REPORT

Southwold Harbour Study

Wave Modelling Report

Client: East Suffolk Council

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HASKONINGDHV UK LTD.

Westpoint
Peterborough Business Park
Lynch Wood
Peterborough
PE2 6FZ
United Kingdom
Industry & Buildings
VAT registration number: 792428892

+44 1733 3344 55 **T**
info@uk.rhdhv.com **E**
royalhaskoningdhv.com **W**

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Author(s):	Amy Savage

Drafted by:	Vu Luong, Amy Savage
Checked by:	Amy Savage
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1 Introduction

1.1 Background

The many studies undertaken for Southwold Harbour and the Blyth Estuary demonstrate the complex issues surrounding planning for the future management of the area. These complexities are compounded by uncertainties about the future behaviour of the estuary under different management and climate change scenarios, which could affect the use of the harbour and the aspirations of harbour users and other local stakeholders. These issues have become increasingly critical as decisions are needed on the continued operational use of the harbour and management of the South Pier, which is in poor condition in places[1].

This project will develop an Investment Plan for the continued use of Southwold Harbour. The planned programme of investment needs to be driven by the important aspirations for use and management of the harbour of a wide range of stakeholders. Understanding these aspirations under different scenarios is a key aspect of the study. Different scenarios will be assessed based on an improved understanding of the physical behaviour of the harbour and estuary.

The scope of the Southwold Harbour Investment Plan project includes the development of hydrodynamic models to assess the present-day hydraulic regime for waves and currents in the entrance to Southwold Harbour. This includes calculation of water depths, wave heights and current speeds at various stages of the tide, to determine whether the present day and potential future conditions meet the operational requirements of the harbour users.

The wave and tidal flow modelling needs to assess the expected impact of the future management cases for the harbour and estuary on the harbour regime. This includes considering the influence that the South Pier has on wave activity within the Harbour Entrance and at the North Wall, as well as potential future changes to the river regime e.g., increased tidal volume, on flow speed and depth through the harbour and the Blackshore area. The sedimentation behaviour of the harbour and its expected response to the present day and future wave and tidal climate and storm events is also to be assessed.

The results of the modelling for the future management scenarios will inform the assessment of the residual functional life of the harbour entrance structures and identification of possible structural improvements to the harbour that would enhance present and future conditions for navigation and moorings. The wave and tidal models will be used to assess the expected performance of the potential structural improvements, and to identify future monitoring requirements to support the future management of the harbour and estuary.

1.2 General approach to wave and tidal modelling

The proposed approach to the wave and tidal modelling to be undertaken for this project aims to achieve a true representation of the hydrodynamic behaviour within the harbour area. Key considerations include:

- Diffraction around the North and South Piers;
- Wave reflections through the harbour entrance, including sensitivity to wave angle;
- Wave transmission through the gaps in the South Pier; and
- Wave reflection from the various structures in the outer harbour, including the North Wall and the various structures around the Dunwich Creek entrance.
- Influence of flows from the Dunwich Creek on tidal flows
- Influence of the Dunwich Creek on sedimentation opposite the North Wall (shoal bank)

Particular issues that will be considered in the assessment of the modelling results include:

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[1] *Refer to Condition Inspection Report, Appendix A to the main report*

- Wave and current behaviour in the harbour entrance, considered against operational requirements for vessels;
- Wave behaviour at the North Wall and other vessel moorings, considered against requirements for safe mooring;
- Wave and current behaviour over and around the shoal bank at the landward end of the South Pier; and
- Wave and current interactions around the Dunwich Creek entrance, including
    - Wave reflection from the timber piles
    - Influence of the spending beaches on wave dynamics.

The results from the wave and tidal flow modelling will be used in combination to assess the potential for sedimentation and/or scour throughout the estuary, for the agreed scenarios. This analysis will focus on those scenarios and options which change the harbour entrance structures. The assessment will be informed by the agreed baseline, including information from stakeholders.

Figure 1-1: Satellite image - wave diffraction around the piers and wave disturbance in the entrance channel (Google Earth, 2020)

1.3 Key issues and approach to wave modelling

The wave disturbance issues in the harbour may be due to wave reflections from each side of the entrance channel. Wave reflection can be sensitive to wave angle. Wave energy transmission through the South Pier e.g., through the ‘windows’ in the sheet piles, may also be a cause of wave disturbance at the North Wall. These issues will be considered in the modelling.

The approach taken to the wave modelling was first to simulate the existing condition to understand the operational issues within the harbour. The model performance was validated against local observations (through discussion in stakeholder meetings), and by applying our experience. The wave disturbance model was then used to assess conditions for the Do Nothing scenario, assuming failure of the South Pier.
The project scope included for the assessment of three options for structural measures to improve conditions in the harbour e.g., potential improvements to the South Pier, or other changes to the harbour layout.

1.4 This Report

This report sets out the approach taken to the wave modelling completed for the Southwold Harbour Study. **Section 2** includes the site conditions used as input data for the models. **Section 3** describes the methodology and results of the Wave Transformation Modelling. **Section 4** describes the methodology and introduces the results of the wave penetration modelling. Figures showing the model results are provided as appendices to this report, and discussion of the model results is included in the main project report.

2 Site Conditions

2.1 Data collection

Data was collected from East Suffolk Council, the Environment Agency, and the UK Met Office, as well as various open-source datasets. All available information has been reviewed to identify relevant data for the model build and subsequent calibration. This has included consideration of the feedback provided by stakeholders during the workshop held in December 2019, such as comments on wave interactions in the harbour entrance and around the mouth of the Dunwich Creek. This information has contributed to developing our baseline understanding of the estuary's hydro-geomorphological behaviour. The sections which follow summarise the information that was been used to provide input data for the tidal model.

2.2 Offshore wind and waves

Offshore wind and wave data has been purchased from the UK Met Office WWIII model, at location 52.265^{o}N, 1.996^{o}E (**Figure 2-2**). The data point is about 22km from the Blyth estuary, where the water depth is about 31m.

The data obtained was the frequency tables covering the period of 1980 – 2019, with the wave data included as **Table 2-1** and used to produce the wave rose provided as **Figure 2-2.**

Figure 2-1: Location of the Met Office wave data point

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Table 2-1: Annual occurrence frequency (%) of significant wave heights at the Met Office data point (1980-2019)

Hm0 (m)	Directional sectors (°N)												Total
	0	30	60	90	120	150	180	210	240	270	300	330	
0-0.5	3.66	3.33	2.00	0.99	0.77	0.94	2.22	2.13	0.77	0.47	0.43	0.84	**18.54**
0.5-1	7.00	8.20	3.62	1.68	1.17	1.45	5.04	6.22	2.21	1.19	1.17	1.78	**40.71**
1-1.5	3.21	3.06	2.01	0.89	0.58	0.79	3.44	4.63	1.39	0.76	0.58	0.90	**22.25**
1.5-2	1.39	1.10	0.80	0.41	0.24	0.33	2.27	2.55	0.52	0.31	0.24	0.30	**10.46**
2-2.5	0.73	0.41	0.45	0.25	0.10	0.17	1.33	1.05	0.16	0.08	0.07	0.10	**4.90**
2.5-3	0.35	0.20	0.21	0.09	0.03	0.07	0.69	0.27	0.03	0.02	0.01	0.02	**1.99**
3-3.5	0.14	0.13	0.09	0.04	0.00	0.03	0.29	0.08	0.01	0.00	0.00	0.01	**0.82**
3.5-4	0.05	0.05	0.03	0.01	0.00	0.01	0.08	0.01	0.01	0.00	0.00	0.00	**0.24**
4-4.5	0.01	0.01	0.01	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	**0.07**
4.5-5	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	**0.01**
5-5.5	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.01**
5.5-6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
6-6.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Total	**16.53**	**16.50**	**9.24**	**4.37**	**2.90**	**3.78**	**15.39**	**16.94**	**5.09**	**2.83**	**2.49**	**3.94**	**100.00**

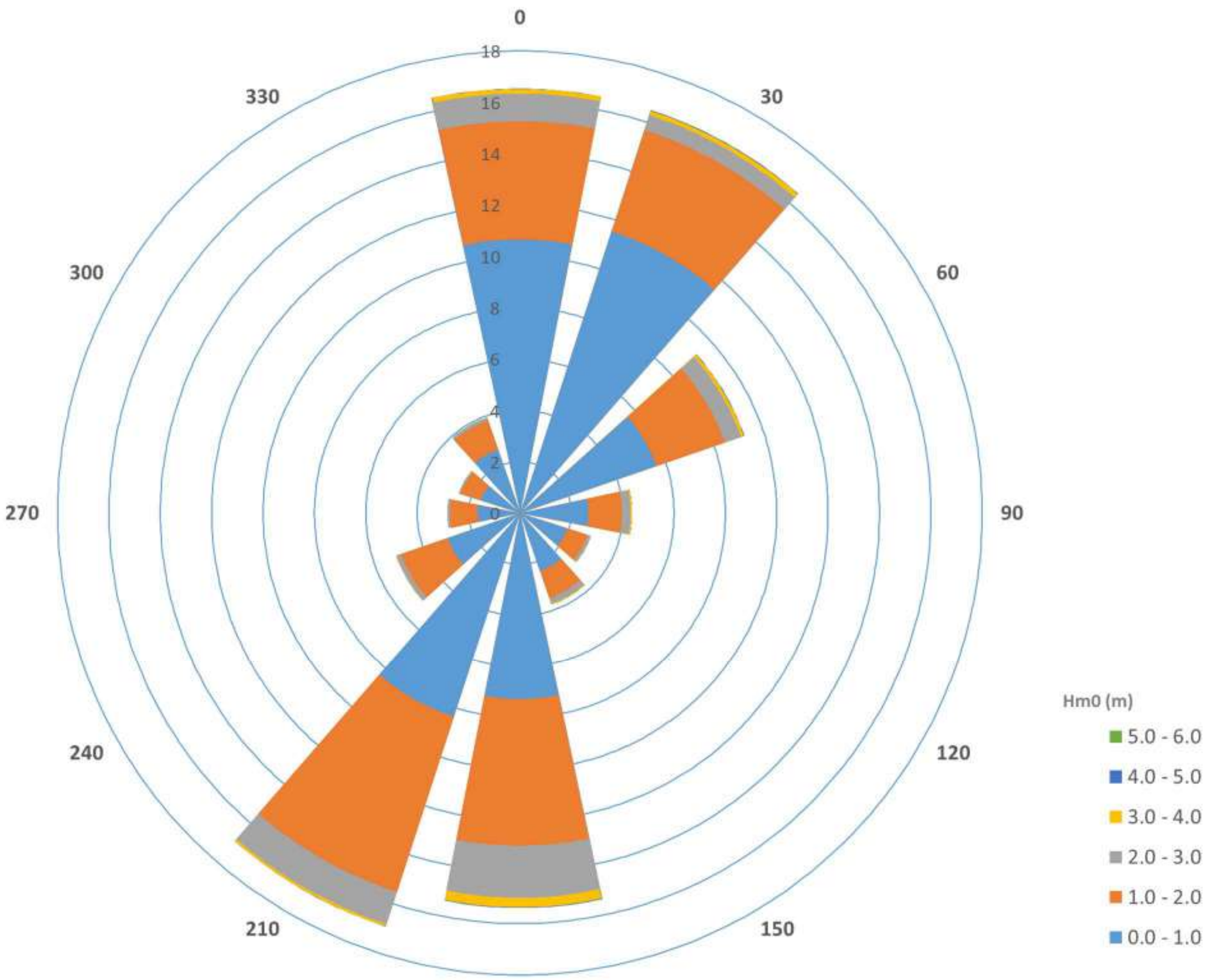

Figure 2-2: Annual wave rose offshore of Southwold (1980 – 2019)

2.3 Extreme wind and waves

The wind and wave data were analysed using Royal HaskoningDHV's in-house tool (Extreme 2.01). The results are provided in the tables below.

Table 2-2: Extreme significant wave heights (m) at the Met Office data point (1980-2019)

sectors (°N)	Return period (years)							
	0.083	**0.5**	**1**	**5**	**10**	**20**	**50**	**100**
0	2.52	3.40	3.74	4.53	4.87	5.20	5.65	5.99
30	2.62	3.71	4.13	5.11	5.53	5.94	6.50	6.92
60	2.34	3.29	3.66	4.51	4.87	5.23	5.72	6.08
90	1.93	2.94	3.32	4.21	4.59	4.97	5.47	5.85
120	1.46	2.29	2.60	3.31	3.62	3.93	4.33	4.64
150	1.78	2.79	3.18	4.07	4.45	4.83	5.34	5.72
180	3.01	4.11	4.54	5.52	5.94	6.36	6.92	7.34
210	2.58	3.47	3.81	4.61	4.95	5.29	5.74	6.08
240	1.78	2.60	2.91	3.63	3.94	4.25	4.66	4.97
270	1.50	2.34	2.65	3.38	3.69	4.00	4.42	4.73
300	1.37	2.13	2.42	3.07	3.36	3.64	4.01	4.29
330	1.57	2.42	2.73	3.47	3.79	4.11	4.53	4.84
All Dir.	**3.53**	**4.47**	**4.84**	**5.68**	**6.04**	**6.41**	**6.89**	**7.25**

Table 2-3: Extreme hourly average wind speed (m/s) at the Met Office data point (1980-2019)

sectors (°N)	Return period (years)							
	0.083	**0.5**	**1**	**5**	**10**	**20**	**50**	**100**
0	10.83	14.68	16.15	19.55	21.01	22.47	24.41	25.87
30	10.69	14.37	15.77	19.02	20.42	21.82	23.67	25.07
60	10.55	14.00	15.31	18.37	19.68	21.00	22.73	24.04
90	10.24	13.79	15.14	18.28	19.62	20.97	22.76	24.10
120	9.45	13.37	14.86	18.31	19.79	21.27	23.23	24.70
150	10.61	14.94	16.59	20.41	22.05	23.70	25.87	27.51
180	13.40	17.82	19.52	23.45	25.14	26.84	29.07	30.76
210	14.97	19.22	20.85	24.64	26.27	27.90	30.05	31.68
240	13.78	17.76	19.28	22.83	24.35	25.87	27.89	29.42
270	13.07	17.29	18.91	22.66	24.28	25.89	28.02	29.64
300	11.23	14.86	16.25	19.46	20.84	22.22	24.05	25.43
330	10.83	14.58	16.07	19.42	20.86	22.30	24.21	25.65
ALL	**16.93**	**20.63**	**22.05**	**25.37**	**26.79**	**28.21**	**30.10**	**31.52**

2.4 Bathymetry

The bathymetric data for the wave model has been obtained from the following sources:

- Detailed bathymetric survey with 0.5 x 0.5m resolution, undertaken by Shore in February 2020, as shown in **Figure 2-3**. This survey extends from approximately 100m offshore of the seaward end of the harbour piers up to the Bailey bridge. These data are referenced to OSGB36-BNG (X,Y) and ODN elevation (Z). Further details provided in **Section 3.2** of the main project report, and **Appendix A**.
- Seazone data provided by HR Wallingford Ltd, collected in September 2016 and covering an extended area around the Blyth estuary (**Figure 2-4**). These data are referenced to Chart Datum;
- The C-map data covering the North Sea area, extracted from the world-wide Electronic Chart Database (C-Map database) by Jeppesen Norway (**Figure 2-5**). These data are referenced to Chart Datum.

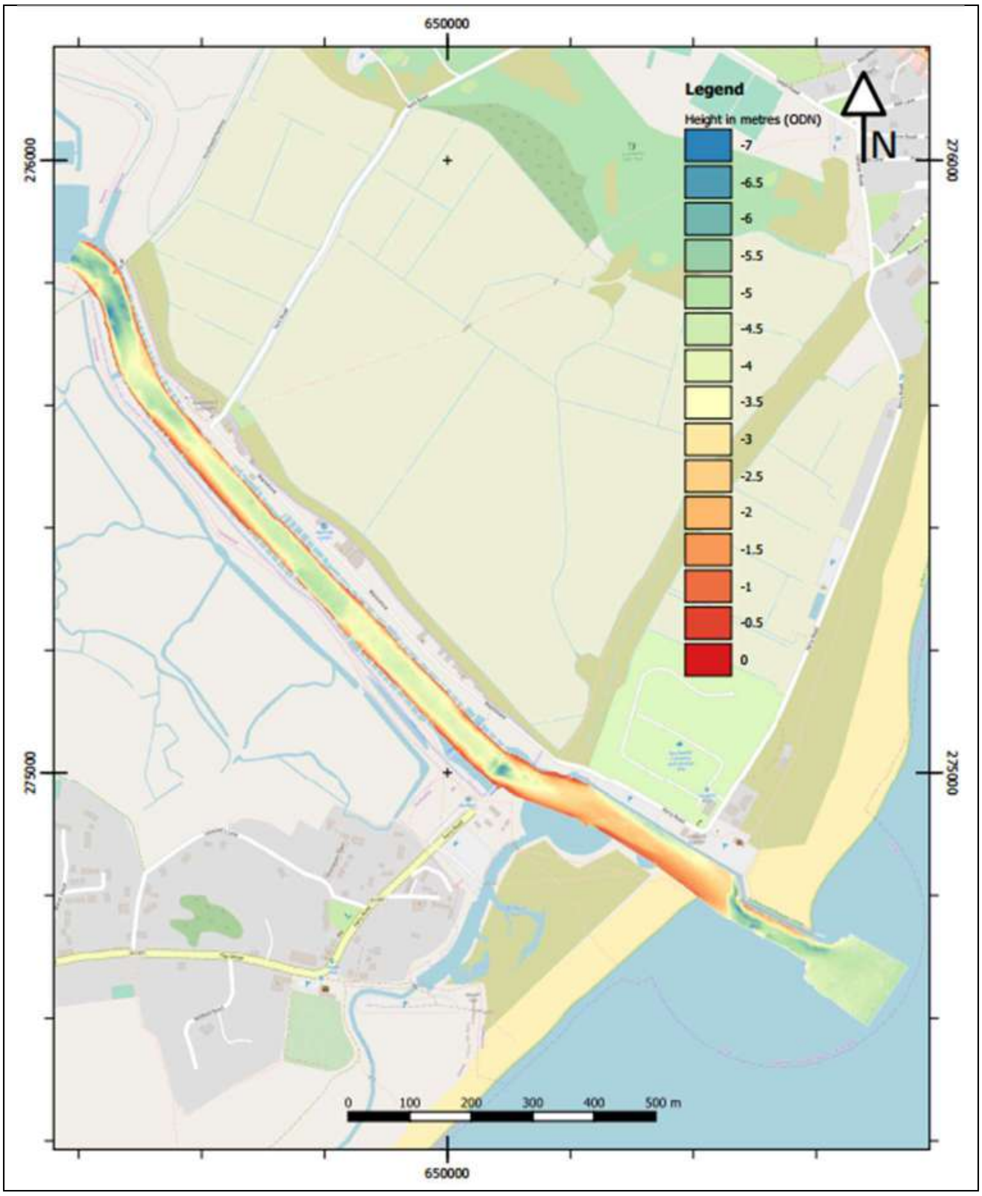

Figure 2-3: Detailed bathymetric survey data

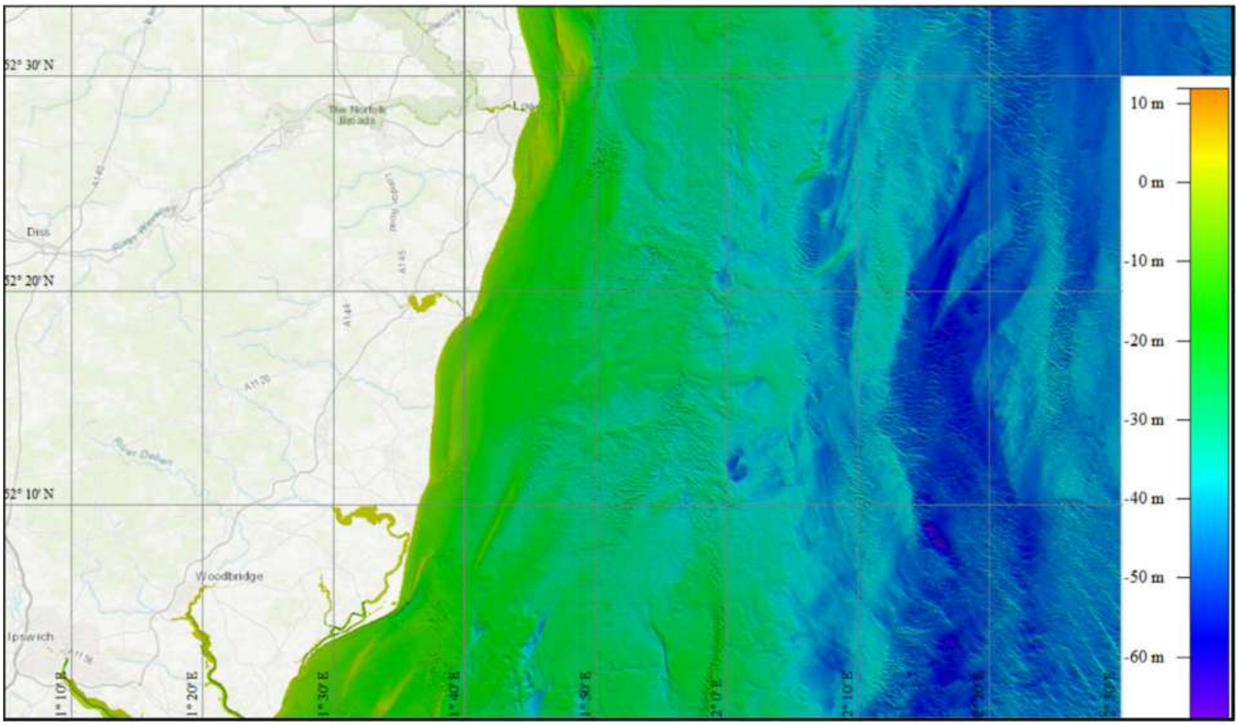

Figure 2-4: Seazone data

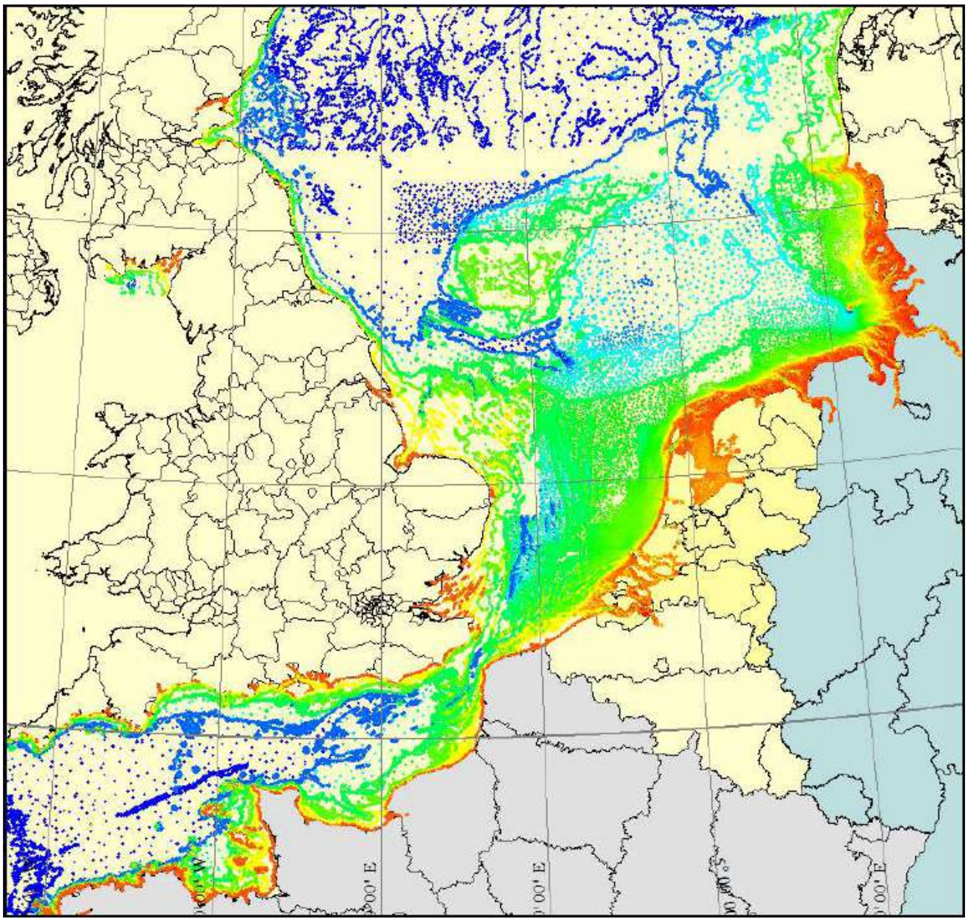

Figure 2-5: C-map data

2.5 Water levels

Water levels at Southwold, including extreme water levels, have been extracted from the United Kingdom Climate Predictions 2018 (UKCP 2018) from Lowestoft (20km north) and Felixstowe (45km south). An interpolation has also been made between the two locations to derive the conditions at Southwold. However, it is noted that water levels observed at Southwold are typically more comparable to those at Lowestoft. Extreme water levels included in **Table 2-4** below are based on the RCP 8.5 scenario (high emission scenario).

Table 2-4: Water Levels

Return Period (years) (AEP %)	Water Level (m ODN)				
	Lowestoft		Southwold	Felixstowe	
	mCD	mODN	mODN	mCD	mODN
MLWS	0.64	-0.86	-0.9	0.46	-1.49
MHWS	2.58	1.08	1.2	3.86	1.91
1 (100%)	3.60	2.10	2.32	4.71	2.76
5 (20%)	3.96	2.46	2.66	5.00	3.05
10 (10%)	4.12	2.62	2.81	5.13	3.18
50 (2%)	4.51	3.01	3.18	5.46	3.51
100 (1%)	4.67	3.17	3.31	5.61	3.66

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3 Wave Transformation Modelling

3.1 Model domain

The model domain for the MIKE21SW wave model is shown in **Figure 3-1**Error! Reference source not found. below.

Figure 3-1: Proposed MIKE21 model domain

3.2 Computational mesh

The computational mesh for the MIKE21SW wave model is shown in **Figure 3-2**, with the fine mesh used at the harbour entrance shown in **Figure 3-3**.

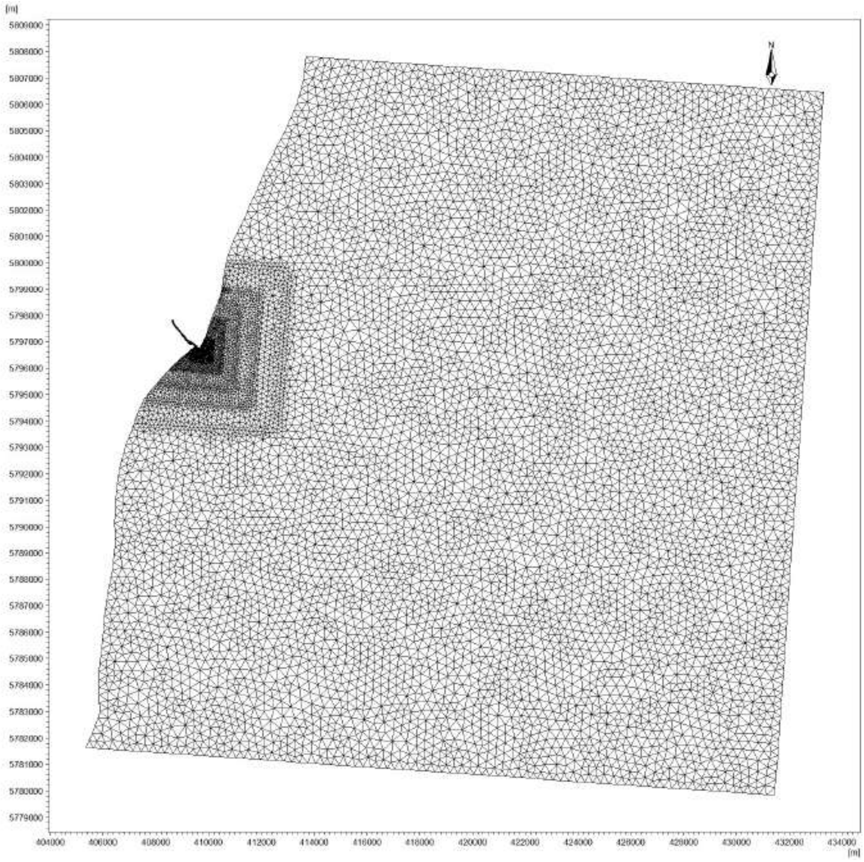

Figure 3-2: Computation mesh

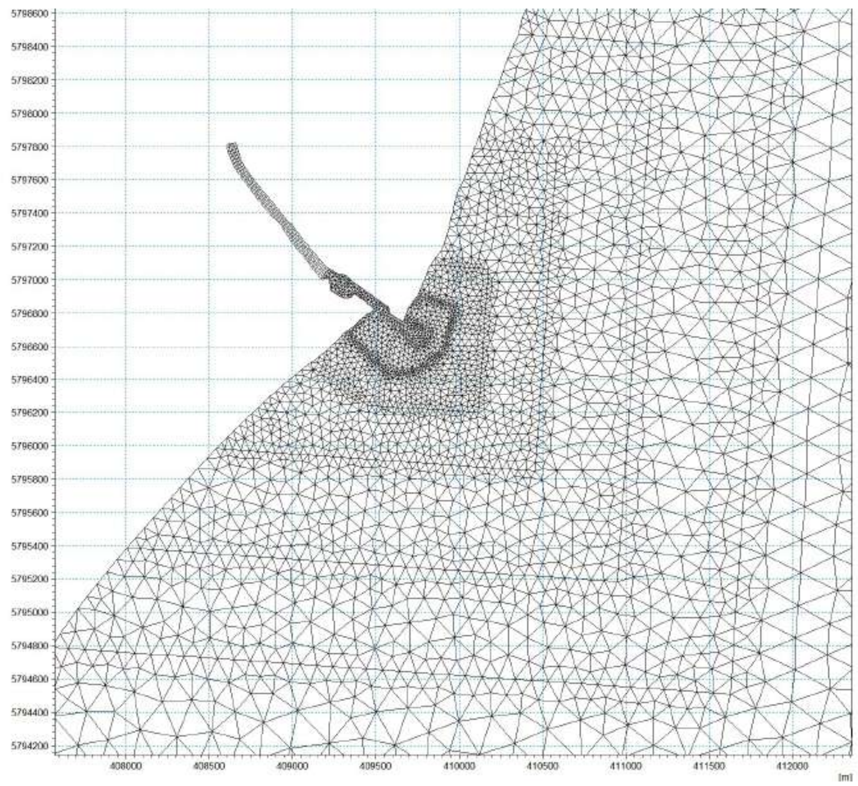

Figure 3-3: Fine computation mesh at the project location

3.3 Sensitivity tests

Based on the extreme analysis of the offshore wave data, two wave conditions were proposed for sensitivity testing of the wave transformation model, as in the table below. Water levels are based on levels at Felixstowe, to chart datum.

Table 3-1: Wave parameter for sensitivity tests

Test condition	Hm0 (m)	Tp (s)	Wind speed (m/s)	Water Level (mCD)
Operational	3.0	8.0	15	4.71
Extreme	7.0	15.0	25	5.61

The sensitivity test results were extracted at 2 points for analysis, as shown in **Figure 3-4**:

- Point P1, at the location of the offshore boundary for the proposed MIKE3 Wave model, at a seabed level of approx. -16.0 mCD; and
- Point P2, at the inshore location in front of the estuary, at a sea bed level of approx. -4.0 mCD.

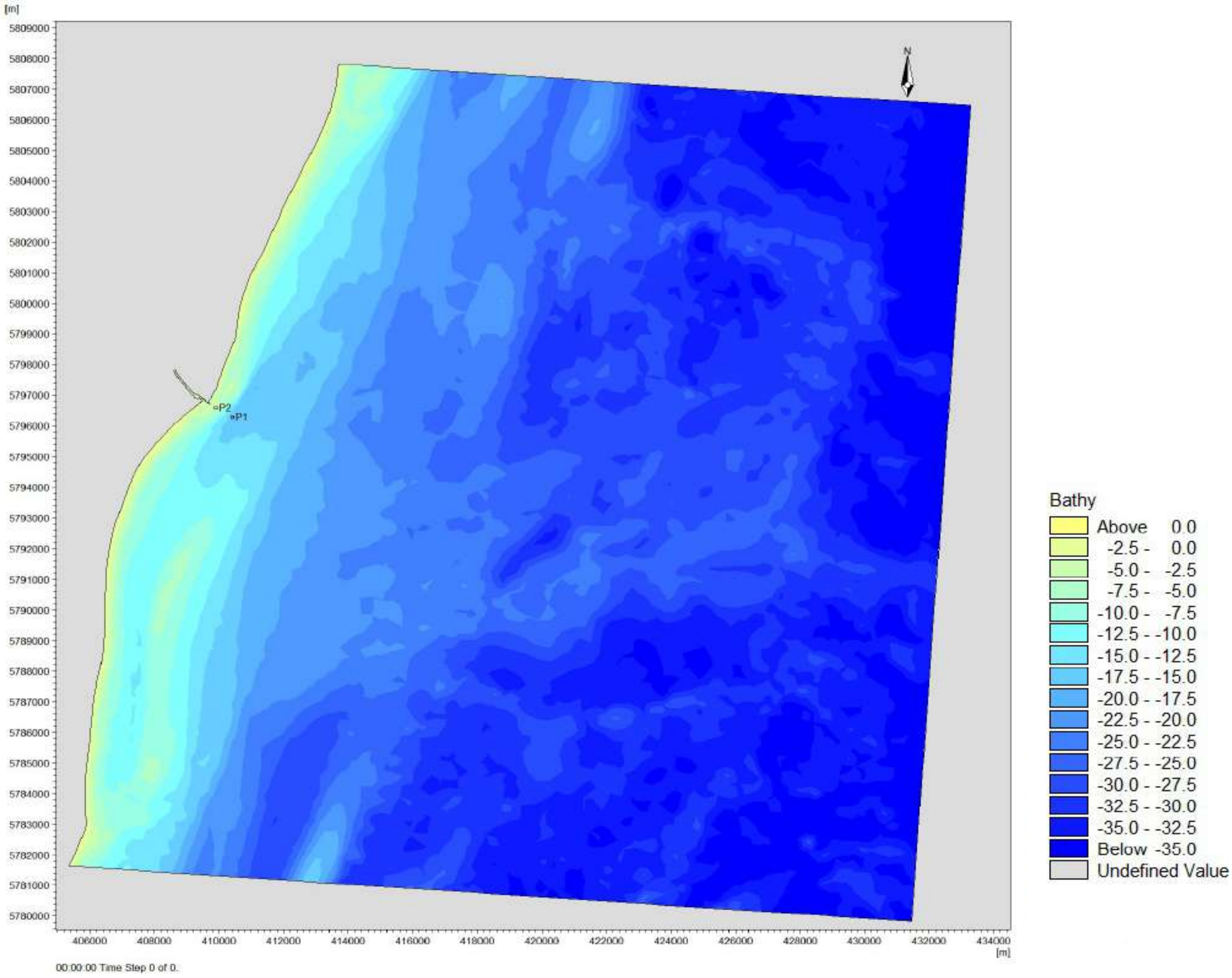

Figure 3-4: Model domain, bathymetry, and output point locations

The test cases applied for operational and extreme waves are listed in the table below. In total, 18 test runs were completed. The results from the test runs are provided in **Appendix A**.

Table 3-2: Sensitivity test runs

Test No.	MWD (°N)	Breaking coef. (-)	Bottom friction, kn (mm)	Note
1	0	0.8	0.2	Tests with directions and wave breaking coefficient
2	90	0.8	0.2	
3	180	0.8	0.2	
4	0	0.6	0.2	
5	90	0.6	0.2	
6	180	0.6	0.2	
7	0	0.8	0.0	Test with bottom friction
8	0	0.8	0.4	
9	0	0.8	1.0	

The wave conditions at the output points are set out in **Table 3-3** below. These results show that:

- The waves coming from the north reduced more in height than the ones coming from the south and from the east.
- Breaking coefficient has little/no influence on reduction of wave heights in the operational conditions (see **Figure 3-5**).
- In the extreme tests, breaking coefficient has significant influence on reduction of wave heights (see **Figure 3-6**). A breaking coefficient of 0.80 is proposed.
-
-
- **Table** 3-4 below shows that the bottom frictions have no influence on the wave height in the operational tests and have a small influence in the extreme test. A bottom coefficient of 0.2mm is proposed for the production runs.

The basic settings for the wave transformation model are summarised in **Table** 3-5.

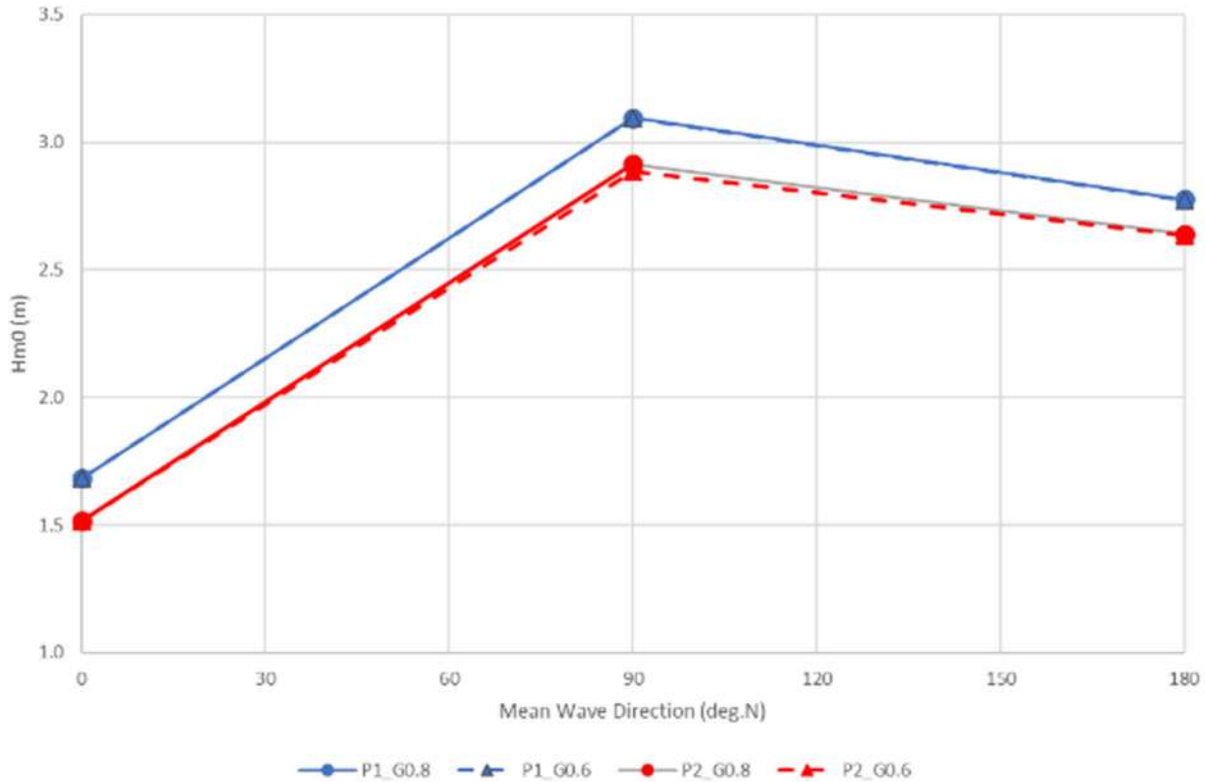

Figure 3-5: Influence of breaking coefficient for the operational tests

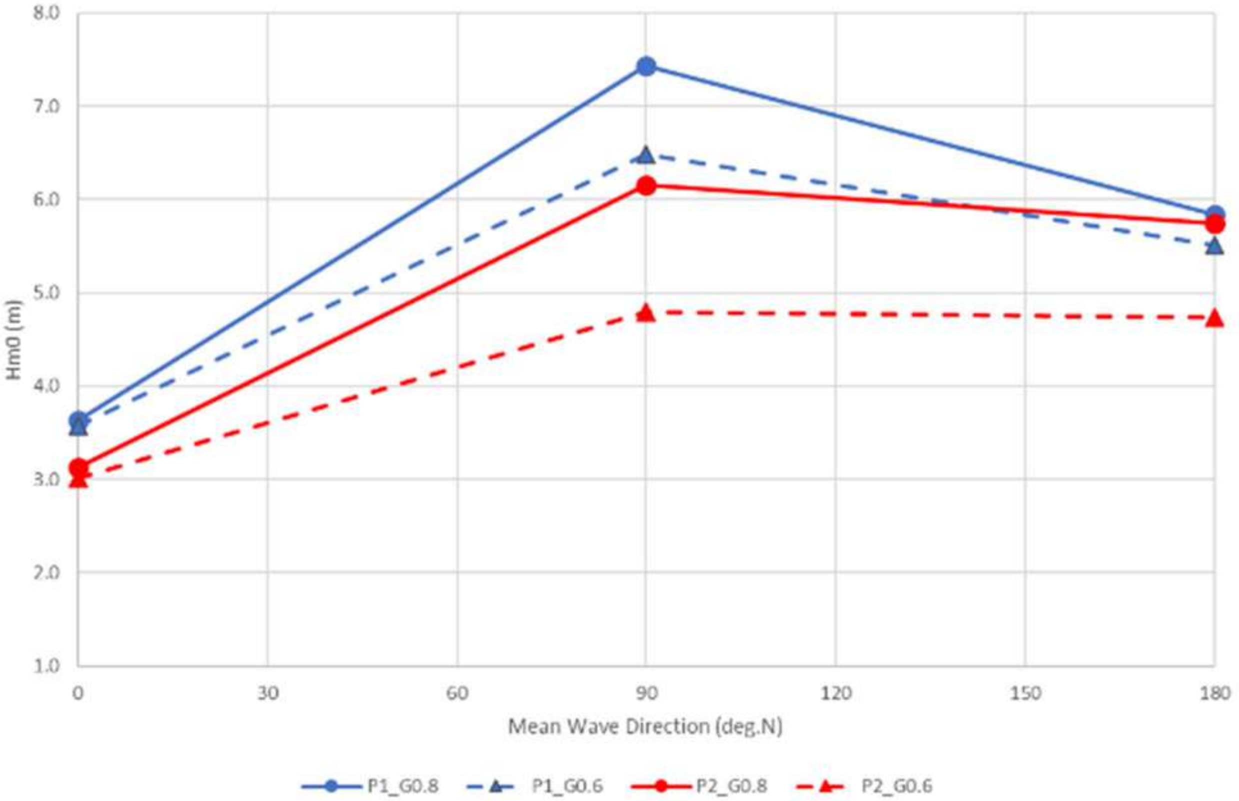

Figure 3-6: Influence of breaking coefficient for the extreme tests

Table 3-3: Wave parameters at the output points

Test case	Hm0 (m)		Tp (s)		MWD (°N)	
	P1	P2	P1	P2	P1	P2
O1_D000_G080	1.7	1.5	8	8	44	57
O2_D090_G080	3.1	2.9	8	8	92	102
O3_D180_G080	2.8	2.6	8	8	162	156
O4_D000_G060	1.7	1.5	8	8	44	57
O5_D090_G060	3.1	2.9	8	8	92	102
O6_D180_G060	2.8	2.6	8	8	162	155
O7_D000_Kn0000	1.7	1.5	8	8	44	57
O8_D000_Kn0004	1.7	1.5	8	8	44	57
O9_D000_Kn0010	1.7	1.5	8	8	44	57
E1_D000_G080	3.6	3.1	15	15	55	78
E2_D090_G080	7.4	6.2	15	15	94	109
E3_D180_G080	5.8	5.7	15	15	146	141
E4_D000_G060	3.6	3.0	15	15	56	80
E5_D090_G060	6.5	4.8	15	15	93	108
E6_D180_G060	5.5	4.7	15	15	143	139
E7_D000_Kn0000	3.8	3.3	15	15	55	79
E8_D000_Kn0004	3.6	3.1	15	15	55	78
E9_D000_Kn0010	3.6	3.1	15	15	55	78

Table 3-4: The effect of bottom friction on wave height

Bottom friction, Kn (mm)	Operation wave		Extreme wave	
	Hm0_p1	Hm0_p2	Hm0_p1	Hm0_p2
0.00	1.69	1.53	3.79	3.28
0.20	1.68	1.52	3.63	3.13
0.40	1.68	1.52	3.62	3.12
1.00	1.68	1.51	3.58	3.08

Table 3-5: Settings for wave transformation model

Spectral formulation	**Fully Spectral**
Time formulation	Quasi Stationary
Frequency discretization	Logarithmic, Min. freq. = 0.04 Hz, 26 freq.
Directional discretization	360 deg, 72 directions
Separation of wind and Swell	No
Water level conditions	Constant
Current conditions	No
Wind Forcing	Constant
Diffraction	No
Wave-wave interaction	Quadruplet
Wave breaking	constant gama = 0.8
Bottom friction	Nikuradse roughness, kn = 0.2mm
White capping	Default

3.4 Test Conditions

The run conditions were established based on the extreme analysis results. The wind speeds were combined with waves with the same direction and return period. Extreme water levels at Felixstowe are used as the boundary condition (refer to **Table 2-4).** The combined run conditions are set out in **Table 3-6.**

The extreme offshore wave conditions were transformed to the Blyth estuary, to enable boundary conditions to be derived for an assessment of wave penetration into the Blyth estuary. The wave transformation will also derive design conditions for the breakwaters.

Table 3-7 presents the list of all 24 extreme runs. For ease of reference the model run ID is the combination of Return Period (RP) and offshore direction.

Table 3-6: Run conditions for MIKE21 SW

Dir. (°N)	1 year Return Period Water Level = 4.71mCD			1 year Return Period Water Level = 5.13mCD			1 year Return Period Water Level = 5.61mCD		
	Hm0 (m)	Tp (s)	U10 (m/s)	Hm0 (m)	Tp (s)	U10 (m/s)	Hm0 (m)	Tp (s)	U10 (m/s)
0	3.74	10.50	16.15	4.87	12.50	21.01	5.99	14.00	25.87
30	4.13	10.00	15.77	5.53	11.00	20.42	6.92	15.00	25.07
60	3.66	8.00	15.31	4.87	9.50	19.68	6.08	10.00	24.04
90	3.32	7.50	15.14	4.59	8.00	19.62	5.85	9.00	24.10
120	2.60	7.00	14.86	3.62	7.50	19.79	4.64	8.00	24.70
150	3.18	7.00	16.59	4.45	7.50	22.05	5.72	8.00	27.51
180	4.54	8.50	19.52	5.94	9.00	25.14	7.34	10.00	30.76
210	3.81	8.00	20.85	4.95	8.00	26.27	6.08	9.00	31.68

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Table 3-7: Wave transformation model run list

Return Period (years)	Extreme Water Level (mCD)	Run ID	Direction (°N)	Hm0 (m)	Tp (s)	U10(m/s)
1	4.71	RP001_DIR000	0	3.74	10.50	16.15
		RP001_DIR030	30	4.13	10.00	15.77
		RP001_DIR060	60	3.66	8.00	15.31
		RP001_DIR090	90	3.32	7.50	15.14
		RP001_DIR120	120	2.60	7.00	14.86
		RP001_DIR150	150	3.18	7.00	16.59
		RP001_DIR180	180	4.54	8.50	19.52
		RP001_DIR210	210	3.81	8.00	20.85
10	5.13	RP010_DIR000	0	4.87	12.50	21.01
		RP010_DIR030	30	5.53	11.00	20.42
		RP010_DIR060	60	4.87	9.50	19.68
		RP010_DIR090	90	4.59	8.00	19.62
		RP010_DIR120	120	3.62	7.50	19.79
		RP010_DIR150	150	4.45	7.50	22.05
		RP010_DIR180	180	5.94	9.00	25.14
		RP010_DIR210	210	4.95	8.00	26.27
100	5.61	RP100_DIR000	0	5.99	14.00	25.87
		RP100_DIR030	30	6.92	15.00	25.07
		RP100_DIR060	60	6.08	10.00	24.04
		RP100_DIR090	90	5.85	9.00	24.10
		RP100_DIR120	120	4.64	8.00	24.70
		RP100_DIR150	150	5.72	8.00	27.51
		RP100_DIR180	180	7.34	10.00	30.76
		RP100_DIR210	210	6.08	9.00	31.68

3.5 Wave Transformation Model Results

The model results for the wave transformation model are presented as 2D plots in **Appendix B**, and as wave parameters for 3 output points in **Table 3-9**. The output points are shown in **Figure 3-7**, with their details provided in **Table 3-8**.

Table 3-8: Details of wave transformation output points

Point name	Easting (m)	Northing (m)	Bed level (mCD)
P1	410400	5796300	-15.8
P2	409750	5796720	-4.2
P3	409700	5796660	-4.3

The wave transformation modelling results show that:

- The shoaling processes have significant impact on mean wave direction for the waves that come from the 0°N and 210°N sectors. For example, offshore waves from 210°N will change to 160°N in front of the estuary and can penetrate into the river.
- The waves that travel from offshore towards the Blyth estuary have a mean wave direction in the range of 70°N to 160°N. With the current alignment of the harbour mouth these waves will be able to penetrate further into the estuary.

- All 8 conditions of 1-year return period waves should be modelled in the wave penetration study.

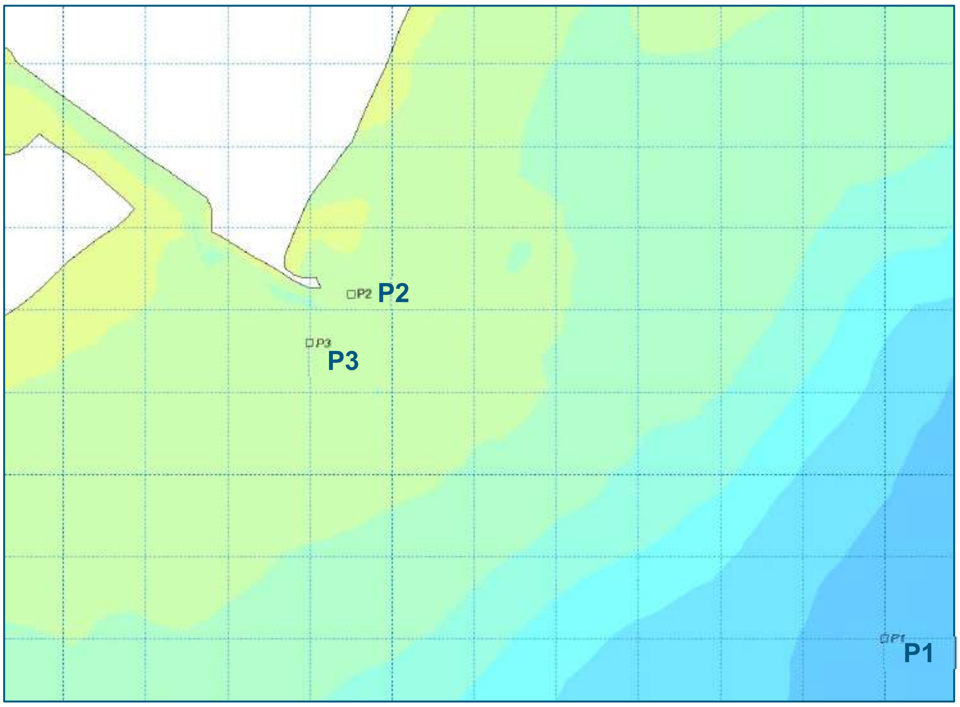

Figure 3-7: Output locations

Table 3-9: Wave parameters at the output points

Return period (years) (AEP, %)	Run ID	Hm0 (m)			Tp (s)			MWD (°N)		
		P1	P2	P3	P1	P2	P3	P1	P2	P3
1	RP001_DIR000	2.0	1.9	1.8	10.5	10.5	10.5	49	74	71
	RP001_DIR030	3.0	2.9	2.7	9.8	9.9	9.9	59	82	79
	RP001_DIR060	3.1	3.0	2.8	8.0	8.0	8.0	71	88	86
	RP001_DIR090	3.1	2.9	2.9	7.5	7.6	7.6	92	103	102
	RP001_DIR120	2.8	2.6	2.7	7.1	7.1	7.1	118	123	120
	RP001_DIR150	3.1	2.9	3.0	7.2	7.2	7.2	143	142	139
	RP001_DIR180	4.0	3.7	3.7	8.6	8.6	8.6	160	153	151
	RP001_DIR210	3.4	3.0	3.1	7.8	7.9	7.9	180	168	167
10	RP010_DIR000	2.6	2.6	2.4	12.6	12.6	12.6	52	78	75
	RP010_DIR030	4.1	3.9	3.6	10.8	10.9	10.9	61	85	82
	RP010_DIR060	4.4	4.0	3.9	9.5	9.5	9.5	73	93	91
	RP010_DIR090	4.3	3.9	4.0	8.1	8.2	8.2	92	105	104
	RP010_DIR120	4.1	3.8	3.9	7.8	7.9	7.9	117	123	120
	RP010_DIR150	4.6	4.1	4.2	7.9	8.0	8.0	141	140	137
	RP010_DIR180	5.6	4.5	4.5	9.1	9.3	9.3	159	151	149
	RP010_DIR210	4.7	4.0	4.0	8.0	8.1	8.1	180	166	165
100	RP100_DIR000	3.2	3.3	3.0	14.0	14.0	14.0	54	80	76
	RP100_DIR030	5.3	4.8	4.6	15.0	15.1	15.1	64	91	87
	RP100_DIR060	5.9	4.7	4.6	10.0	10.1	10.1	73	95	93
	RP100_DIR090	6.0	4.7	4.8	9.4	9.5	9.5	92	108	106
	RP100_DIR120	5.6	4.6	4.7	8.7	8.7	8.7	116	123	120
	RP100_DIR150	6.3	4.8	4.9	8.8	8.9	8.9	138	138	135
	RP100_DIR180	7.1	5.0	5.0	10.3	10.4	10.4	155	148	146

	RP100_DIR210	5.7	4.6	4.6	8.9	9.0	9.0	178	164	163

4 Wave Penetration Modelling

4.1 Methodology

4.1.1 Model domain

Figure 4-1 shows the extent of the Mike21 BW model, and the bathymetry at the mouth of the harbour.

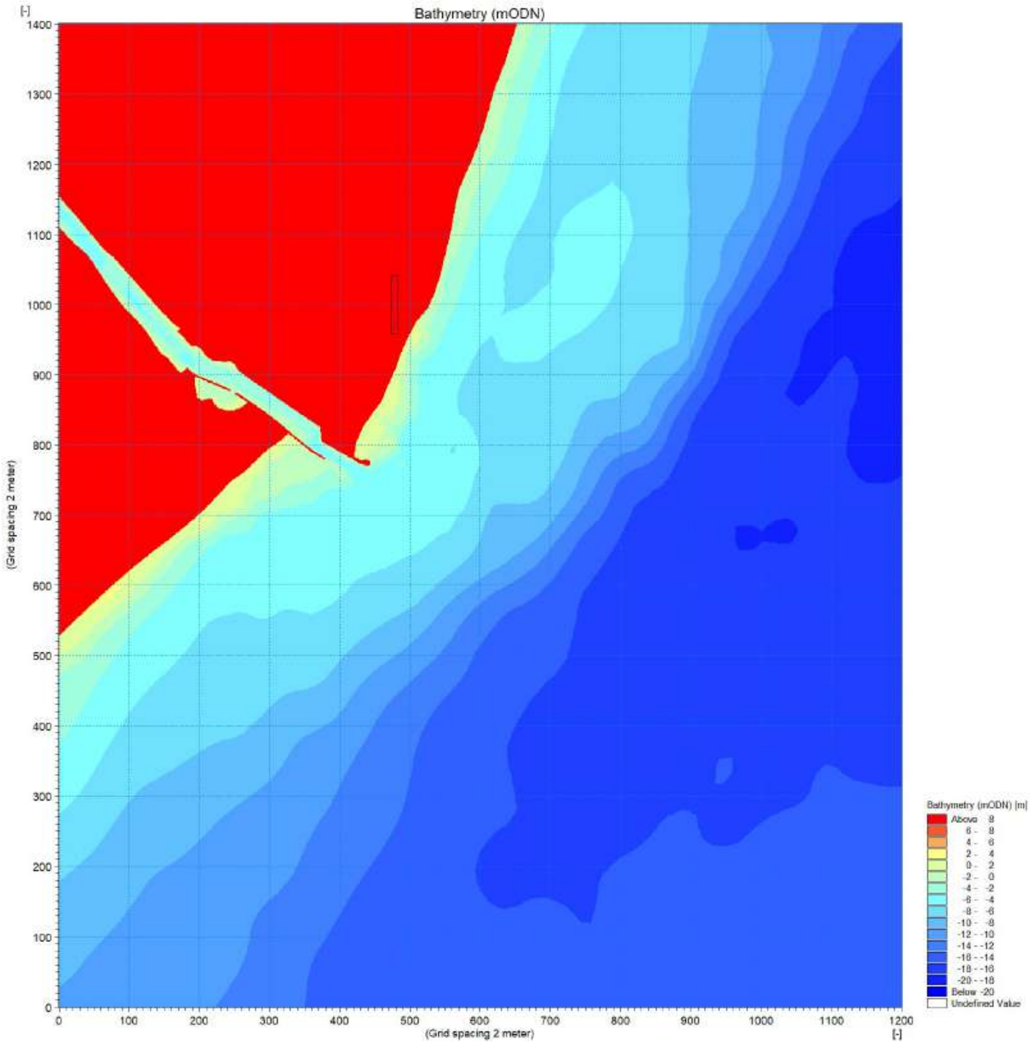

Figure 4-1: Model domain and bathymetry of the existing condition at Southwold Harbour

4.1.2 Modelling Settings

The basic settings for the model are summarised below:

- Model tool used MIKE21 BW which solves the Boussinesq equations
- Model domain covers an area of approx. 2.4 x 2.8 km
- Rectangular grid size of 2.0 x2.0m

- Bottom friction: Bottom friction is excluded for these short wave simulations. This is because the area covered is relatively small and with the exception of high waves and/or very shallow water there is insufficient distance for the bed resistance to have a significant effect on short wave propagation.
- Wave breaking: Water depth within Southwold harbour is of the order of 5m. For this depth, operational waves with Hs=2m would not break. Therefore, depth induced wave breaking is not important and need not be considered in the model.
- Partial reflection boundaries: The reflection coefficients applied to each type of structure are summarised in **Table 4-1**.
- Wave conditions at the boundary of the model has been generated using JONSWAP spectrum, with the default spectral shape parameters (γ= 3.3, σ_a = 0.07, σ_b = 0.09) was used.

