BEFORE THE HON'BLE NATONAL GREEN TRIBUNAL
PRINCIPAL BENCH, AT NEW DELHI
ORIGINAL APPLICATION NO. 1313 OF 2024

IN THE MATTER OF:

V SRIKANTH … APPLICANT

VERSUS

STATE OF ANDHRA PRADESH & ORS. … RESPONDENTS

INDEX FOR VOLUME-VII

FILED BY:

D/8495/2018

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PLACE: NEW DELHI
DATE: 26.09.2025

CHAPTER – 4

ENVIRONMENTAL MONITORING STUDIES

4.0 ENVIRONMENTAL MONITORING STUDIES – Oct’24 to March’25

S.No	ATTRIBUTE	SCOPE	STUDIES CARRIED OUT
1.	Ambient Air Quality	Collection of ambient air at Seven locations in and outside of port premises	Ambient Air samples collected at 7 locations for PM10, PM2.5, SO2, NOx & NH3 (monthly once) for the period of 01.10.2024 to 31.10.2025.
2.	Marine Water and Surface Water Quality	Collection of Marine Water at six locations. • Port Entrance (Approach Channel) • Turning Circle • Coal Berth • Reclamation Area (Mutable) • Buckingham Canal • Khandaleru Creek	Marine Water samples from Port Entrance, Turning Circle, Coal Berth and Reclamation Area are collection weekly once. Samples for Buckingham Canal and Khandaleru Creek are collected monthly once. All the samples are tested for Physical, Chemical and Microbiological parameters Collected for the period of 01.10.2024 to 31.10.2025.
3.	Marine Water Quality for Turbidity	Collection of Marine Water at seven locations. • Port Entrance (Approach Channel) • Turning Circle • Coal Berth • Reclamation Area (Mutable) • 14°19’26”N & 80°15’43”E • 14°16’52”N &80°17’40”E	Marine Water samples from Port Entrance, Turning Circle, Coal Berth and Reclamation Area are collection weekly once. Deep Sea water Samples are collected monthly once. Collected for the period of 01.10.2024 to 31.10.2025.

		• 14º16’11”N & 80º17’40”E	
4.	Marine Sediment	Collected at • Port Entrance (Approach Channel) • Turning Circle • Coal Berth • Reclamation Area (Mutable)	Collected at four locations and analyzed for the hereunder weekly once. • Sediment Compositions • pH • Nitrogen • Phosphorus • Potassium • Sodium • Benthos Communities • Heavy Metals Collected for the period of 01.10.2024 to 31.10.2025.
5.	Noise Level Intensity	Noise levels were noted at Seven locations inside and outside port premises.	Day and Night Noise levels were noted at • Zero Point • Thamminapatnam • CVR Building • Gopalpuram • Chalivendram • Krishnapatnam • Light House Siding Collected Noise Levels at seven locations for day and night periods once in the month from 01.10.2024 to 31.10.2025.

6.	STP Inlet and Outlet	Inlet and Outlet samples are collected from STP at Port	STP Inlet and Outlet samples are collected monthly once. Collected for the period of 0 01.10.2024 to 31.10.2025.
7.	DG Set Emission Quality	Emission Quality was conducted to DG Sets of port premises	Emission Quality was conducted to DG Sets of port premises, ie PM, NOx, HC & CO (Six months once) for the period of 01.10.2024 to 31.10.2025
8.	Ground Water Quality Monitoring	Collected at • Port Site • Krishnapatnam village • South side of the port • Gopalapuram village	Ground Water samples from Port site, Krishnapatnam village, South side of the port, Gopalapuram village Bore wells water samples are collected half yearly once. All the samples are tested for Physical, Chemical and Microbiological parameters Collected for the period of 01.10.2024 to 31.10.2025.
9.	Soil Quality	Collection of Soil sample at Two locations. • Storage area towards west Buckingham canal • Storage area at Port	Soil samples from Storage area towards west, Storage area at Port Area are collection half yearly once. All the samples are tested for Physical, Chemical parameters. Collected for the period of 01.10.2024 to 31.10.2025.

4.1 METEOROLOGICAL DATA

Meteorological data was collected on hourly basis by installing an auto weather monitoring station at Plant site. The report depicted hereunder represents the data for study period (01.10.2024 to 31.10.2025.)

The following parameters were recorded

- Wind speed
- Wind direction
- Temperature
- Relative humidity
- Rainfall

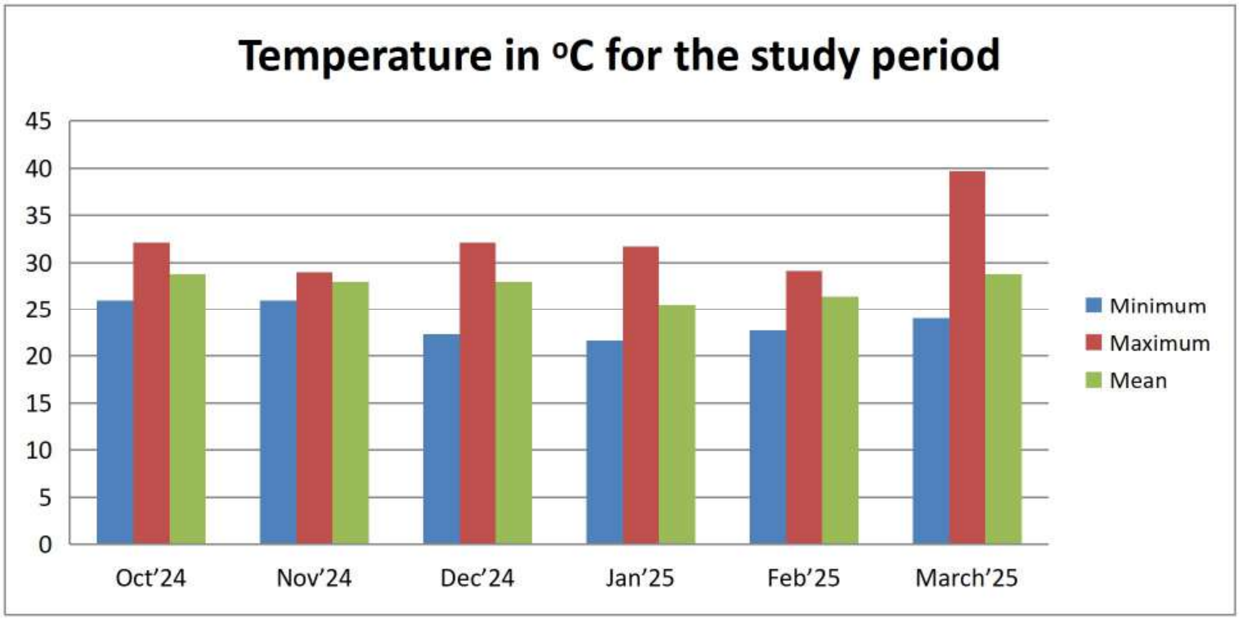
MINIMUM AND MAXIMUM VALUES OF RELATIVE HUMIDITY, TEMPERATURE AND RAINFALL DURING STUDY PERIOD (01.04.2024 to 31.09.2024.).

Temperature in ^{o}C	Oct'24	Nov'24	Dec'24	Jan'25	Feb'25	March'25
Minimum	26.0	26.0	22.3	21.6	22.7	24.0
Maximum	32.1	29.0	32.1	31.7	29.1	39.7
Mean	28.8	28.0	28.0	25.5	26.4	28.8

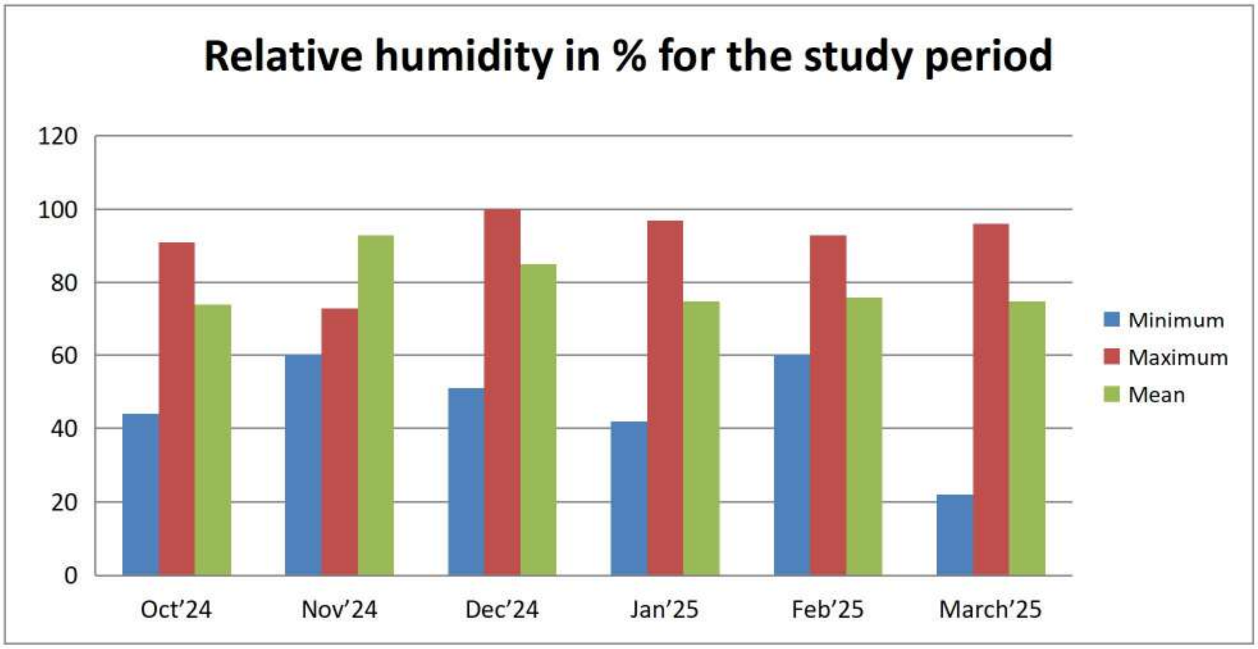
Relative Humidity %	Oct'24	Nov'24	Dec'24	Jan'25	Feb'25	March'25
Minimum	44	60	51	42	60	22
Maximum	91	73	100	97	93	96
Mean	74	93	85	75	76	75

Rainfall in mm	Oct'24	Nov'24	Dec'24	Jan'25	Feb'25	March'25
Minimum	0.1	0.1	0.1	0.1	-	-
Maximum	48.4	29.2	27.3	6.2	-	-
Cumulative	439.06	324.5	153.7	6.91	-	-

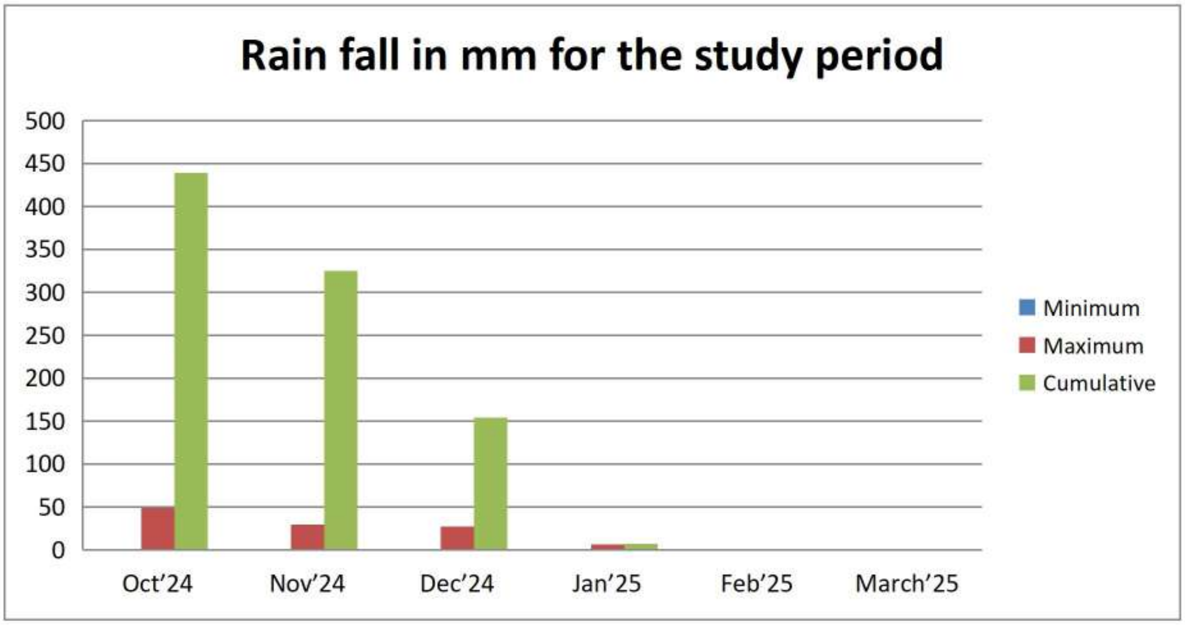
Graphical interpretation of Minimum and Maximum values of and Temperature during study period.



Graphical Interpretation of Minimum and Maximum values of Relative Humidity during study period.



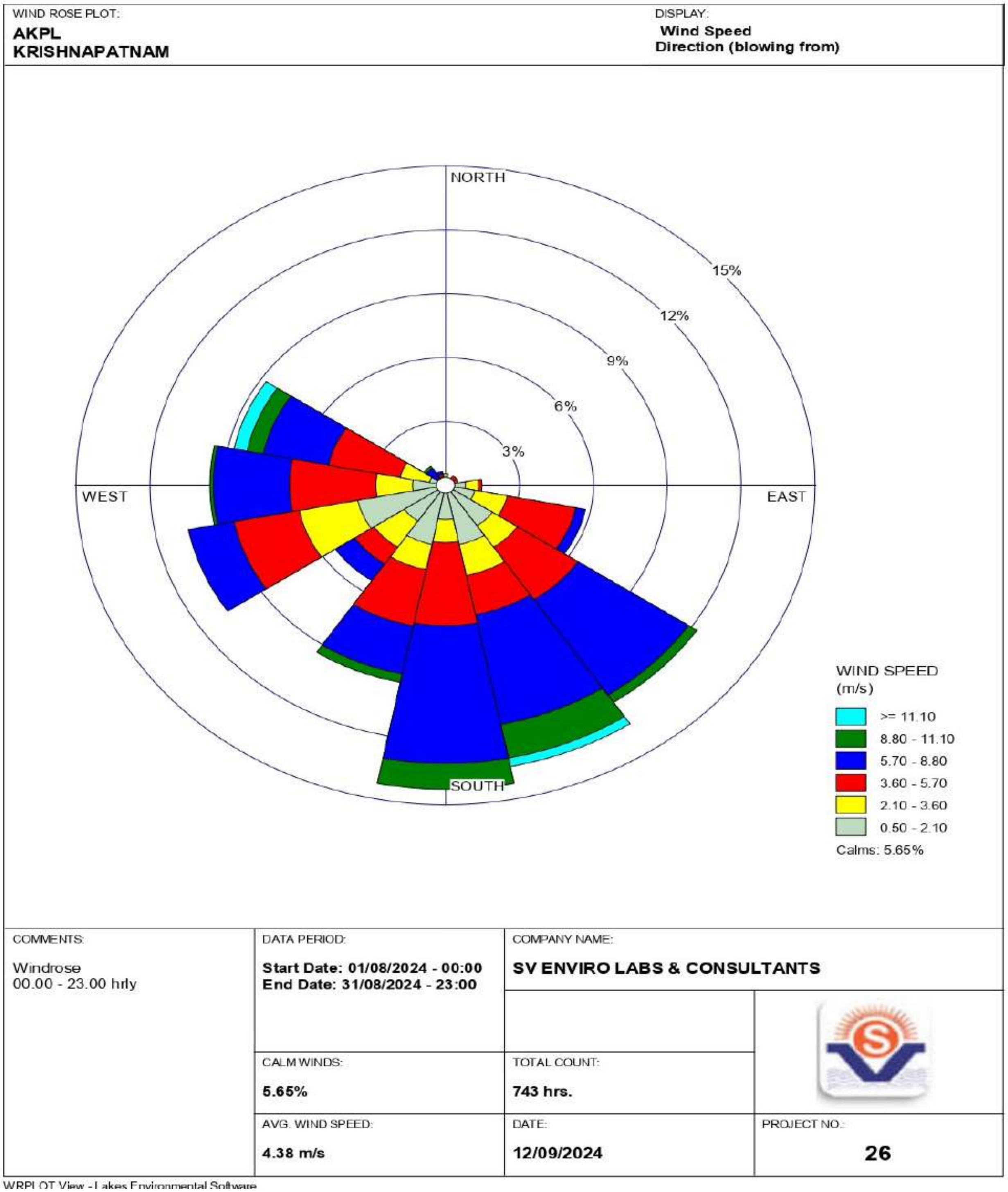
Graphical Interpretation of Minimum and Maximum values of Rainfall during study period.



WIND PATTERN – (April'24 – Sep'24)

Predominant Wind directions	Distribution in Percentage	Wind rose Enclosed as
ENE	18.1 %	Fig – 7
E	11.3%	
NE	9.52%	
ESE	7.38%	

Fig-7. Wind rose diagram for 00.00 – 23.00 hrs (24hrly)



4.2 AMBIENT AIR QUALITY MONITORING

The ambient air quality was assessed through a network of 07 AAQM stations within 10 Km radius of project site (5 stations in buffer zone & 2 location inside plant area).

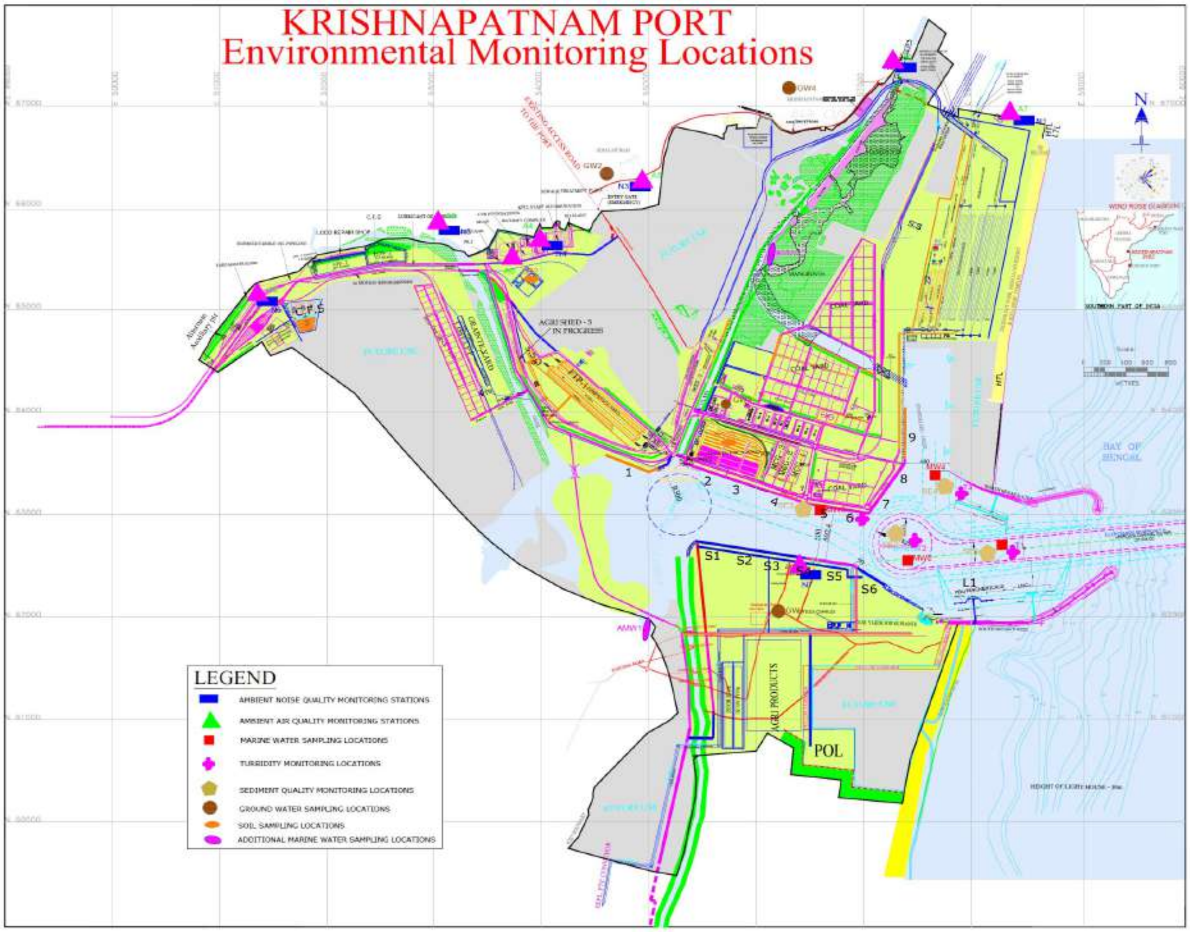
The locations of ambient air quality stations are shown in Fig – 4is given below:

Table No- 2

DETAILS OF AMBIENT AIR QUALITY MONITORING LOCATIONS

Station code	Location	Direction w.r.t. Project site	Environmental setting
A1	At Zero Point	W	Industrial
A2	At Thamminapatnam Village	S	Industrial
A3	At CVR Building	WNW	Residential
A4	At Gopalpuram Village	NW	Residential
A5	At Chalivendram	WNW	Residential
A6	At Krishnapatnam	NNW	Residential
A7	At Light House	SW	Residential

Fig 4. AMBIENT AIR SAMPLING STATIONS LOCATION MAP



Summary of Analysis of Ambient Air Quality in the Study Area at A1 –Zero Point for the period of Oct'24 – March'25.

	PM_{10} (µg/m³)	$PM_{2.5}$ (µg/m³)	SO_2 (µg/m³)	NO_X (µg/m³)	NH3 (µg/m³)
Oct'24	61.5	24.3	13.1	14.0	BDL
Nov'24	63.9	26.2	14.0	15.4	BDL
Dec'24	66.3	27.8	13.2	14.5	BDL
Jan'25	68.9	28.6	14.1	15.8	BDL
Feb'25	64.6	26.4	12.7	14.2	BDL
March'25	69.2	29.5	13.9	15.6	BDL
NAAQS Standards	**100**	**60**	**80**	**80**	**400**

Summary of Analysis of Ambient Air Quality in the Study Area at A2 –Thamminipatnam for the period of Oct'24 – March'25.

	PM_{10} (µg/m³)	$PM_{2.5}$ (µg/m³)	SO_2 (µg/m³)	NO_X (µg/m³)	NH3 (µg/m³)
Oct'24	51.4	21.2	10.6	13.1	BDL
Nov'24	54.3	23.1	12.0	14.5	BDL
Dec'24	56.8	24.6	11.6	13.5	BDL
Jan'25	60.3	26.1	12.5	14.9	BDL
Feb'25	57.4	24.2	10.9	13.1	BDL
March'25	62.7	26.9	12.3	14.6	BDL
NAAQS Standards	**100**	**60**	**80**	**80**	**400**

Summary of Analysis of Ambient Air Quality in the Study Area at A3 –CVR for the period of Oct'24 – March'25.

	PM_{10} (µg/m³)	$PM_{2.5}$ (µg/m³)	SO_2 (µg/m³)	NO_X (µg/m³)	NH3 (µg/m³)
Oct'24	49.3	19.5	9.0	10.4	BDL
Nov'24	52.6	21.3	10.7	11.9	BDL
Dec'24	55.1	23.4	9.6	10.7	BDL
Jan'25	58.7	25.3	10.8	11.9	BDL
Feb'25	55.3	23.1	9.5	11.0	BDL
March'25	60.8	25.6	11.4	13.2	BDL
NAAQS Standards	**100**	**60**	**80**	**80**	**400**

Summary of Analysis of Ambient Air Quality in the Study Area at A4 –Gopalpuram for the period of Oct'24 – March'25.

	PM_{10} (µg/m³)	$PM_{2.5}$ (µg/m³)	SO_2 (µg/m³)	NO_X (µg/m³)	NH3 (µg/m³)
Oct'24	48.3	19.6	10.2	12.1	BDL
Nov'24	51.5	20.8	11.0	12.9	BDL
Dec'24	54.2	22.0	10.4	11.6	BDL
Jan'25	58.6	24.5	11.4	12.8	BDL
Feb'25	53.9	22.4	10.2	11.5	BDL
March'25	57.3	25.1	11.6	12.8	BDL
NAAQS Standards	**100**	**60**	**80**	**80**	**400**

Summary of Analysis of Ambient Air Quality in the Study Area at A5 –Chalivendram for the period of Oct'24 – March'25.

	PM_{10} (µg/m³)	$PM_{2.5}$ (µg/m³)	SO_2 (µg/m³)	NO_X (µg/m³)	NH3 (µg/m³)
Oct'24	46.2	18.5	11.3	12.0	BDL
Nov'24	49.5	19.9	12.6	13.9	BDL
Dec'24	51.8	21.3	11.9	12.6	BDL
Jan'25	55.2	23.9	12.7	13.5	BDL
Feb'25	52.1	21.3	11.0	12.3	BDL
March'25	55.7	23.5	12.4	13.2	BDL
NAAQS Standards	**100**	**60**	**80**	**80**	**400**

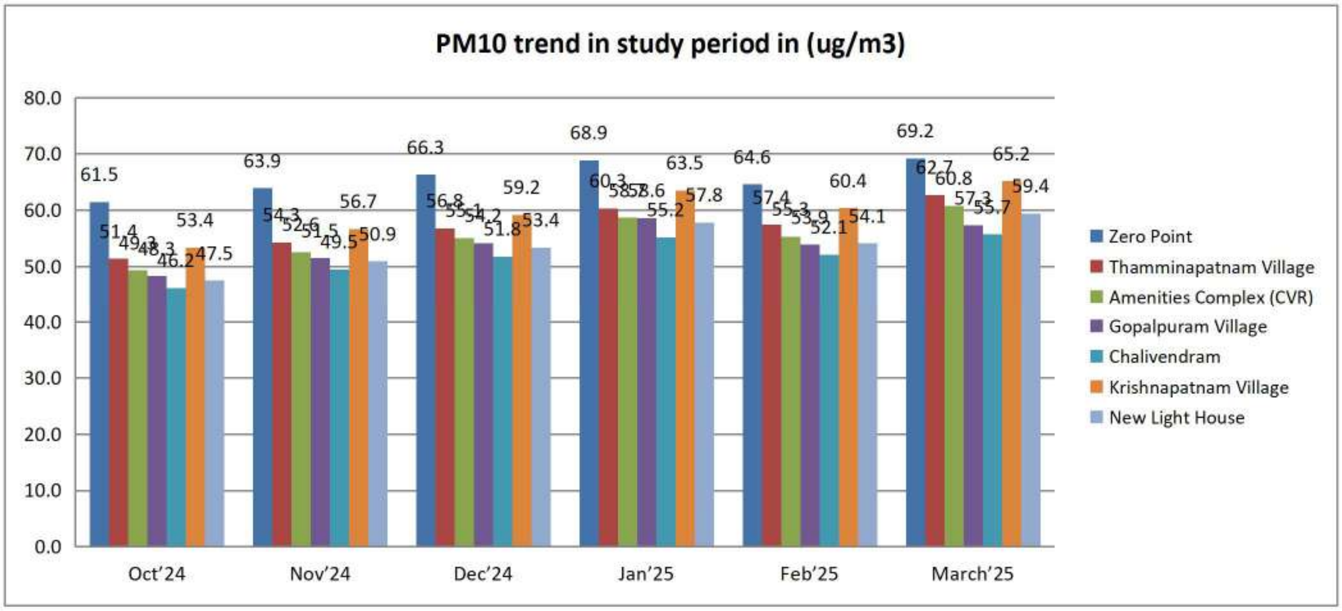
Summary of Analysis of Ambient Air Quality in the Study Area at A6 –Krishnapatnam for the period of Oct'24 – March'25.

