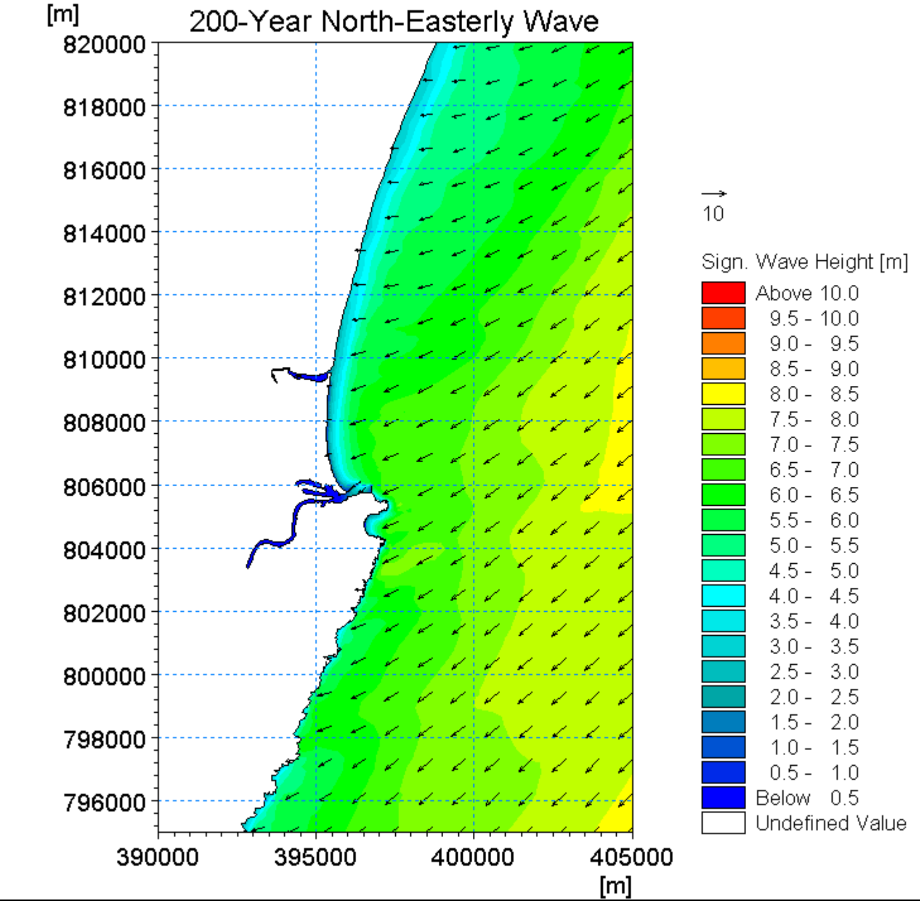
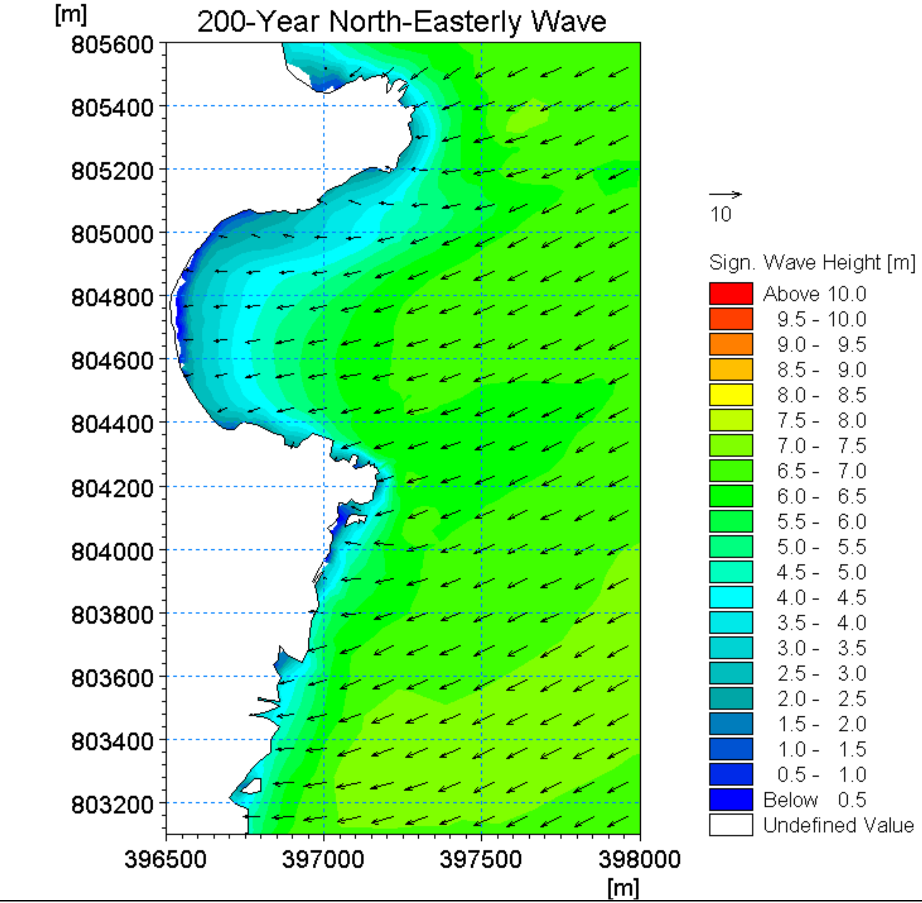


Figure B-7: Significant wave height and wave propagation direction: 1 in 200 Year Wave

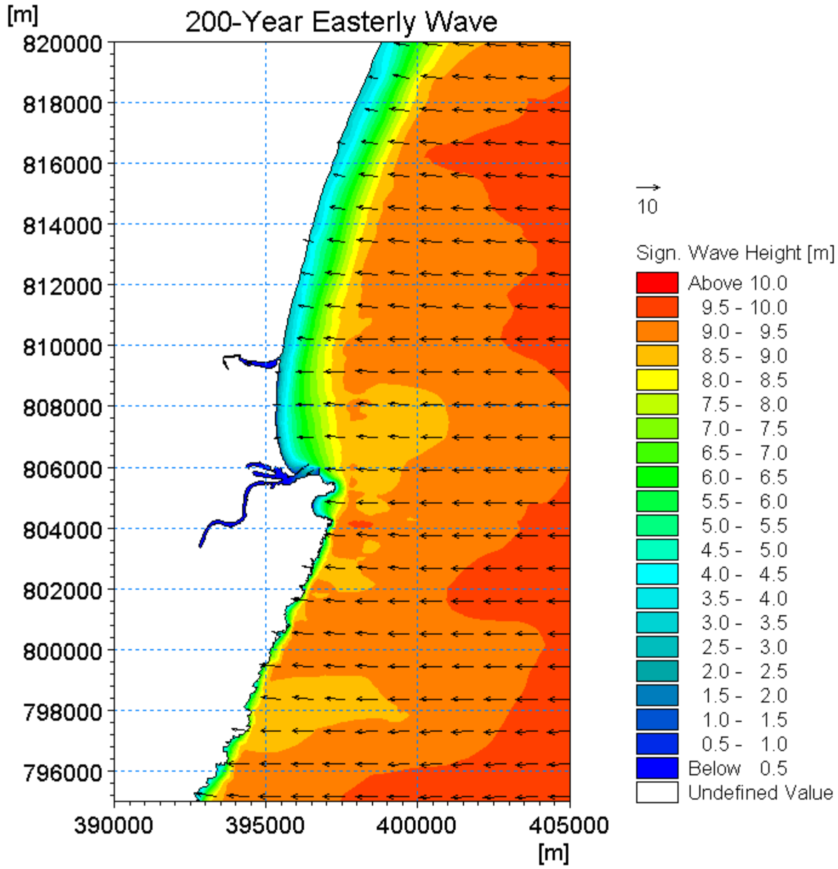
North-Easterly Wave: Over a Large Extent



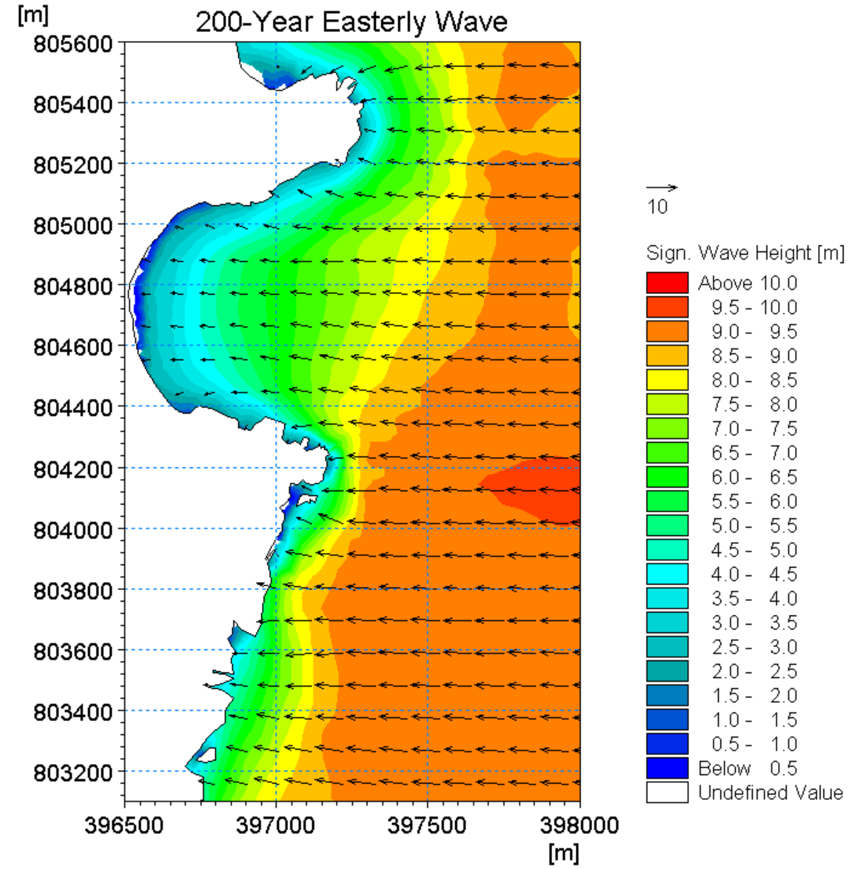
North-Easterly Wave: Local to the Development



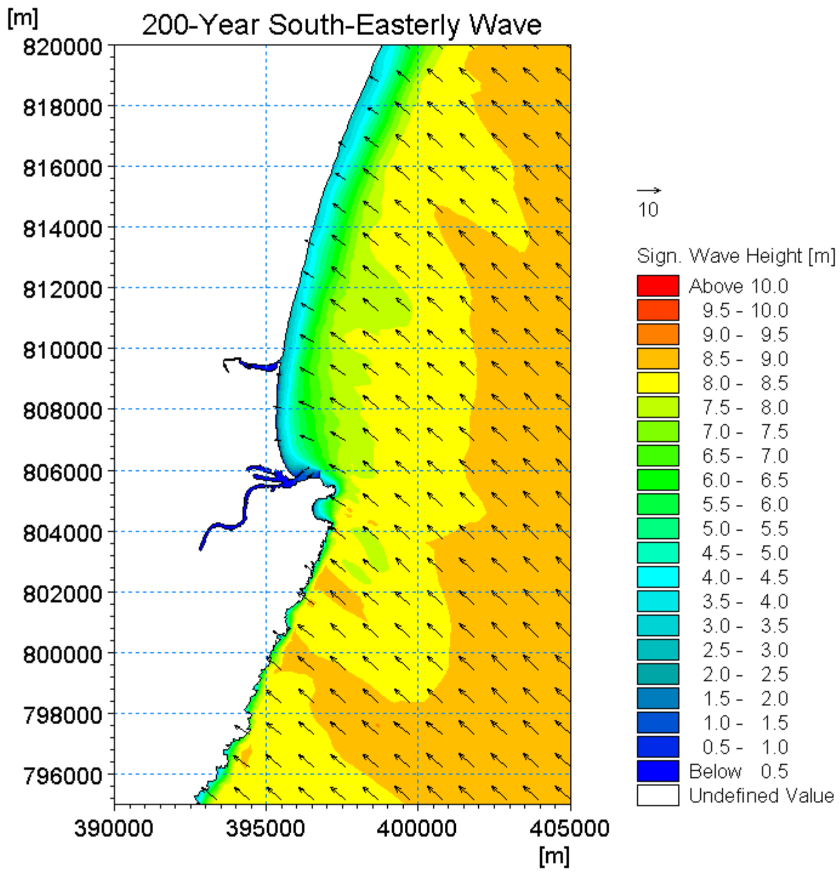
Easterly Wave: Over a Large Extent



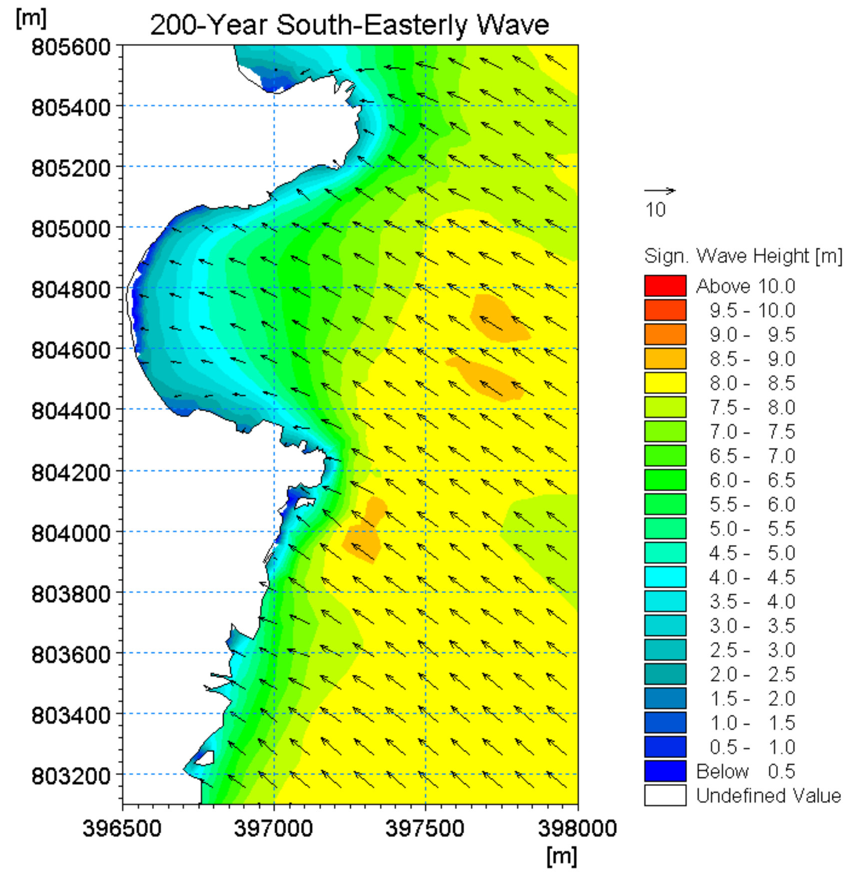
Easterly Wave: Local to the Development



South-Easterly Wave: Over a Large Extent



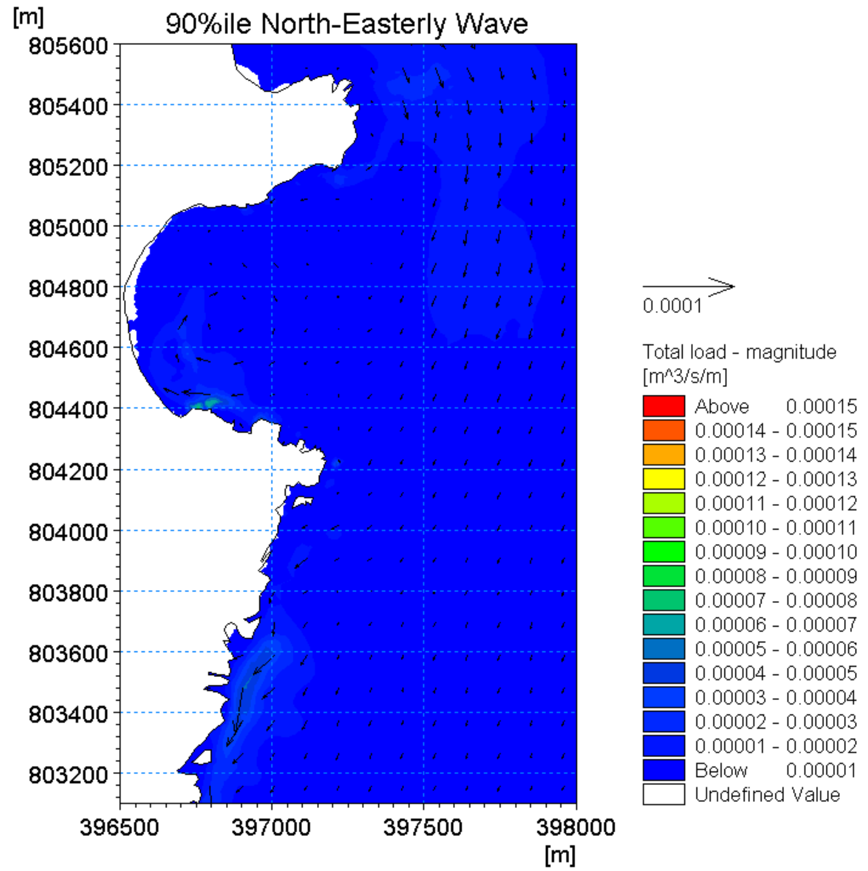
South-Easterly Wave: Local to the Development



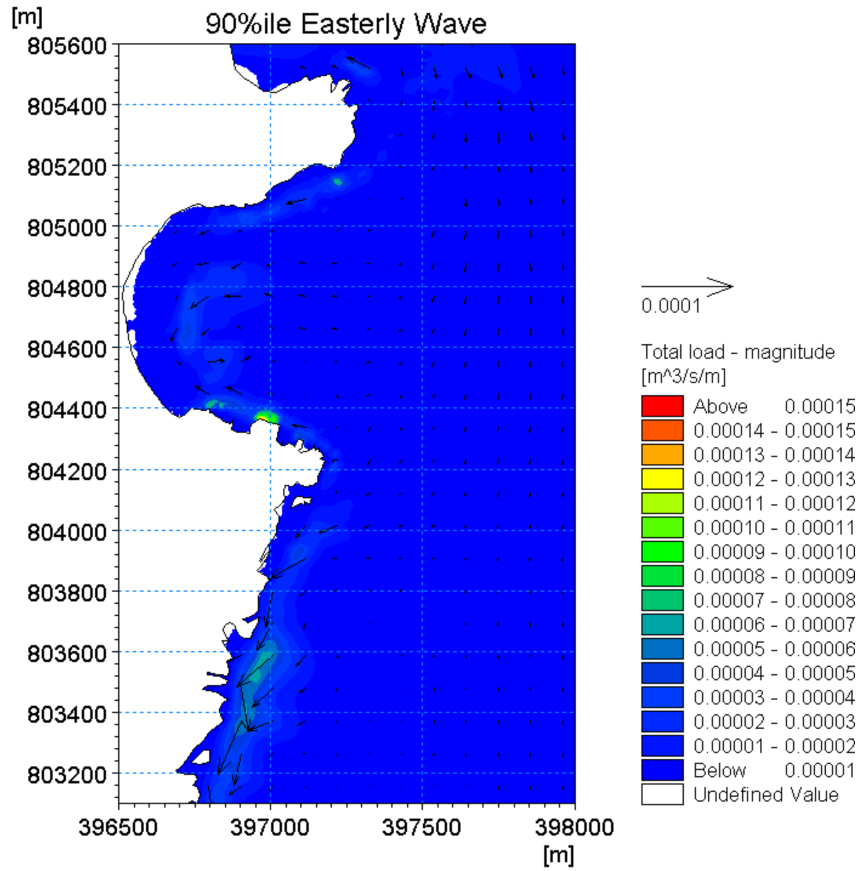
B.3 Sediment Transport

Figure B-8: Sediment transport pathway on a mean spring tide: 90%ile Waves

North-Easterly Wave



Easterly Wave



South-Easterly Wave

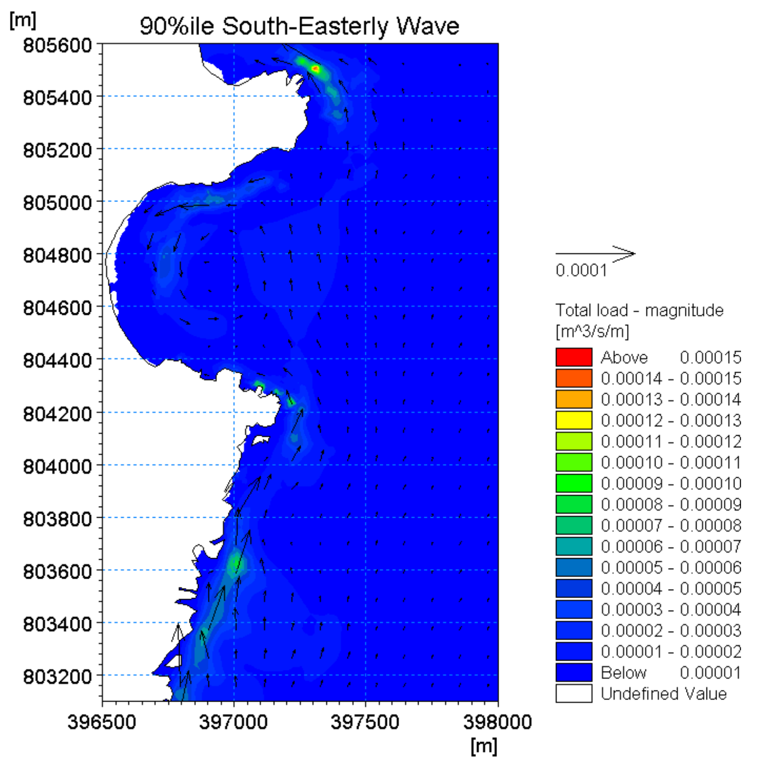
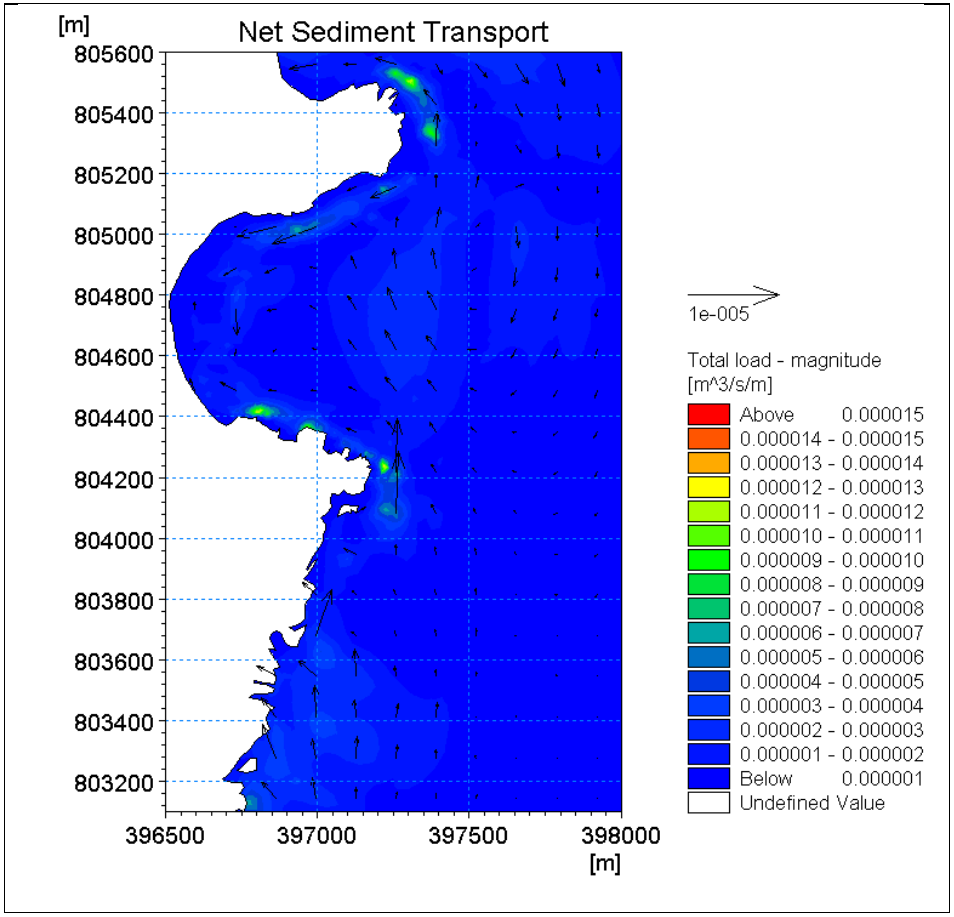