Table 4-1: Reflection coefficients

Boundary / structure types	Reflection coefficient
Natural sandy beach	0.20
Rock revetments and breakwater	0.45
Concrete baffle wall	0.85
Vertical wall	1.00

4.2 Model Run Scenarios

4.2.1 Future management scenarios

The following future scenarios for management of the estuary were assessed using the wave and tidal models:

- **E1. Do Nothing:** No further works to the flood defences or harbour structures.
- **E2. Improve Estuary Defences:** Estuary defences are maintained and improved to provide protection against a 1 in 100-year return period (1% AEP) surge event, allowing for sea level rise to 2070.
- **E3. SMP Policy position:** Harbour entrance and mid and upper estuary defences are improved to keep pace with increasing water levels and (possibly increasing) tidal flow volumes. Some banks on south side of estuary are realigned, allowing flooding.
- **E4. EA Strategy position:** Management of mid and upper estuary defences is withdrawn by 2030. Rock terminal groyne would be built at Gun Hill to reduce the risk of beach erosion if the North Pier was to fail (the benefits of retaining the North Pier are acknowledged in the EA Strategy).

For scenarios E2 and E3, it is assumed that the harbour entrance structures are maintained or improved, as necessary. The wave modelling considers a range of options for the improvement of the harbour entrance structures. For scenario E3, the condition of the harbour entrance structures would be allowed to deteriorate and eventually fail. For the purposes of the wave modelling, scenario E4 is the same as scenario E0, with failure of the harbour entrance structures. These management scenarios are described in more detail in **Section 7** of the main project report.

4.2.2 Options for harbour entrance structures

The options summarised in **Table 4-2** are under consideration for the harbour entrance structures and were represented in the wave penetration model. The option layouts and the associated reflection coefficients are shown in **Appendix D**.

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Table 4-2: Options for the harbour entrance structures

Option	Comments
H0. Baseline[2]	This model layout represents the existing configuration of Southwold Harbour in 2020. The Present Day scenario has been modelled to allow the wave and tidal models to be calibrated. Model results for this layout will also demonstrate the performance of options involving repairs, like-for-like replacement, or solutions with comparable hydraulic performance to the existing South Pier.
H1. Do Nothing	South Pier removed up to Length C (retaining solid section). This option is considered as a worst case to demonstrate potential impacts (e.g., increased flood risk), in case of failure of the S Pier. Model results will show the impact that failure of the South Pier would have on wave conditions in the harbour. This layout also enables assessment of a management option which chooses to remove part of the South Pier e.g. with the aim of widening the channel to mitigate the impact of an increased tidal prism.
H2. Do Minimum (maintain)	In terms of the wave modelling, this option is the same as Option H0 (Baseline).
H3. Do Minimum (repair)	In terms of the wave modelling, this option is the same as Option H0 (Baseline).
H4. Repair then replace	In terms of the wave modelling, this option is the same as Option H6 (Breakwater).
H5. Replace South Pier with a similar structure	In terms of the wave modelling, this option is the same as Option H0 (Baseline).
H6. Replace South Pier with a (rock) breakwater	The existing South Pier is replaced with a rock armour breakwater, or rock armour is constructed around the existing structure, on the same alignment.
H6a. Rock armour breakwater + baffles	As for H2, but with the addition of concrete baffles to the North Pier wall (above the SHED revetment) and to the South Training Wall, to increase wave energy dissipation through the entrance channel.
H6b. Rock armour breakwater + rock armour to S training wall	As for H2, with rock armour also placed along the South training arm, from the beach up to Dunwich Creek. The shoal bank opposite the Knuckle / North Wall would be dredged to enable placement of this rock armour.
H6c. Vertical-faced breakwater	The existing south pier will be modelled with a fully reflective boundary, to represent replacement of the structure with a sheet-piled pier structure with a vertical face.
H6d: Rock armour breakwater + rock groyne to narrow the channel	The existing South Pier is replaced with a rock armour breakwater on the same alignment. A rock groyne is constructed to narrow the channel near the Lifeboat Station.

4.2.3 Run Conditions

The wave penetration model was run for 1-year and 1-month wave conditions, for waves originating from 8 offshore directions: 0, 30, 60, 90, 120, 150, 180 and 210°N. These wave parameters have been extracted from MIKE21SW modelling results.

The wave parameters for the 1-year return period conditions are presented in **Table 4-3**. The 1-month return period conditions are given in **Table 4-4**. This provides additional information compared to the agreed project scope. The waves with peak periods longer than 8 seconds are considered to be swell waves, with the shorter period waves being locally generated 'sea' waves.

[2] *For the baseline scenario (H0), the South Pier is shown in the model layouts and results plots with a shorter length, because the 'windows' in the outer part of the pier are represented in the bathymetry by increasing the sea bed level to the lower level of the windows.*

4.3 Assessment Criteria

The guidelines for the maximum acceptable wave heights for small vessels are based on the 1995 PIANC publication for the criteria of movements of moored ships in harbours, which are presented in **Table 4-5** below. The acceptable frequency of occurrence is up to a few times per year.

The criteria for smaller vessels are much stricter than those for larger vessels. Small craft like service boats, rescue boats and survey and support vessels will not exceed 20m. For these types of vessel, a maximum wave height of 0.15-0.30m can be accepted, depending on wave direction and period. It is anticipated that tugs and barges can be moored in higher wave heights, up to 0.5-0.8m, depending on wave direction.

Table 4-3: 1-year return period model run conditions

Offshore wave direction (°N)	Wave conditions in front of the Blyth Estuary			
	Hm0 (m)	Tp (s)	MWD (°N)	Wave type
0	2.40	10.50	50	Swell
30	3.30	10.00	60	Swell
60	3.20	8.00	70	Swell
90	3.20	7.50	90	Seas
120	2.80	7.50	120	Seas
150	3.10	7.50	140	Seas
180	4.00	8.60	160	Swell
210	3.50	8.00	180	Swell

Table 4-4: 1-month return period model run conditions

Offshore wave direction (°N)	Wave conditions in front of the Blyth Estuary			
	Hm0 (m)	Tp (s)	MWD (°N)	Wave type
0	1.40	10.00	50	Swell
30	2.10	9.50	60	Swell
60	2.10	7.50	70	Seas
90	1.90	7.50	90	Seas
120	1.60	7.50	120	Seas
150	1.80	7.50	140	Seas
180	2.50	8.00	160	Swell
210	1.80	7.50	180	Seas

Table 4-5: Limiting Operational Wave Heights (PIANC 1995 Workgroup 24 Criteria for Movements of Moored Ships in Harbours)

Ship Length (m)	Beam/Quartering Seas		Head Seas	
	Period (s)	**Hm0 (m)**	**Period (s)**	**Hm0 (m)**
4-10	< 2.0	0.20	< 2.5	0.20
	2.0 – 4.0	0.10	2.5 – 4.0	0.15
	> 4.0	0.15	> 4.0	0.20
10-16	< 3.0	0.25	< 3.5	0.30
	3.0 – 5.0	0.15	3.5 – 5.5	0.20
	> 5.0	0.20	> 5.5	0.30
20	< 4.0	0.30	< 4.5	0.30
	4.0 – 6.0	0.15	4.5 – 7.0	0.25
	> 6.0	0.25	> 7.0	0.30

4.4 Model Results

4.4.1 Baseline conditions (present day harbour layout)

The 2D result plots are presented in Appendix C for each of the wave penetration model runs for the present-day harbour layout. The wave conditions in front of the North Wall within Southwold Harbour are summarised in Table 4-6 below.

Based on the limiting wave conditions for small vessels set out in **Table 4-5** above, the wave penetration modelling results show that the present-day conditions within shown in the **Table 4-7**: are not good for the safe mooring of boats at the North Wall under the 1-month return period conditions. These results suggest that mooring at the North Wall could be restricted for about 20-30% of the year.

Table 4-6: Wave conditions in front of the North Wall, Southwold Harbour

Offshore wave direction (°N)	Range of Hm0 (m) in front of harbour	
	1 Year	1 month
0	0.7 - 1.0	0.4-0.7
30	0.8 - 1.2	0.5-0.8
60	0.6-1.0	0.4-0.8
90	0.6 - 1.4	0.5-1.2
120	1.0 - 2.2	0.6-2.0
150	1.0 - 2.6	0.7-2.0
180	1.5 -3.5	1.0-2.4
210	1.3 - 3.3	1.0-2.0

4.4.2 Option modelling results

The 1-year return period wave conditions inside the Blyth estuary are summarised in **Table 4-7** below. The 2D result figures are presented in **Appendix E**.

Table 4-7: Wave conditions inside the Blyth estuary (1-year wave conditions)

Layout	Location	Hm0 (m) due to waves from Offshore Direction (°N)							
		0	**30**	**60**	**90**	**120**	**150**	**180**	**210**
H0 Present-day Baseline	Harbour front	0.7-1.0	0.8-1.2	0.6-1.0	0.6-1.4	1.0-2.2	1.0-2.6	1.5 -3.5	1.3-3.3
	Dunwich - Walberswick	0.5-1.5	0.6-1.8	0.5-1.4	0.5-1.3	0.7-1.8	0.7-2.0	1.0-2.3	0.7-2.1
	Upstream Moorings	0.3-0.5	0.3-0.6	0.3-0.7	0.3-0.6	0.3-0.7	0.3-0.7	0.6-0.9	0.4-0.7
H1 Do Nothing	Harbour front	0.7-1.0	0.8-1.2	0.6-1.0	0.6-1.5	1.0-2.4	1.0-3.0	1.5-3.7	1.3-3.5
	Dunwich - Walberswick	0.5-1.5	0.7-1.8	0.5-1.4	0.5-1.5	0.7-2.0	0.8-2.3	1.0-3.0	0.7-2.3
	Upstream Moorings	0.3-0.5	0.4-0.6	0.3-0.7	0.4-0.6	0.4-0.7	0.5-0.7	0.7-1.0	0.5-0.7
H6 Rock Breakwater	Harbour front	0.5-0.6	0.6-0.8	0.4-0.6	0.4-0.7	0.4-0.7	0.4-0.8	0.6-0.8	0.4-0.6
	Dunwich - Walberswick	0.4-0.9	0.4-0.9	0.3-0.7	0.4-0.7	0.4-0.7	0.4-0.8	0.4-0.8	0.4-0.6
	Upstream Moorings	0.3-0.4	0.3-0.4	0.2-0.3	0.2-0.3	0.2-0.3	0.2-0.3	0.3-0.4	0.2-0.3
H6a Rock Breakwater + Concrete Baffles	Harbour front	0.4-0.6	0.4-0.7	0.3-0.4	0.3-0.4	0.3-0.4	0.3-0.4	0.4-0.6	0.3-0.4
	Dunwich - Walberswick	0.3-0.6	0.4-0.6	0.2-0.4	0.2-0.4	0.2-0.3	0.2-0.3	0.4-0.6	0.2-0.3
	Upstream Moorings	0.3-0.4	0.3-0.4	0.2-0.3	0.2-0.3	0.1-0.2	0.1-0.2	0.2-0.3	0.1-0.2
H6b Rock breakwater + rock to South training arm	Harbour front	0.4-0.6	0.4-0.7	0.3-0.5	0.3-0.5	0.4-0.6	0.4-0.7	0.4-0.8	0.3-0.6
	Dunwich – Walberswick	0.3-0.6	0.3-0.6	0.2-0.4	0.2-0.4	0.2-0.4	0.2-0.5	0.3-0.7	0.2-0.4
	Upstream Moorings	0.3-0.4	0.2-0.3	0.2-0.3	0.2-0.3	0.1-0.2	0.2-0.3	0.2-0.3	0.1-0.2
H6c Vertical Pier walls	Harbour front	1.0-1.5	1.0-1.8	1.0-2.0	1.0-2.0	0.7-1.8	1.0-2.0	1.4-2.8	1.0-2.7
	Dunwich – Walberswick	0.7-1.7	0.8-2.0	0.6-1.8	0.6-1.5	0.6-1.5	0.7-1.8	0.8-2.0	0.6-1.5

	Upstream Moorings	0.5-0.7	0.5-0.8	0.4-0.7	0.4-0.6	0.4-0.6	0.4-0.6	0.6-0.8	0.4-0.6
H6d Rock breakwater + narrow channel	Harbour front	0.4-0.6	0.5-0.8	0.3-0.5	0.3-0.6	0.3-0.6	0.4-0.7	0.5-0.8	0.3-0.6
	Dunwich – Walberswick	0.3-0.5	0.3-0.6	0.3-0.5	0.2-0.5	0.2-0.5	0.3-0.6	0.4-0.6	0.3-0.5
	Upstream Moorings	0.2-0.3	0.2-0.3	0.2-0.3	0.2-0.3	0.2-0.3	0.2-0.3	0.2-0.3	<0.25

The modelling results show that the replacement of the South Pier with a rock breakwater (Option H2) significantly improves the wave conditions. The options with additional improvements such as concrete baffles give a slight further reduction in wave height for some wave directions.

Appendix A

Wave Disturbance Modelling – Sensitivity Test Results

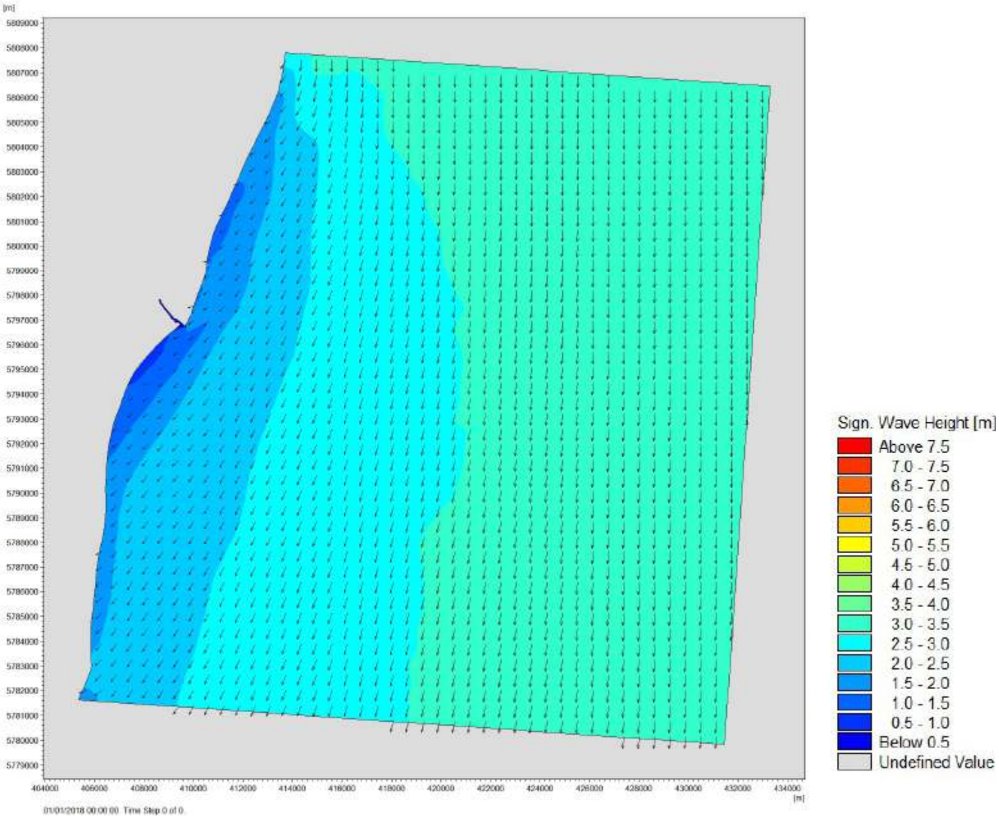

Figure A1: Operational Wave, Test case 1: Wave from 0°N

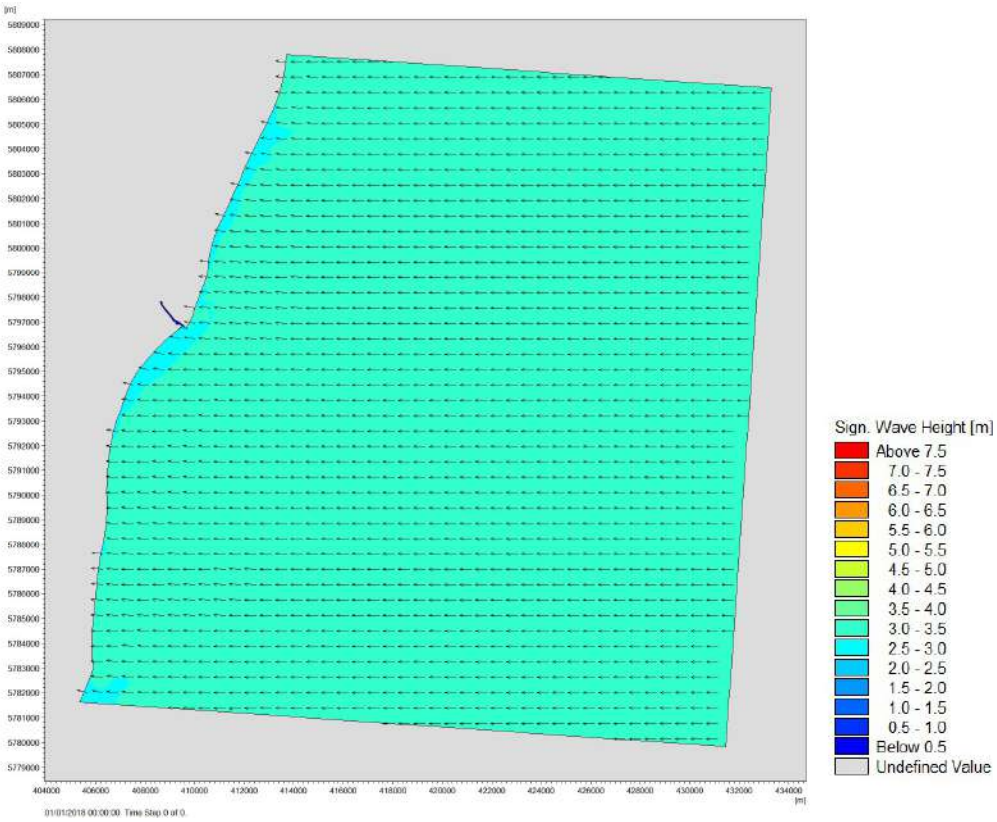

Figure A2: Operational Wave, Test case 2: Wave from 90°N

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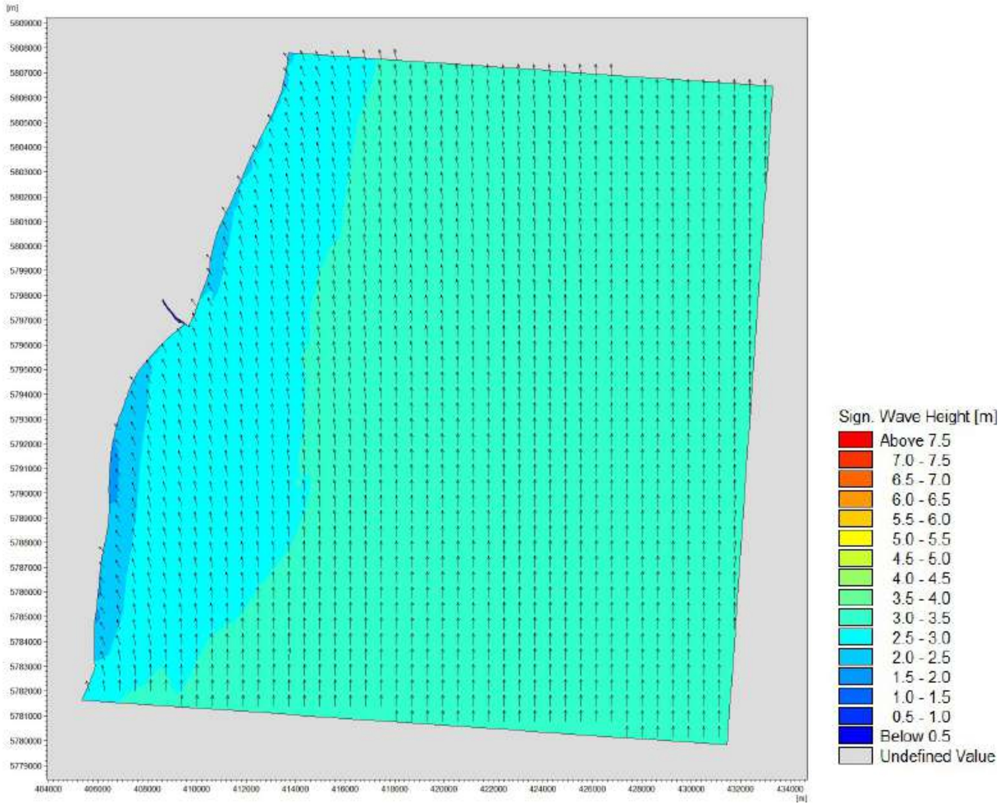


Figure A3: Operational Wave, Test case 3: Wave from 180°N

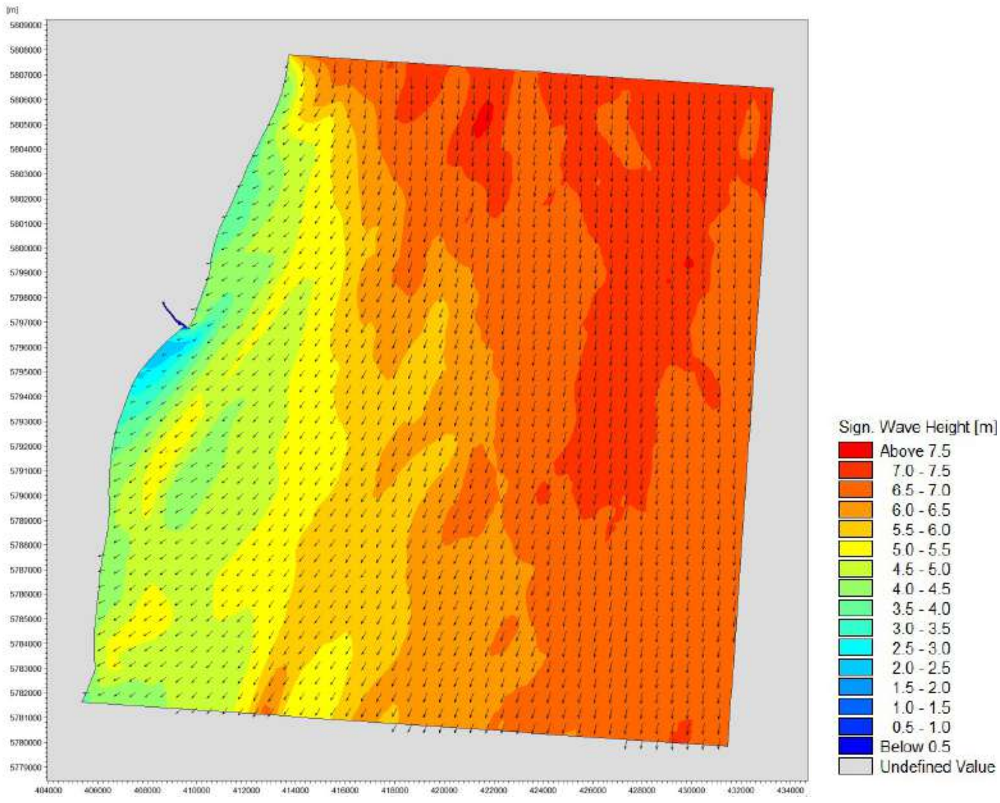


Figure A4: Extreme Wave, Test case 1: Wave from 0°N

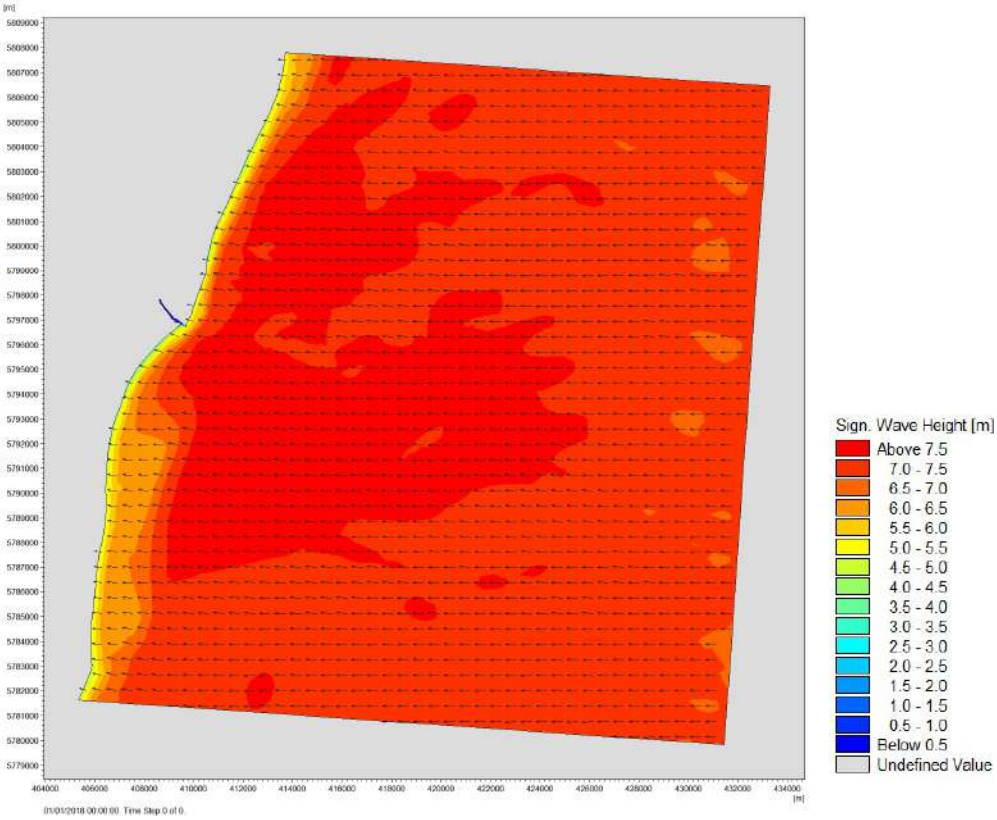
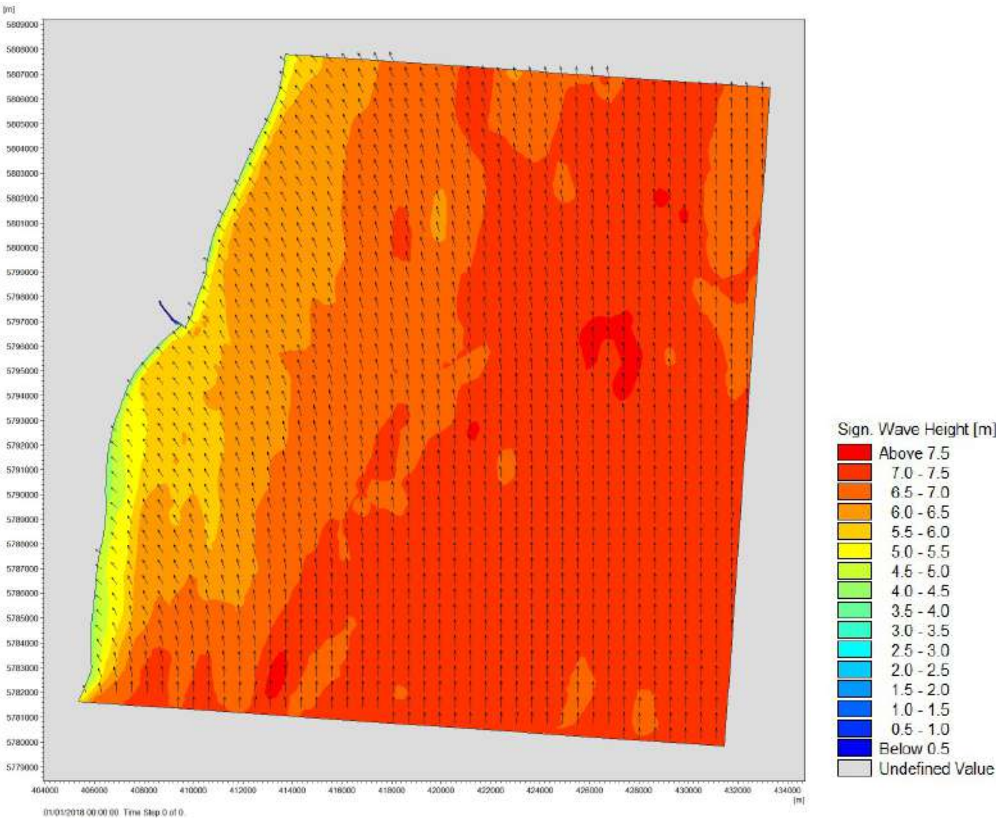


Figure A5: Extreme Wave, Test case 2: Wave from 90°N



Appendix B

Wave Transformation Model Results

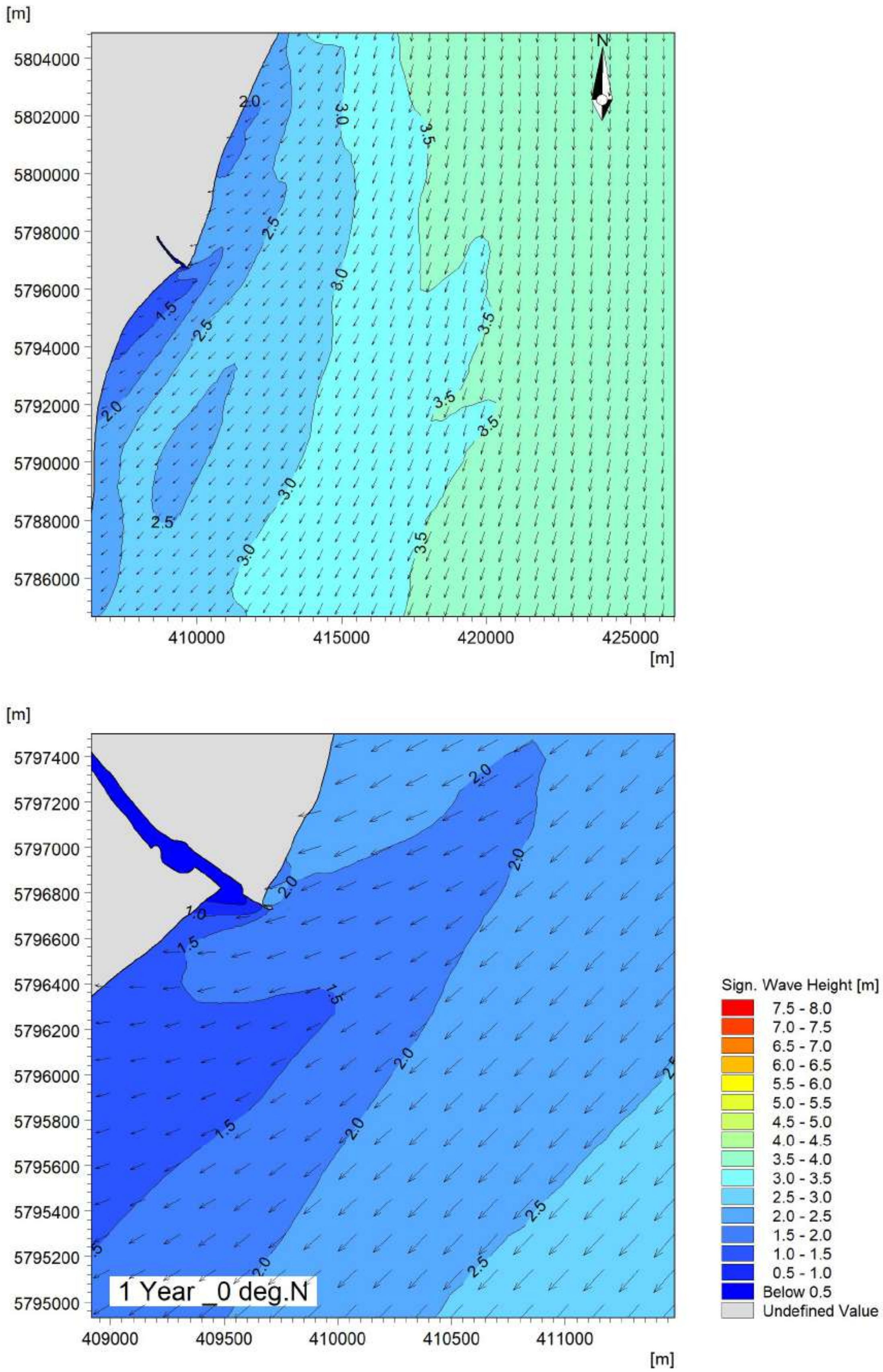


Figure B1: 1 Year Return Period - Wave transformation for 0°N

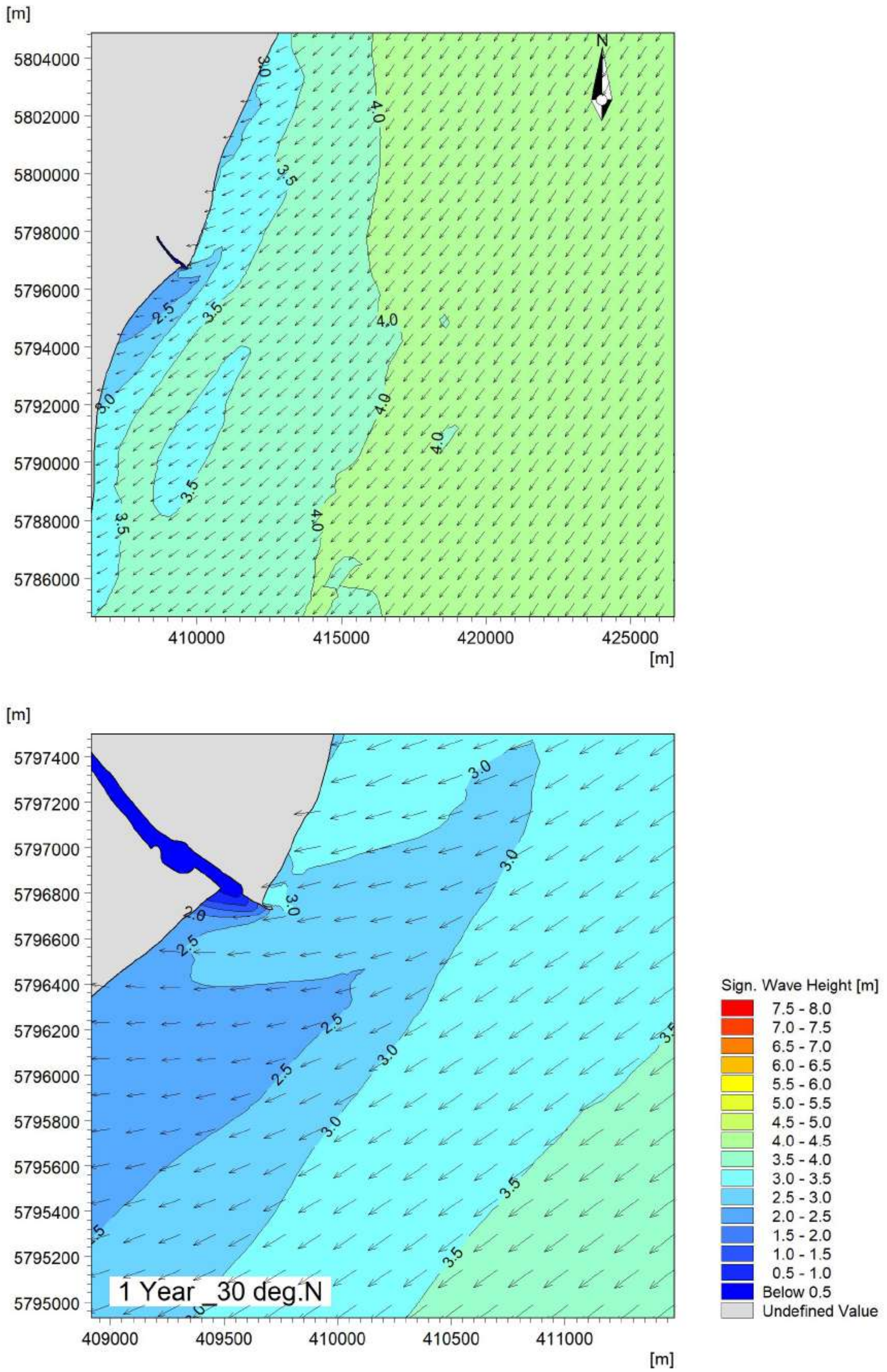


Figure B2: 1 Year Return Period - Wave transformation for 30°N

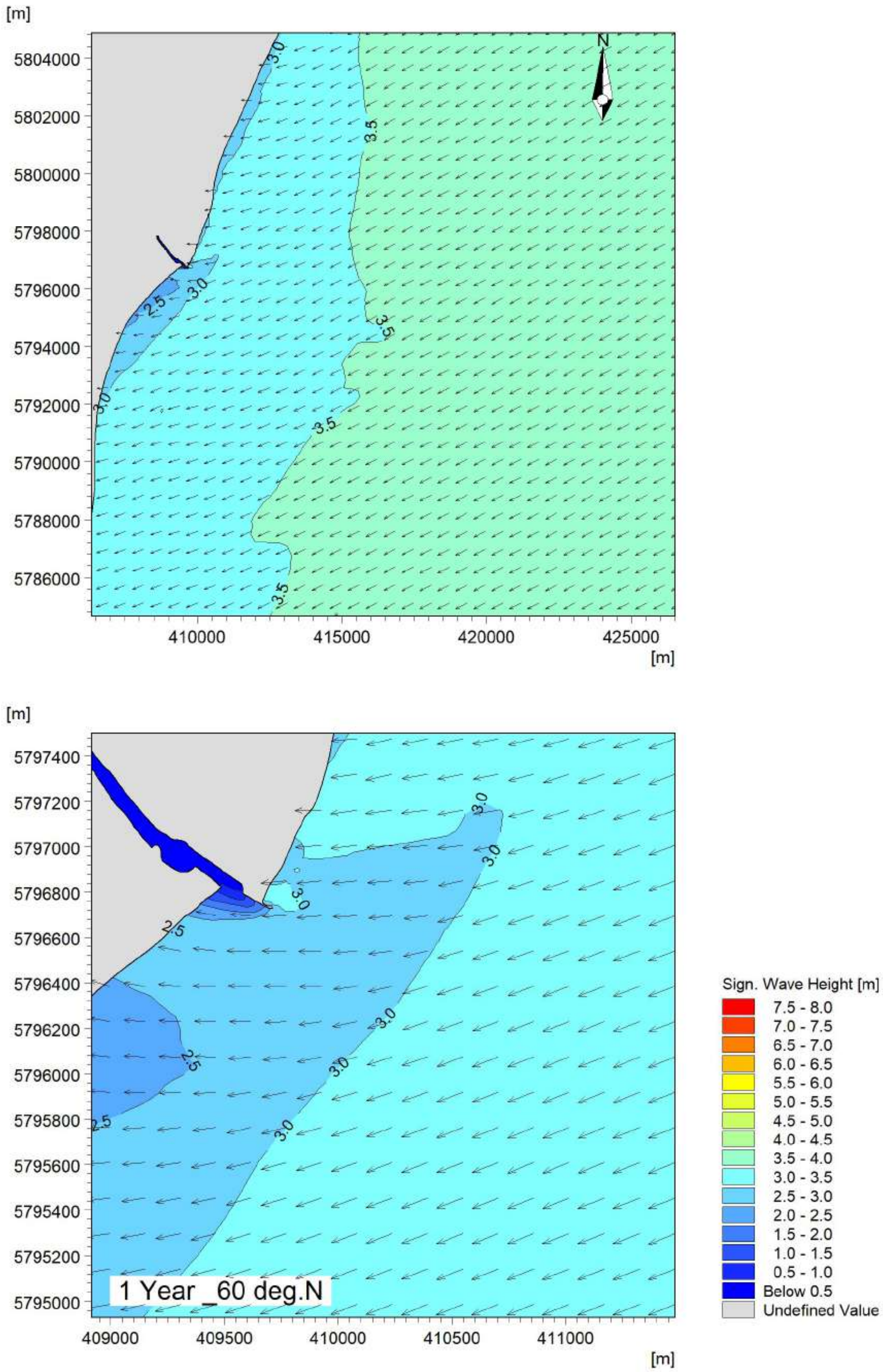


Figure B3: 1 Year Return Period - Wave transformation for 60°N

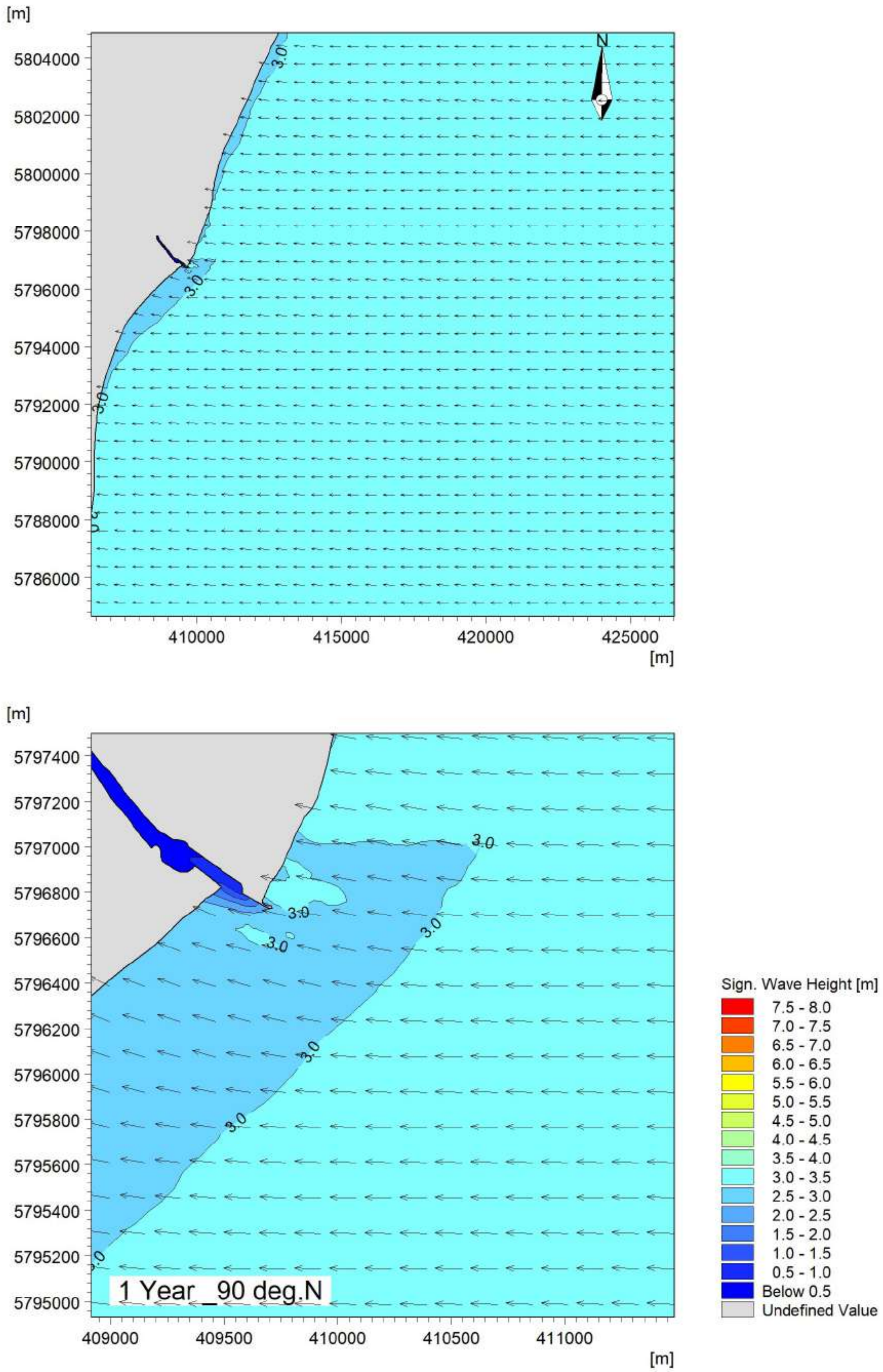


Figure B4: 1 Year Return Period - Wave transformation for 90°N

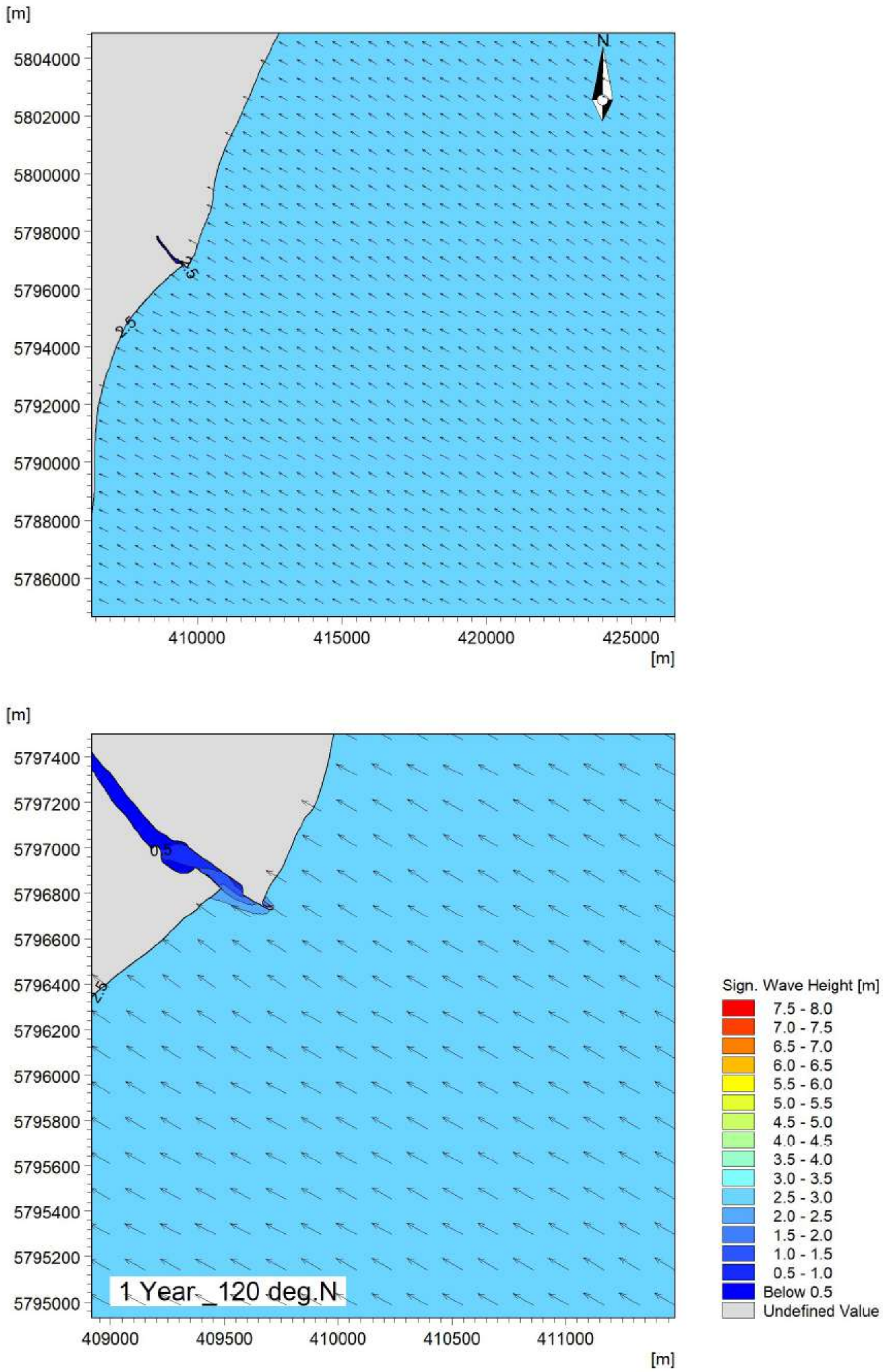
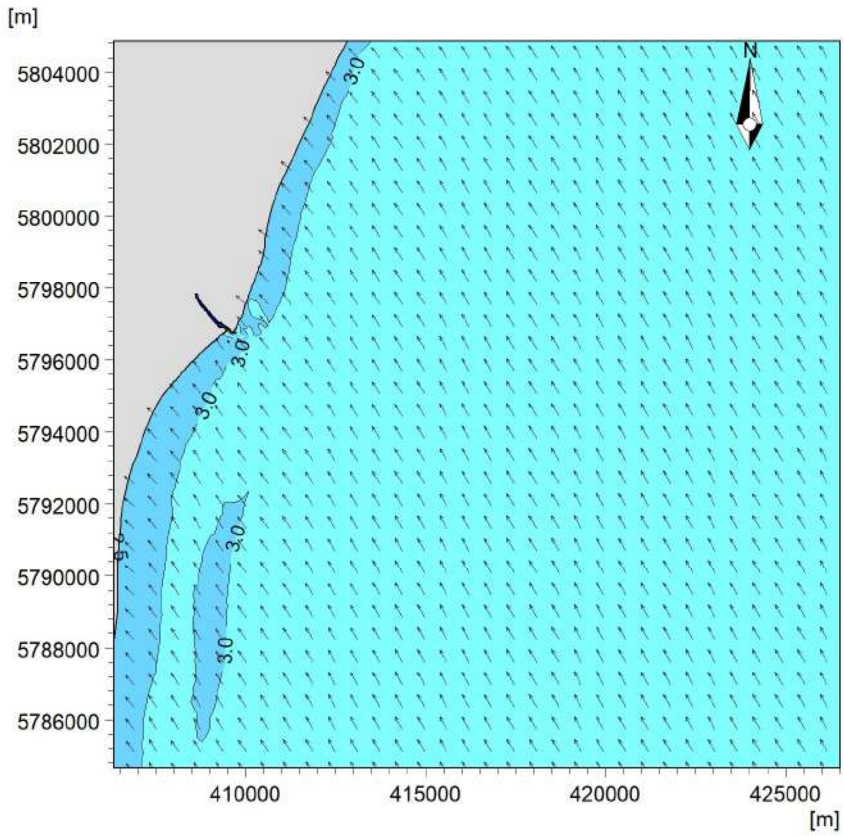