	PM_{10} (µg/m³)	$PM_{2.5}$ (µg/m³)	SO_2 (µg/m³)	NO_X (µg/m³)	NH3 (µg/m³)
Oct'24	53.4	22.0	10.6	12.1	BDL
Nov'24	56.7	24.5	11.3	13.6	BDL
Dec'24	59.2	26.1	10.4	12.3	BDL
Jan'25	63.5	27.8	11.2	13.1	BDL
Feb'25	60.4	25.8	10.6	12.2	BDL
March'25	65.2	27.9	12.4	14.2	BDL
NAAQS Standards	**100**	**60**	**80**	**80**	**400**

Summary of Analysis of Ambient Air Quality in the Study Area at A7 –Light House for the period of Oct'24 – March'25.

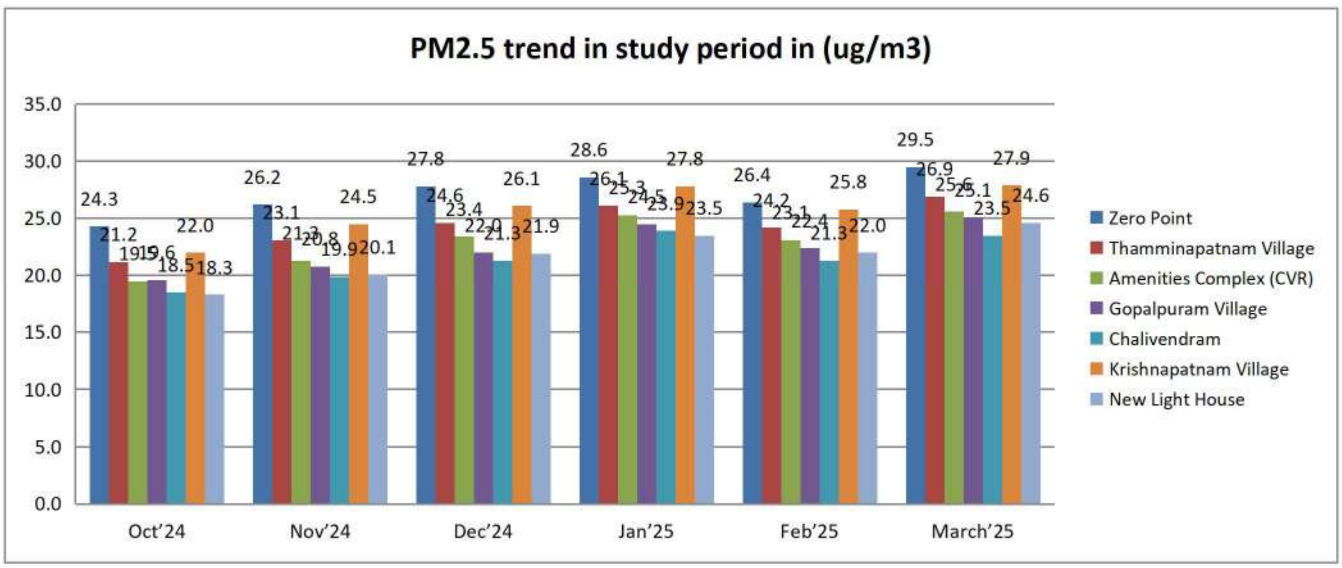
	PM_{10} (µg/m^3)	$PM_{2.5}$ (µg/m^3)	SO_2 (µg/m^3)	NO_X (µg/m^3)	NH3 (µg/m^3)
Oct'24	47.5	18.3	7.6	9.8	BDL
Nov'24	50.9	20.1	8.9	11.0	BDL
Dec'24	53.4	21.9	8.2	10.9	BDL
Jan'25	57.8	23.5	9.4	11.2	BDL
Feb'25	54.1	22.0	8.6	10.0	BDL
March'25	59.4	24.6	9.8	11.5	BDL
NAAQS Standards	**100**	**60**	**80**	**80**	**400**

Summary of Analysis of Ambient Air Quality in the Study Area – PM10 for Oct'24 – March'25.



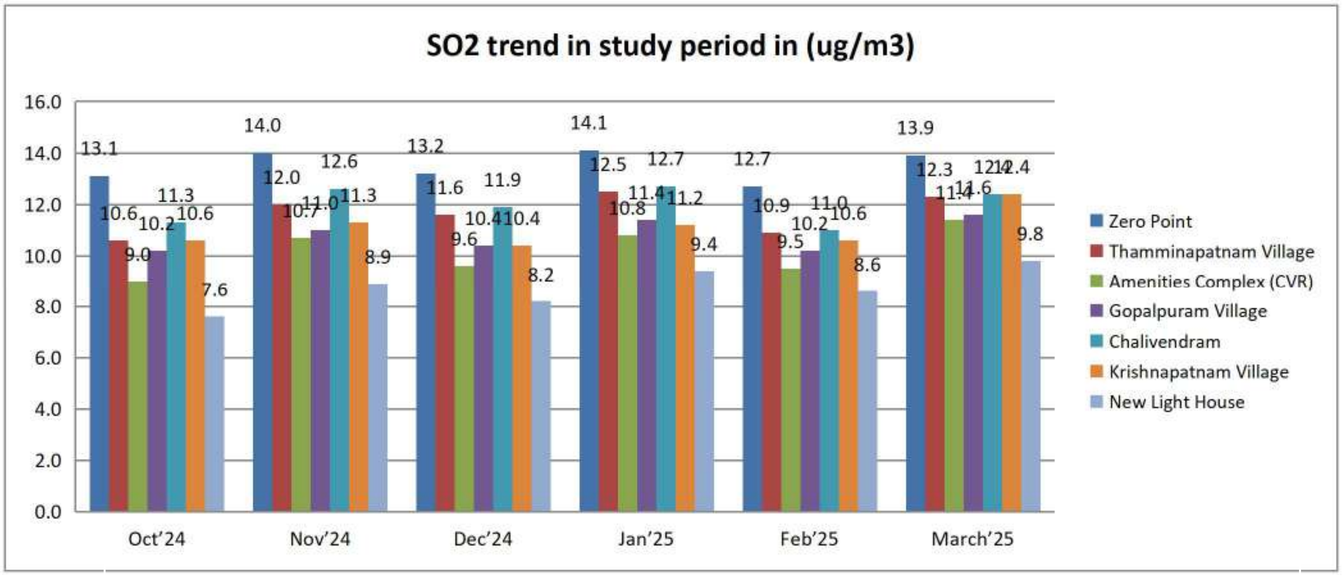
- ***PM10 varied between 46.2 to 69.2 µg/m,^{3} Minimum: Chalivendram***
- ***Maximum: Zero Point, NAAQ Standard: 100µg/m^3***

Summary of Analysis of Ambient Air Quality in the Study Area – PM2.5 for Oct'24 – March'25.



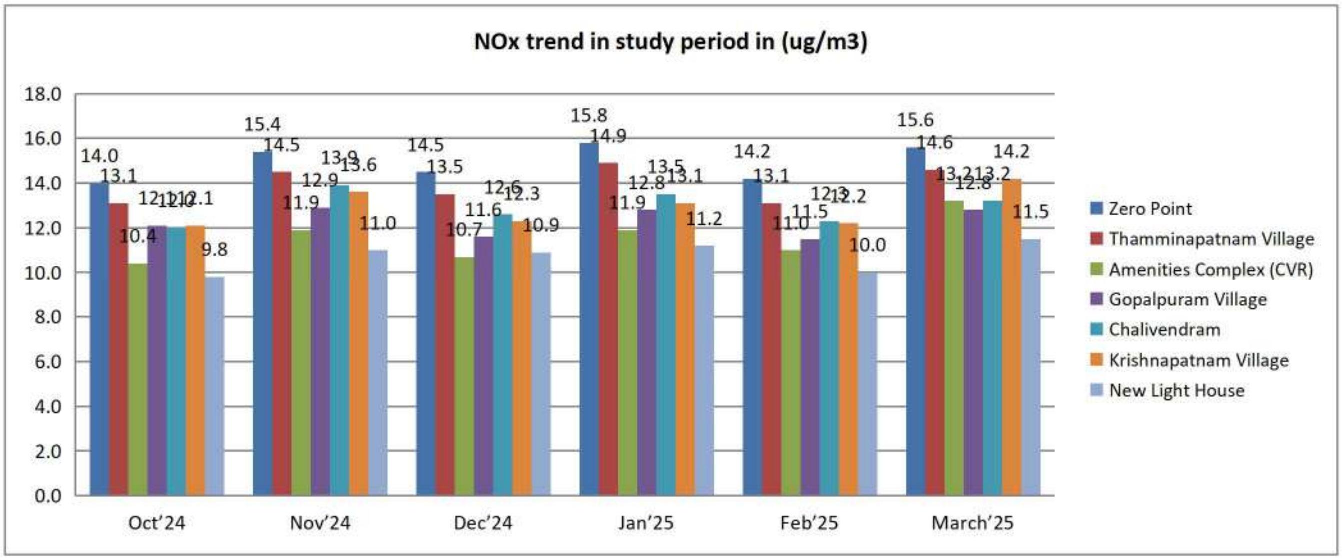
- ***$PM_{2.5}$ Varied between 18.3 to 29.5 µg/m^3, Minimum: New light house***
- ***Maximum ;Zero Point, NAAQ Standard : 60 µg/m^3***

Summary of Analysis of Ambient Air Quality in the Study Area – SO2 for Oct'24 – March'25.



- ***SO_2 Varied between 7.6 to 14.1 μg/m^3, Minimum : New Light House***
- ***Maximum : Zero Point, NAAQ Standard : 80 μg/m^3***

Summary of Analysis of Ambient Air Quality in the Study Area – NOx for Oct'24 – March'25.



- ***NOx Varied between 9.8 to 15.8 μg/m^3, Minimum :New Light House***
- ***Maximum :Zero Point , NAAQ Standards : 80 μg/m^3***

4.3 AMBIENT NOISE LEVEL INTENSITY

Collection of ambient noise levels at Seven locations (6 locations at nearby villages & 1 location near plant). Spot noise levels where measured with a precalibrated Noise Level Meter – SL Lutron 4001 for day and night periods.

Table No-3

DETAILS OF NOISE MONITORING LOCATIONS

STATION CODE	LOCATIONS	DIRECTION w.r.t PROJECT SITE
N1	At Zero Point	W
N2	At Thamminapatnam Village	S
N3	At CVR Building	WNW
N4	At Gopalpuram Village	NW
N5	At Chalivendram	WNW
N6	At Krishnapatnam	NNW
N7	At Light House	SW

The noise monitoring locations are depicted in **Fig – 5**

The noise levels monitored during the study period are given hereunder in form of Leq day, Leq night compared with CPCB Standards.

Location Code	Environmental Setting	CPCB norms Leq (Dba)	
		Day	Night
N1	Industrial	75	70
N2	Industrial	75	70
N3	Residential	55	45
N4	Residential	55	45
N5	Residential	55	45
N6	Residential	55	45
N7	Residential	55	45

Noise Level Data for the above locations are enclosed as Table - 4.5.1&4.5.2

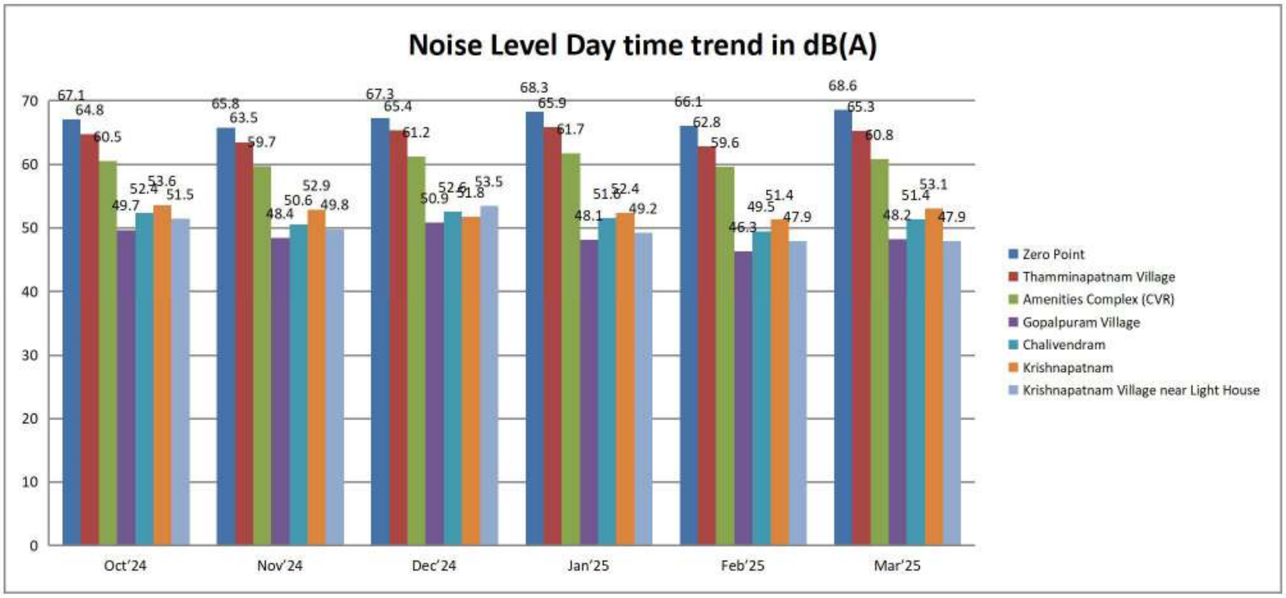


TABLE-4.5.1

Location	Oct'24	Nov'24	Dec'24	Jan'25	Feb'25	March'25
Zero Point	67.1	65.8	67.3	68.3	66.1	68.6
Thamminapatnam Village	64.8	63.5	65.4	65.9	62.8	65.3
Amenities Complex (CVR)	60.5	59.7	61.2	61.7	59.6	60.8
Gopalpuram Village	49.7	48.4	50.9	48.1	46.3	48.2
Chalivendram	52.4	50.6	52.6	51.6	49.5	51.4
Krishnapatnam	53.6	52.9	51.8	52.4	51.4	53.1
Krishnapatnam Village near Light House	51.5	49.8	53.5	49.2	47.9	47.9

- ***Industrial Day time noise level varied between 47.9 to 68.6 dB(A)***
- ***Residential Day time noise level varied between 46.3 to 53.6 dB(A)***
- ***NAAQ Standard: Industrial -75 Db(A):Residential –55dB(A)***

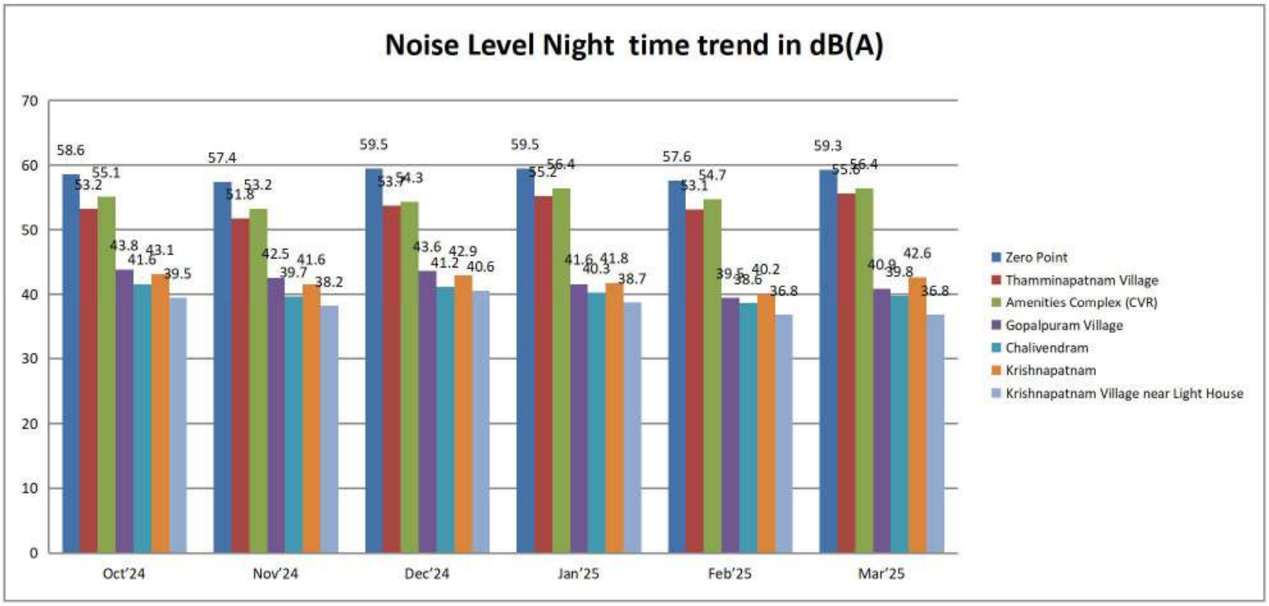


TABLE-4.5.2

Location	Oct'24	Nov'24	Dec'24	Jan'25	Feb'25	March'25
Zero Point	58.6	57.4	59.5	59.5	57.6	59.3
Thamminapatnam Village	53.2	51.8	53.7	55.2	53.1	55.6
Amenities Complex (CVR)	55.1	53.2	54.3	56.4	54.7	56.4
Gopalpuram Village	43.8	42.5	43.6	41.6	39.5	40.9
Chalivendram	41.6	39.7	41.2	40.3	38.6	39.8
Krishnapatnam	43.1	41.6	42.9	41.8	40.2	42.6
Krishnapatnam Village near Light House	39.5	38.2	40.6	38.7	36.8	36.8

- ***Industrial Night time noise level varied between 36.8 to 59.5 dB(A)***
- ***Residential Night time noise level varied between 38.6 to 43.8 dB(A)***
- ***NAAQ Standard: Industrial -70 Db(A) ,Residential-45 dB(A)***

4.4 Marine Water and Surface Water Quality

4.4.1 Sampling Locations

Marine water sampling is carried out once in every week at Four sampling locations in the port. In addition to marine quality sampling, surface water quality sampling is also carried out at two locations in the creek once in every month. The marine water and surface water sampling locations are given in **Table-4** and **Figure–5.**

Table No- 4
MARINE WATER QUALITY AND SURFACE WATER MONITORING LOCATIONS

Location Code	Location
Marine Water Quality Sampling Location	
MW1	Coal Berth
MW2	Turning Circle
MW3	Approach Channel
MW4	Reclamation Area (Mutable)
Surface Water Sampling Location	
SW1	Kandaleru Creek
SW2	Buckingham Canal

- Analysis results of the water samples collected from the above locations are enclosed

The methodology for sample collection and preservation techniques was followed as per the Standard Operating Procedures (SOP) mentioned in table hereunder:

Table No- 5

Standard Operating Procedures (SOP) For Water Sampling

Parameter	Sample Collection	Sample Size	Storage/ Preservation
pH	Grab sampling Plastic /glass container	50 ml	Refrigeration, can be stored for 7 days
Electrical Conductivity	Grab sampling Plastic /glass container	50 ml	Refrigeration, can be stored for 7 days
Total suspended solids	Grab sampling Plastic /glass container	100 ml	Refrigeration, can be stored for 7 days
Total Dissolved Solids	Grab sampling Plastic /glass container	100 ml	Refrigeration, can be stored for 7 days
BOD	Grab sampling Plastic /glass container	500 ml	Refrigeration, 48 hrs
Hardness	Grab sampling Plastic /glass container	100 ml	Add HNO_3 to pH<2, refrigeration; 6 months
Chlorides	Grab sampling Plastic /glass container	50 ml	Not required; 28 days
Sulphates	Grab sampling Plastic /glass container	100 ml	Refrigeration; 28 days
Nitrates	Plastic containers	100 ml	Refrigeration; 48 hrs
Fluorides	Plastic containers only	100 ml	Not required; 28 days
Alkalinity	Plastic/ glass containers	100 ml	Refrigeration; 14 days
Ammonia	Plastic/ glass containers	100 ml	Add H_2SO_4 to pH>2, refrigeration, 28 days
Heavy Metals (Ar, Cd, Mn, Cu, Fe, Zn, Pb etc.)	Plastic/ Glass rinse with 1+1 HNO_3	500 ml	Filter, add HNO_3 to pH>2; Grab sample; 6 months

Source: Standard Methods for the Examination of Water and Wastewater, Published By APHA, 24th Edition,2023

The analytical techniques used for water analysis is given in the table hereunder:

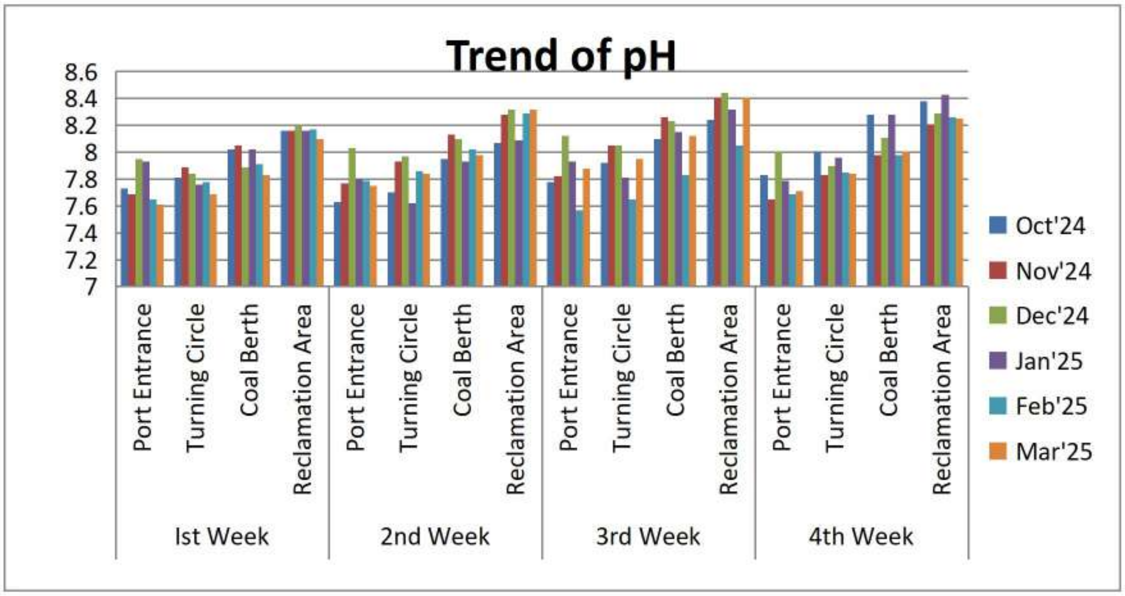
Table No- 6

Analytical Techniques for Water Analysis

S.No	Parameter	Method
1.	pH	APHA, 4500-H+B, 24th Ed., 2023
2.	Colour	APHA, 2120-C/2120-B, 24th Ed., 2023
3.	Odour	APHA, 2150, 24th Ed., 2023
4.	Temperature	APHA, 2550-A+B, 24th Ed., 2023
5.	Oil & Grease	APHA, 5520-D, 24th Ed., 2023
6.	Total Suspended Solids	APHA, 2540-D, 24th Ed., 2023
7.	Total Dissolved Solids	APHA, 2540-C, 24th Ed., 2023
8.	Total Residual Chlorine	APHA, 4500-Cl B, 24th Ed., 2023
9.	Biochemical Oxygen Demand	APHA, 5210-B, 24th Ed., 20234500-OC, 24th Ed., 2023
10.	Chemical Oxygen Demand	APHA, 5220-B, 24th Ed., 2023
11.	Free Ammonia	IS 3025
12.	Ammonical Nitrogen	APHA, 4500-NH_3 B, 24th Ed., 2023
13.	Total Kjeldhal Nitrogen	APHA, 4500-Norg B, 24th Ed., 2023
14.	Zinc	APHA, 3111-B, 24th Ed., 2023
15.	Lead	APHA, 3111-B, 24th Ed., 2023
16.	Cadmium	APHA, 3111-B, 24th Ed., 2023
17.	Mercury	APHA, 3112-B, 24th Ed., 2023
18.	Arsenic	APHA, 3114-B, 24th Ed., 2023
19.	Copper	APHA, 3111-B, 24th Ed., 2023
20.	Nickel	APHA, 3111-B, 24th Ed., 2023
21.	Cyanide	APHA, 4500-CNB, 24th Ed., 2023
22.	Fluoride	APHA, 4500-FD, 24th Ed., 2023 (SPANDS Methods)
23.	Phosphates	APHA, 4500-PD, 24th Ed., 2023
24.	Sulphates	APHA, 4500-SO_4^{2-} E, 24th Ed., 2023
25.	Sulphide	APHA, 4500-S^{2-}, 24th Ed., 2023
26.	Manganese	APHA, 3111-B, 24th Ed., 2023
27.	Iron	APHA, 3111-B, 24th Ed., 2023
28.	Phenolic Compounds	APHA, 5530-B, 24th Ed., 2023
29.	Bio Assay Test	IS 6582