Figure B-9: Net sediment transport pathway: Baseline



Appendix C Impact Results

C.1 Hydrodynamics

Figure C-1: Operational change in maximum water level under a mean spring tide

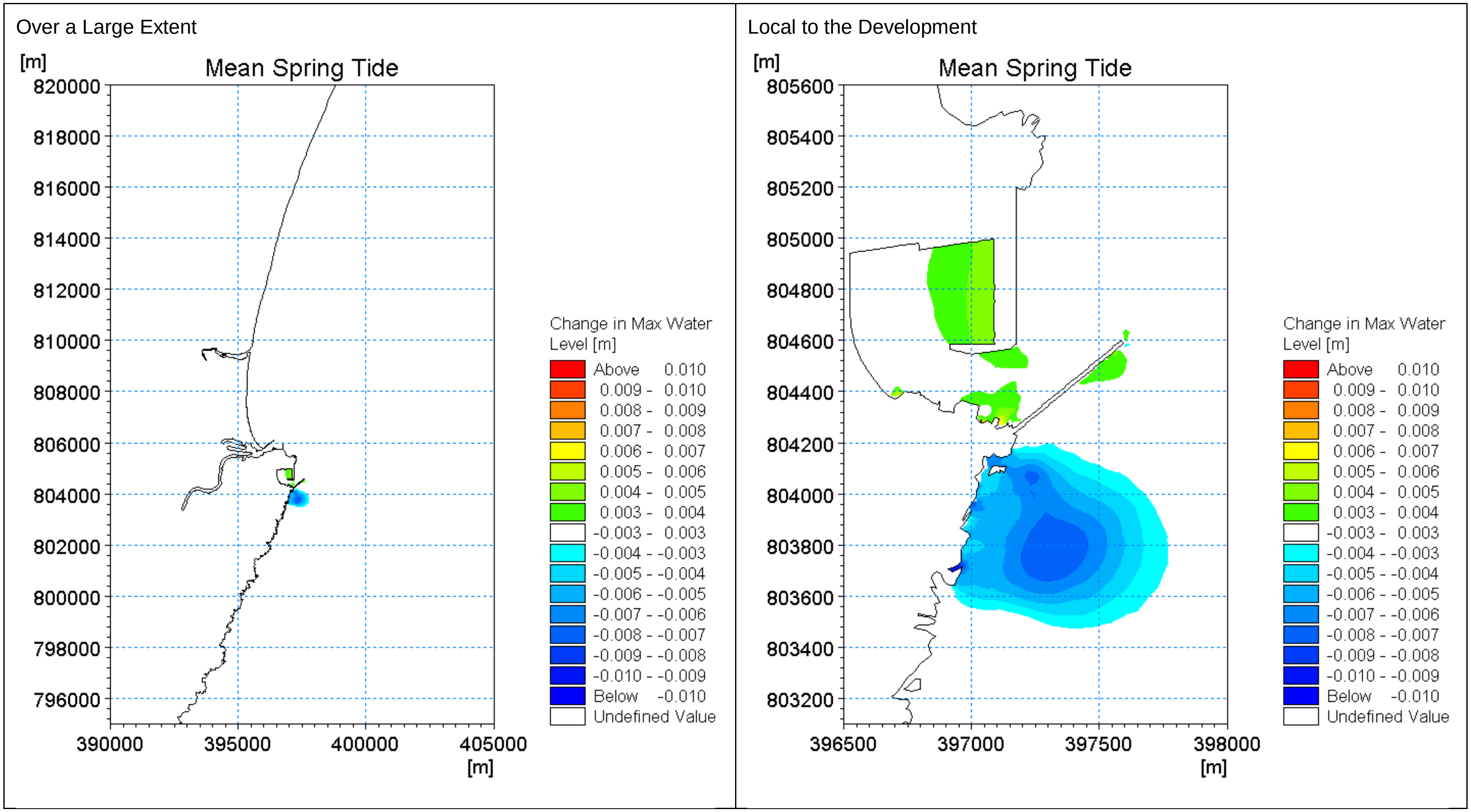


Figure C-2: Operational change in maximum water level under storm surge

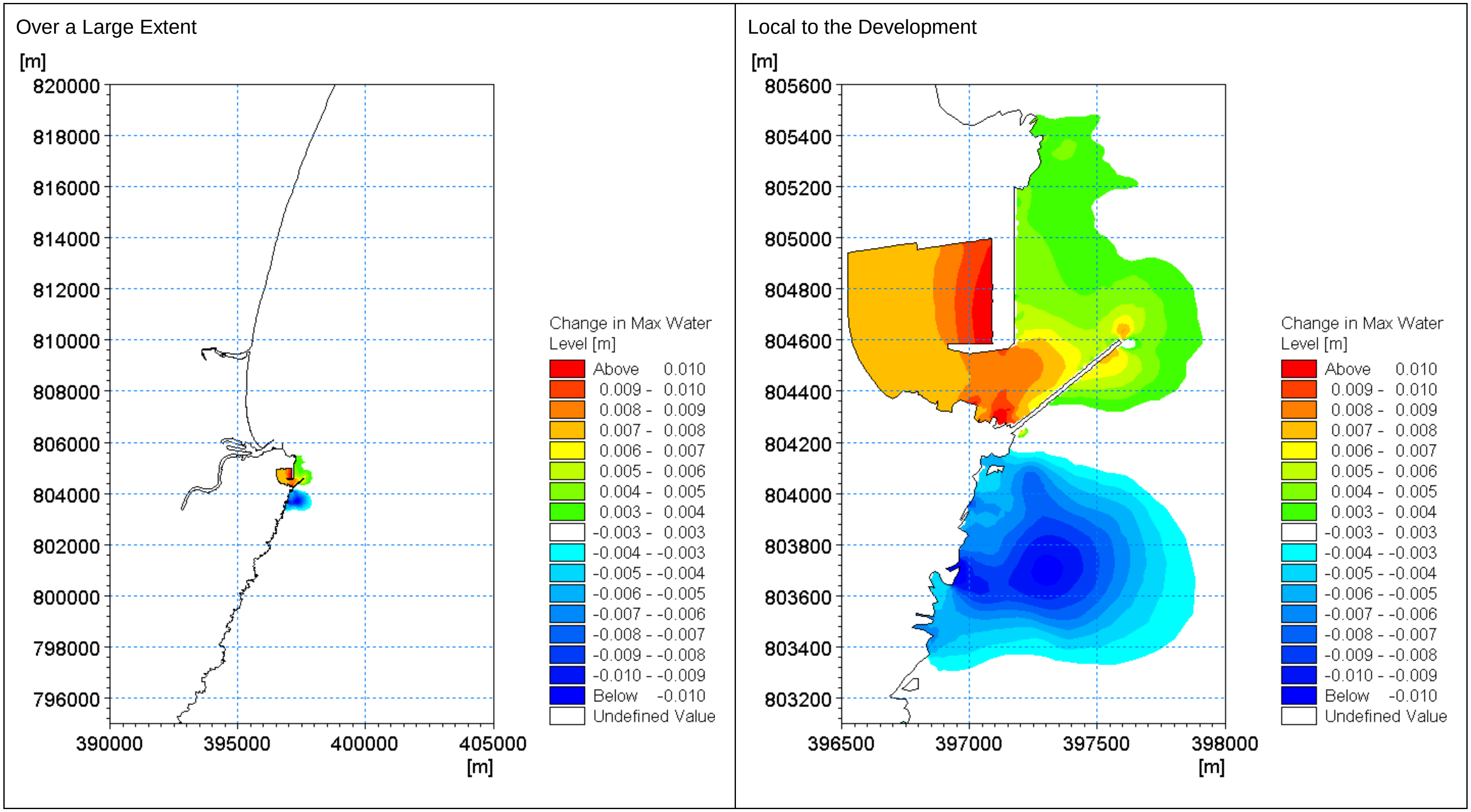
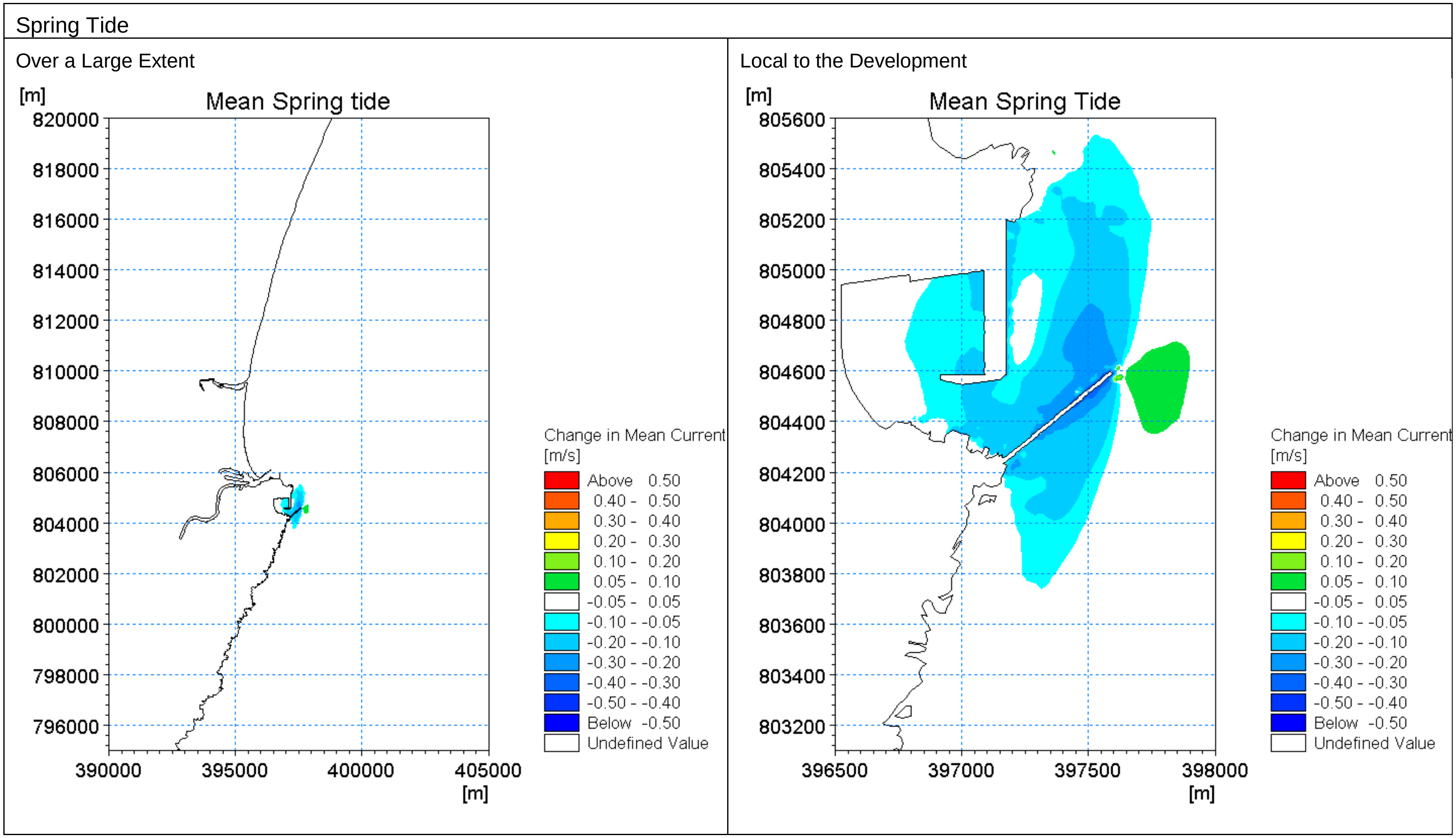


Figure C-3: Operational change in mean current speed



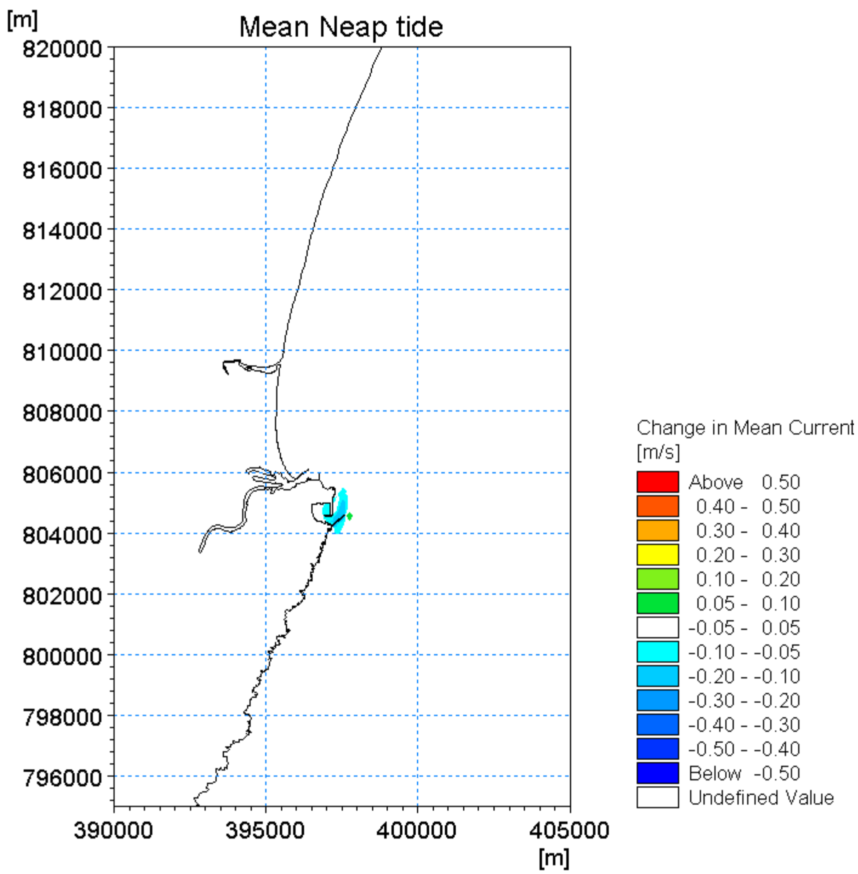
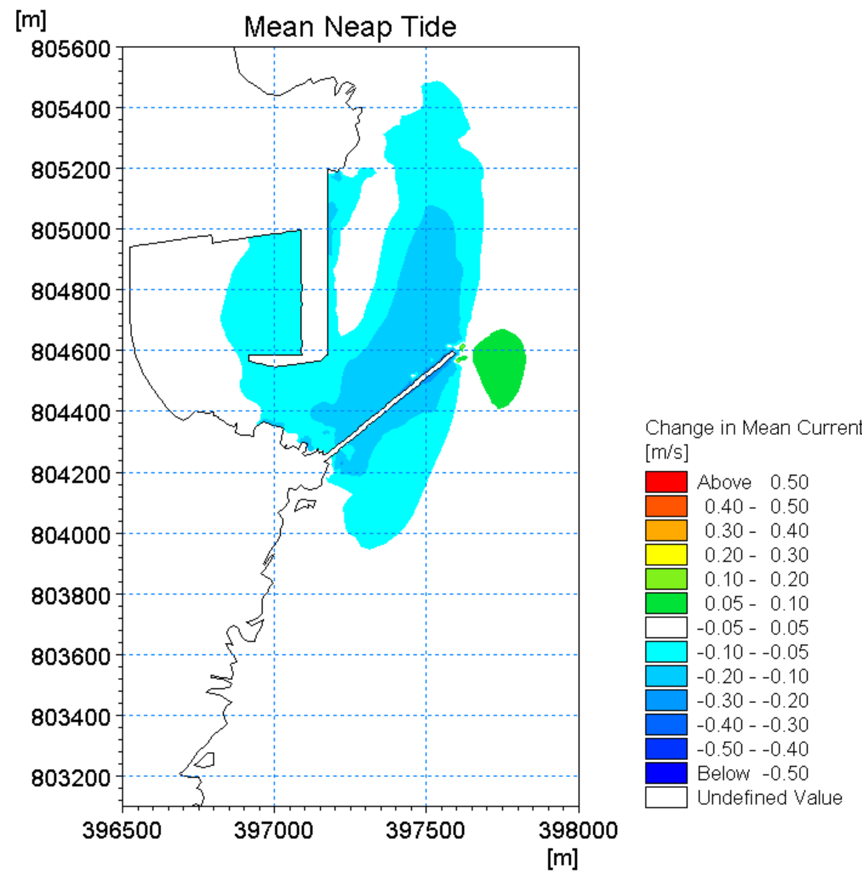
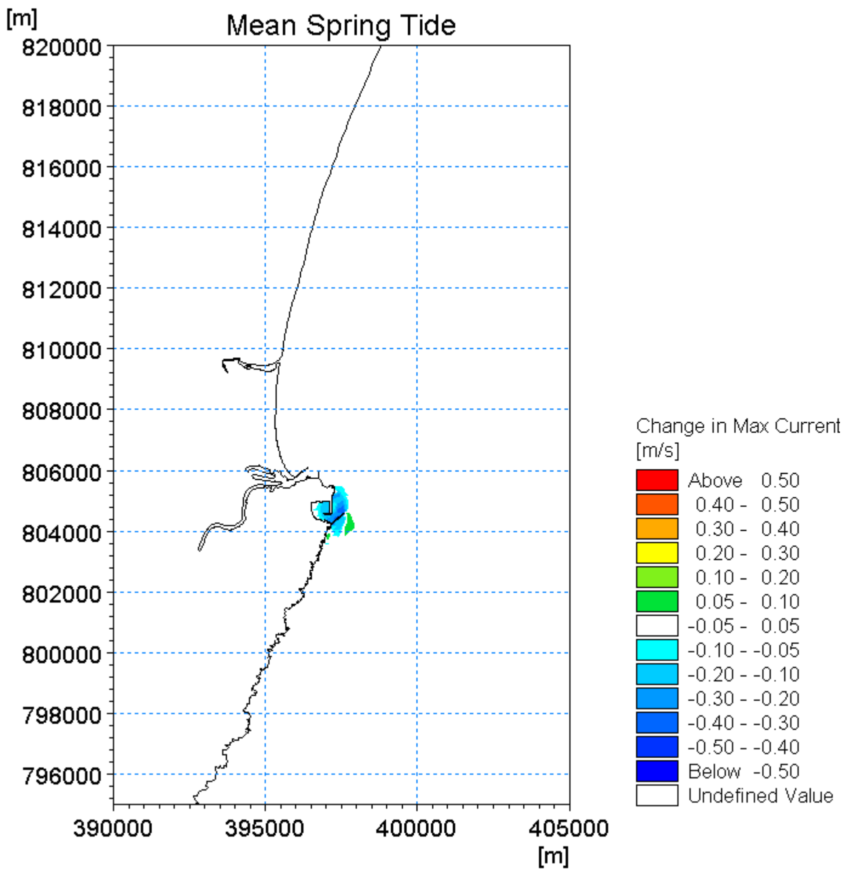
Neap Tide	
Over a Large Extent	Local to the Development
	

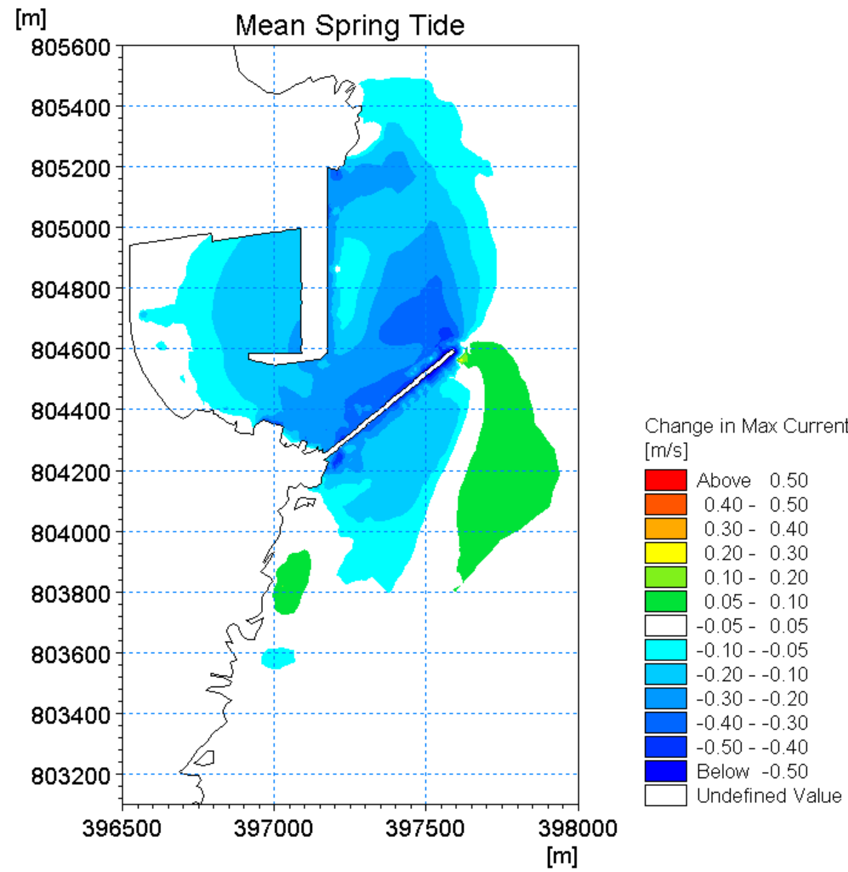
Figure C-4: Operational change in maximum current speed

Spring Tide

Over a Large Extent

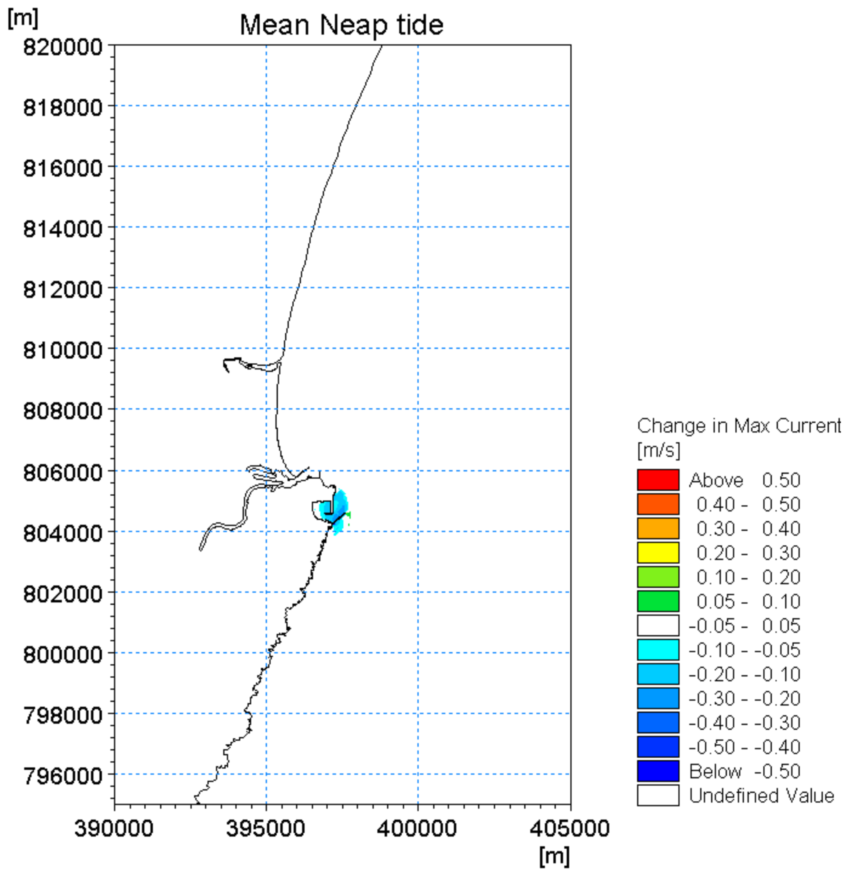


Local to the Development



Neap Tide

Over a Large Extent



Local to the Development

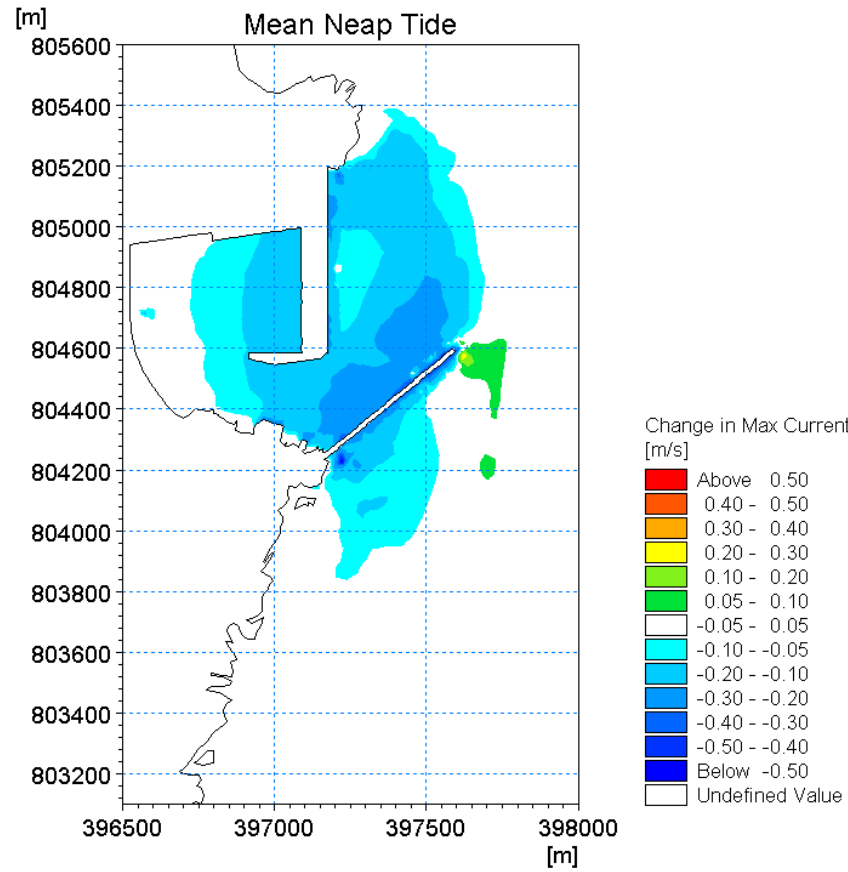
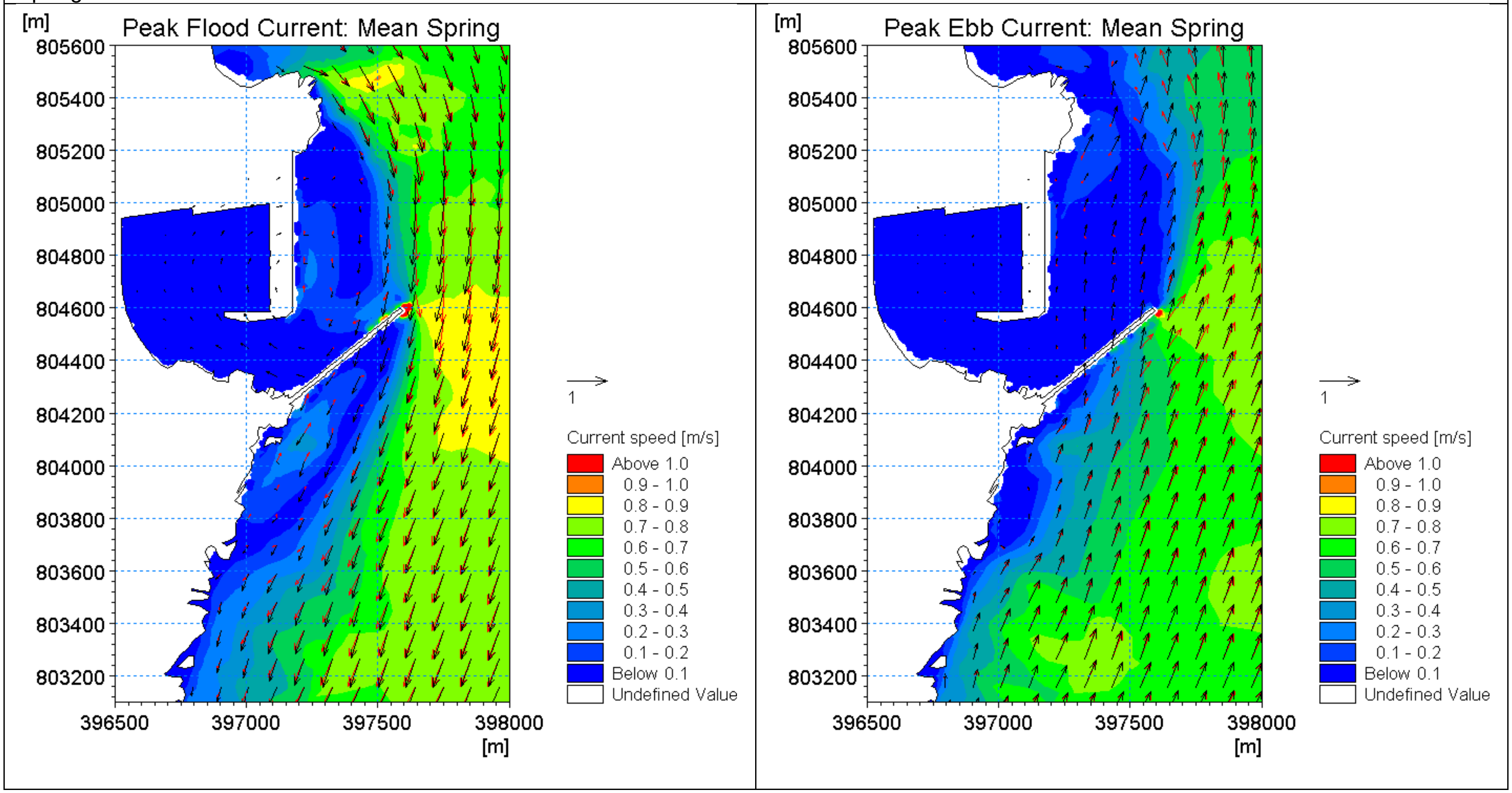