Figure B5: 1 Year Return Period - Wave transformation for 120°N



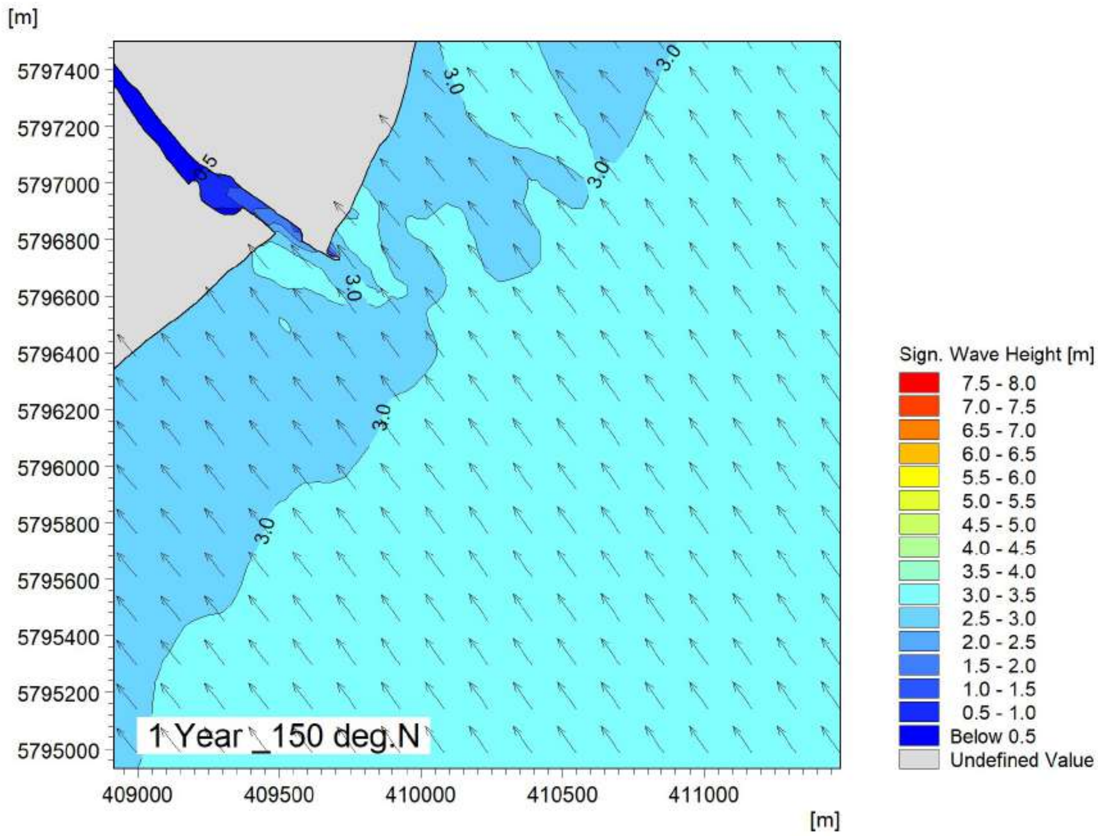


Figure B6: 1 Year Return Period - Wave transformation for 150°N

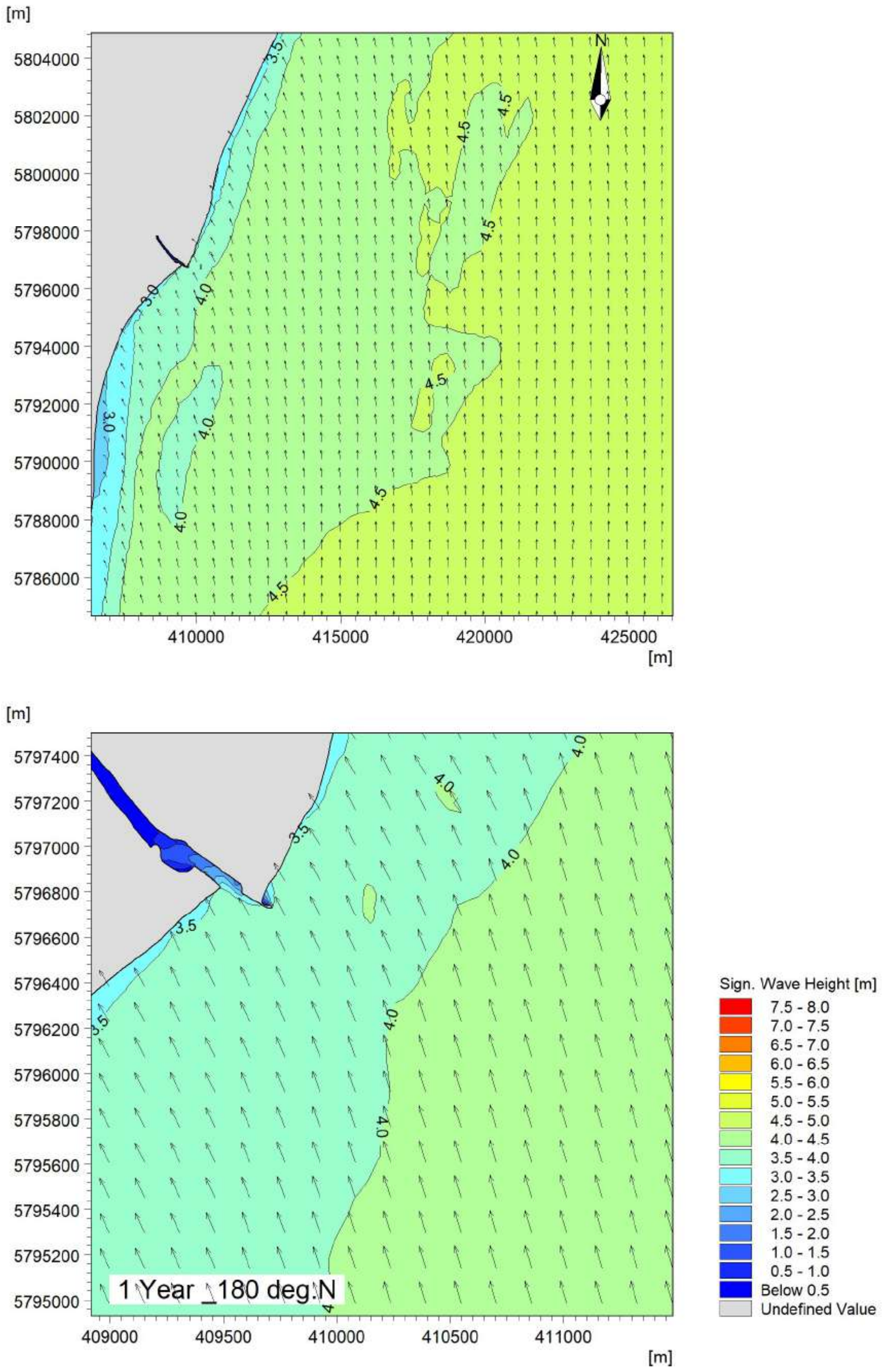


Figure B7: 1 Year Return Period - Wave transformation for 180°N

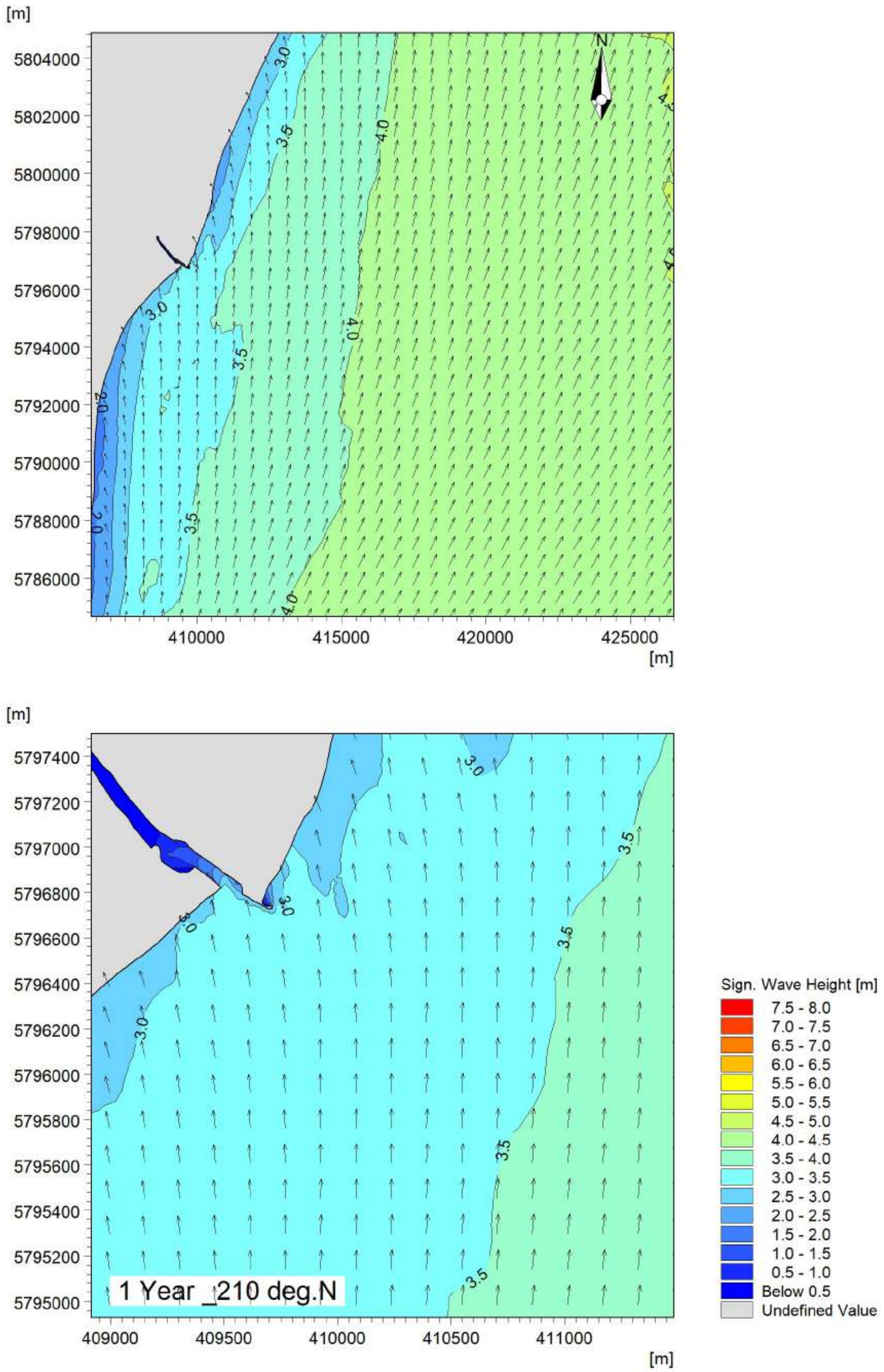


Figure B8: 1 Year Return Period - Wave transformation for 210°N

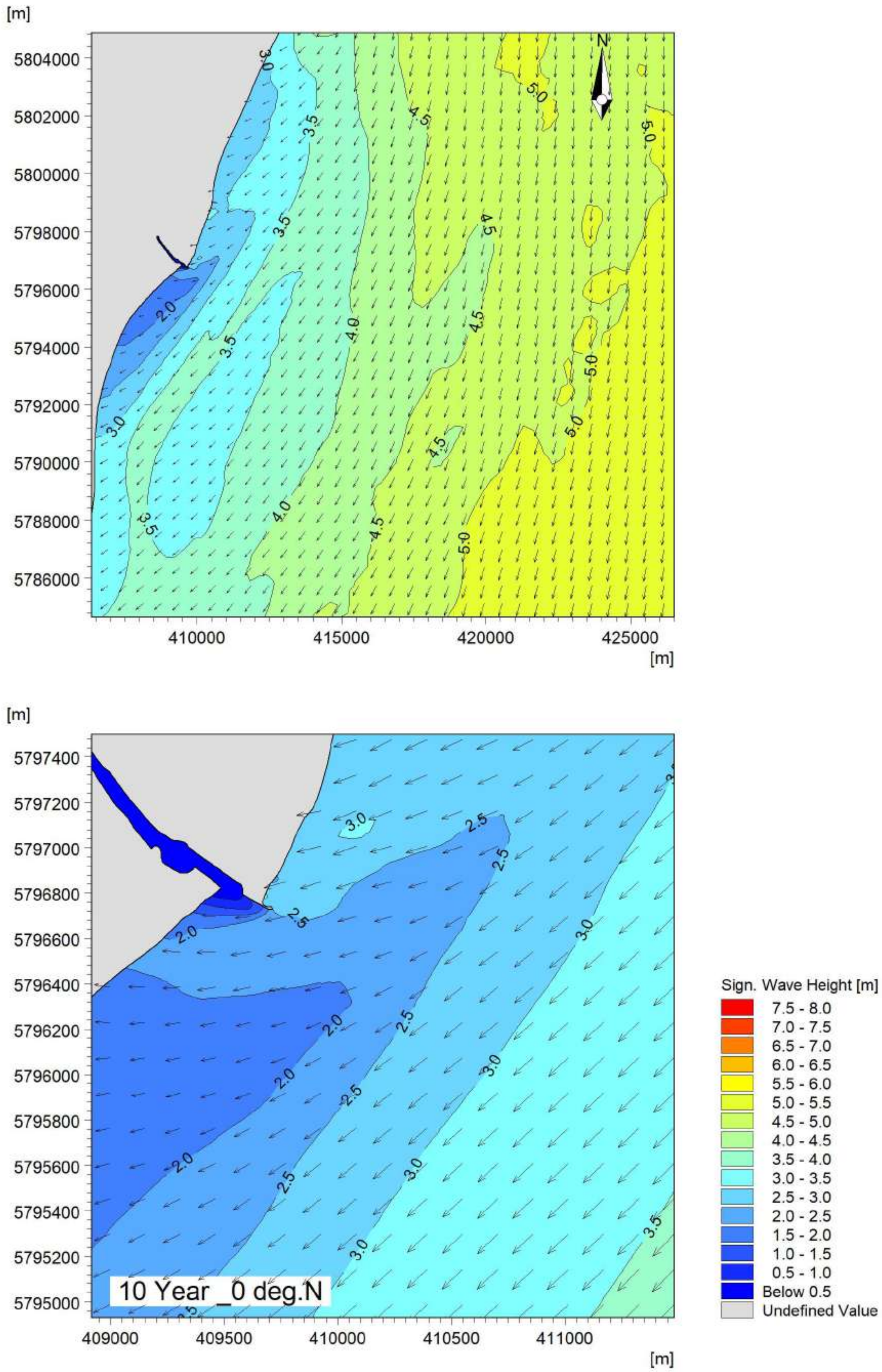


Figure B9: 10 Year Return Period - Wave transformation for 0°N

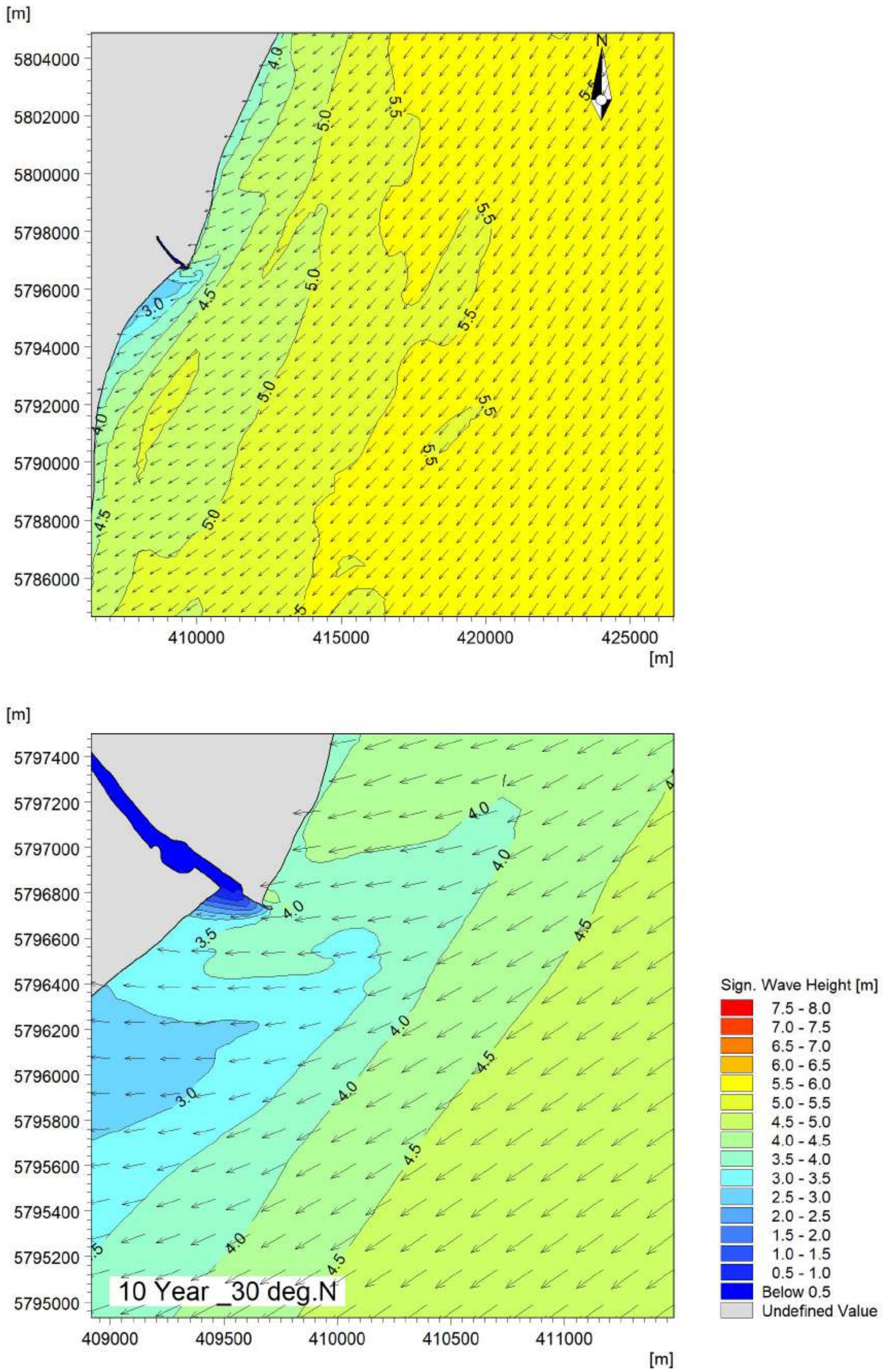


Figure B10: 10 Year Return Period - Wave transformation for 30°N

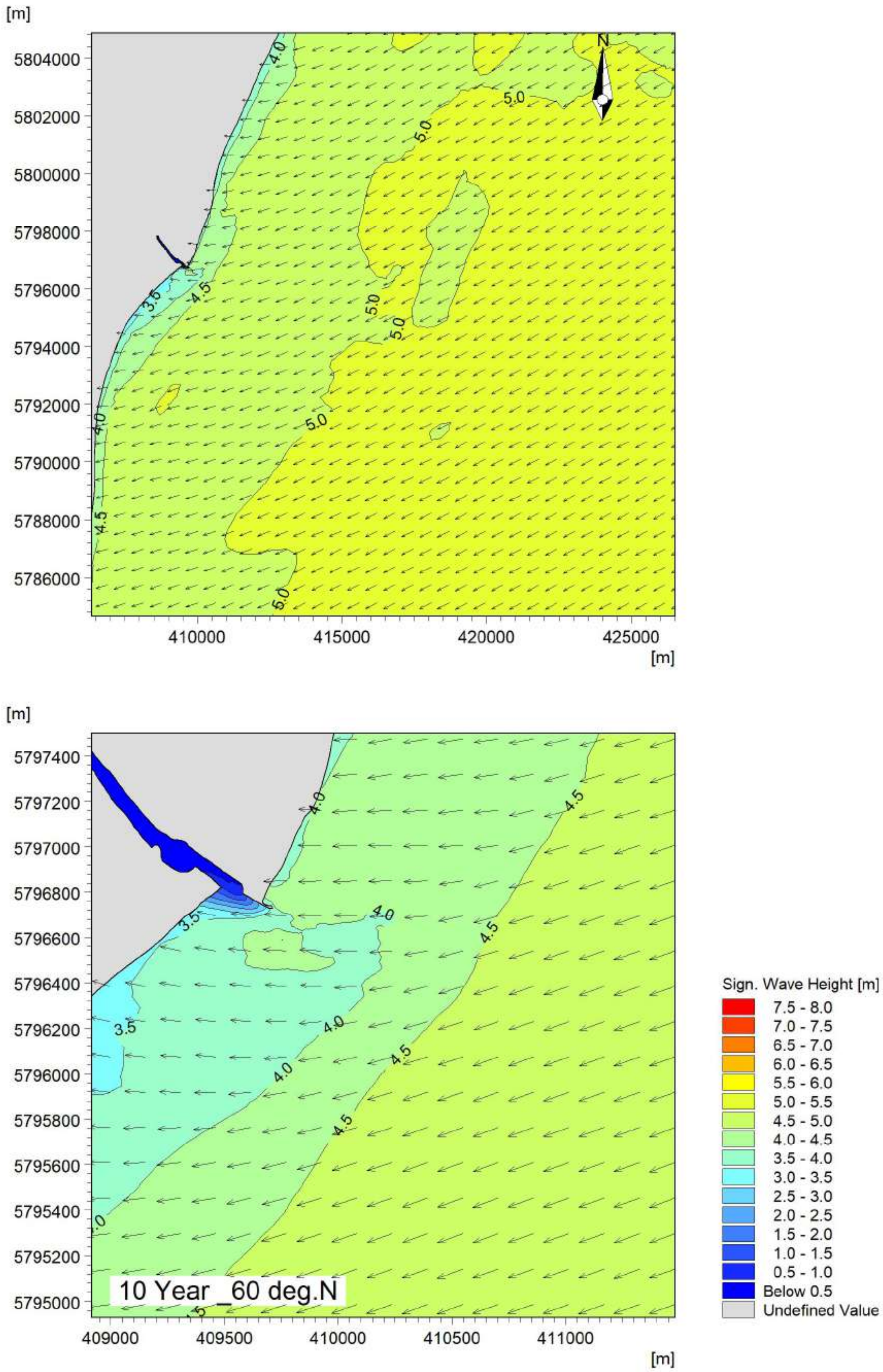


Figure B11: 10 Year Return Period - Wave transformation for 60°N

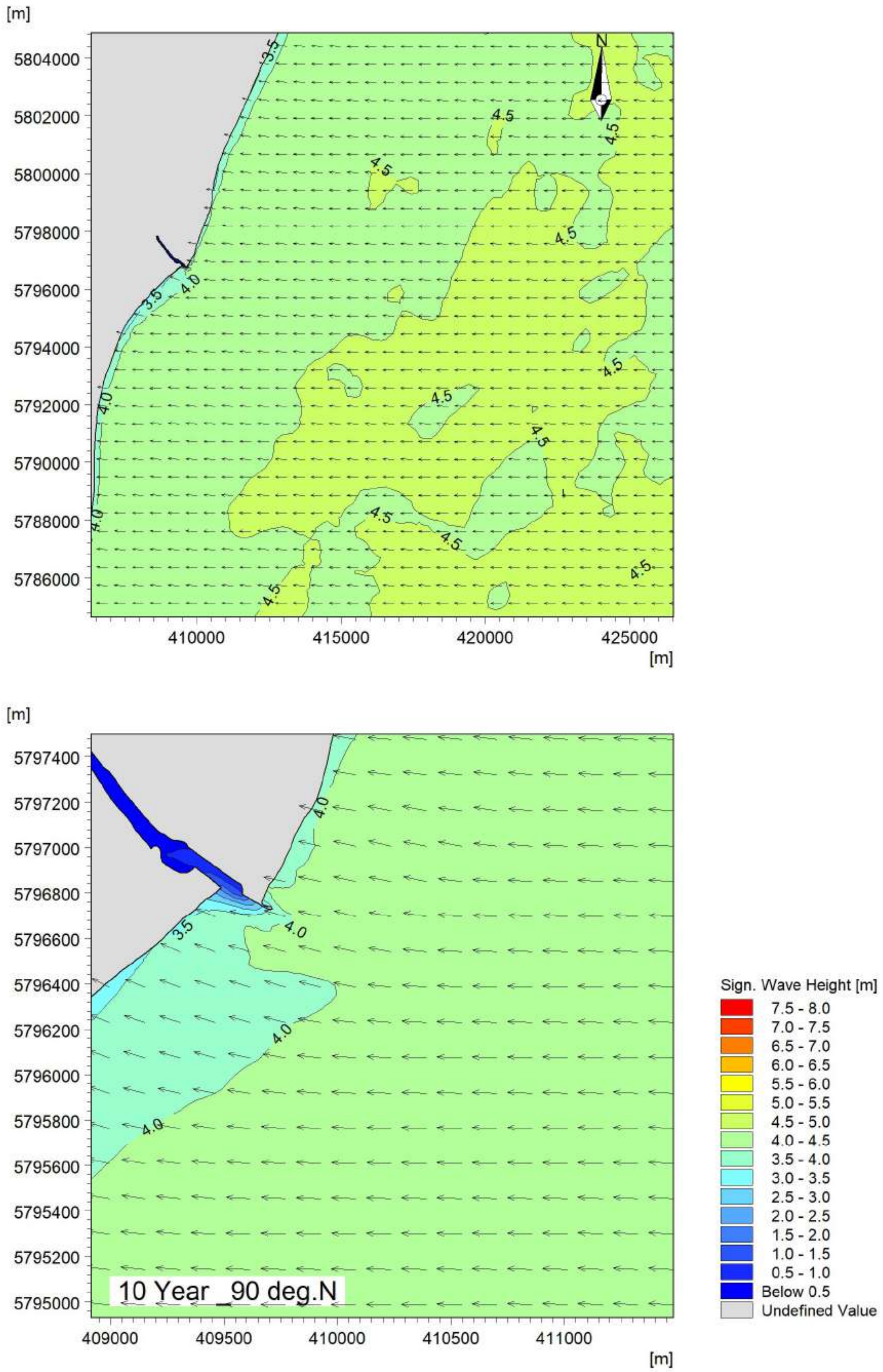


Figure B12: 10 Year Return Period - Wave transformation for 90°N

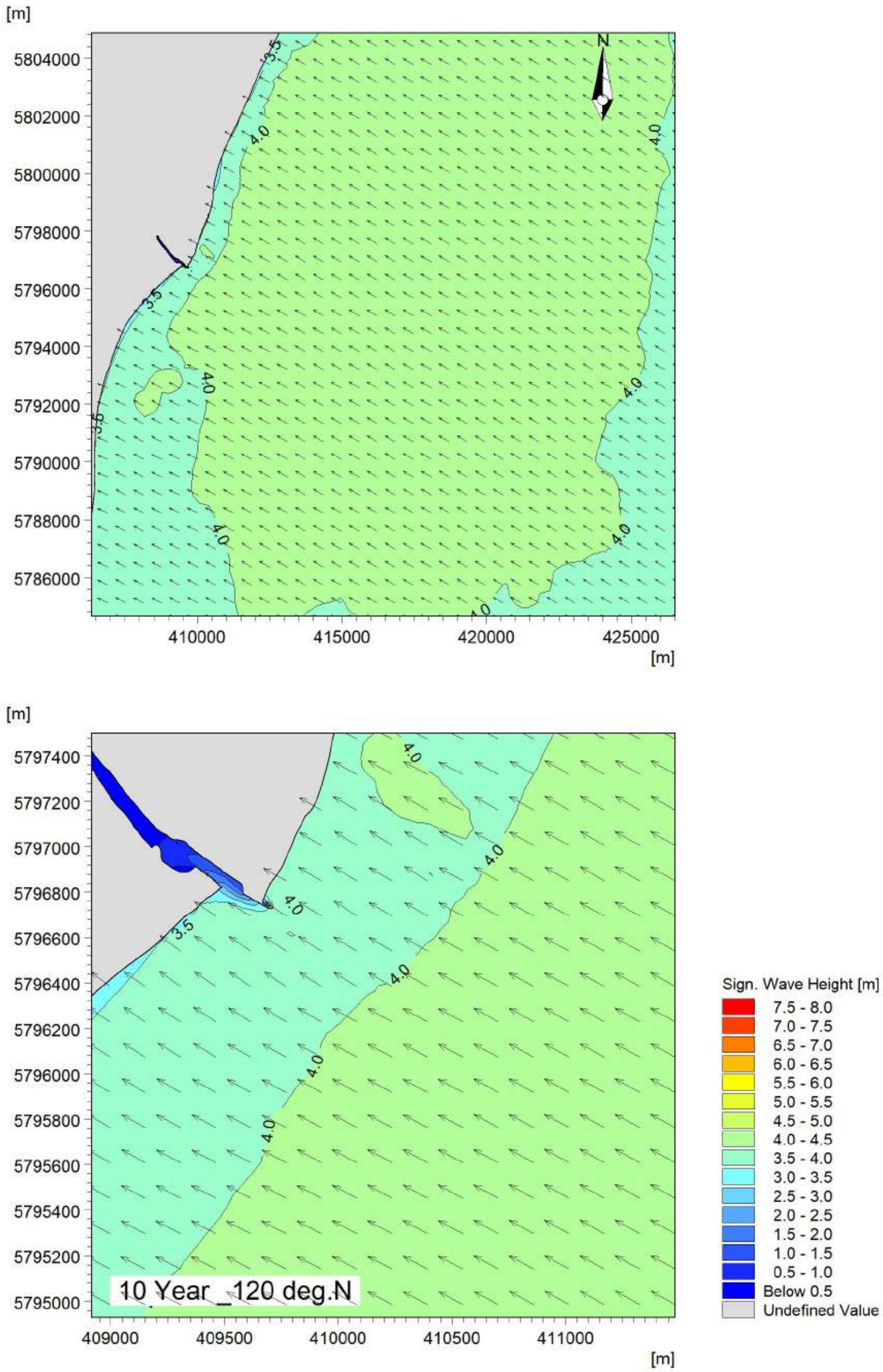


Figure B13: 10 Year Return Period - Wave transformation for 120°N

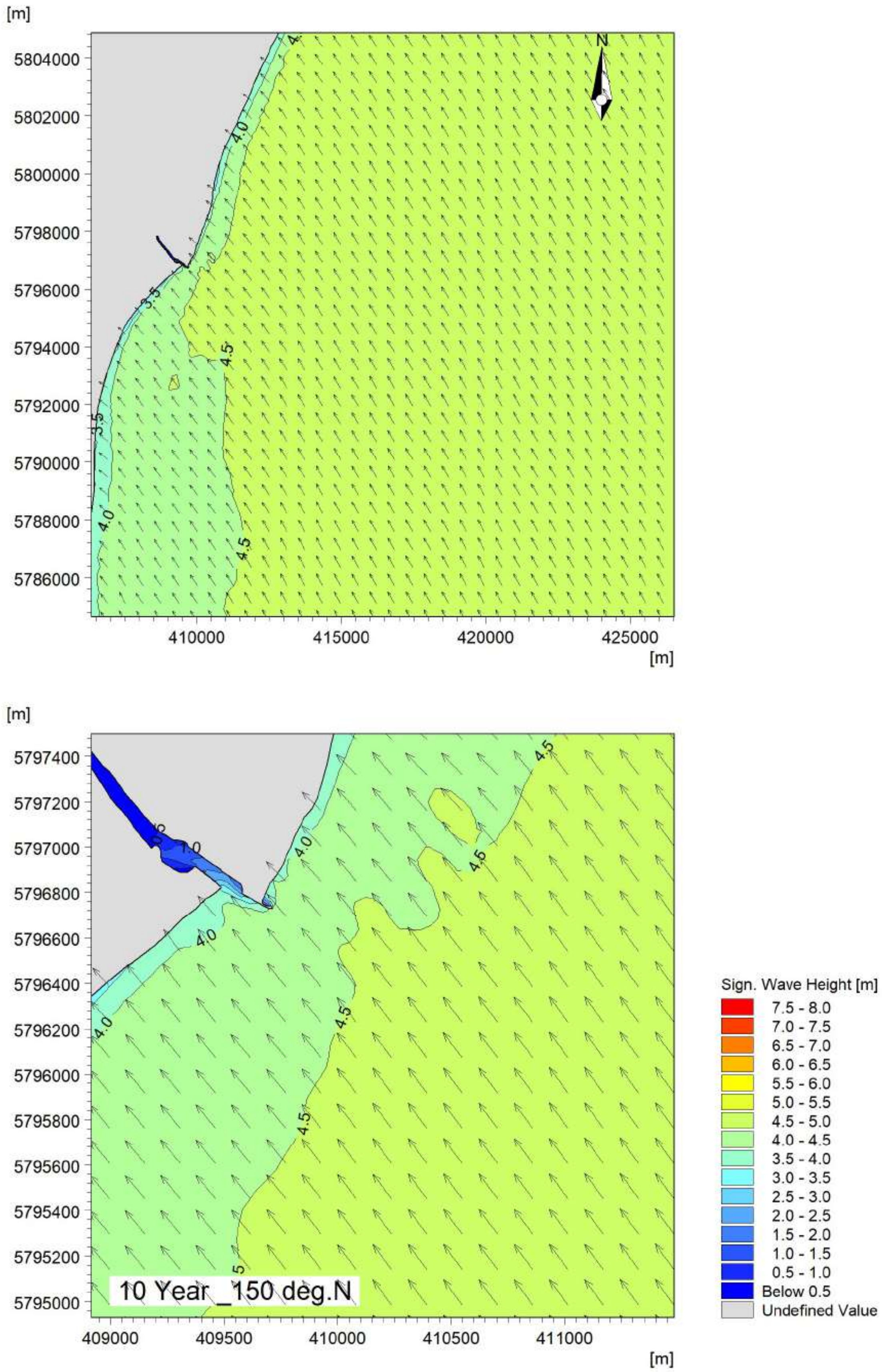


Figure B14: 10 Year Return Period - Wave transformation for 150°N

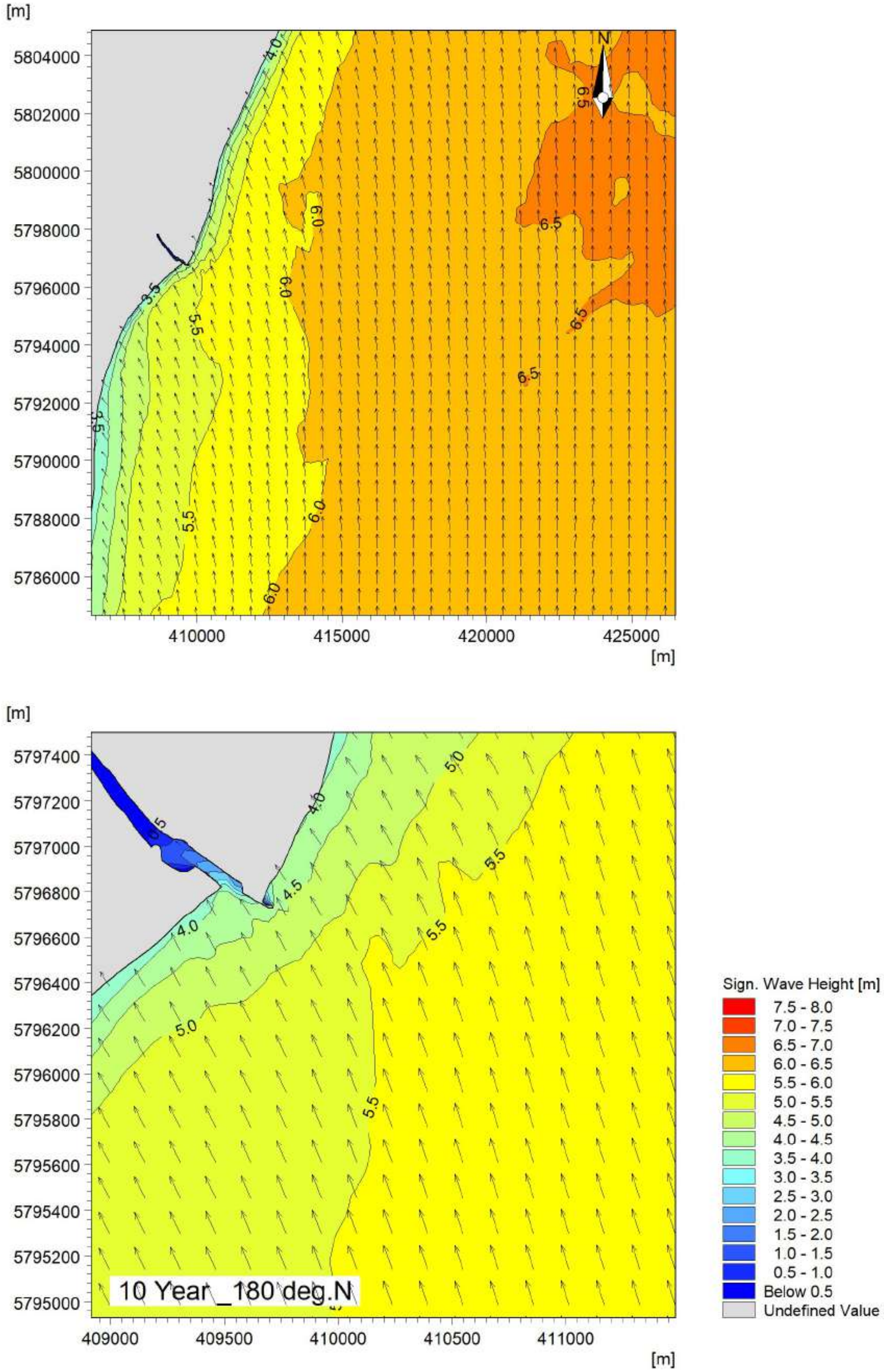


Figure B15: 10 Year Return Period - Wave transformation for 180°N

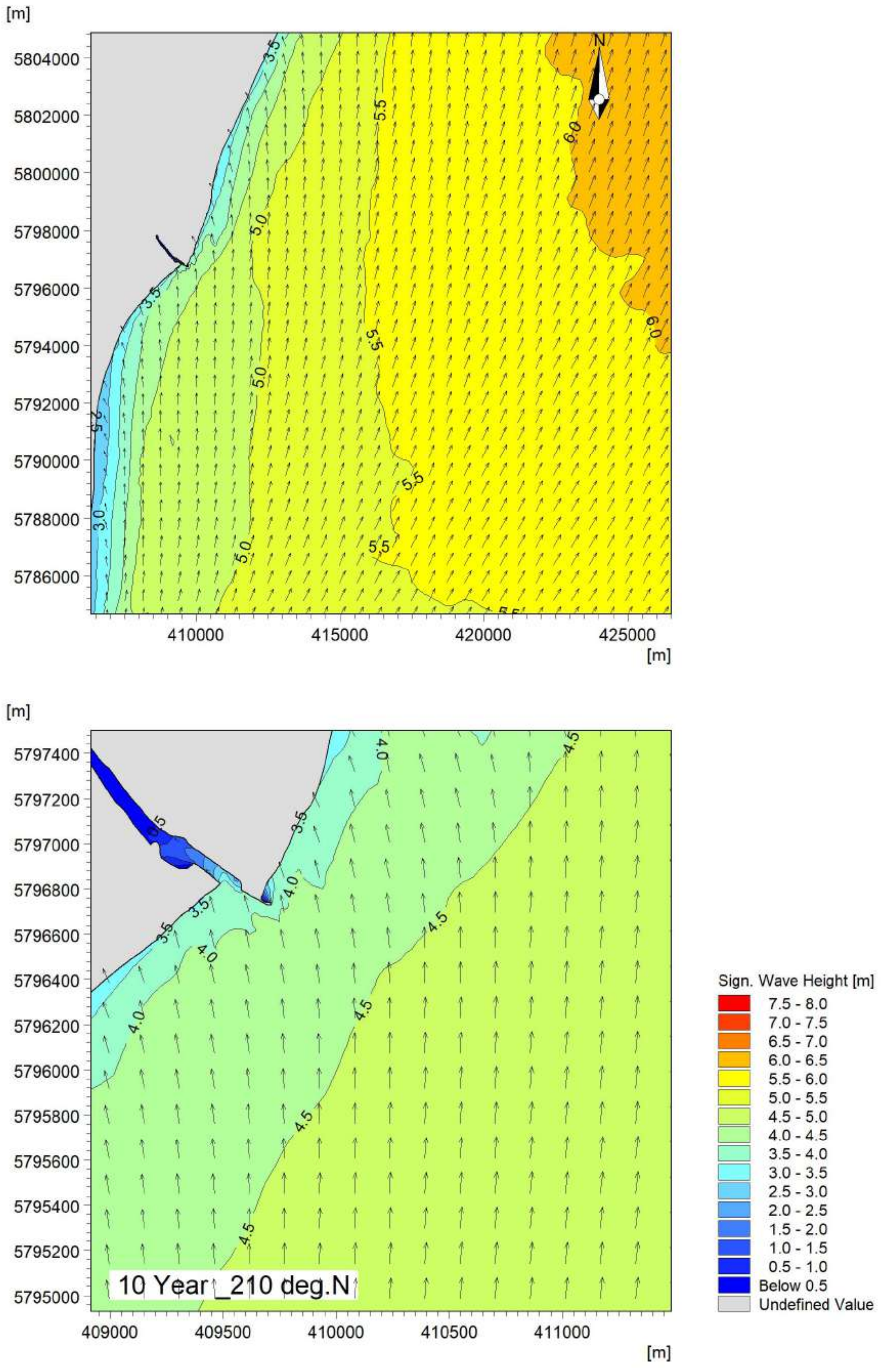


Figure B16: 10 Year Return Period - Wave transformation for 210°N

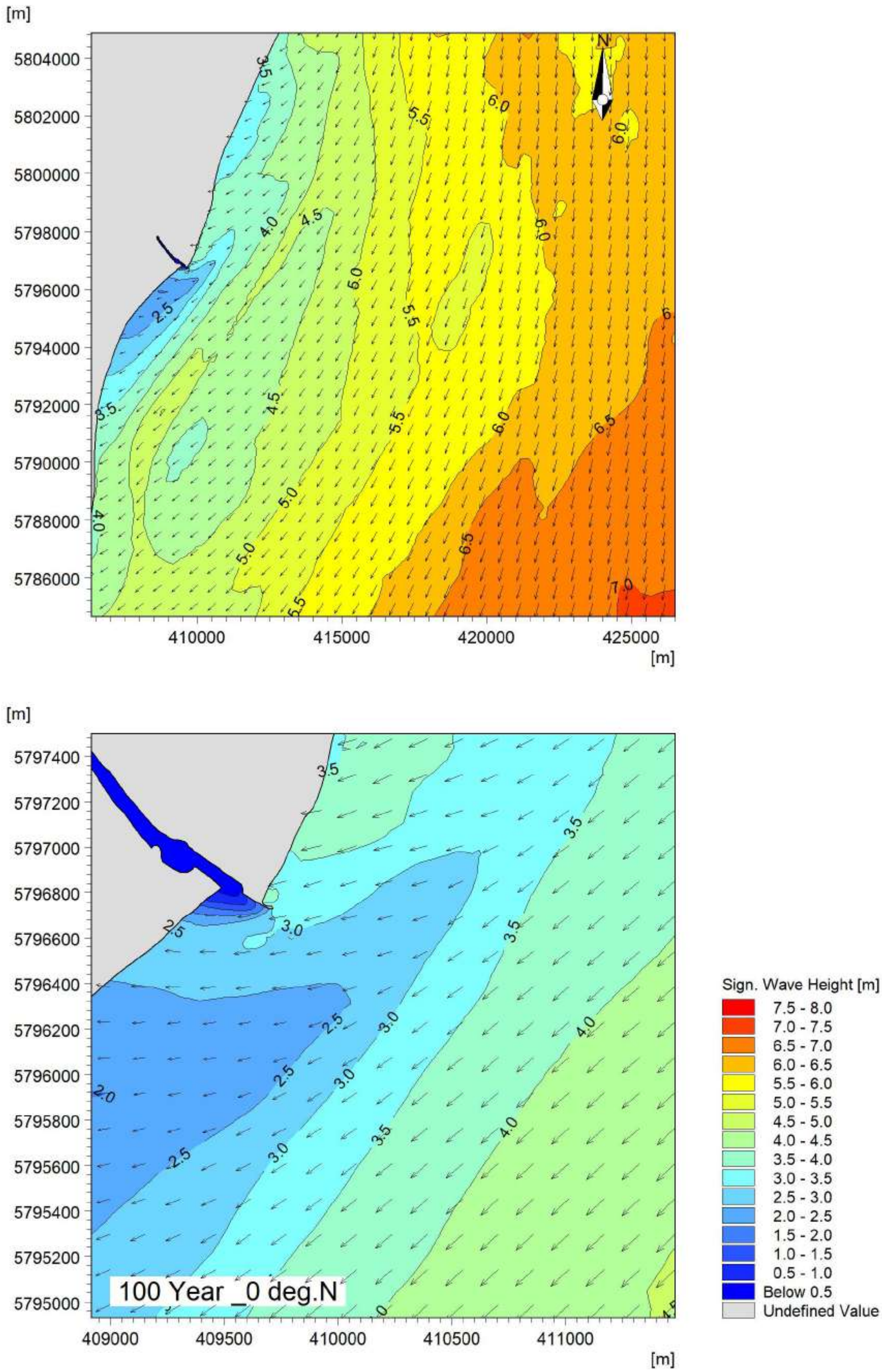


Figure B17: 100 Year Return Period - Wave transformation for 0°N

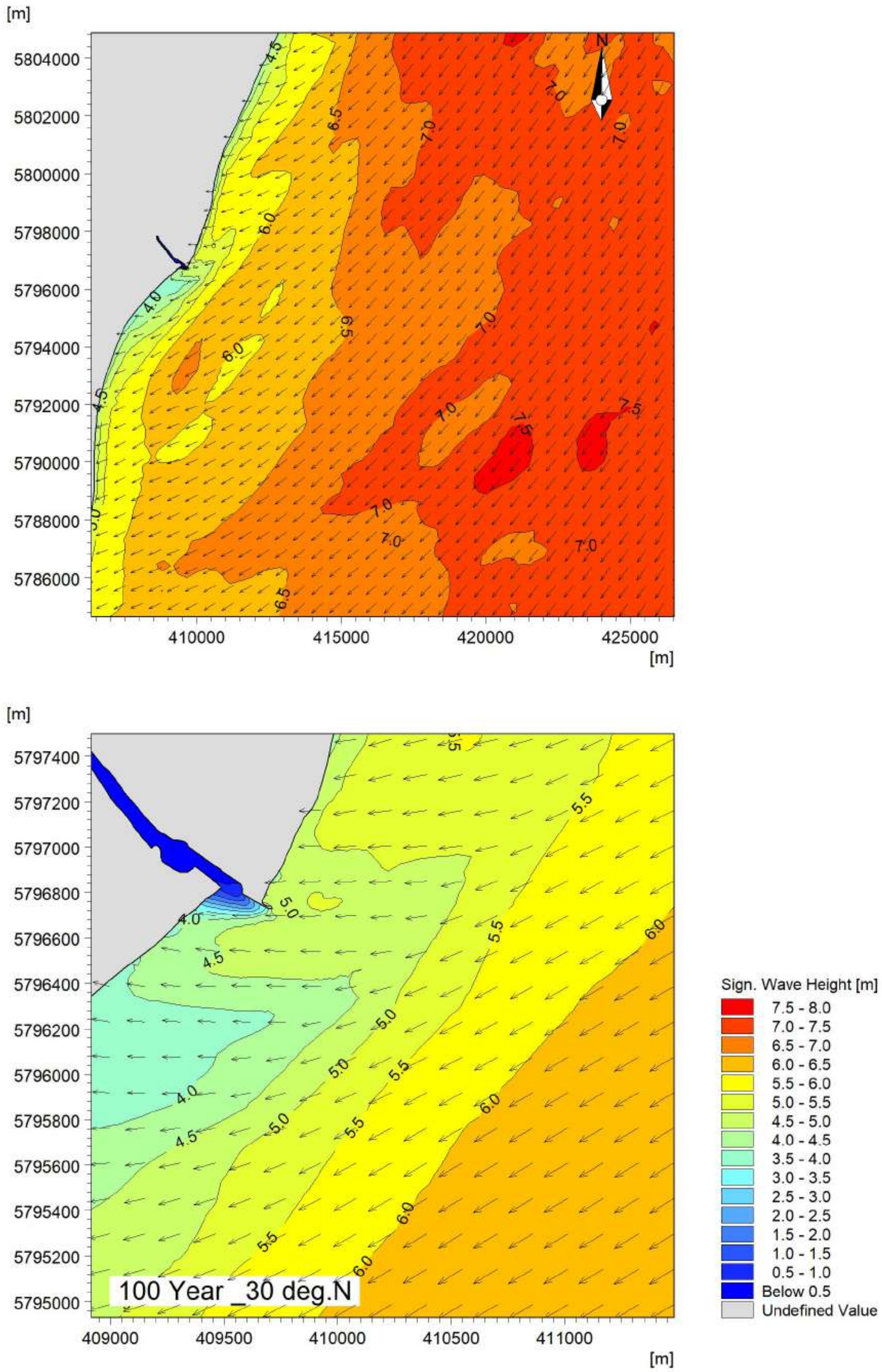


Figure B18: 100 Year Return Period - Wave transformation for 30°N

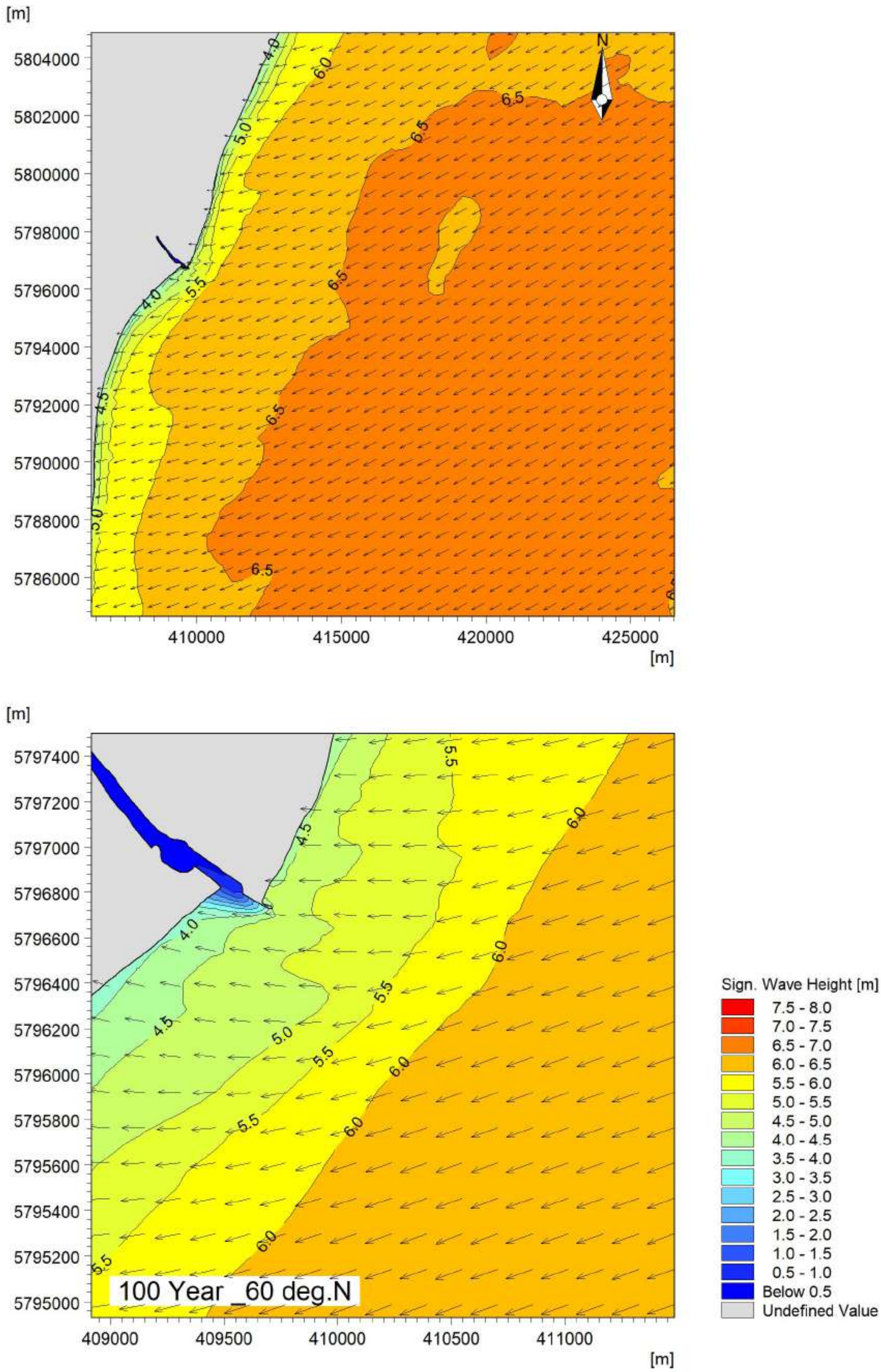


Figure B19: 100 Year Return Period - Wave transformation for 60°N

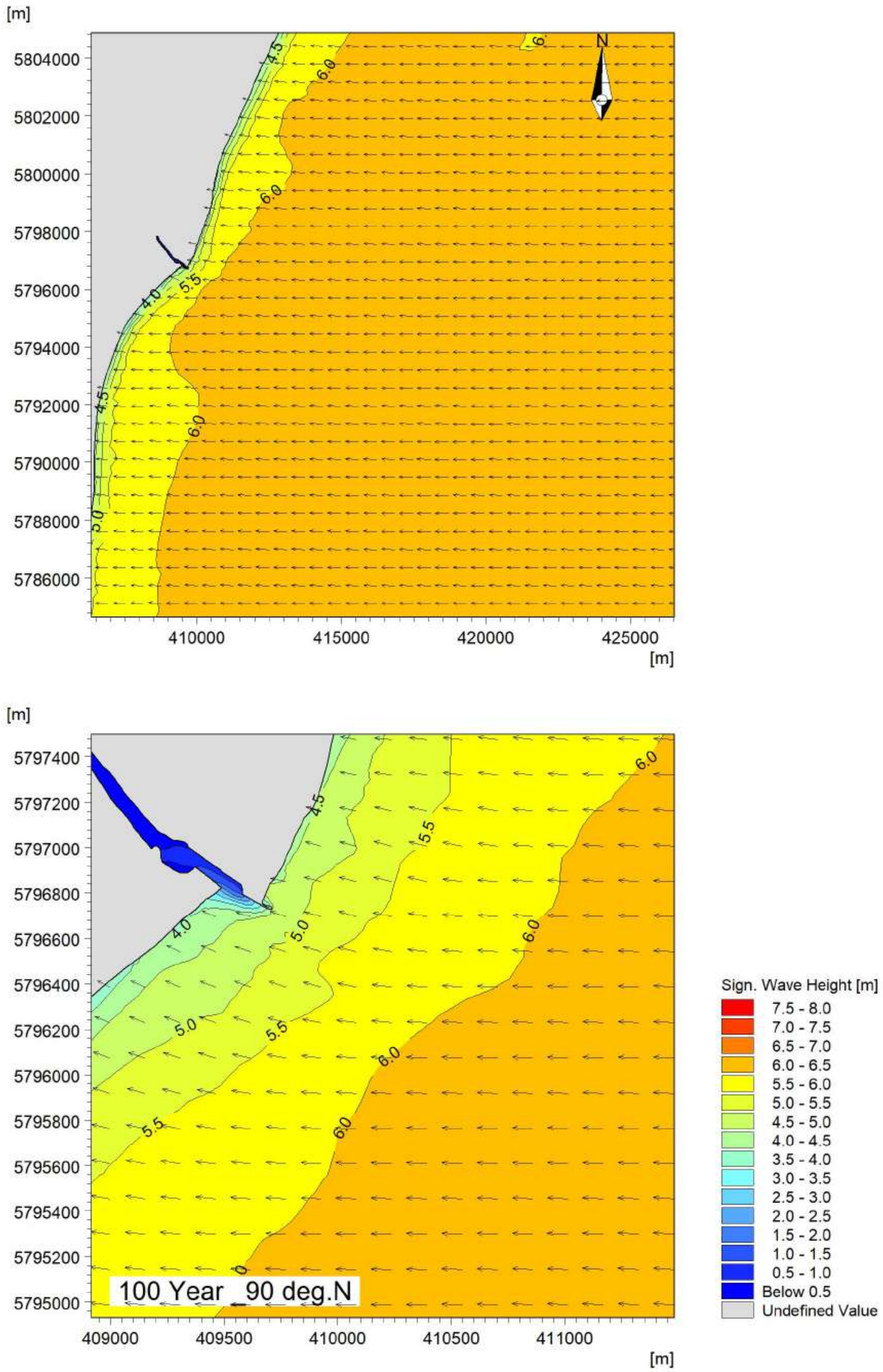


Figure B20: 100 Year Return Period - Wave transformation for 90°N

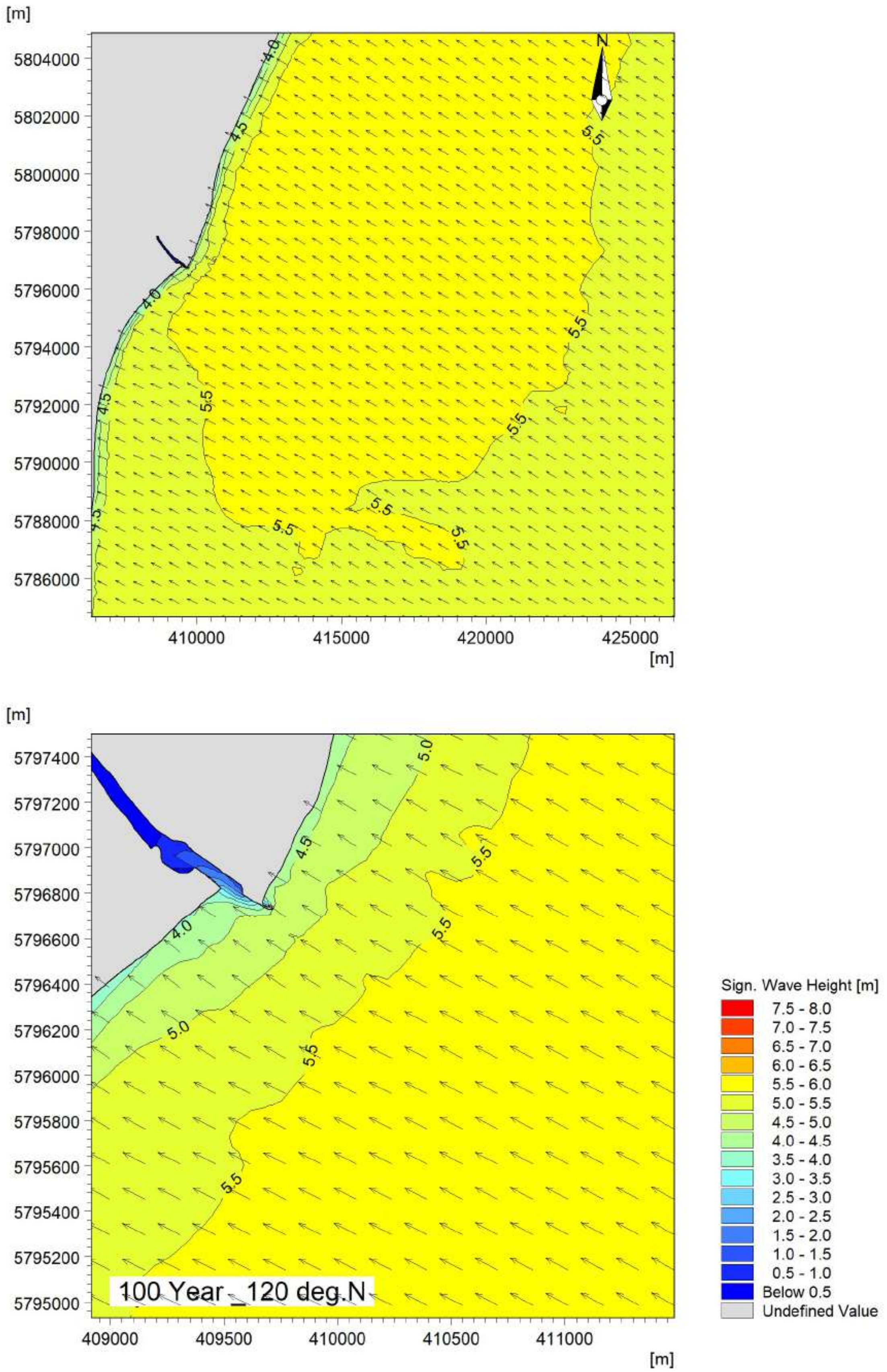


Figure B21: 100 Year Return Period - Wave transformation for 120°N

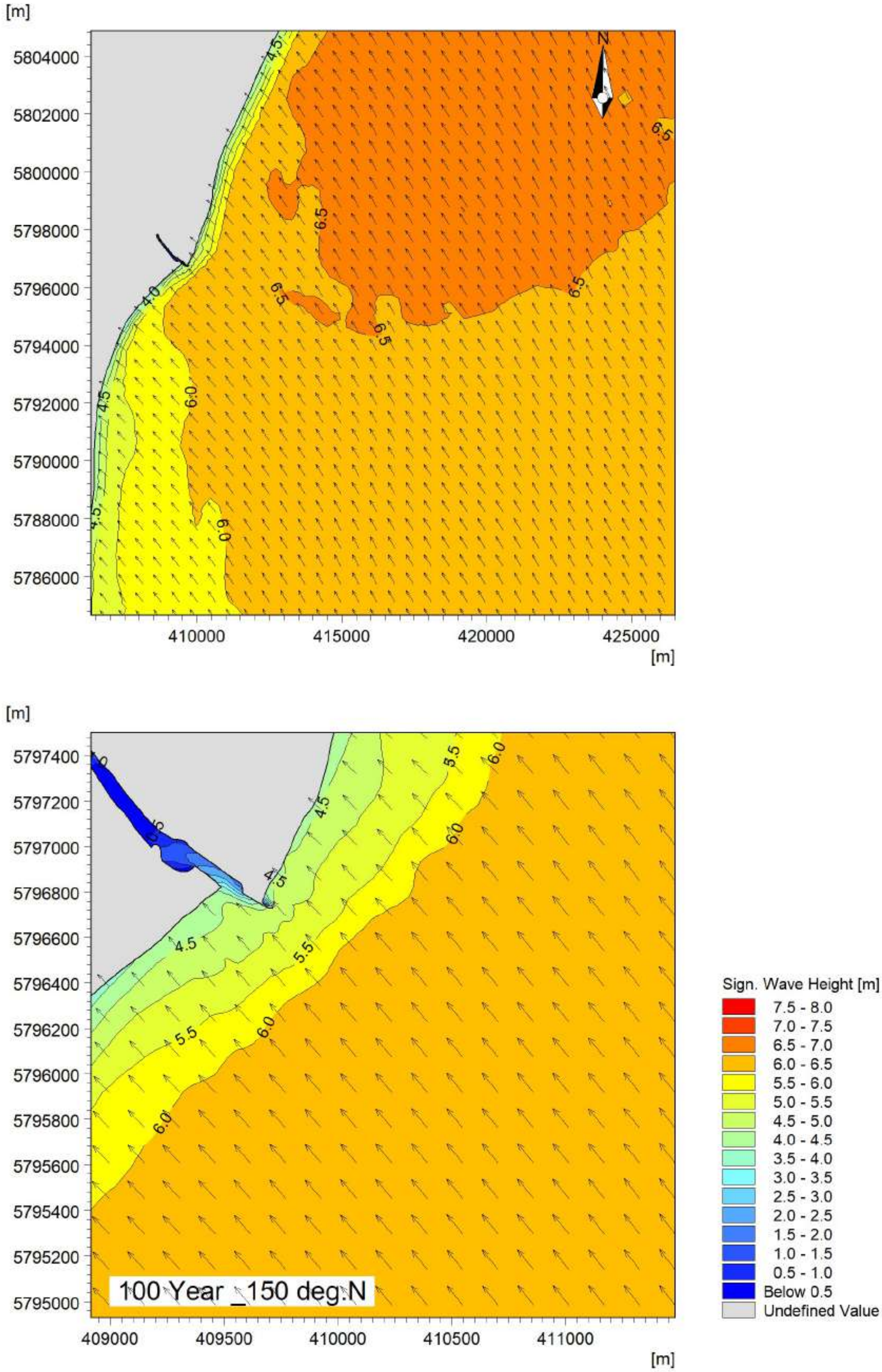


Figure B22: 100 Year Return Period - Wave transformation for 150°N

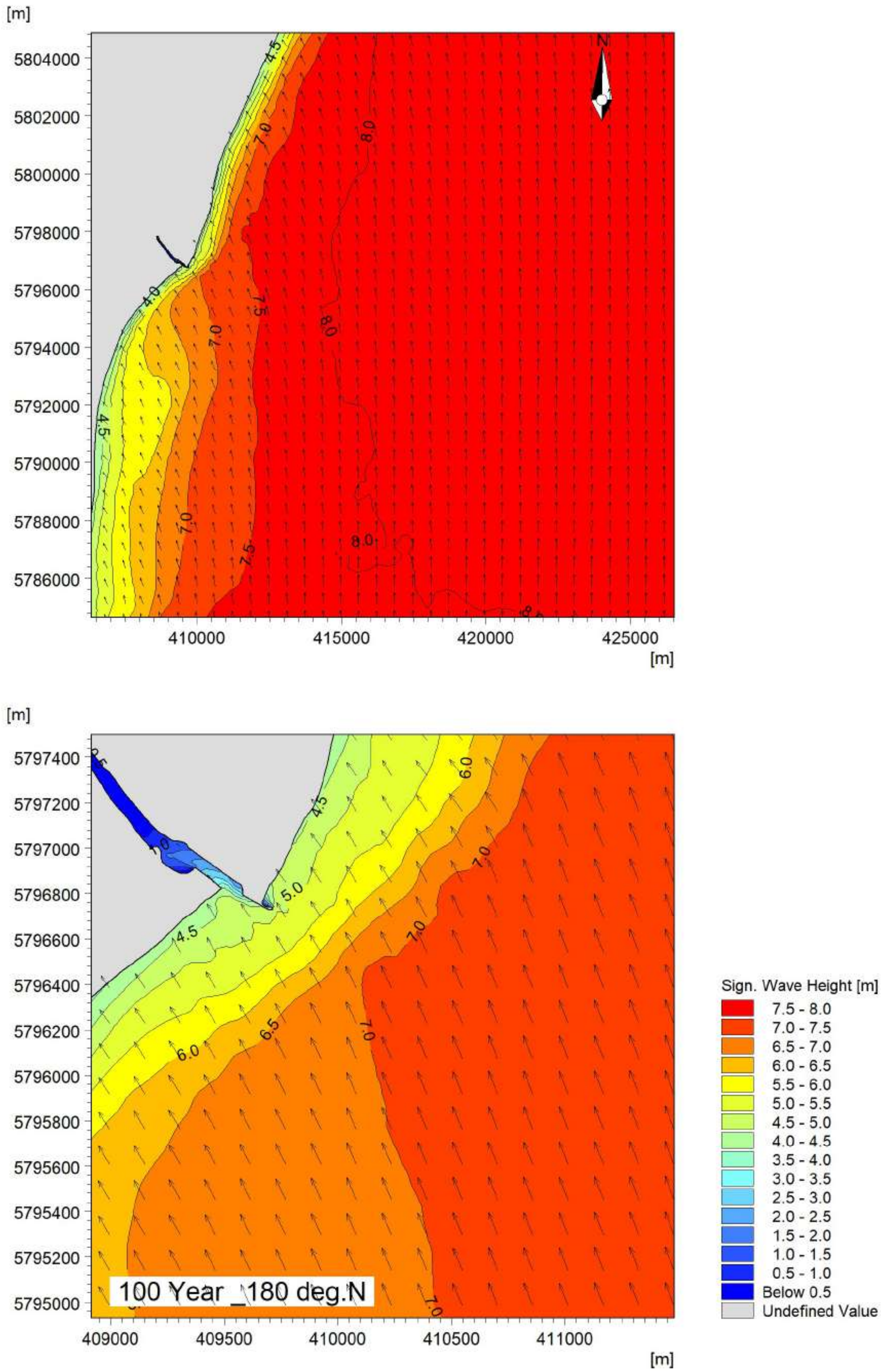


Figure B23: 100 Year Return Period - Wave transformation for 180°N

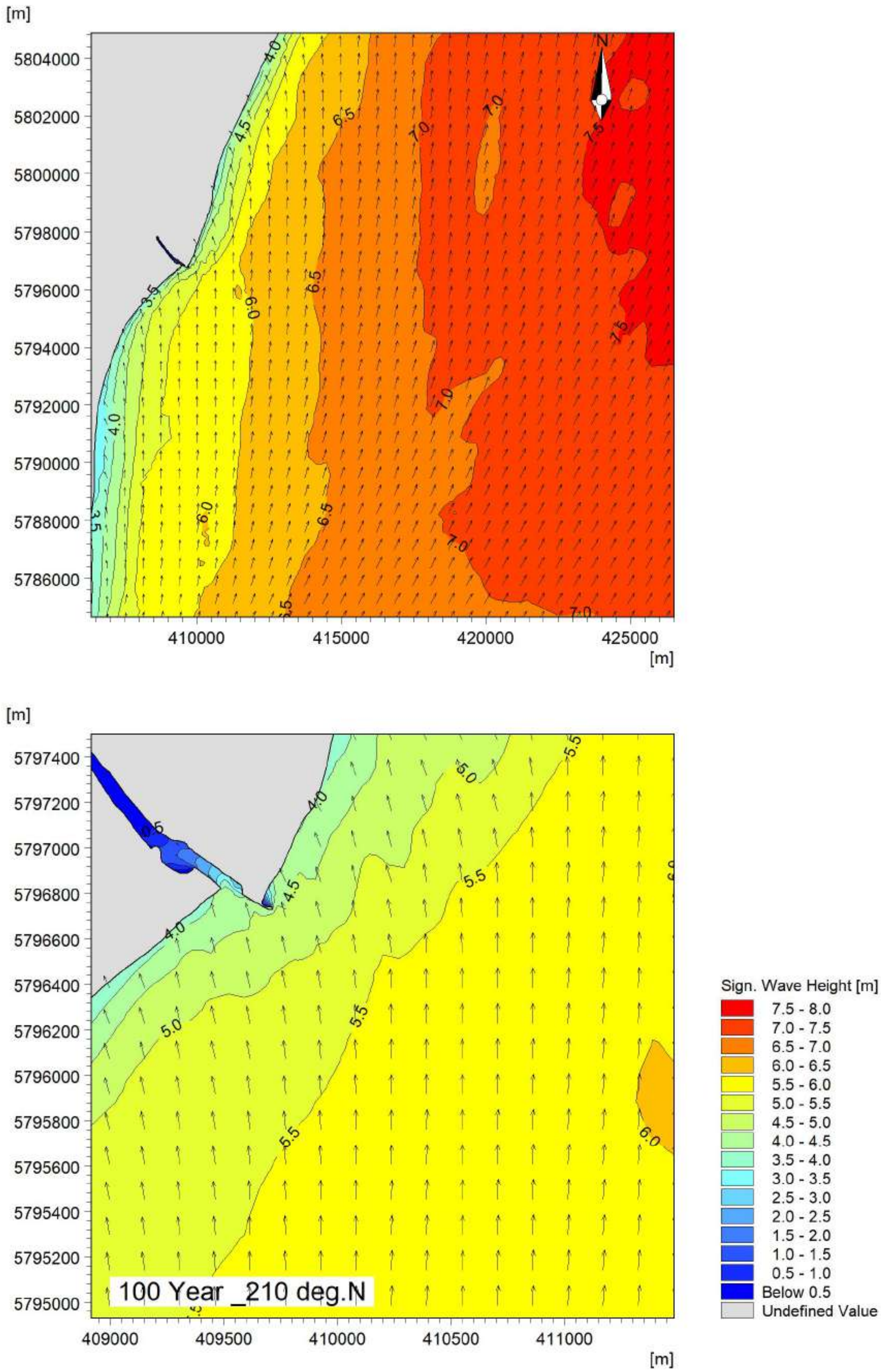