Marine water samples have been collected in the port and the results of the same are shown below in **Table.**

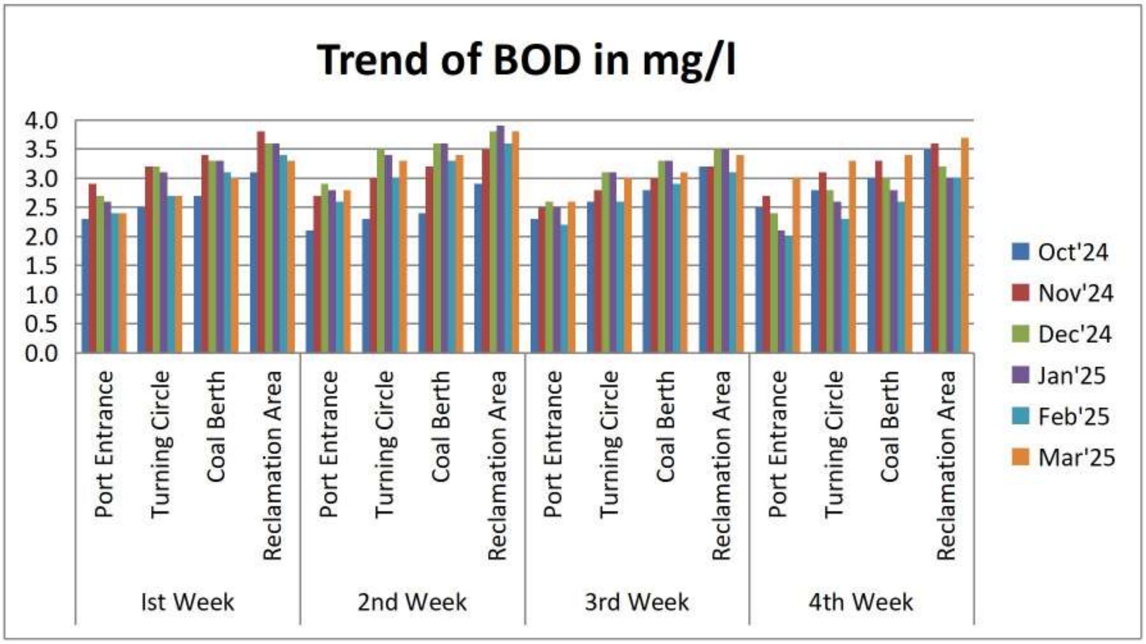
Status of Marine water Quality



pH of Marine water varied between 7.57 to 8.44

Month	Ist Week				2nd Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	7.73	7.81	8.02	8.16	7.63	7.7	7.95	8.07
Nov'24	7.69	7.89	8.05	8.16	7.77	7.93	8.13	8.28
Dec'24	7.95	7.84	7.89	8.2	8.03	7.97	8.10	8.32
Jan'25	7.93	7.76	8.02	8.16	7.80	7.62	7.93	8.09
Feb'25	7.65	7.78	7.91	8.17	7.79	7.86	8.02	8.29
Mar'25	7.61	7.69	7.83	8.10	7.75	7.84	7.98	8.32

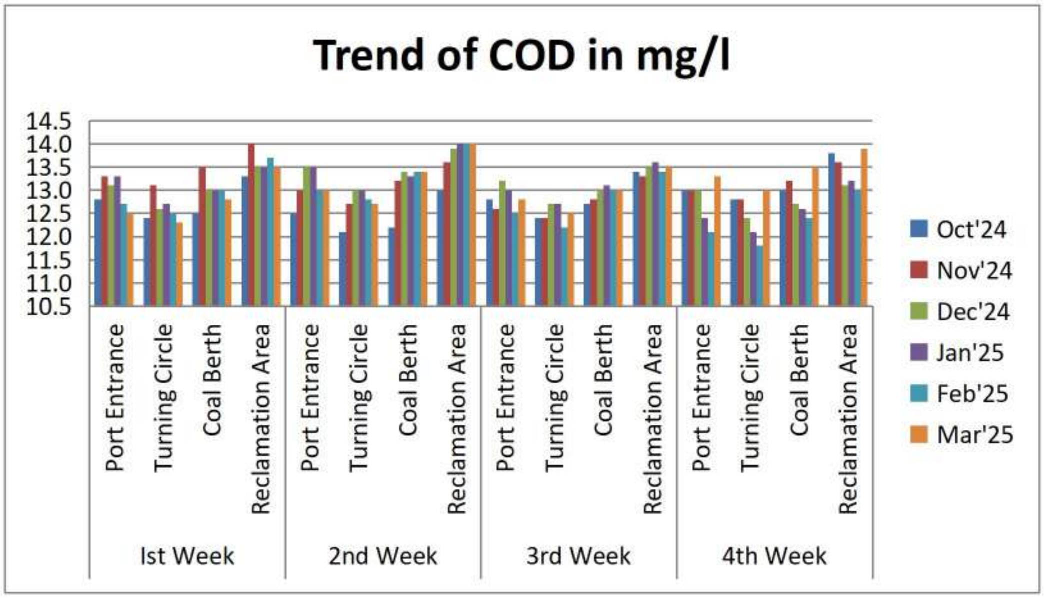
Month	3rd Week				4th Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	7.78	7.92	8.10	8.24	7.83	8.01	8.28	8.38
Nov'24	7.82	8.05	8.26	8.41	7.65	7.83	7.98	8.21
Dec'24	8.12	8.05	8.23	8.44	8.01	7.90	8.11	8.29
Jan'25	7.93	7.81	8.15	8.32	7.79	7.96	8.28	8.43
Feb'25	7.57	7.65	7.83	8.05	7.69	7.85	7.98	8.26
Mar'25	7.88	7.95	8.12	8.41	7.71	7.84	8.01	8.25



❖ **BOD of Marine Water varied between 2.0 to 3.9 mg/l**

Month	Ist Week				2nd Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	2.3	2.5	2.7	3.1	2.1	2.3	2.4	2.9
Nov'24	2.9	3.2	3.4	3.8	2.7	3.0	3.2	3.5
Dec'24	2.7	3.2	3.3	3.6	2.9	3.5	3.6	3.8
Jan'25	2.6	3.1	3.3	3.6	2.8	3.4	3.6	3.9
Feb'25	2.4	2.7	3.1	3.4	2.6	3.0	3.3	3.6
Mar'25	2.4	2.7	3.0	3.3	2.8	3.3	3.4	3.8

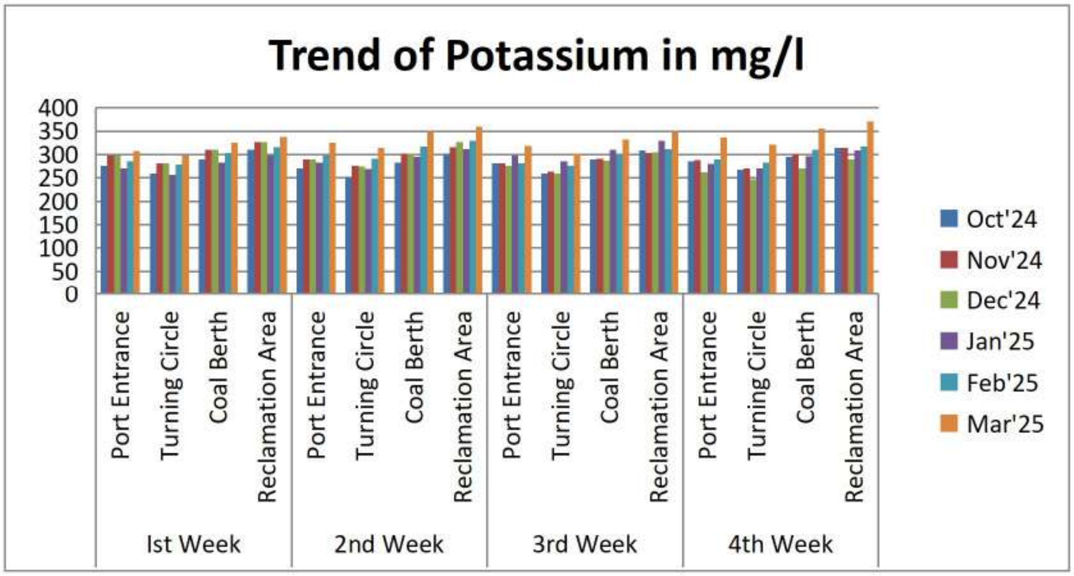
Month	3rd Week				4th Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	2.3	2.6	2.8	3.2	2.5	2.8	3.0	3.5
Nov'24	2.5	2.8	3.0	3.2	2.7	3.1	3.3	3.6
Dec'24	2.6	3.1	3.3	3.5	2.4	2.8	3.0	3.2
Jan'25	2.5	3.1	3.3	3.5	2.1	2.6	2.8	3.0
Feb'25	2.2	2.6	2.9	3.1	2.0	2.3	2.6	3.0
Mar'25	2.6	3.0	3.1	3.4	3.0	3.3	3.4	3.7



- **COD of Marine Water varied between 11.8 to 14.0 mg/l**

Month	Ist Week				2nd Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	12.8	12.4	12.5	13.3	12.5	12.1	12.2	13.0
Nov'24	13.3	13.1	13.5	14.0	13.0	12.7	13.2	13.6
Dec'24	13.1	12.6	13.0	13.5	13.5	13.0	13.4	13.9
Jan'25	13.3	12.7	13.0	13.5	13.5	13.0	13.3	14.0
Feb'25	12.7	12.5	13.0	13.7	13.0	12.8	13.4	14.0
Mar'25	12.5	12.3	12.8	13.5	13.0	12.7	13.4	14.0

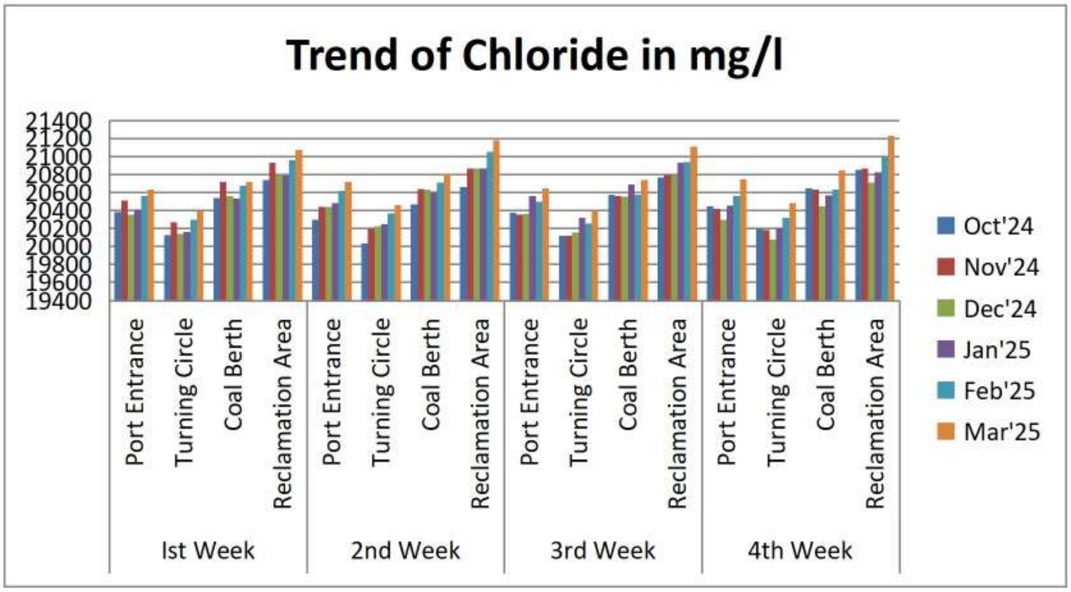
Month	3rd Week				4th Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	12.8	12.4	12.7	13.4	13.0	12.8	13.0	13.8
Nov'24	12.6	12.4	12.8	13.3	13.0	12.8	13.2	13.6
Dec'24	13.2	12.7	13.0	13.5	13.0	12.4	12.7	13.1
Jan'25	13.0	12.7	13.1	13.6	12.4	12.1	12.6	13.2
Feb'25	12.5	12.2	13.0	13.4	12.1	11.8	12.4	13.0
Mar'25	12.8	12.5	13.0	13.5	13.3	13.0	13.5	13.9



❖ **Potassium Concentration in Marine water varied between 247 to 371 mg/l**

Month	Ist Week				2nd Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	276	259	290	310	270	252	283	302
Nov'24	298	281	310	327	290	276	302	316
Dec'24	298	281	310	327	290	275	301	327
Jan'25	270	256	283	298	283	269	295	312
Feb'25	286	278	304	316	298	291	317	330
Mar'25	307	298	326	338	325	314	349	360

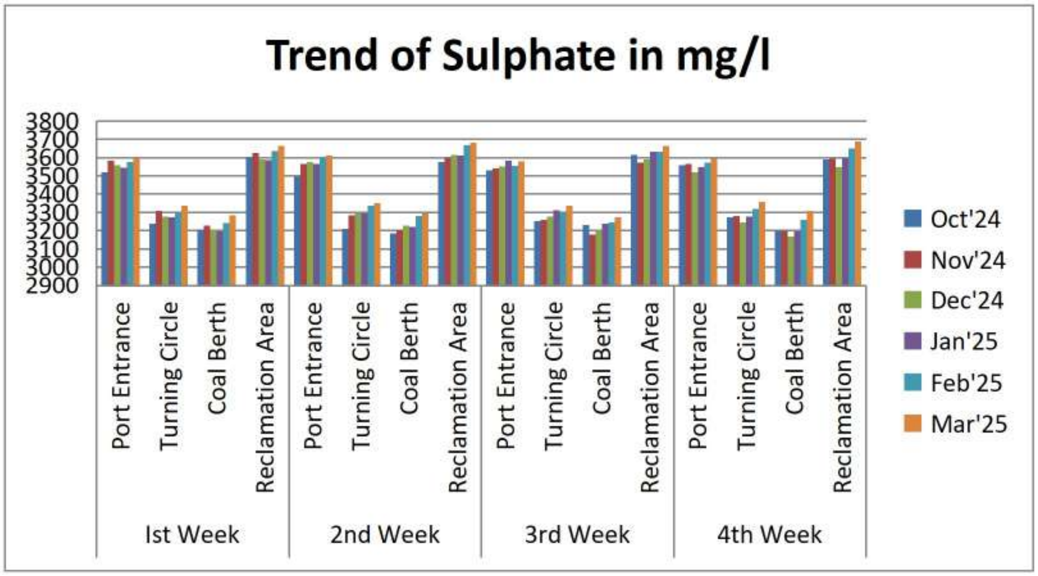
Month	3rd Week				4th Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	281	260	289	309	286	267	295	315
Nov'24	281	263	291	304	288	271	300	315
Dec'24	276	260	287	305	262	247	271	290
Jan'25	298	286	310	330	280	271	296	309
Feb'25	282	276	300	311	289	283	310	317
Mar'25	318	302	332	349	336	321	355	371



❖ **Chloride concentration in Marine water varied between 20033 to 21227 mg/l**

Month	Ist Week				2nd Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	20382	20127	20542	20735	20297	20033	20469	20659
Nov'24	20512	20270	20714	20933	20438	20198	20641	20867
Dec'24	20356	20143	20562	20794	20442	20227	20632	20870
Jan'25	20410	20162	20531	20789	20485	20248	20610	20863
Feb'25	20563	20297	20671	20962	20620	20368	20708	21054
Mar'25	20632	20389	20716	21073	20714	20463	20807	21178

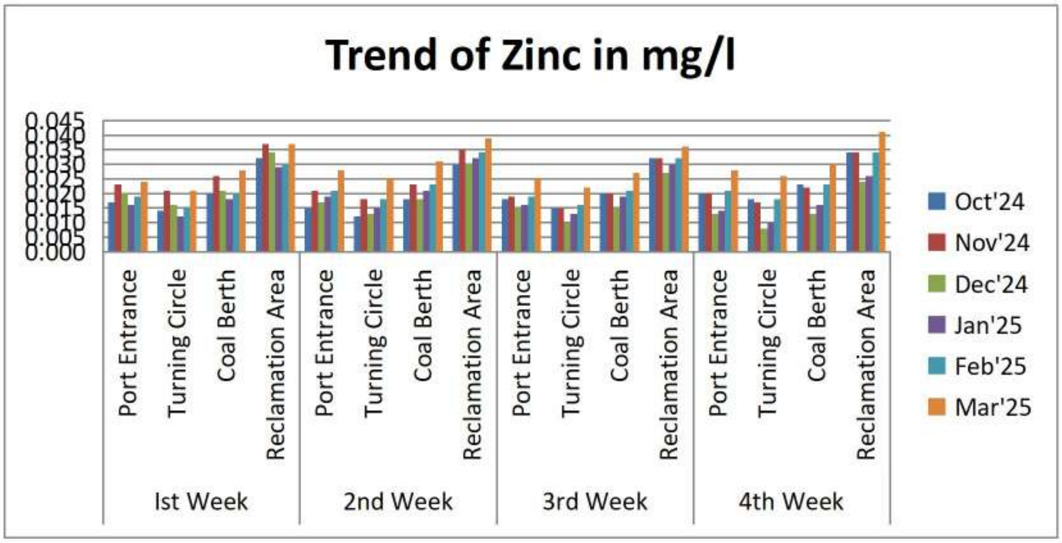
Month	3rd Week				4th Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	20373	20117	20573	20769	20449	20199	20649	20851
Nov'24	20355	20122	20562	20798	20417	20180	20629	20869
Dec'24	20362	20158	20550	20787	20296	20074	20450	20708
Jan'25	20561	20315	20687	20932	20451	20203	20566	20826
Feb'25	20496	20258	20576	20936	20564	20316	20635	21004
Mar'25	20649	20389	20739	21106	20745	20482	20846	21227



❖ **Sulphate concentration in Marine water varied between 3167 to 3687 mg/l**

Month	Ist Week				2nd Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	3519	3237	3208	3604	3495	3211	3184	3576
Nov'24	3583	3308	3229	3624	3564	3284	3202	3602
Dec'24	3559	3278	3204	3590	3576	3294	3227	3613
Jan'25	3543	3272	3196	3586	3567	3296	3220	3610
Feb'25	3575	3302	3240	3636	3603	3338	3281	3669
Mar'25	3596	3337	3283	3665	3610	3352	3296	3681

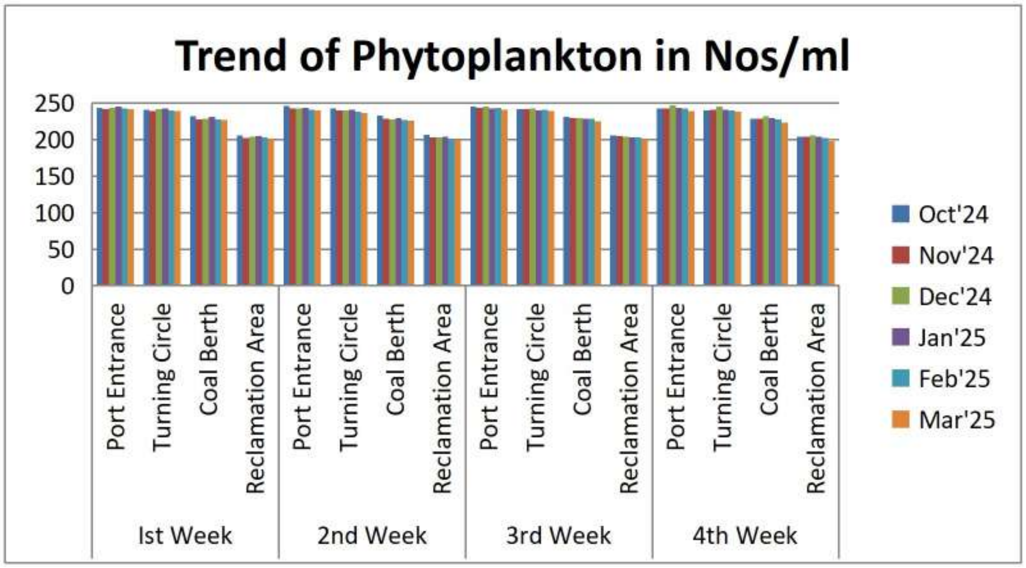
Month	3rd Week				4th Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	3531	3253	3232	3614	3557	3275	3200	3590
Nov'24	3542	3258	3177	3574	3565	3281	3198	3594
Dec'24	3550	3276	3203	3591	3521	3245	3167	3546
Jan'25	3583	3312	3238	3632	3547	3276	3197	3597
Feb'25	3555	3301	3244	3632	3572	3318	3260	3649
Mar'25	3578	3336	3273	3664	3593	3359	3310	3687



- **Zinc concentration in Marine water varied between 0.008 to 0.041 mg/l**

Month	Ist Week				2nd Week			
	Port Entrance	**Turning Circle**	**Coal Berth**	**Reclamation Area**	**Port Entrance**	**Turning Circle**	**Coal Berth**	**Reclamation Area**
Oct'24	0.017	0.014	0.020	0.032	0.015	0.012	0.018	0.030
Nov'24	0.023	0.021	0.026	0.037	0.021	0.018	0.023	0.035
Dec'24	0.020	0.016	0.021	0.034	0.017	0.013	0.018	0.030
Jan'25	0.016	0.012	0.018	0.029	0.019	0.015	0.021	0.032
Feb'25	0.019	0.015	0.020	0.030	0.021	0.018	0.023	0.034
Mar'25	0.024	0.021	0.028	0.037	0.028	0.025	0.031	0.039

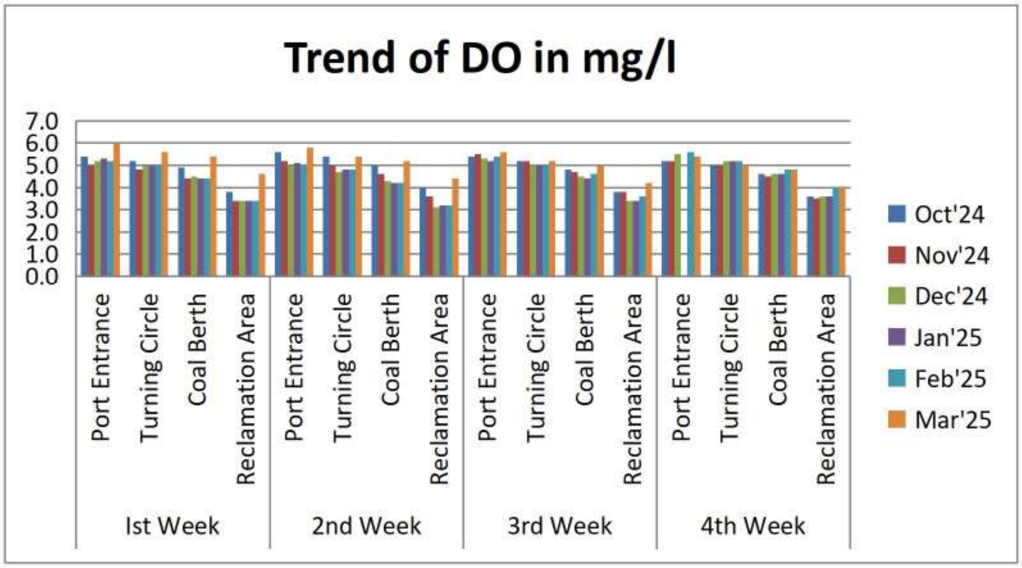
Month	3rd Week				4th Week			
	Port Entrance	**Turning Circle**	**Coal Berth**	**Reclamation Area**	**Port Entrance**	**Turning Circle**	**Coal Berth**	**Reclamation Area**
Oct'24	0.018	0.015	0.020	0.032	0.020	0.018	0.023	0.034
Nov'24	0.019	0.015	0.020	0.032	0.020	0.017	0.022	0.034
Dec'24	0.015	0.010	0.015	0.027	0.013	0.008	0.013	0.024
Jan'25	0.016	0.013	0.019	0.030	0.014	0.010	0.016	0.026
Feb'25	0.019	0.016	0.021	0.032	0.021	0.018	0.023	0.034
Mar'25	0.025	0.022	0.027	0.036	0.028	0.026	0.030	0.041



❖ **Phytoplankton in Marine water varied between 198 to 247 No./ml**

Month	Ist Week				2nd Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	244	241	232	206	246	243	233	207
Nov'24	242	239	228	202	243	240	229	203
Dec'24	244	242	229	204	243	240	228	203
Jan'25	245	243	231	205	244	241	230	204
Feb'25	243	240	228	203	241	238	227	201
Mar'25	242	239	227	201	240	237	226	200

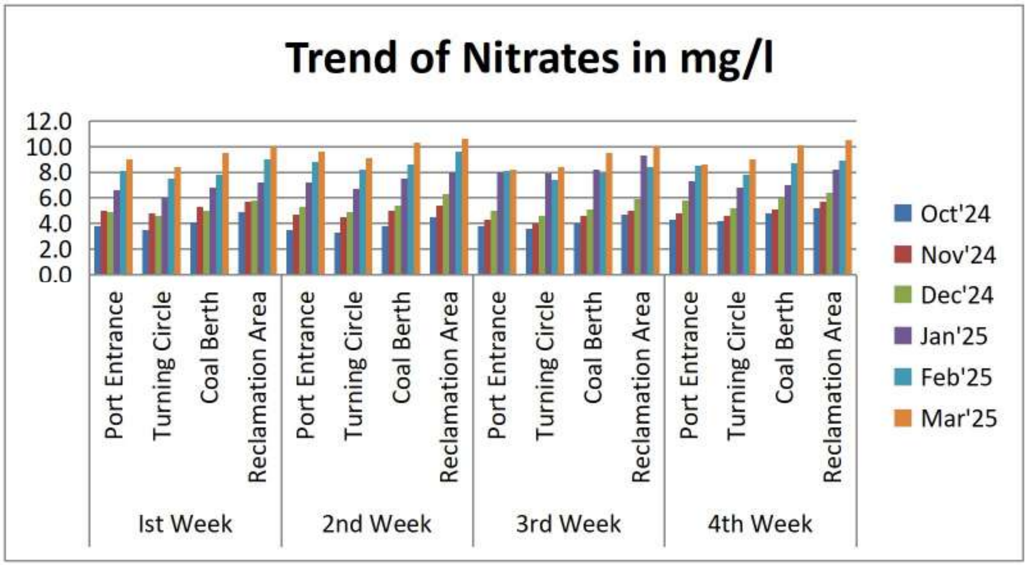
Month	3rd Week				4th Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	245	242	231	206	243	240	229	204
Nov'24	244	242	230	205	243	241	229	204
Dec'24	245	243	230	204	247	245	232	206
Jan'25	243	240	229	203	244	241	230	204
Feb'25	244	241	229	203	243	240	228	202
Mar'25	241	239	225	201	239	238	223	198