Figure C-5: Current vector plot showing change in current direction: Average Conditions

Spring Tide



Neap Tide

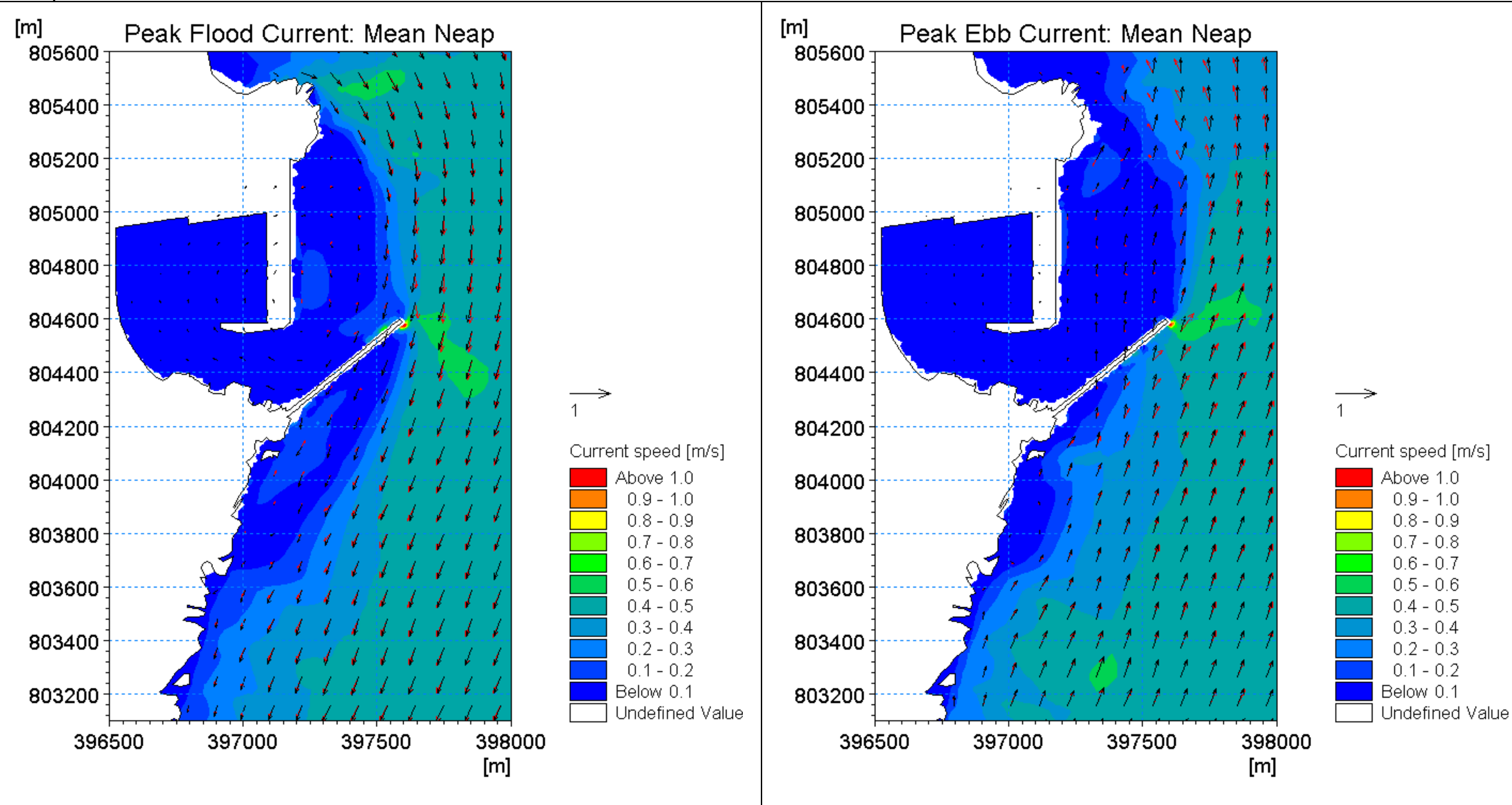
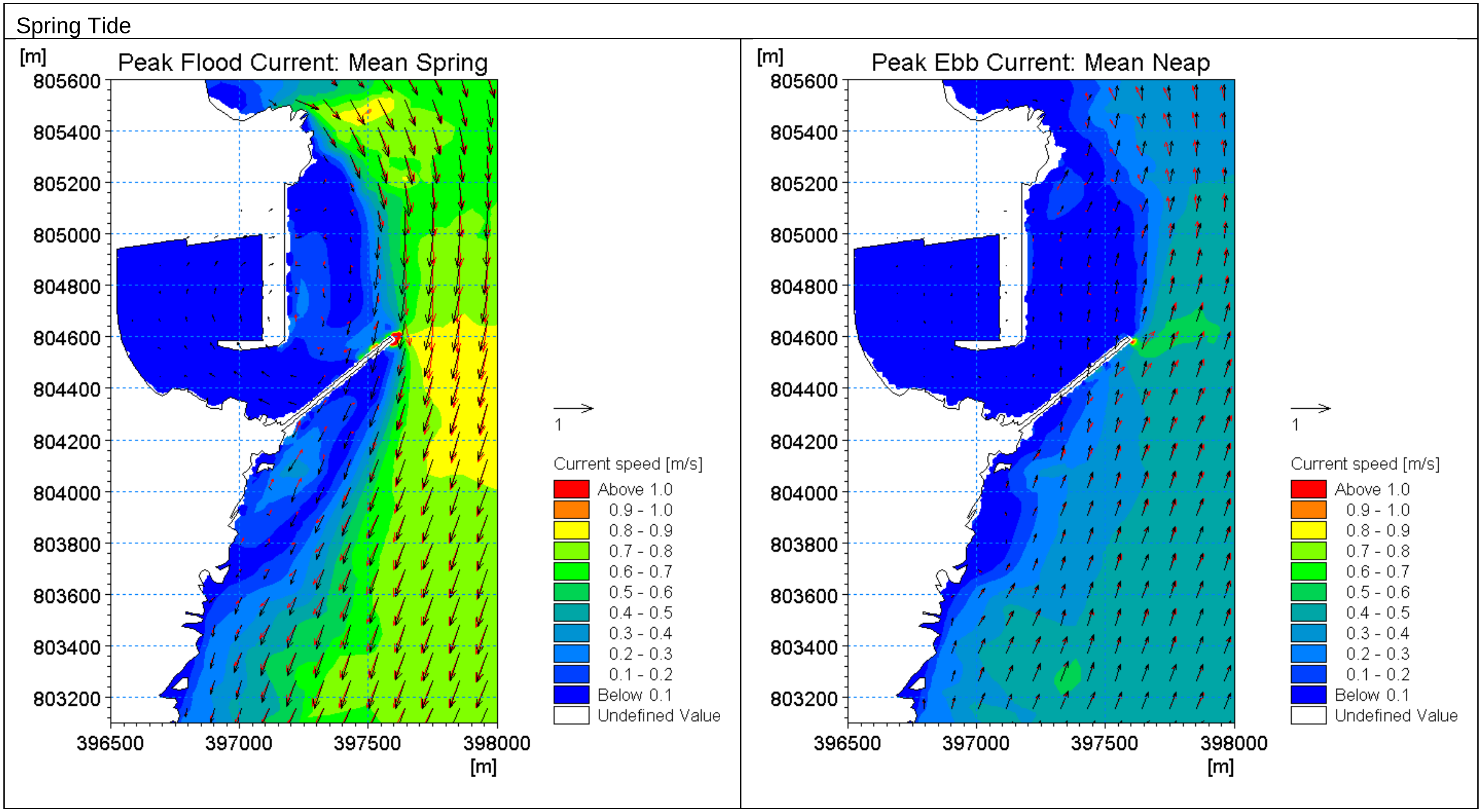
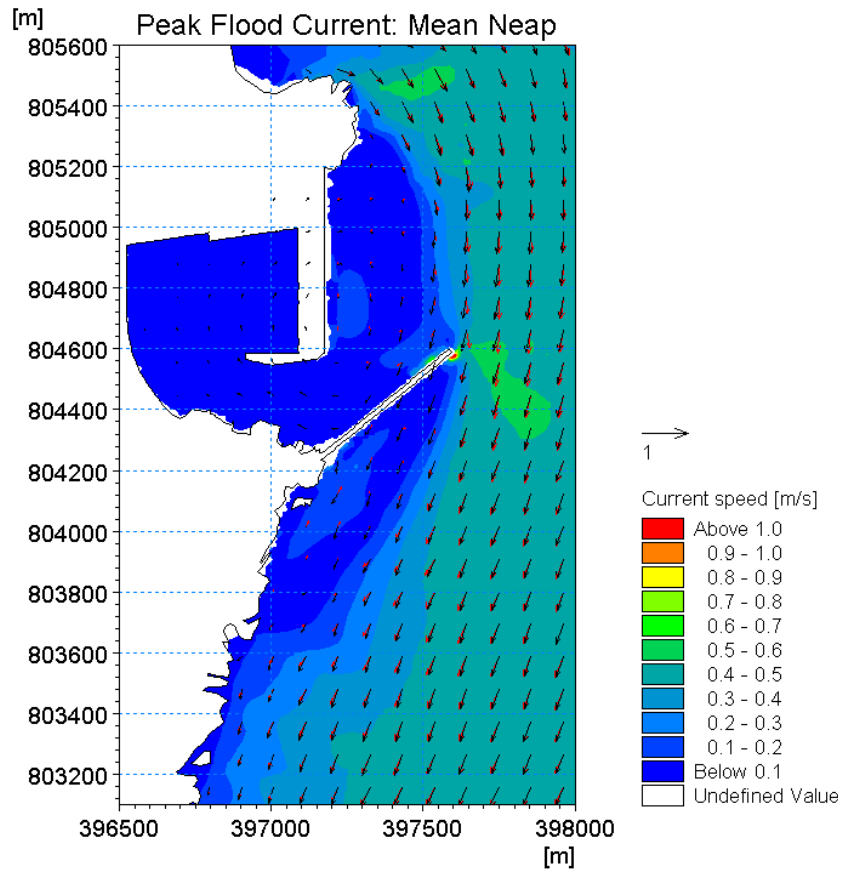

Peak Flood Current: Mean Neap
Peak Ebb Current: Mean Neap
[m]
805600
805400
805200
805000
804800
804600
804400
804200
804000
803800
803600
803400
803200
396500
397000
397500
398000
1
Current speed [m/s]
Above 1.0
0.9 - 1.0
0.8 - 0.9
0.7 - 0.8
0.6 - 0.7
0.5 - 0.6
0.4 - 0.5
0.3 - 0.4
0.2 - 0.3
0.1 - 0.2
Below 0.1
Undefined Value

Figure C-6: Current vector plot showing change in current direction: Storm Conditions



Neap Tide


Peak Flood Current: Mean Neap
[m]
805600
805400
805200
805000
804800
804600
804400
804200
804000
803800
803600
803400
803200
396500
397000
397500
398000
[m]
1
Current speed [m/s]
Above 1.0
0.9 - 1.0
0.8 - 0.9
0.7 - 0.8
0.6 - 0.7
0.5 - 0.6
0.4 - 0.5
0.3 - 0.4
0.2 - 0.3
0.1 - 0.2
Below 0.1
Undefined Value

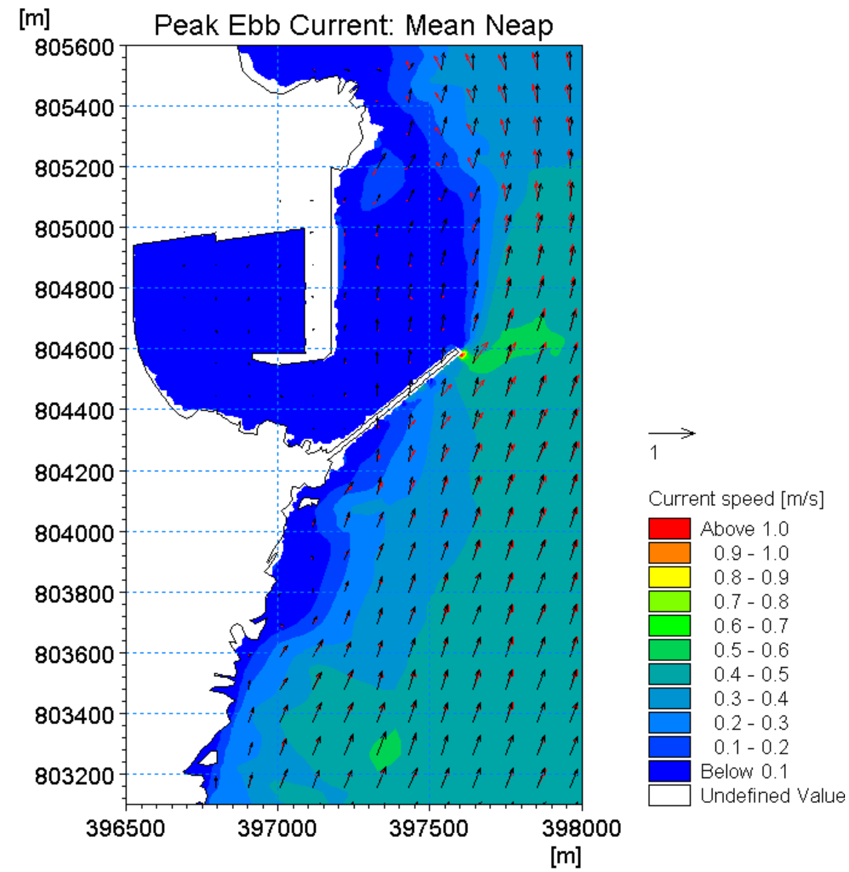
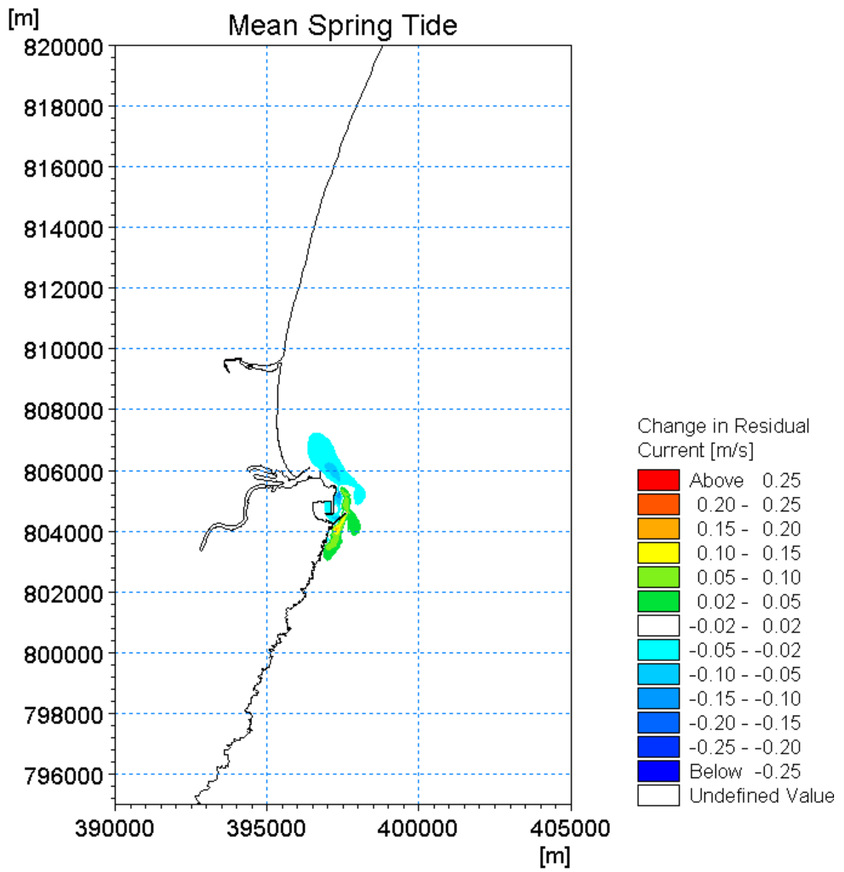

Peak Ebb Current: Mean Neap
[m]
805600
805400
805200
805000
804800
804600
804400
804200
804000
803800
803600
803400
803200
396500
397000
397500
398000
[m]
1
Current speed [m/s]
Above 1.0
0.9 - 1.0
0.8 - 0.9
0.7 - 0.8
0.6 - 0.7
0.5 - 0.6
0.4 - 0.5
0.3 - 0.4
0.2 - 0.3
0.1 - 0.2
Below 0.1
Undefined Value

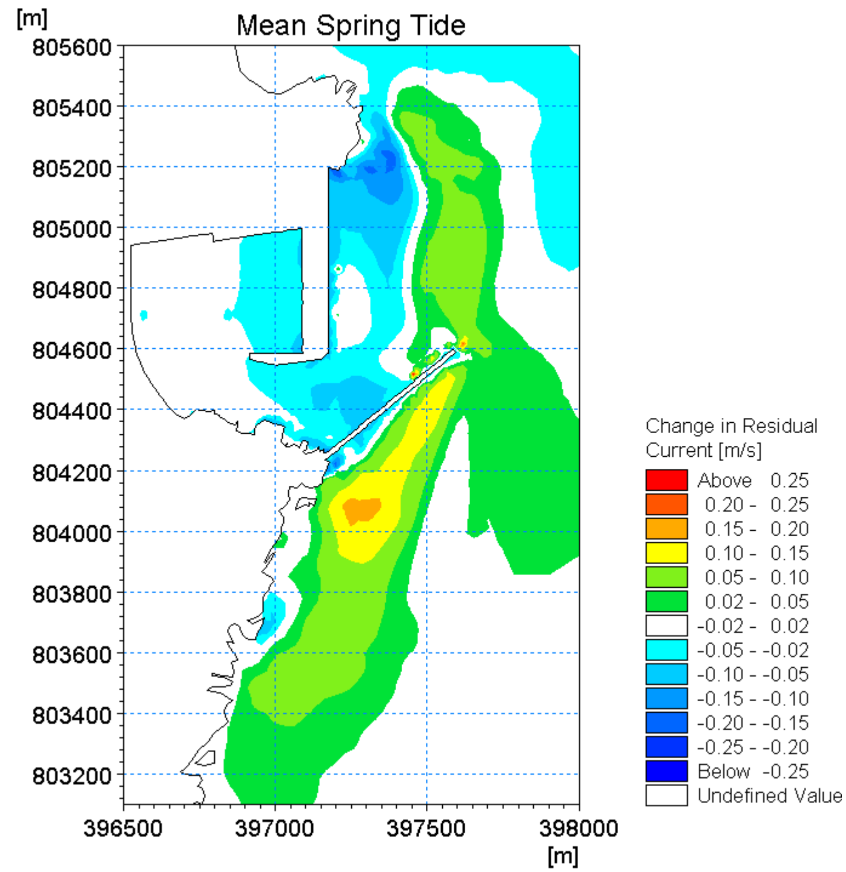
Figure C-7: Operational change in residual current speed

Spring Tide

Over a Large Extent

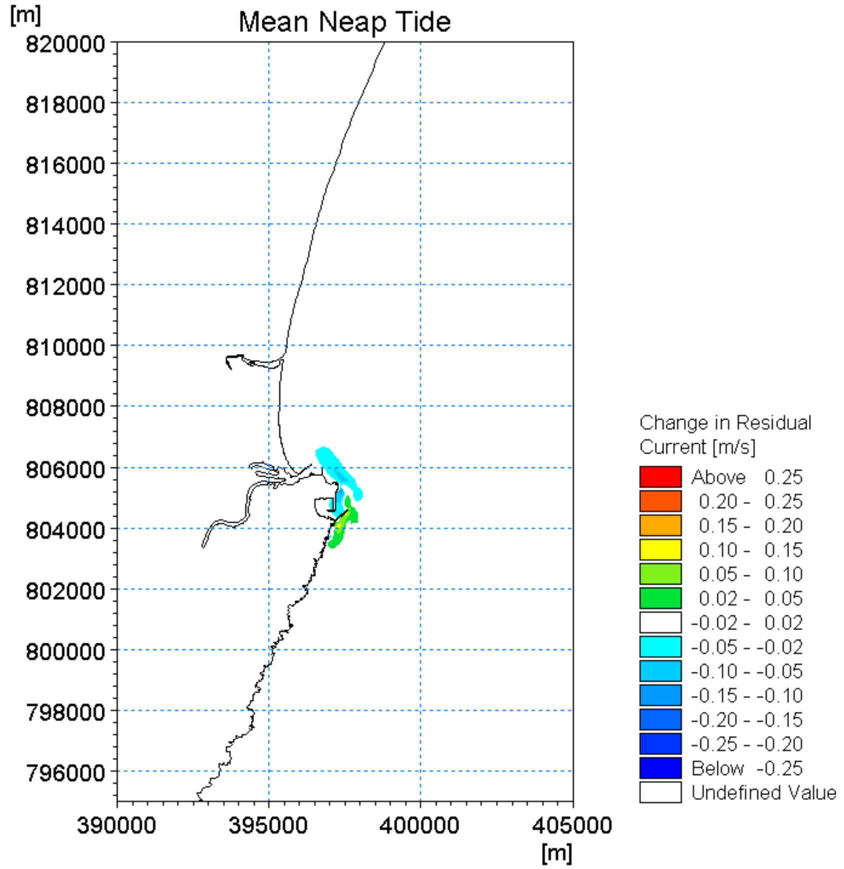


Local to the Development



Neap Tide

Over a Large Extent



Local to the Development

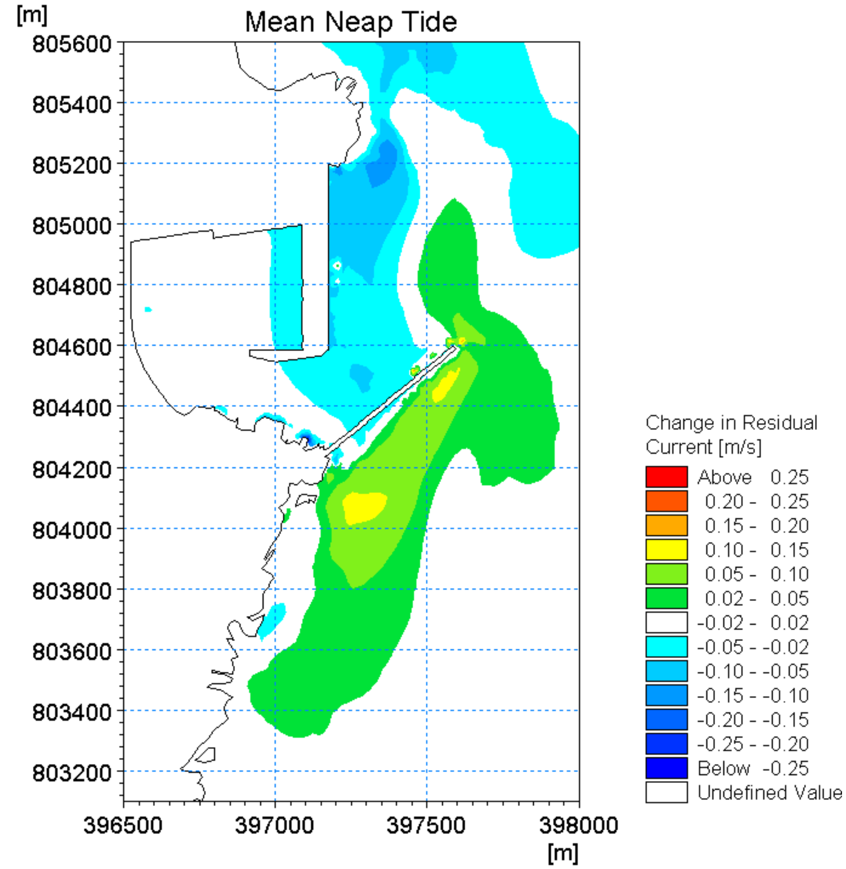


Figure C-8: Current vector plot showing change in residual current direction: Average Conditions