Figure B24: 100 Year Return Period - Wave transformation for 210°N

Appendix C

Wave Penetration Modelling Results – Baseline Conditions

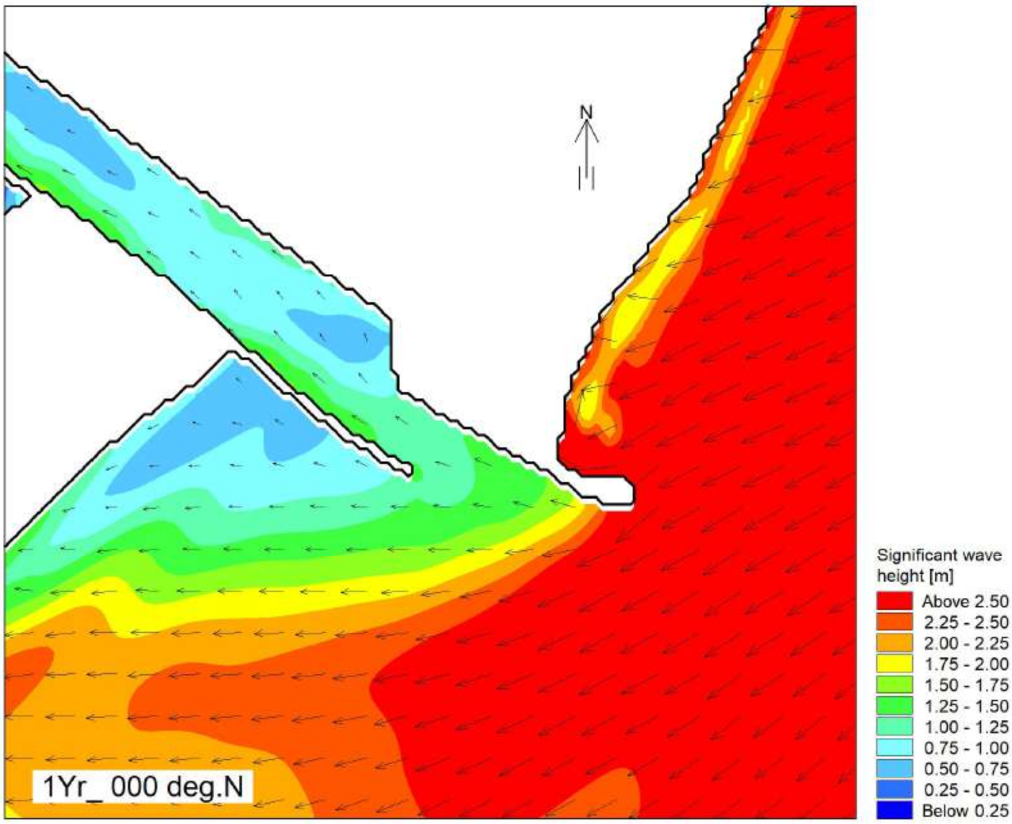


Figure C1: Penetration of 1 year wave (swell) from 0°N

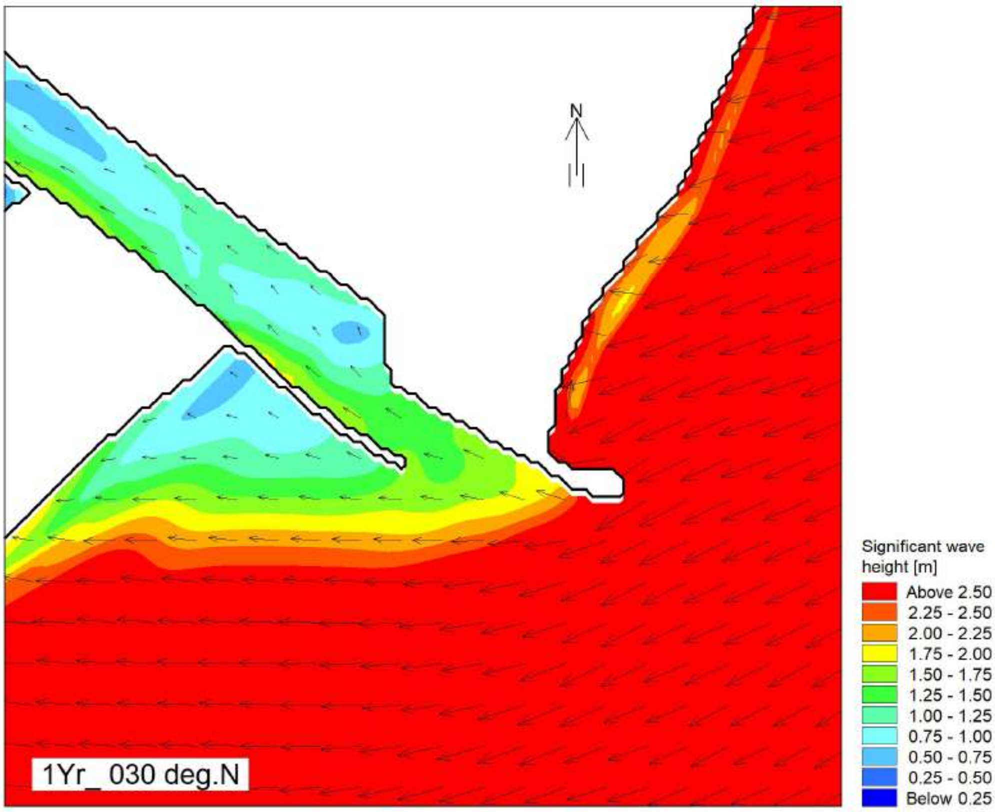


Figure C2: Penetration of 1 year wave (swell) from 30°N

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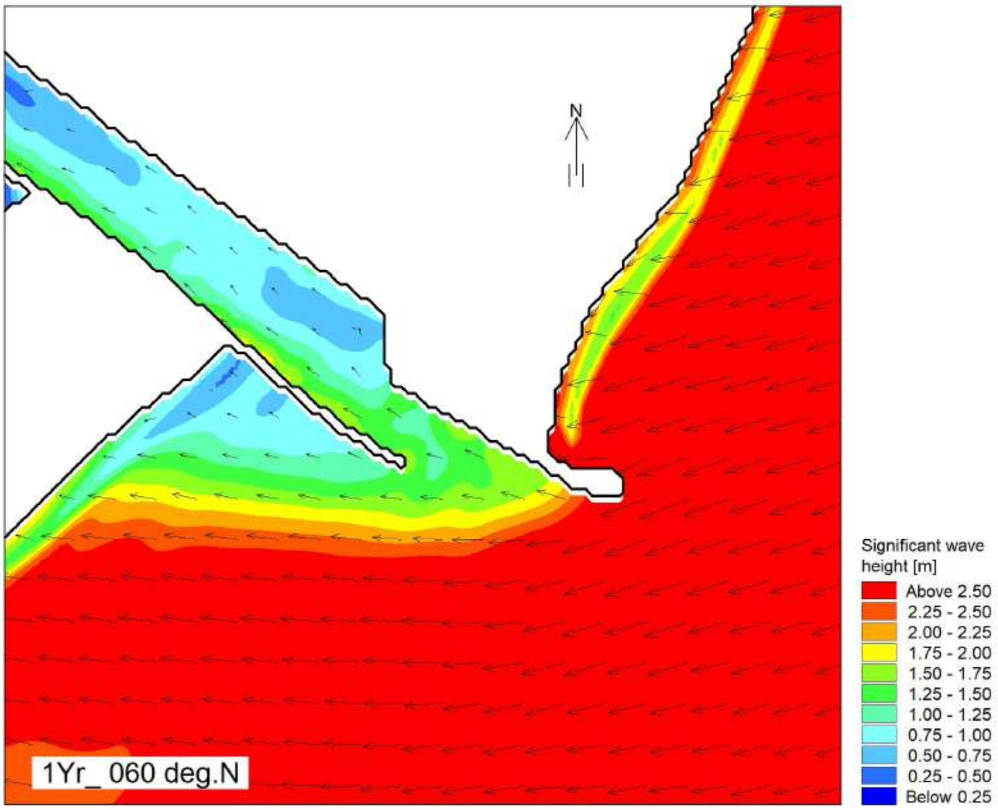

Figure C3: Penetration of 1 year wave (swell) from 60°N

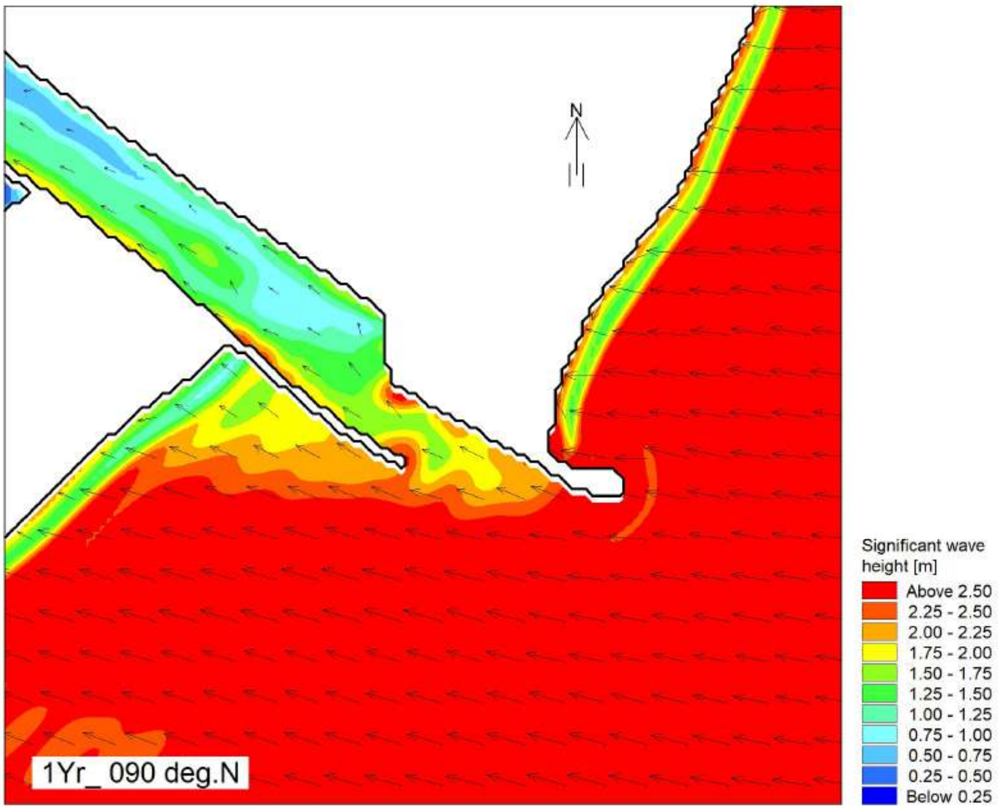

Figure C4: Penetration of 1 year wave (seas) from 90°N

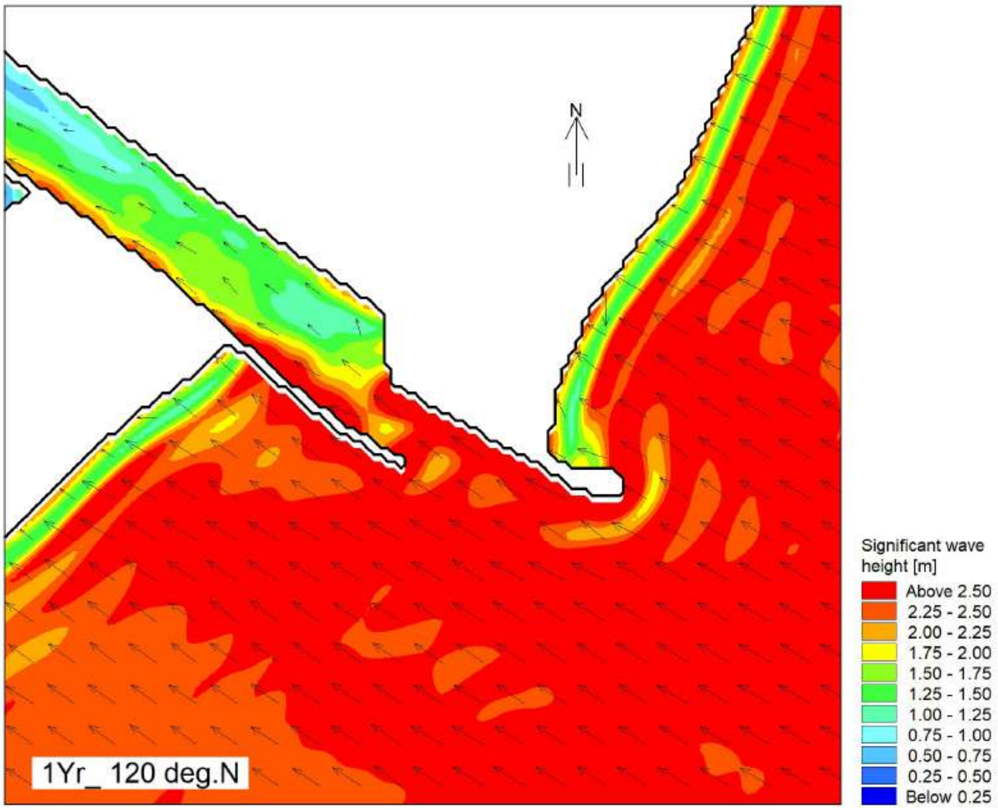

Figure C5: Penetration of 1 year wave (seas) from 120°N

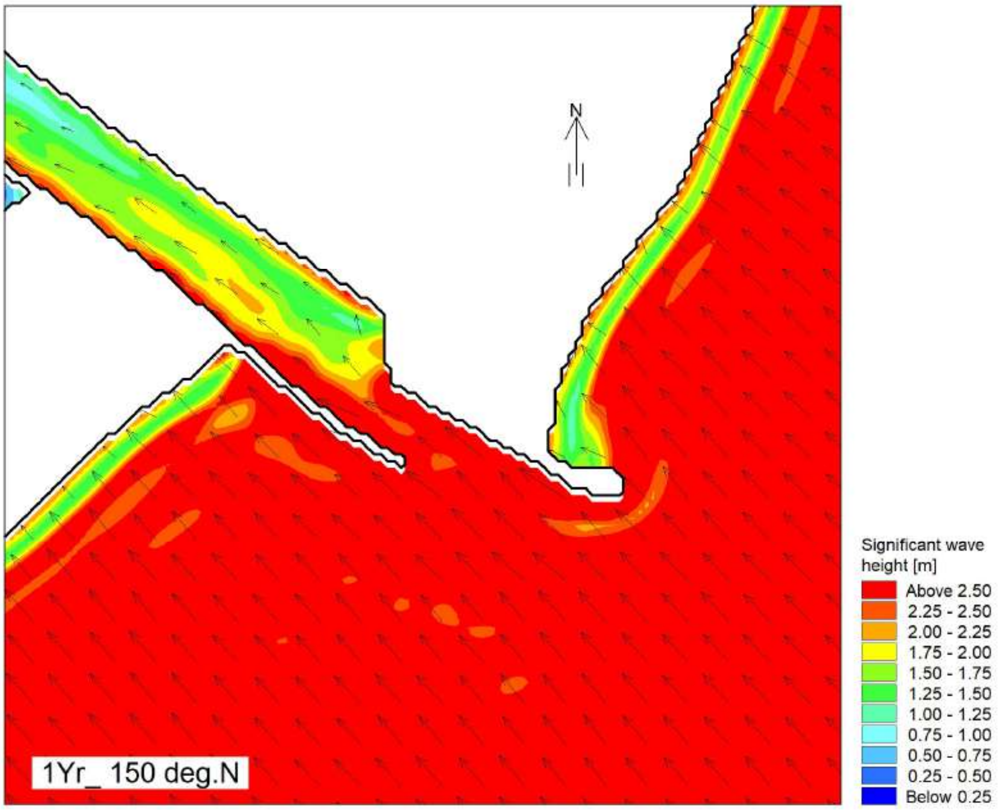

Figure C6: Penetration of 1 year wave (seas) from 150°N

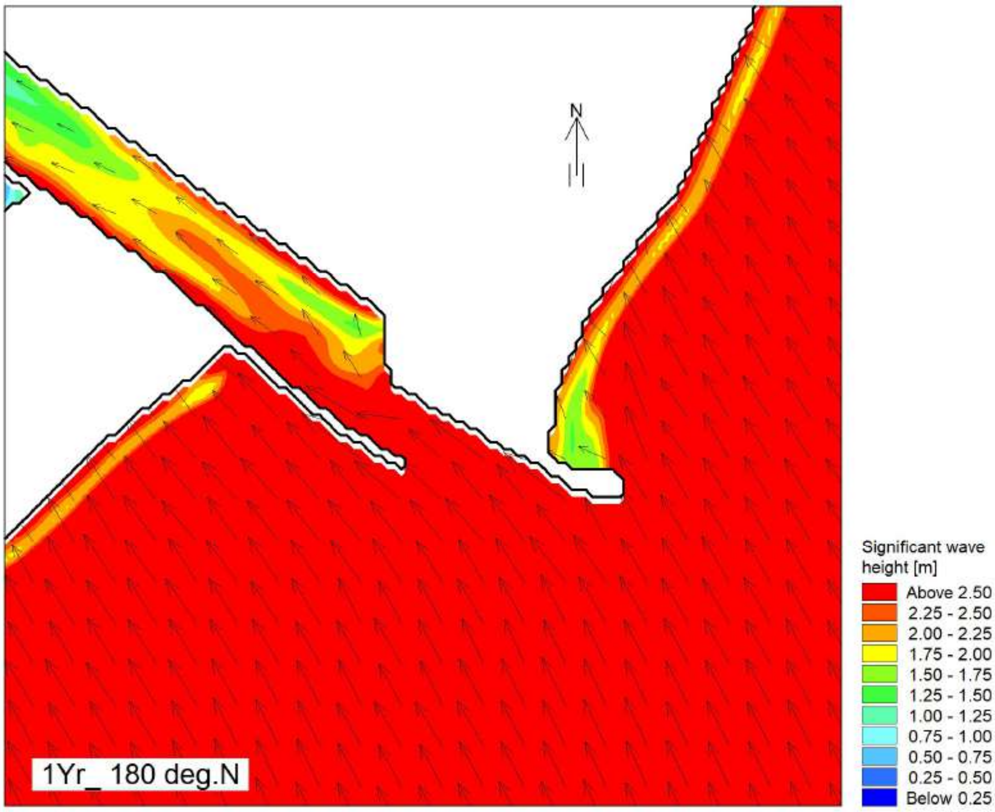

Figure C7: Penetration of 1 year wave (swell) from 180°N

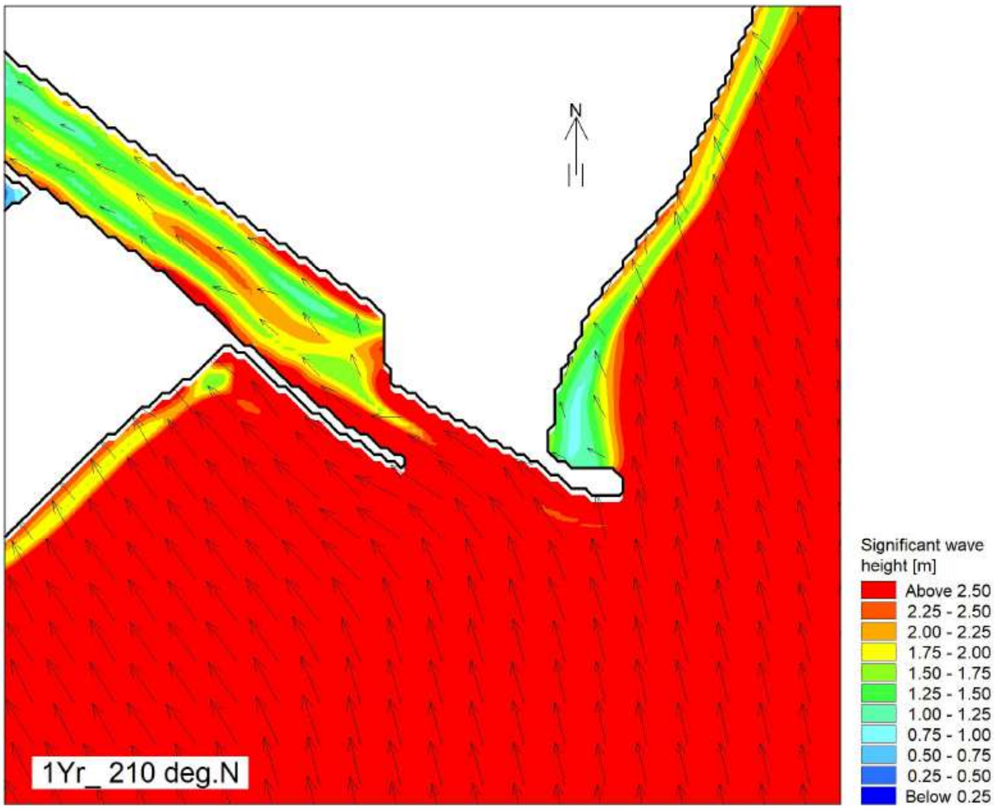

Figure C8: Penetration of 1 year wave (swell) from 210°N

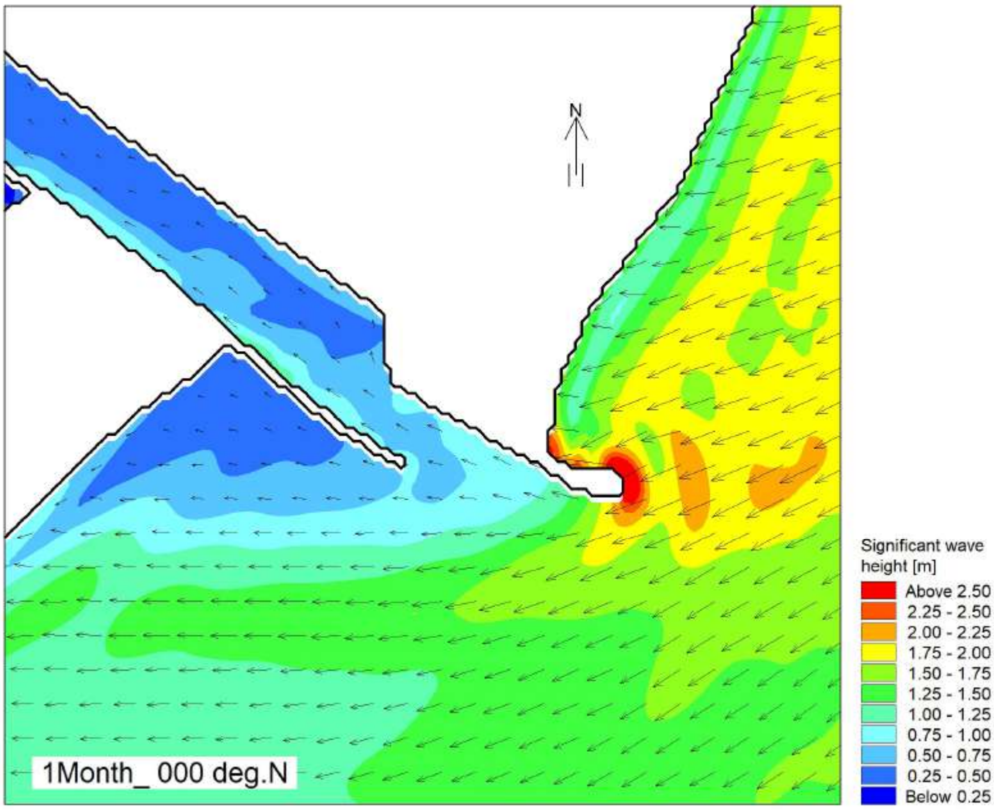

Figure C9: Penetration of 1 month (swell) wave from 0°N

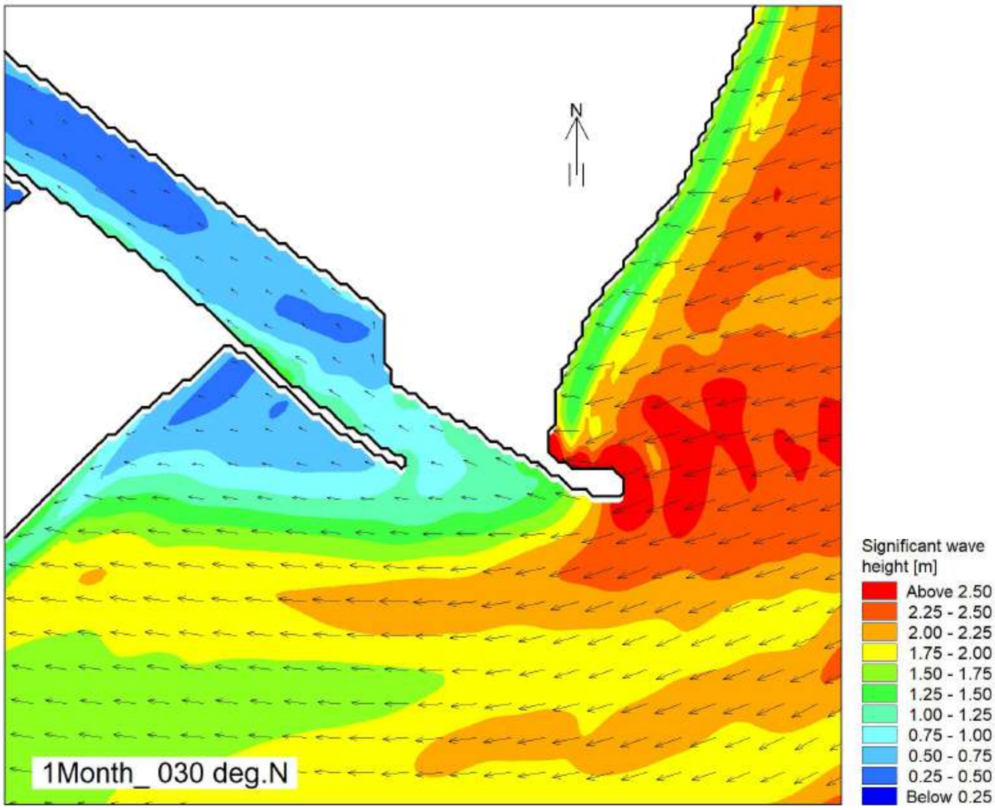

Figure C10: Penetration of 1 month (swell) wave from 30°N

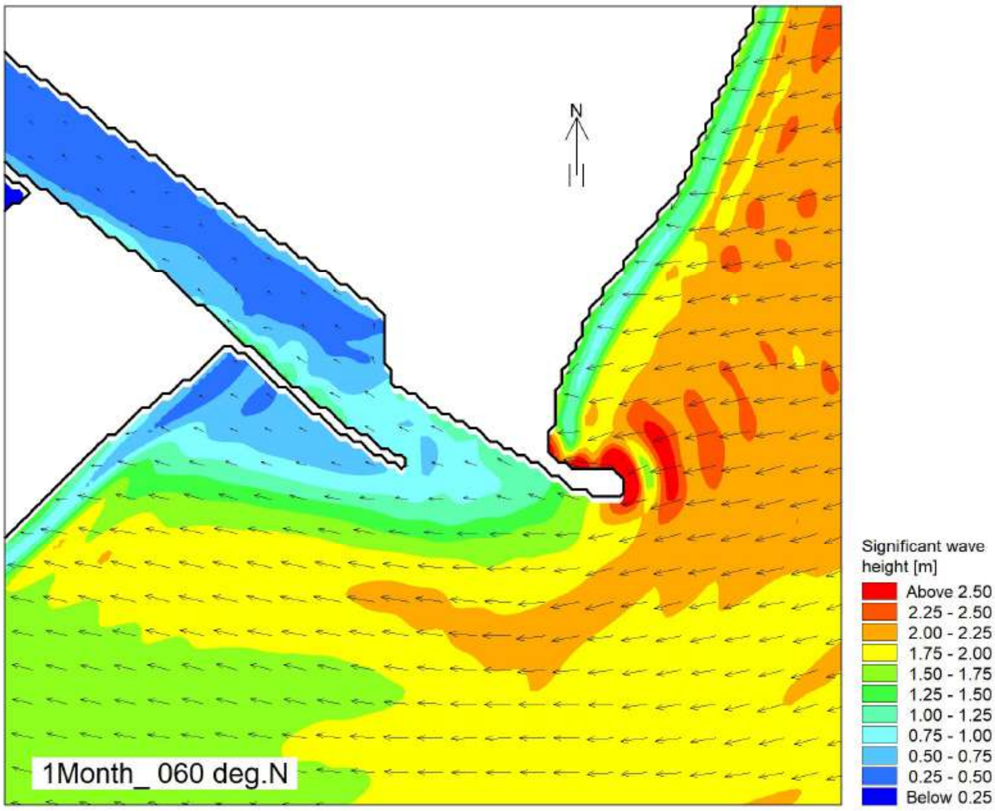

Figure C11: Penetration of 1 month wave (seas) from 60°N

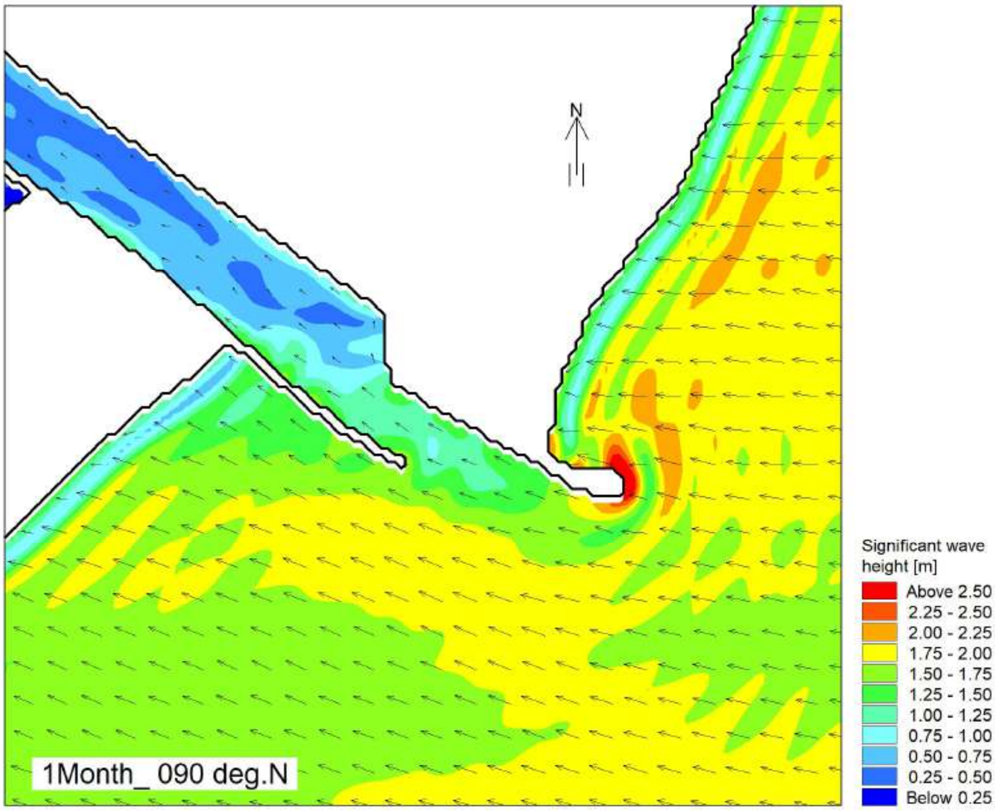

Figure C12: Penetration of 1 month wave (seas) from 90°N

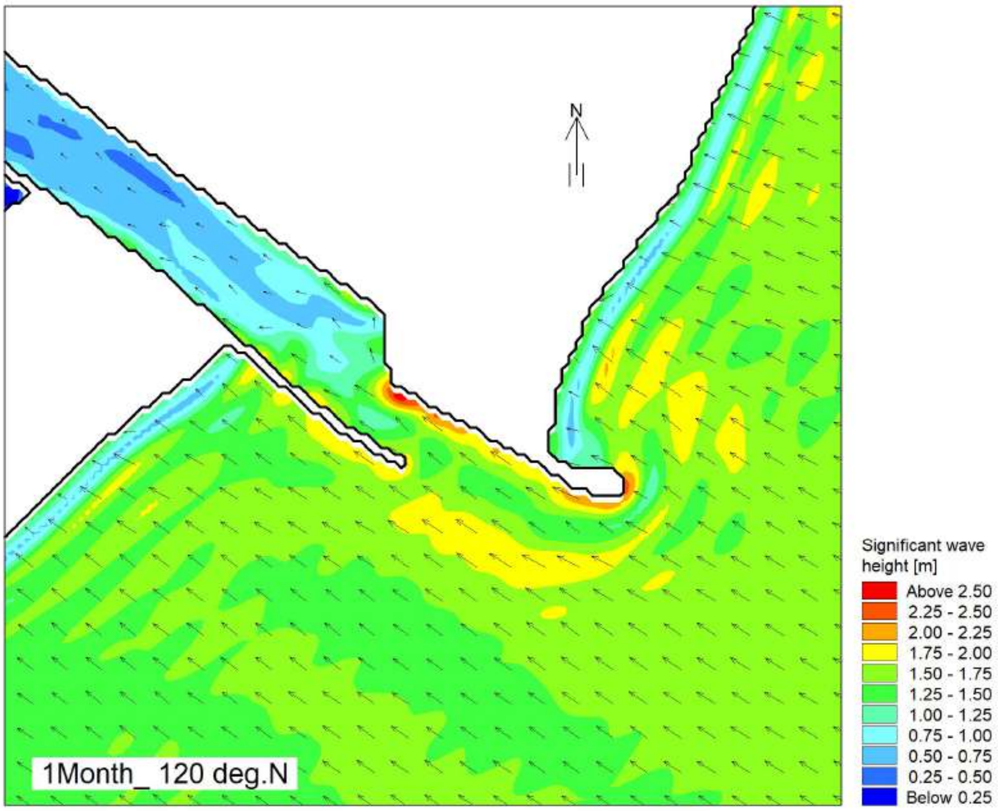

Figure C13: Penetration of 1 month wave (seas) from 120°N

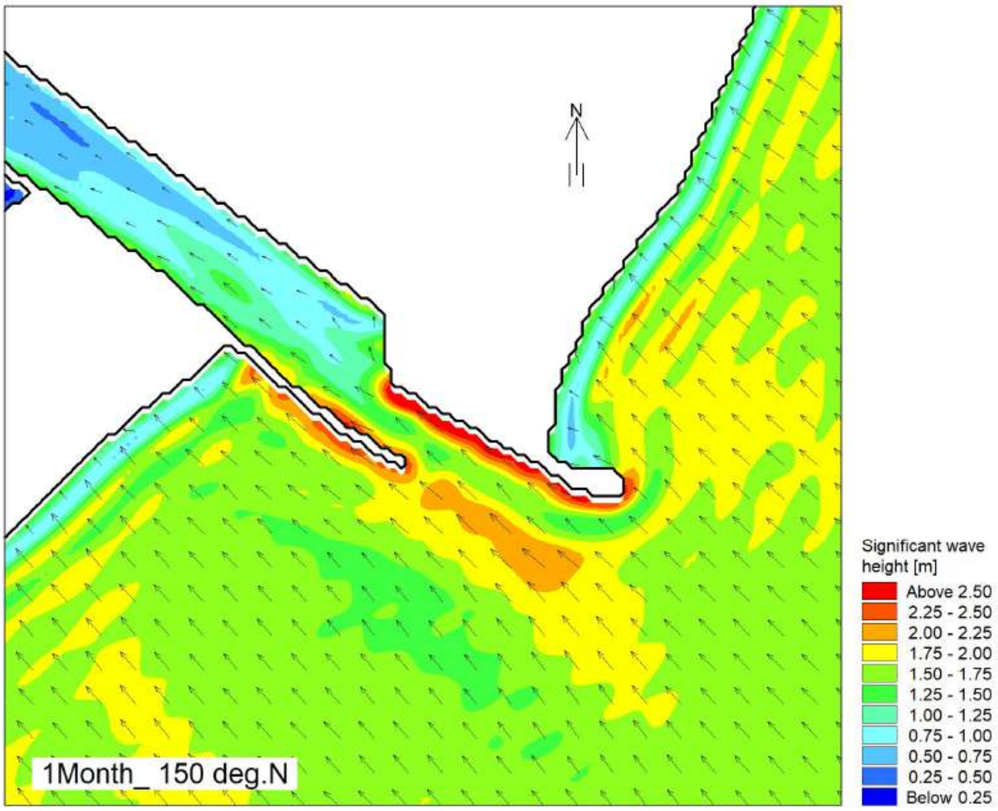

Figure C14: Penetration of 1 month wave (seas) from 150°N

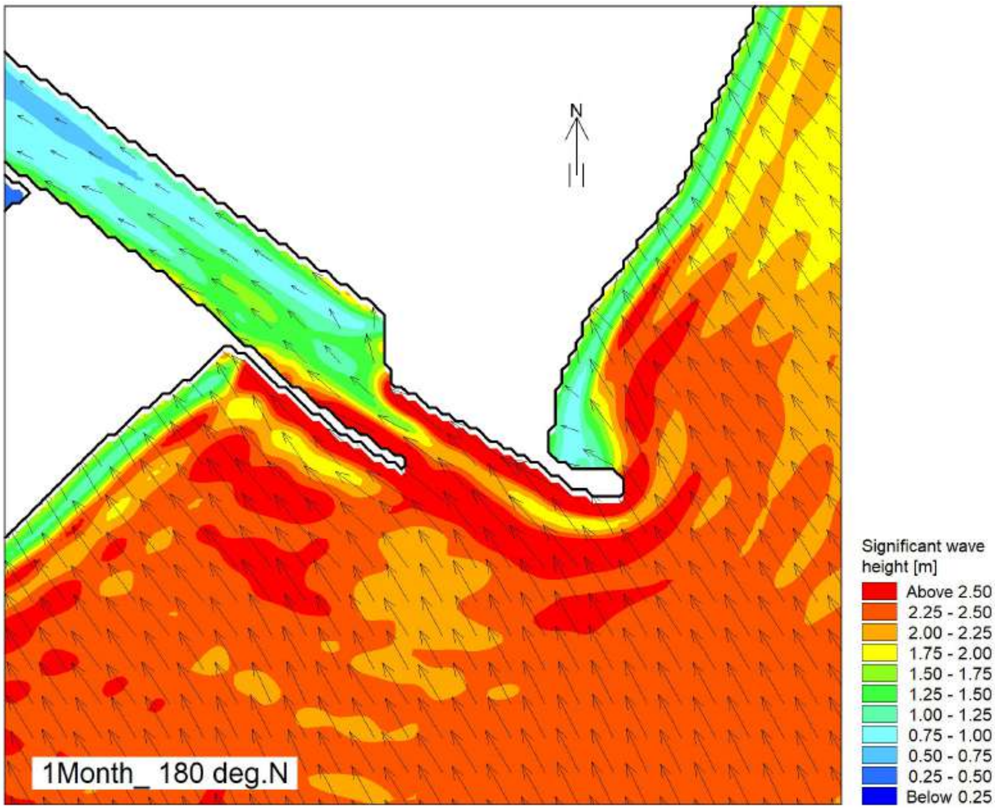

Figure C15: Penetration of 1 month wave (swell) from 180°N

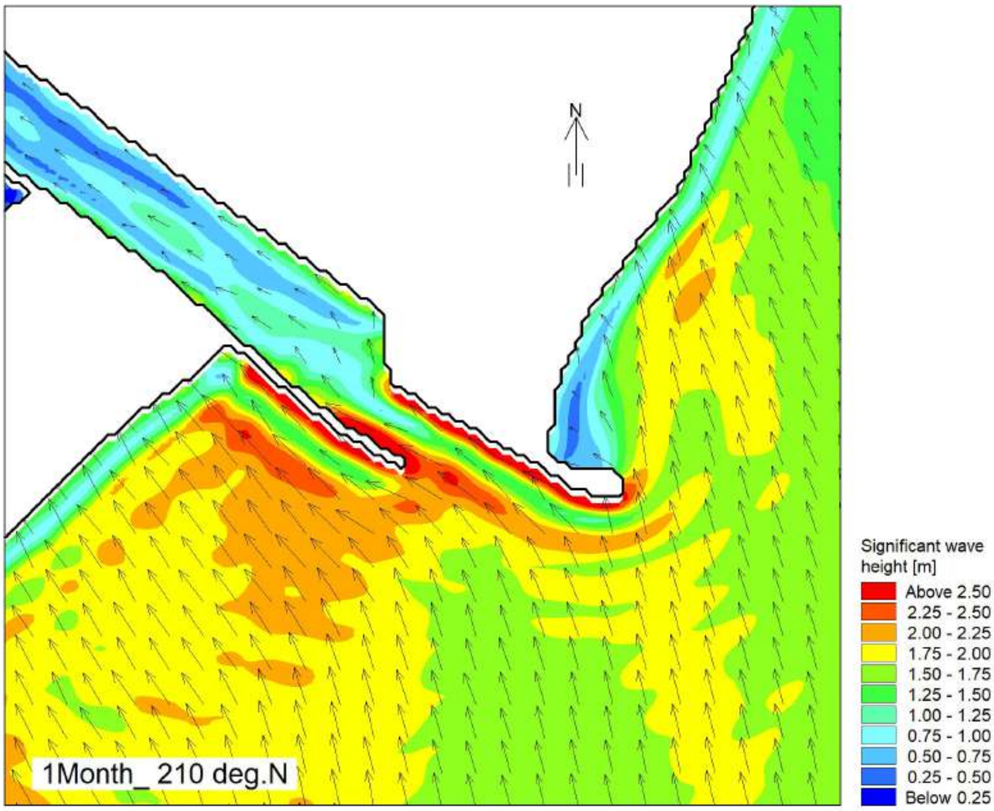

Figure C16: Penetration of 1 month wave (seas) from 210°N

Appendix D

Option Modelling Layouts

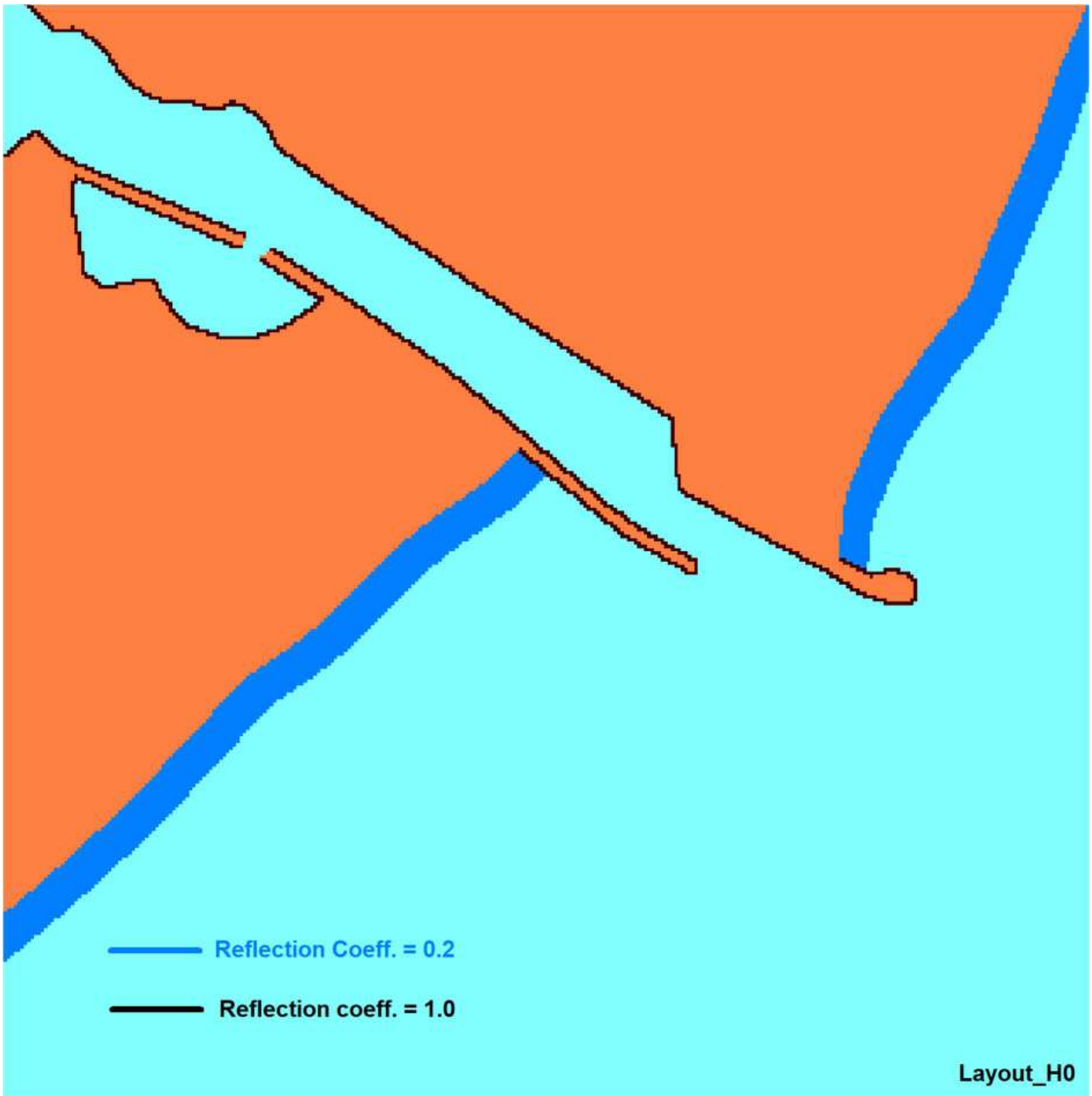

Figure D1: Layout H0 – Baseline (Present-day conditions)

Note – The South Pier is shown with a shorter length, because the ‘windows’ in the outer part of the pier are represented in the bathymetry by increasing the sea bed level to the lower level of the windows.