❖ **DO in Marine water varied between 3.1 to 6.0 mg/l**

Month	Ist Week				2nd Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	5.4	5.2	4.9	3.8	5.6	5.4	5.0	4.0
Nov'24	5.0	4.8	4.4	3.4	5.2	5.0	4.6	3.6
Dec'24	5.2	5.0	4.5	3.4	5.0	4.7	4.3	3.1
Jan'25	5.3	5.0	4.4	3.4	5.1	4.8	4.2	3.2
Feb'25	5.2	5.0	4.4	3.4	5.0	4.8	4.2	3.2
Mar'25	6.0	5.6	5.4	4.6	5.8	5.4	5.2	4.4

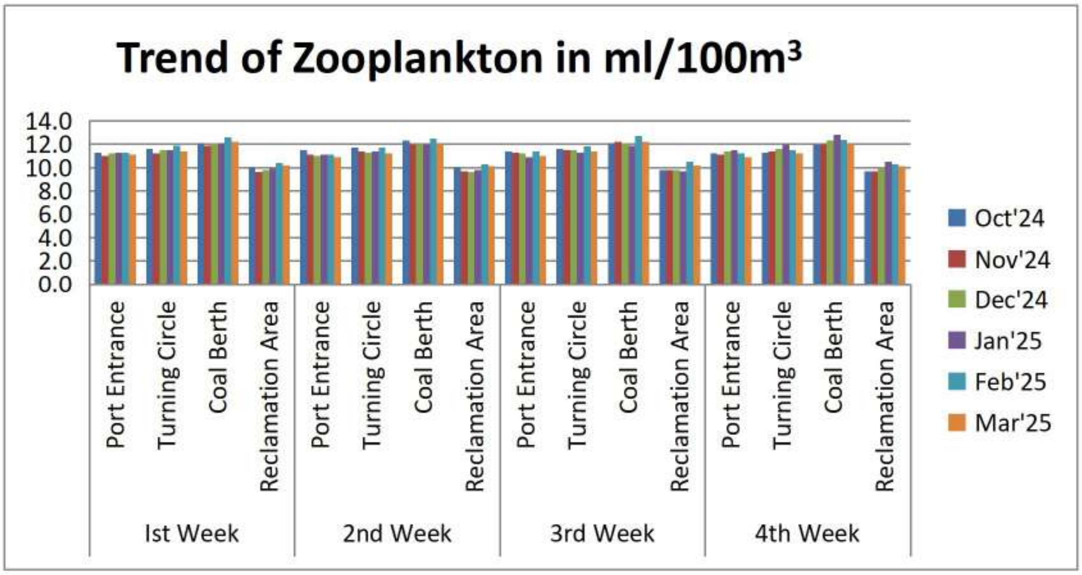
Month	3rd Week				4th Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	5.4	5.2	4.8	3.8	5.2	5.0	4.6	3.6
Nov'24	5.5	5.2	4.7	3.8	5.2	5.0	4.5	3.5
Dec'24	5.3	5.0	4.5	3.4	5.5	5.2	4.6	3.6
Jan'25	5.2	5.0	4.4	3.4	s	5.2	4.6	3.6
Feb'25	5.4	5.0	4.6	3.6	5.6	5.2	4.8	4.0
Mar'25	5.6	5.2	5.0	4.2	5.4	5.0	4.8	4.0



- **Nitrates in Marine water varied between 3.3 to 10.6 mg/l**

Month	Ist Week				2nd Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	3.8	3.5	4.1	4.9	3.5	3.3	3.8	4.5
Nov'24	5.0	4.8	5.3	5.7	4.7	4.5	5.0	5.4
Dec'24	4.9	4.6	5.0	5.8	5.3	4.9	5.4	6.3
Jan'25	6.6	6.0	6.8	7.2	7.2	6.7	7.5	8.0
Feb'25	8.1	7.5	7.8	9.0	8.8	8.2	8.6	9.6
Mar'25	9.0	8.4	9.5	10.0	9.6	9.1	10.3	10.6

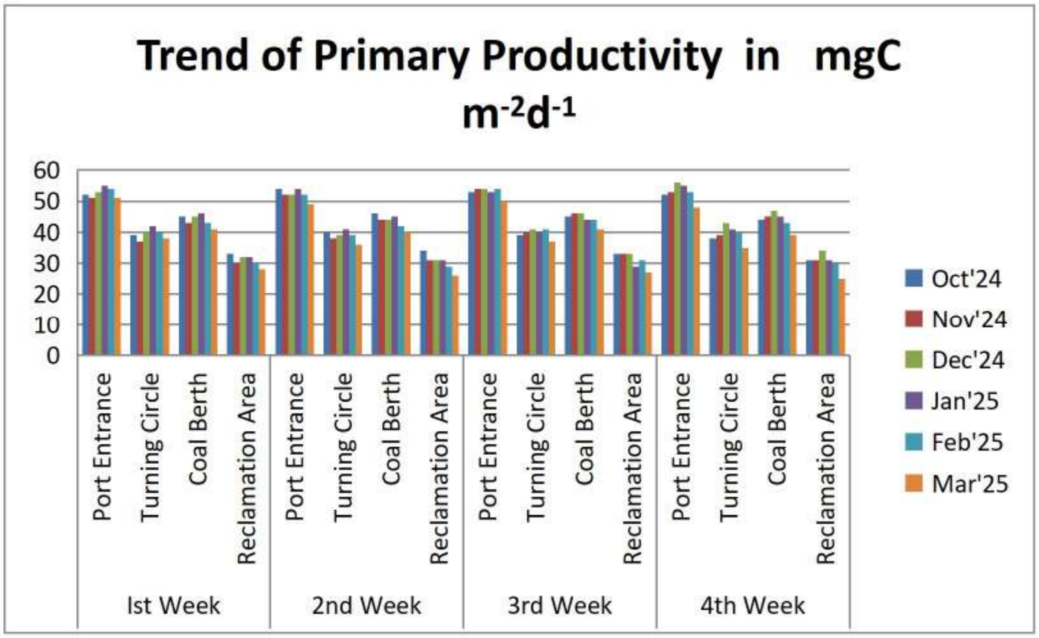
Month	3rd Week				4th Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	3.8	3.6	4.0	4.7	4.3	4.2	4.8	5.2
Nov'24	4.3	4.0	4.6	5.0	4.8	4.6	5.1	5.7
Dec'24	5.0	4.6	5.1	5.9	5.8	5.2	6.0	6.4
Jan'25	8.0	7.9	8.2	9.3	7.3	6.8	7.0	8.2
Feb'25	8.1	7.4	7.9	8.4	8.5	7.8	8.7	8.9
Mar'25	8.2	8.4	9.5	10.0	8.6	9.0	10.1	10.5



❖ **Zoo plankton in Marine water varied between 9.6 to 12.8 ml/100m^3**

Month	Ist Week				2nd Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	11.3	11.6	12.1	10.0	11.5	11.7	12.3	10.0
Nov'24	11.0	11.2	11.9	9.6	11.1	11.4	12.0	9.7
Dec'24	11.2	11.5	12.1	9.8	11.0	11.3	12.0	9.6
Jan'25	11.3	11.5	12.1	9.9	11.1	11.4	12.0	9.8
Feb'25	11.3	11.9	12.6	10.4	11.1	11.7	12.5	10.3
Mar'25	11.1	11.4	12.2	10.2	10.9	11.2	12.0	10.1

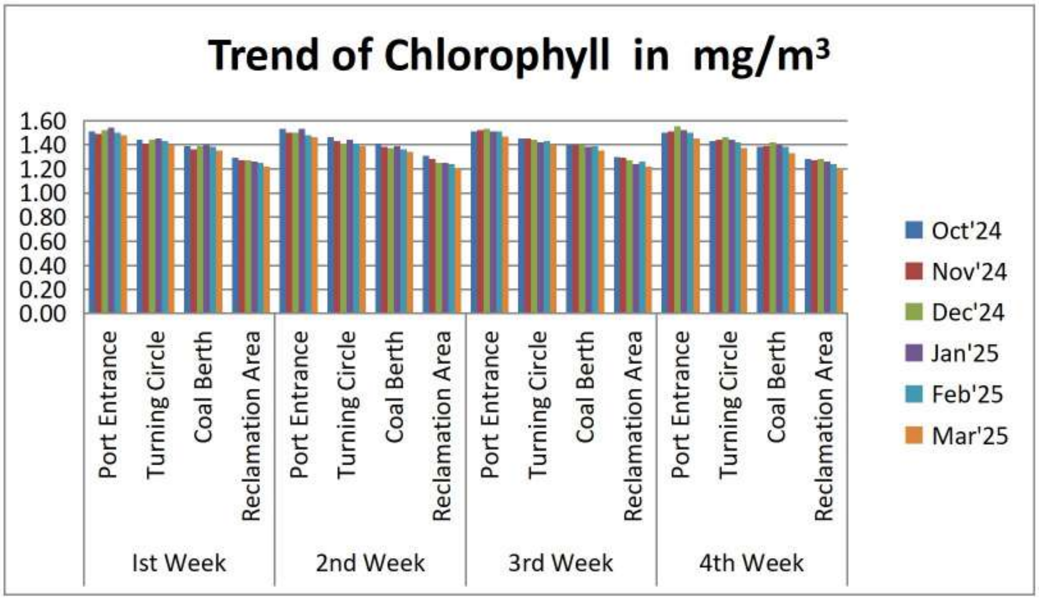
Month	3rd Week				4th Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	11.4	11.6	12.1	9.8	11.2	11.3	12.0	9.7
Nov'24	11.3	11.5	12.2	9.8	11.1	11.4	12.0	9.7
Dec'24	11.2	11.5	12.1	9.8	11.4	11.6	12.3	10.0
Jan'25	10.9	11.3	11.9	9.7	11.5	12.0	12.8	10.5
Feb'25	11.4	11.8	12.7	10.5	11.2	11.5	12.4	10.3
Mar'25	11.0	11.4	12.2	10.2	10.9	11.2	12.0	10.1



- **Primary Productivity in Marine water varied between 25 to 56 mg $m^{-2}d^{-1}$**

Month	Ist Week				2nd Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	52	39	45	33	54	40	46	34
Nov'24	51	37	43	30	52	38	44	31
Dec'24	53	40	45	32	52	39	44	31
Jan'25	55	42	46	32	54	41	45	31
Feb'25	54	40	43	30	52	39	42	29
Mar'25	51	38	41	28	49	36	40	26

Month	3rd Week				4th Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	53	39	45	33	52	38	44	31
Nov'24	54	40	46	33	53	39	45	31
Dec'24	54	41	46	33	56	43	47	34
Jan'25	53	40	44	29	55	41	45	31
Feb'25	54	41	44	31	53	40	43	30
Mar'25	50	37	41	27	48	35	39	25



- **Chlorophyll in Marine water varied between 1.2 to 1.55 mg/m^3**

Month	Ist Week				2nd Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	1.51	1.44	1.39	1.29	1.53	1.46	1.41	1.31
Nov'24	1.49	1.41	1.36	1.27	1.50	1.43	1.38	1.28
Dec'24	1.52	1.44	1.39	1.27	1.50	1.41	1.37	1.25
Jan'25	1.54	1.45	1.40	1.26	1.53	1.44	1.39	1.25
Feb'25	1.50	1.43	1.38	1.25	1.48	1.41	1.36	1.24
Mar'25	1.48	1.40	1.35	1.22	1.46	1.39	1.34	1.21

Month	3rd Week				4th Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	1.51	1.45	1.40	1.30	1.50	1.43	1.38	1.28
Nov'24	1.52	1.45	1.40	1.29	1.51	1.44	1.39	1.27
Dec'24	1.53	1.44	1.40	1.27	1.55	1.46	1.42	1.28
Jan'25	1.51	1.42	1.38	1.24	1.52	1.44	1.40	1.26
Feb'25	1.51	1.43	1.39	1.26	1.50	1.42	1.38	1.24
Mar'25	1.47	1.40	1.35	1.22	1.45	1.37	1.33	1.20

Summary of Marine water quality results for six months of period Oct 24 – March 25

- pH - values are in the range 7.57 to 8.44
- BOD -values are in the range 2.0 to 3.9 mg/l
- COD - values are in the range 11.8 to 14.0 mg/l
- Potassium - values are in the range 247 to 371 mg/l
- Chloride - values are in the range 20033 to 21227 mg/l
- Sulphates - values are in the range to 3167 to 3687 mg/l
- Zinc - values are in the range 0.008 to 0.041 mg/l
- Phytoplankton - values are in the range 198 to 247 No./ml
- DO - values are in the range 3.1 to 6.0 mg/l
- Nitrates - values are in the range 3.3 to 10.6 mg/l
- Zoo plankton - values are in the range 9.6 to 12.8 ml/100m^3
- Primary productivity - values are in the range 25 to 56 mgC $m^{-2}d^{-1}$
- Chlorophyll - values are in the range 1.20 to 1.55 mg/m^3

4.5 Marine Water Turbidity

Marine water turbidity is carried out on one day every week at each of the four locations of Marine Water quality sampling (MT1, MT2 ,MT3 and MT4). Turbidity levels are monitored during Low Tide, Medium Tide and High Tide.

MARINE TURBIDITY MONITORING LOCATIONS

Sampling Code	Name of the Location
MT1	Coal Berth
MT2	Turning circle
MT3	Approach channel
MT4	Reclamation Area (Mutable)

4.5.1 Marine Deep Sea Turbidity

Marine water turbidity is carried out in the deep water i.e., at the dredged material disposal area on one day every month at three locations.

4.5.2 Sampling Locations

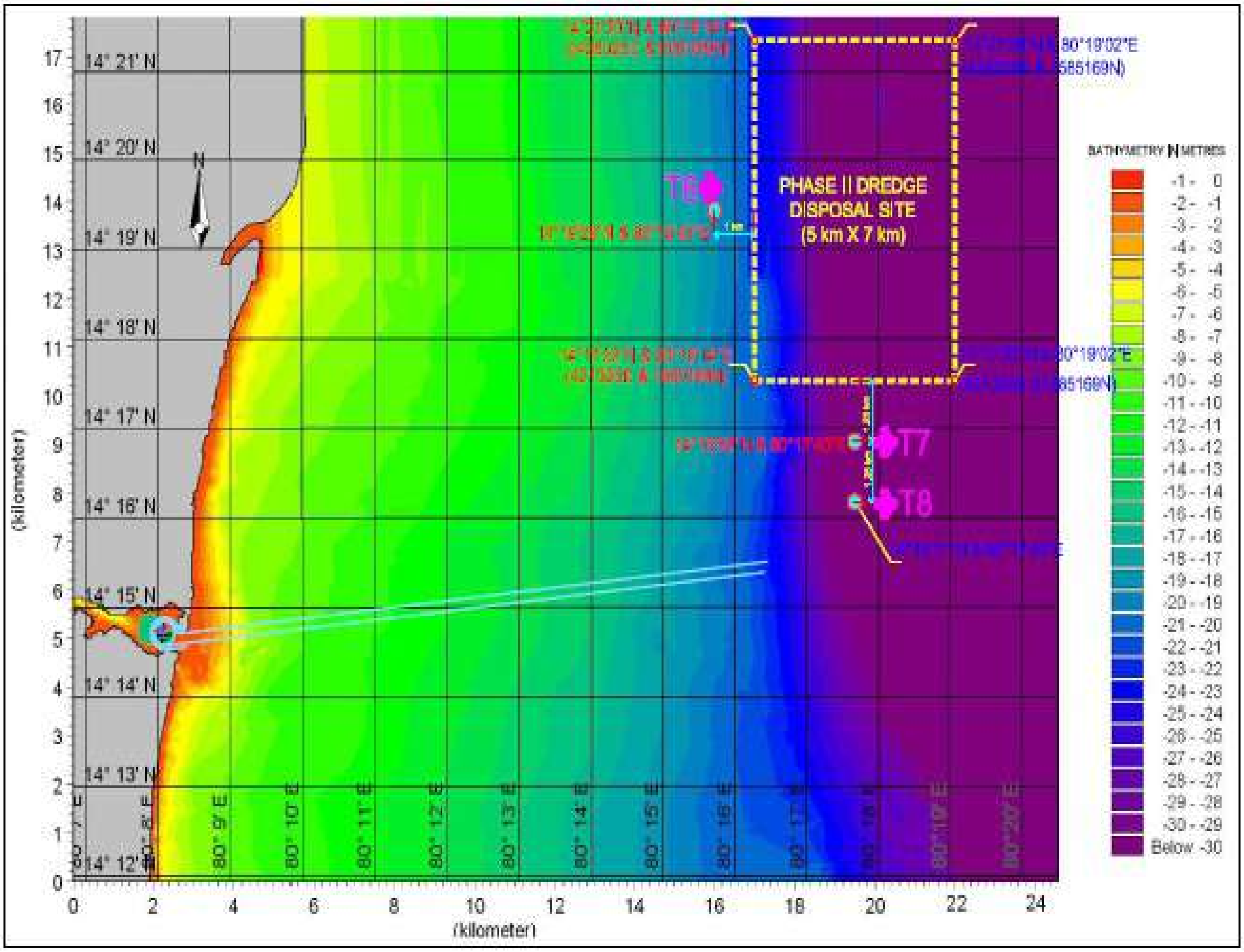
Turbidity levels are monitored during Low Tide, Medium Tide and High Tide. Monitoring locations listed below and **Figure–5.**

MARINE DEEP SEA TURBIDITY MONITORING LOCATIONS

Location Code	Geographical Co-ordinates
DS1	$14^0$19'26"N ; $80^0$15'43"E
DS2	$14^0$16'52"N ; $80^0$17'40"E
DS3	$14^0$16'11"N ; $80^0$17'40"E

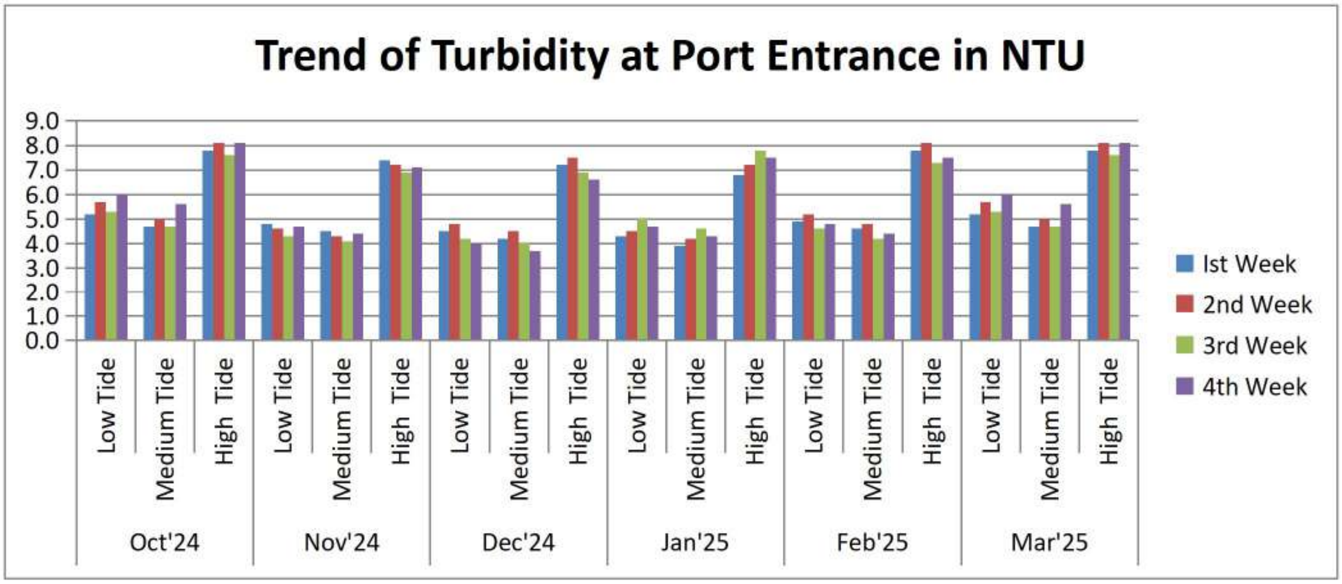
FIGURE-5

KRISHNAPATNAM PORT DEEP SEA MONITORING LOCATIONS

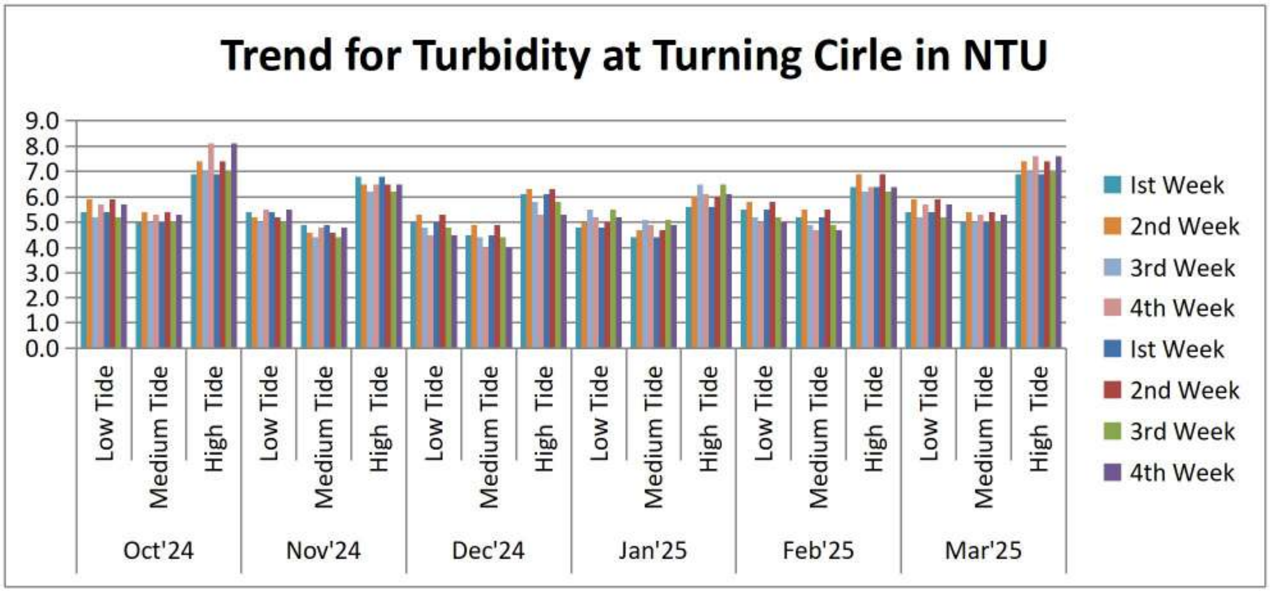


CODE	PARAMETERS	CO-ORDINATES OF MONITORING STATION
	Turbidity Monitoring	
T6		14°19'26"N & 80°15'43"E
T7		14°16'52"N & 80°17'40"E
T8		14°16'11"N & 80°17'40"E

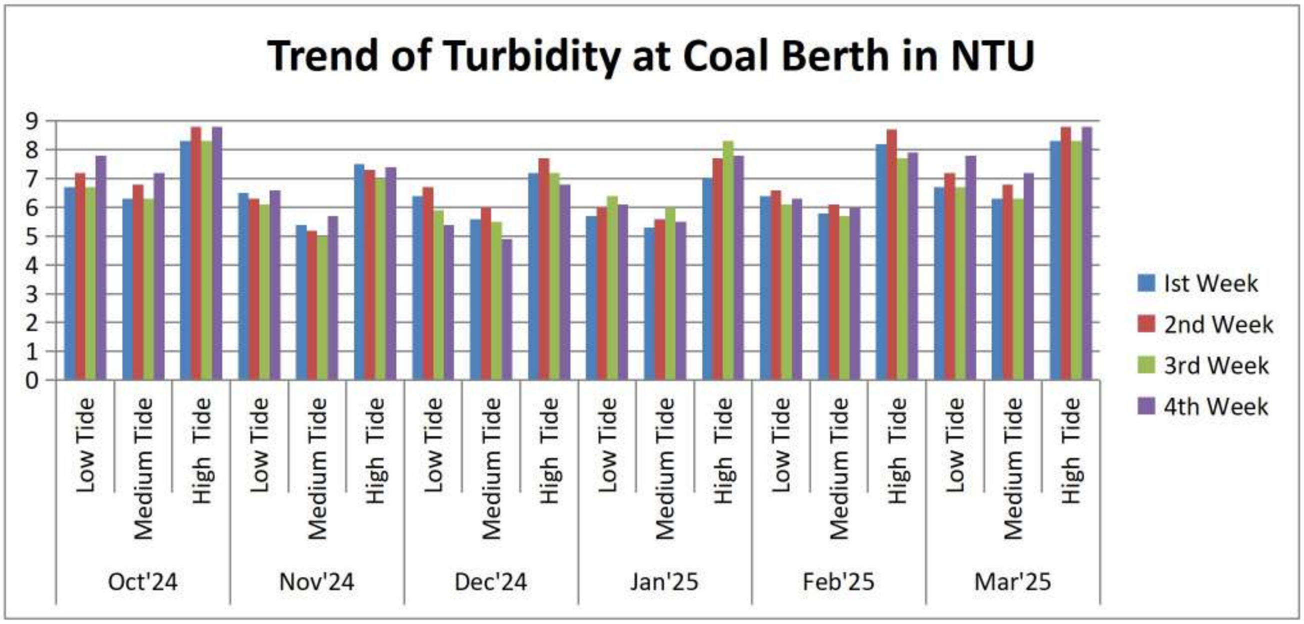
Status of Turbidity in Marine Water



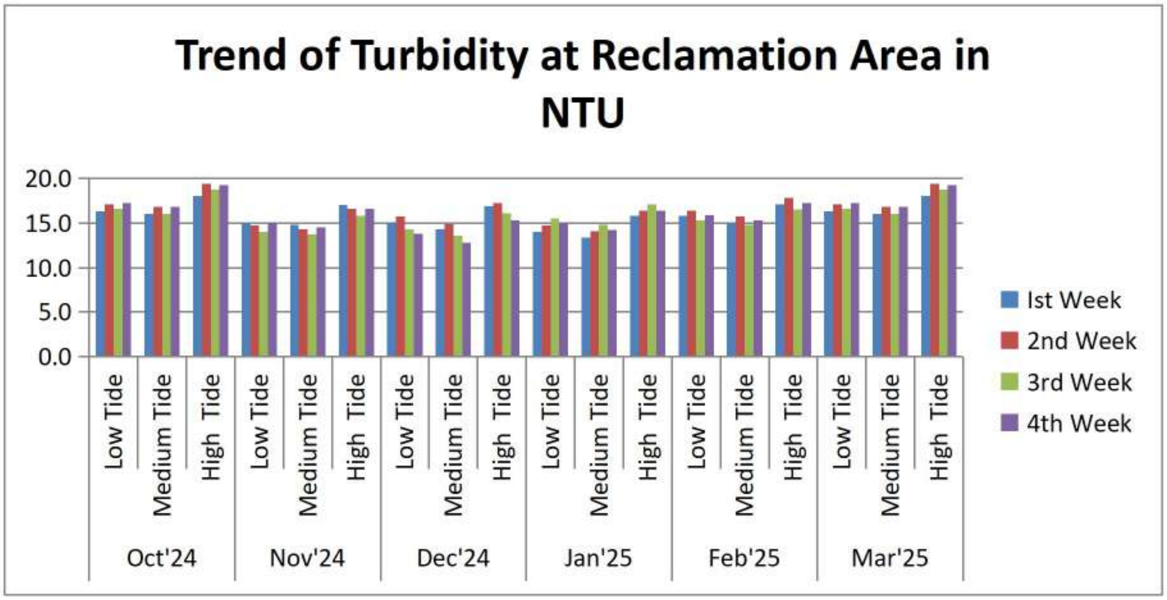
Month		Ist Week	2nd Week	3rd Week	4th Week	Month		Ist Week	2nd Week	3rd Week	4th Week
Oct'24	Low Tide	5.2	5.7	5.3	6.0	Jan'25	Low Tide	4.3	4.5	5	4.7
	Medium Tide	4.7	5.0	4.7	5.6		Medium Tide	3.9	4.2	4.6	4.3
	High Tide	7.8	8.1	7.6	8.1		High Tide	6.8	7.2	7.8	7.5
Nov'24	Low Tide	4.8	4.6	4.3	4.7	Feb'25	Low Tide	4.9	5.2	4.6	4.8
	Medium Tide	4.5	4.3	4.1	4.4		Medium Tide	4.6	4.8	4.2	4.4
	High Tide	7.4	7.2	6.9	7.1		High Tide	7.8	8.1	7.3	7.5
Dec'24	Low Tide	4.5	4.8	4.2	4	Mar'25	Low Tide	5.2	5.7	5.3	6
	Medium Tide	4.2	4.5	4	3.7		Medium Tide	4.7	5	4.7	5.6
	High Tide	7.2	7.5	6.9	6.6		High Tide	7.8	8.1	7.6	8.1