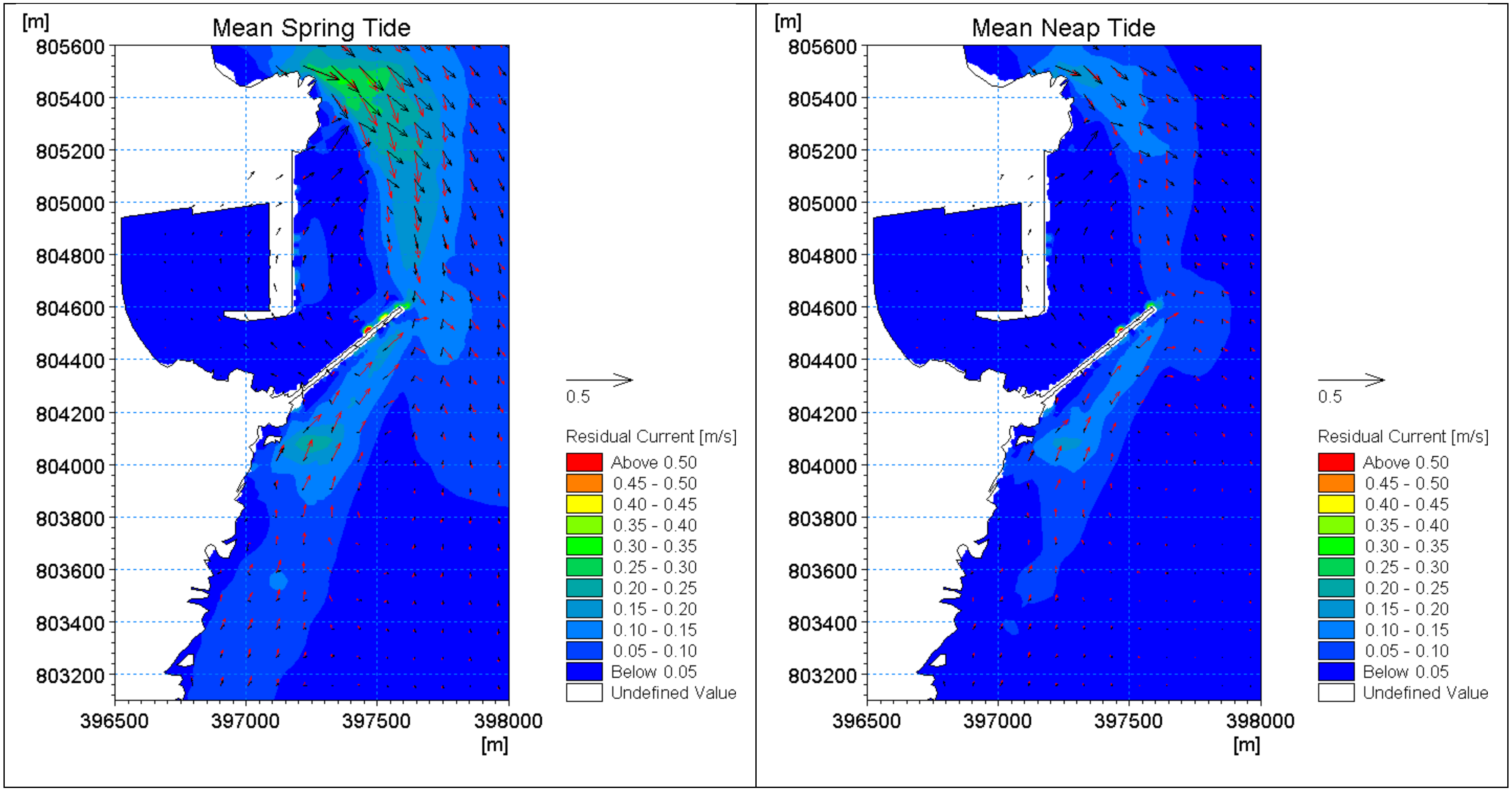
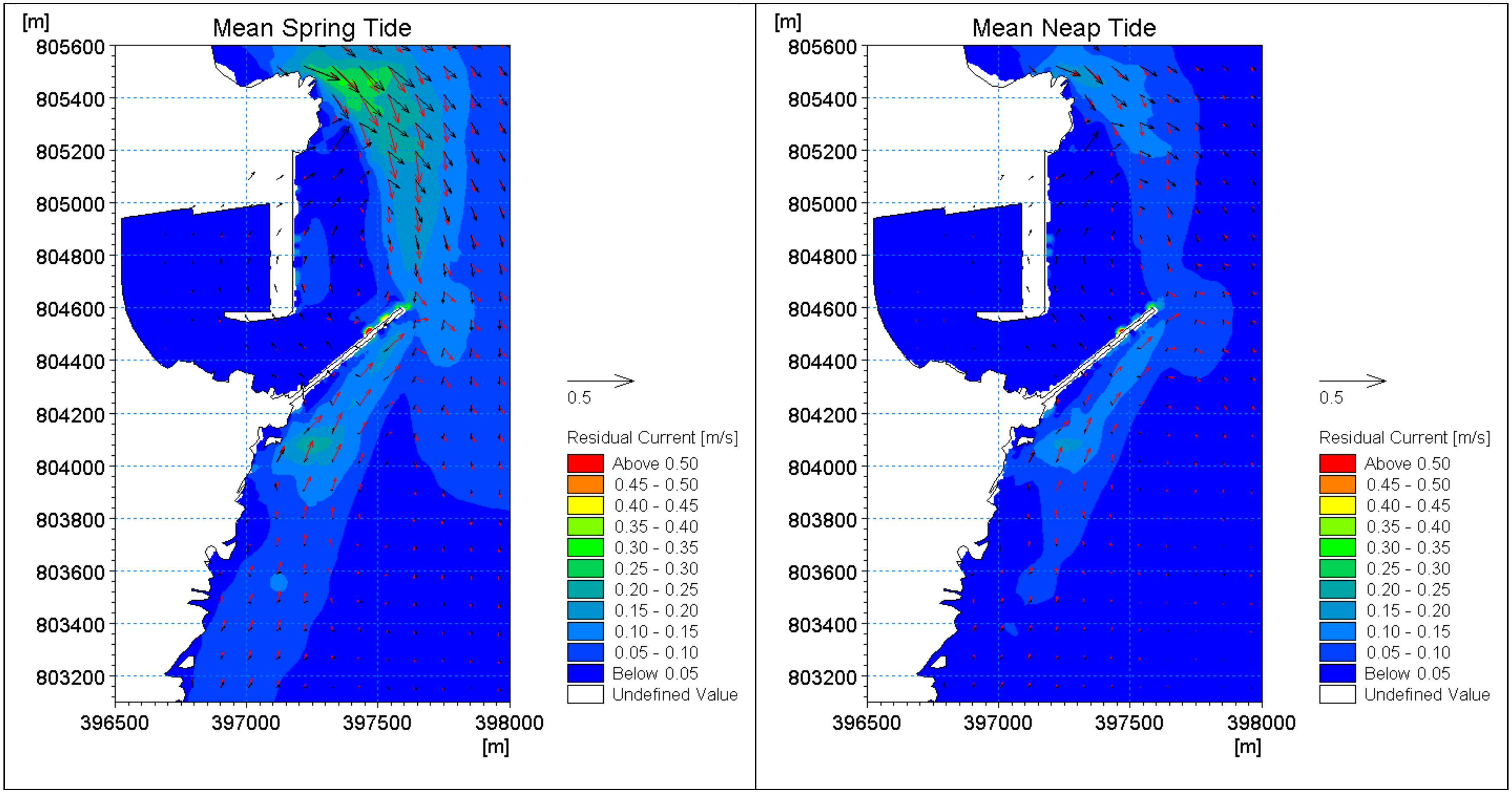


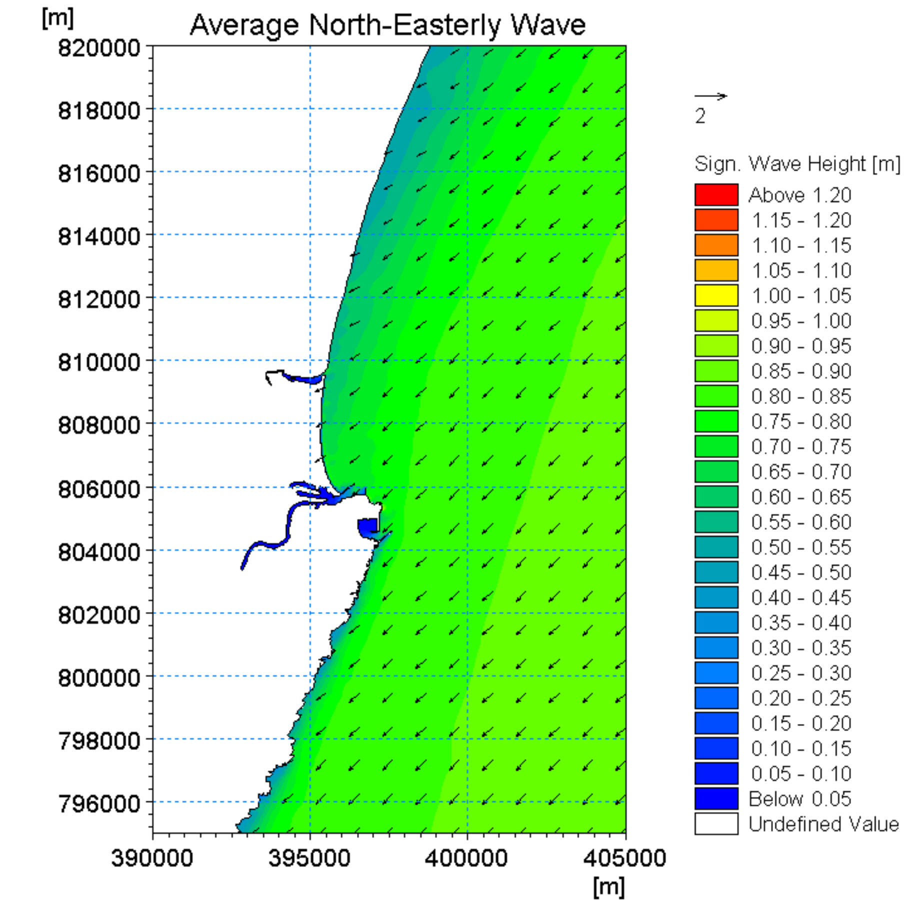
Figure C-9: Current vector plot showing change in residual current direction: Storm Conditions



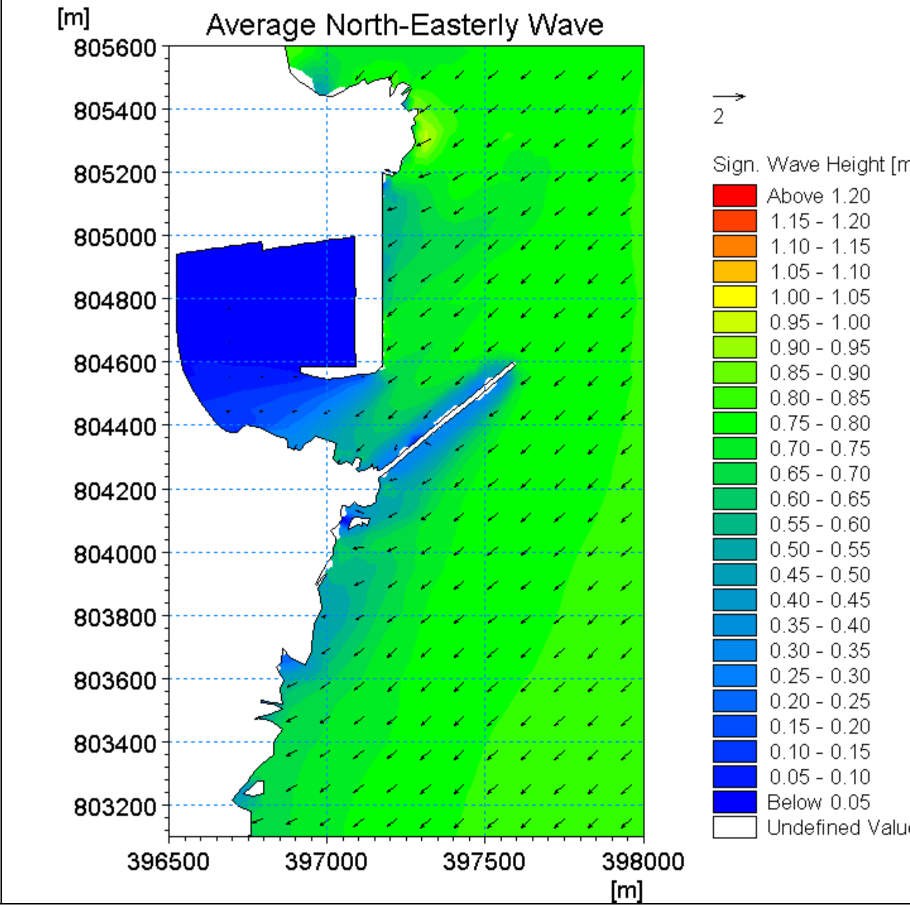
C.2 Wave Climate

Figure C-10: Significant wave height and wave propagation direction: Average Wave

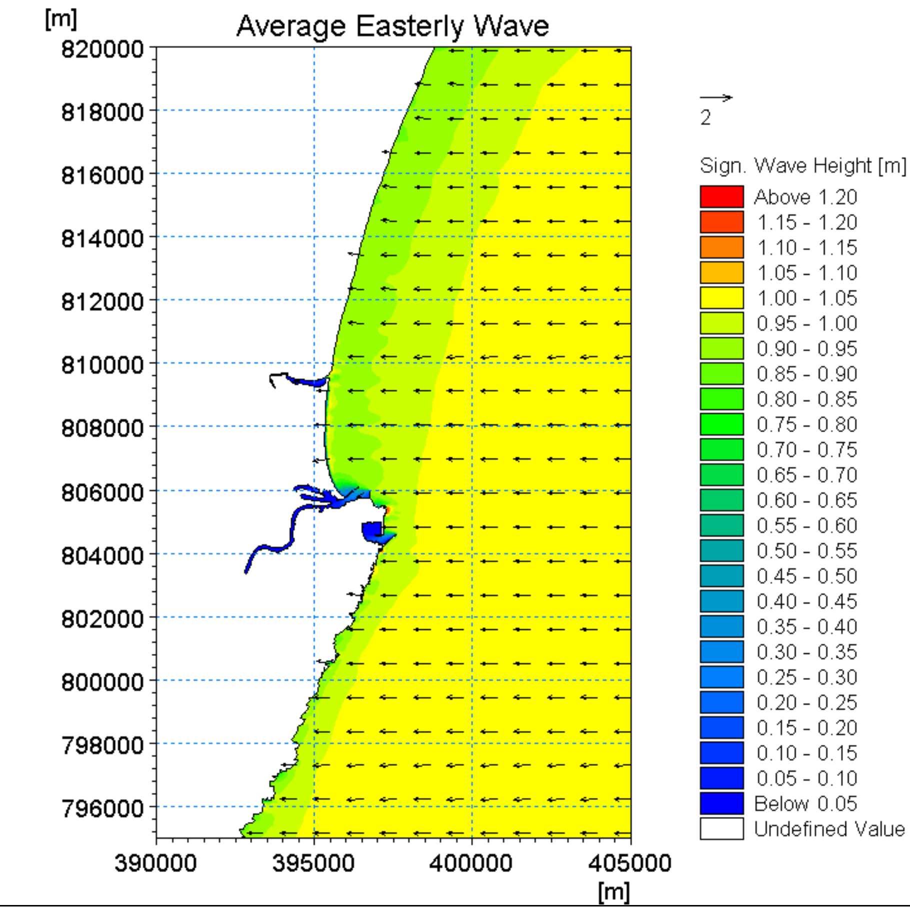
North-Easterly Wave: Over a Large Extent



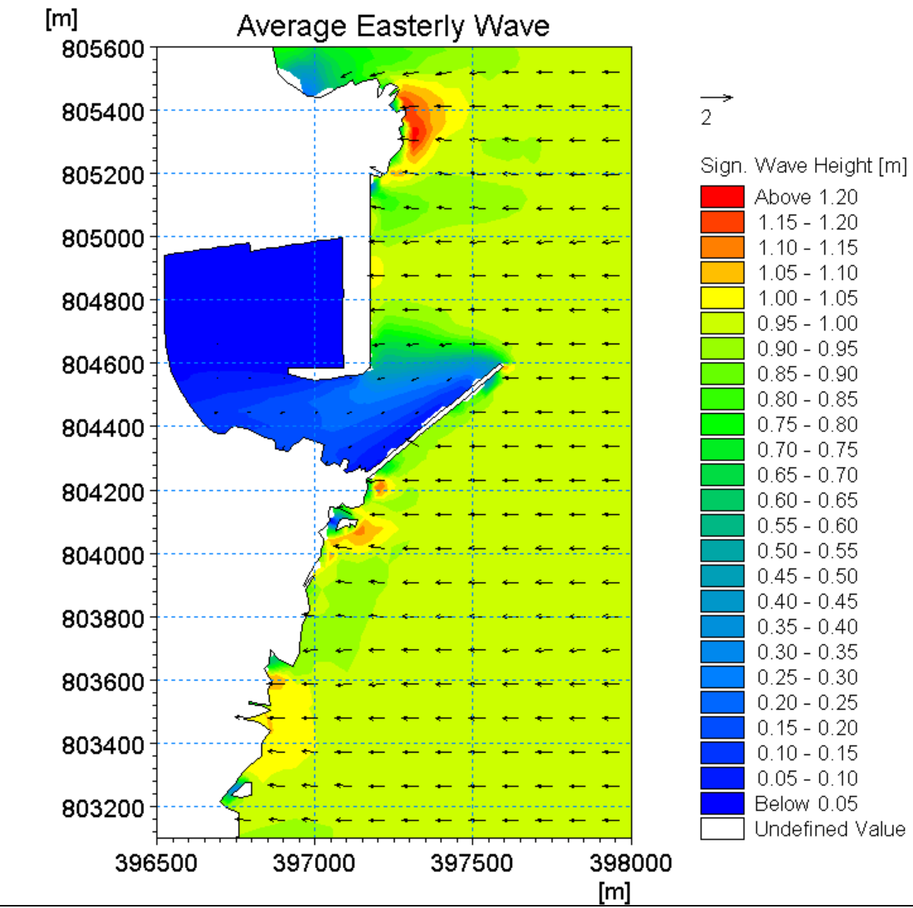
North-Easterly Wave: Local to the Development



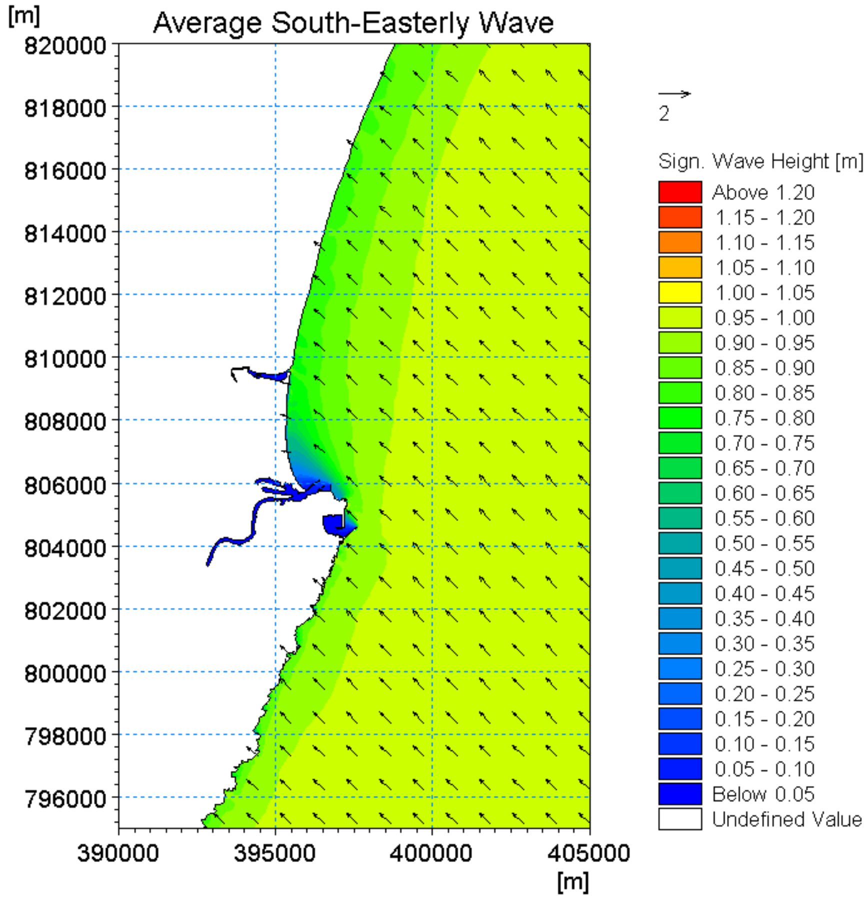
Easterly Wave: Over a Large Extent



Easterly Wave: Local to the Development



Easterly Wave: Over a Large Extent



Easterly Wave: Local to the Development

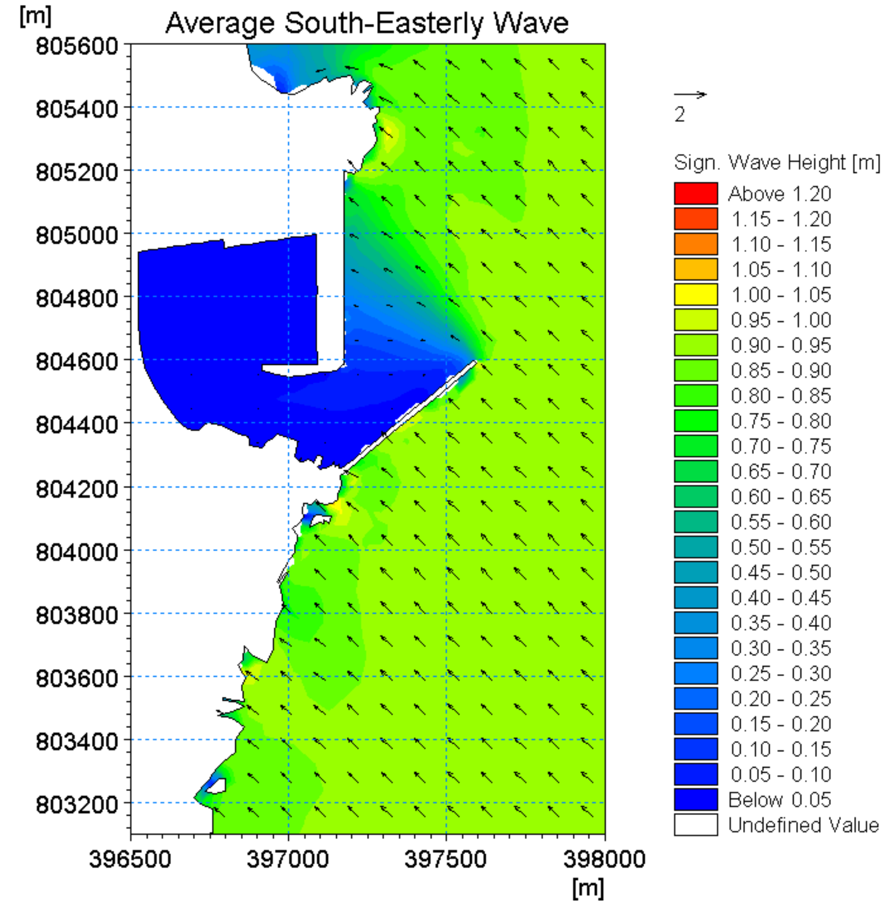
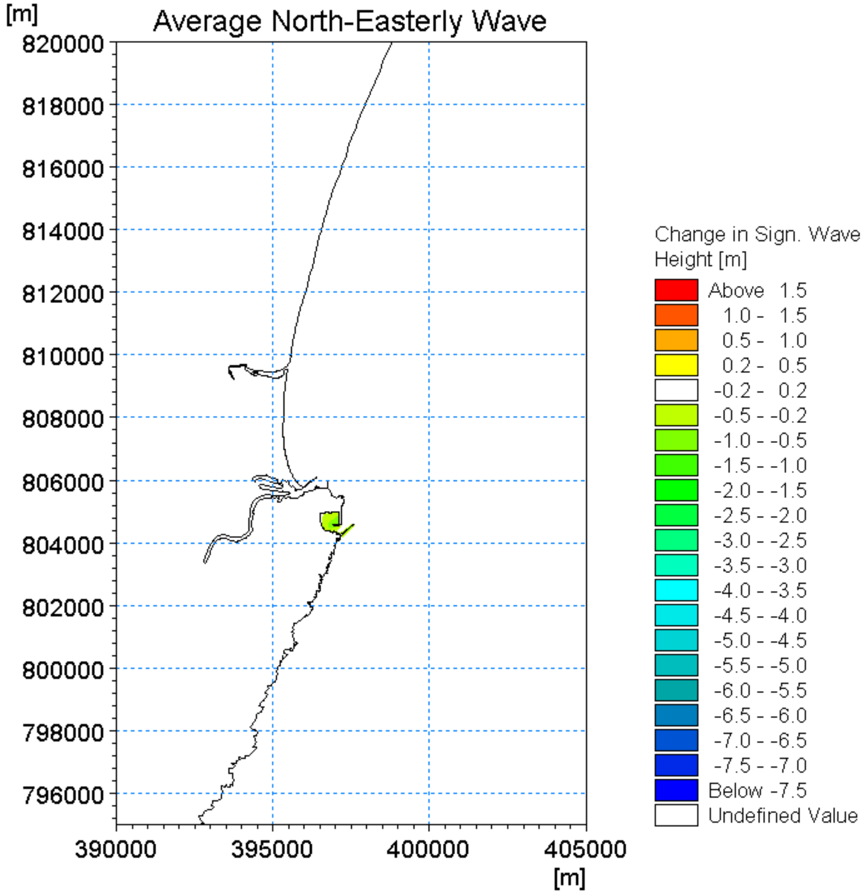
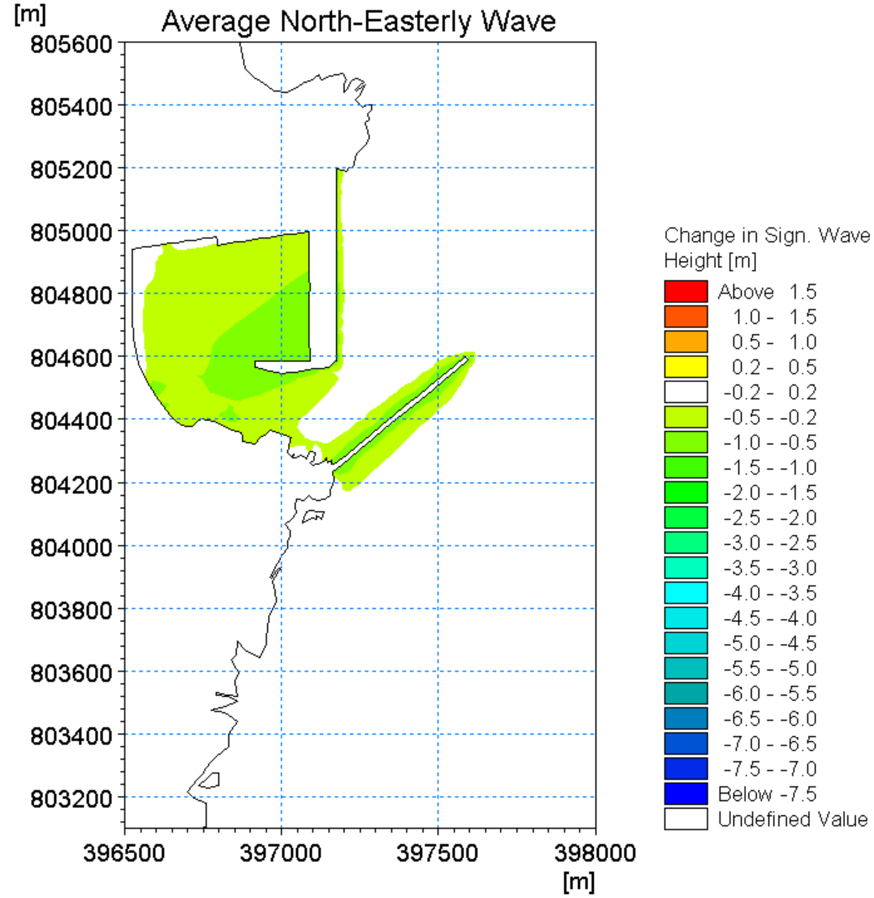