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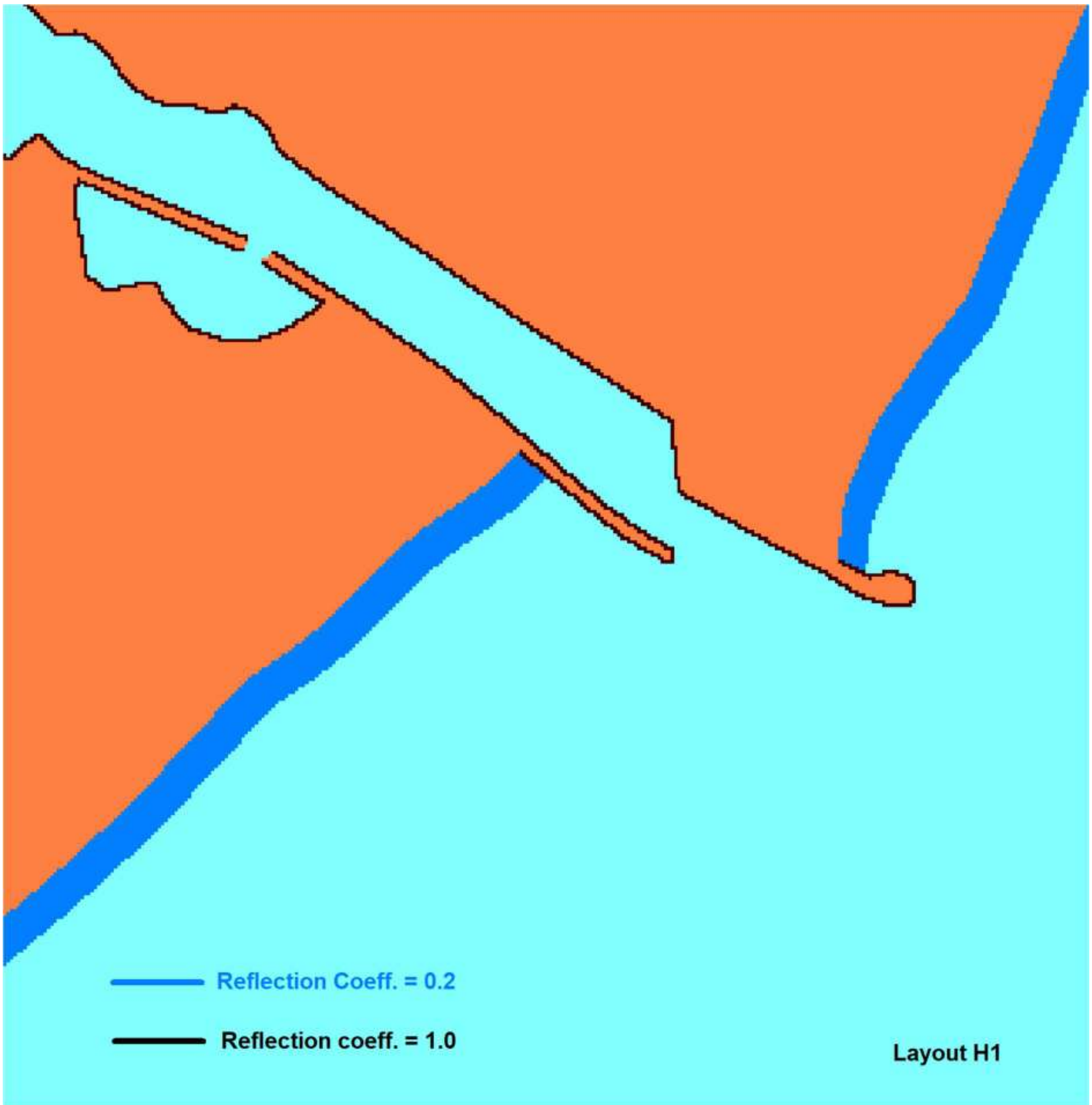

Figure D2: Layout H1 and the reflection coefficients

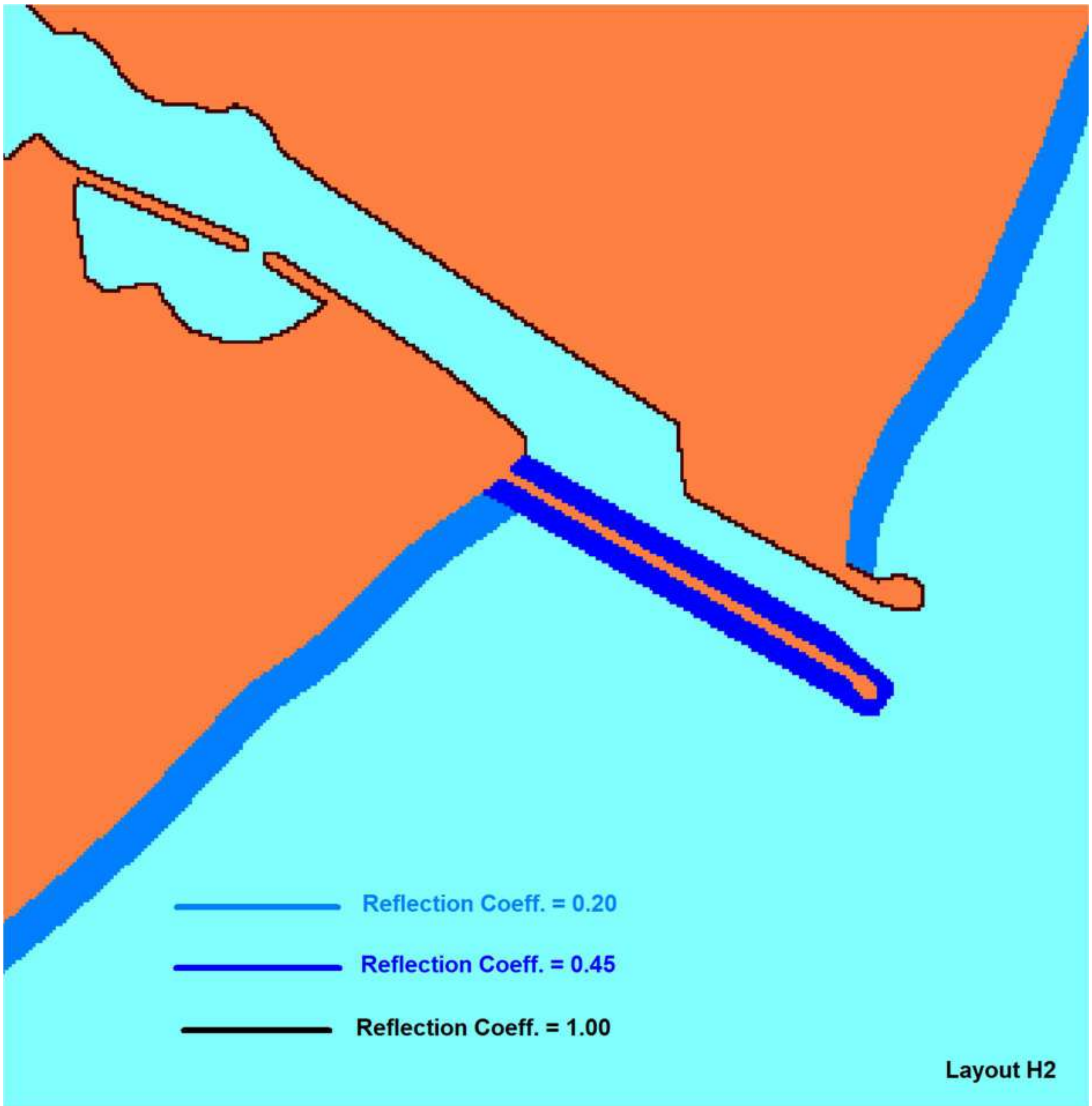

Figure D3: Layout H2 and the reflection coefficients

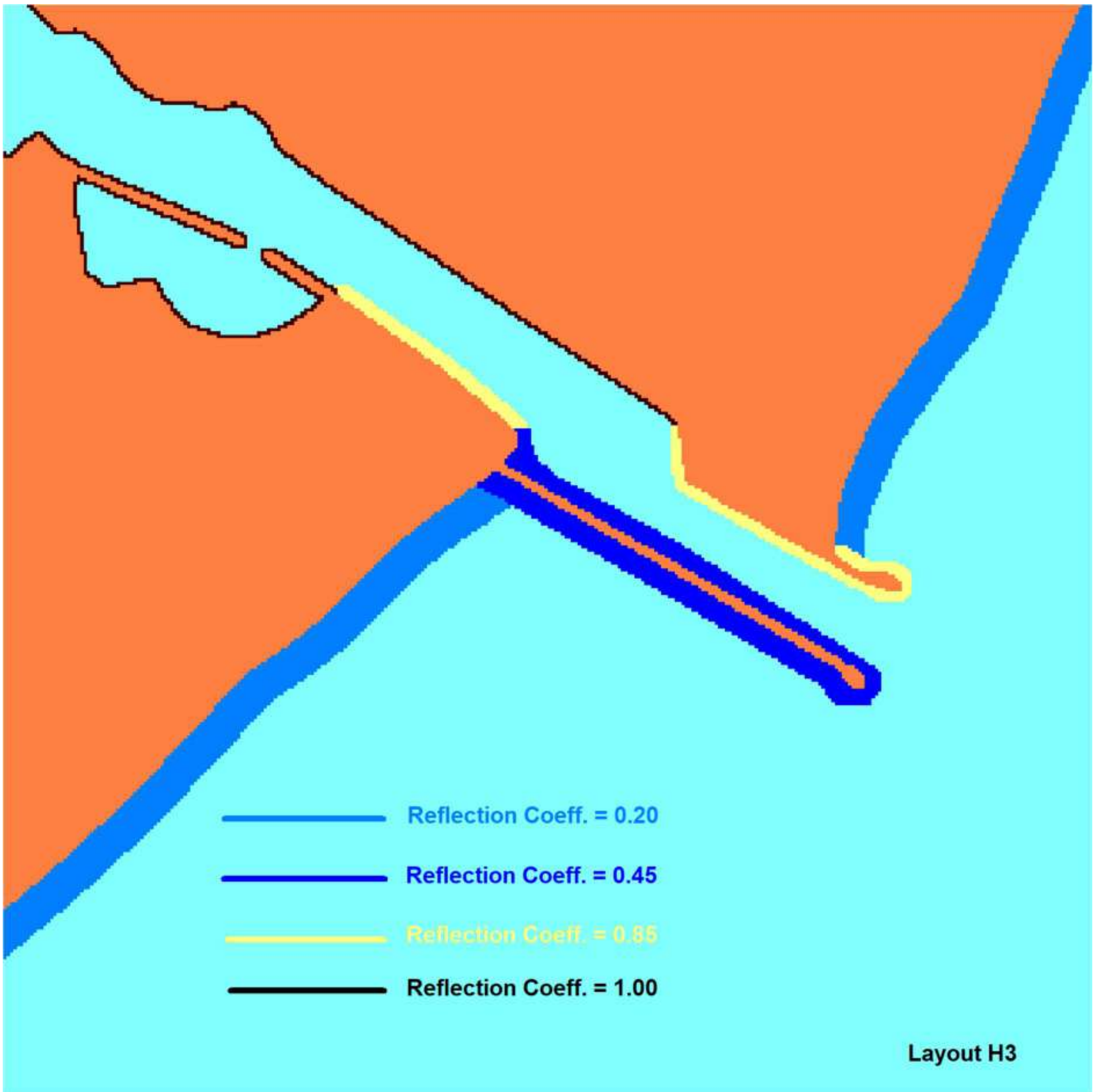

Figure D4: Layout H3 and the reflection coefficients

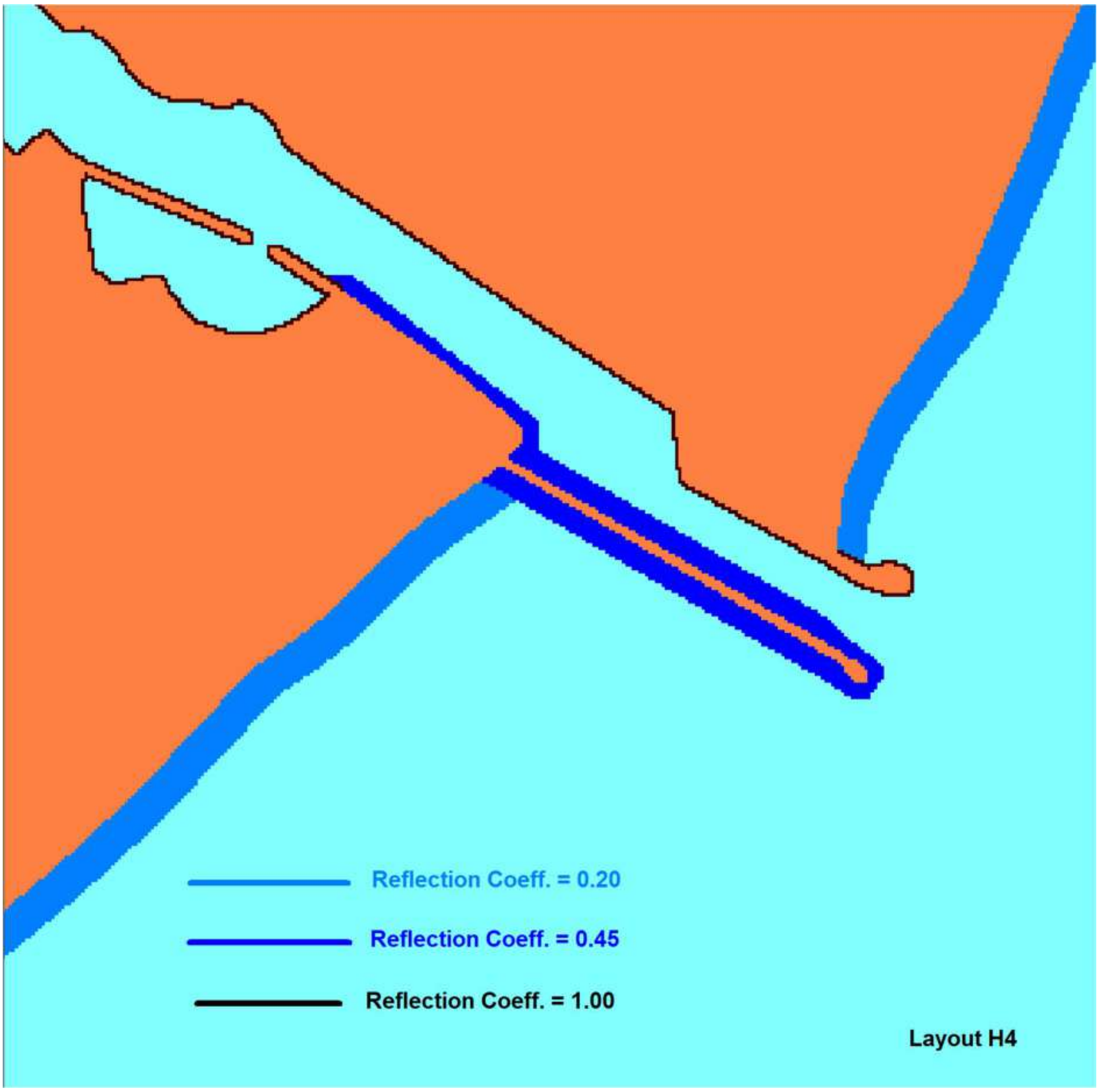

Figure D5: Layout H4 and the reflection coefficients

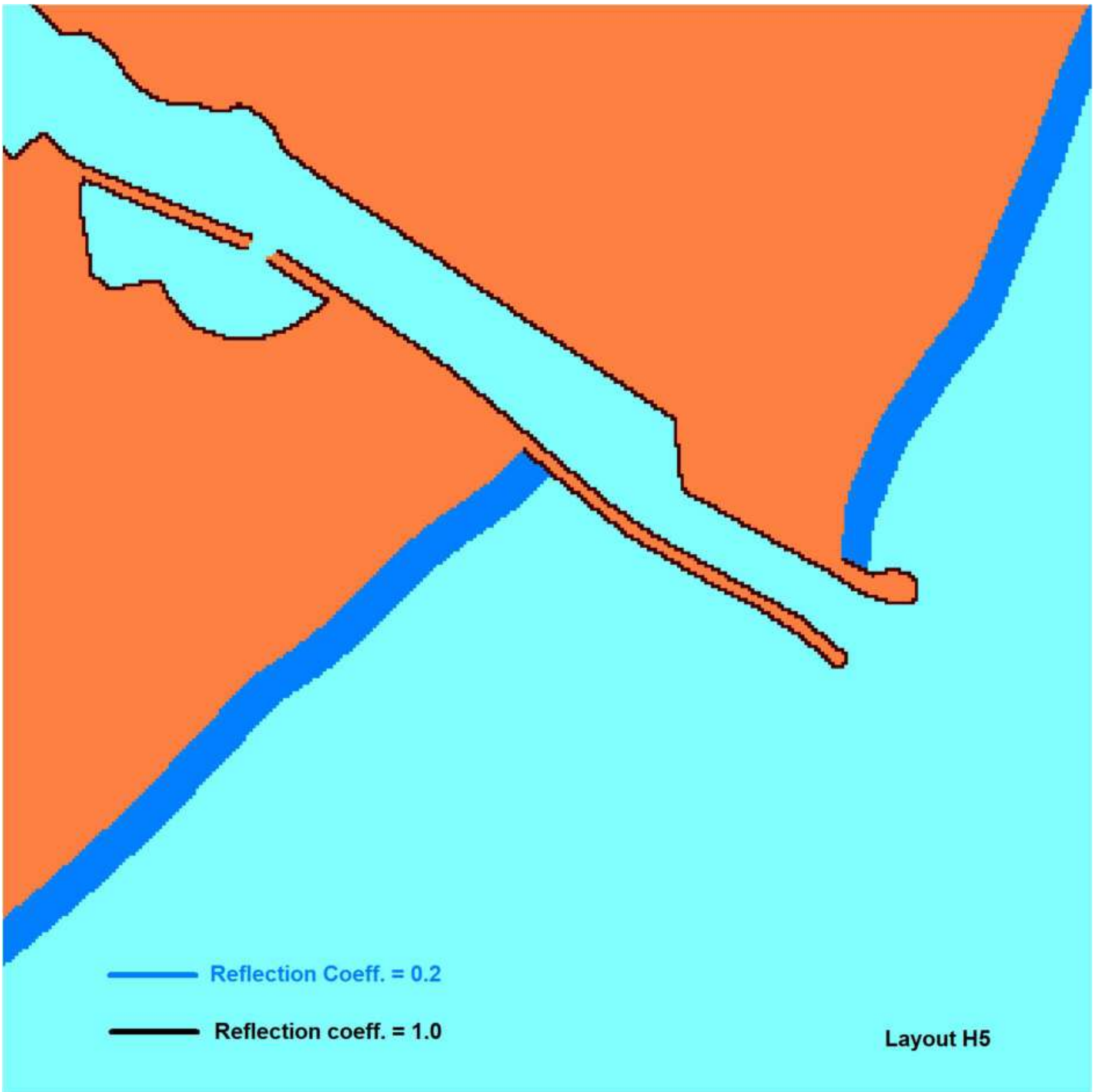

Figure D6: Layout H5 and the reflection coefficients

Appendix E

Option Modelling Results

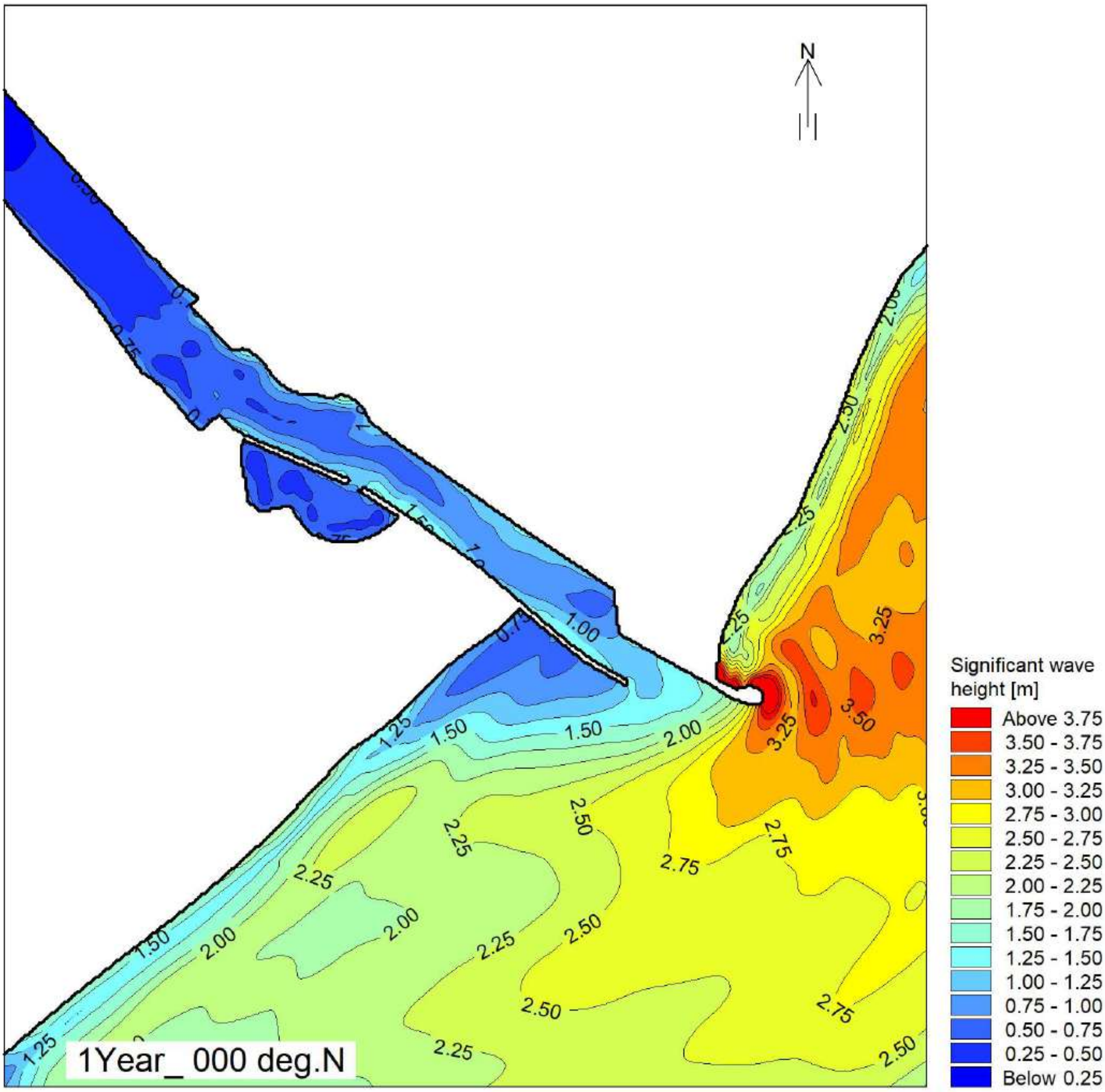

Figure E1: Layout H0, 1 year wave from 0°N

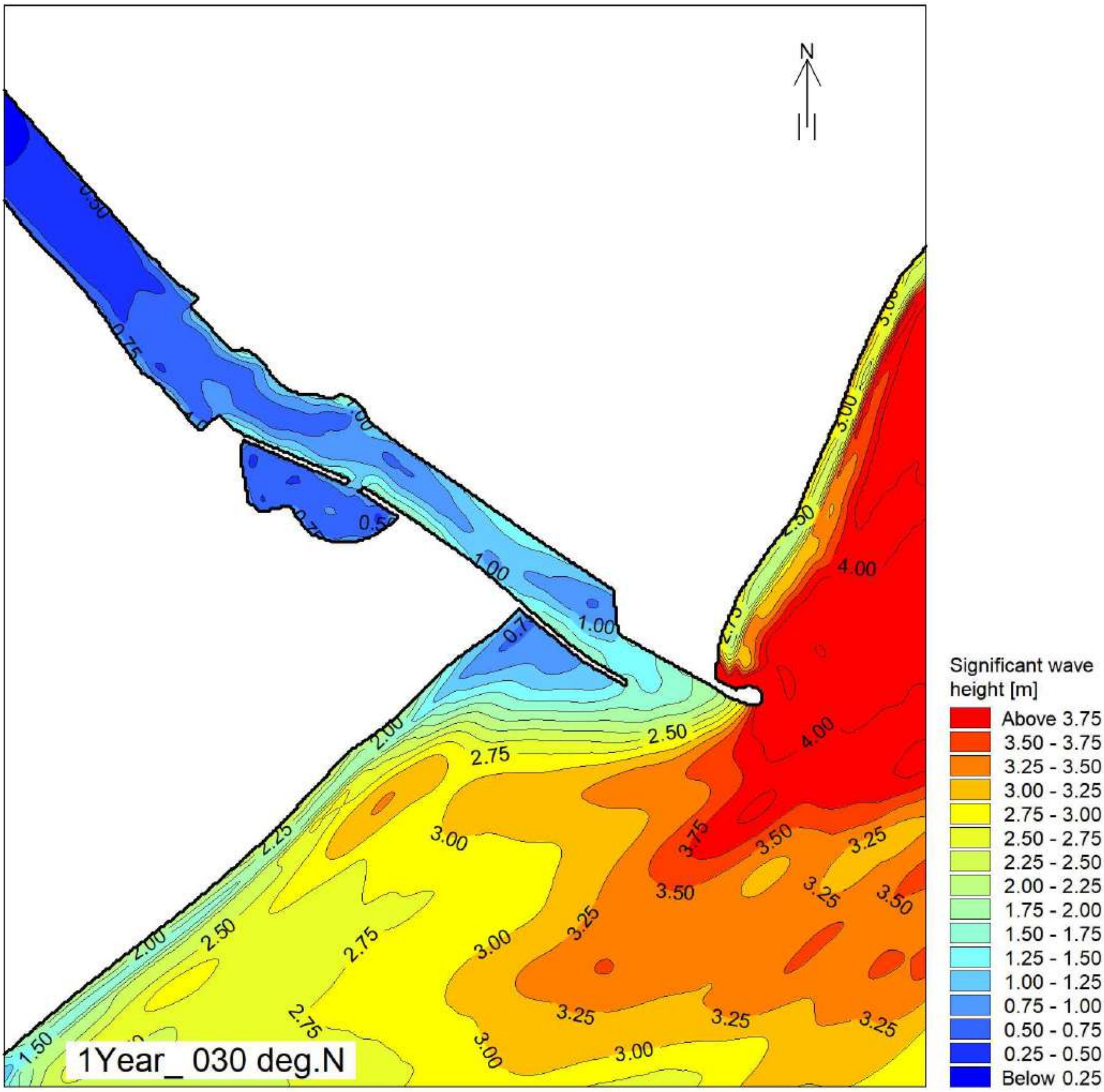

Figure E2: Layout H0, 1 year wave from 30°N

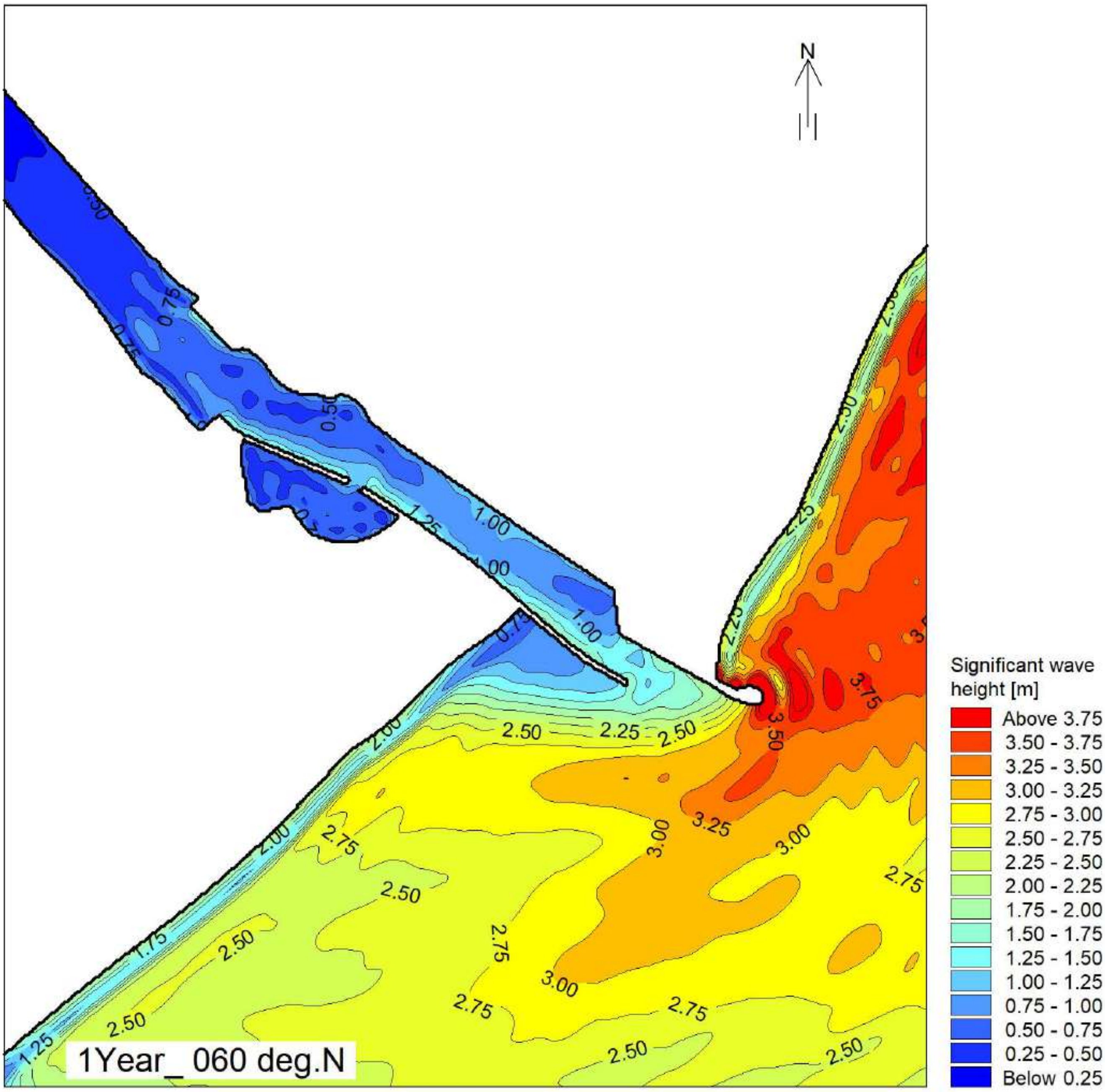

Figure E3: Layout H0, 1 year wave from 60°N

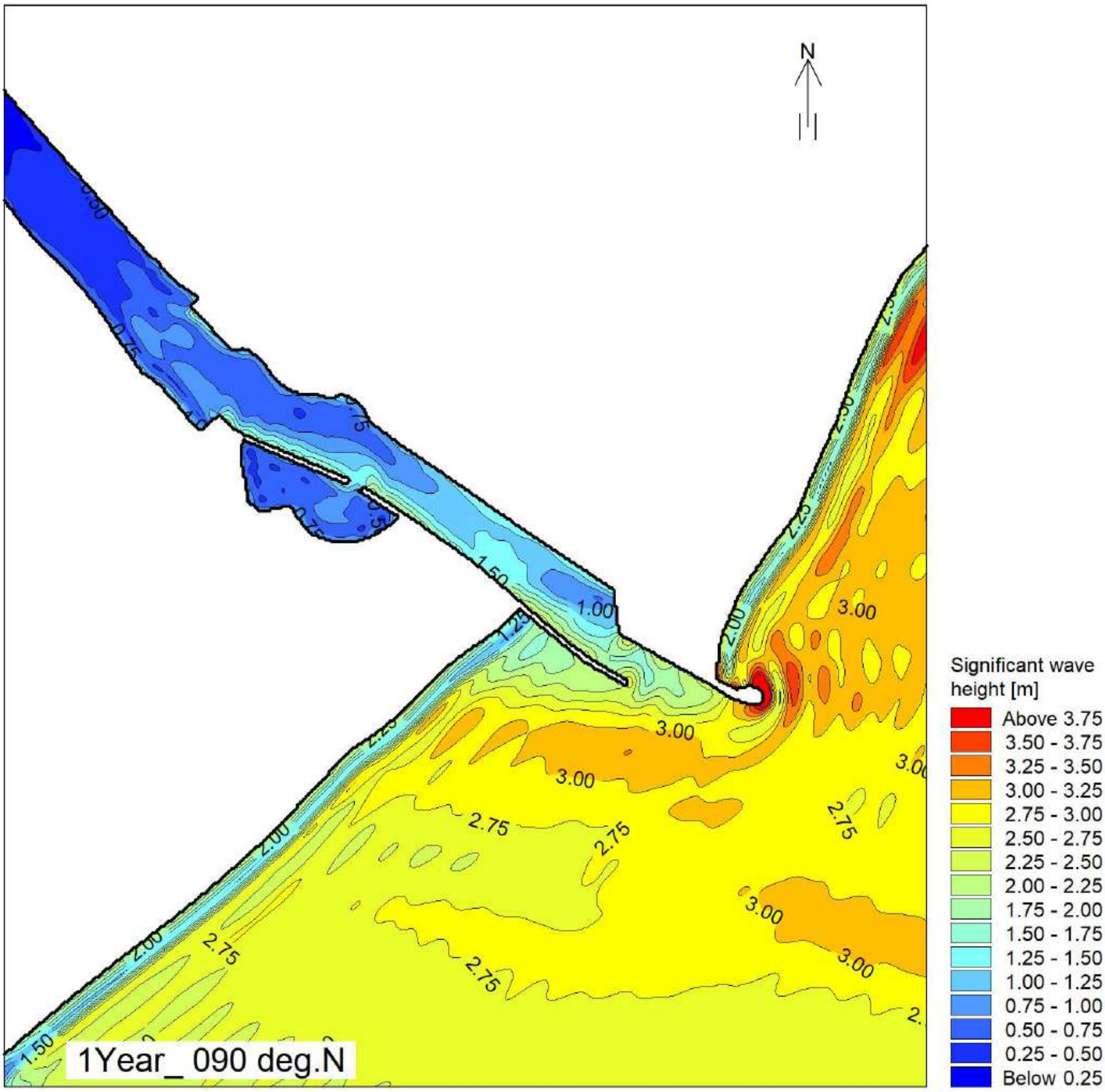

Figure E4: Layout H0, 1 year wave from 90°N

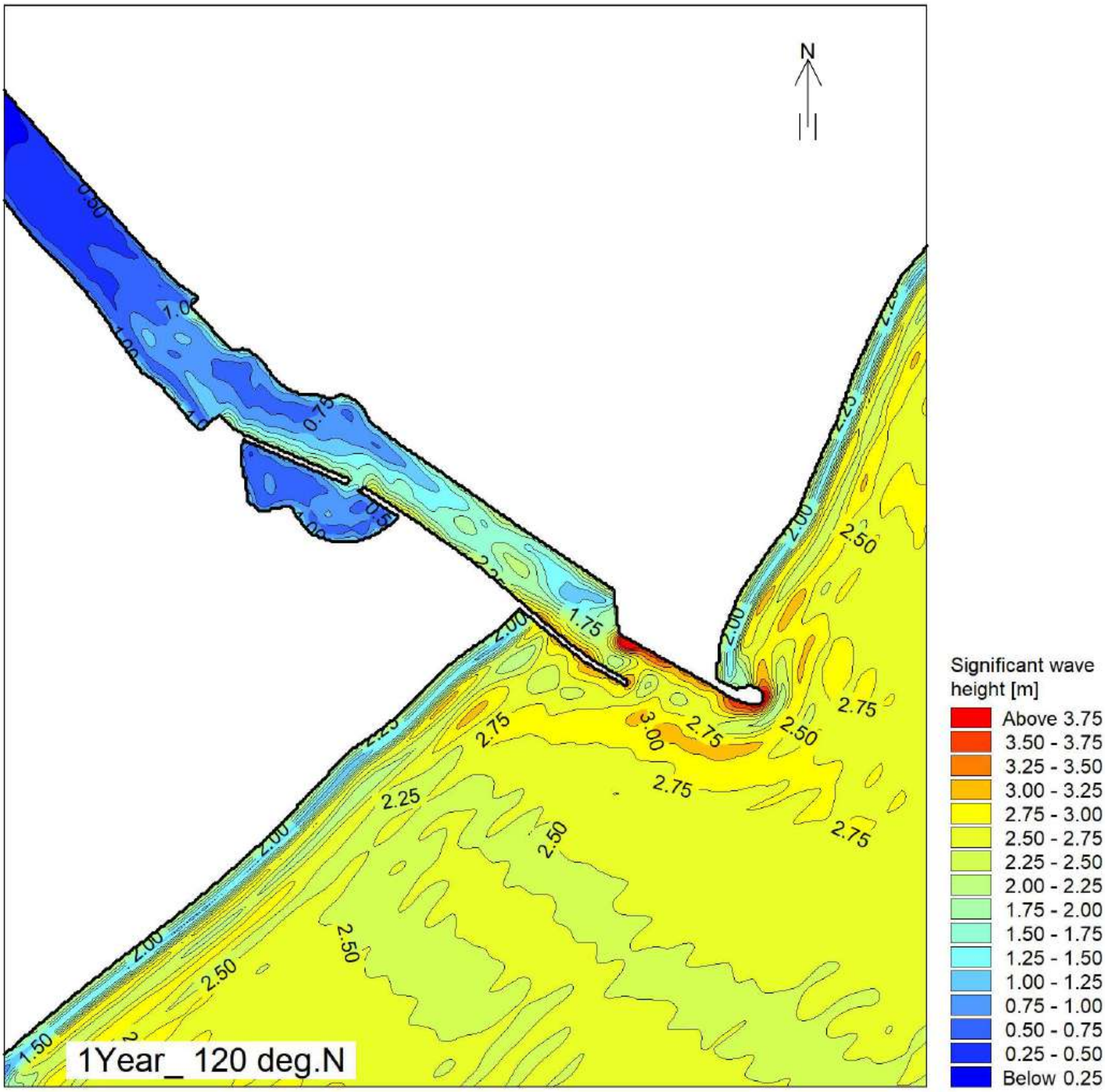

Figure E5: Layout H0, 1 year wave from 120°N

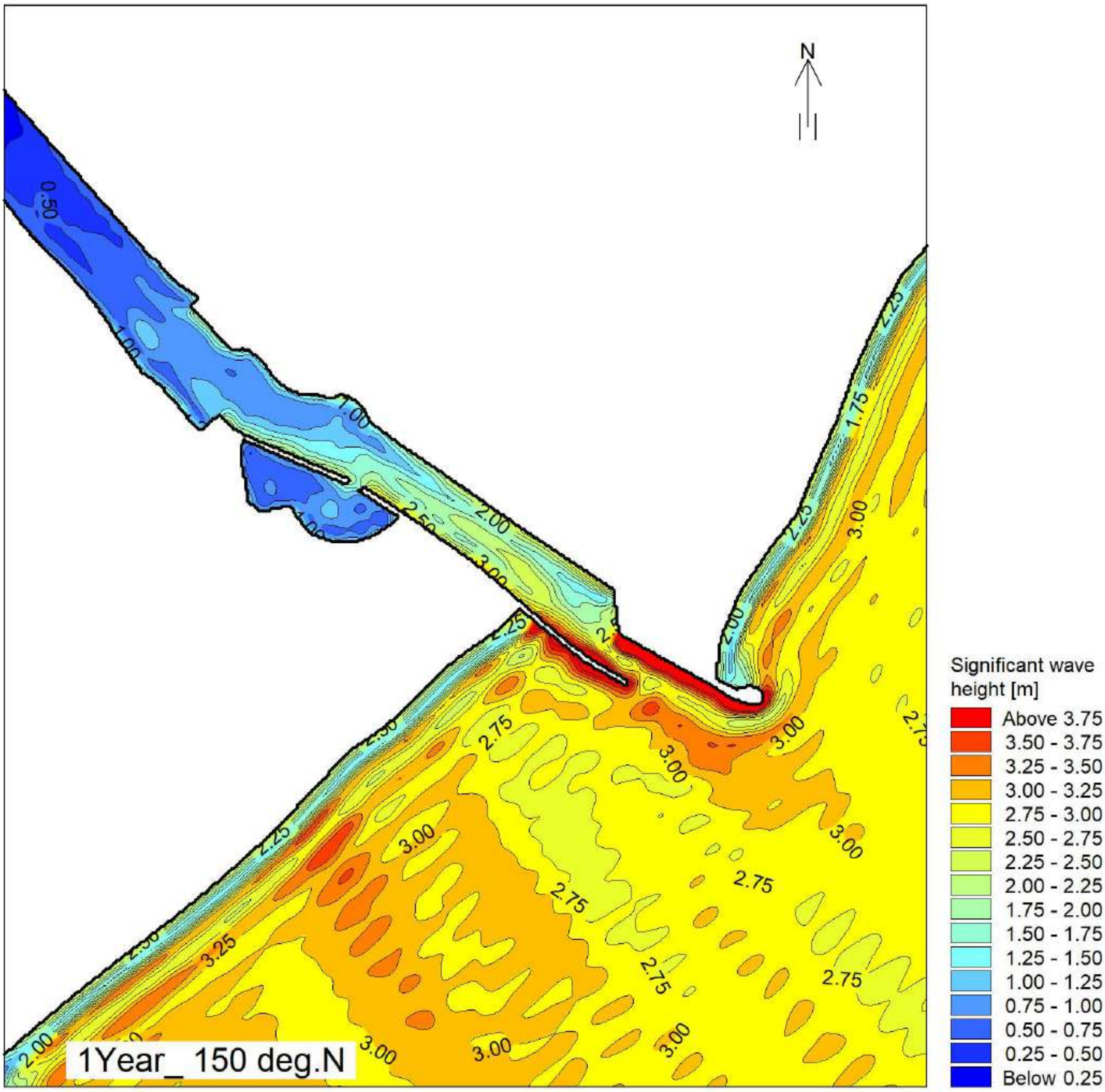

Figure E6: Layout H0, 1 year wave from 150°N

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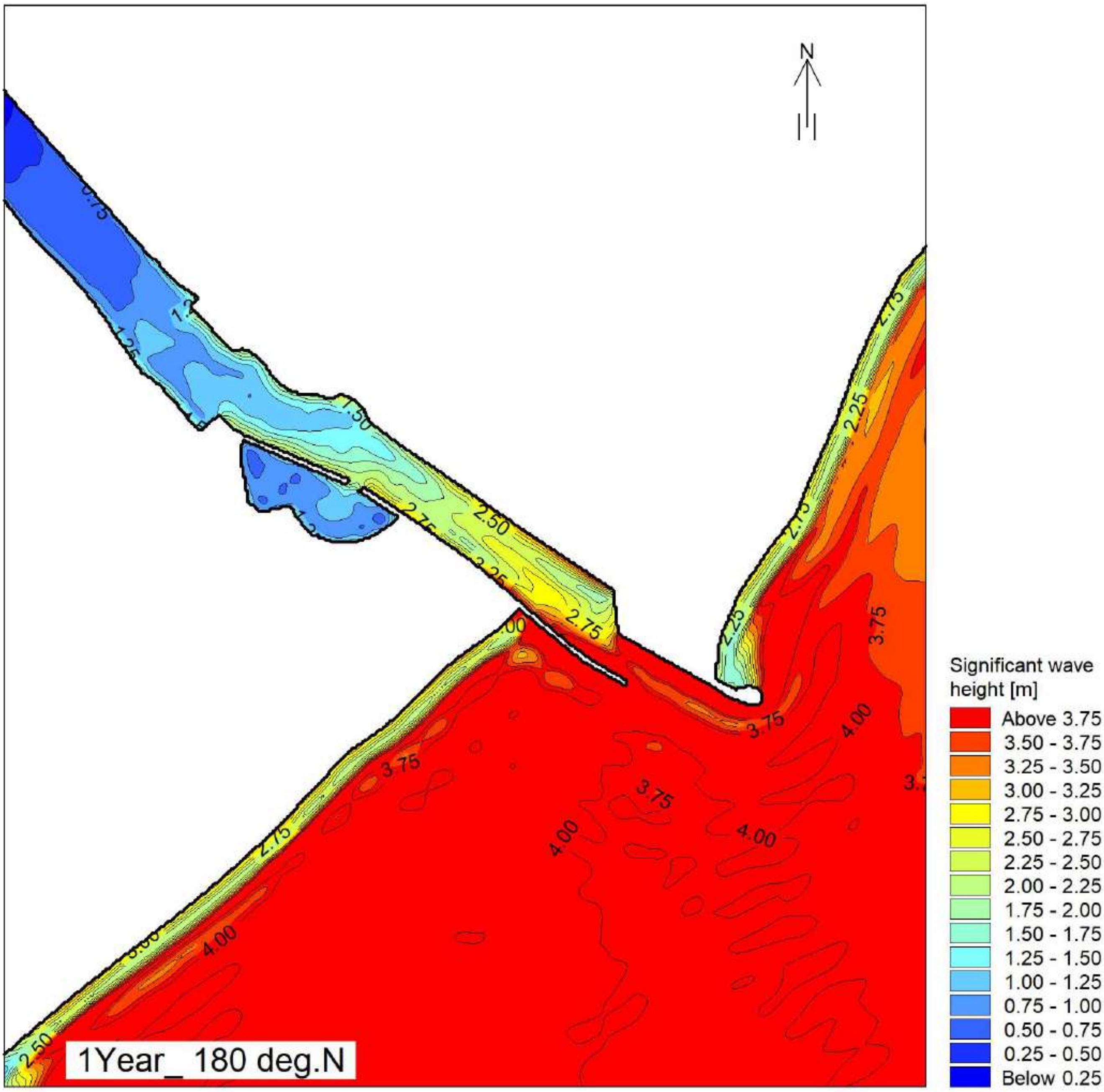