Month		Ist Week	2nd Week	3rd Week	4th Week	Month		Ist Week	2nd Week	3rd Week	4th Week
Oct'24	Low Tide	5.4	5.9	5.2	5.7	Jan'25	Low Tide	4.8	5.0	5.5	5.2
	Medium Tide	5.0	5.4	5.0	5.3		Medium Tide	4.4	4.7	5.1	4.9
	High Tide	6.9	7.4	7.0	8.1		High Tide	5.6	6.0	6.5	6.1
Nov'24	Low Tide	5.4	5.2	5.0	5.5	Feb'25	Low Tide	5.5	5.8	5.2	5.0
	Medium Tide	4.9	4.6	4.4	4.8		Medium Tide	5.2	5.5	4.9	4.7
	High Tide	6.8	6.5	6.2	6.5		High Tide	6.4	6.9	6.2	6.4
Dec'24	Low Tide	5.0	5.3	4.8	4.5	Mar'25	Low Tide	5.4	5.9	5.2	5.7
	Medium Tide	4.5	4.9	4.4	4.0		Medium Tide	5.0	5.4	5.0	5.3
	High Tide	6.1	6.3	5.8	5.3		High Tide	6.9	7.4	7.0	7.6



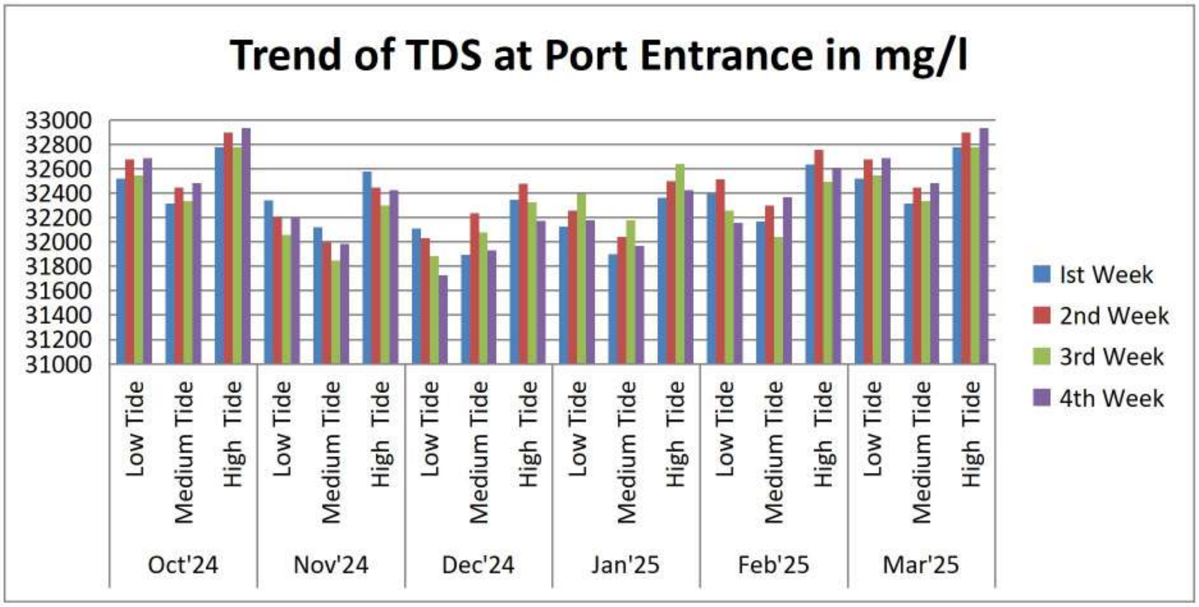
Month		Ist Week	2nd Week	3rd Week	4th Week	Month		Ist Week	2nd Week	3rd Week	4th Week
Oct'24	Low Tide	6.7	7.2	6.7	7.8	Jan'25	Low Tide	5.7	6.0	6.4	6.1
	Medium Tide	6.3	6.8	6.3	7.2		Medium Tide	5.3	5.6	6.0	5.5
	High Tide	8.3	8.8	8.3	8.8		High Tide	7.0	7.7	8.3	7.8
Nov'24	Low Tide	6.5	6.3	6.1	6.6	Feb'25	Low Tide	6.4	6.6	6.1	6.3
	Medium Tide	5.4	5.2	5.0	5.7		Medium Tide	5.8	6.1	5.7	6.0
	High Tide	7.5	7.3	7.0	7.4		High Tide	8.2	8.7	7.7	7.9
Dec'24	Low Tide	6.4	6.7	5.9	5.4	Mar'25	Low Tide	6.7	7.2	6.7	7.8
	Medium Tide	5.6	6.0	5.5	4.9		Medium Tide	6.3	6.8	6.3	7.2
	High Tide	7.2	7.7	7.2	6.8		High Tide	8.3	8.8	8.3	8.8



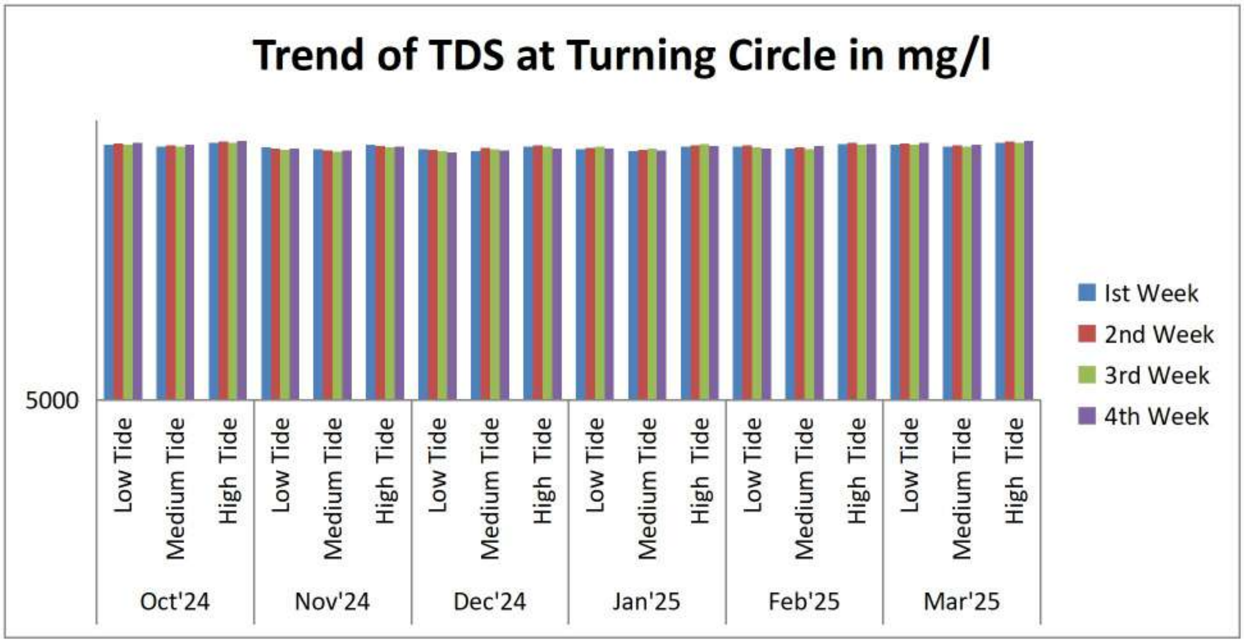
Month		Ist Week	2nd Week	3rd Week	4th Week	Month		Ist Week	2nd Week	3rd Week	4th Week
Oct'24	**Low Tide**	16.3	17.1	16.6	17.2	**Jan'25**	**Low Tide**	14.0	14.7	15.5	15.0
	Medium Tide	16.0	16.8	16.0	16.8		**Medium Tide**	13.4	14.1	14.8	14.2
	High Tide	18.0	19.4	18.7	19.2		**High Tide**	15.8	16.4	17.1	16.4
Nov'24	**Low Tide**	15.0	14.7	14.0	15.1	**Feb'25**	**Low Tide**	15.8	16.4	15.3	15.9
	Medium Tide	14.8	14.3	13.7	14.5		**Medium Tide**	15.0	15.7	14.8	15.3
	High Tide	17.0	16.6	15.8	16.6		**High Tide**	17.1	17.8	16.5	17.2
Dec'24	**Low Tide**	15.1	15.7	14.3	13.8	**Mar'25**	**Low Tide**	16.3	17.1	16.6	17.2
	Medium Tide	14.3	14.9	13.6	12.8		**Medium Tide**	16.0	16.8	16.0	16.8
	High Tide	16.9	17.2	16.1	15.3		**High Tide**	18.0	19.4	18.7	19.2

Summary of Turbidity: Coal berth varied between 4.9 to 8.8 NTU: Turning circle varied between 4.0 to 8.1 NTU and Approach channel varied between 3.7 to 8.1 NTU: Reclamation Area varied between 12.8 to 19.4 NTU

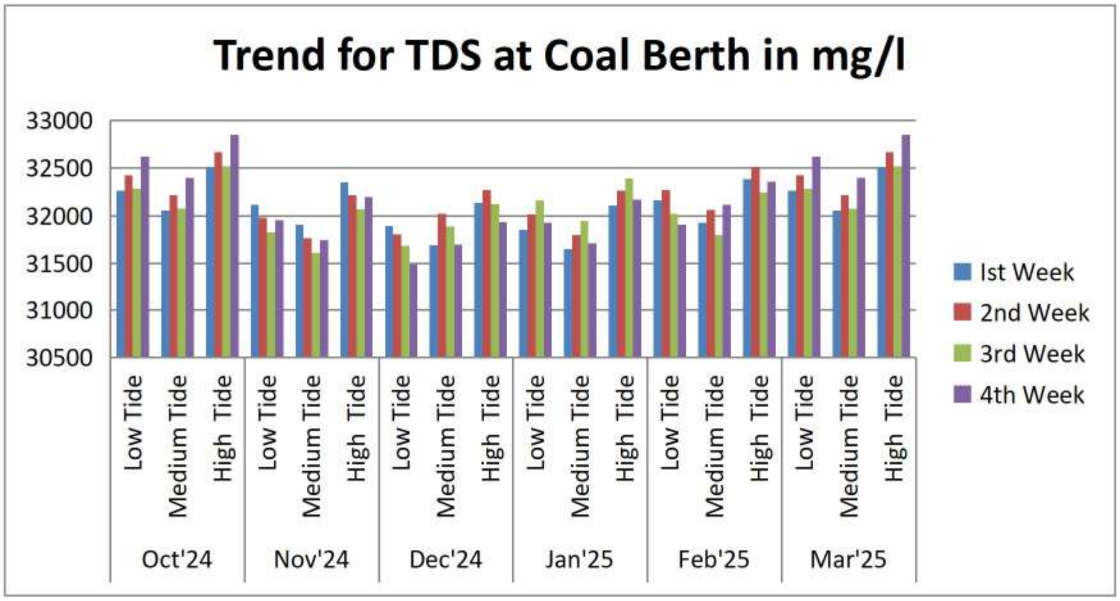
Status of Total Dissolved Solids in Marine Water



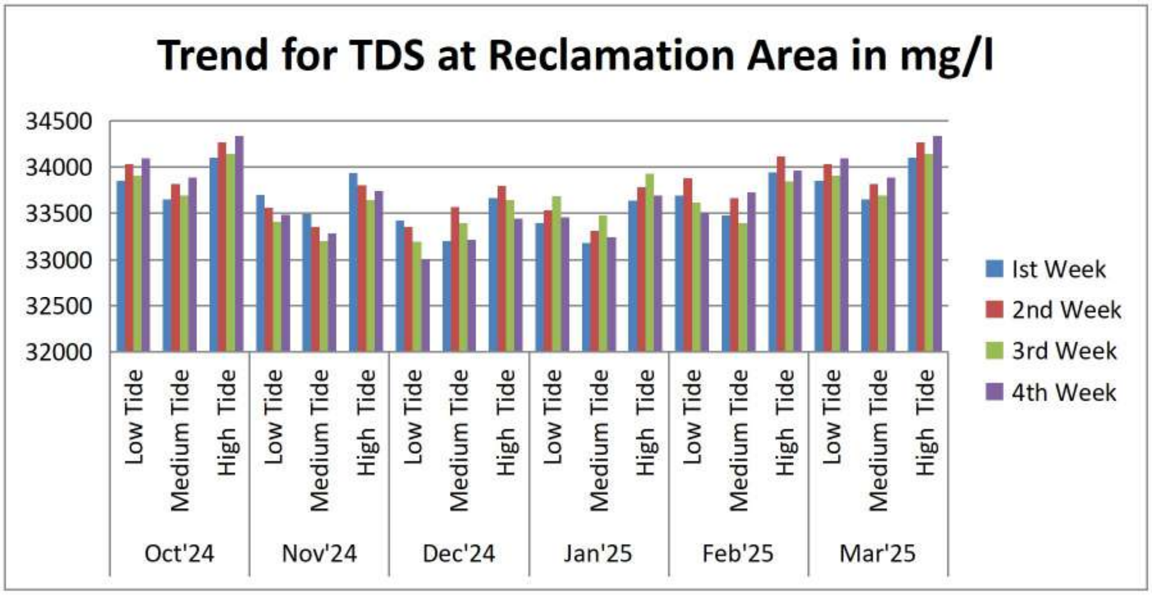
Month		Ist Week	2nd Week	3rd Week	4th Week	Month		Ist Week	2nd Week	3rd Week	4th Week
Oct'24	Low Tide	32520	32676	32545	32691	Jan'25	Low Tide	32126	32258	32396	32178
	Medium Tide	32316	32448	32336	32485		Medium Tide	31898	32042	32178	31968
	High Tide	32780	32898	32778	32935		High Tide	32362	32498	32642	32425
Nov'24	Low Tide	32341	32205	32058	32196	Feb'25	Low Tide	32396	32516	32258	32159
	Medium Tide	32120	31996	31846	31985		Medium Tide	32170	32297	32043	32369
	High Tide	32578	32449	32297	32428		High Tide	32634	32758	32493	32610
Dec'24	Low Tide	32112	32032	31883	31725	Mar'25	Low Tide	32520	32676	32545	32691
	Medium Tide	31893	32236	32081	31930		Medium Tide	32316	32448	32336	32485
	High Tide	32349	32476	32326	32175		High Tide	32780	32898	32778	32935



Month		Ist Week	2nd Week	3rd Week	4th Week	Month		Ist Week	2nd Week	3rd Week	4th Week
Oct'24	Low Tide	32378	32518	32396	32589	Jan'25	Low Tide	31945	32095	32235	32013
	Medium Tide	32175	32310	32185	32379		Medium Tide	31721	31878	32020	31796
	High Tide	32615	32752	32626	32828		High Tide	32184	32337	32475	32252
Nov'24	Low Tide	32164	32029	31867	31988	Feb'25	Low Tide	32224	32372	32145	32028
	Medium Tide	31948	31817	31662	31782		Medium Tide	31998	32156	31928	32238
	High Tide	32396	32268	32114	32235		High Tide	32459	32610	32375	32478
Dec'24	Low Tide	31940	31872	31726	31564	Mar'25	Low Tide	32378	32518	32396	32589
	Medium Tide	31725	32078	31945	31778		Medium Tide	32175	32310	32186	32379
	High Tide	32180	32319	32181	32012		High Tide	32615	32752	32626	32828



Month		Ist Week	2nd Week	3rd Week	4th Week	Month		Ist Week	2nd Week	3rd Week	4th Week
Oct'24	Low Tide	32263	32425	32284	32618	Jan'25	Low Tide	31856	32012	32165	31924
	Medium Tide	32058	32216	32074	32400		Medium Tide	31652	31797	31947	31708
	High Tide	32512	32671	32519	32850		High Tide	32110	32261	32394	32167
Nov'24	Low Tide	32118	31978	31829	31956	Feb'25	Low Tide	32164	32268	32019	31908
	Medium Tide	31909	31768	31612	31745		Medium Tide	31928	32062	31797	32119
	High Tide	32353	32217	32068	32196		High Tide	32387	32516	32247	32358
Dec'24	Low Tide	31891	31806	31684	31488	Mar'25	Low Tide	32263	32425	32284	32618
	Medium Tide	31690	32021	31889	31695		Medium Tide	32058	32216	32074	32400
	High Tide	32138	32268	32124	31936		High Tide	32512	32671	32519	32850

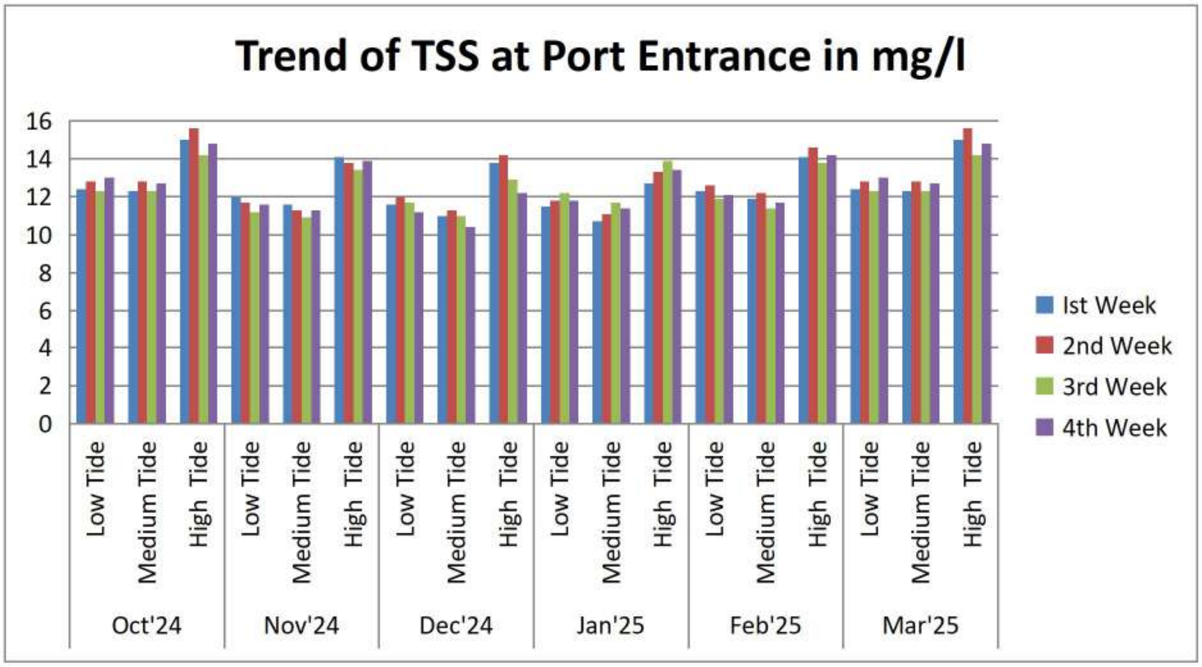


Month		Ist Week	2nd Week	3rd Week	4th Week	Month		Ist Week	2nd Week	3rd Week	4th Week
Oct'24	**Low Tide**	33855	34032	33910	34097	**Jan'25**	**Low Tide**	33392	33536	33687	33460
	Medium Tide	33651	33819	33695	33886		**Medium Tide**	33178	33315	33475	33240
	High Tide	34098	34270	34145	34336		**High Tide**	33638	33785	33928	33696
Nov'24	**Low Tide**	33697	33561	33412	33487	**Feb'25**	**Low Tide**	33695	33881	33617	33513
	Medium Tide	33489	33356	33205	33285		**Medium Tide**	33478	33668	33398	33725
	High Tide	33934	33806	33645	33742		**High Tide**	33945	34112	33848	33963
Dec'24	**Low Tide**	33420	33356	33192	33006	**Mar'25**	**Low Tide**	33855	34032	33910	34097
	Medium Tide	33205	33568	33398	33214		**Medium Tide**	33651	33819	33695	33886
	High Tide	33662	33799	33642	33446		**High Tide**	34098	34270	34145	34336

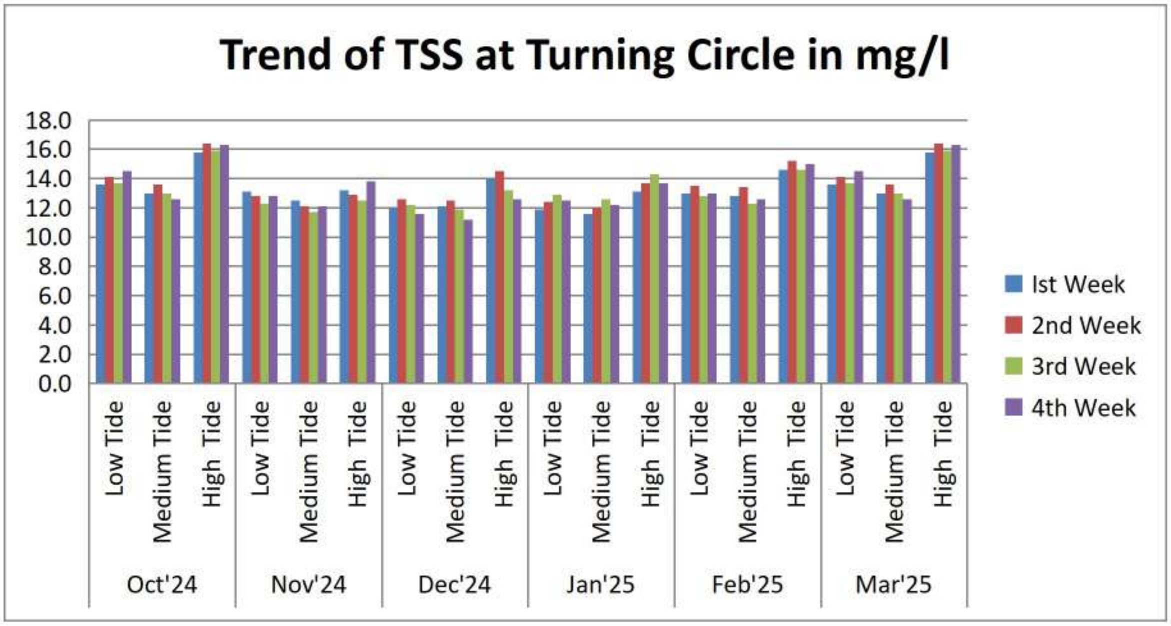
Summary of TDS of Marinne water quality results

- **TDS** - Values are in the range of 31725 to 32935 mg/l at Port Entrance (Approach Channel).
  - Values are in the range of 31564 to 32828 mg/l at Turning Circle
  - Values are in the range of 31488 to 32850 mg/l at Coal Berth
  - Values are in range of 33006 to 34336 at Reclamation Area