Figure C-11: Operational change in significant wave height: Average Wave

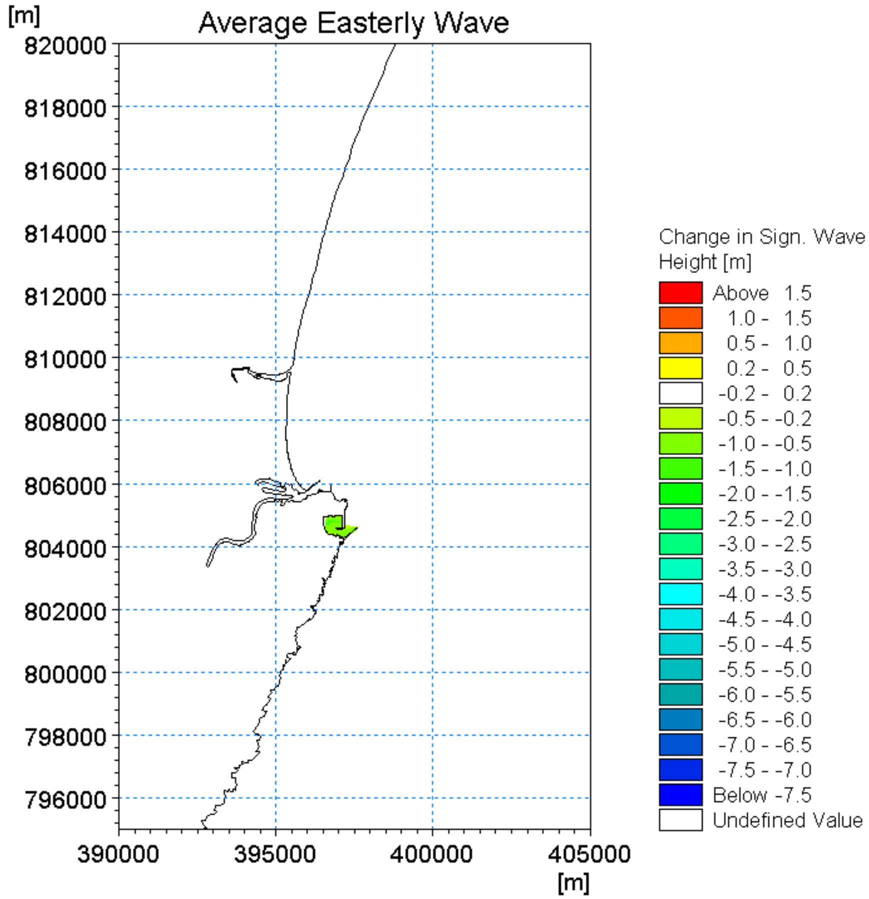
North-Easterly Wave: Over a Large Extent



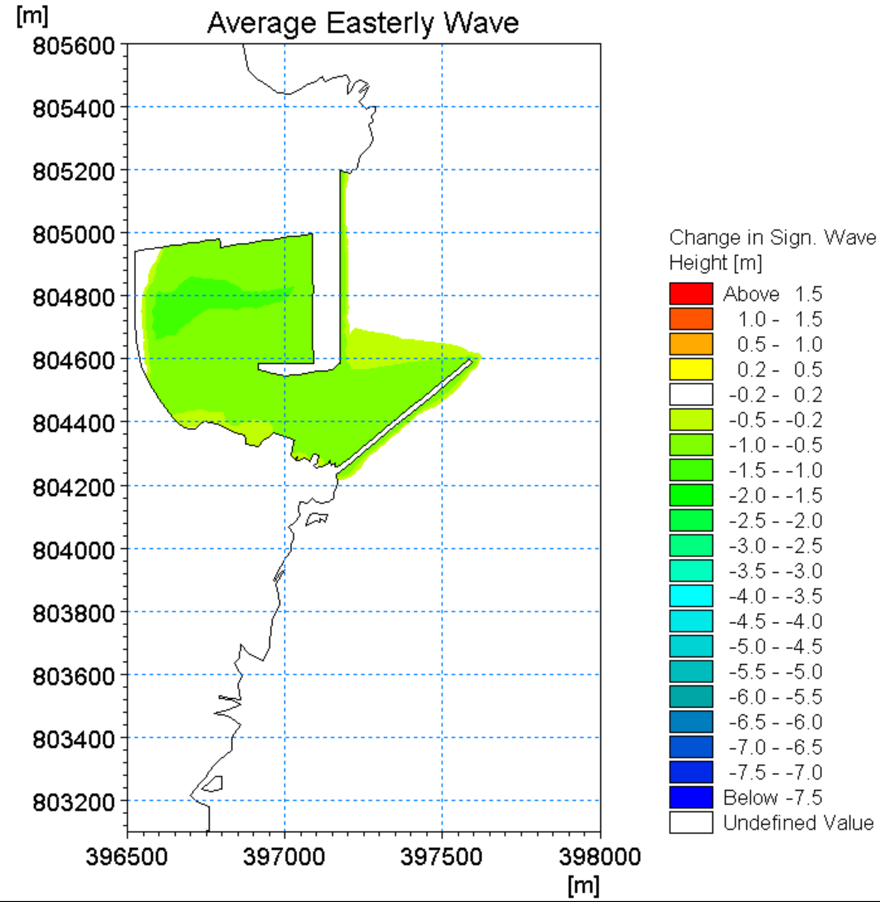
North-Easterly Wave: Local to the Development



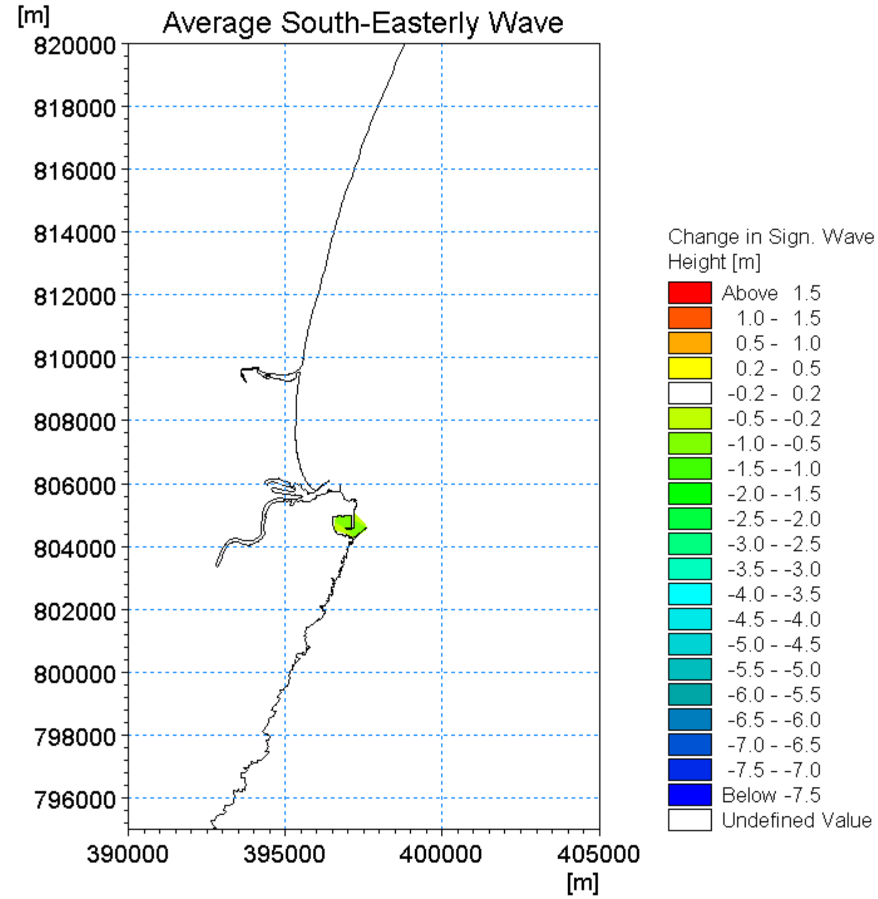
Easterly Wave: Over a Large Extent



Easterly Wave: Local to the Development



South-Easterly Wave: Over a Large Extent



South-Easterly Wave: Local to the Development

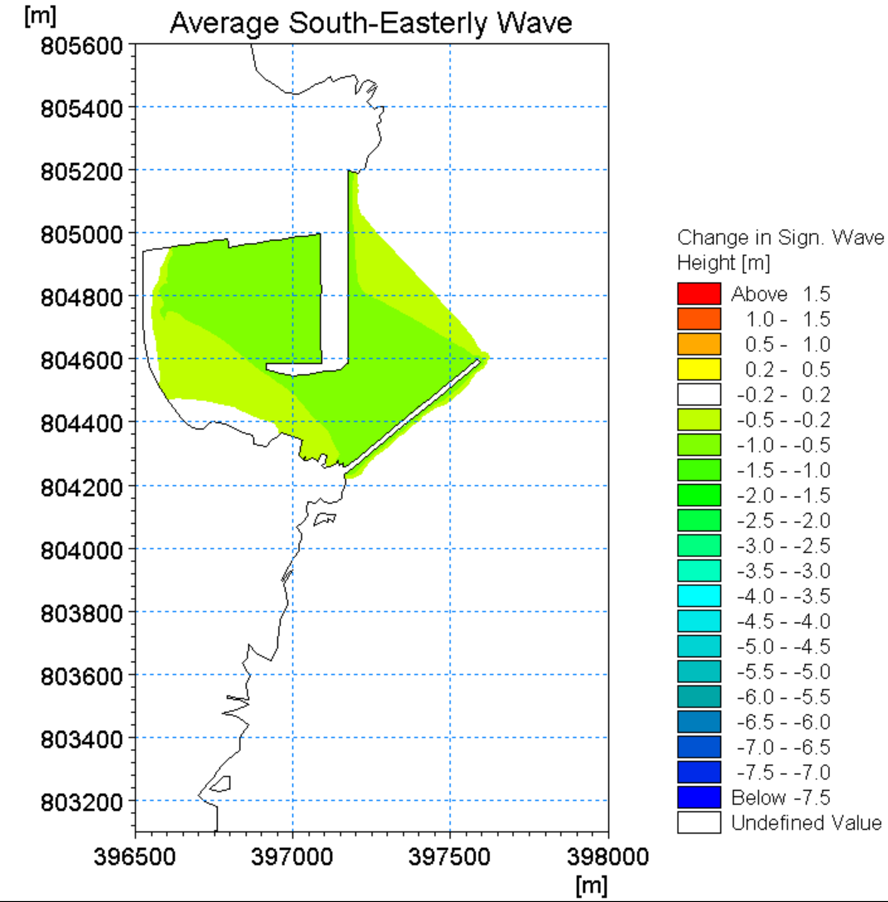
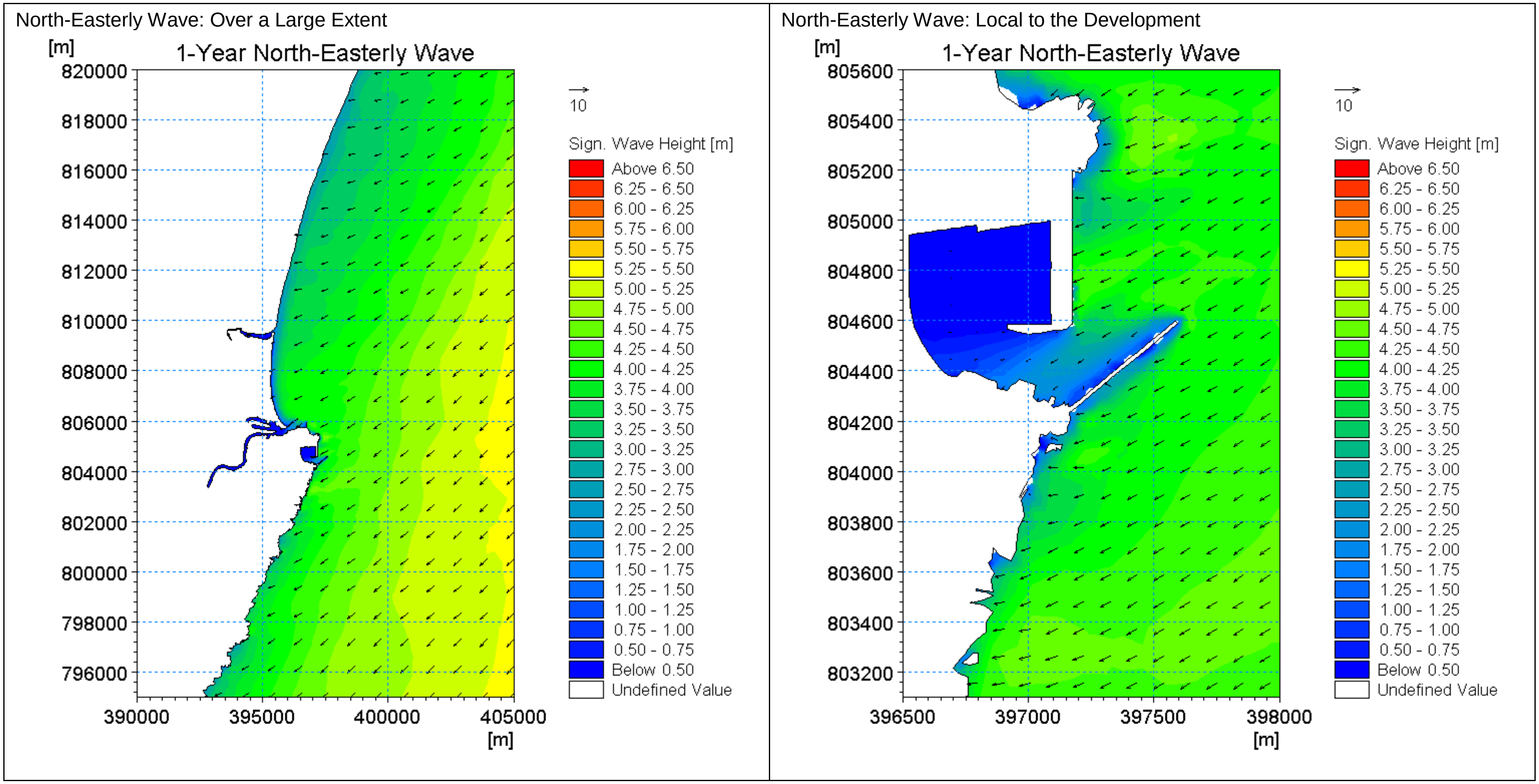
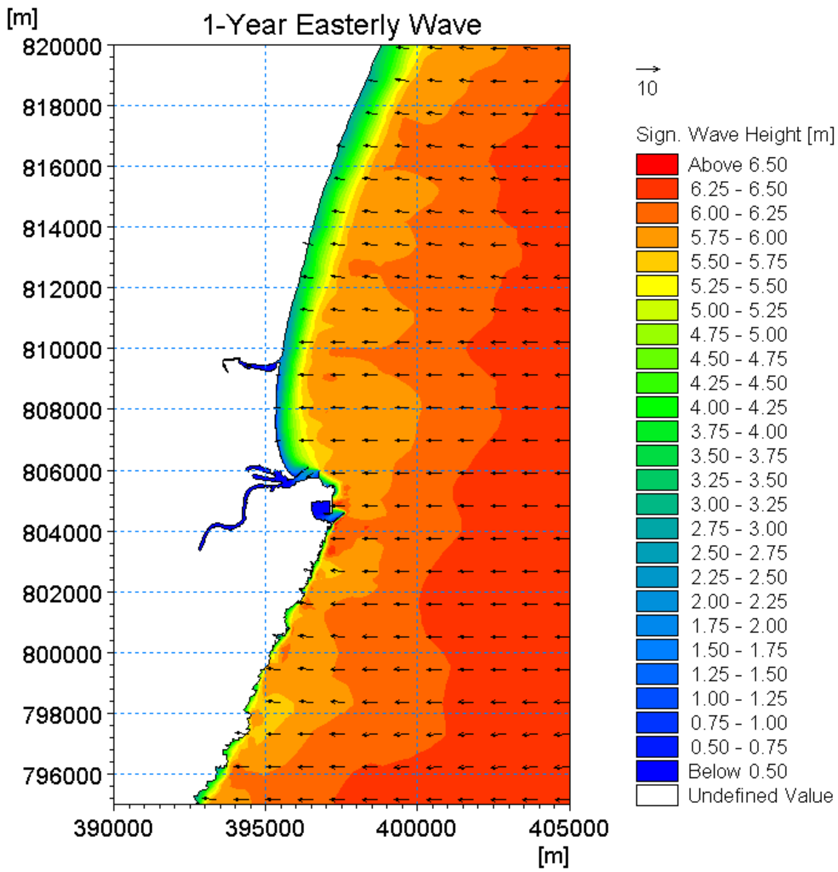


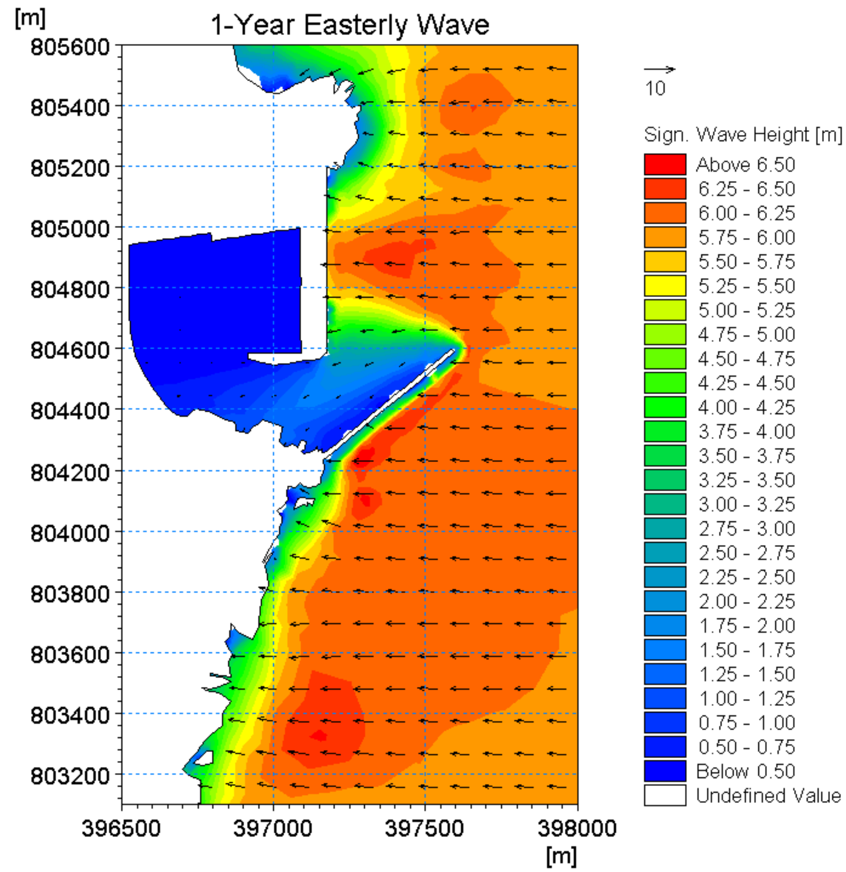
Figure C-12: Significant wave height and wave propagation direction: 1 in 1 Year Wave