Figure E7: Layout H0, 1 year wave from 180°N

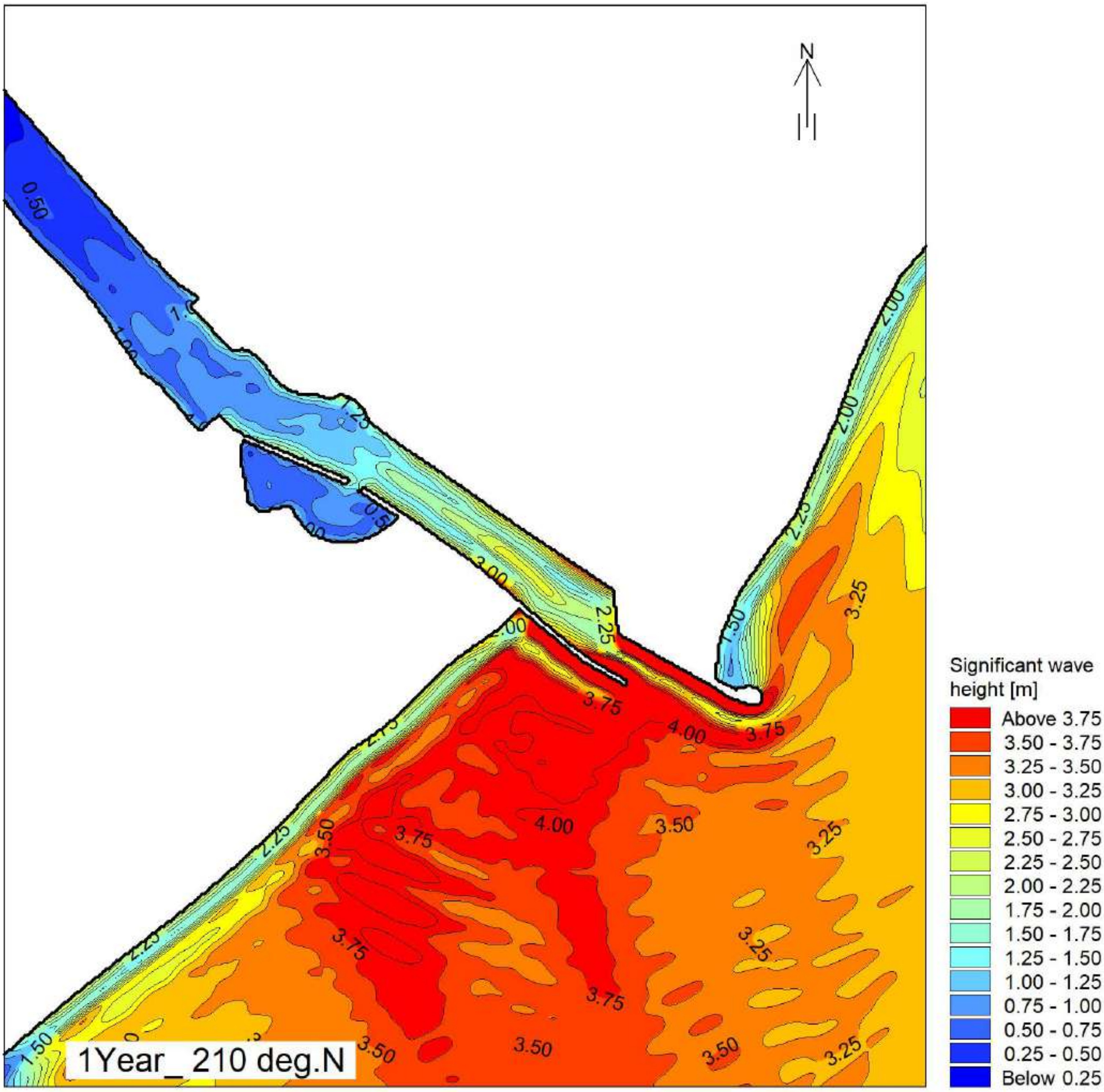

Figure E8: Layout H0, 1 year wave from 210°N

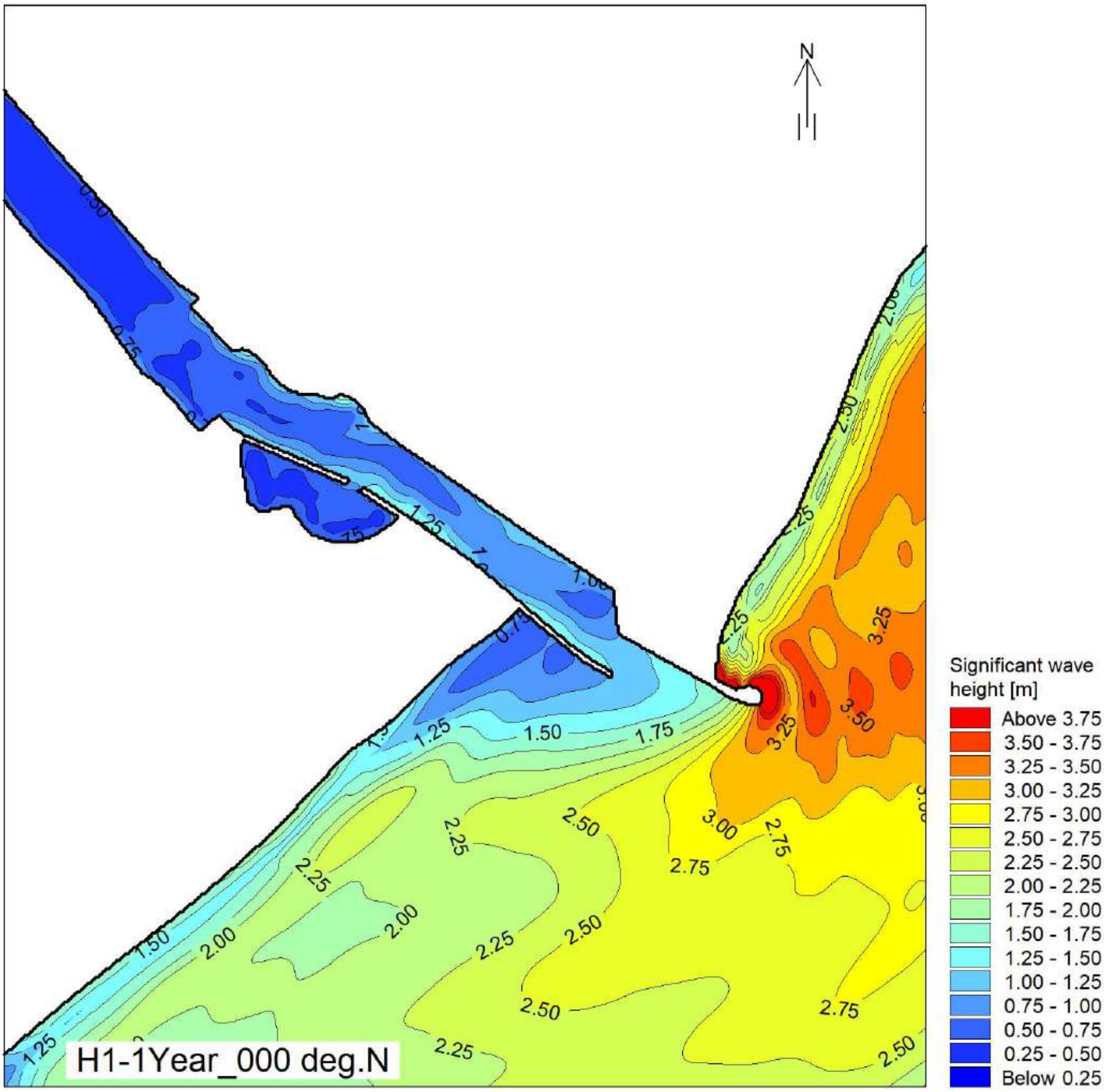

Figure E9: Layout H1, 1 year wave from 0°N

Royal HaskoningDHV

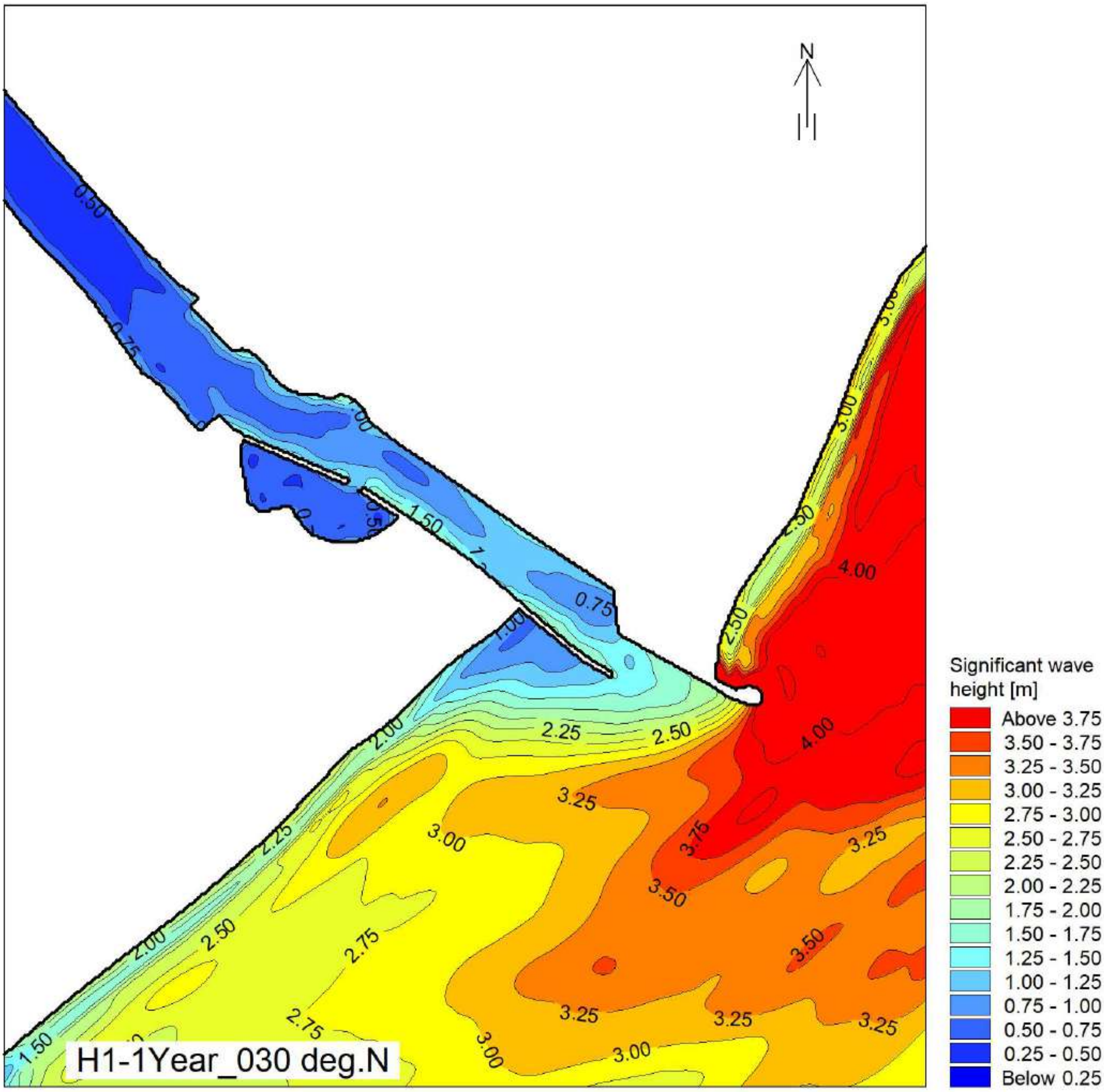

Figure E10: Layout H1, 1 year wave from 30°N

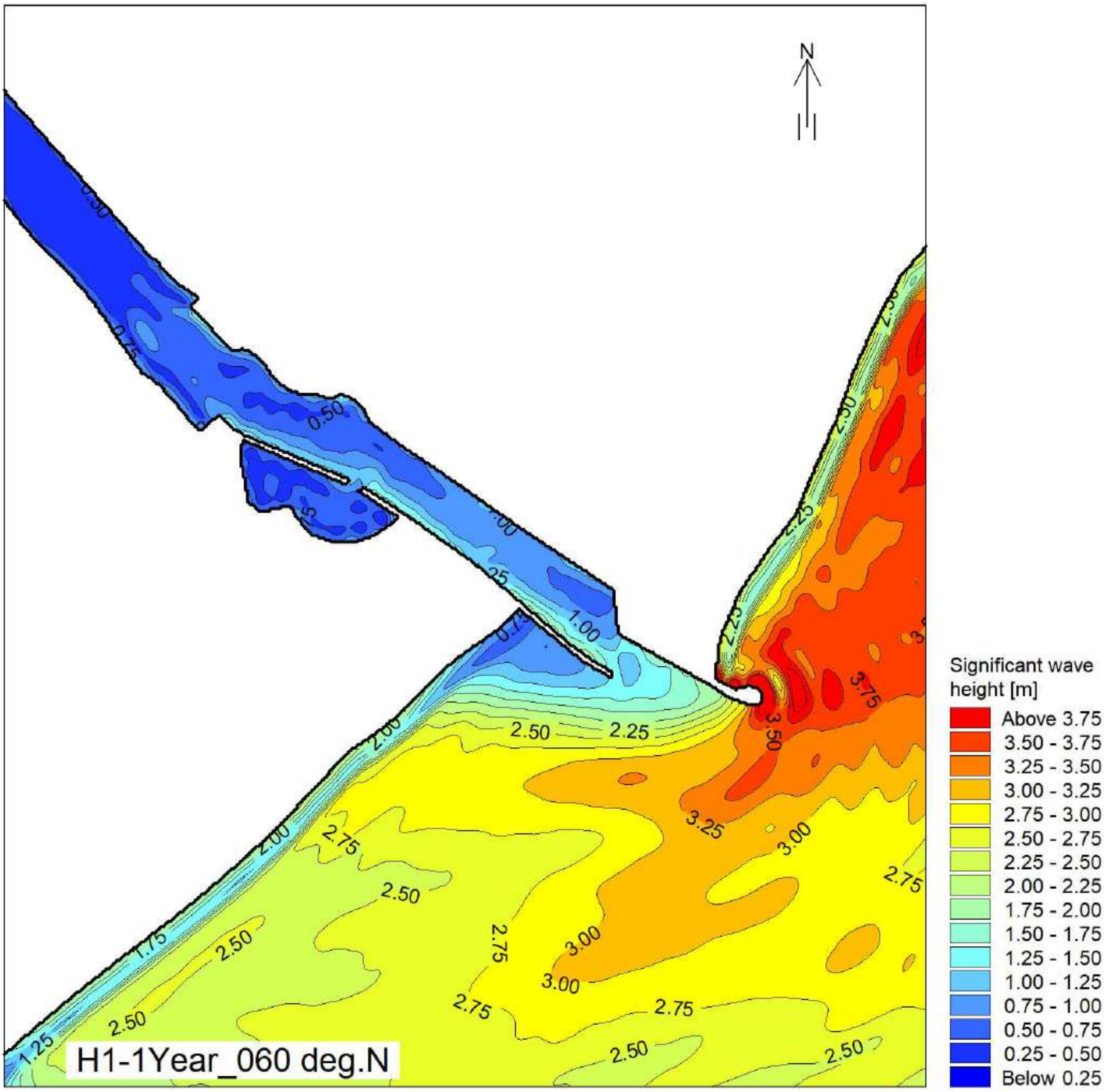

Figure E11: Layout H1, 1 year wave from 60°N

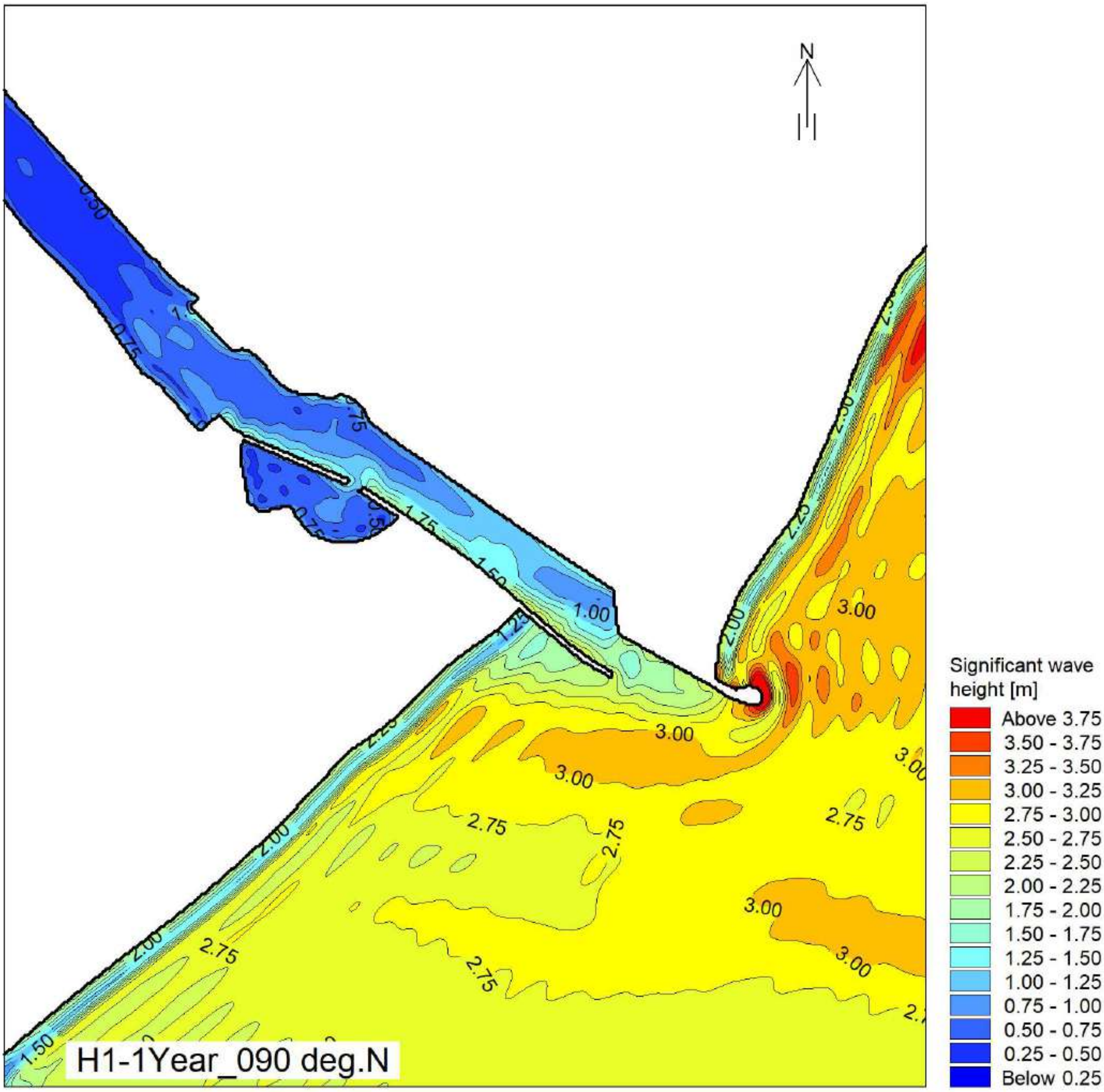

Figure E12: Layout H1, 1 year wave from 90°N

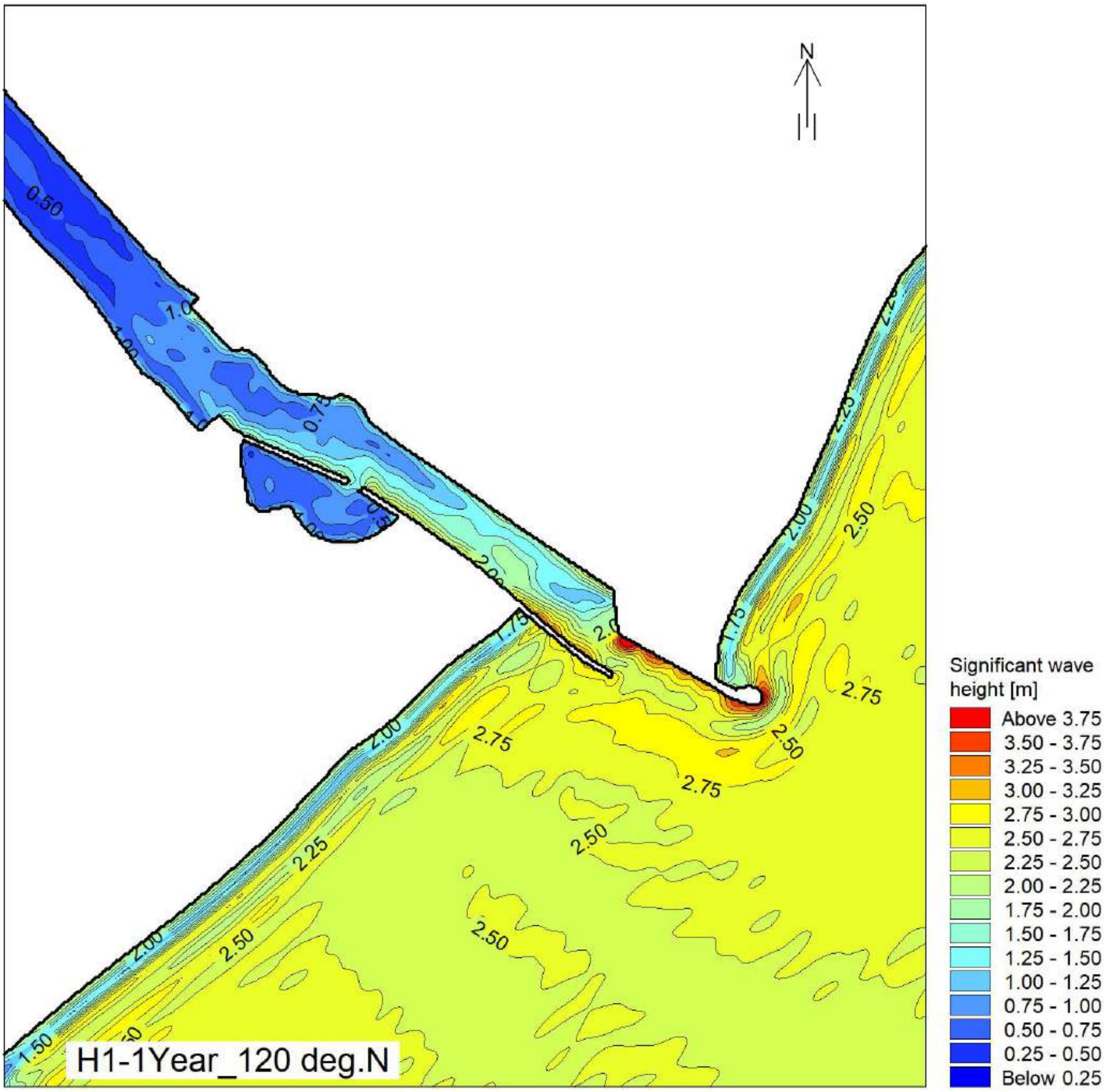

Figure E13: Layout H1, 1 year wave from 120°N

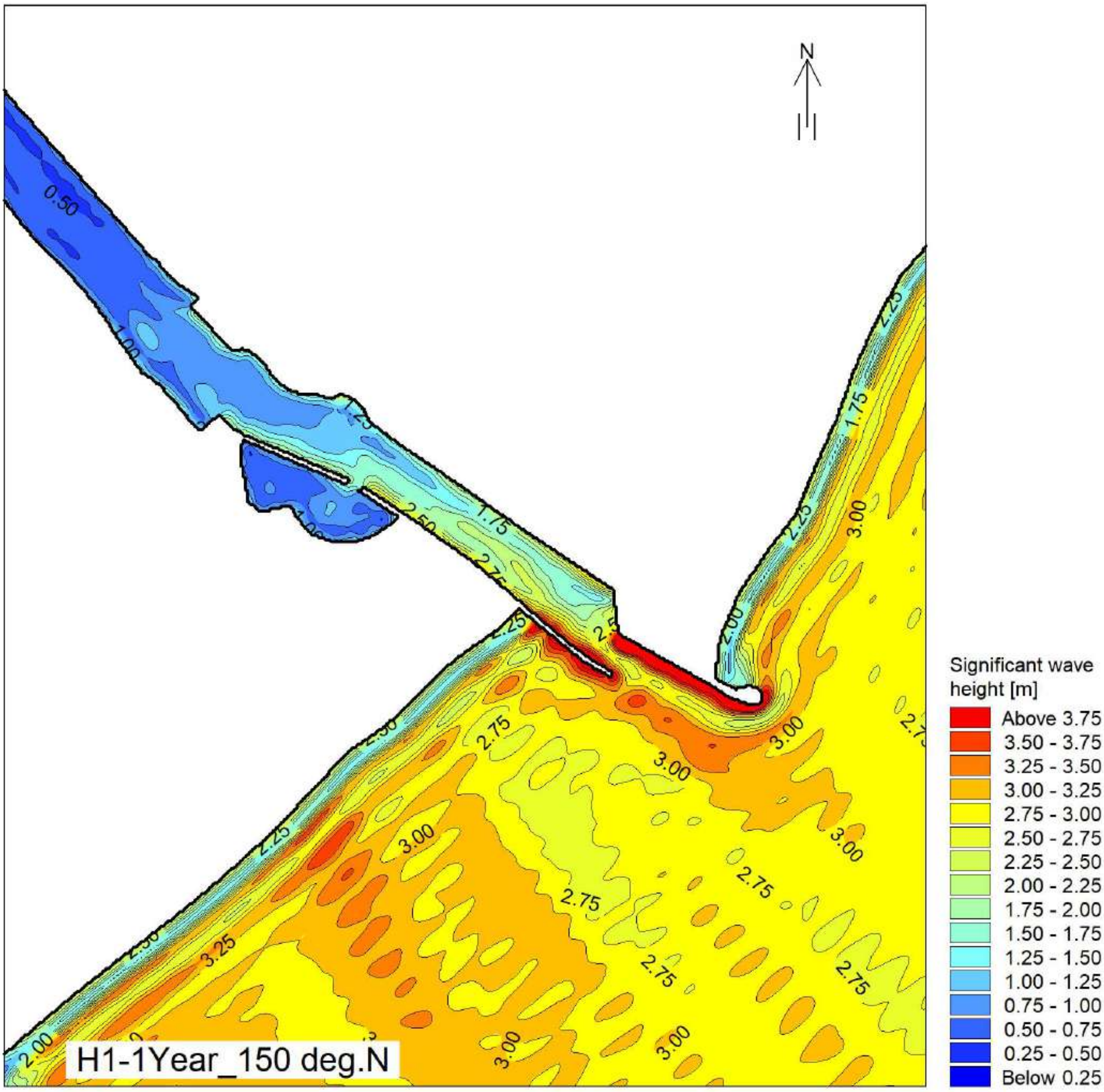

Figure E14: Layout H1, 1 year wave from 150°N

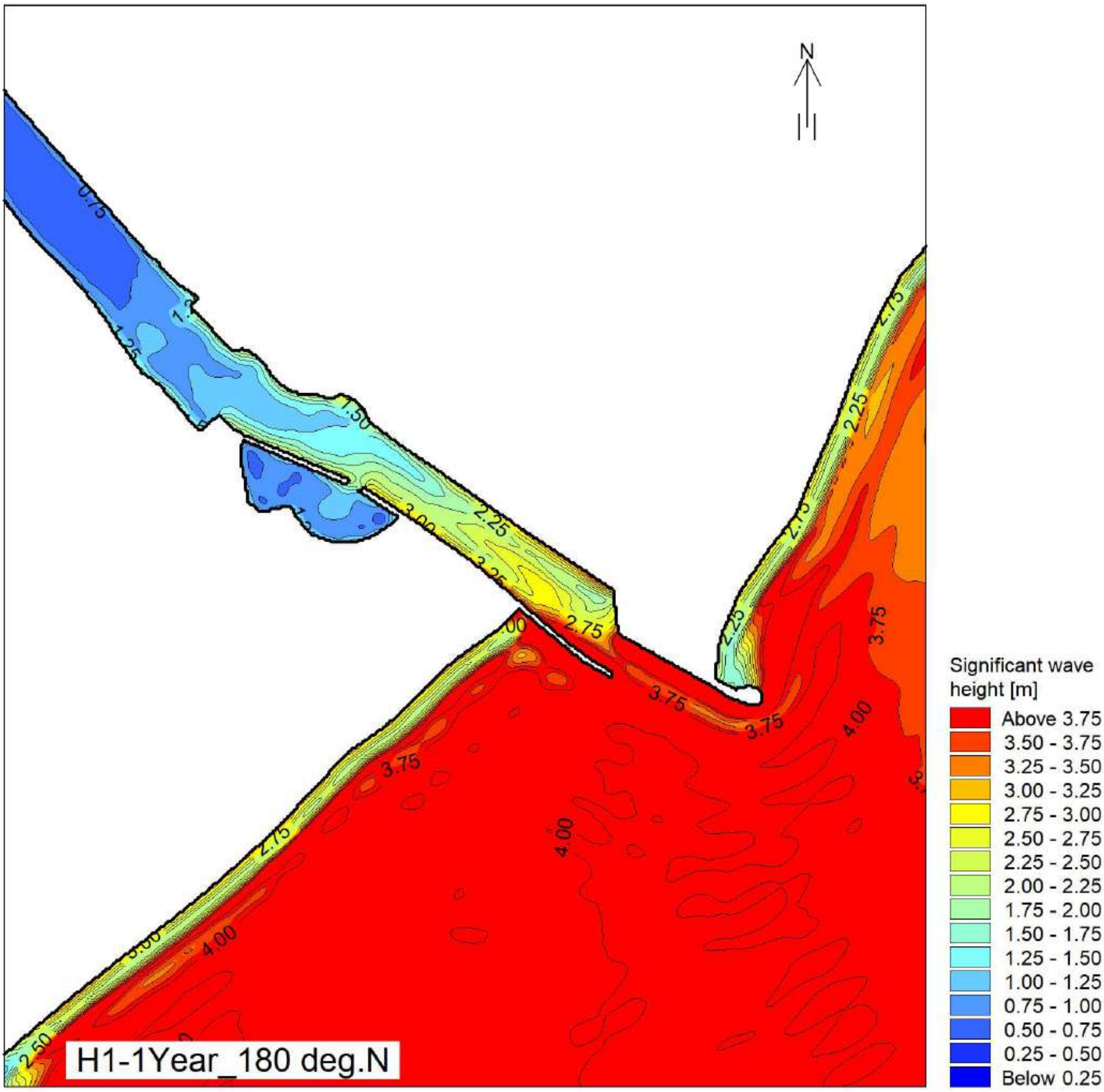

Figure E15: Layout H1, 1 year wave from 180°N

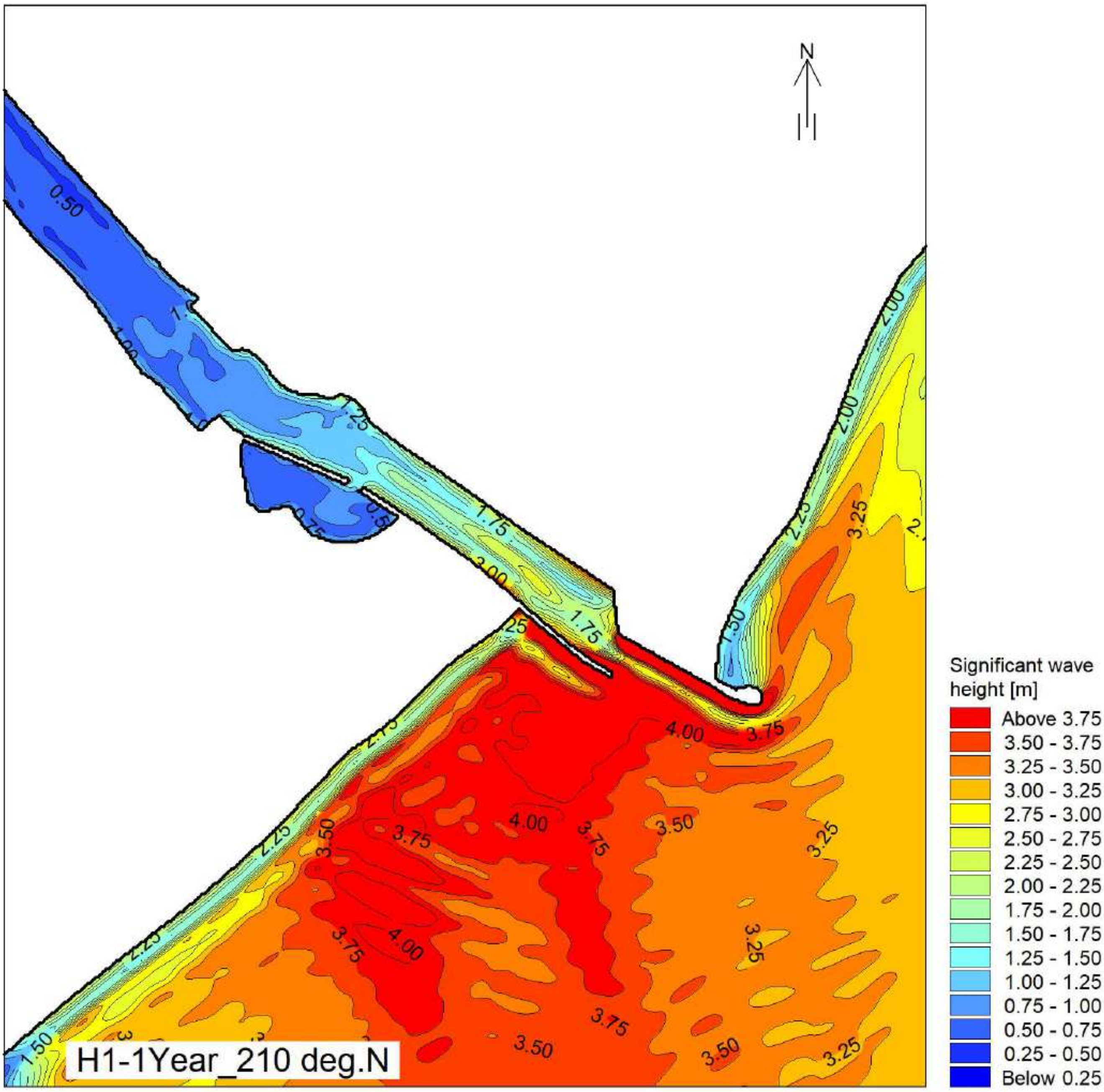

Figure E16: Layout H1, 1 year wave from 210°N

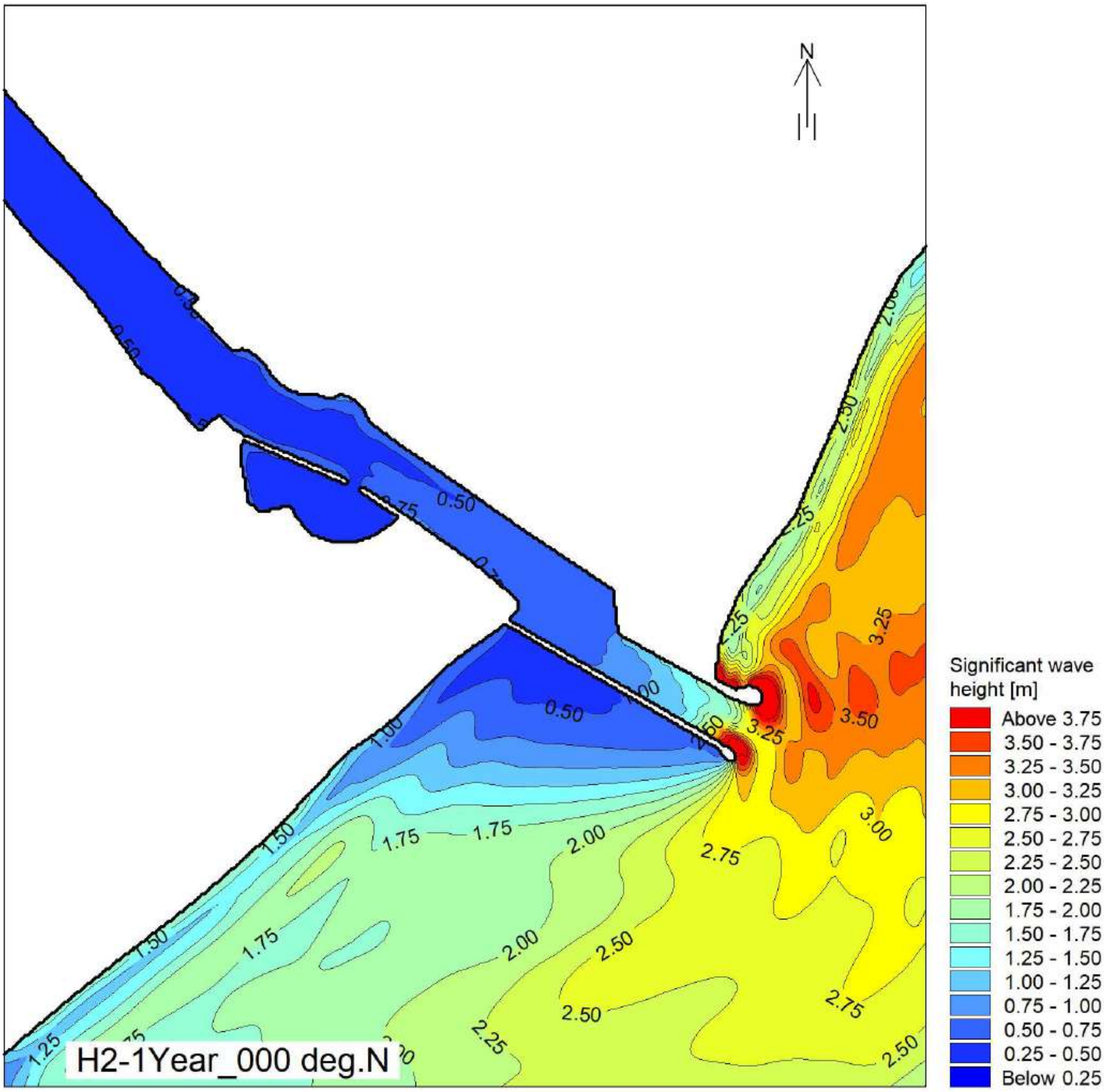

Figure E17: Layout H2, 1 year wave from 0°N

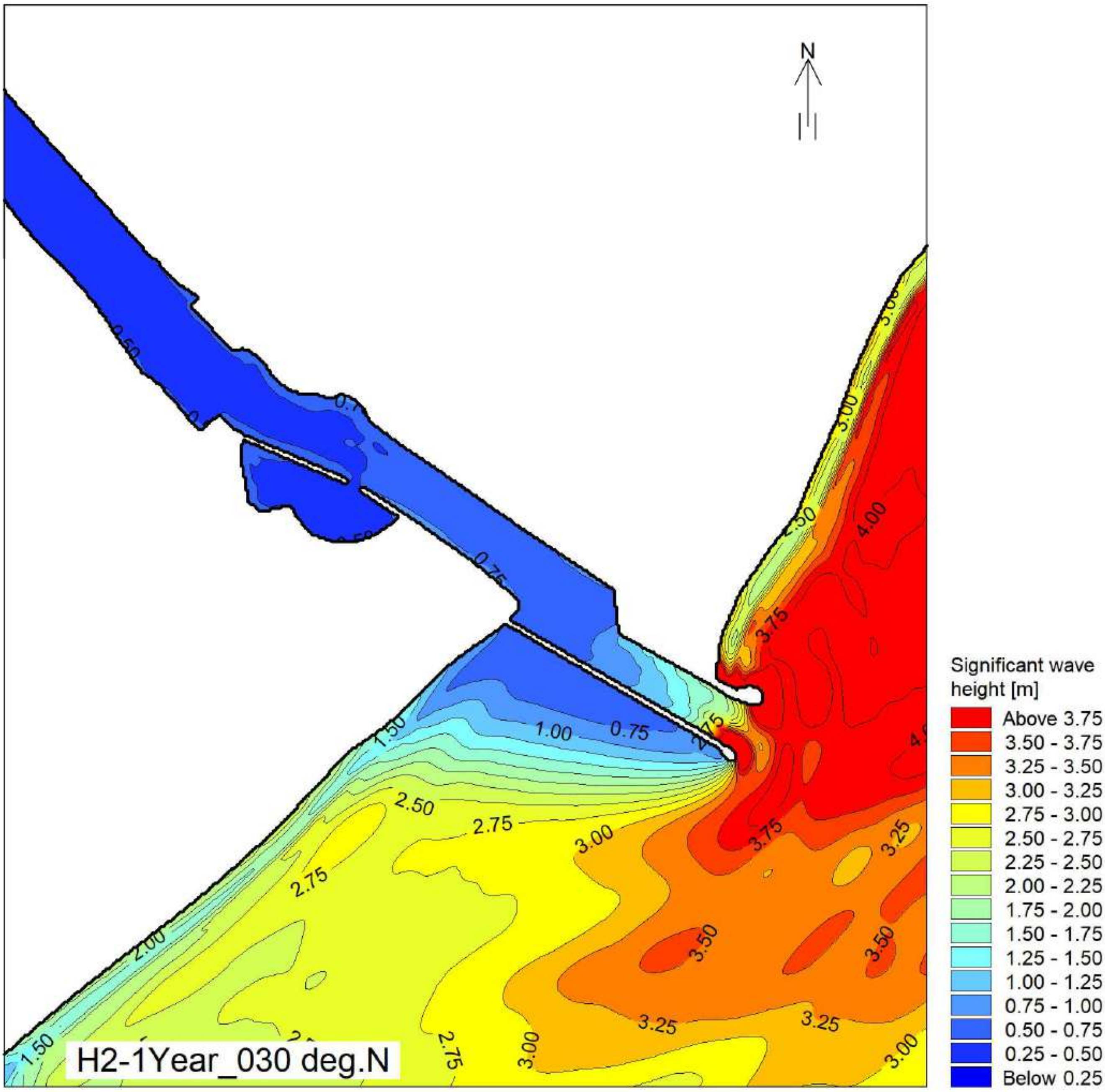

Figure E18: Layout H2, 1 year wave from 30°N

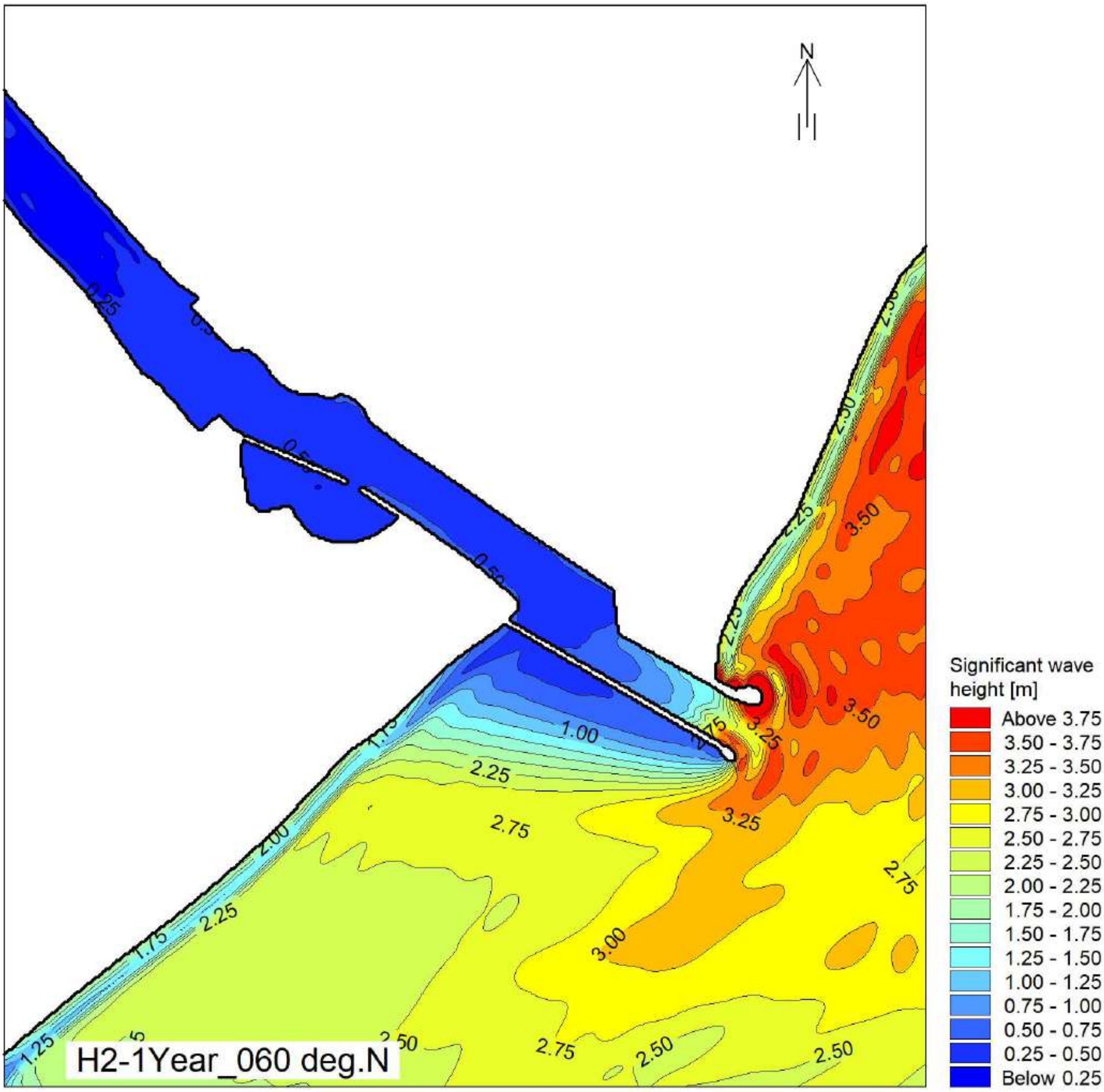

Figure E19: Layout H2, 1 year wave from 60°N

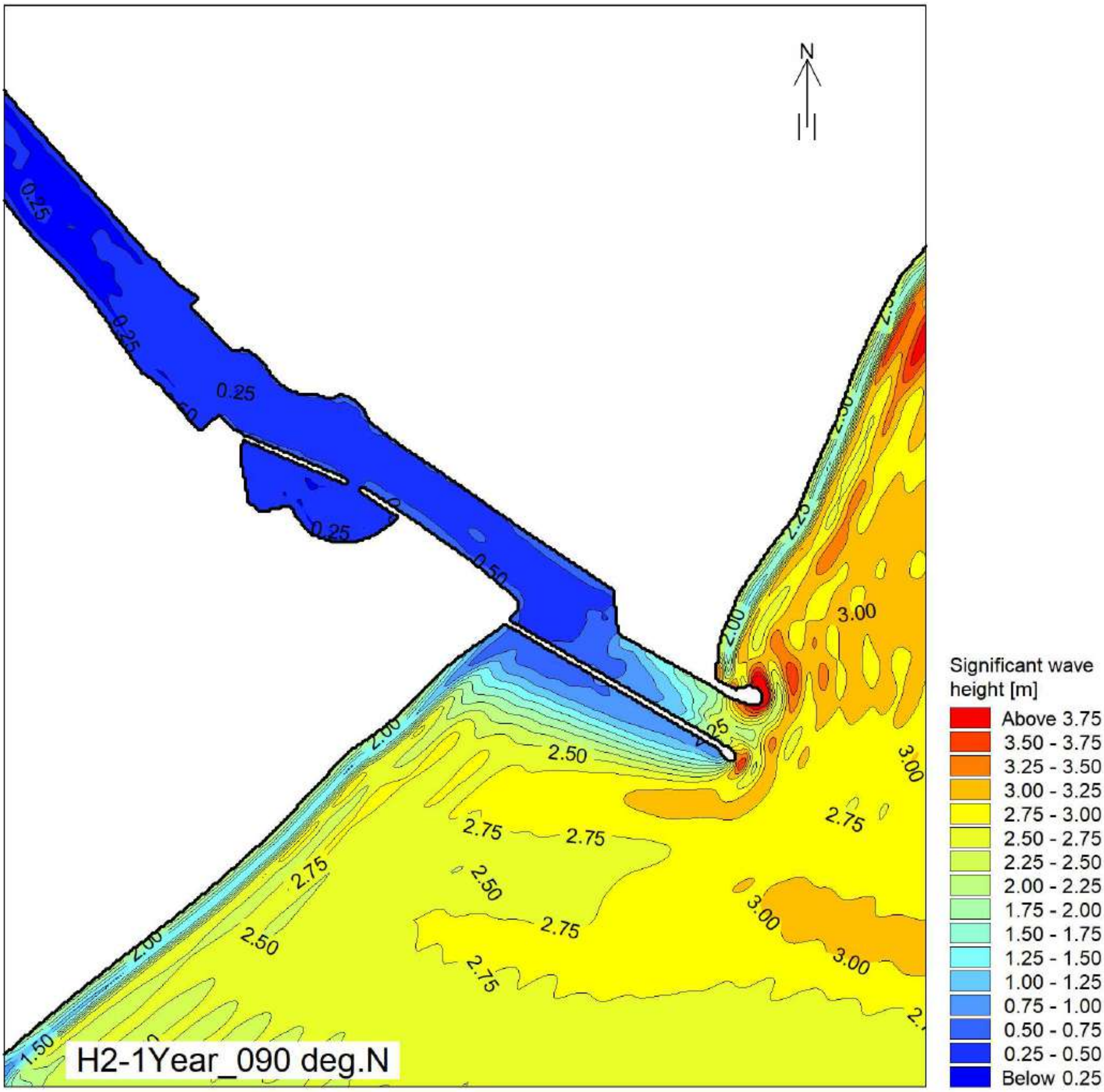

Figure E20: Layout H2, 1 year wave from 90°N

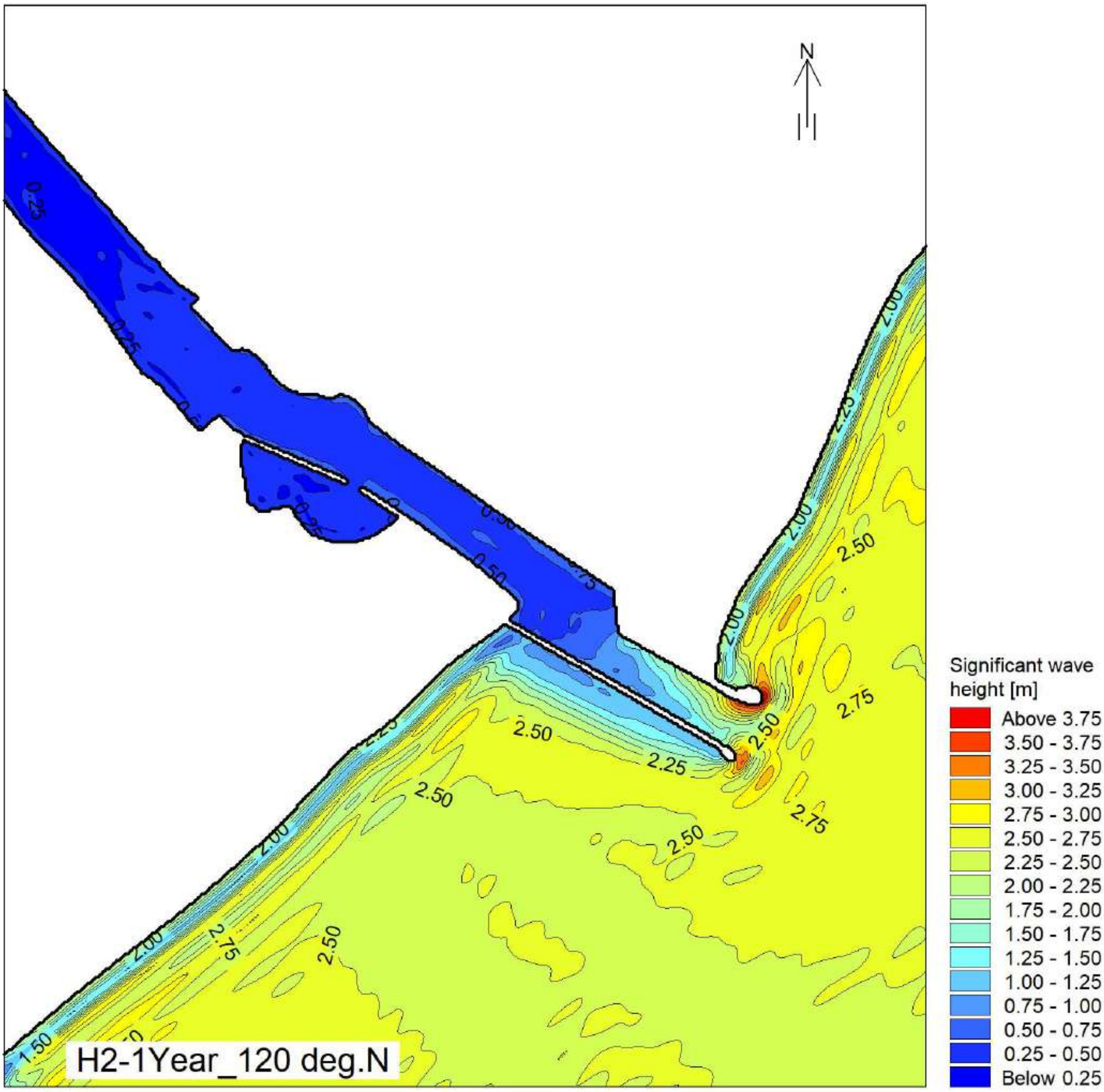

Figure E21: Layout H2, 1 year wave from 120°N

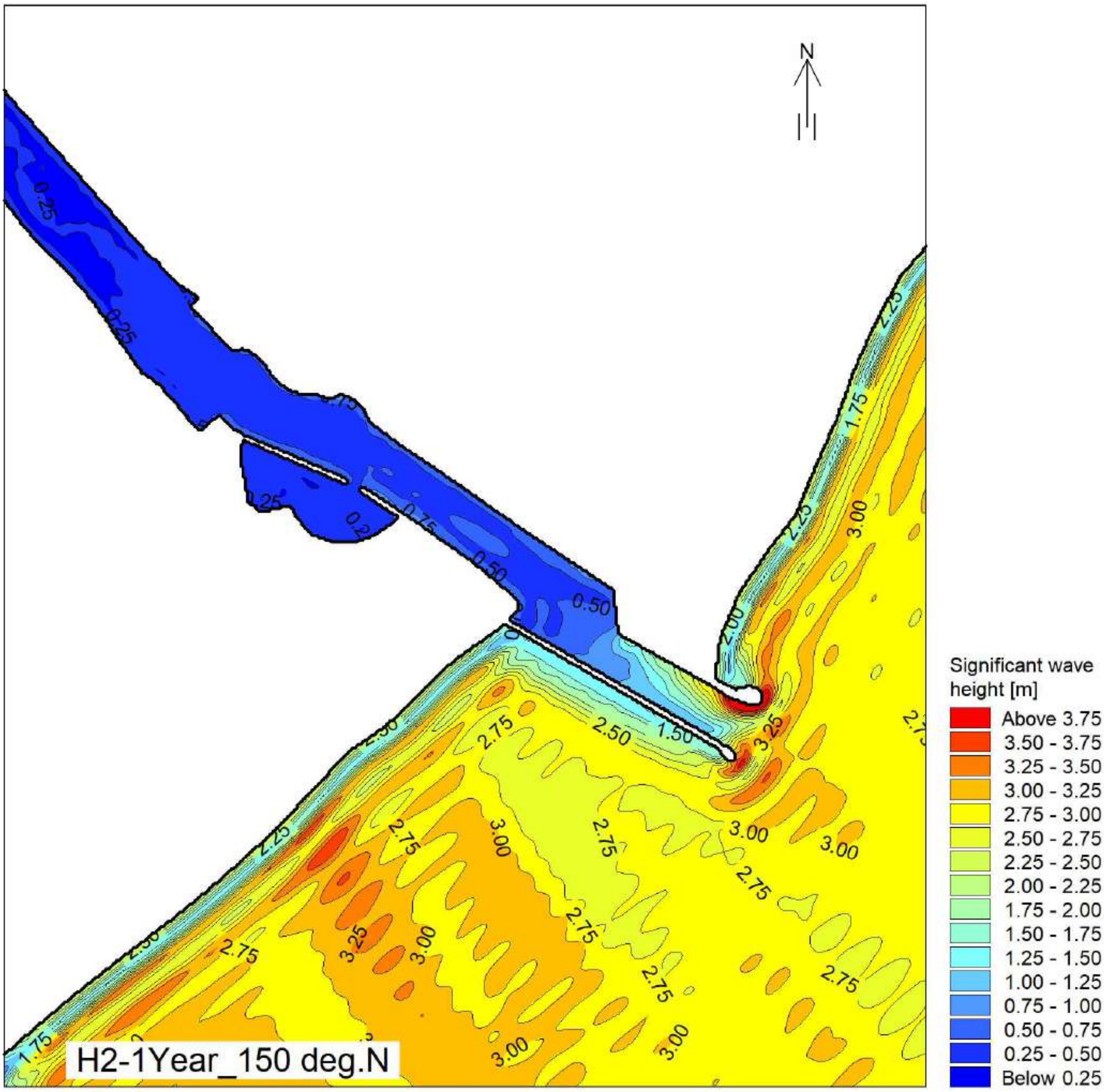

Figure E22: Layout H2, 1 year wave from 150°N

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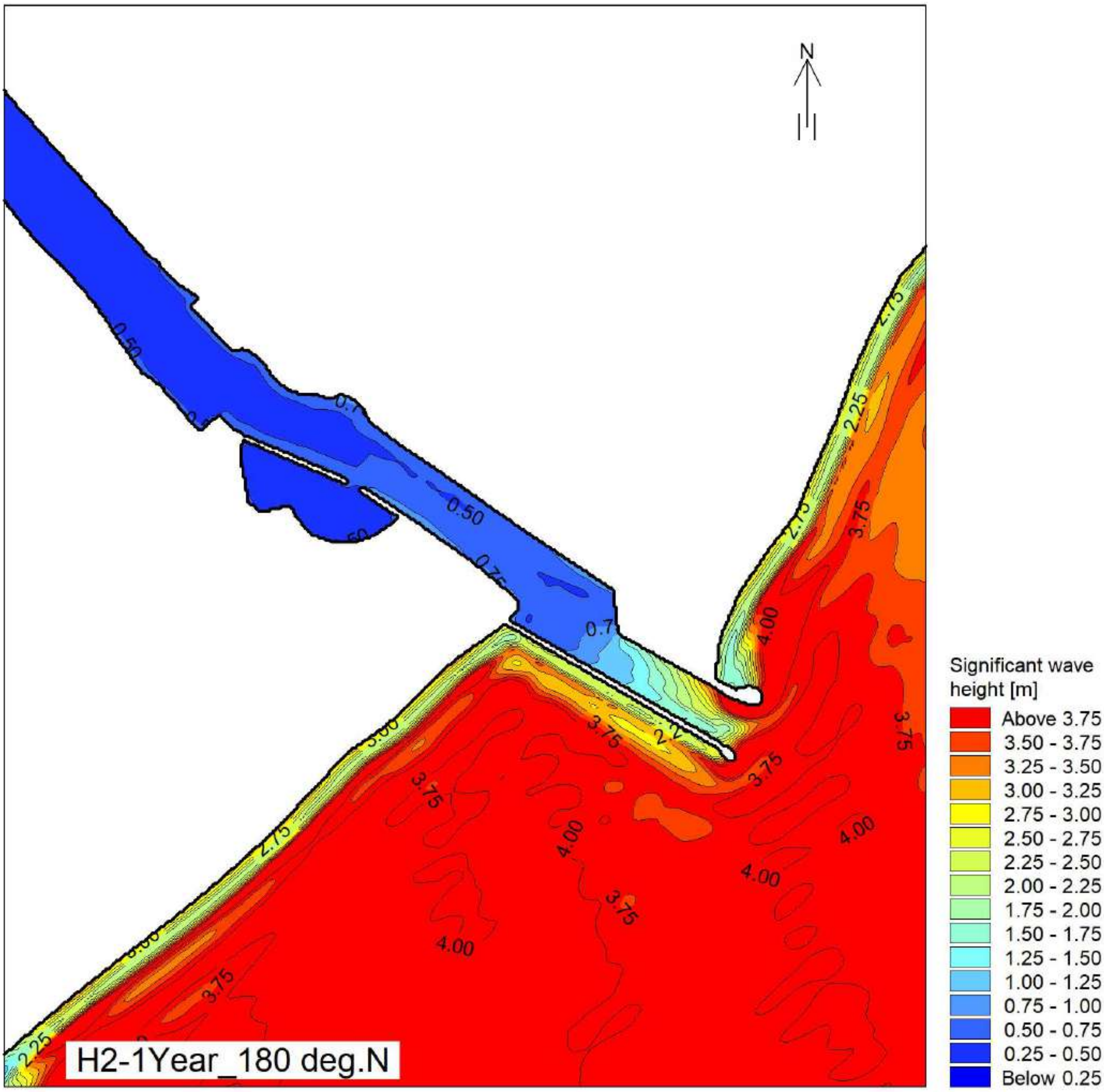