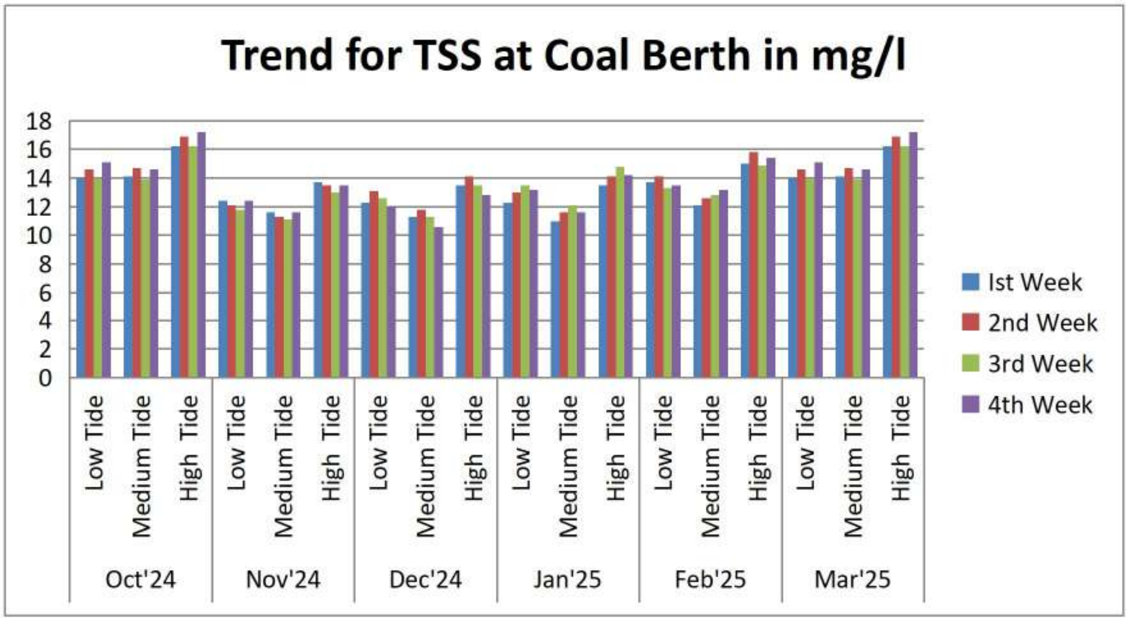
Status of Total Suspended Solids in Marine Water



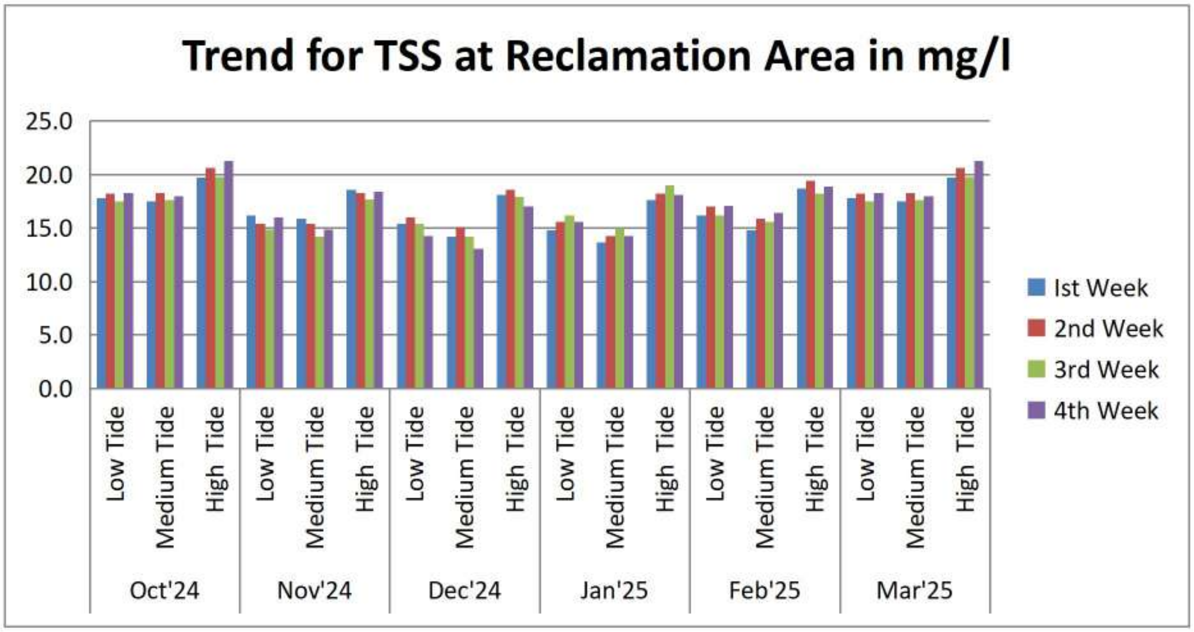
Month		Ist Week	2nd Week	3rd Week	4th Week	Month		Ist Week	2nd Week	3rd Week	4th Week
Oct'24	Low Tide	12.4	12.8	12.3	13.0	Jan'25	Low Tide	11.5	11.8	12.2	11.8
	Medium Tide	12.3	12.8	12.3	12.7		Medium Tide	10.7	11.1	11.7	11.4
	High Tide	15.0	15.6	14.2	14.8		High Tide	12.7	13.3	13.9	13.4
Nov'24	Low Tide	12.0	11.7	11.2	11.6	Feb'25	Low Tide	12.3	12.6	11.9	12.1
	Medium Tide	11.6	11.3	10.9	11.3		Medium Tide	11.9	12.2	11.4	11.7
	High Tide	14.1	13.8	13.4	13.9		High Tide	14.1	14.6	13.8	14.2
Dec'24	Low Tide	11.6	12.0	11.7	11.2	Mar'25	Low Tide	12.4	12.8	12.3	13.0
	Medium Tide	11.0	11.3	11.0	10.4		Medium Tide	12.3	12.8	12.3	12.7
	High Tide	13.8	14.2	12.9	12.2		High Tide	15.0	15.6	14.2	14.8



Month		Ist Week	2nd Week	3rd Week	4th Week	Month		Ist Week	2nd Week	3rd Week	4th Week
Oct'24	Low Tide	13.6	14.1	13.7	14.5	Jan'25	Low Tide	11.9	12.4	12.9	12.5
	Medium Tide	13.0	13.6	13.0	12.6		Medium Tide	11.6	12.0	12.6	12.2
	High Tide	15.8	16.4	15.9	16.3		High Tide	13.1	13.7	14.3	13.7
Nov'24	Low Tide	13.1	12.8	12.3	12.8	Feb'25	Low Tide	13.0	13.5	12.8	13.0
	Medium Tide	12.5	12.1	11.7	12.1		Medium Tide	12.8	13.4	12.3	12.6
	High Tide	13.2	12.9	12.5	13.8		High Tide	14.6	15.2	14.6	15.0
Dec'24	Low Tide	12.0	12.6	12.2	11.6	Mar'25	Low Tide	13.6	14.1	13.7	14.5
	Medium Tide	12.1	12.5	11.9	11.2		Medium Tide	13.0	13.6	13.0	12.6
	High Tide	14.0	14.5	13.2	12.6		High Tide	15.8	16.4	15.9	16.3

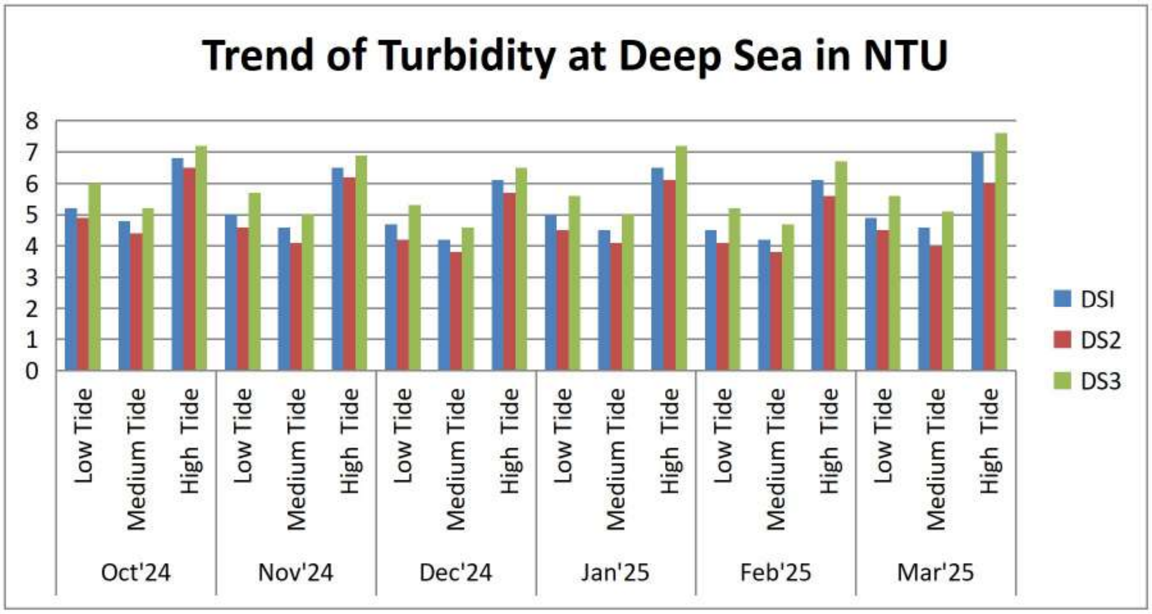


Month		Ist Week	2nd Week	3rd Week	4th Week	Month		Ist Week	2nd Week	3rd Week	4th Week
Oct'24	Low Tide	14.0	14.6	14.0	15.1	Jan'25	Low Tide	12.3	13.0	13.5	13.2
	Medium Tide	14.1	14.7	13.9	14.6		Medium Tide	11.0	11.6	12.1	11.6
	High Tide	16.2	16.9	16.2	17.2		High Tide	13.5	14.1	14.8	14.2
Nov'24	Low Tide	12.4	12.1	11.8	12.4	Feb'25	Low Tide	13.7	14.1	13.3	13.5
	Medium Tide	11.6	11.3	11.1	11.6		Medium Tide	12.1	12.6	12.8	13.2
	High Tide	13.7	13.5	13.0	13.5		High Tide	15.0	15.8	14.9	15.4
Dec'24	Low Tide	12.3	13.1	12.6	12.0	Mar'25	Low Tide	14.0	14.6	14.0	15.1
	Medium Tide	11.3	11.8	11.3	10.6		Medium Tide	14.1	14.7	13.9	14.6
	High Tide	13.5	14.1	13.5	12.8		High Tide	16.2	16.9	16.2	17.2

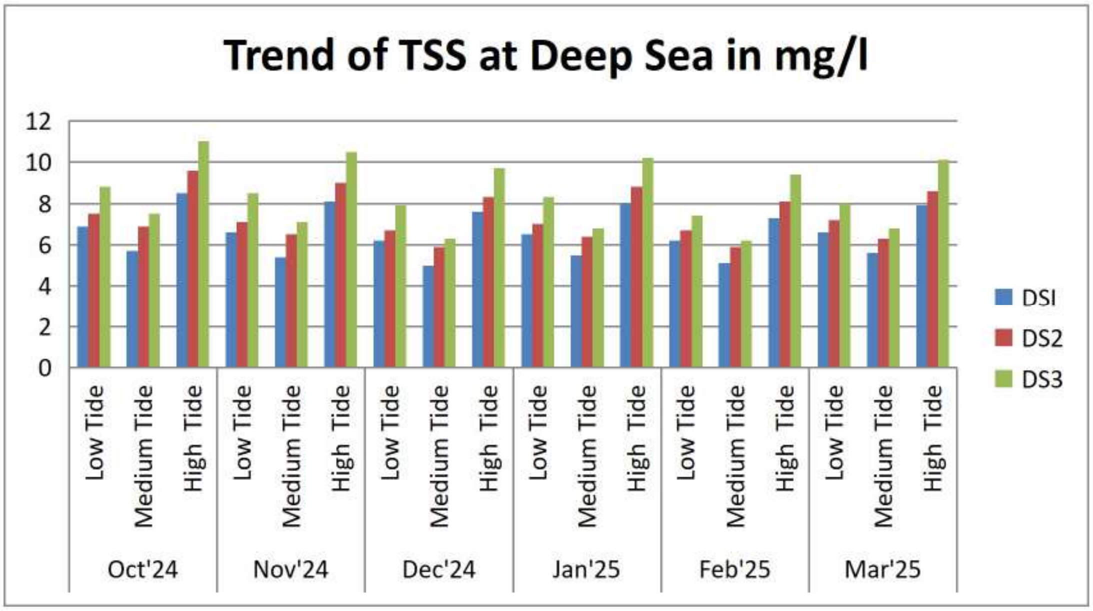


Month		Ist Week	2nd Week	3rd Week	4th Week	Month		Ist Week	2nd Week	3rd Week	4th Week
Oct'24	**Low Tide**	17.8	18.2	17.5	18.3	**Jan'25**	**Low Tide**	14.8	15.6	16.2	15.6
	Medium Tide	17.5	18.3	17.6	18.0		**Medium Tide**	13.7	14.3	15.0	14.3
	High Tide	19.7	20.6	19.8	21.3		**High Tide**	17.6	18.2	19.0	18.1
Nov'24	**Low Tide**	16.2	15.4	14.9	16.0	**Feb'25**	**Low Tide**	16.2	17.0	16.2	17.1
	Medium Tide	15.9	15.4	14.2	14.9		**Medium Tide**	14.8	15.9	15.6	16.4
	High Tide	18.6	18.3	17.7	18.4		**High Tide**	18.7	19.4	18.2	18.9
Dec'24	**Low Tide**	15.4	16.0	15.4	14.3	**Mar'25**	**Low Tide**	17.8	18.2	17.5	18.3
	Medium Tide	14.2	15.1	14.2	13.1		**Medium Tide**	17.5	18.3	17.6	18.0
	High Tide	18.1	18.6	17.9	17.0		**High Tide**	19.7	20.6	19.8	21.3

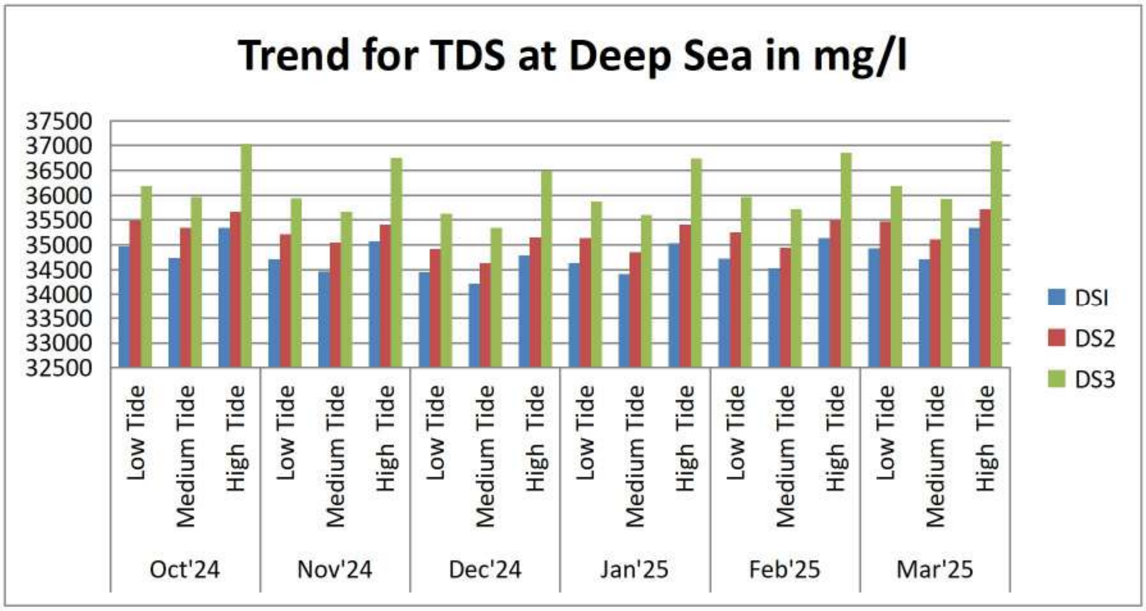
Status of Deep Sea Water Quality



Month		DSI	DS2	DS3	Month		DSI	DS2	DS3
Oct'24	Low Tide	5.2	4.9	6.0	Jan'25	Low Tide	5.0	4.5	5.6
	Medium Tide	4.8	4.4	5.2		Medium Tide	4.5	4.1	5.0
	High Tide	6.8	6.5	7.2		High Tide	6.5	6.1	7.2
Nov'24	Low Tide	5.0	4.6	5.7	Feb'25	Low Tide	4.5	4.1	5.2
	Medium Tide	4.6	4.1	5.0		Medium Tide	4.2	3.8	4.7
	High Tide	6.5	6.2	6.9		High Tide	6.1	5.6	6.7
Dec'24	Low Tide	4.7	4.2	5.3	Mar'25	Low Tide	4.9	4.5	5.6
	Medium Tide	4.2	3.8	4.6		Medium Tide	4.6	4.0	5.1
	High Tide	6.1	5.7	6.5		High Tide	7.0	6.0	7.6



Month		DSI	DS2	DS3	Month		DSI	DS2	DS3
Oct'24	**Low Tide**	6.9	7.5	8.8	**Jan'25**	**Low Tide**	6.5	7.0	8.3
	Medium Tide	5.7	6.9	7.5		**Medium Tide**	5.5	6.4	6.8
	High Tide	8.5	9.6	11.0		**High Tide**	8.0	8.8	10.2
Nov'24	**Low Tide**	6.6	7.1	8.5	**Feb'25**	**Low Tide**	6.2	6.7	7.4
	Medium Tide	5.4	6.5	7.1		**Medium Tide**	5.1	5.9	6.2
	High Tide	8.1	9.0	10.5		**High Tide**	7.3	8.1	9.4
Dec'24	**Low Tide**	6.2	6.7	7.9	**Mar'25**	**Low Tide**	6.6	7.2	8.0
	Medium Tide	5.0	5.9	6.3		**Medium Tide**	5.6	6.3	6.8
	High Tide	7.6	8.3	9.7		**High Tide**	7.9	8.6	10.1



Month		DSI	DS2	DS3	Month		DSI	DS2	DS3
Oct'24	Low Tide	34970	35491	36182	Jan'25	Low Tide	34635	35130	35879
	Medium Tide	34737	35349	35961		Medium Tide	34410	34852	35604
	High Tide	35349	35664	37037		High Tide	35027	35410	36746
Nov'24	Low Tide	34707	35209	35941	Feb'25	Low Tide	34717	35246	35965
	Medium Tide	34468	35039	35664		Medium Tide	34530	34936	35714
	High Tide	35073	35410	36751		High Tide	35141	35498	36852
Dec'24	Low Tide	34449	34920	35631	Mar'25	Low Tide	34935	35476	36184
	Medium Tide	34214	34637	35346		Medium Tide	34710	35108	35924
	High Tide	34787	35147	36490		High Tide	35337	35716	37094

4.6 Marine Sediment Quality

4.6.1 Sampling Locations

The Marine sediment sampling is carried out once in every week at four locations in the port listed below**.**

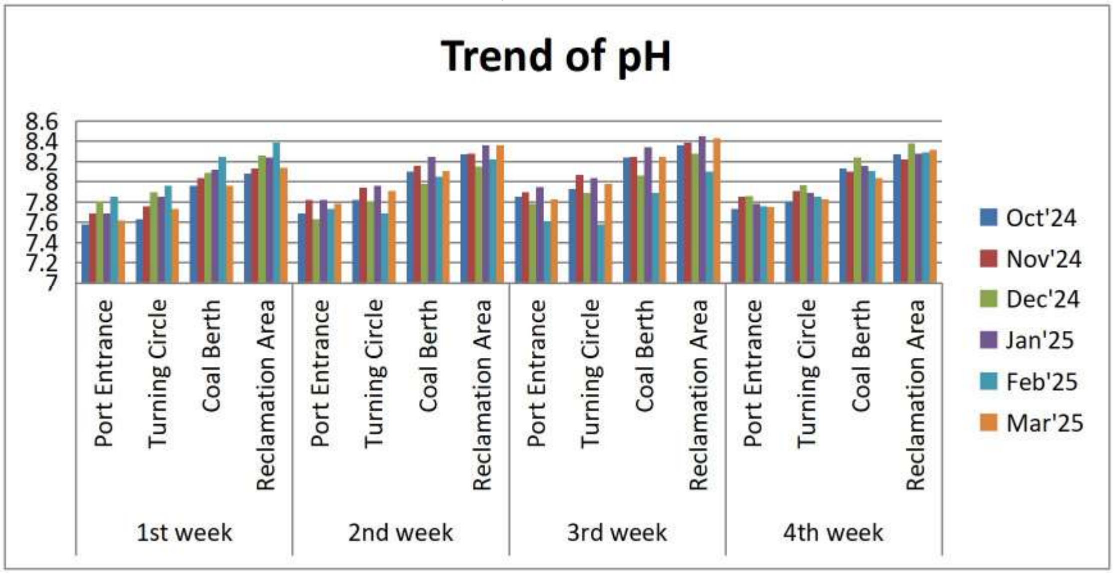
MARINE SEDIMENT MONITORING LOCATIONS

SI.No	Location
1	Port Entrance
2	Turning Circle
3	Coal Berth
4	Reclamations Area

4.6.2 Method of Sampling

Marine sediment samples are collected using Van Veen Grab Sampler for analyzing Physical, Chemical and Biological parameters and presence of Heavy metals.

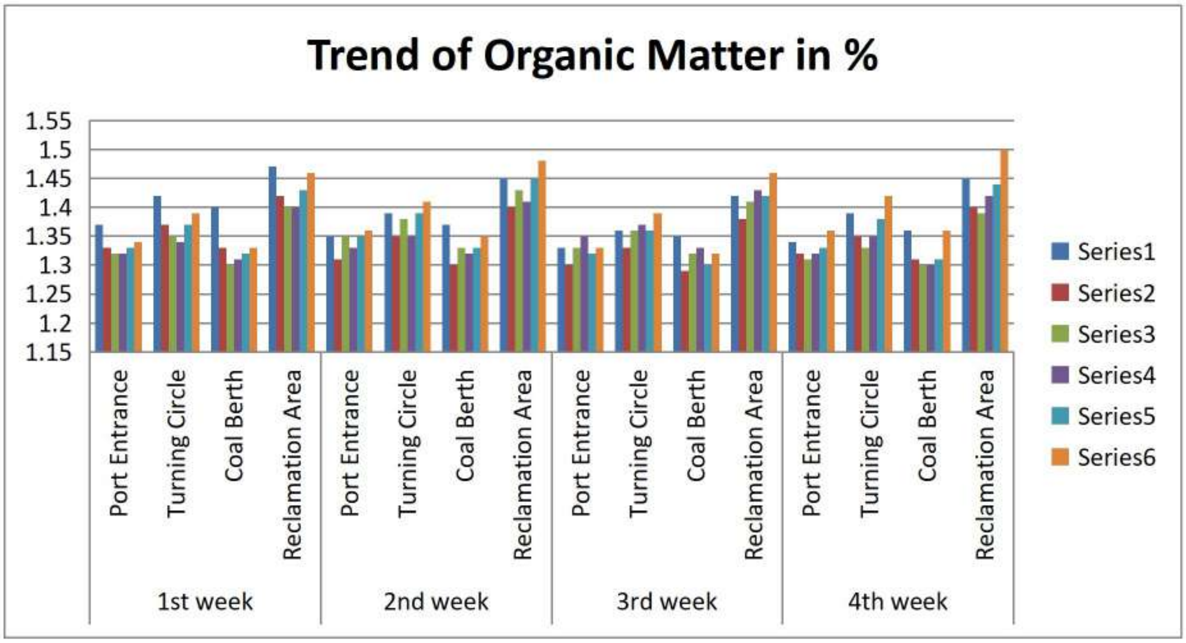
Status of Marine Sediments Quality



pH in Marine sediment varied between 7.58 to 8.45

Month	Ist Week				2nd Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	7.58	7.63	7.96	8.08	7.69	7.82	8.10	8.27
Nov'24	7.69	7.76	8.04	8.13	7.82	7.94	8.16	8.28
Dec'24	7.81	7.90	8.09	8.26	7.63	7.81	7.98	8.15
Jan'25	7.69	7.85	8.12	8.24	7.82	7.96	8.25	8.36
Feb'25	7.85	7.96	8.25	8.39	7.73	7.69	8.05	8.22
Mar'25	7.62	7.73	7.96	8.14	7.78	7.91	8.11	8.36

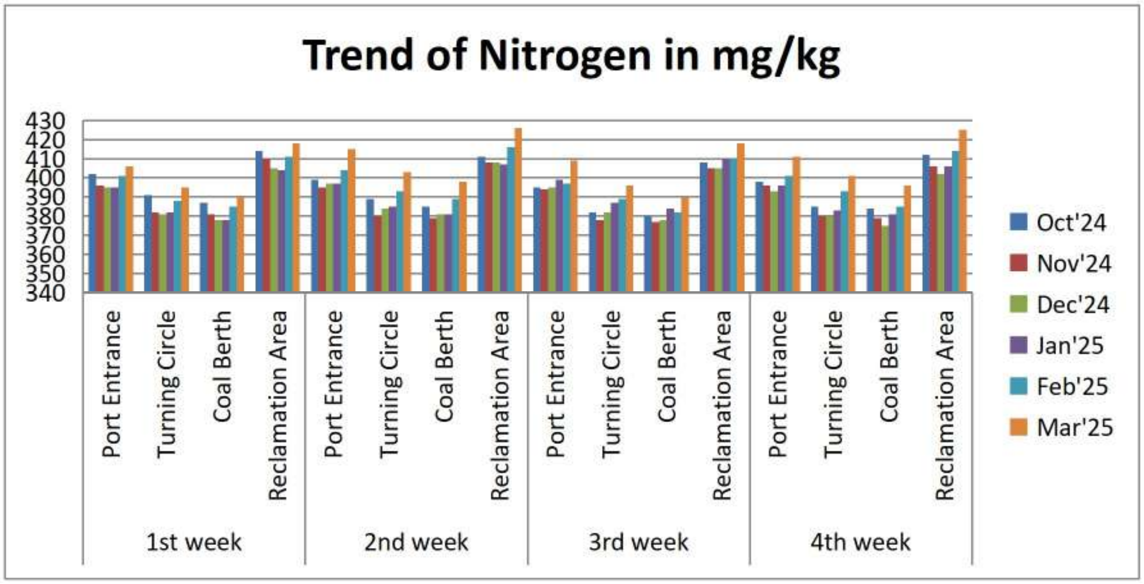
Month	3rd Week				4th Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	7.85	7.93	8.24	8.36	7.73	7.81	8.13	8.27
Nov'24	7.90	8.07	8.25	8.39	7.85	7.91	8.10	8.22
Dec'24	7.78	7.89	8.06	8.28	7.86	7.97	8.24	8.38
Jan'25	7.95	8.04	8.34	8.45	7.78	7.89	8.16	8.28
Feb'25	7.61	7.58	7.89	8.10	7.76	7.85	8.11	8.29
Mar'25	7.83	7.98	8.25	8.43	7.75	7.83	8.04	8.32