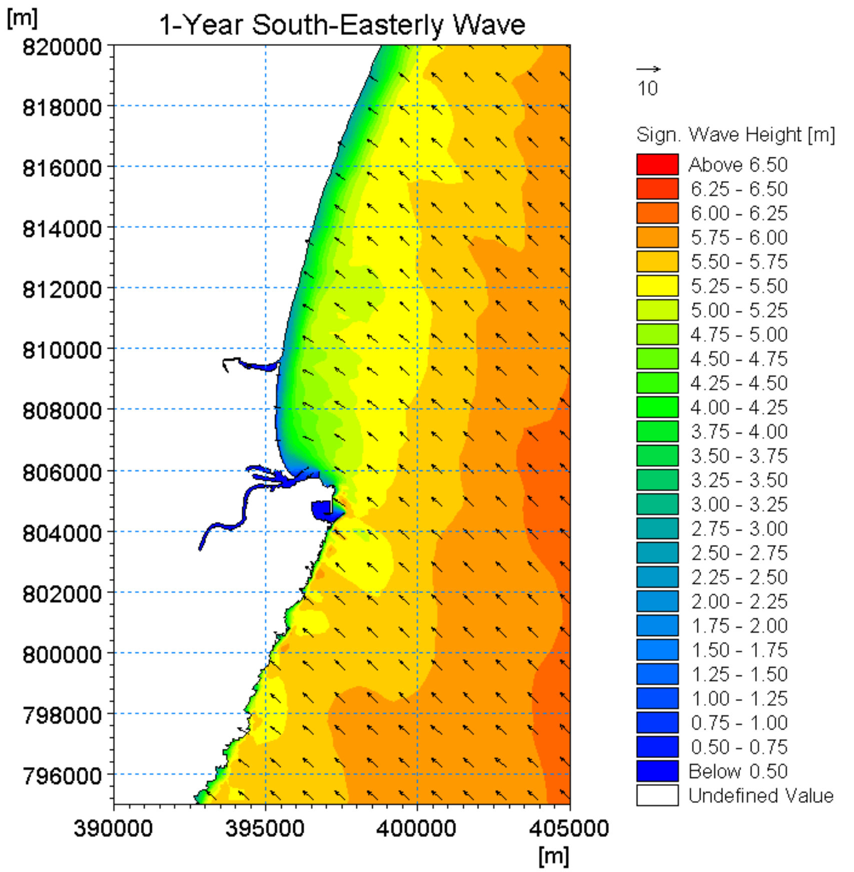
Easterly Wave: Over a Large Extent



Easterly Wave: Local to the Development



South-Easterly Wave: Over a Large Extent



South-Easterly Wave: Local to the Development

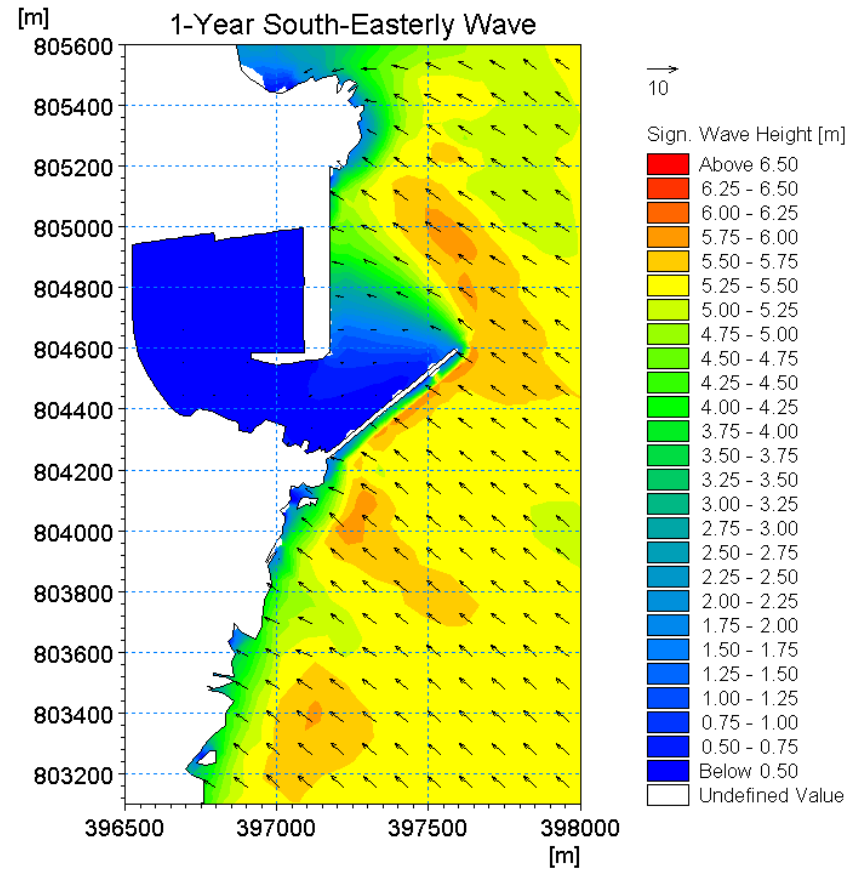
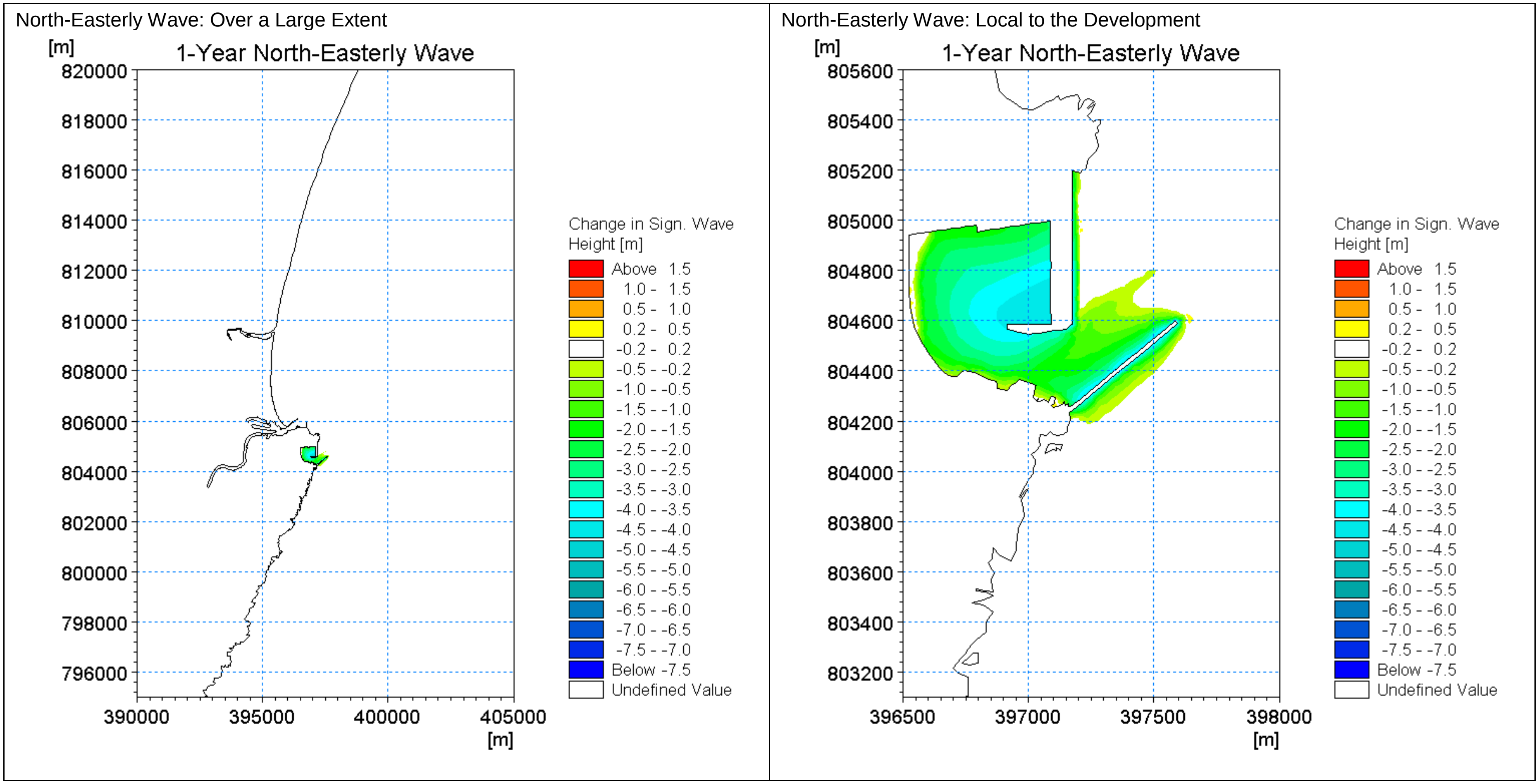
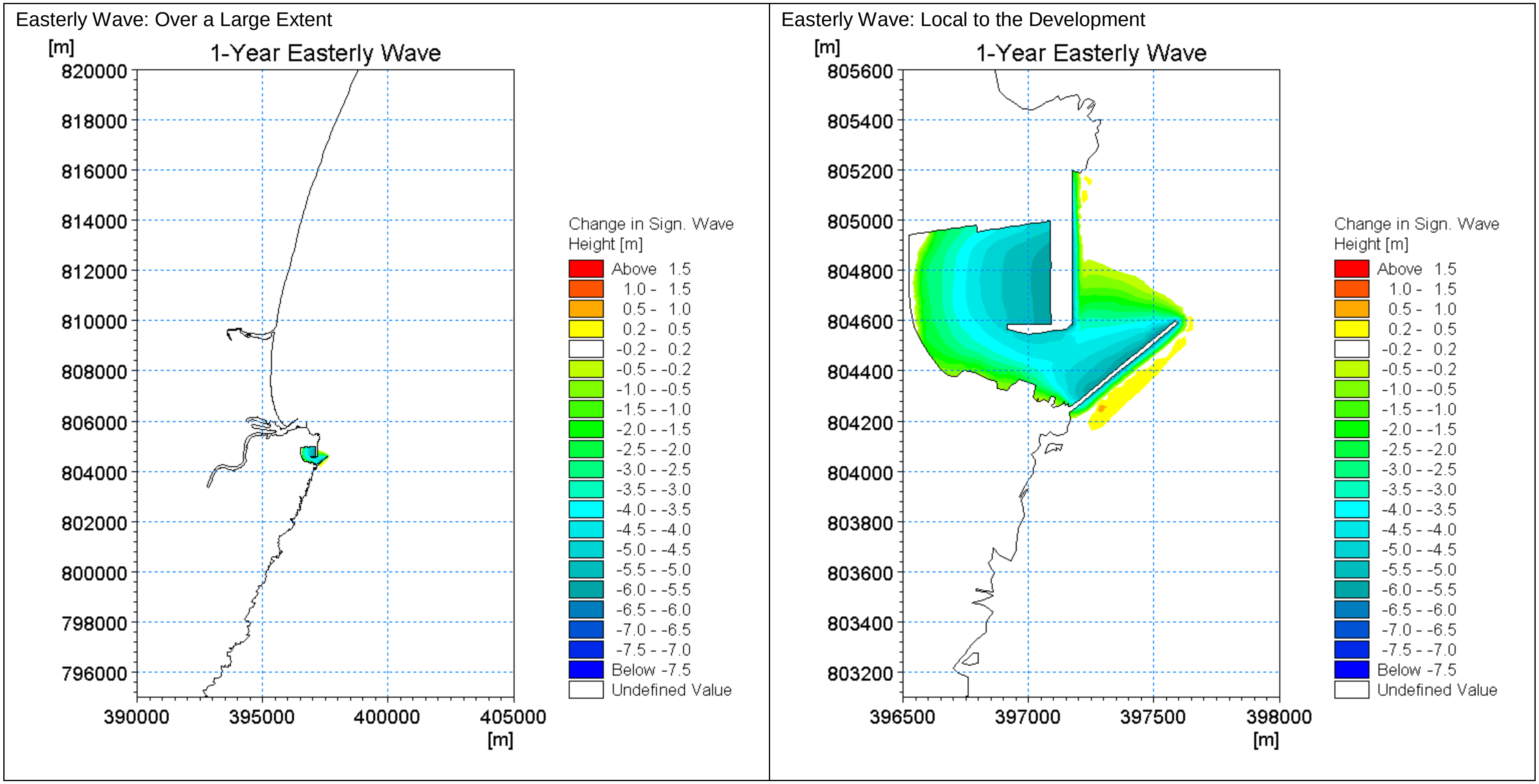
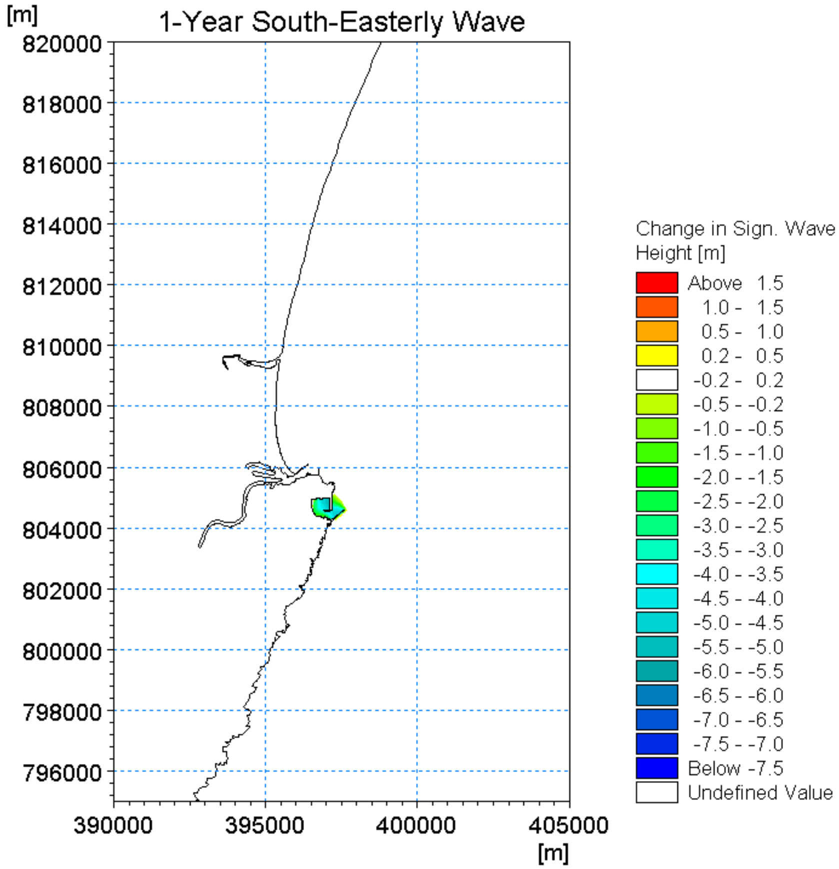


Figure C-13: Operational change in significant wave height: 1 in 1 Year Wave




Easterly Wave: Over a Large Extent
1-Year Easterly Wave
[m]
820000
818000
816000
814000
812000
810000
808000
806000
804000
802000
800000
798000
796000
390000
395000
400000
405000
[m]
Change in Sign. Wave Height [m]
Above 1.5
1.0 - 1.5
0.5 - 1.0
0.2 - 0.5
-0.2 - 0.2
-0.5 - -0.2
-1.0 - -0.5
-1.5 - -1.0
-2.0 - -1.5
-2.5 - -2.0
-3.0 - -2.5
-3.5 - -3.0
-4.0 - -3.5
-4.5 - -4.0
-5.0 - -4.5
-5.5 - -5.0
-6.0 - -5.5
-6.5 - -6.0
-7.0 - -6.5
-7.5 - -7.0
Below -7.5
Undefined Value
Easterly Wave: Local to the Development
1-Year Easterly Wave
[m]
805600
805400
805200
805000
804800
804600
804400
804200
804000
803800
803600
803400
803200
396500
397000
397500
398000
[m]
Change in Sign. Wave Height [m]
Above 1.5
1.0 - 1.5
0.5 - 1.0
0.2 - 0.5
-0.2 - 0.2
-0.5 - -0.2
-1.0 - -0.5
-1.5 - -1.0
-2.0 - -1.5
-2.5 - -2.0
-3.0 - -2.5
-3.5 - -3.0
-4.0 - -3.5
-4.5 - -4.0
-5.0 - -4.5
-5.5 - -5.0
-6.0 - -5.5
-6.5 - -6.0
-7.0 - -6.5
-7.5 - -7.0
Below -7.5
Undefined Value

South-Easterly Wave: Over a Large Extent



South-Easterly Wave: Local to the Development

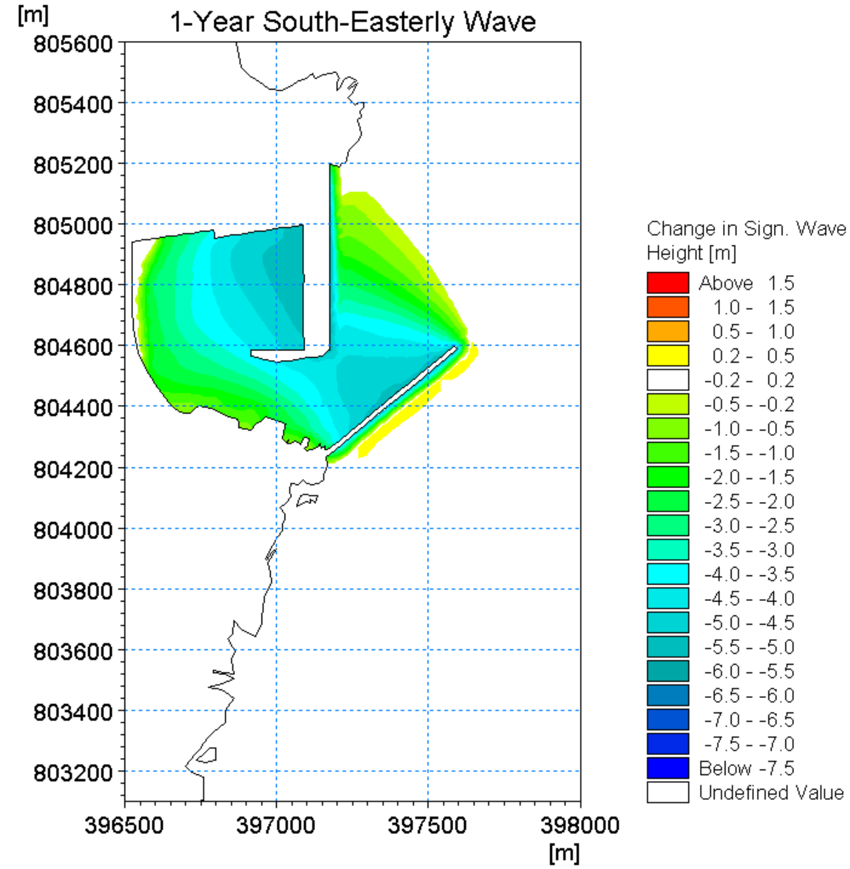
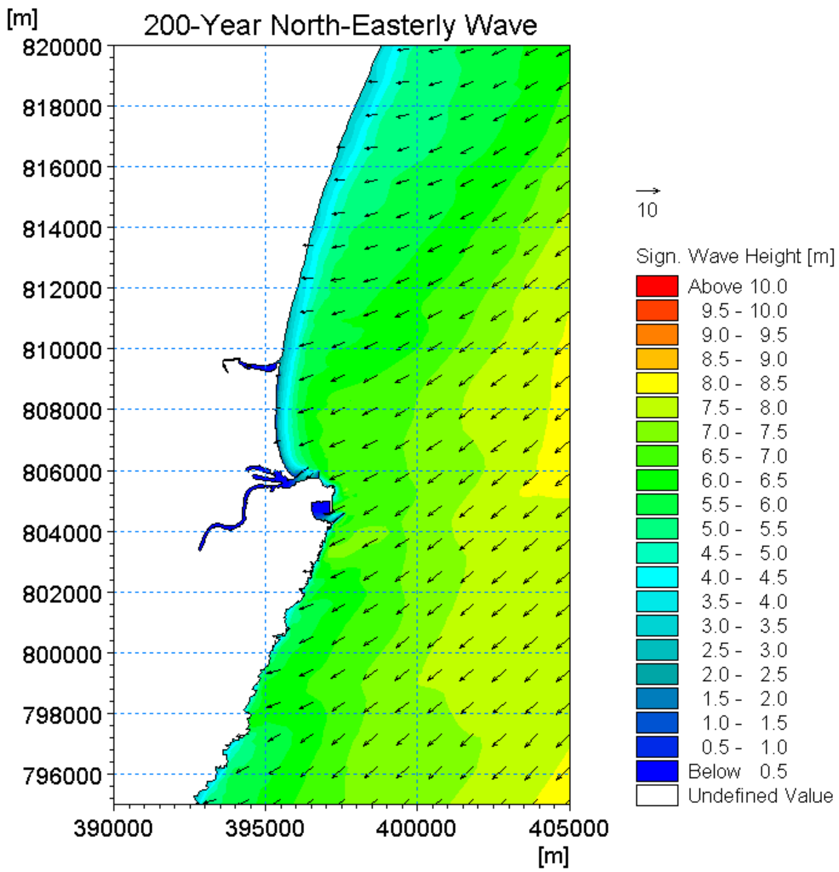
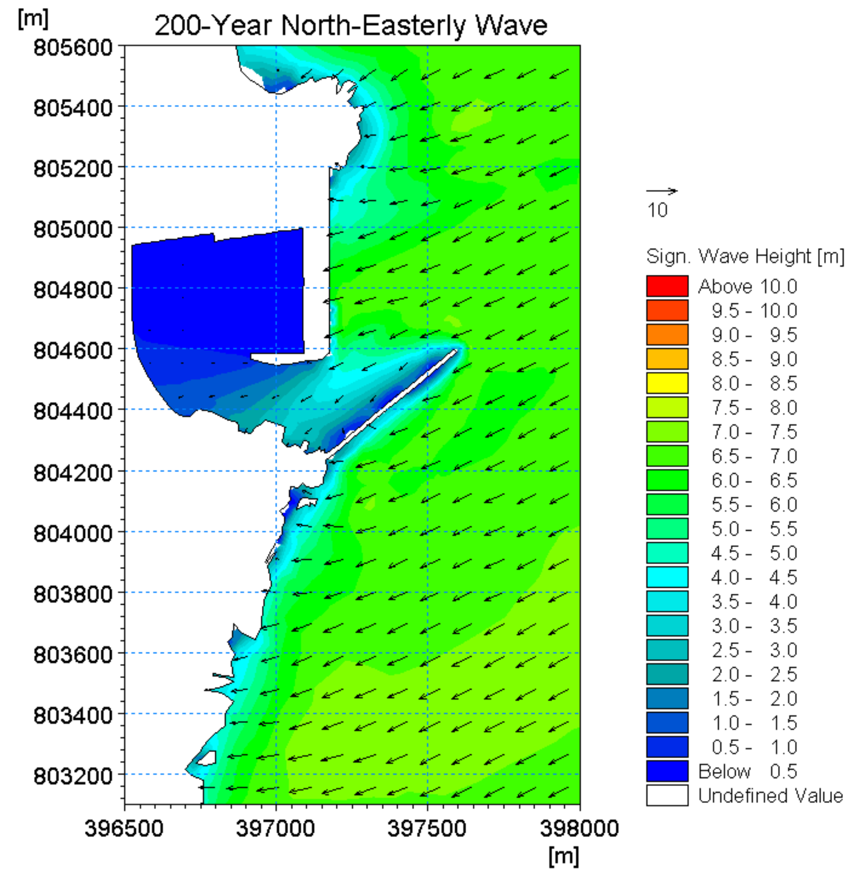


Figure C-14: Significant wave height and wave propagation direction: 1 in 200 Year Wave

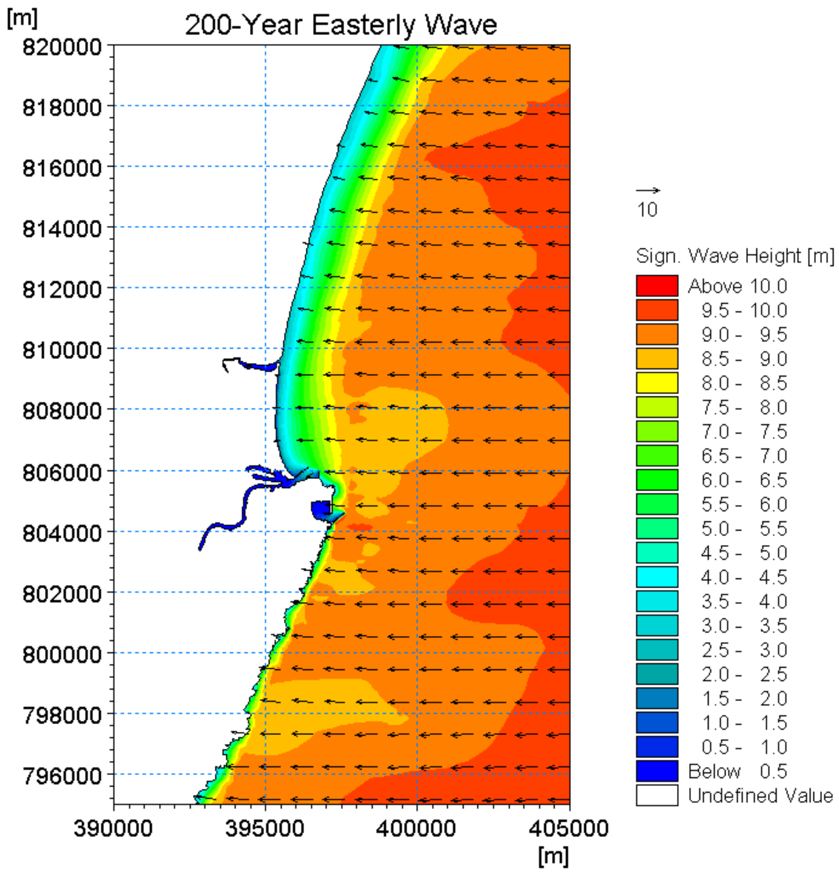
North-Easterly Wave: Over a Large Extent



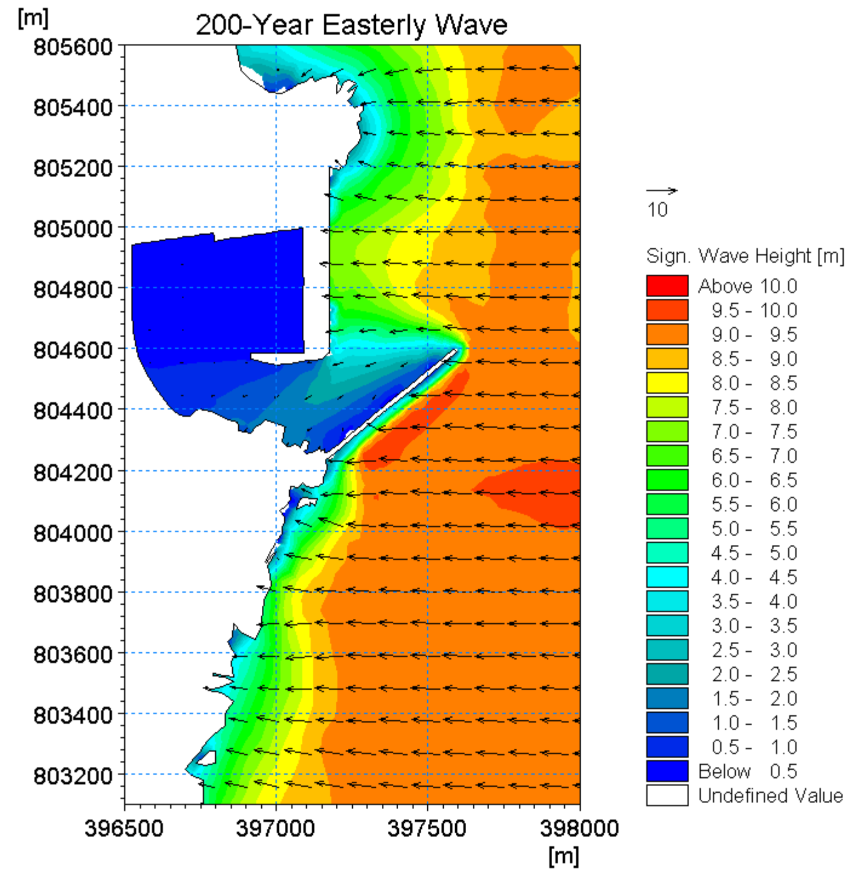
North-Easterly Wave: Local to the Development