Figure E23: Layout H2, 1 year wave from 180°N

Royal HaskoningDHV

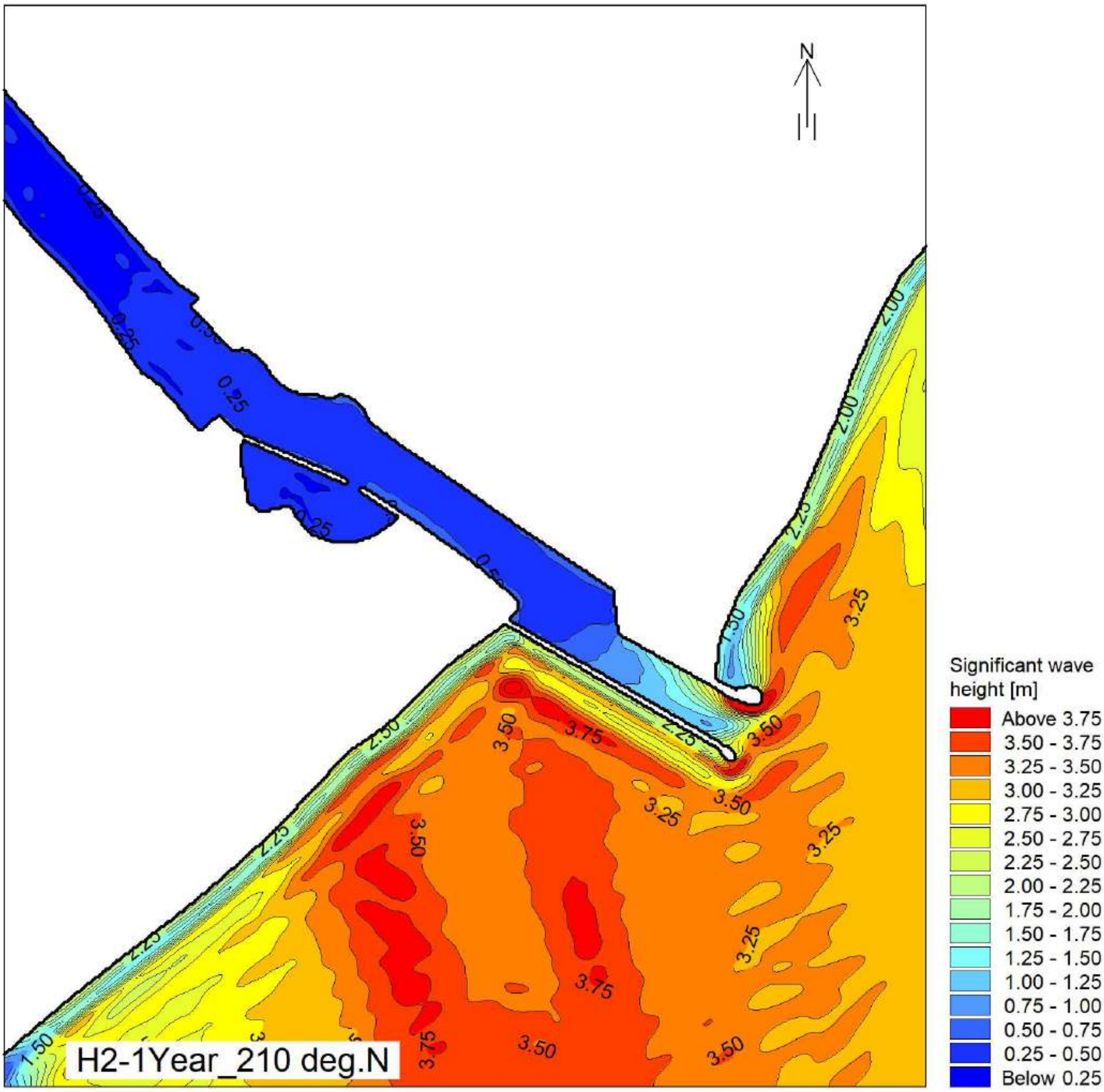

Figure E24: Layout H2, 1 year wave from 210°N

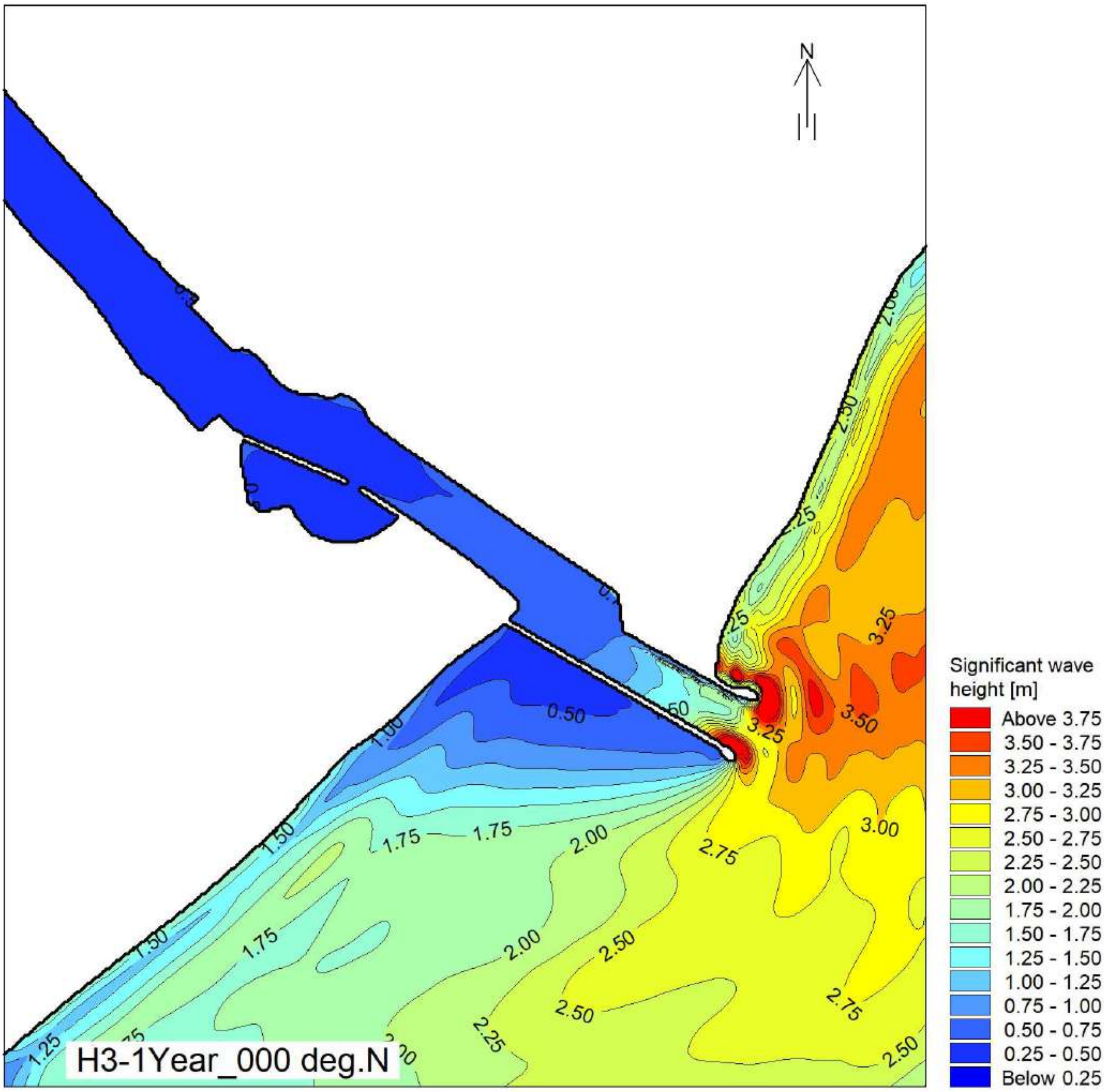

Figure E25: Layout H3, 1 year wave from 0°N

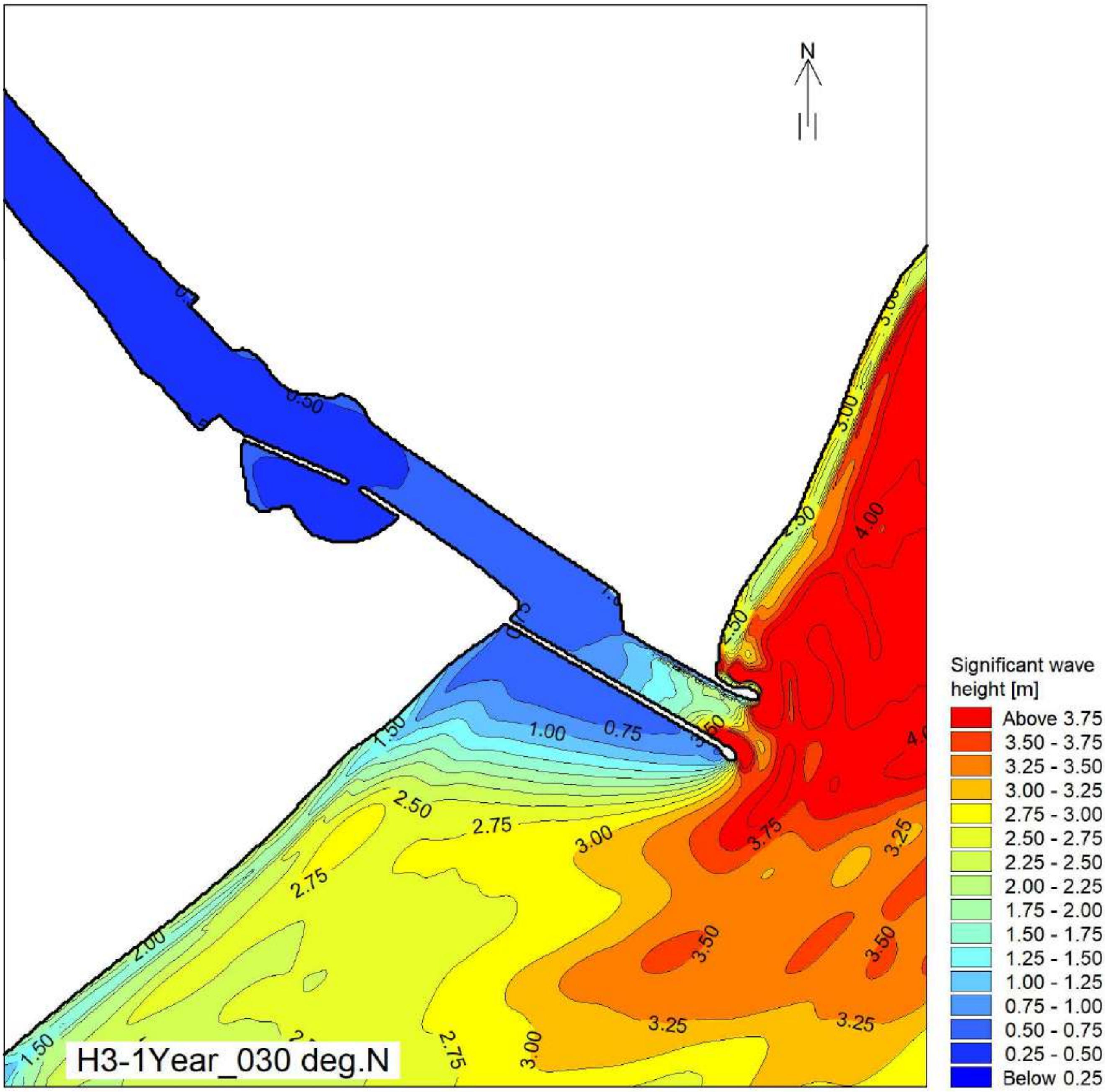

Figure E26: Layout H3, 1 year wave from 30°N

Royal HaskoningDHV

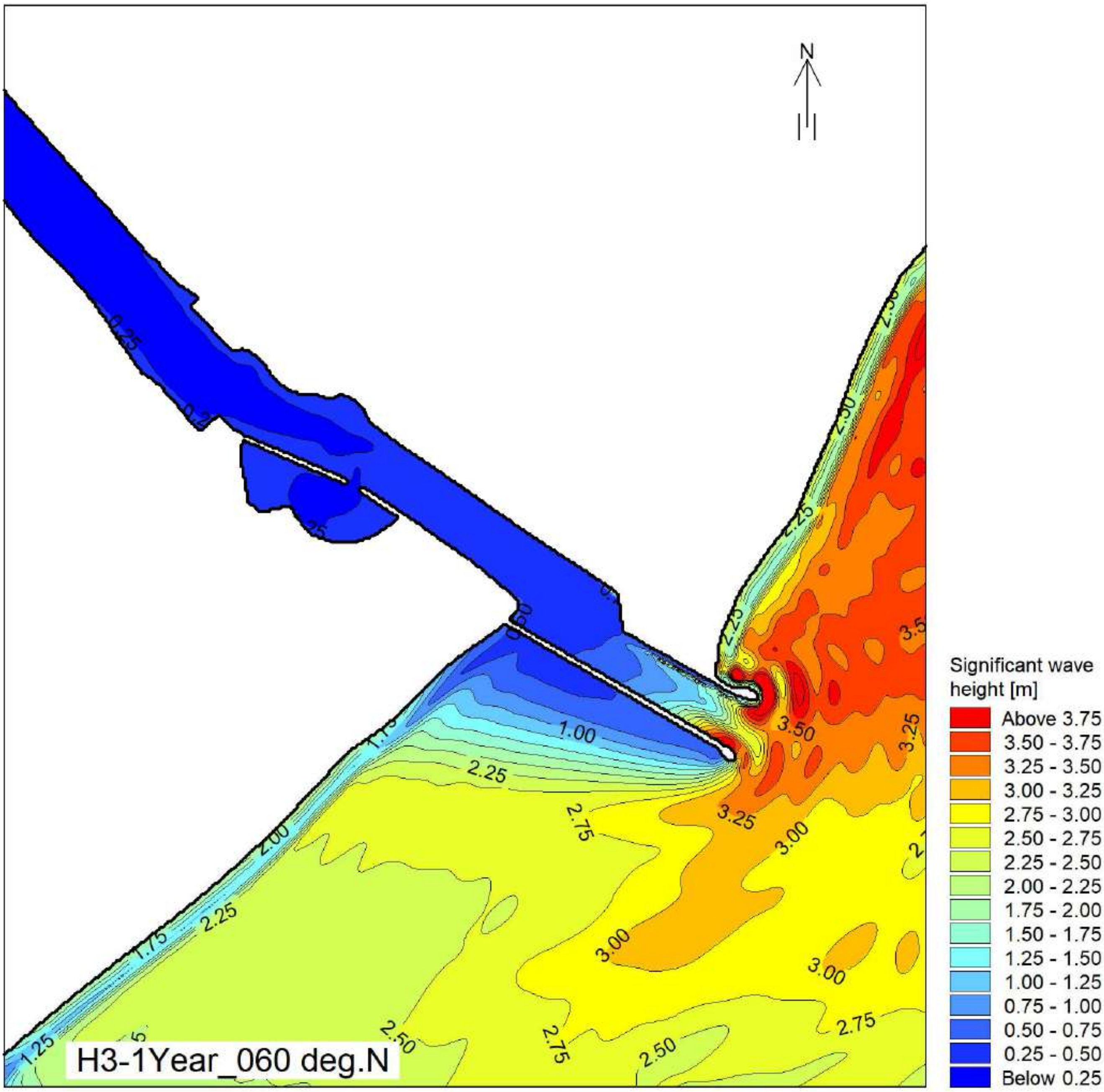

Figure E27: Layout H3, 1 year wave from 60°N

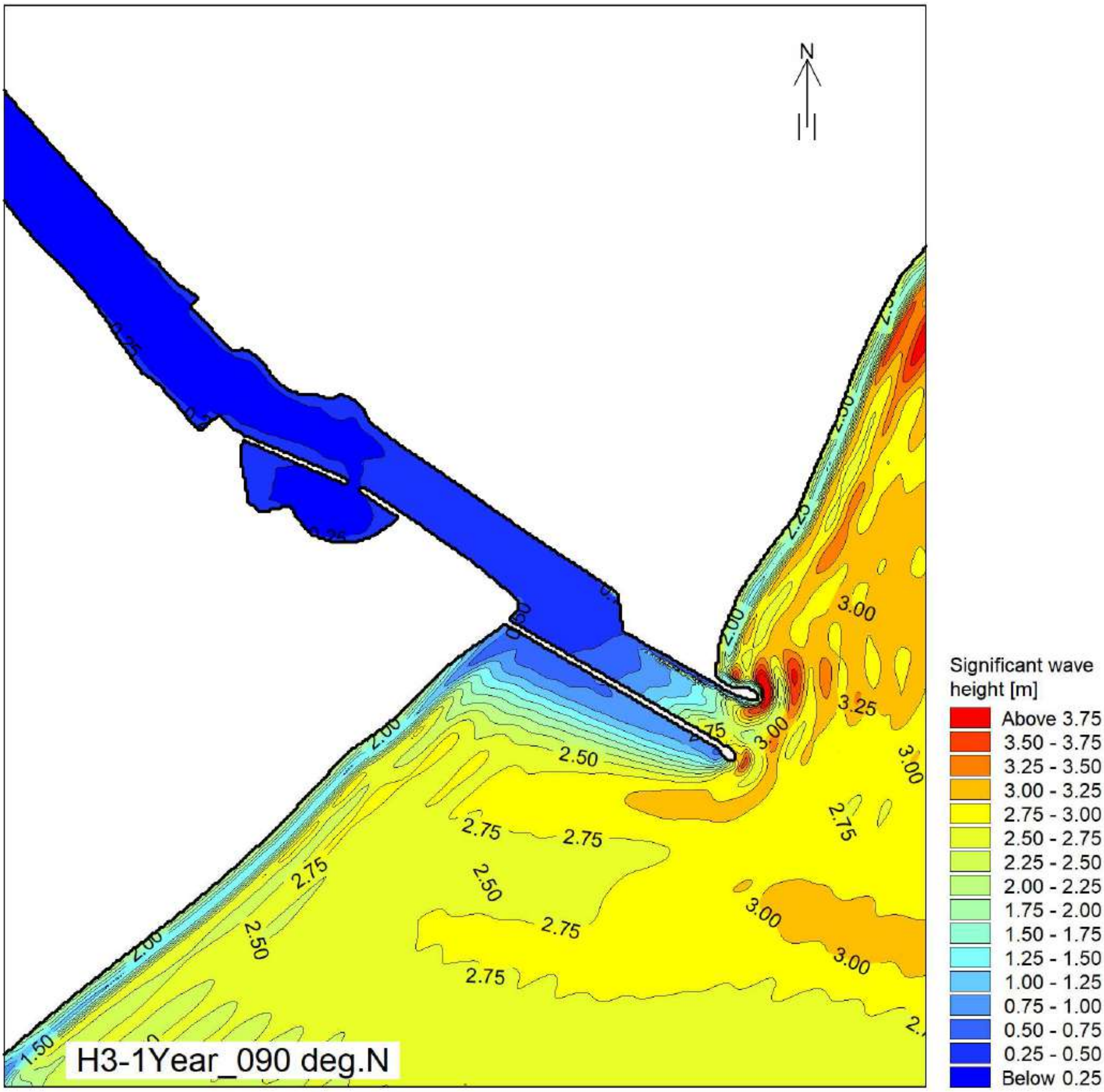

Figure E28: Layout H3, 1 year wave from 90°N

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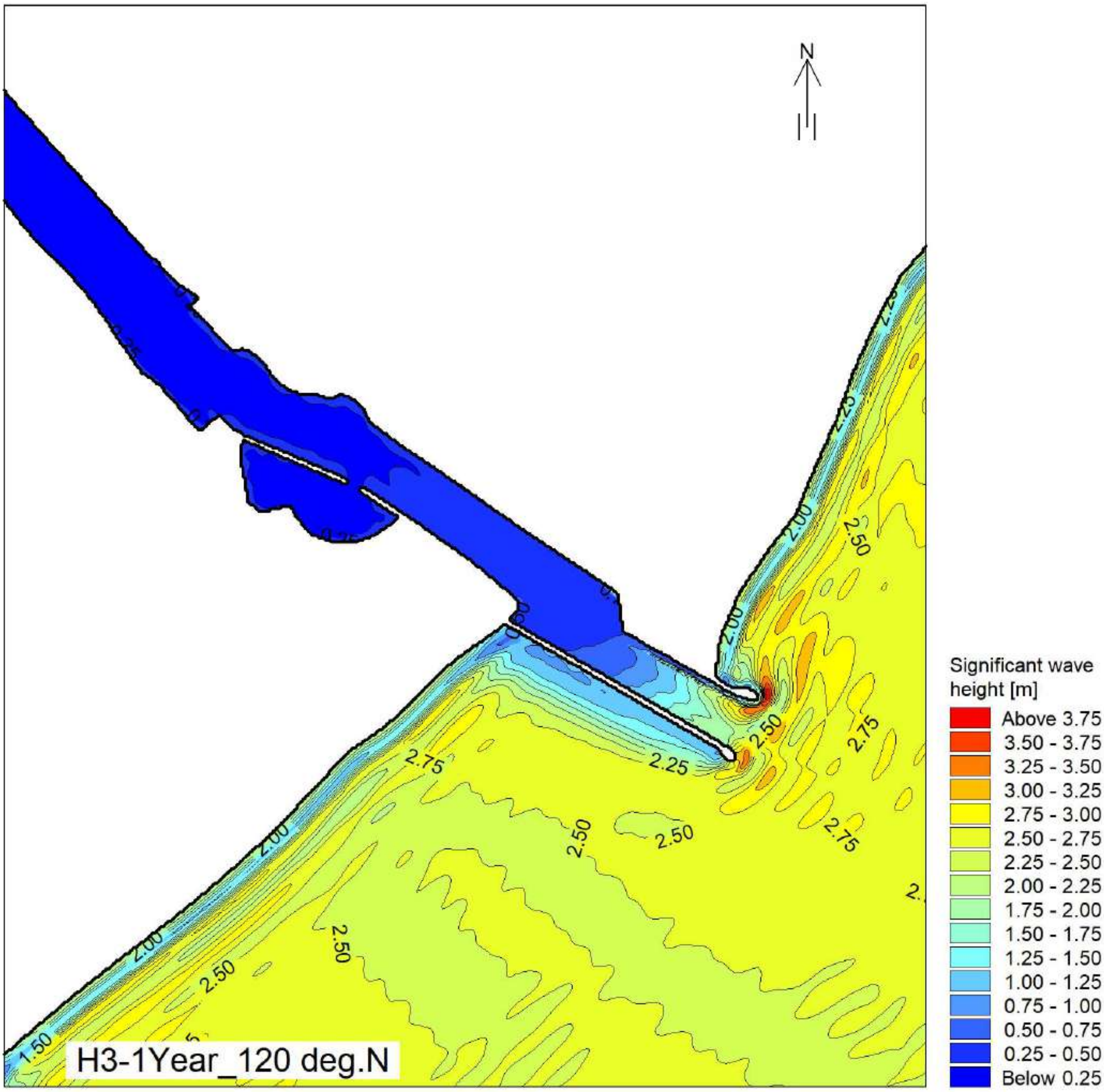