Organic Matter in Marine sediment varied between 1.29 to 1.50 %

Month	Ist Week				2nd Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	1.37	1.42	1.40	1.47	1.35	1.39	1.37	1.45
Nov'24	1.33	1.37	1.33	1.42	1.31	1.35	1.30	1.40
Dec'24	1.32	1.35	1.30	1.40	1.35	1.38	1.33	1.43
Jan'25	1.32	1.34	1.31	1.40	1.33	1.35	1.32	1.41
Feb'25	1.33	1.37	1.32	1.43	1.35	1.39	1.33	1.45
Mar'25	1.34	1.39	1.33	1.46	1.36	1.41	1.35	1.48

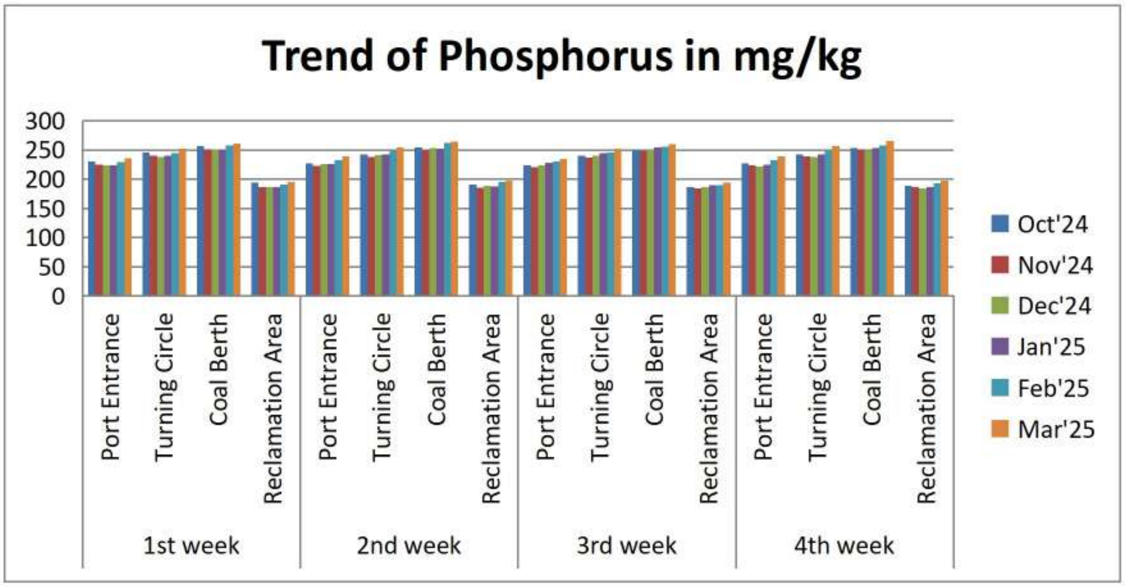
Month	3rd Week				4th Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	1.33	1.36	1.35	1.42	1.34	1.39	1.36	1.45
Nov'24	1.30	1.33	1.29	1.38	1.32	1.35	1.31	1.40
Dec'24	1.33	1.36	1.32	1.41	1.31	1.33	1.30	1.39
Jan'25	1.35	1.37	1.33	1.43	1.32	1.35	1.30	1.42
Feb'25	1.32	1.36	1.30	1.42	1.33	1.38	1.31	1.44
Mar'25	1.33	1.39	1.32	1.46	1.36	1.42	1.36	1.50



Nitrogen In Marine sediment varied between 375 to 426 mg/kg

Month	Ist Week				2nd Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	402	391	387	414	399	389	385	411
Nov'24	396	382	381	410	395	380	379	408
Dec'24	395	381	378	405	397	384	381	408
Jan'25	395	382	378	404	397	385	381	407
Feb'25	401	388	385	411	404	393	389	416
Mar'25	406	395	390	418	415	403	398	426

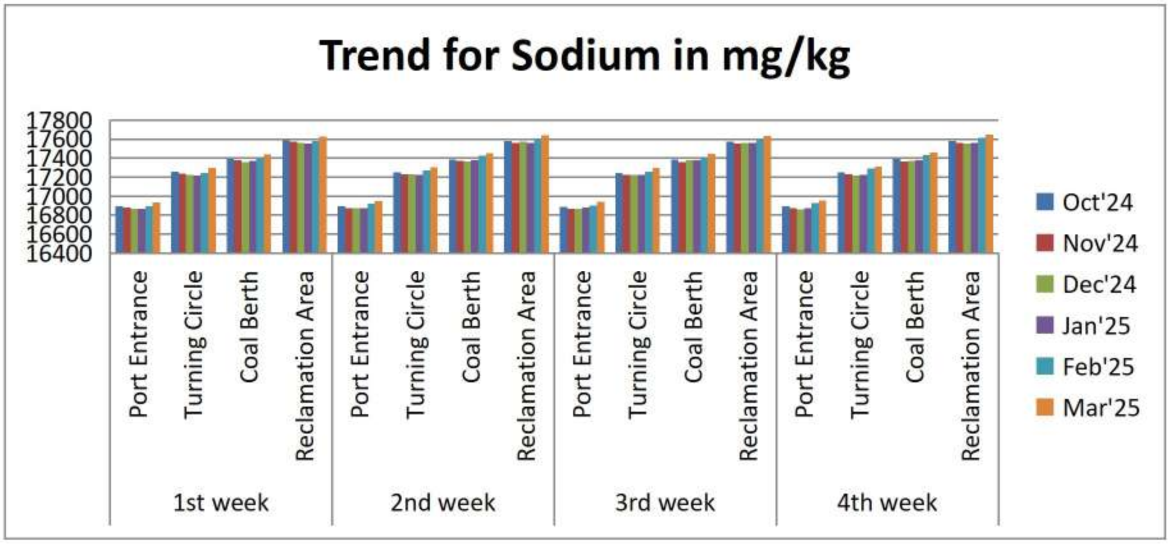
Month	3rd Week				4th Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	395	382	380	408	398	385	384	412
Nov'24	394	378	377	405	396	380	379	406
Dec'24	395	382	378	405	393	380	375	402
Jan'25	399	387	384	410	396	383	381	406
Feb'25	397	389	382	410	401	393	385	414
Mar'25	409	396	390	418	411	401	396	425



Phosphorous in Marine sediment varied between 184 to 265 mg/kg

Month	Ist Week				2nd Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	230	246	257	194	227	243	254	191
Nov'24	225	240	251	187	223	238	250	185
Dec'24	224	238	251	186	226	241	253	189
Jan'25	224	240	250	186	226	243	252	188
Feb'25	229	245	258	191	233	249	262	195
Mar'25	236	252	261	195	239	255	264	198

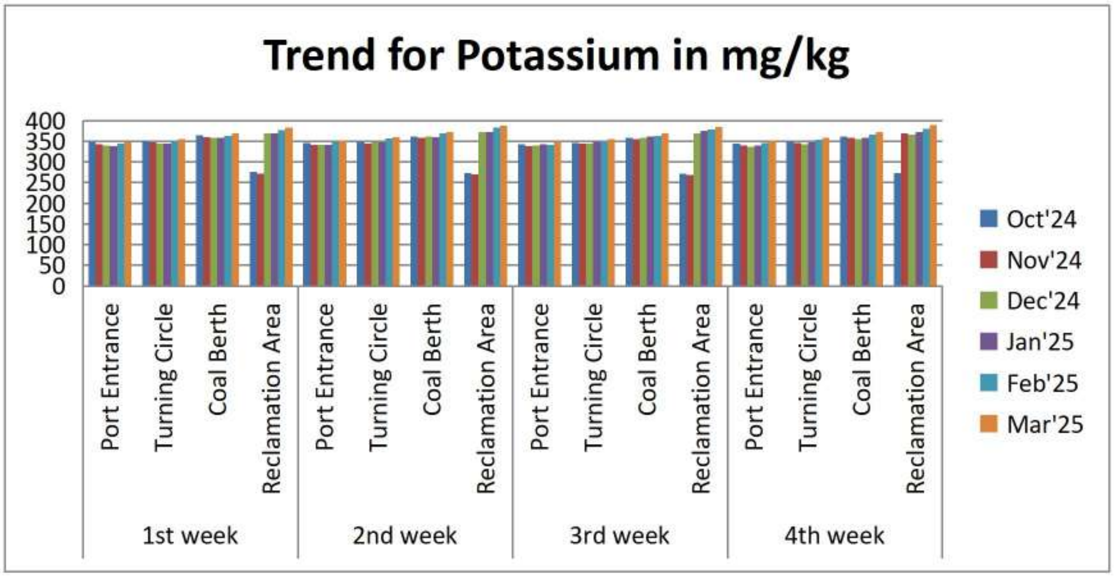
Month	3rd Week				4th Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	224	240	250	187	227	242	253	189
Nov'24	221	237	249	184	224	239	251	186
Dec'24	224	240	250	186	222	238	248	184
Jan'25	228	245	255	190	225	242	253	187
Feb'25	230	246	256	190	233	249	258	193
Mar'25	235	252	260	194	239	257	265	198



Sodium in Marine sediment varied between 16860 to 17645 mg/kg

Month	Ist Week				2nd Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct’24	16895	17256	17392	17584	16891	17250	17388	17580
Nov’24	16880	17238	17377	17575	16872	17230	17369	17563
Dec’24	16869	17223	17361	17560	16875	17231	17368	17571
Jan’25	16864	17218	17374	17555	16872	17221	17377	17558
Feb’25	16896	17245	17400	17582	16920	17272	17426	17610
Mar’25	16932	17297	17438	17627	16945	17306	17450	17640

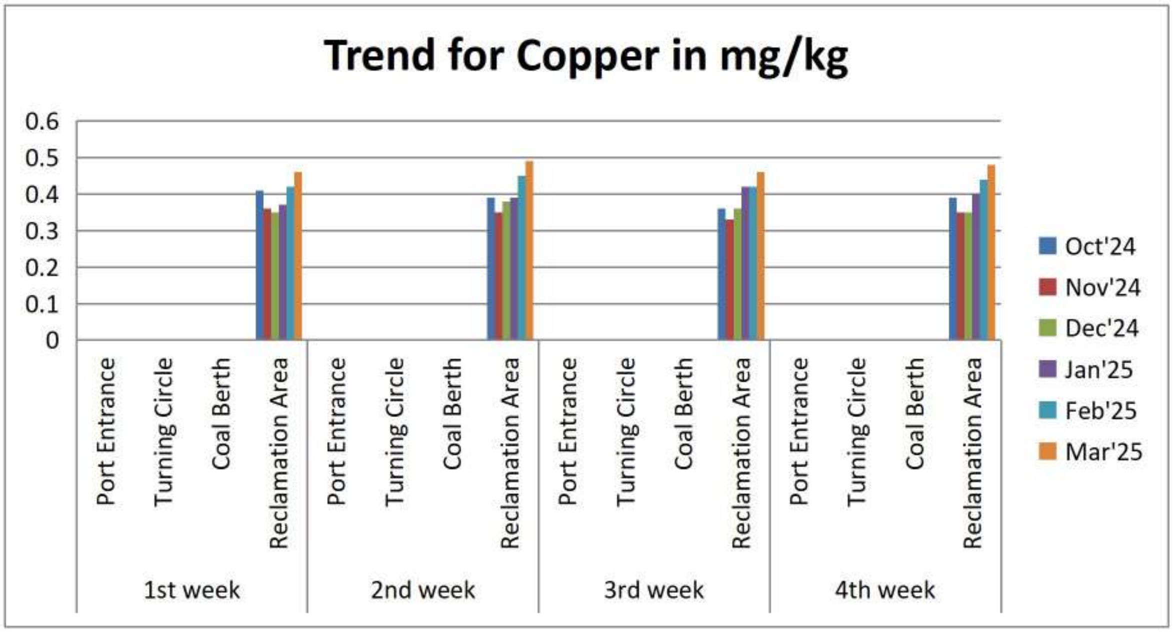
Month	3rd Week				4th Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct’24	16887	17246	17385	17577	16891	17249	17389	17581
Nov’24	16867	17225	17361	17556	16873	17232	17367	17562
Dec’24	16868	17224	17379	17560	16860	17214	17370	17551
Jan’25	16877	17226	17381	17562	16874	17221	17376	17558
Feb’25	16902	17258	17412	17598	16925	17290	17430	17615
Mar’25	16940	17301	17443	17633	16951	17312	17457	17645



Potassium in Marine sediment varied between 268 to 389 mg/kg

Month	Ist Week				2nd Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	349	351	365	277	346	349	362	274
Nov'24	343	347	360	272	341	345	358	270
Dec'24	340	345	358	370	342	348	361	372
Jan'25	339	345	358	369	341	347	360	372
Feb'25	344	351	363	377	349	357	370	384
Mar'25	348	356	369	384	353	360	372	388

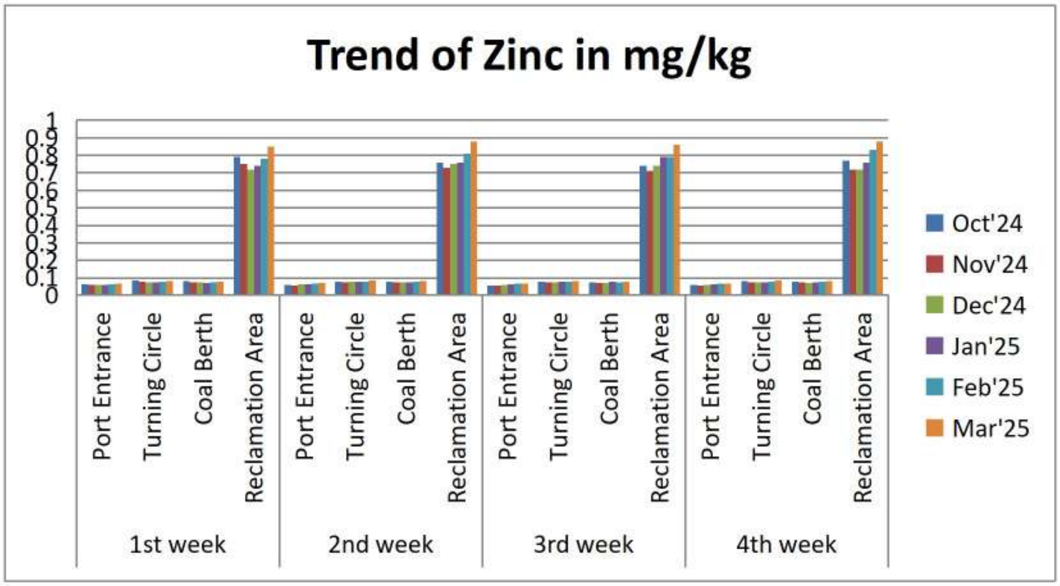
Month	3rd Week				4th Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	343	346	359	271	345	349	362	274
Nov'24	339	344	356	268	340	346	359	370
Dec'24	340	345	359	370	337	343	356	367
Jan'25	343	350	362	375	340	347	359	372
Feb'25	342	351	363	378	346	354	367	381
Mar'25	349	356	369	385	353	359	373	389



Copper in Marine Sediment varied between 0.33 to 0.49 mg/kg

Month	Ist Week				2nd Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	< 0.01	< 0.01	< 0.01	0.41	< 0.01	< 0.01	< 0.01	0.39
Nov'24	< 0.01	< 0.01	< 0.01	0.36	< 0.01	< 0.01	< 0.01	0.35
Dec'24	< 0.01	< 0.01	< 0.01	0.35	< 0.01	< 0.01	< 0.01	0.38
Jan'25	< 0.01	< 0.01	< 0.01	0.37	< 0.01	< 0.01	< 0.01	0.39
Feb'25	< 0.01	< 0.01	< 0.01	0.42	< 0.01	< 0.01	< 0.01	0.45
Mar'25	< 0.01	< 0.01	< 0.01	0.46	< 0.01	< 0.01	< 0.01	0.49

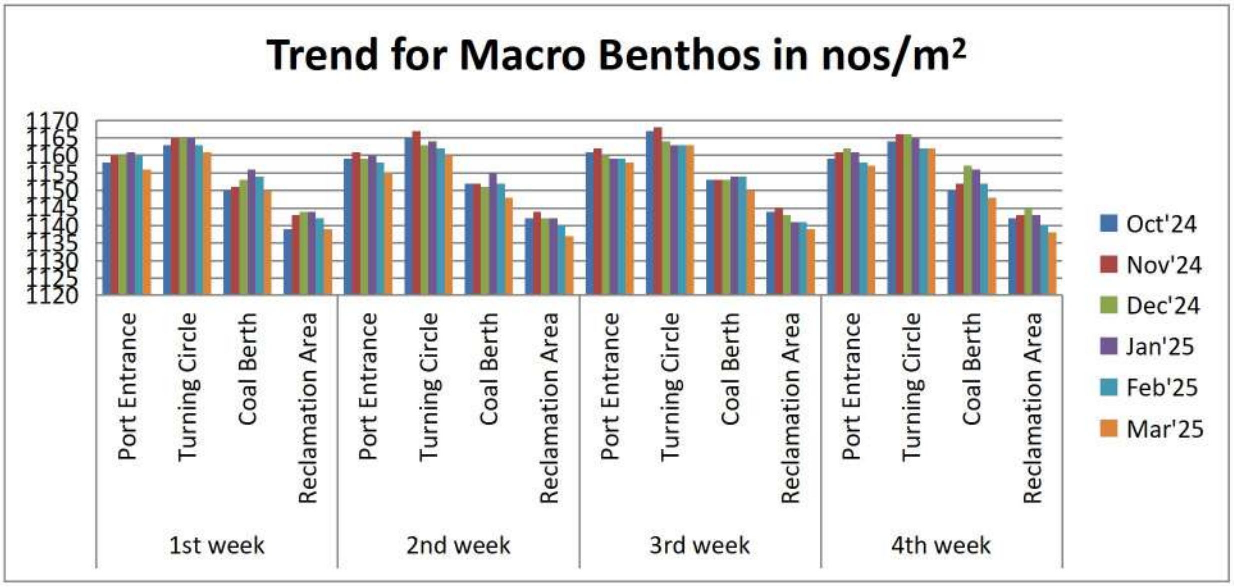
Month	3rd Week				4th Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	< 0.01	< 0.01	< 0.01	0.36	< 0.01	< 0.01	< 0.01	0.39
Nov'24	< 0.01	< 0.01	< 0.01	0.33	< 0.01	< 0.01	< 0.01	0.35
Dec'24	< 0.01	< 0.01	< 0.01	0.36	< 0.01	< 0.01	< 0.01	0.35
Jan'25	< 0.01	< 0.01	< 0.01	0.42	< 0.01	< 0.01	< 0.01	0.4
Feb'25	< 0.01	< 0.01	< 0.01	0.42	< 0.01	< 0.01	< 0.01	0.44
Mar'25	< 0.01	< 0.01	< 0.01	0.46	< 0.01	< 0.01	< 0.01	0.48



Zinc in Marine sediment varied between 0.056 to 0.88 mg/kg

Month	Ist Week				2nd Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	0.065	0.084	0.081	0.79	0.061	0.080	0.078	0.76
Nov'24	0.060	0.078	0.076	0.75	0.058	0.075	0.073	0.73
Dec'24	0.060	0.076	0.073	0.72	0.063	0.078	0.074	0.75
Jan'25	0.061	0.075	0.072	0.74	0.063	0.077	0.075	0.76
Feb'25	0.065	0.078	0.076	0.78	0.068	0.080	0.079	0.81
Mar'25	0.068	0.082	0.080	0.85	0.070	0.085	0.083	0.88

Month	3rd Week				4th Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	0.058	0.078	0.076	0.74	0.061	0.081	0.079	0.77
Nov'24	0.056	0.073	0.072	0.71	0.058	0.075	0.074	0.72
Dec'24	0.061	0.075	0.072	0.74	0.059	0.073	0.070	0.72
Jan'25	0.065	0.079	0.078	0.79	0.063	0.076	0.075	0.76
Feb'25	0.066	0.078	0.076	0.79	0.067	0.080	0.078	0.83
Mar'25	0.067	0.082	0.080	0.86	0.069	0.085	0.083	0.88



Macro Benthos in Marine Sediment varied between 1137 to 1168 nos/m²

Month	Ist Week				2nd Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	1158	1163	1150	1139	1159	1165	1152	1142
Nov'24	1160	1165	1151	1143	1161	1167	1152	1144
Dec'24	1160	1165	1153	1144	1159	1163	1151	1142
Jan'25	1161	1165	1156	1144	1160	1164	1155	1142
Feb'25	1160	1163	1154	1142	1158	1162	1152	1140
Mar'25	1156	1161	1150	1139	1155	1160	1148	1137

Month	3rd Week				4th Week			
	Port Entrance	Turning Circle	Coal Berth	Reclamation Area	Port Entrance	Turning Circle	Coal Berth	Reclamation Area
Oct'24	1161	1167	1153	1144	1159	1164	1150	1142
Nov'24	1162	1168	1153	1145	1161	1166	1152	1143
Dec'24	1160	1164	1153	1143	1162	1166	1157	1145
Jan'25	1159	1163	1154	1141	1161	1165	1156	1143
Feb'25	1159	1163	1154	1141	1158	1162	1152	1140
Mar'25	1158	1163	1150	1139	1157	1162	1148	1138

Summary of marine sediments quality results for Six months of Oct'24 – March'25

- Organic matter - value are in the range 1.29 to 1.50 %
- Nitrogen -value are in the range 375 to 426 mg/kg
- Phosphorous - value are in the range 184 to 265 mg/kg
- Sodium - value are in the range 16860 to 17645 mg/kg
- Potassium - value are in the range 268 to 389 mg/kg
- Copper - value are in the range 0.33 to 0.49 mg/kg
- Zinc -value are in the range 0.056 to 0.88 mg/kg
- Macro Benthos - value are in the range 1137 to 1168 nos/m^2

TEST REPORT OF GROUND WATER SAMPLES

DATE OF COLLECTION : 19-03-2025

S. No.	Parameter	Unit	Port Site (Bore Well)	Krishnapatnam Village	South Side of the Port	Gopalpuram Village	IS: 10500-2012 Specification
1.	pH	--	7.51	7.44	7.29	7.33	6.5 – 8.5
2	Electrical Conductivity	µmhos	1201	1068	1378	1244	-
3	TDS	mg/l	803	629	849	736	500
4	Total Alkalinity as $CaCO_3$	mg/l	255	229	341	245	200
5	Chlorides as Cl^-	mg/l	351	268	322	209	250
6	Sodium	mg/l	138	102	143	91.4	-
7	Potassium	mg/l	44.7	26.9	28.1	12.5	-
8	Fluorides as F^-	mg/l	0.51	0.47	0.60	0.45	1.0
9	Nitrates as NO^-_3	mg/l	4.93	5.44	4.03	4.66	45
10	Cyanide as CN	mg/l	< 0.01	< 0.01	< 0.01	< 0.01	0.05
11	Total Hardness as $CaCO_3$	mg/l	129	109	142	113	200
12	Salinity	ppt	0.058	0.03	0.06	0.02	-
13	Sulphates as SO^{-2}_4	mg/l	97.6	68.3	71.2	80.1	200
14	COD	mg/l	< 10.0	< 10.0	< 10.0	< 10.0	-
15	Mercury as Hg	mg/l	< 0.001	< 0.001	< 0.001	< 0.001	0.001
16	Cadmium as Cd	mg/l	< 0.001	< 0.001	< 0.001	< 0.001	0.003
17	Arsenic as As	mg/l	< 0.01	< 0.01	< 0.01	< 0.01	0.01
18	Selenium	mg/l	< 0.05	< 0.05	< 0.05	< 0.05	-
19	Iron as Fe	mg/l	0.07	0.03	0.08	0.11	0.3
20	Lead as Pb	mg/l	< 0.01	< 0.01	< 0.01	< 0.01	0.01
21	Zinc as Zn	mg/l	0.12	0.06	0.04	0.07	5.0
22	Chromium as Cr^{6+}	mg/l	< 0.01	< 0.01	< 0.01	< 0.01	0.05
23	Total Coliforms	CFU/ml	Not Detected	Not Detected	Not Detected	Not Detected	Shall not be detected in 100ml
24	Fecal Coliforms	CFU/ml	Not Detected	Not Detected	Not Detected	Not Detected	Shall not be detected in 100ml

Note: . All the above parameters have been tested as per APHA 24th Edition, 2023.

4.8 SOIL QUALITY

For studying soil profile of the region, sampling locations are selected to assess the existing soil characteristics in and around the port area representing various land use conditions.

4.8.1 Sampling Locations

A total two number of samples collected from the sampling sites. The details of the soil sampling locations are given below.

The soil samples are collected and analyzed once in six months.

SOIL QUALITY MONITORING LOCATIONS

Location Code	Name of the Location
S1	Storage area towards west Buckingham Canal
S2	Storage Area at Port

TEST REPORT OF SOIL SAMPLES

DATE OF COLLECTION **:** 19-03-2025

S. NO.	PARAMETER	UNIT	S1	S2
1.	pH(1:5)	--	7.28	7.19
2.	EC(1:5)	µmhos	537	601
3.	Texture			
	a. Sand	%	51.8	47.6
	b. Silt	%	23.2	20.1
	c. Clay	%	25.0	32.3
4	Available Nitrogen	kg/ha	202	217
5	Available Phosphorus	kg/ha	10	13
6	Available Potassium	kg/ha	443	469
7	Exchangeable Sodium	mg/kg	171	183
8	Exchangeable Calcium	mg/kg	109	134
9	Exchangeable Magnesium	mg/kg	25	37
10	SAR (SAR)	-	2.16	1.59
11	Water Soluble Chlorides	mg/kg	146	175
12	Organic Carbon	%	0.27	0.38
13	Lead	mg/kg	6.1	5.1
14	Cadmium	mg/kg	0.14	0.07
15	Copper	mg/kg	7.4	7.5
16	Zinc	mg/kg	6.9	7.8

4.9 STP INLET AND OUTLET ANALYSIS

Frequency: STP Inlet and Outlet samples are collected monthly once.