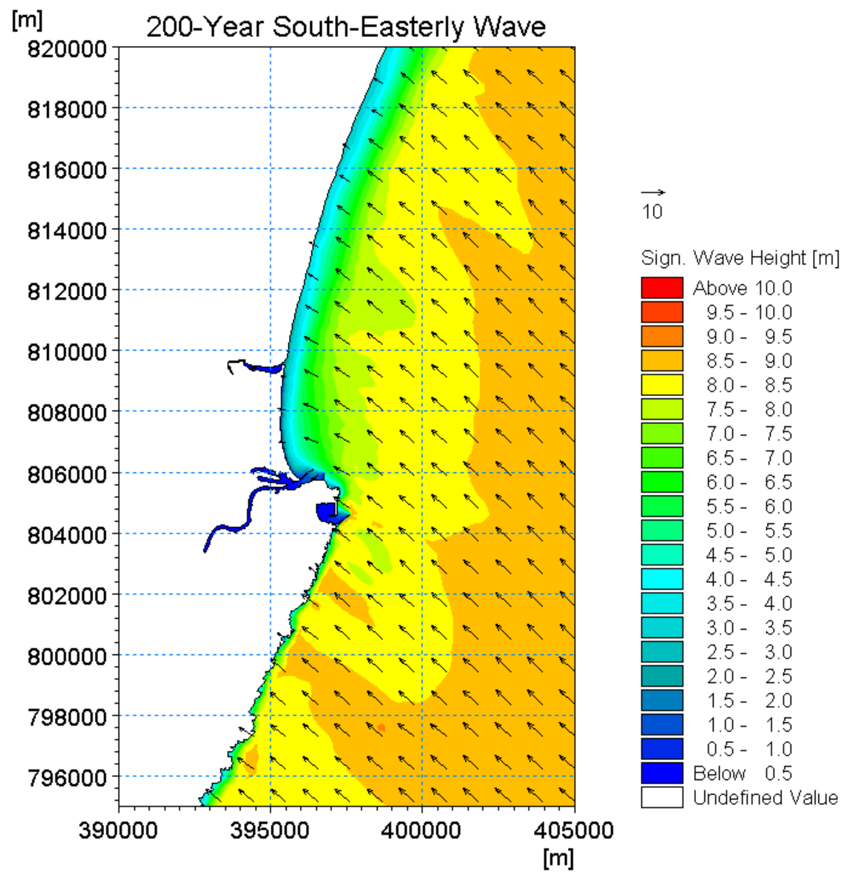
Easterly Wave: Over a Large Extent



Easterly Wave: Local to the Development



South-Easterly Wave: Over a Large Extent



South-Easterly Wave: Local to the Development

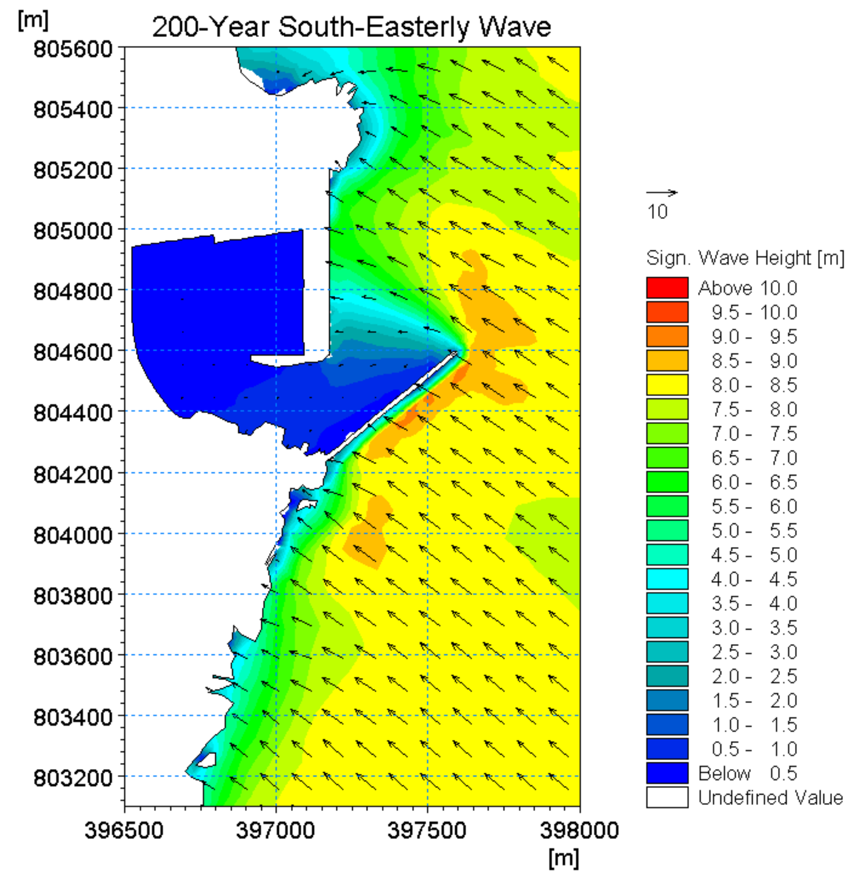
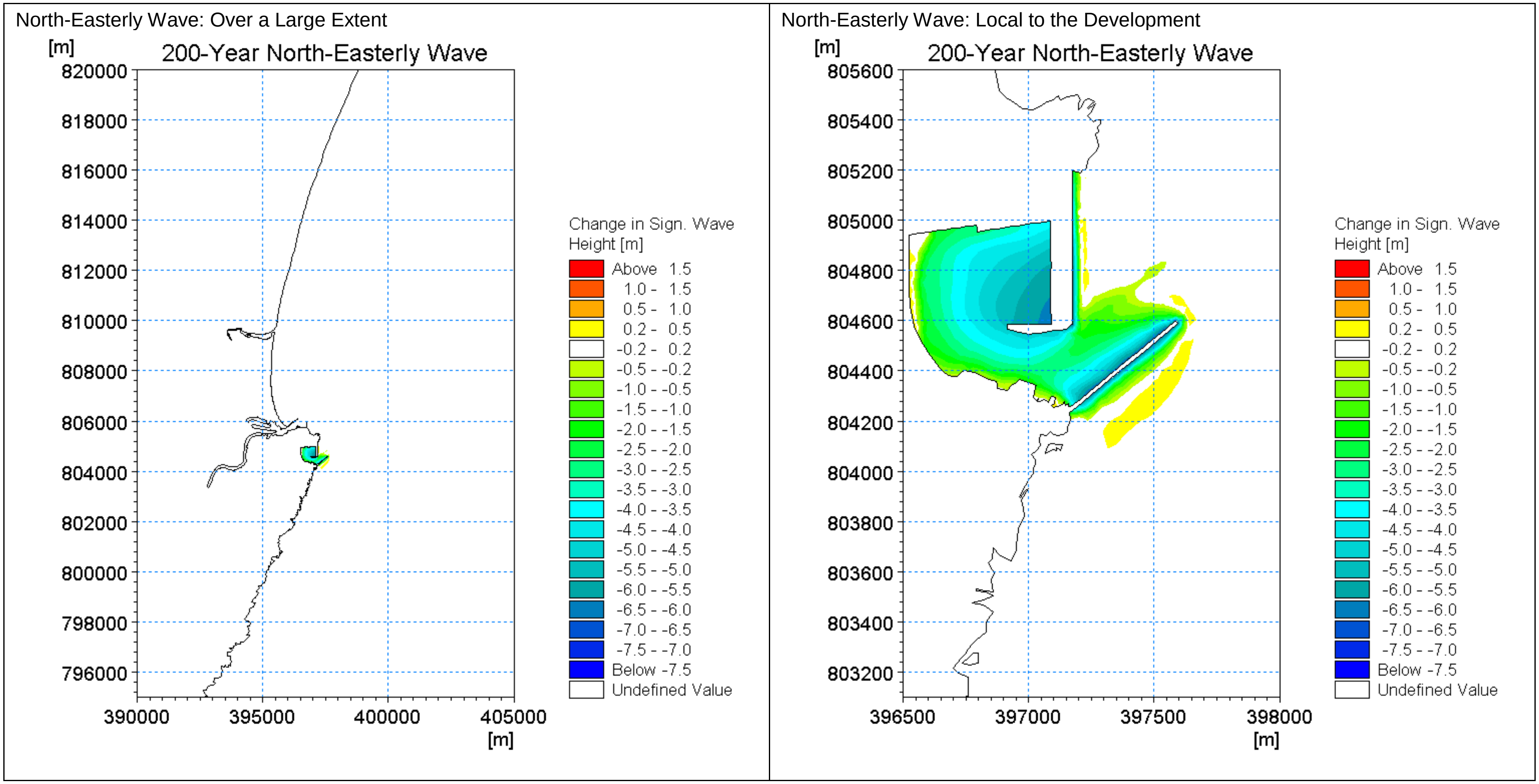
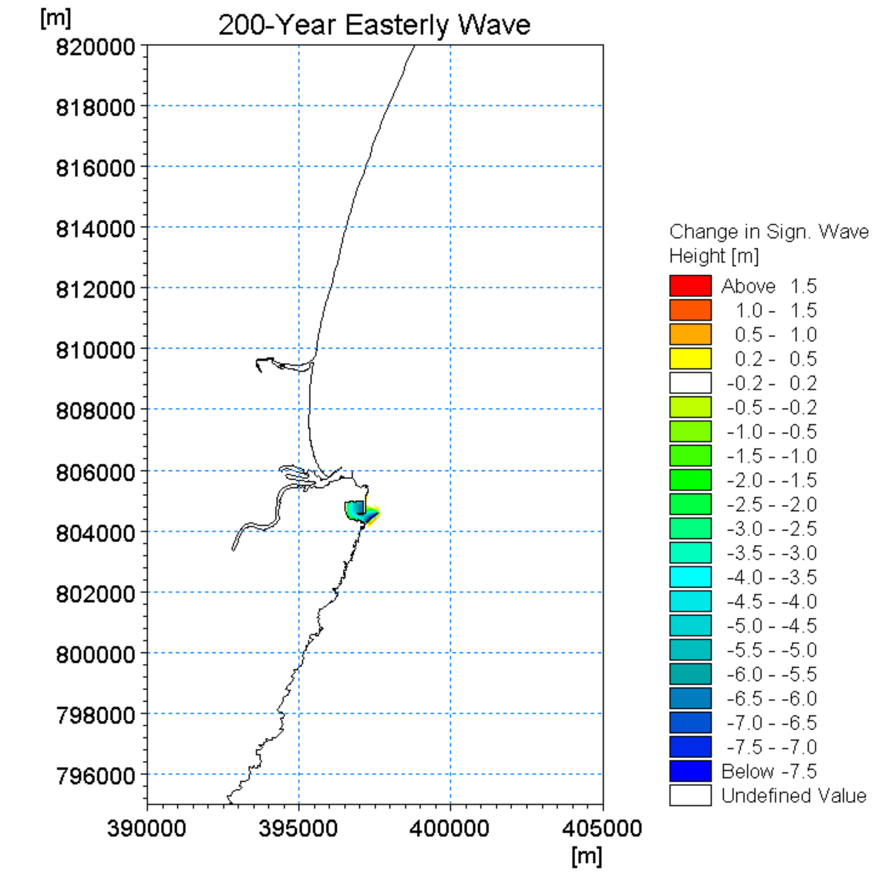


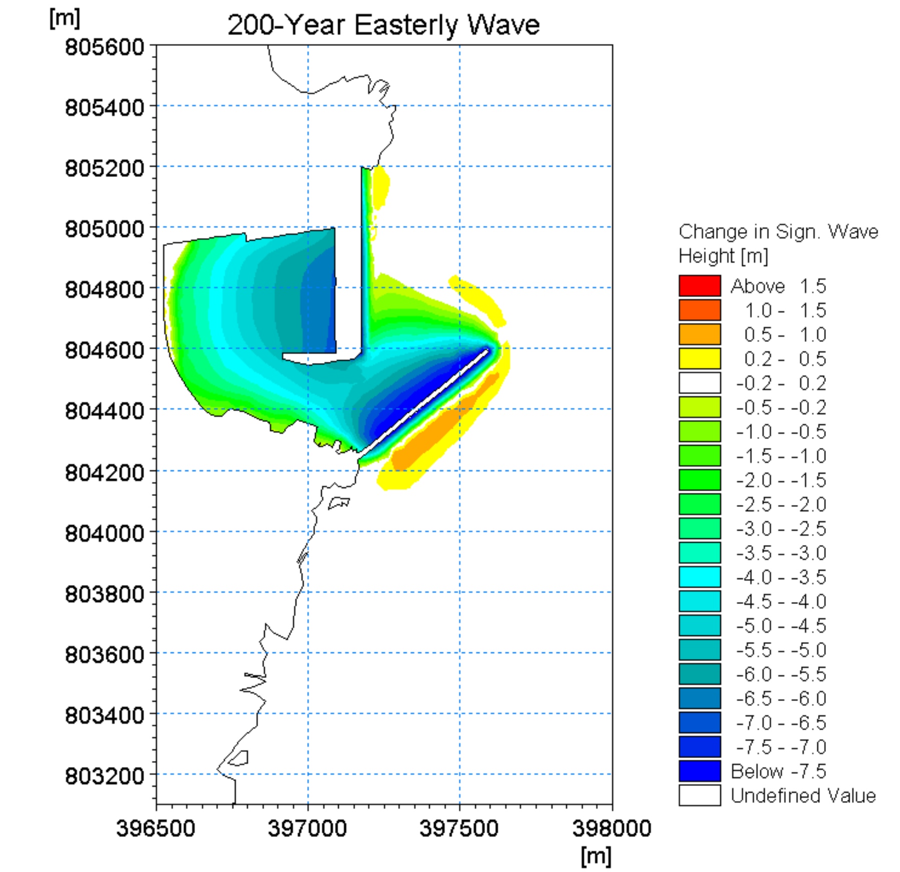
Figure C-15: Operational change in significant wave height: 1 in 200 Year Wave



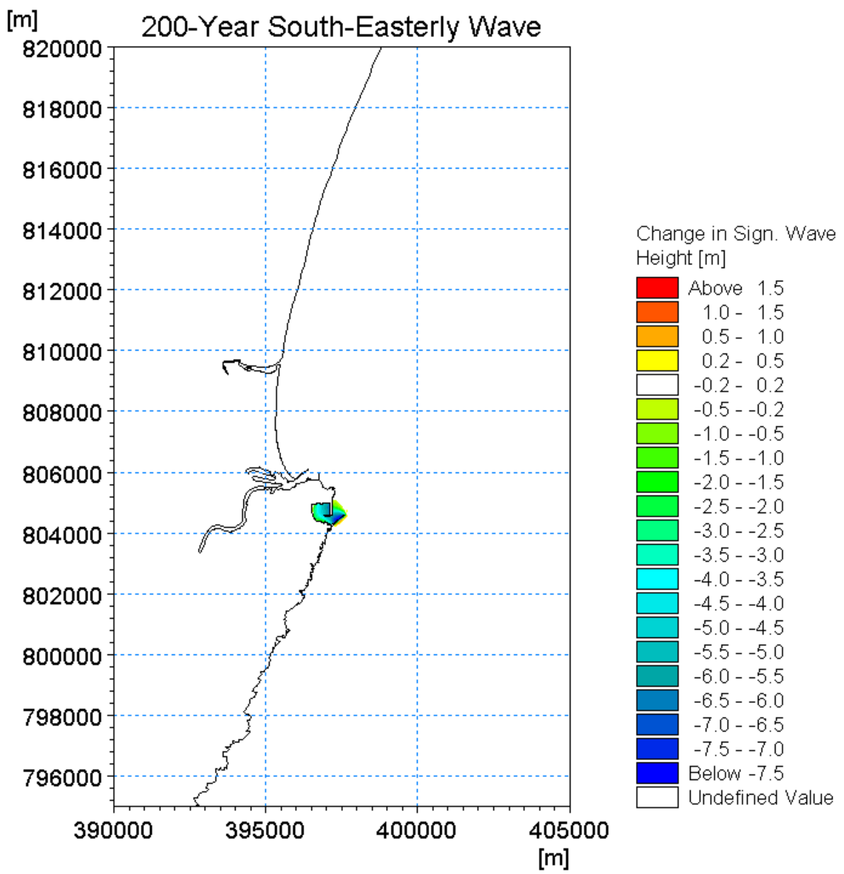
Easterly Wave: Over a Large Extent



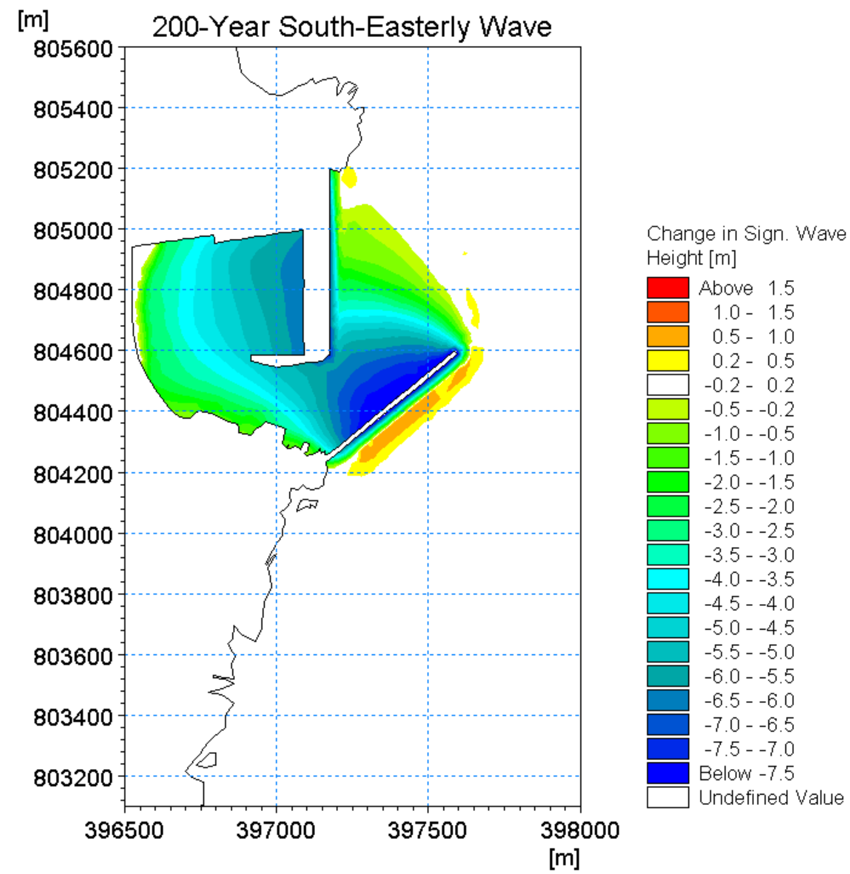
Easterly Wave: Local to the Development



South-Easterly Wave: Over a Large Extent

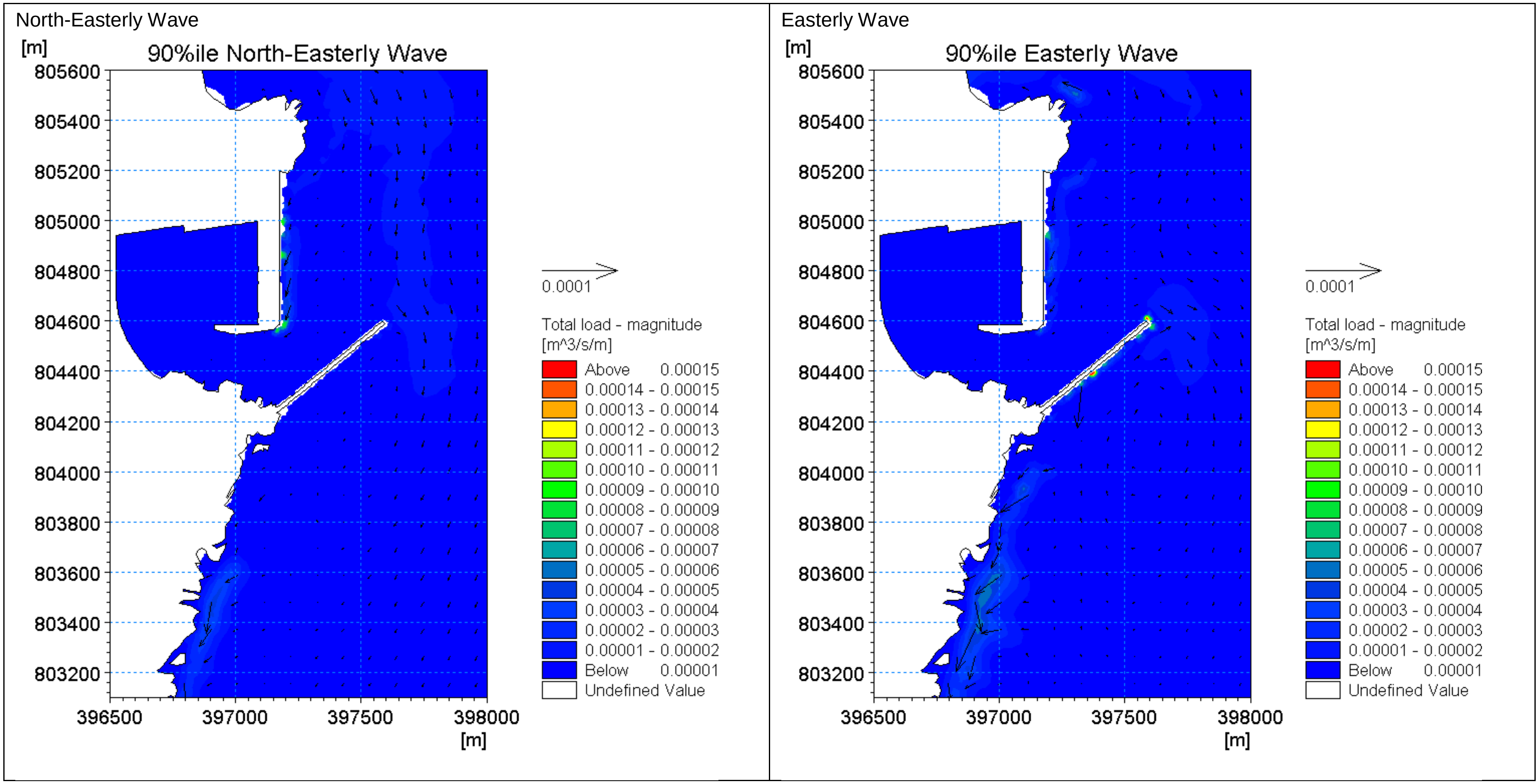


South-Easterly Wave: Local to the Development



C.3 Sediment Transport

Figure C-16: Sediment transport pathway on a mean spring tide: Operational Phase



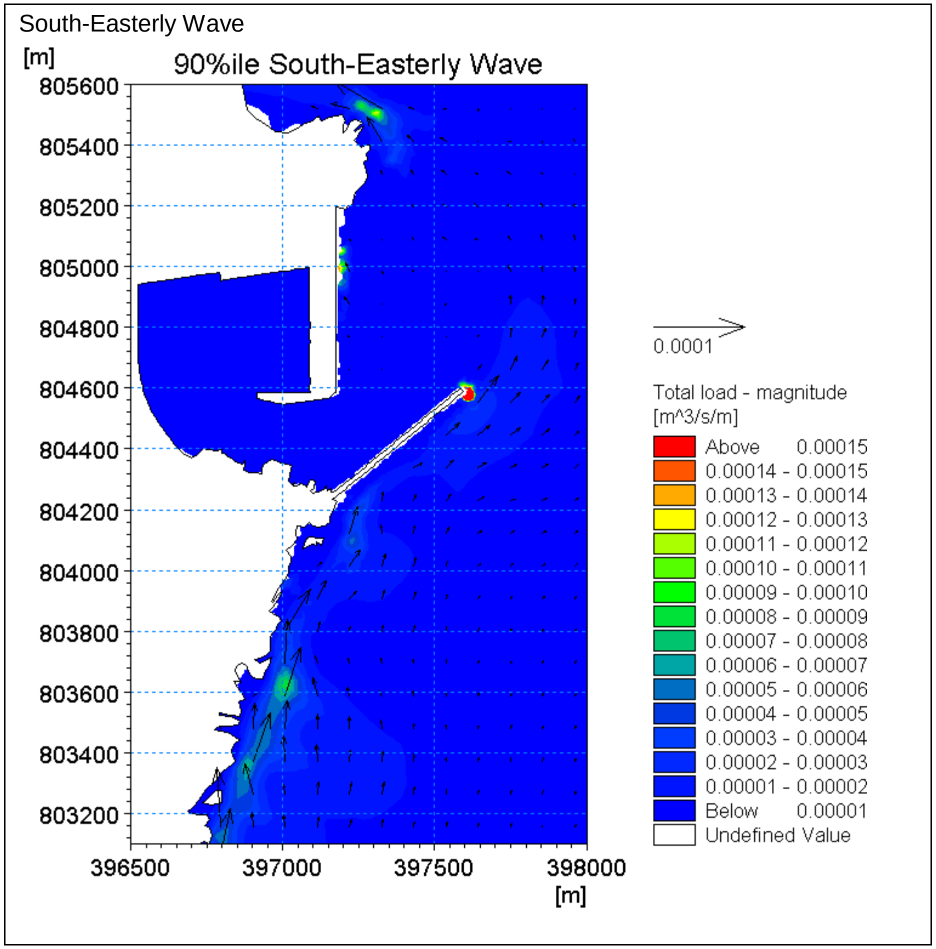

South-Easterly Wave
90%ile South-Easterly Wave
[m]
805600
805400
805200
805000
804800
804600
804400
804200
804000
803800
803600
803400
803200
396500
397000
397500
398000
[m]
0.0001
Total load - magnitude
[m^3/s/m]
Above 0.00015
0.00014 - 0.00015
0.00013 - 0.00014
0.00012 - 0.00013
0.00011 - 0.00012
0.00010 - 0.00011
0.00009 - 0.00010
0.00008 - 0.00009
0.00007 - 0.00008
0.00006 - 0.00007
0.00005 - 0.00006
0.00004 - 0.00005
0.00003 - 0.00004
0.00002 - 0.00003
0.00001 - 0.00002
Below 0.00001
Undefined Value

Figure C-17: Comparison of net sediment transport pathway between Baseline and Operational Phase