Figure E29: Layout H3, 1 year wave from 120°N

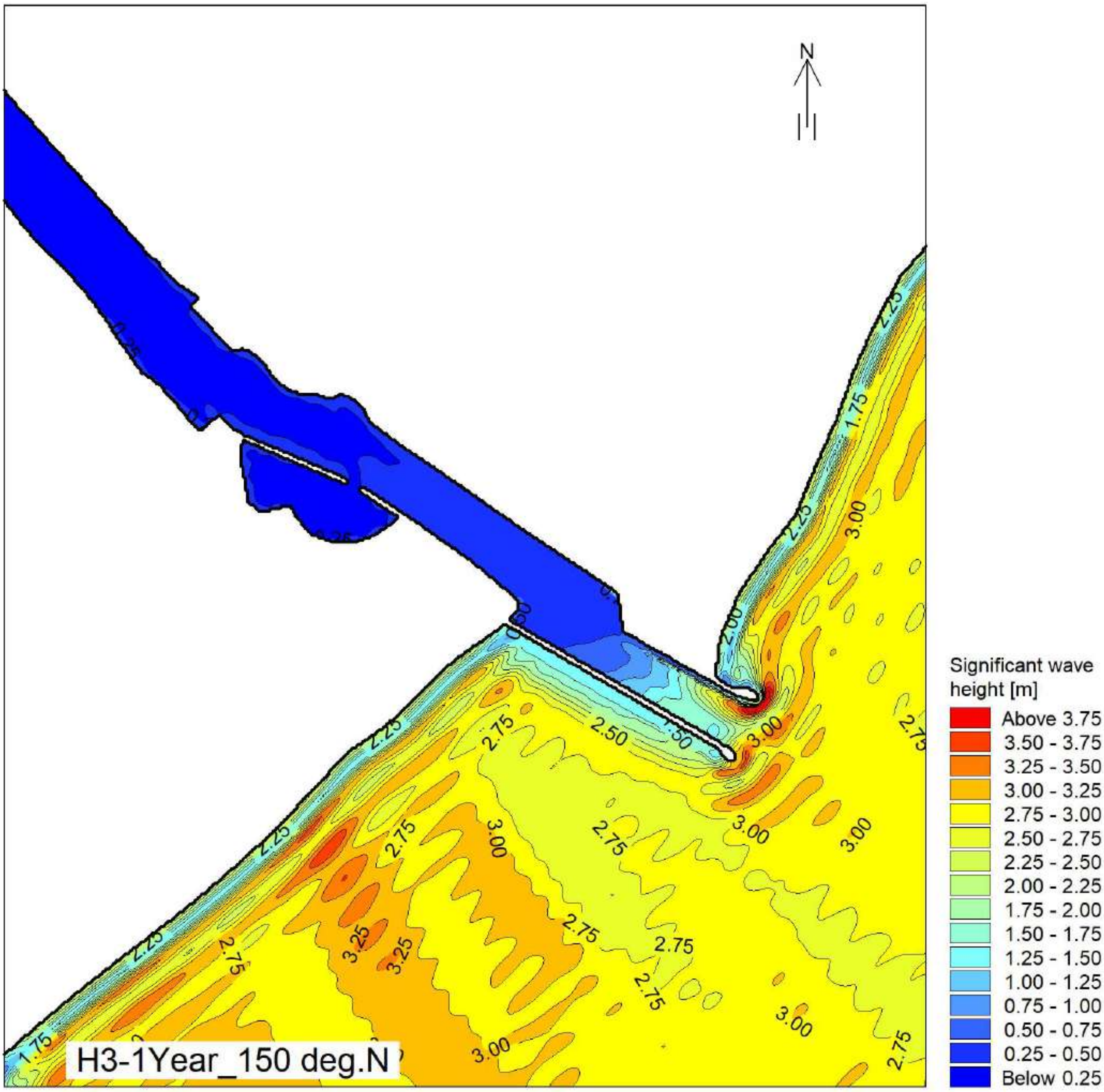

Figure E30: Layout H3, 1 year wave from 150°N

Royal HaskoningDHV

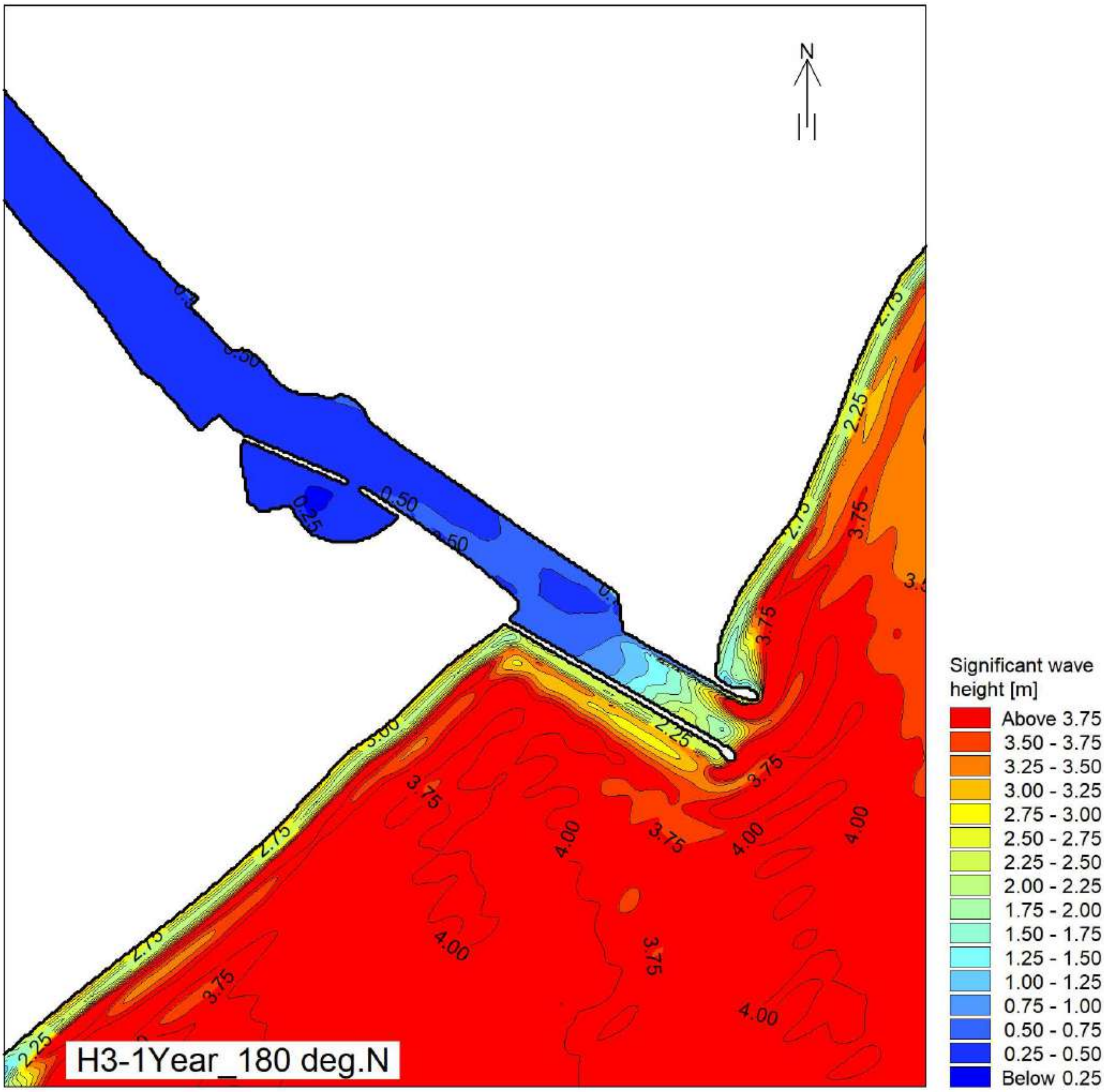

Figure E31: Layout H3, 1 year wave from 180°N

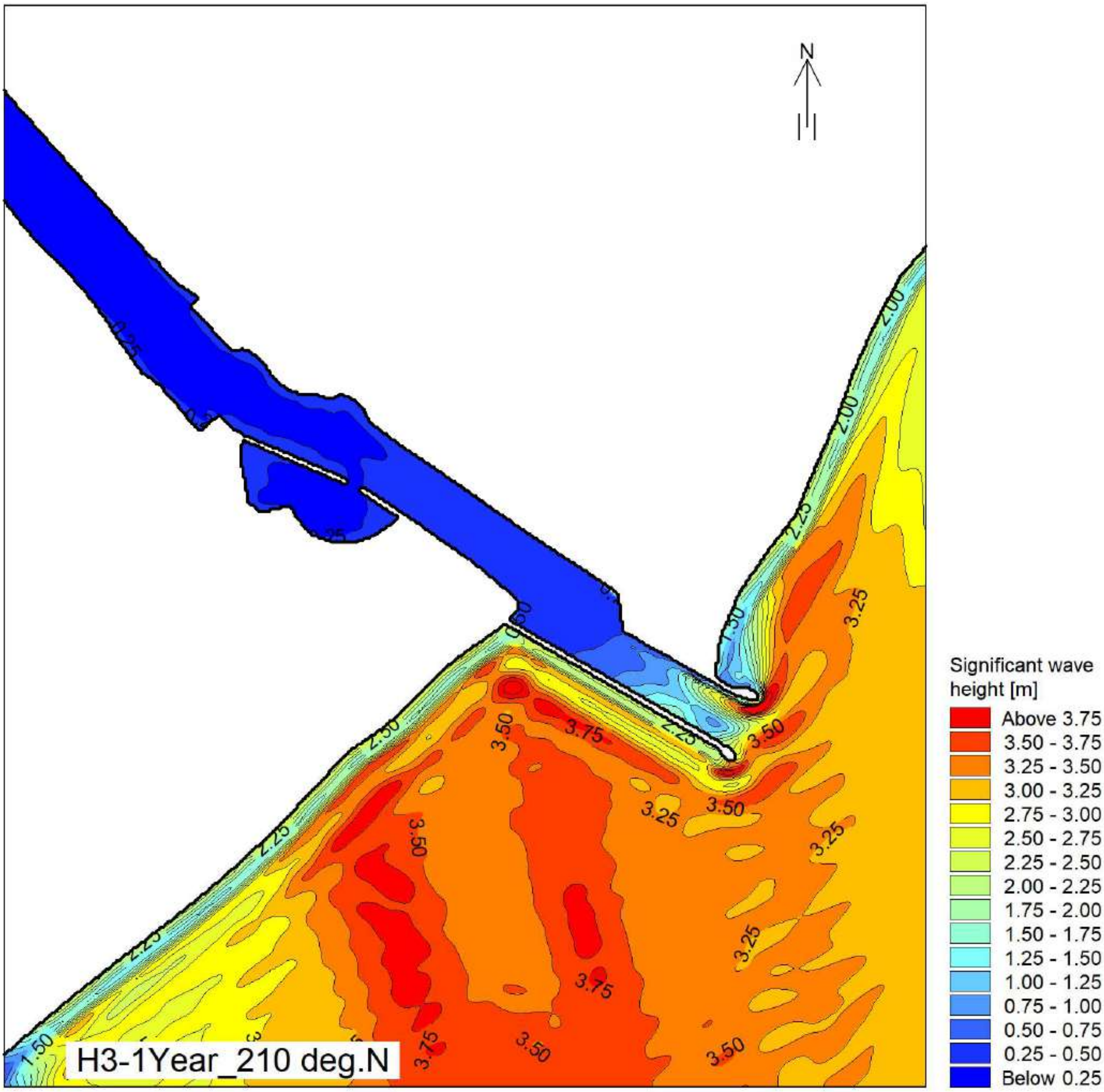

Figure E32: Layout H3, 1 year wave from 210°N

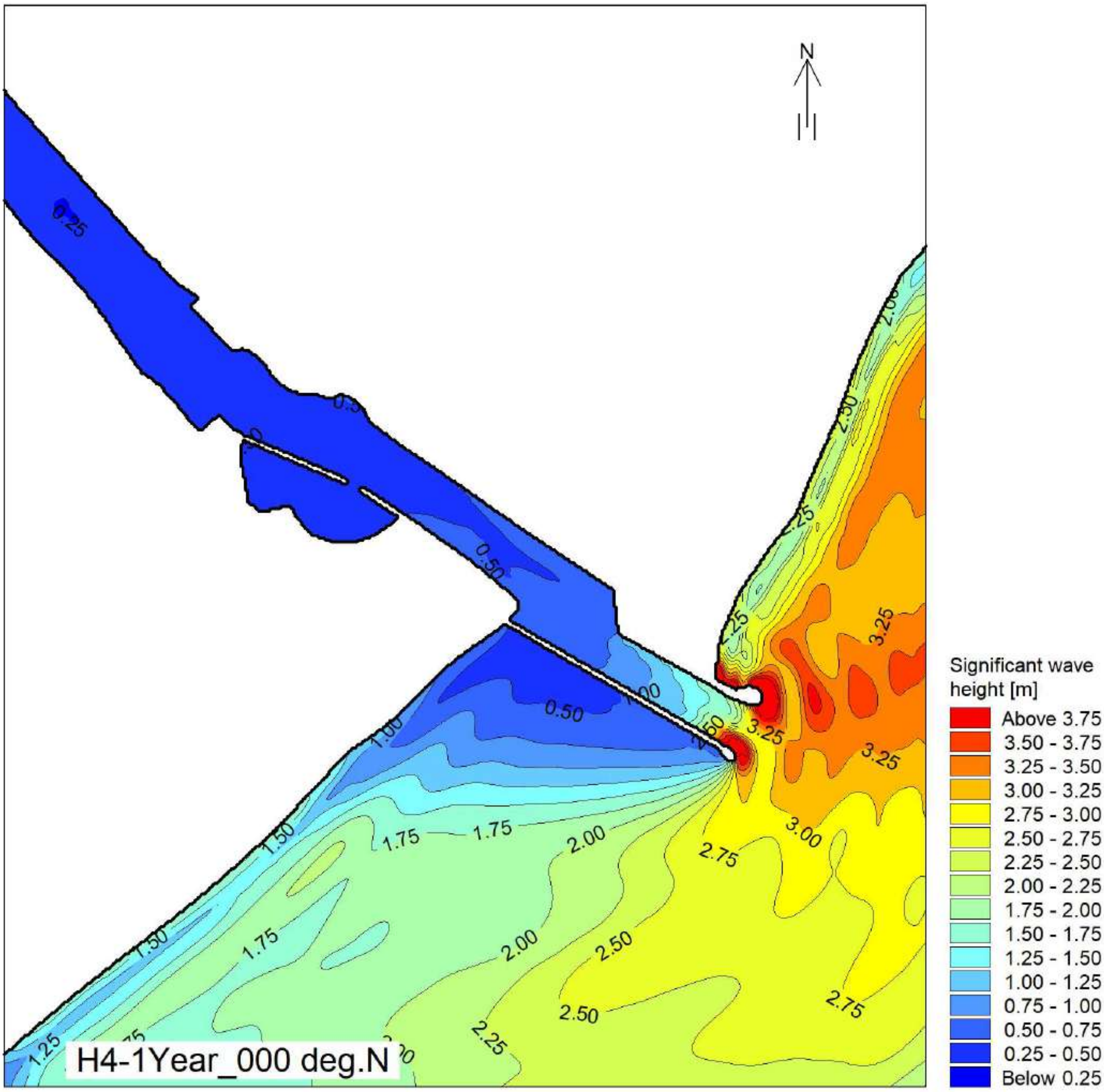

Figure E33: Layout H4, 1 year wave from 0°N

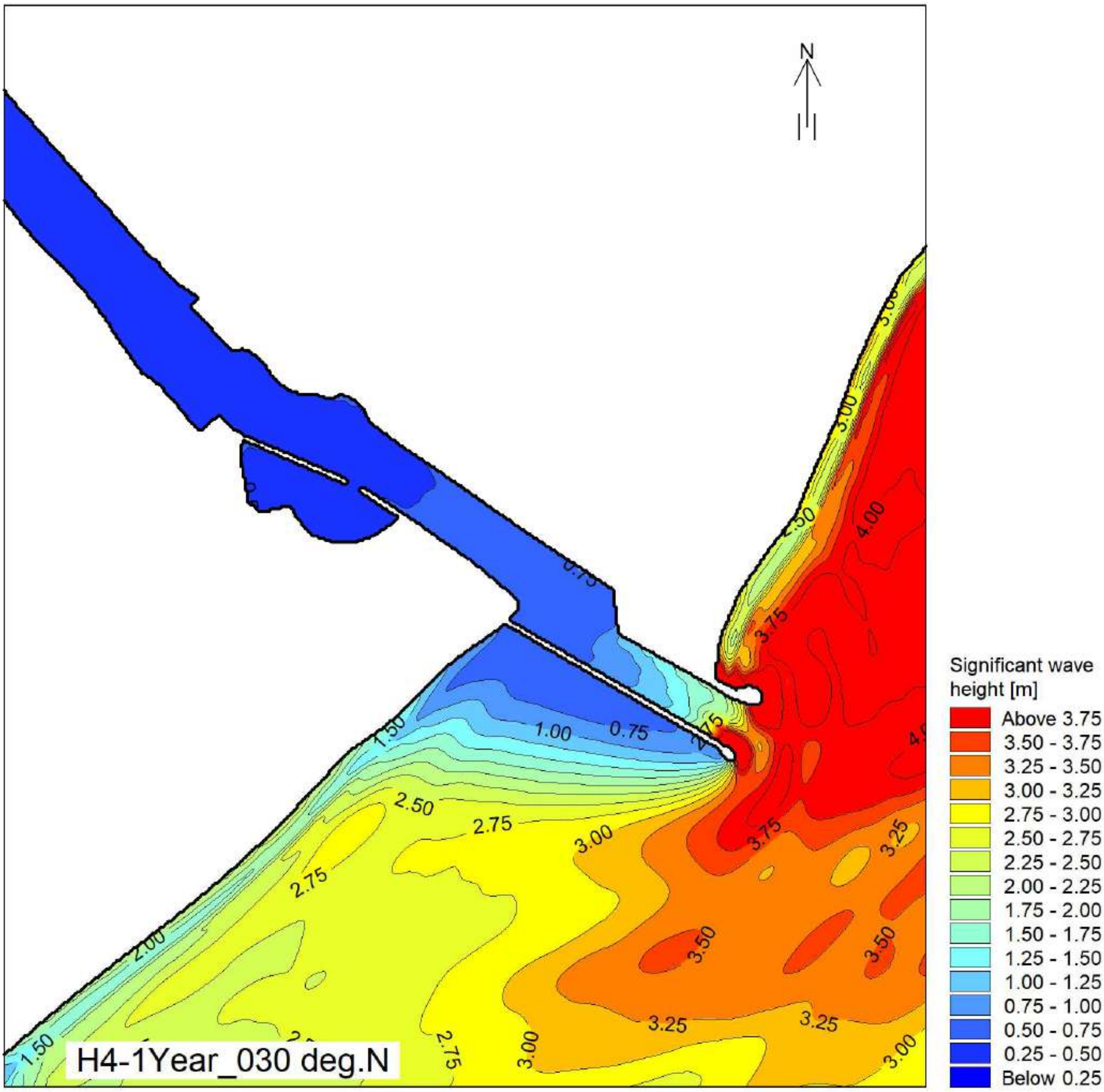

Figure E34: Layout H4, 1 year wave from 30°N

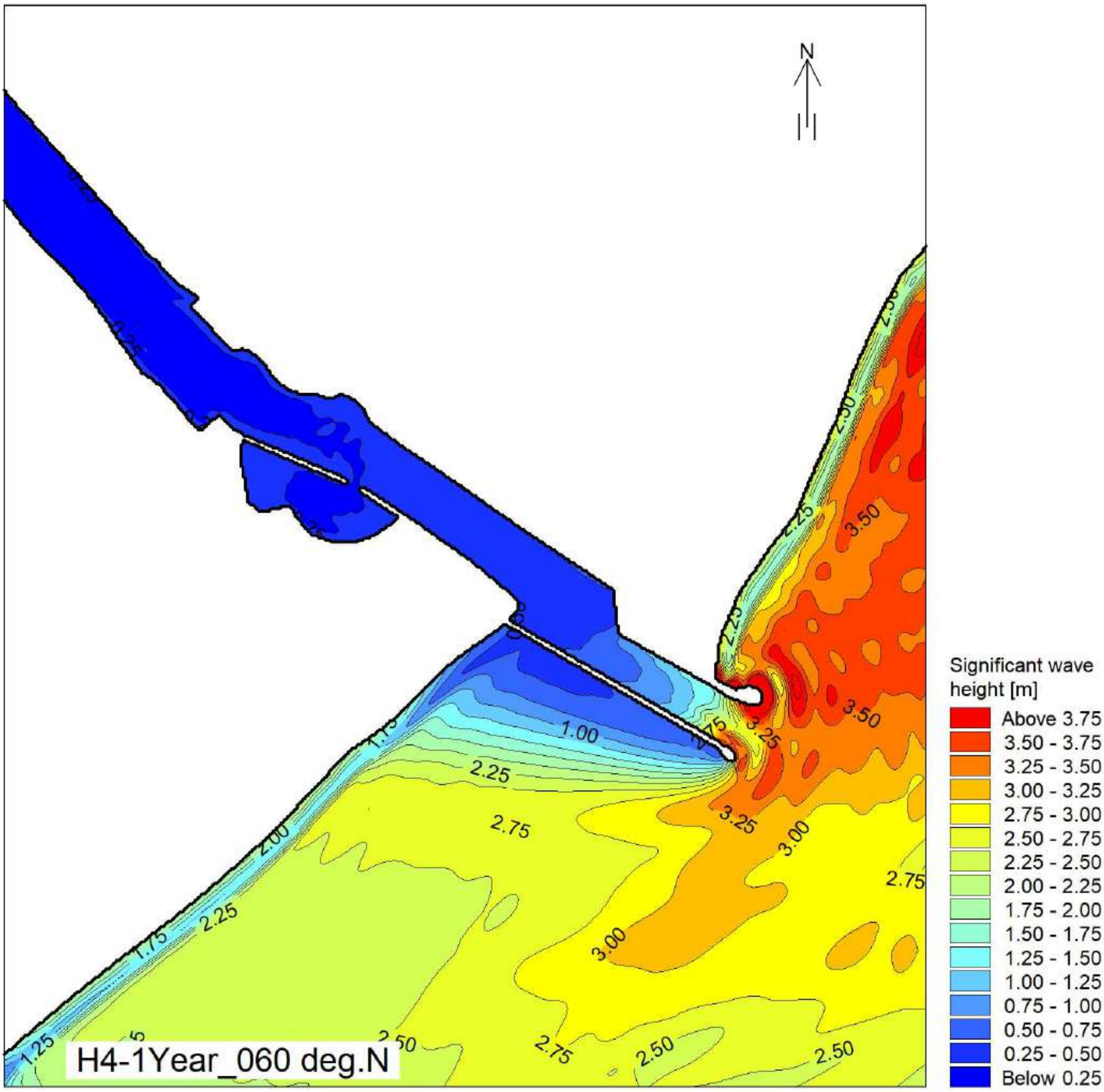

Figure E35: Layout H4, 1 year wave from 60°N

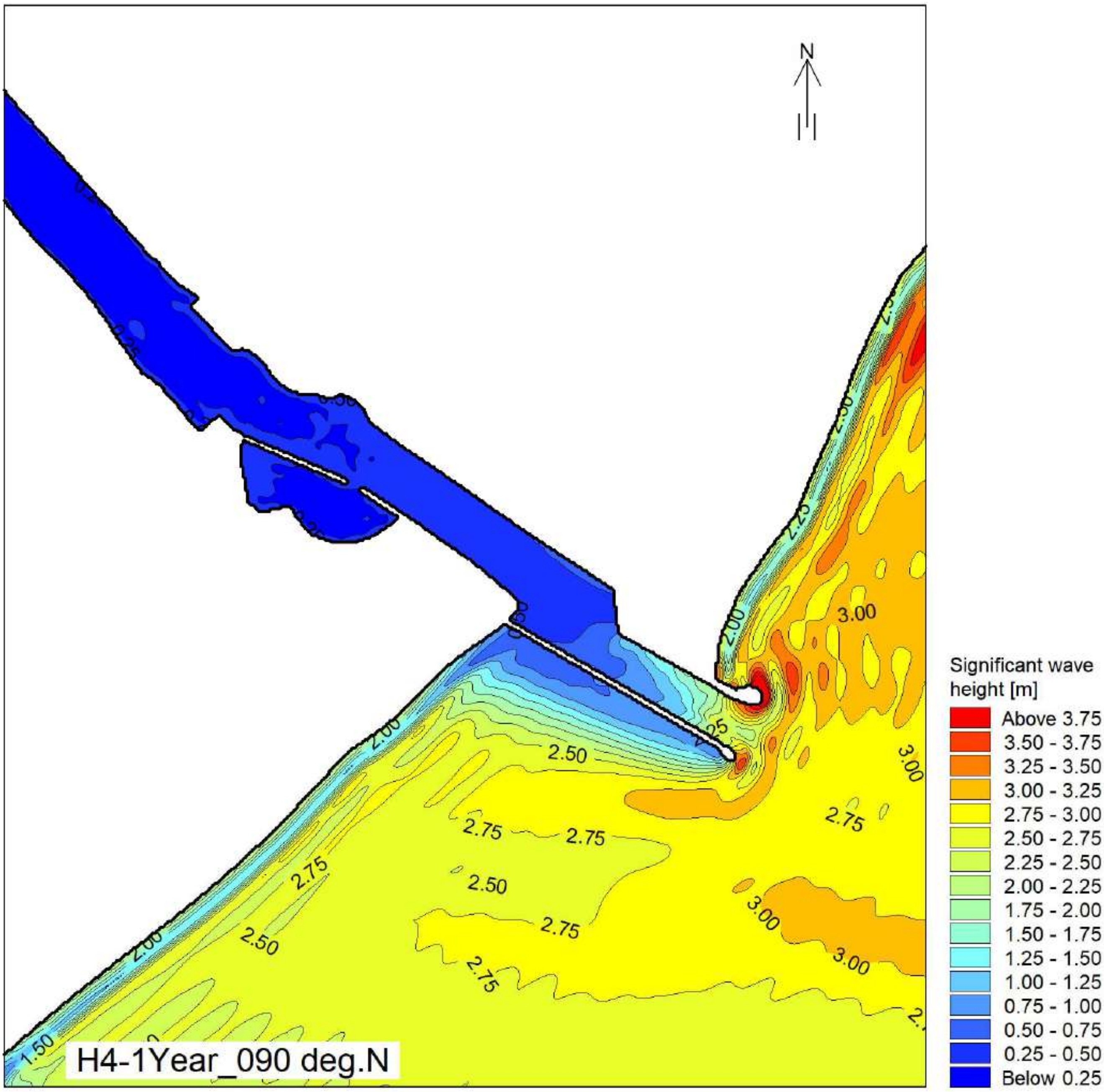

Figure E36: Layout H4, 1 year wave from 90°N

Royal HaskoningDHV

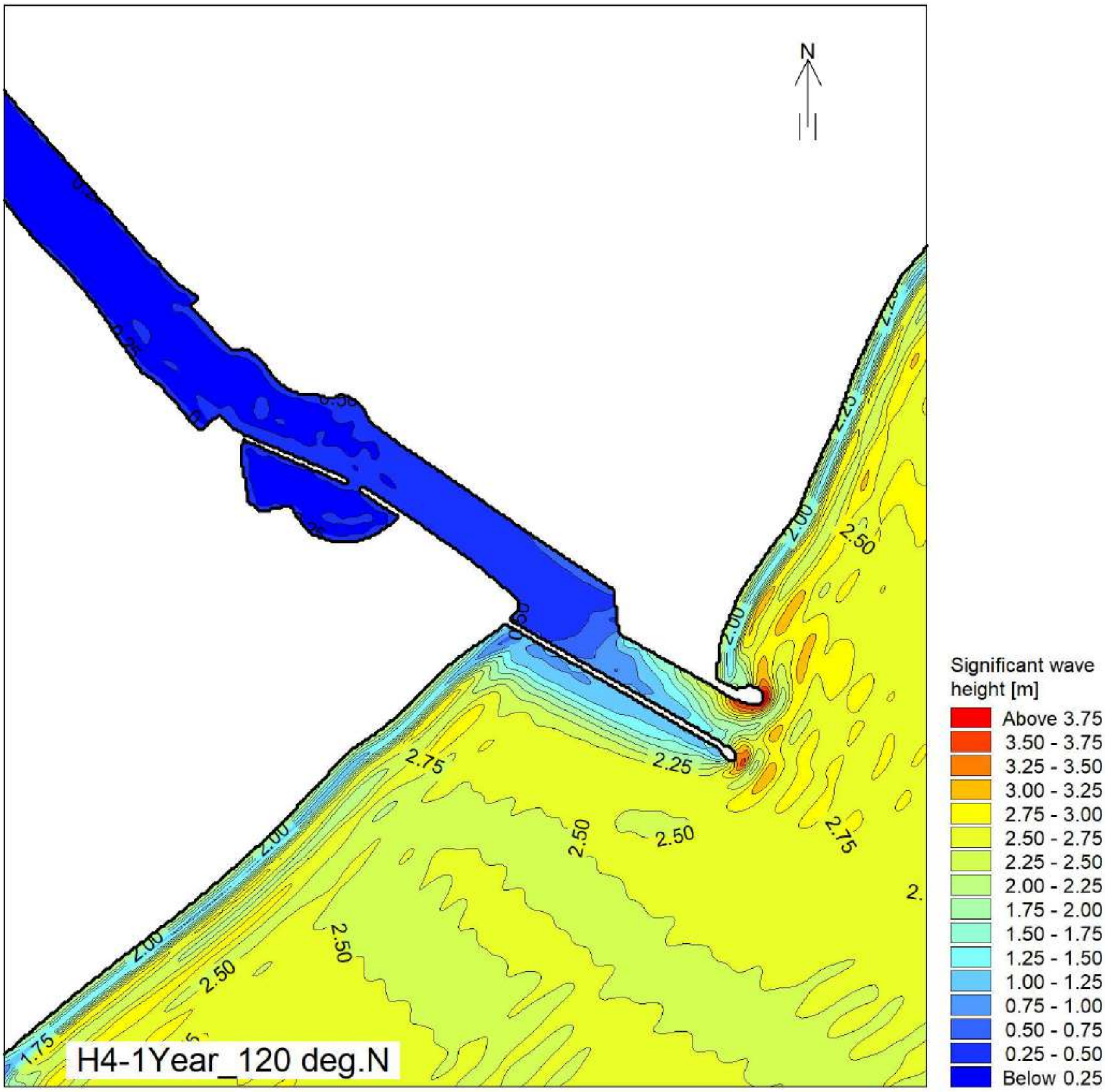

Figure E37: Layout H4, 1 year wave from 120°N

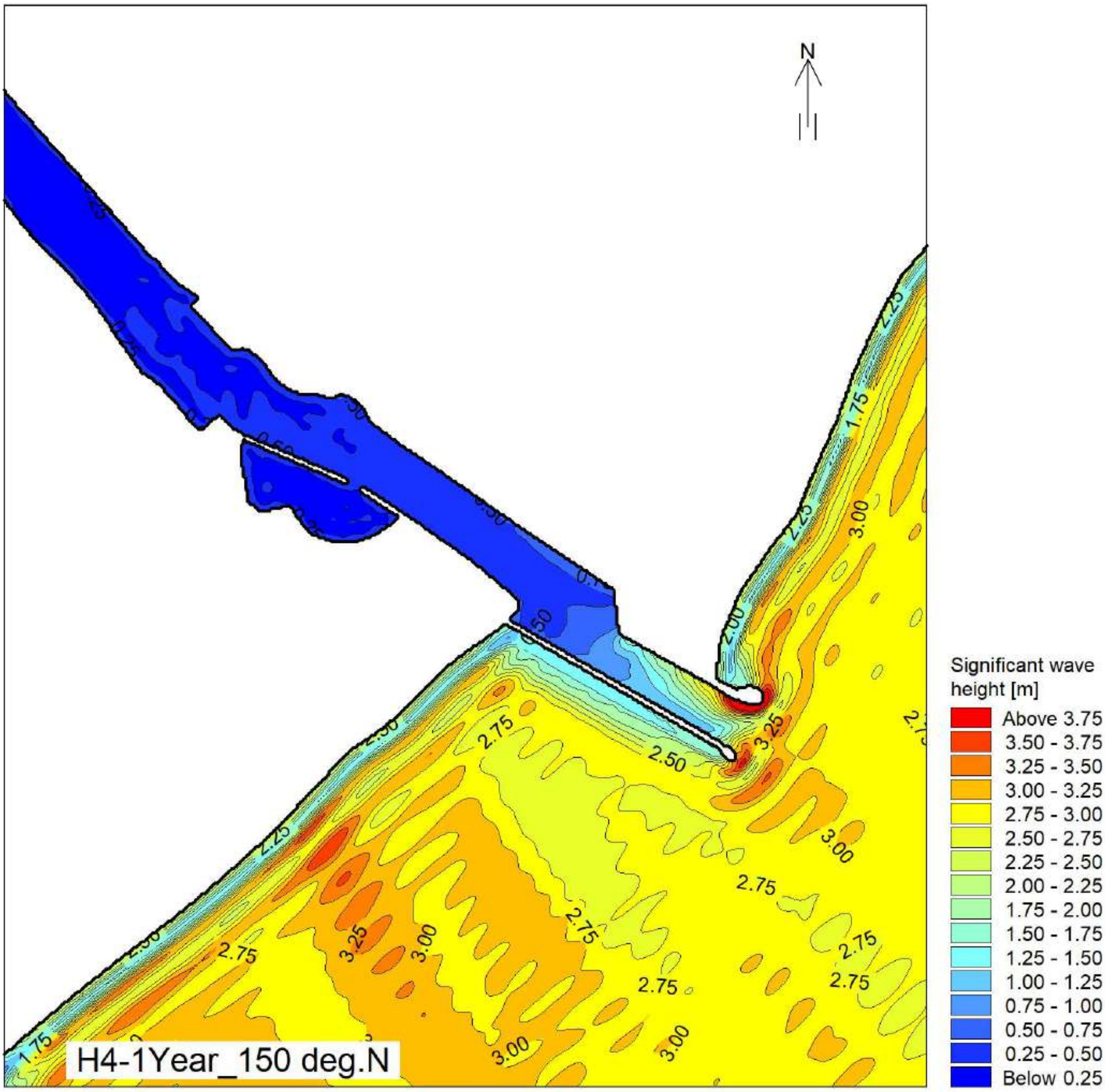

Figure E38: Layout H4, 1 year wave from 150°N

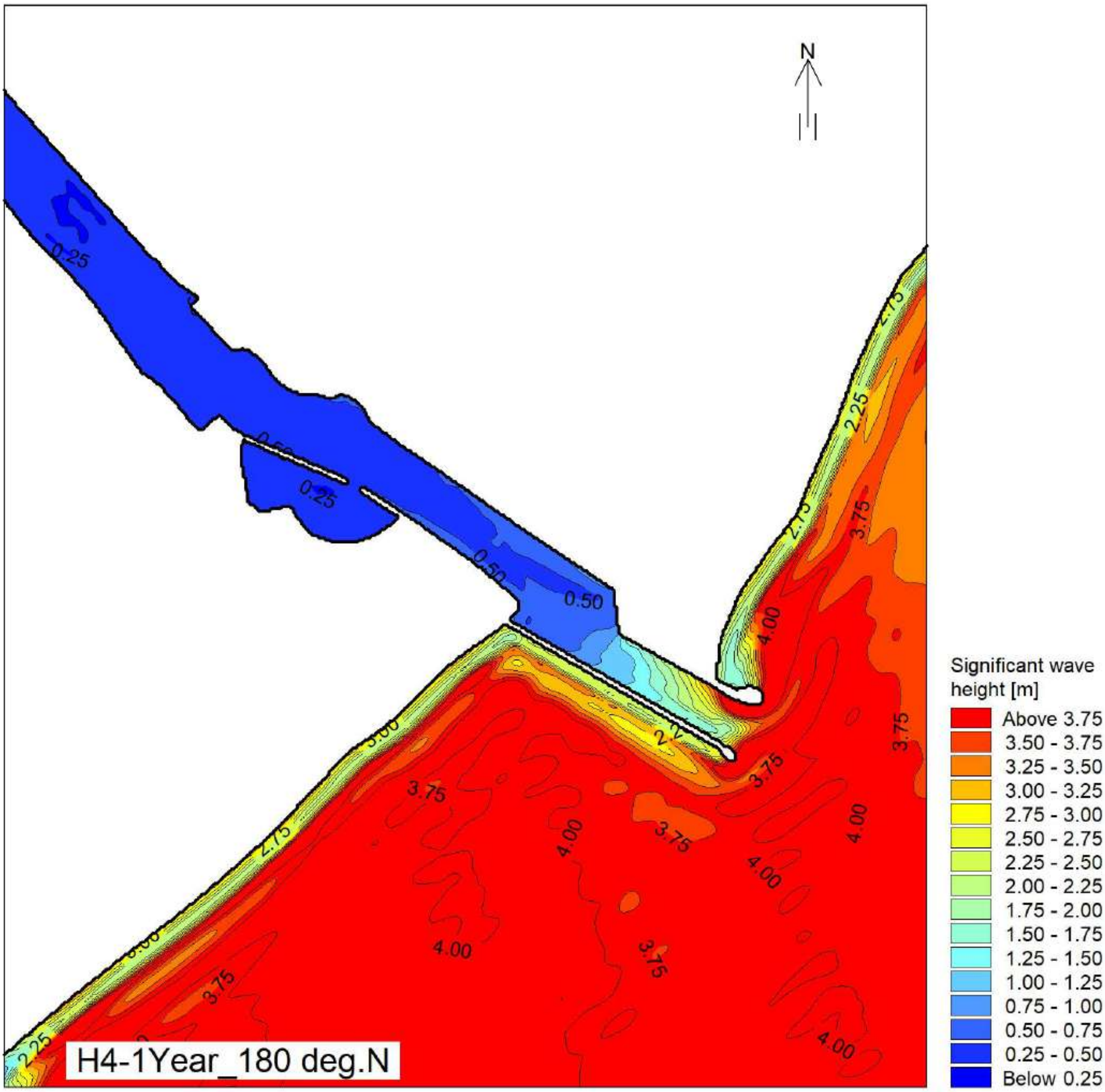

Figure E39: Layout H4, 1 year wave from 180°N

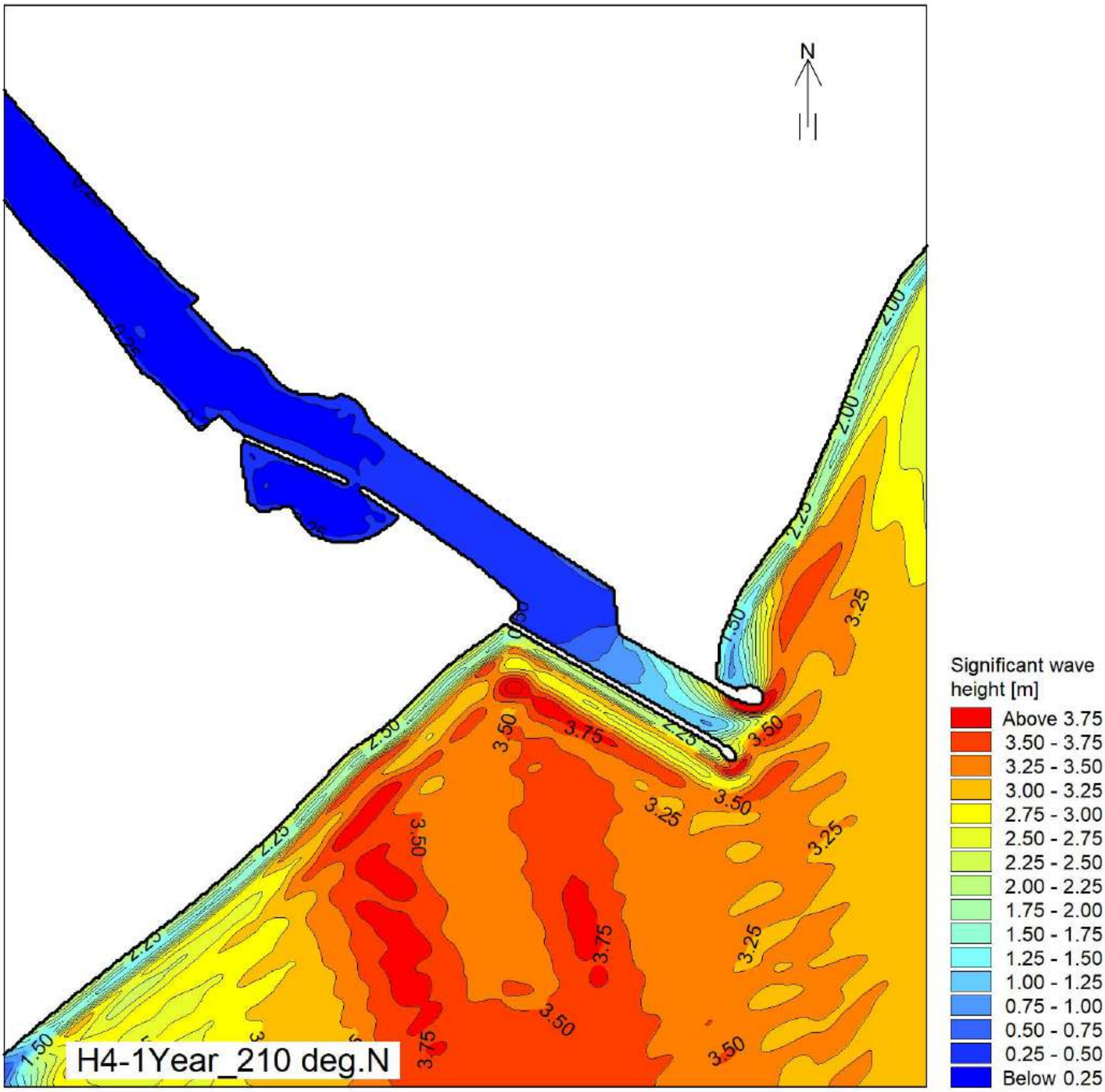

Figure E40: Layout H4, 1 year wave from 210°N

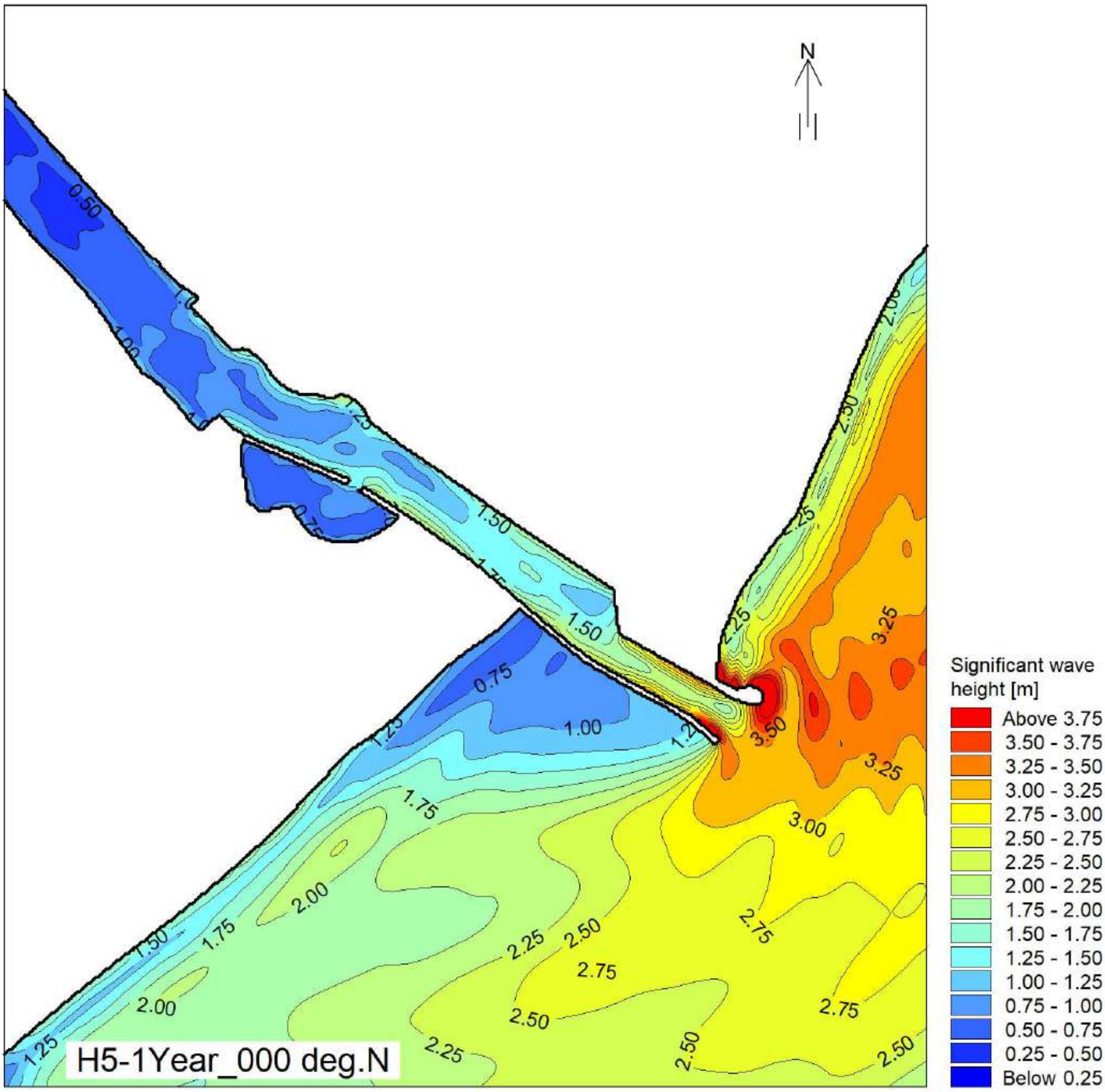

Figure E41: Layout H5, 1 year wave from 0°N

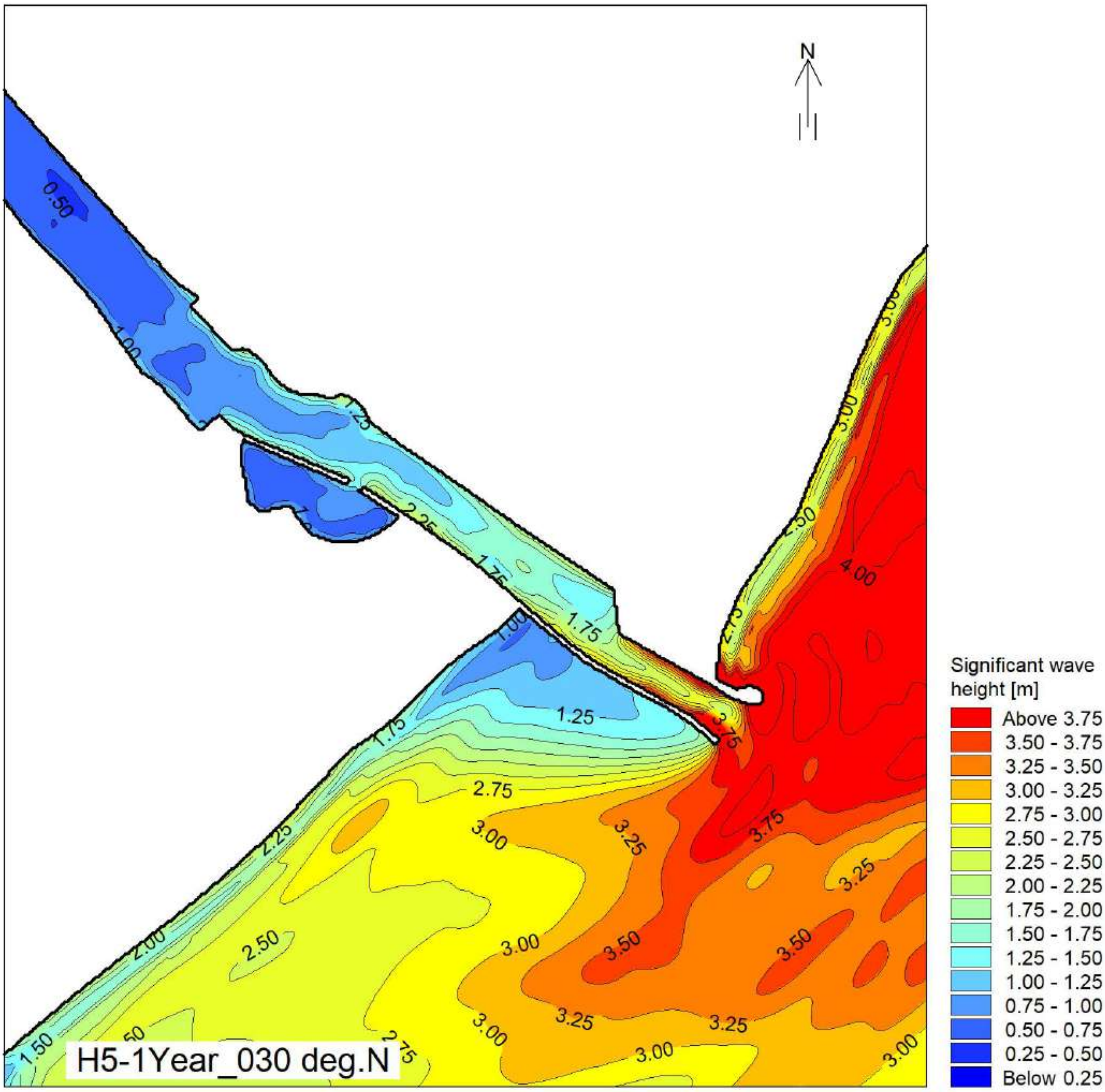

Figure E42: Layout H5, 1 year wave from 30°N

Royal HaskoningDHV

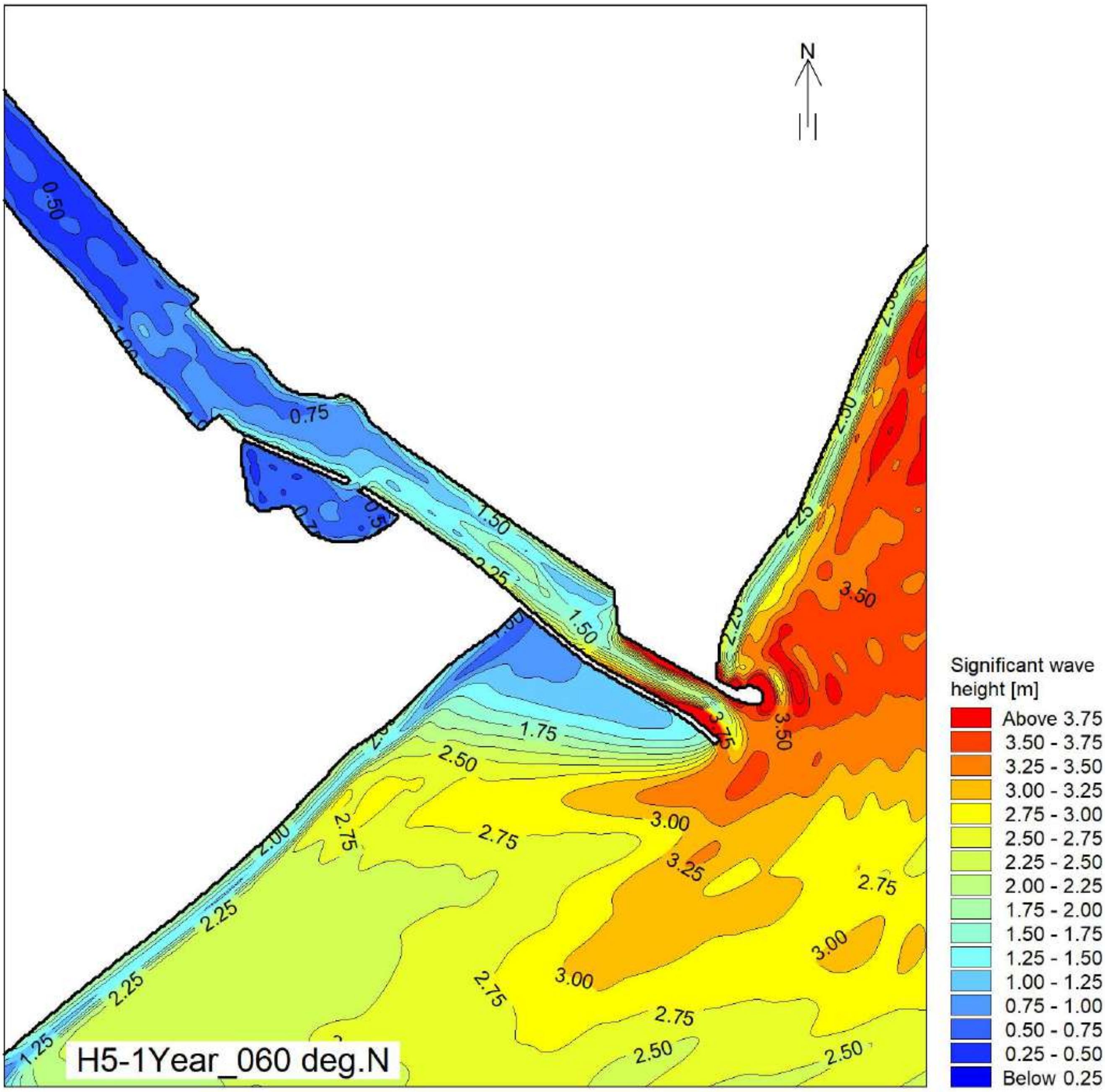

Figure E43: Layout H5, 1 year wave from 60°N

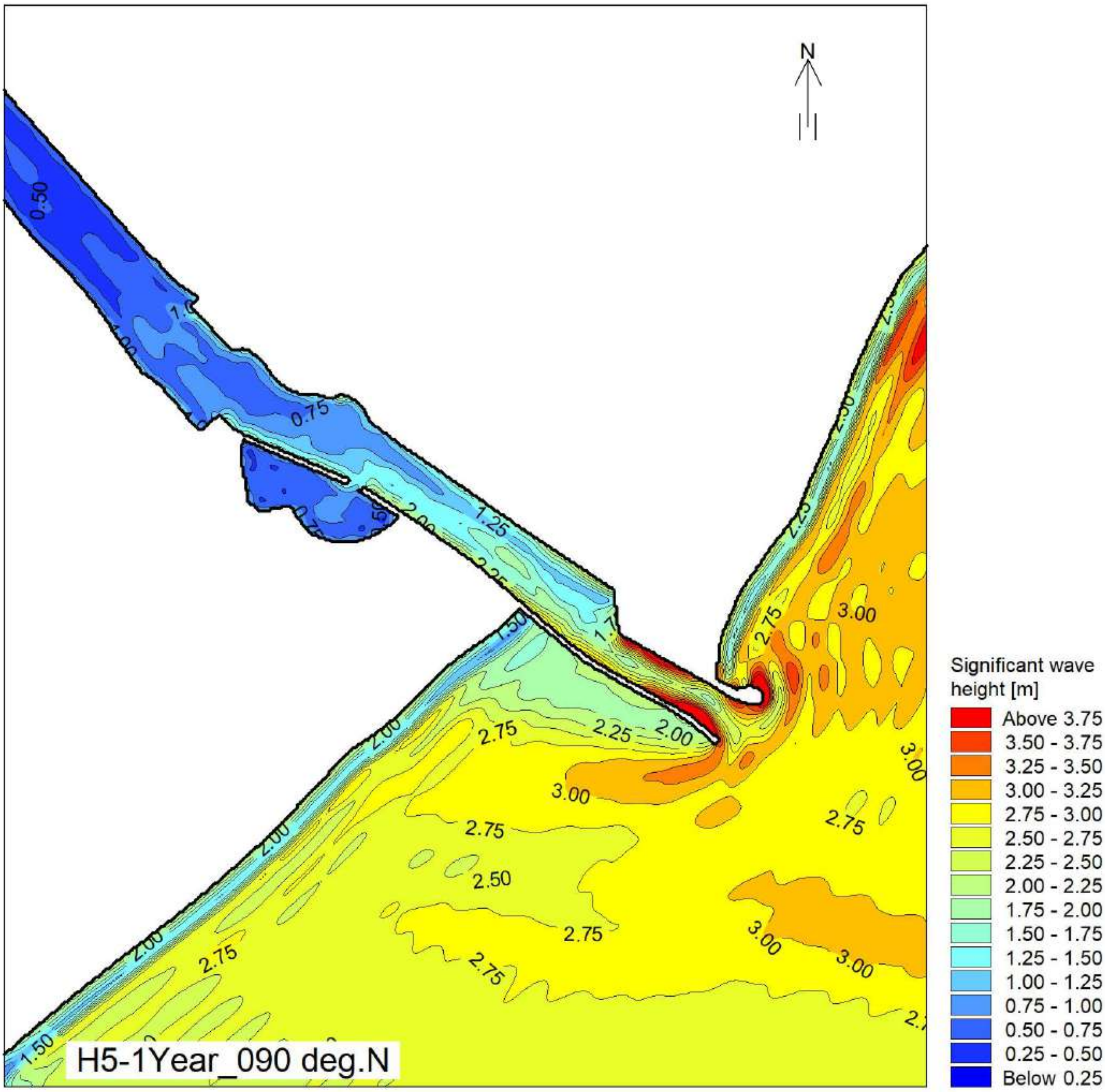

Figure E44: Layout H5, 1 year wave from 90°N

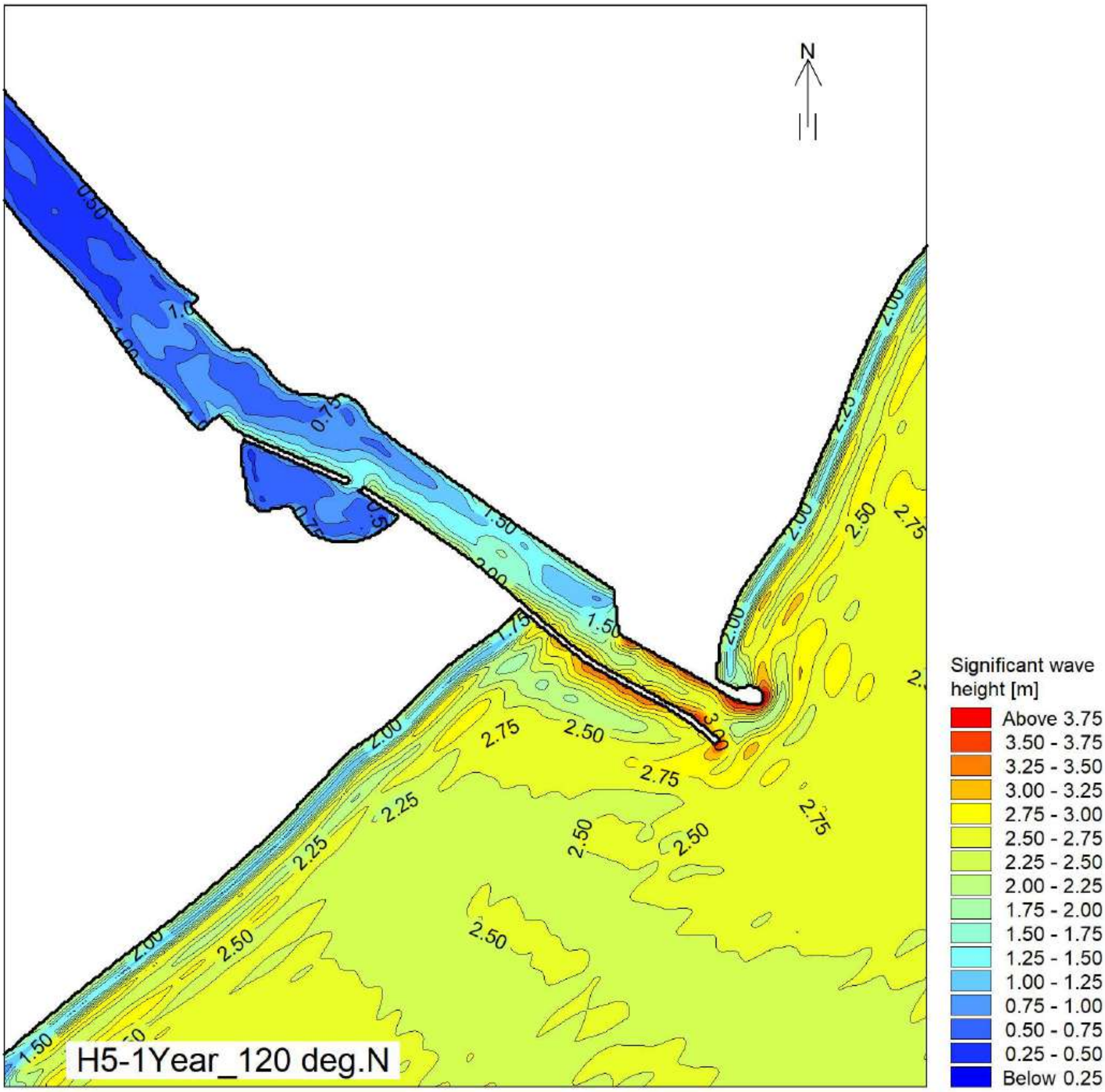

Figure E45: Layout H5, 1 year wave from 120°N

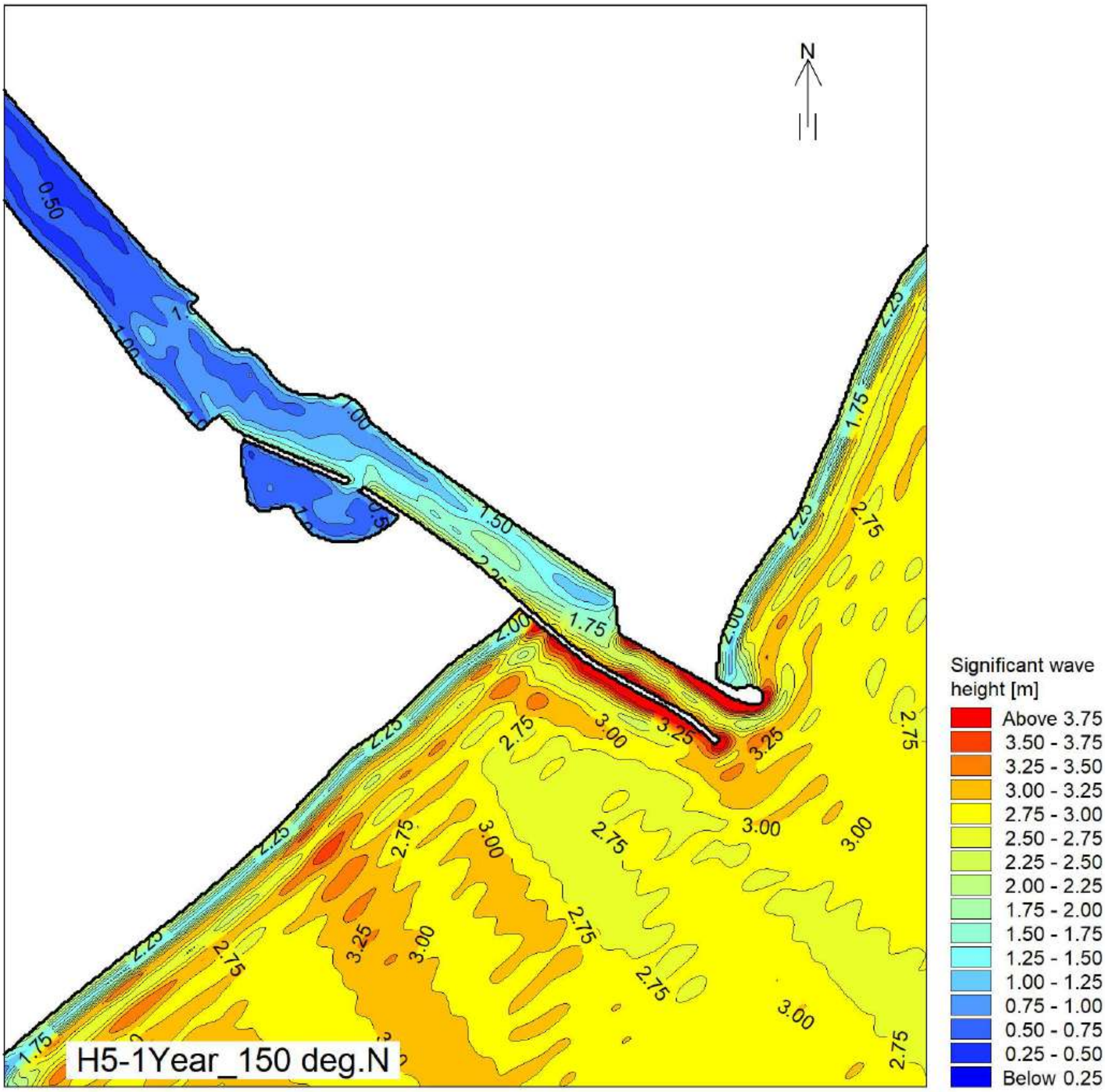

Figure E46: Layout H5, 1 year wave from 150°N

Royal HaskoningDHV

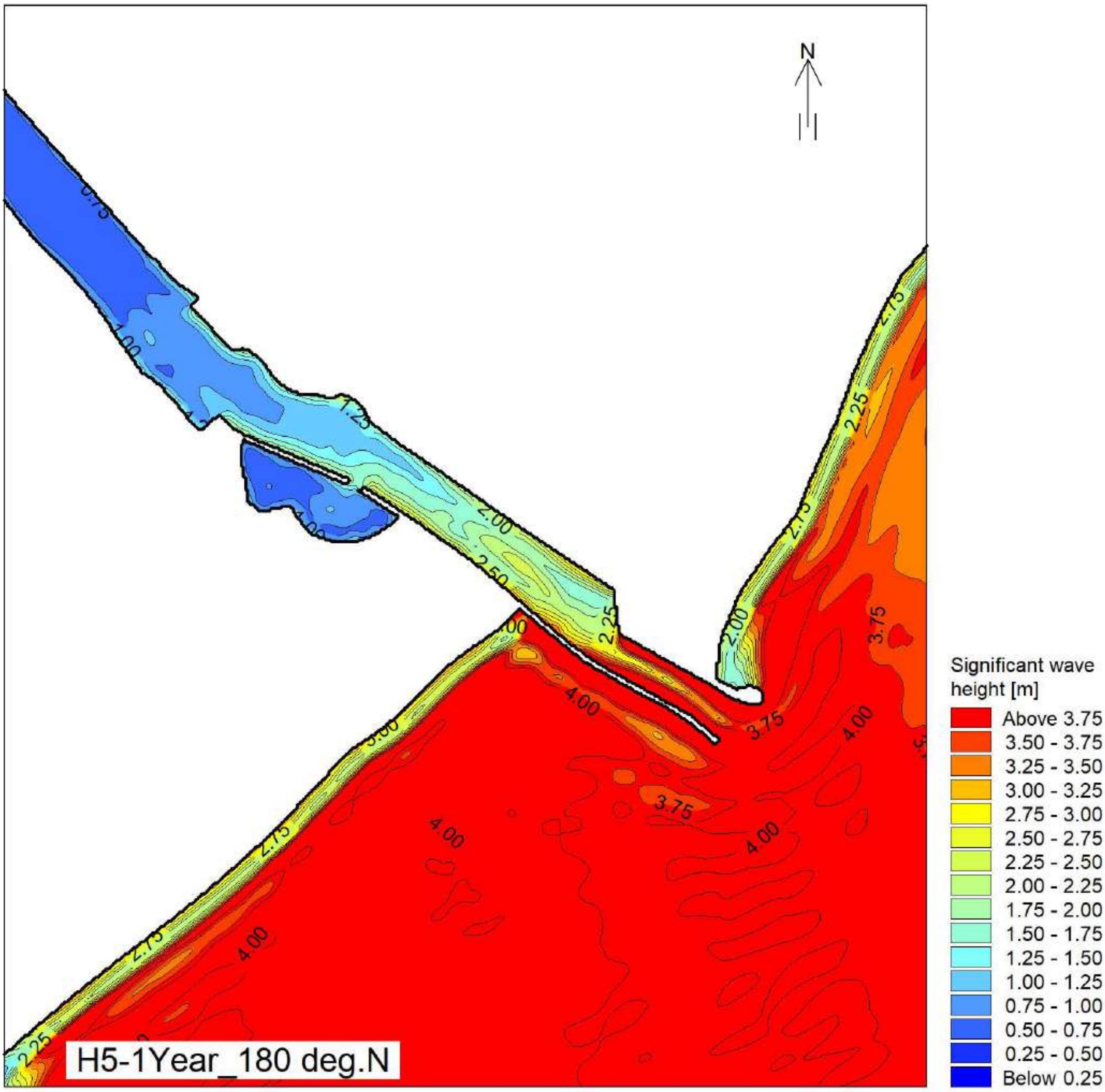

Figure E47: Layout H5, 1 year wave from 180°N

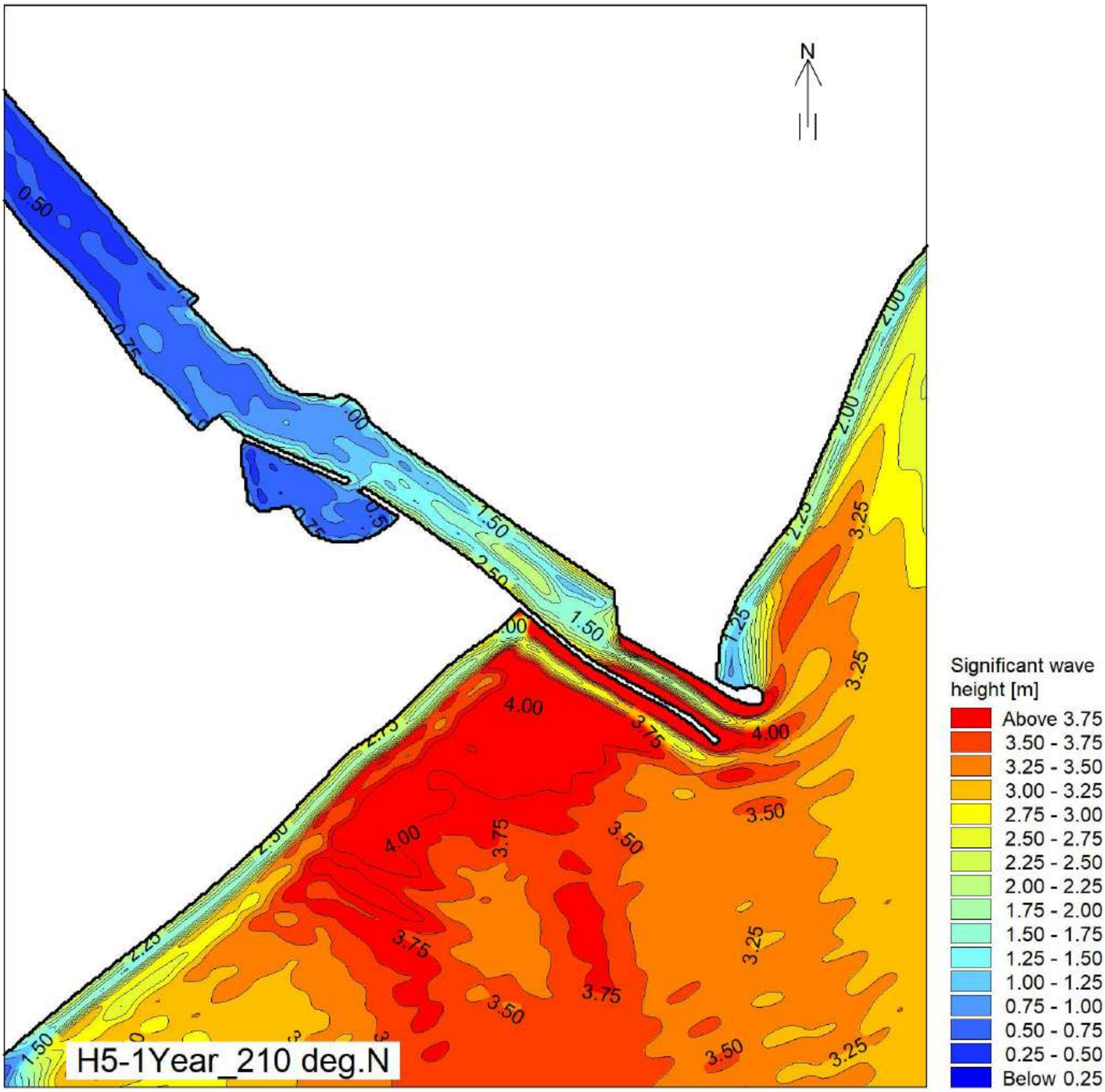

Figure E48: Layout H5, 1 year wave from 210°N

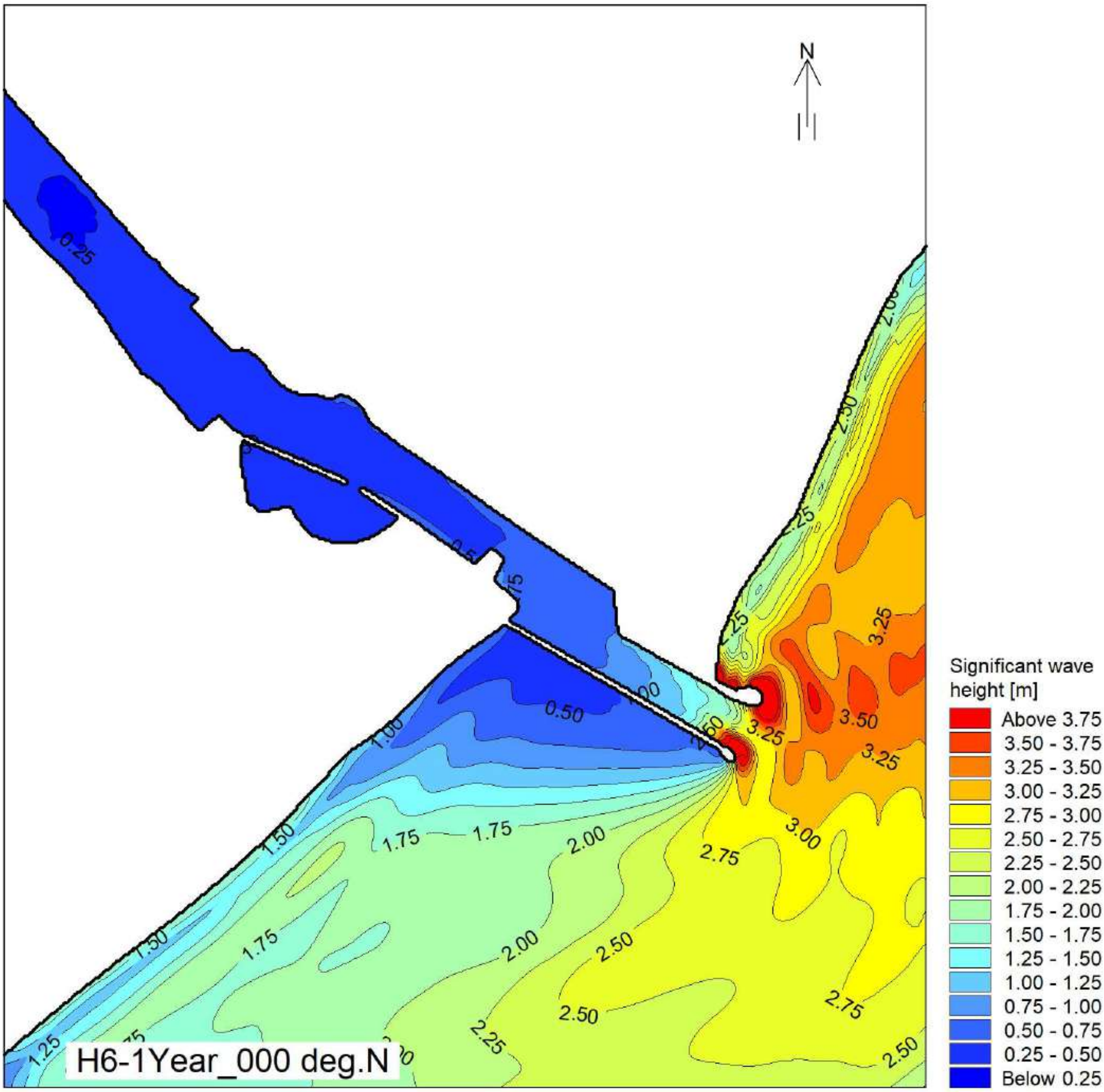

Figure E49: Layout H6, 1 year wave from 0°N

Royal HaskoningDHV

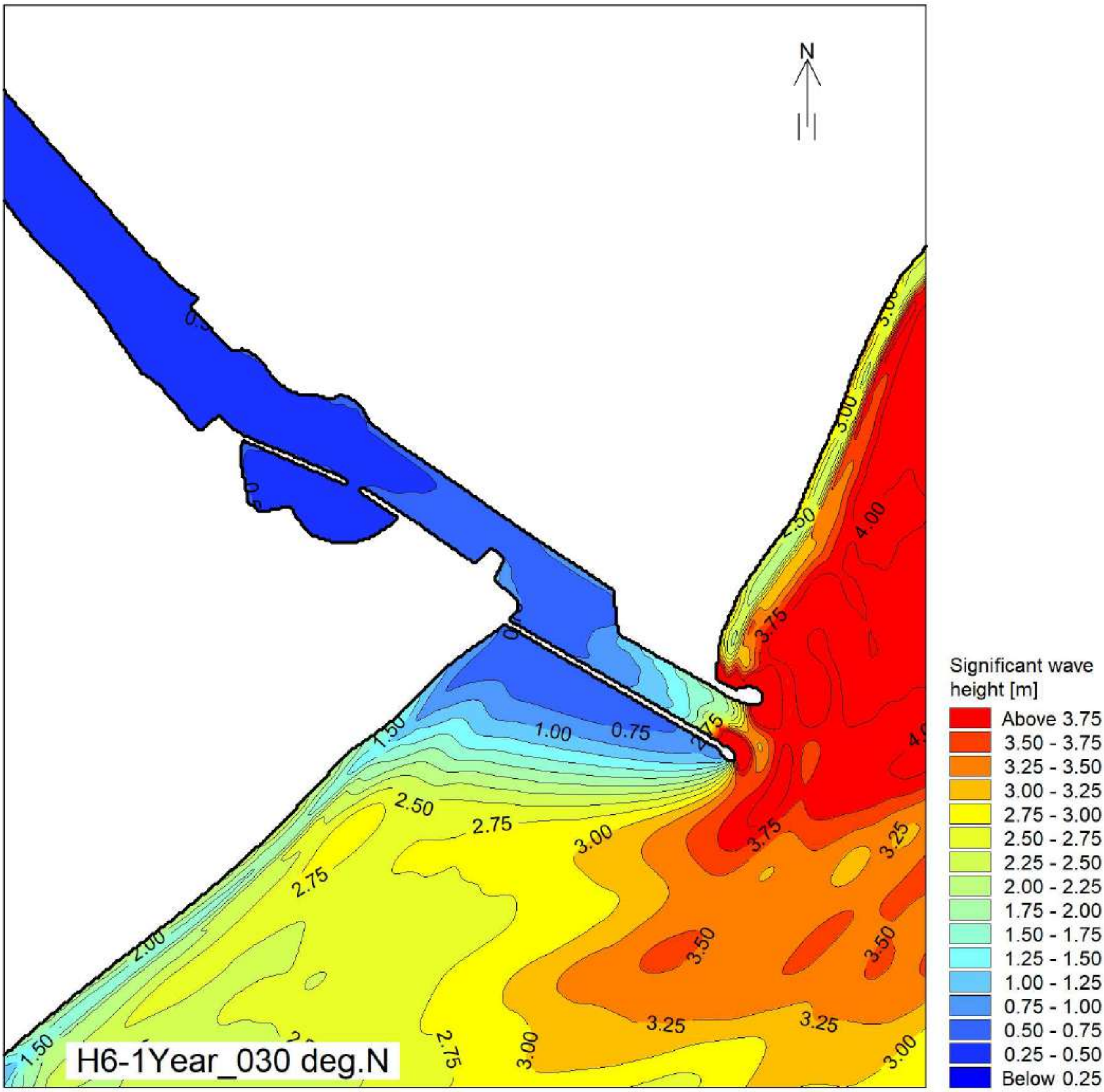

Figure E50: Layout H6, 1 year wave from 30°N

Royal HaskoningDHV

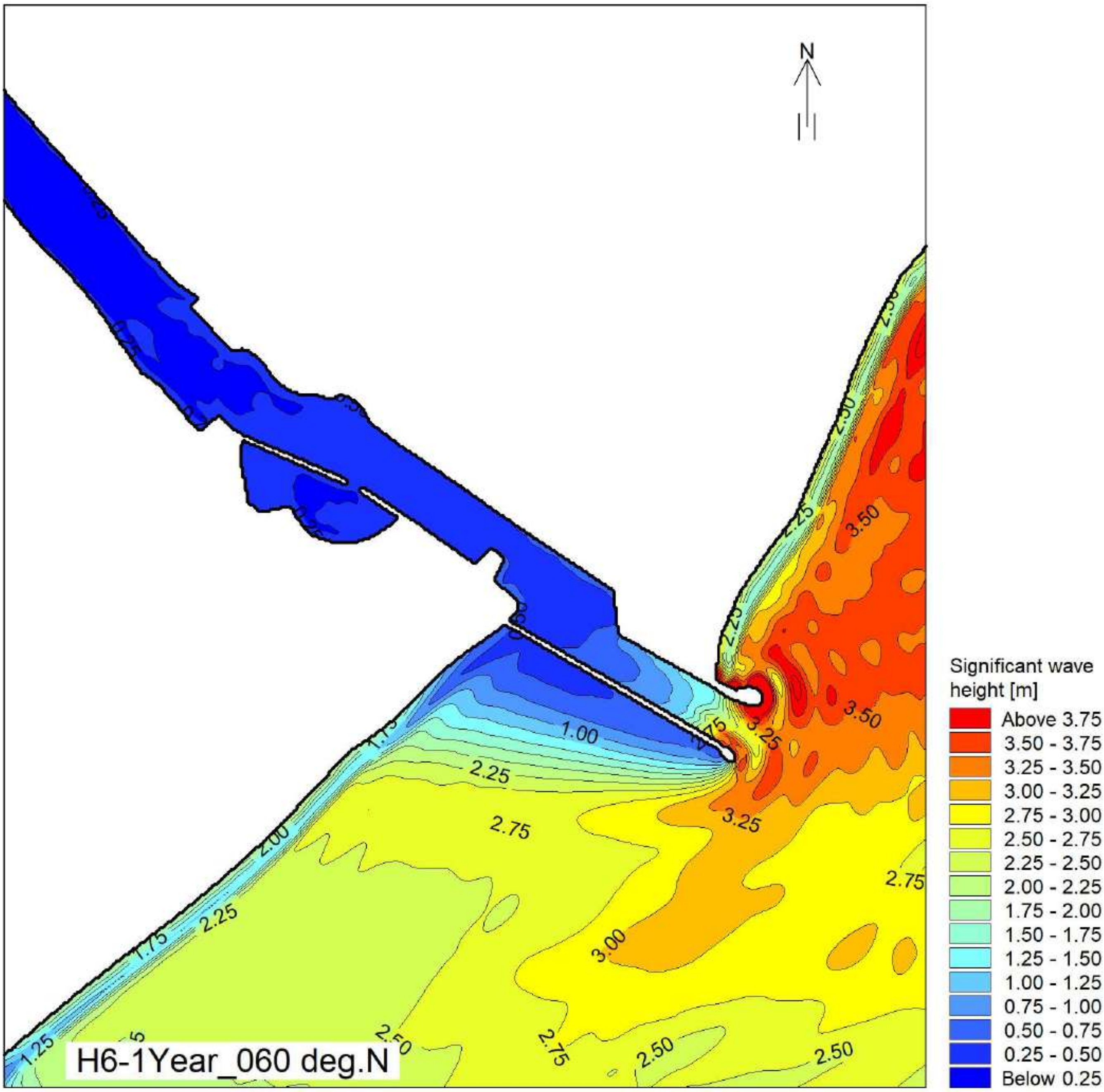

Figure E51: Layout H6, 1 year wave from 60°N

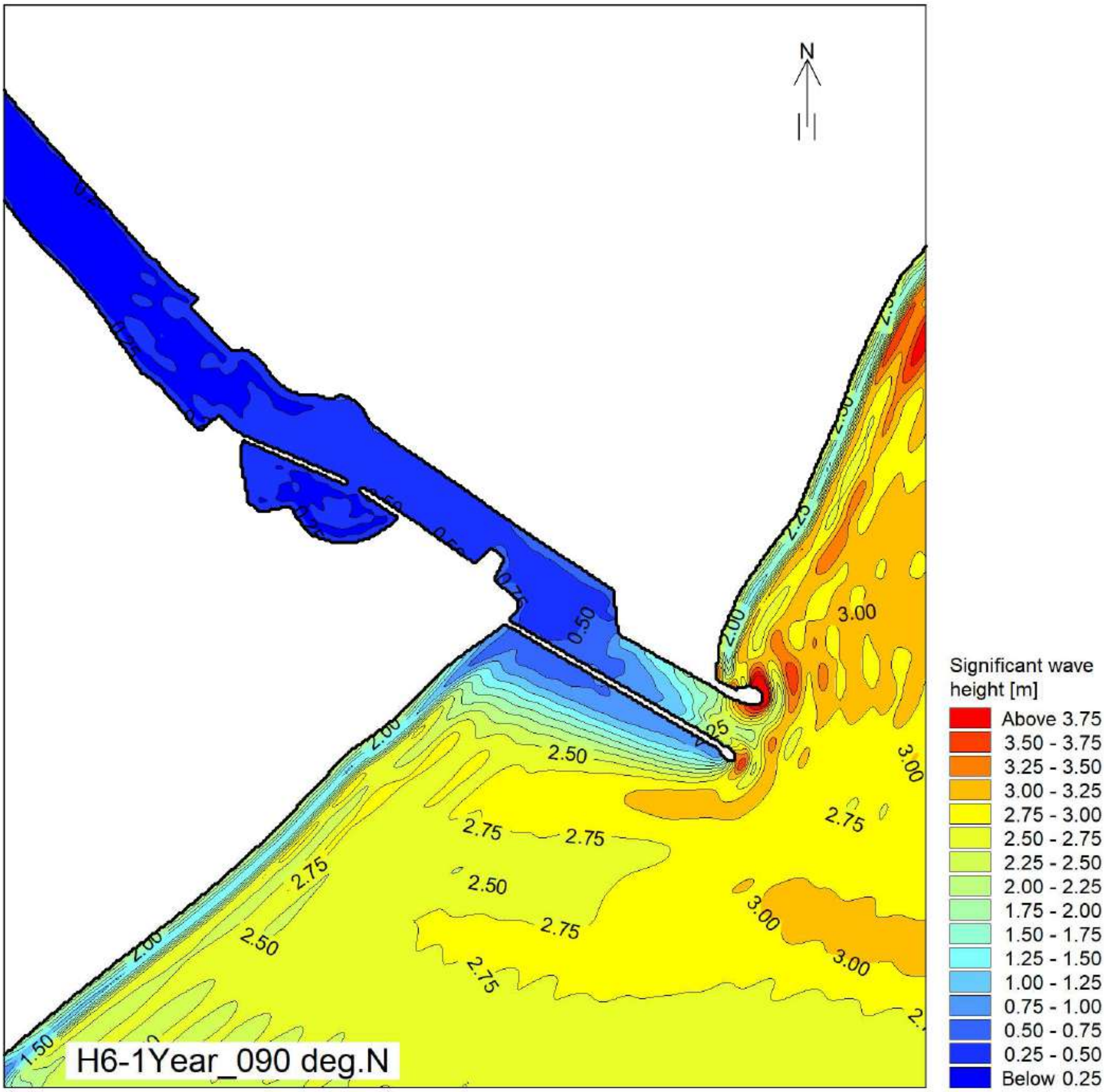

Figure E52: Layout H6, 1 year wave from 90°N

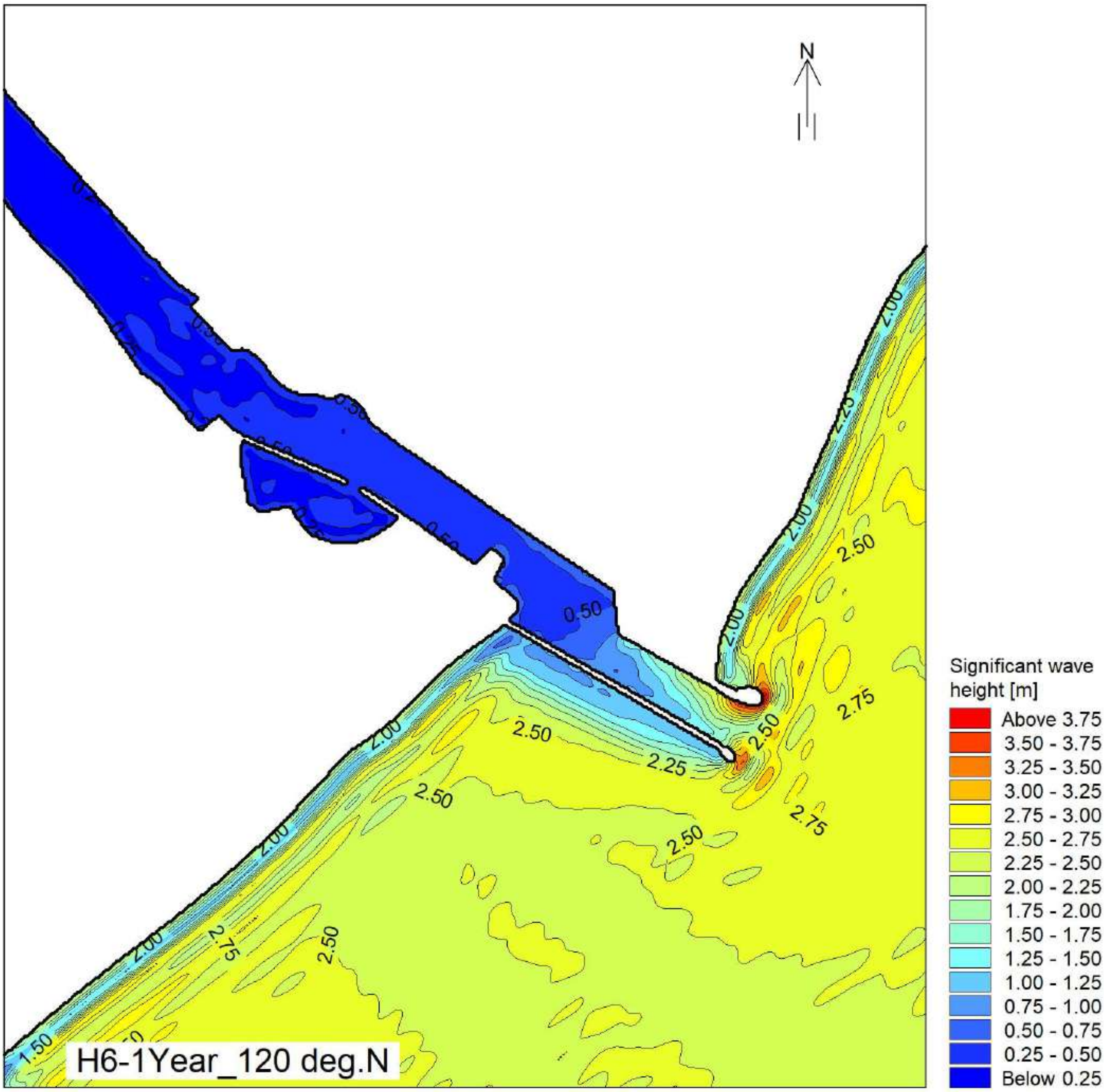

Figure E53: Layout H6, 1 year wave from 120°N

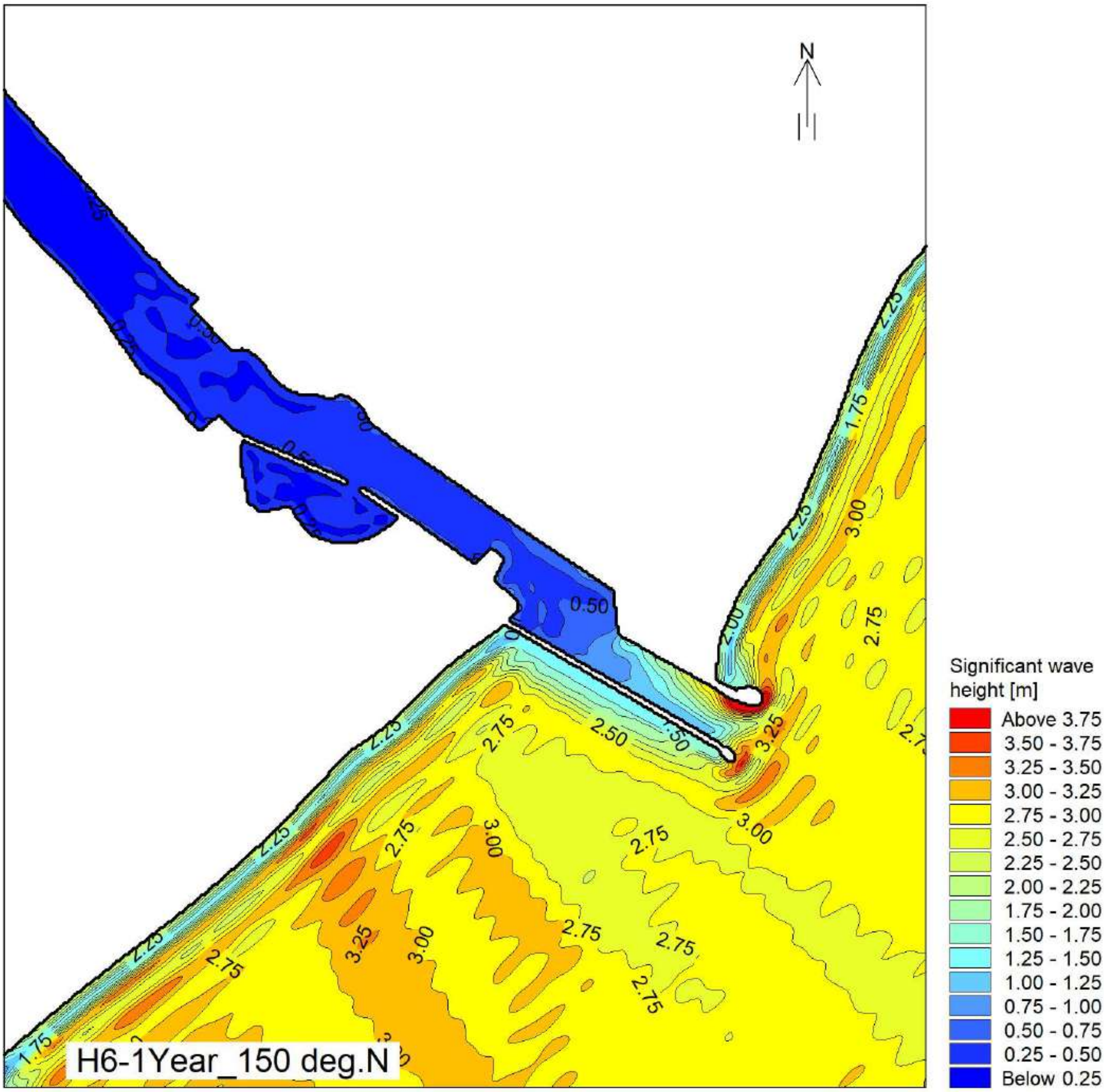

Figure E54: Layout H6, 1 year wave from 150°N

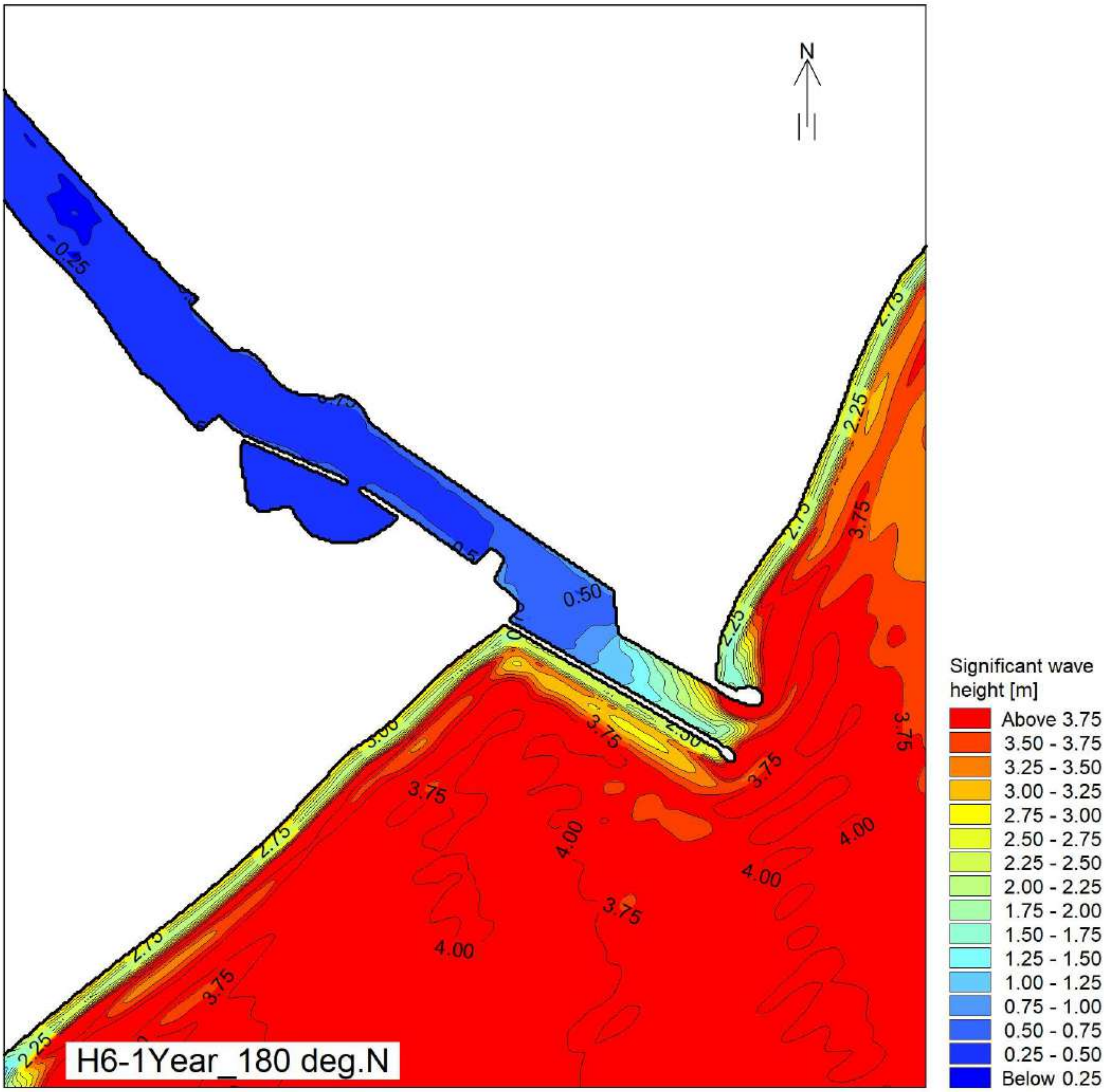

Figure E55: Layout H6, 1 year wave from 180°N

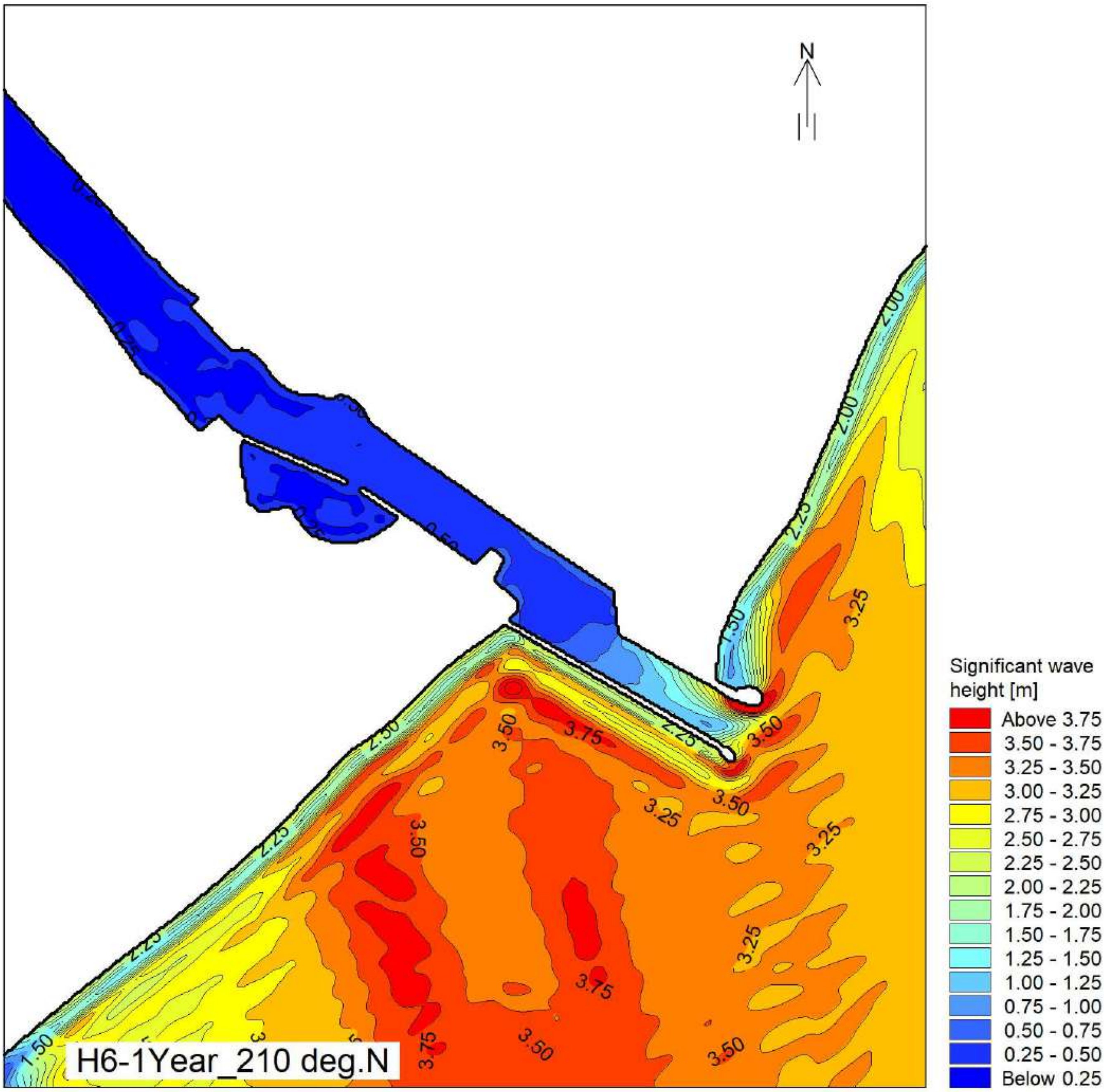

Figure E56: Layout H6, 1 year wave from 210°N