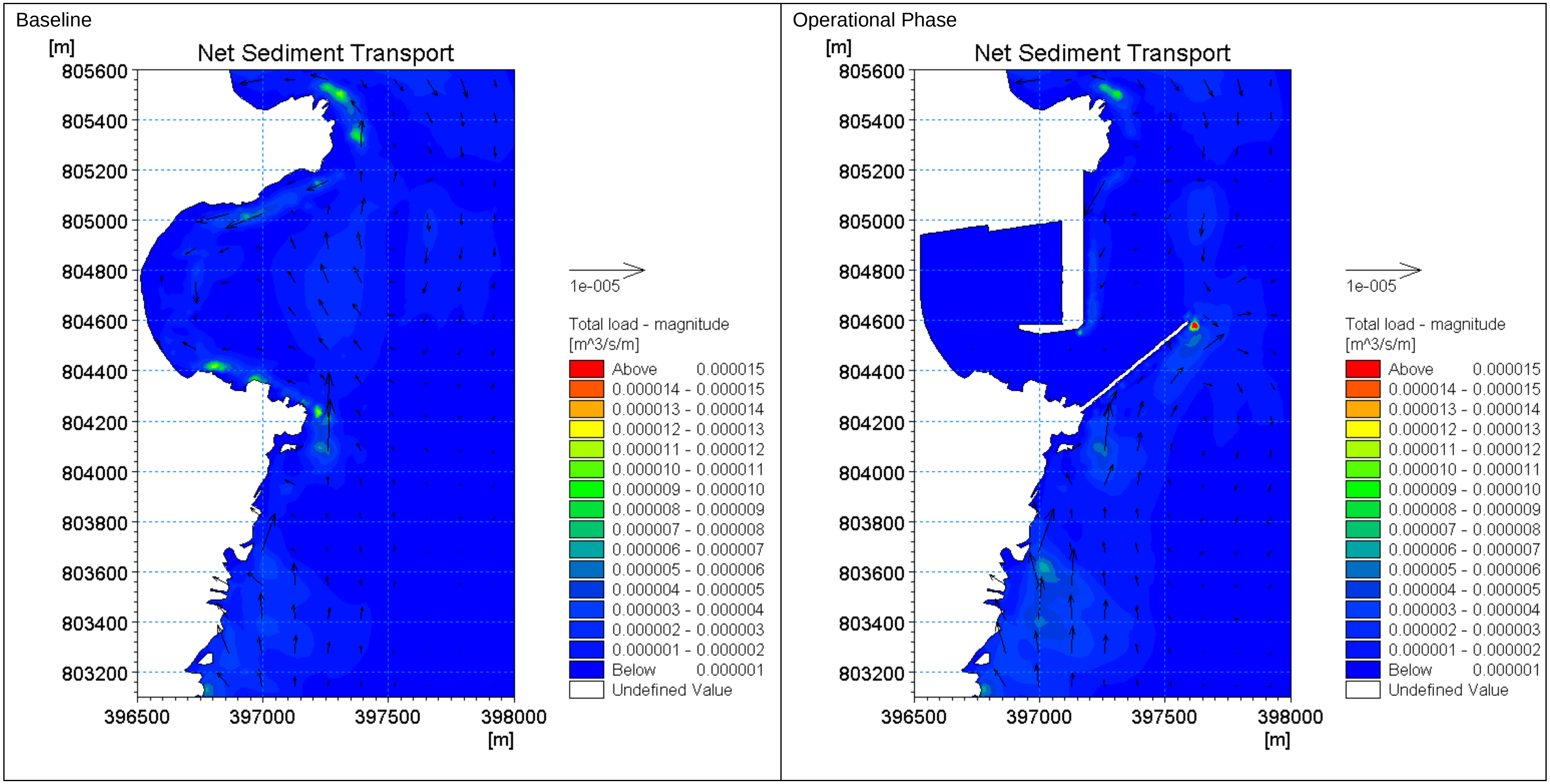
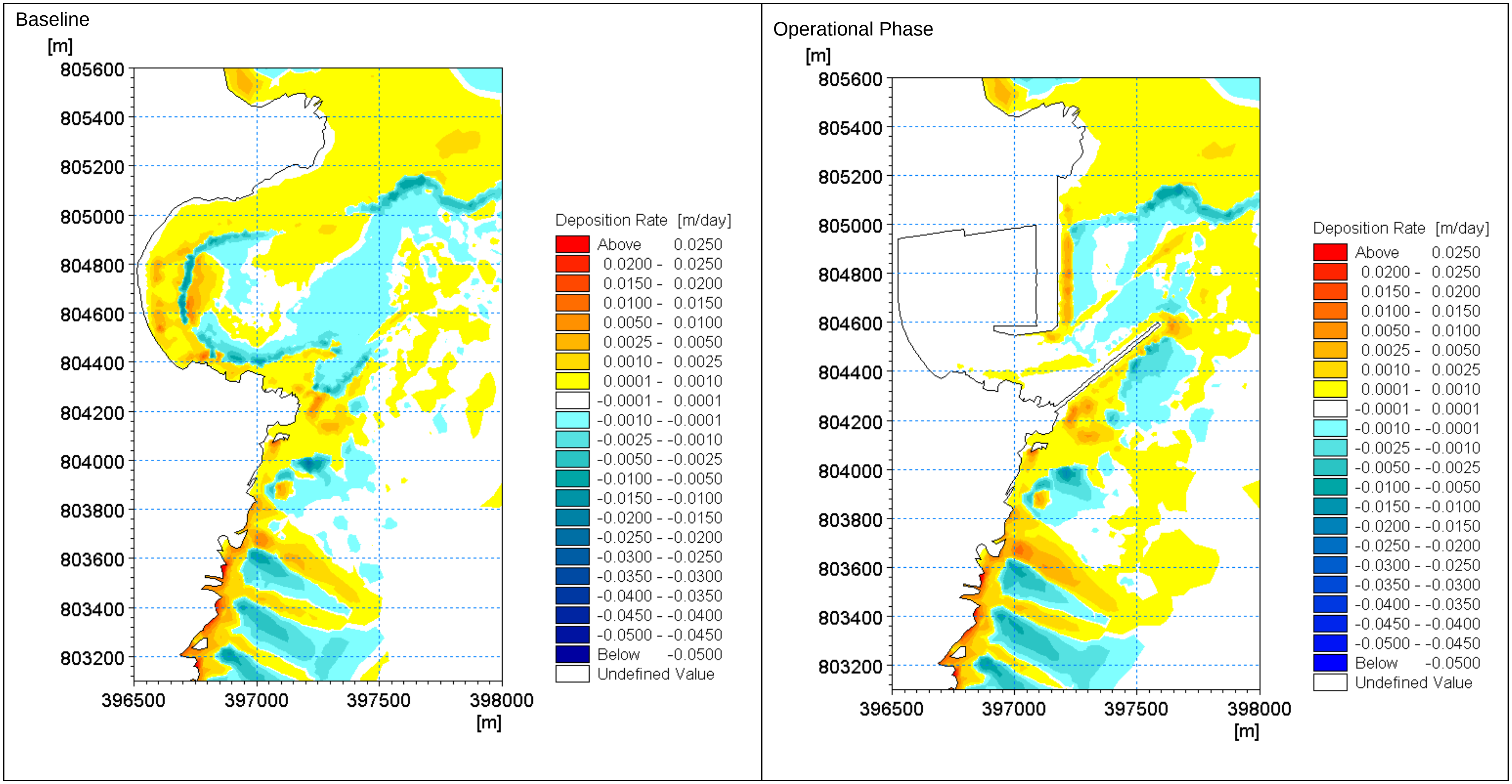


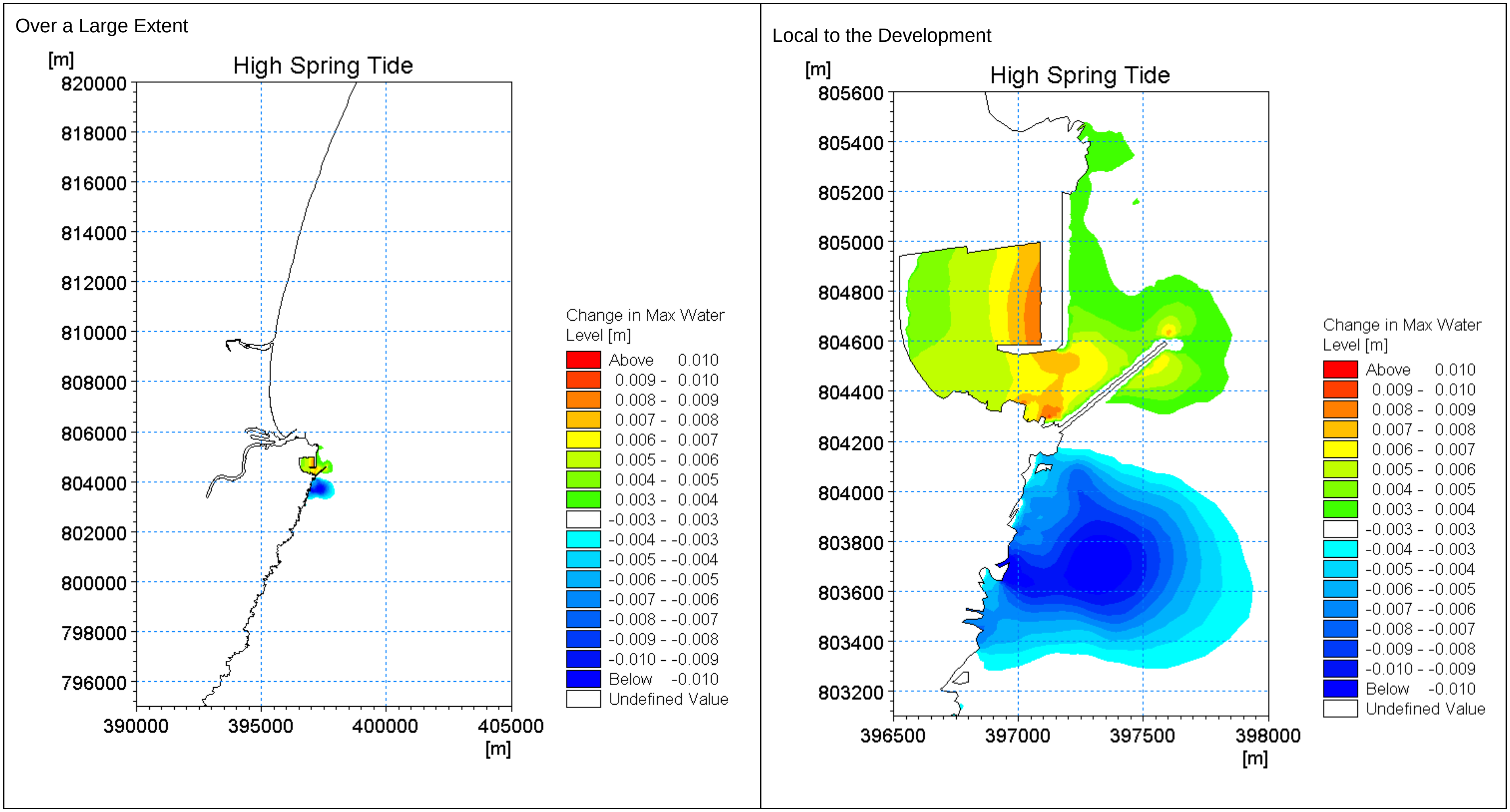
Figure C-18: Comparison of deposition and erosion patterns between Baseline and Operational Phase



Appendix D Future Climate Results

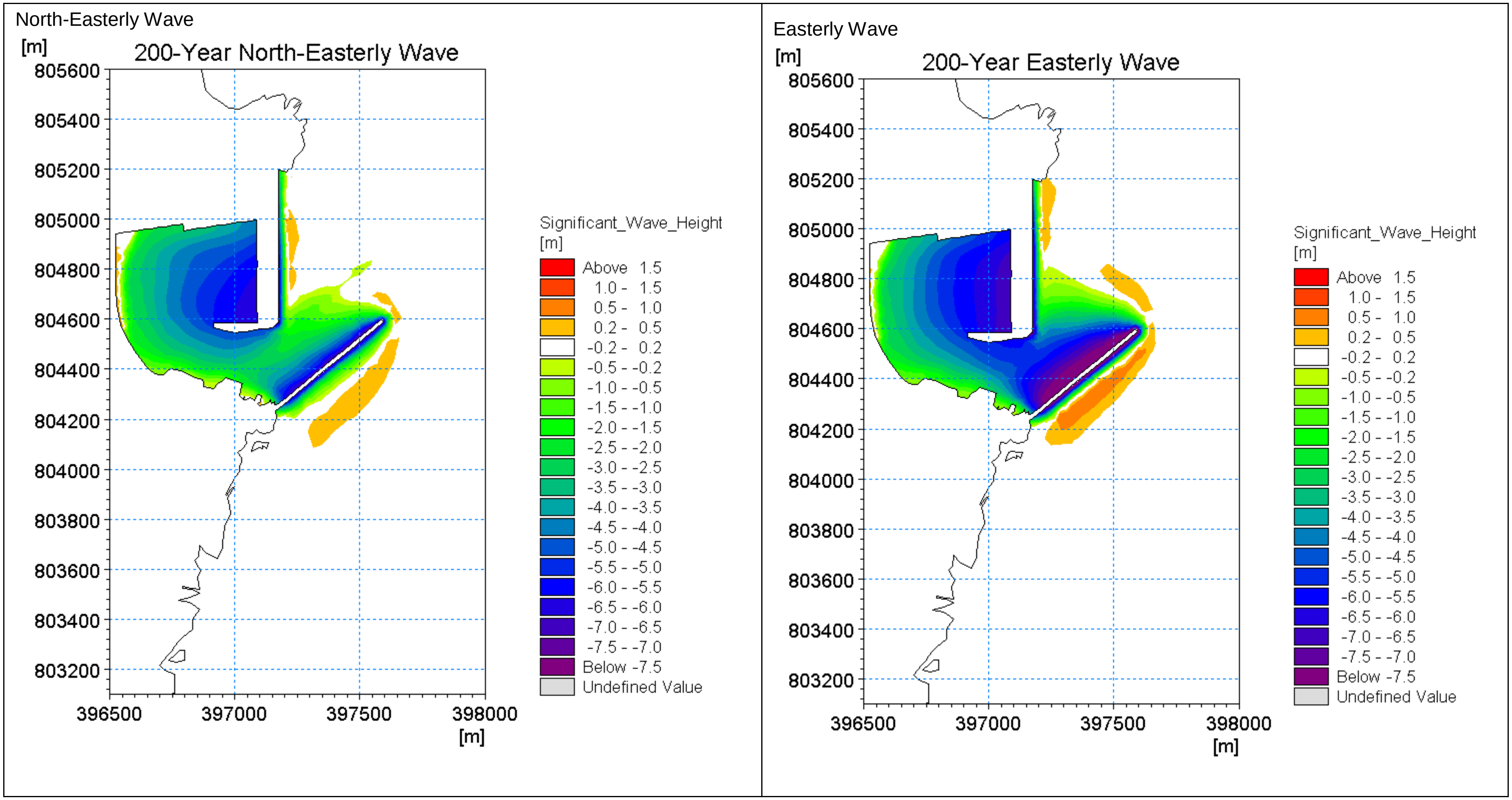
D.1 Hydrodynamics

Figure D-1: Change in maximum water level under extreme future conditions

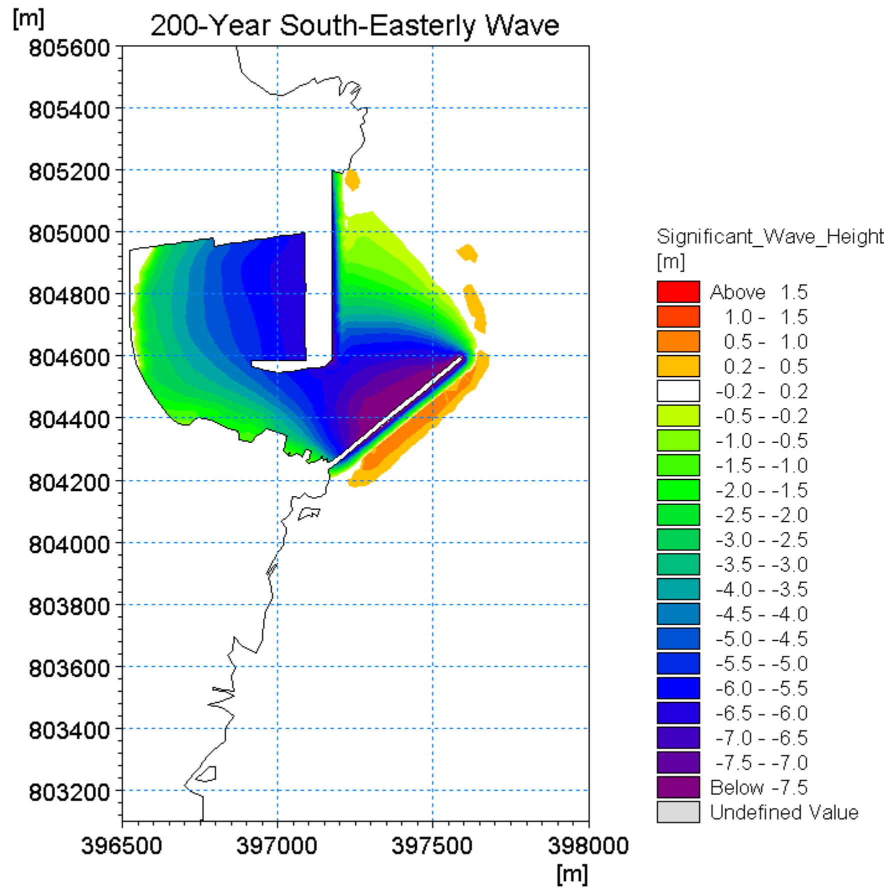


D.2 Wave Climate

Figure D-2: Change in significant wave height under extreme future conditions



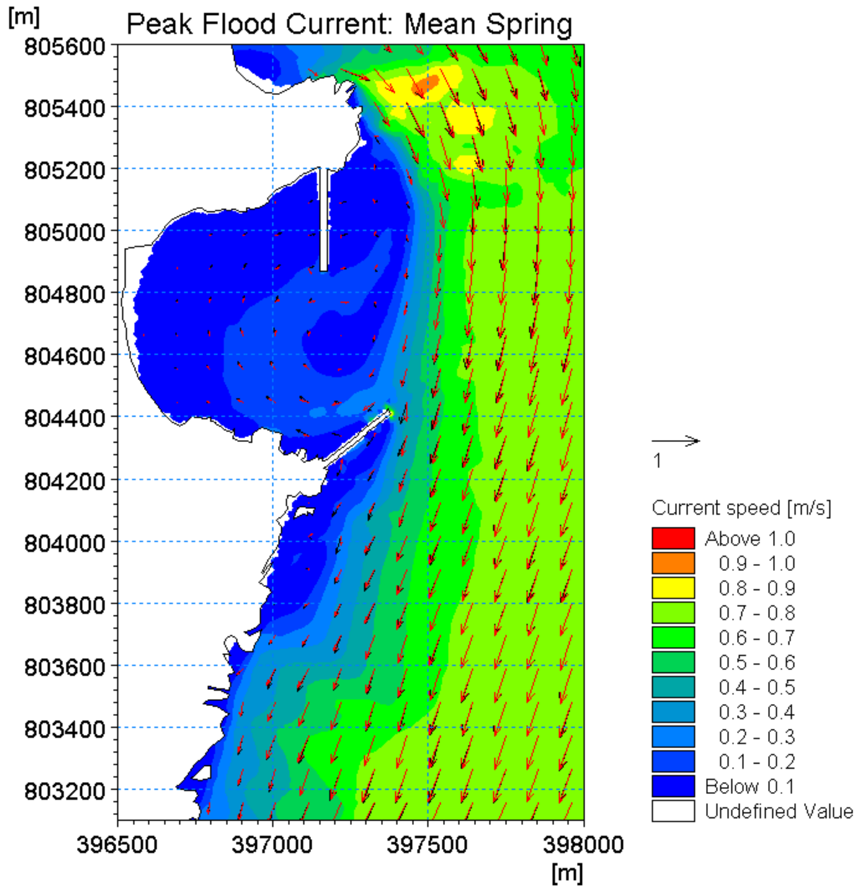
South-Easterly Wave

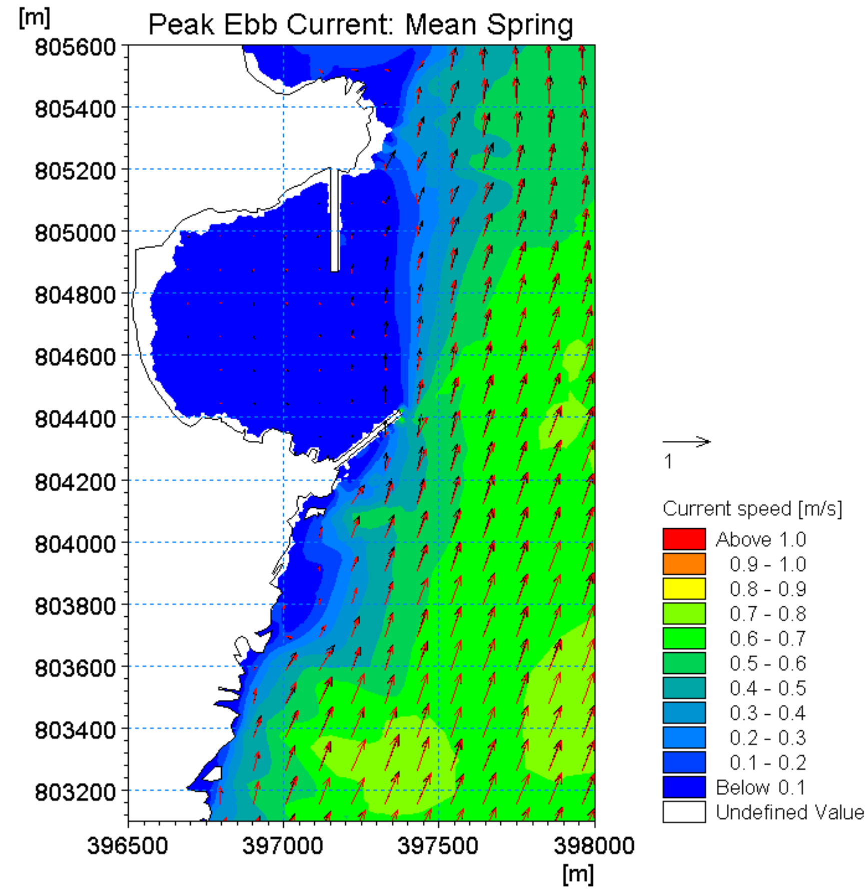


Appendix E Construction Phase Results

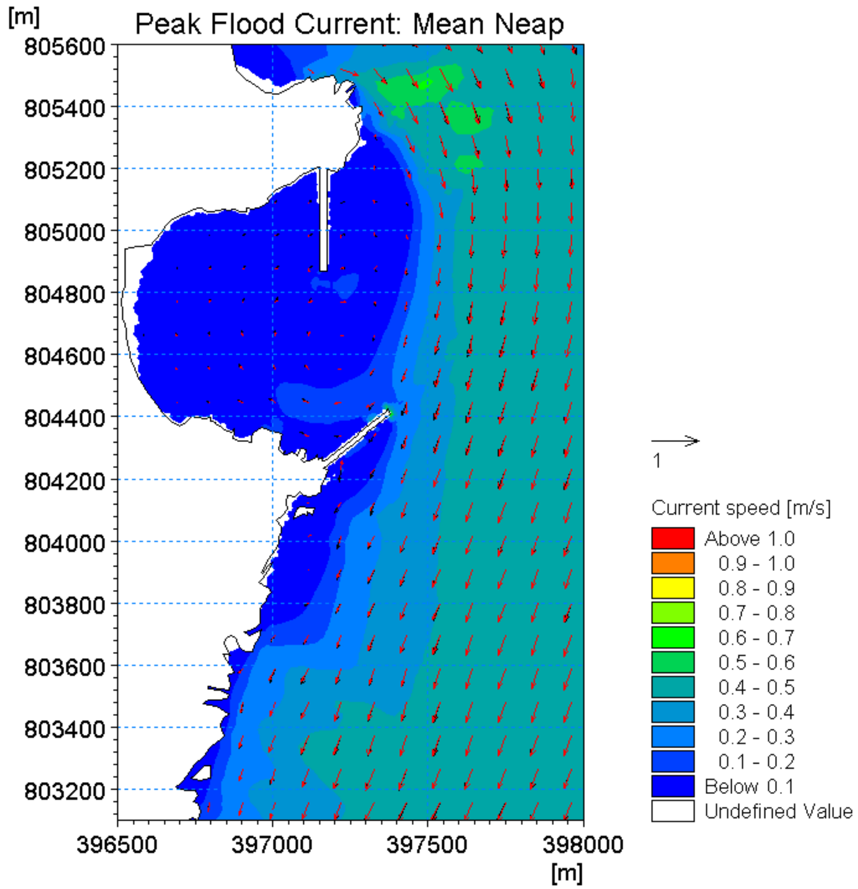
Figure E-1: Current vector plot showing difference in current between Construction Phase and Baseline

Spring Tide





Neap Tide


Peak Flood Current: Mean Neap
[m]
805600
805400
805200
805000
804800
804600
804400
804200
804000
803800
803600
803400
803200
396500
397000
397500
398000
[m]
1
Current speed [m/s]
Above 1.0
0.9 - 1.0
0.8 - 0.9
0.7 - 0.8
0.6 - 0.7
0.5 - 0.6
0.4 - 0.5
0.3 - 0.4
0.2 - 0.3
0.1 - 0.2
Below 0.1
Undefined Value

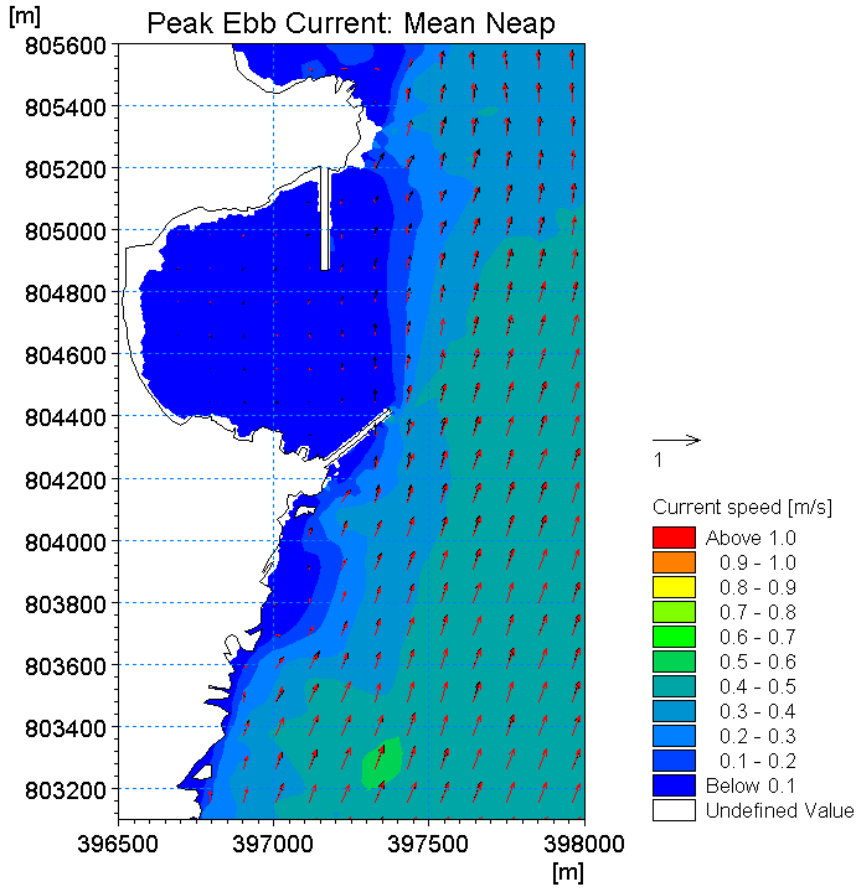

Peak Ebb Current: Mean Neap
[m]
805600
805400
805200
805000
804800
804600
804400
804200
804000
803800
803600
803400
803200
396500
397000
397500
398000
[m]
1
Current speed [m/s]
Above 1.0
0.9 - 1.0
0.8 - 0.9
0.7 - 0.8
0.6 - 0.7
0.5 - 0.6
0.4 - 0.5
0.3 - 0.4
0.2 - 0.3
0.1 - 0.2
Below 0.1
Undefined Value

Figure E-2: Vector plot showing difference in residual current between Construction Phase and Baseline