TEST REPORT OF STP INLET – 500KLD

S.No	Parameter	Unit	Oct'24	Nov'24	Dec'24	Jan'25	Feb'25	Mar'25
1	pH	-	7.36	7.13	7.36	7.35	7.23	7.42
2	Total Suspended Solids	mg/l	120	132	120	106	98.0	112
3	BOD 3day 27°C	mg/l	108	116	110	98.0	90.0	101
4	Oil & Grease	mg/l	4.0	5.0	4.0	3.0	3.0	4.0
5	Fecal coliform	MPN/100ml	$15X10^3$	$17X10^3$	$15X10^3$	$12X10^3$	$10X10^3$	$13X10^3$

TEST REPORT OF STP OUTLET – 500KLD

S.No	Parameter	Unit	Oct'24	Nov'24	Dec'24	Jan'25	Feb'25	Mar'25
1	pH	-	7.51	7.34	7.48	7.59	7.41	7.63
2	Total Suspended Solids	mg/l	43.0	49.0	42.0	36.0	31.0	38.0
3	BOD 3day 27°C	mg/l	24.0	27.0	24.0	21.0	18.0	23.0
4	Oil & Grease	mg/l	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
5	Fecal coliform	MPN/100ml	240	270	240	210	180	230

TEST REPORT OF STP INLET – 40KLD

S.No	Parameter	Unit	Oct'24	Nov'24	Dec'24	Jan'25	Feb'25	Mar'25
1	pH	-	7.58	7.67	7.51	7.73	7.56	7.86
2	Total Suspended Solids	mg/l	102	110	98.0	90.0	80.0	88.0
3	BOD 3day 27°C	mg/l	95.0	108	102	94.0	84.0	92.0
4	Oil & Grease	mg/l	4.3	5.0	4.0	3.0	2.0	3.0
5	Fecal coliform	MPN/100ml	$12X10^3$	$14X10^3$	$11X10^3$	$09X10^3$	$07X10^3$	$11X10^3$

TEST REPORT OF STP OUTLET – 40KLD

S.No	Parameter	Unit	Oct'24	Nov'24	Dec'24	Jan'25	Feb'25	Mar'25
1	pH	-	7.29	7.10	7.23	7.32	7.14	7.31
2	Total Suspended Solids	mg/l	17.0	22.0	18.0	14.0	10.0	15.0
3	BOD 3day 27°C	mg/l	20.0	23.0	20.0	18.0	15.0	19.0
4	Oil & Grease	mg/l	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
5	Fecal coliform	MPN/100ml	198	220	190	150	120	160

5.0 STACK EMISSION MONITORING

Sampling of Flue gas emissions of DG Sets was done and their emissions were determined. The Detailed report has been enclosed here.

SAMPLE PARTICULARS : DG SET EMISSION

SOURCE OF COLLECTION :
1) 380 KVA DG SET (Port Admin Building)
2) 250 KVA DG SET (SS - 2)
3) 320 KVA DG SET (Admin Block)
4) DG SET (SS-1)
5) 320 KVA DG SET (GUEST HOUSE)

DATE OF MONITORING : 19-03-2025

TEST REPORT

S.No.	DESCRIPTION	UNIT	RESULT				
			1	2	3	4	5
1.	Diameter of the Stack	mts	0.16	0.16	0.16	0.16	0.16
2.	C/s Area of Stack	sq.mt	0.02	0.02	0.02	0.02	0.02
3.	Pitot Coefficient	-	0.87	0.87	0.87	0.87	0.87
4.	Sp: gravity of Fluid	-	1.0	1.0	1.0	1.0	1.0
5.	Temperature @ DGM	^0C	32	32	33	33	34
6.	Stack temperature	^0C	144	119	141	136	131
7.	Nozzle Diameter	mm	10	10	10	10	10
8.	Exit Velocity	m/sec	12.2	11.2	13.8	10.8	12.9
9.	Gas Quantity	m^3/hr	878	806	993	777	929
10.	Duration of Sampling	minutes	30	30	30	30	30
11.	Fuel used	-	Diesel				

EMISSION RATE

S.NO.	PARAMETER	UNIT	METHOD	RESULT				
				1	2	3	4	5
1.	Particulate Matter – PM	g/kw-hr	IS:11255-P-1	0.11	0.07	0.16	0.18	0.15
2.	Oxides of Nitrogen – NOx	g/kw-hr	IS:11255-P-2	0.83	0.73	1.17	0.91	0.93
3.	Carbon Monoxide – CO	g/kw-hr	IS:11255-P-7	0.37	0.45	0.51	0.35	0.47
4.	Hydrocarbons - HC	g/kw-hr	IS:11255	0.13	0.10	0.19	0.08	0.14

SAMPLE PARTICULARS : DG SET EMISSION

SOURCE OF COLLECTION : 6) 250 KVA DG SET (GUEST HOUSE)
7) 250 KVA DG SET (GARRAGE)
8) 500 KVA DG SET (NCT – 1)
9) 500 KVA DG SET (NCT YARD)
10) 125 KVA DG SET (LIQUID JETTY - L4)

DATE OF START : 19-03-2025

TEST REPORT

S.No.	DESCRIPTION	UNIT	RESULT				
			6	7	8	9	10
1.	Diameter of the Stack	mts	0.16	0.16	0.16	0.16	0.16
2.	C/s Area of Stack	sq.mt	0.02	0.02	0.02	0.02	0.02
3.	Pitot Coefficient	-	0.87	0.87	0.87	0.87	0.87
4.	Sp: gravity of Fluid	-	1.0	1.0	1.0	1.0	1.0
5.	Temperature @ DGM	^{0}C	34	33	32	32	31
6.	Stack temperature	^{0}C	115	121	152	166	112
7.	Nozzle Diameter	mm	10	10	10	10	10
8.	Exit Velocity	m/sec	10.1	11.9	14.5	14.8	10.7
9.	Gas Quantity	m^3/hr	727	856	1044	1065	770
10.	Duration of Sampling	minutes	30	30	30	30	30
11.	Fuel used	-	Diesel				

EMISSION RATE

S.NO.	PARAMETER	UNIT	METHOD	RESULT				
				6	7	8	9	10
1.	Particulate Matter – PM	g/kw-hr	IS:11255-P-1	0.17	0.15	0.22	0.16	0.11
2.	Oxides of Nitrogen – NOx	g/kw-hr	IS:11255-P-2	0.69	1.03	0.98	0.83	0.57
3.	Carbon Monoxide – CO	g/kw-hr	IS:11255-P-7	0.35	0.49	0.47	0.41	0.35
4.	Hydrocarbons - HC	g/kw-hr	IS:11255	0.09	0.16	0.12	0.10	0.07

ANNEXURES

ANNEXURE1

NATIONAL AMBIENT AIR QUALITY STANDARDS
CENTRAL POLLUTION CONTROL BOARD
NOTIFICATION

New Delhi, the 18th November, 2009

No.B-29016/20/90/PCI-L—In exercise of the powers conferred by Sub-section (2) (h) of section 16 of the Air (Prevention and Control of Pollution) Act, 1981 (Act No. 14 of 1981), and in super session of the Notification No(s). S.O. 384(E), dated 11th April, 1994 and S.O. 935(E), dated 14th October, 1998, the Central Pollution Control Board hereby notify the National Ambient Air Quality Standards with immediate effect, namely:-

NATIONAL AMBIENT AIR QUALITY STANDARDS

S. No.	Pollutant	Time Weighted average	Concentration in Ambient Air		Methods of Measurement
			Industrial, Residential, Rural and Other Area	Ecologically sensitive area (notified by Central Govt.)	
(1)	(2)	(3)	(4)	(5)	(6)
1	Sulphur Dioxide (SO_2), µg/m³	Annual*	50	20	• Improved West and Geake • Ultraviolet fluorescence
		24 hours**	80	80	
2	Nitrogen Dioxide (NO_2), µg/m³	Annual*	40	30	• Modified Jacob & Hochheiser (Na-Arsenite) • Chemiluminescence
		24 hours**	80	80	
3	Particulate Matter (size less than 10 µm) or PM_{10} µg/m³	Annual*	60	60	• Gravimetric • TOEM • Beta attenuation
		24 hours**	100	100	
4	Particulate Matter (size less than 2.5 microns) or $PM_{2.5}$ µg/m³	Annual*	40	40	• Gravimetric • TOEM • Beta attenuation
		24 hours**	60	60	
5	Ozone (O_3) µg/m³	8 hours **	100	100	• UV photometric • Chemiluminescence • Chemical method
		1 hour **	180	180	
6	Lead (Pb) µg/m³	Annual*	0.5	0.5	• ASS / ICP method after sampling on EPM 2000 or equivalent filter paper • ED – XRF using
		24 hours**	1.0	1.0	
7	Carbon Monoxide (CO) mg/m³	8 hours**	2	2	Non Dispersive Infra RED (NDIR) Spectroscopy
		1 hour**	4	4	
8	Ammonia (NH_3) µg/m³	Annual*	100	100	• Chemiluminescence • Indophenol blue method
		24 hours**	400	400	
9	Benzene (C_6H_6) µg/m³	Annual*	5	5	• Gas chromatography based continuous analyser • Adsorption and desorption followed by GC analysis
10	Benzo (a) Pyrene (BaP) – particulate phase only ng/m³	Annual*	1	1	Solvent extraction followed by HPLC / GC analysis
11	Arsenic (As) ng/m³	Annual*	6	6	AAS / ICP method after sampling on EPM 2000 or equivalent filter paper
12	Nickel (Ni) ng/m³	Annual*	20	20	AAS / ICP method after sampling on EPM 2000 or equivalent filter paper

* Annual arithmetic mean of minimum 104 measurements in a year at a particular site taken twice a week 24 hourly at uniform intervals.

** 24 hourly or 8 hourly or 1 hourly monitored values, as applicable, shall be complied with 98% of the time in a year. 2% of the time, they may exceed the limits but not on two consecutive days of monitoring.

Note: Whenever and wherever monitoring results on two consecutive days of monitoring exceed the limits specified above for the respective category, it shall be considered adequate reason to institute regular or continuous monitoring and further investigation.

PHOTOGRAPHS

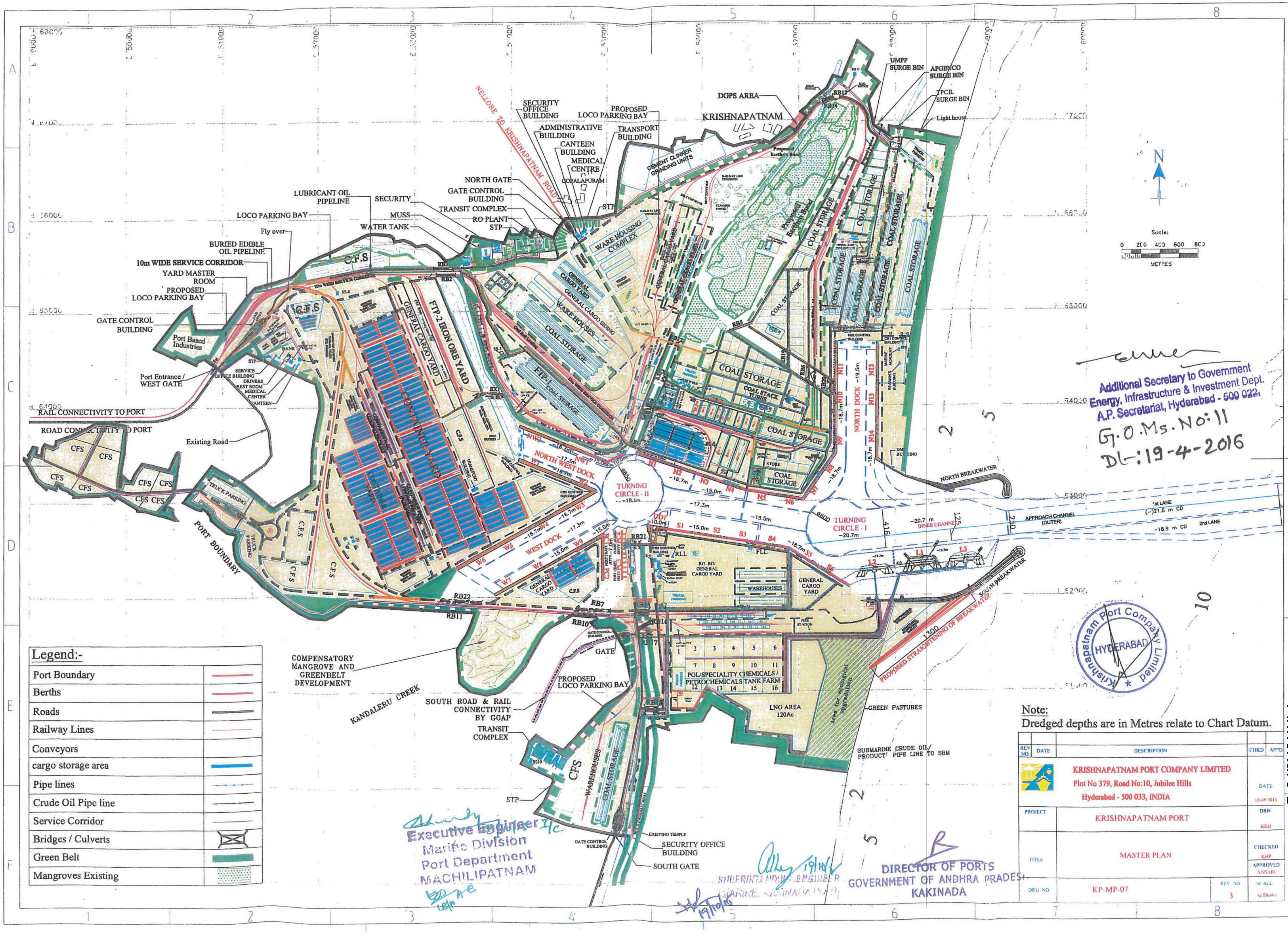
AMBIENT AIR QUALITY SAMPLING LOCATIONS

Thamminipatnam village	Gopalapuram village
	
Chalivendram	**Krishnapatnam village**
	

AMBIENT AIR QUALITY SAMPLING LOCATIONS

New Light House	**Zero Point**
	
Amenities Complex (CVR)	
	

WATER SAMPLING	SEDMENT SAMPLING
	
PHYTOPLANKTON SAMPLING	**NOISE MONITORING**
	



Annexure D

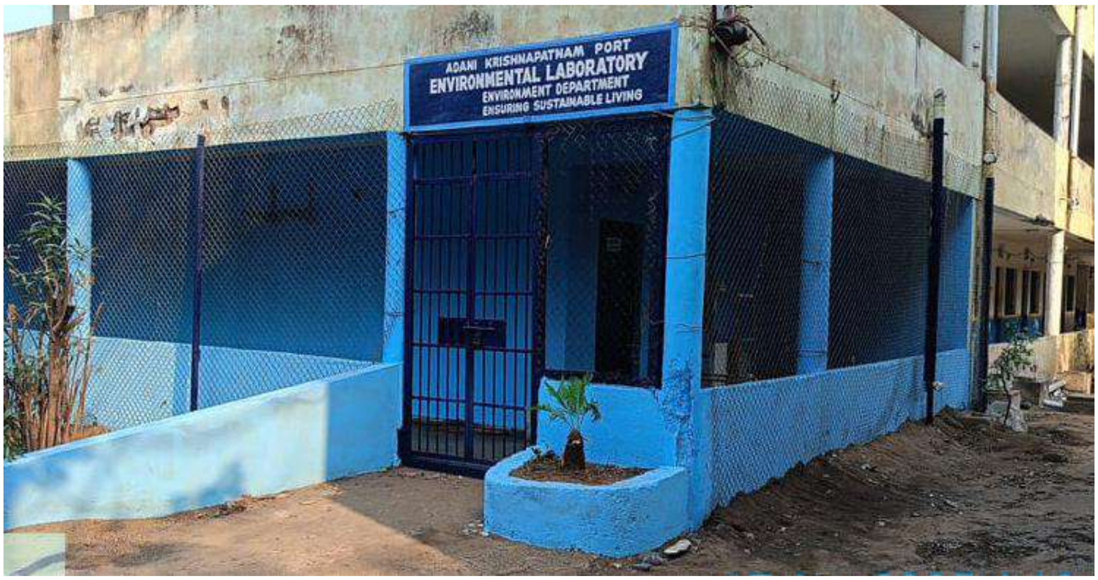
1578

Annexure-E

AKPL has a maintaining in house Environmental Laboratory to carry out the testing of various environmental parameters.

List Of the Equipment's Procured:

1. Digital PH Meter
2. Digital TDS & EC Meter
3. Oil and Grease apparatus
4. BOD Incubator
5. Ambient Air sampler
6. Noise meter
7. DG stack sampling kit
8. Weighing Balance



HR Wallingford
Working with water

EX 5429

Krishnapatnam Port
Hydraulic Modelling Studies

Report EX 5429
Release 7.0
October 2007

Document Information

Project	Krishnapatnam Port
Report title	Hydraulic Modelling Studies
Client	Krishnapatnam Port Company Ltd
Client Representative	Mr M.A.R. Ansari
Project No.	DDR4072
Report No.	EX 5429
Project Manager	Mr T J Chesher
Project Sponsor	Dr J V Smallman

Document History

Date	Release	Prepared	Approved	Authorised	Notes
10/11/06	1.0				Progress update 1
20/12/06	2.0		tjc	jvs	Progress update 2
18/01/06	3.0	jwi	tjc	jvs	Draft Final
12/03/07	4.0	jwi	tjc	jvs	Final report
05/04/07	5.0	jwi	tjc	jvs	Final report updated for comments
24/04/07	6.0	jwi	tjc	jvs	Correction to Section 2.2.4 and summary
20/10/07	7.0	jwi	tjc	jvs	Incorporation of earlier addendum into summary and Section 3.3.3

Prepared ....

Approved ....

Authorised ....

Summary

Krishnapatnam Port

Hydraulic Modelling Studies

Report EX 5429
October 2007

Howe (India) Pvt Ltd are presently undertaking engineering design and impact studies on behalf of Krishnapatnam Port Company Ltd and requested the provision of mathematical modelling studies to assess elements of these studies for the proposed new bulk handling terminal at Krishnapatnam.

The scope of work for these studies comprised tidal flow modelling and channel sedimentation, wave tranquility studies, an assessment of the adequacy of a sand trap, and the requirement for shore protection.

Conclusions and recommendations arising from this study are as follows:

Tidally induced sedimentation

Infill of the channel and port areas was assessed by simulating spring and neap tidal conditions, and calculating the transport of both sand and mud. There is abundant source of sand in the outer estuary and coast, and despite the dam upstream in the river, fine material is also abundant in the water column, hence both sand infill and siltation should be anticipated.

The mud infill prediction yields totals of 115,000m^3/year in Phase I and 540,300m^3/year in Phase II, and this infill is relatively evenly distributed over the deepened areas. Applying the same scaling to the sand infill yields 7,700m^3/year in Phase I and 3,500m^3/year in Phase II. Given the nature of the sand infill (which occurs adjacent to the deep cuts at the western end of the dredged zone and to the north of the turning circle) it is considered that this infill is an over-estimate of the longer-term rate. This is because there will be adjustment to the seabed in the areas where the sand transport is greatest, and this will reduce the sand infill over time. Note that this is not expected to be the case for infill due to silts and muds which will continue to infill the channel. In addition, as highlighted in Section 2.2.2, it is recommended that the dredged zone be extended approximately 200m upstream (west) beyond the berths (with width the same as the dredged berth, and to the same depth) as this will also reduce the amount of maintenance dredging in the berth areas.

In terms of the distribution of the sand infill Figure 2.13 highlights that the sand infill is likely to occur at the berths in Phase I, as well as there being a risk of some sedimentation on the northern side of the turning circle. In Phase II Figure 2.17 indicates that the areas prone to sand infill are in the SW areas of the port.

In respect of the distribution of mud infill, Figures 2.20 and 2.21 indicate that in Phase I the distribution of muddier infill will tend to accumulate over the entire deepened area relatively evenly (especially when it is considered that ship motion will tend to redistribute some of the infill). In Phase II it is concluded from Figures 2.22 and 2.23 that the mud infill will be concentrated in the inner berths to the west of the port, with approximately 80% of the annual

volume quoted above occurring in these areas: the remainder (20%) settling out relatively evenly in the inner channel area and turning circle.

Wave tranquillity

Wave tranquillity was assessed under various input wave conditions including relatively frequent events and extreme events. Results, in the form of wave heights, were tabulated a specific locations near the berths and in the channel. It is clear from the results that the dredged channel causes the wave energy to diverge into the shallow areas to the north and south of the channel.

Downtime at the berths will clearly depend on the types of vessels and operations being considered. These results clearly show that the wave energy reaching the berths from offshore is very low. The wind blowing within the harbour will create surface chop which may be higher than these wave heights but, being of very short per od will not significantly affect the vessels.

Under 100 year cyclone conditions the worst waves at the entrance are predicted to be 2.1m Hs in Phase 1 but even these waves do no not give significant wave disturbance at the berths however downtime would probably be caused due to the direct effect of the wind alone.

In Phase II there are many more vertical quays so, whereas in Phase I the waves were predicted to diverge from the deep channel and be dissipated on the undeveloped areas of the harbour, in Phase II much of this wave energy is reflected back into the harbour so wave heights are generally higher.

It is clear that the quay wall at Position 4, directly in line with the entrance is generally the most exposed. For waves from northeast and east there will be refraction of wave energy into the basin near Position 11 with significant wave heights of up to 0.6m. Waves shoal up onto the shallow area inside the south breakwater behind the Crude and P.O.L Chemical Cargo berths. Under cyclone conditions, these berths (Positions 9 and 10) are expected to experience swell waves of 1.0m Hs.

Applying permissible wave height thresholds provided by Howe India Pvt Ltd, the downtime due to waves at each of the berths in Phase I and Phase II is likely to be less than one day a year except at Berth 4 in Phase II where it is estimated that waves could cause downtime for between 10% and 15% of the time (with a 0.8m threshold). Allowing for typical storm durations it is estimated that this would affect about 100 days a year, hence the operable days would be less than 320 in a year at Berth 4. Using the same methodology a 1.0m threshold at Berth 4 (instead of 0.8m) gives downtime for 2% - 6% of the time, which by the same argument affects about 30-40 separate days a year, however the resolution with only a few wave conditions is rather coarse to be precise.

Waves at Berth 4 are relatively high since the waves pass though the harbour entrance along the channel and then diverge due to refraction towards the sides of the channel. This affects both Berth 4 and the area between Berths 13 and 14.

The effect of wave concentration at Berth 4 occurs with waves from 135°N as well as from 90°N due to the fact that, by the time they reach the harbour entrance the waves have refracted so that they enter directly into the port area. Given this direction of approach of the waves which give rise to the high wave energy at Berth 4, it is concluded that a spur structure on the north or south breakwater is unlikely to be very effective in reducing wave energy at Berth 4.

Wave-generated infill, sand trap assessment and coastal protection

Sediment transport due to waves and wave-generated currents was assessed for the Phase I construction phase and for Phase I and Phase II with various sand trap arrangements. Tests were performed to predict the average annual sedimentation in the port and channel and in the sand traps, and also to assess the infill during storms.

Simulations of the littoral drift under existing conditions yielded net southerly drift which is in contrast to earlier findings and previous studies. On further analysis, however, it is concluded that this southerly net drift is consistent with local geomorphology. The net transport rate is small compared to the gross transport in each direction.

Channel sedimentation was assessed for all scenarios tested. During the construction phase, and post-construction under storm wave conditions sediment bypassing of the structures takes place and there is consequent channel infill. Otherwise, in typical conditions the port breakwaters extend beyond the breaker zone so that the amount of sand bypassing is small and limited to the immediate vicinity of the breakwaters. As a consequence of this finding, it was concluded that there is little direct benefit in constructing a sand trap on either the north or the south breakwater. In order to effectively trap the main stream of sediment, such a trap would be required to placed very close to the breakwater(s) which could compromise their integrity. In the tests simulated, the sand traps accumulate sediment, but not necessarily to the benefit of the channel, which continues to infill.

In order to fully assess the potential benefits of the sand traps, and recognising that the coastline is likely to evolve following construction, further tests were carried out with an evolved seabed, in order to see if bypassing of the structures would increase in the future. Tests suggested that this was not the case, and this is largely due to the length of the breakwaters: the coastline evolution will continue until the beach re-orientates itself into a position of zero net drift, and since the breakwaters extend such a long way offshore, the realignment of the beach/nearshore is such that sediment the transport pathways are not increased. Accordingly, there is no significant evidence to suggest that the sand traps would be more effective in the future when the seabed has evolved.

Infill in the channel and the sand traps tested was assessed, to yield estimates of the annual volume of infill, and infill during storm conditions.

Accuracy considerations have been thoroughly discussed. As highlighted in the original proposal for this study, there is uncertainty in all sediment transport predictions due to natural variability in the various inputs, and also due to the algorithms applied. Based on the best available advice, uncertainty in the predicted volumes of channel and sand trap infill is considered to be a factor 2 to 5.

Options for coastal protection have been discussed. Whereas the coastline is expected to build up immediately adjacent to the port breakwaters, there may be erosion to the north and south as a consequence of the blockage to the littoral drift. Given the relatively high gross northerly and southerly sediment transport and small net transport, and seasonal nature in the longshore drift, it is considered that the site may be characterised by erosion on one side of the port during part of the year, followed by recovery in the second part of the year. Hence rather than large scale erosion on one side of the port and accretion on the other side, as would occur at a site with high net transport to either north or south, the potential erosion of the coast and nearshore may recover each year without intervention. In any event, it is recommended that following construction, regular monitoring of the coastline to either side of the port is carried out in order that intervention could take place if required. Options for coastal defence have been reviewed, and these could be soft measures or hard measures. Soft measures could include re-nourishing simply moving material along the coast to the areas of erosion. The most appropriate estimate of the volumes of material which may be required as re-nourishment of the coast would be that predicted to infill the channel as highlighted in the table in Section 4.8. This is on the basis that under existing conditions sediment passes across the bar system at the entrance to the estuary (possibly being stored on the bar for periods of time) and naturally feeds the coast downdrift. Trapping this volume sediment in the approach channel could lead to a comparable reduction in supply to the downdrift coast.

Of the hard measures available, these would most appropriately be either groynes or shore-detached breakwaters. The post-construction monitoring would provide the most useful information to aid in the location and design (length, spacing) of such structures.

Overall findings and channel and port infill summary

Results of the studies described herein are summarised briefly as follows:

a) Tidally-induced sedimentation is limited to the inner channel and port berth areas. Sand infill will tend to occur in the western (upstream) areas close to the limit of extent of dredging, and extending the dredging a relatively small distance (order 200m with width the same as the dredged berth, and to the same depth) will promote sedimentation in these areas rather than at the berths. Mud infill will, however, tend to occur over much of the inner channel and port areas. Vessel movements will tend to re-distribute the finer bed deposits, potentially spreading the infill into other port areas.

b) Wave tranquillity in the port areas is relatively low, with only Berth 4 in Phase II being highlighted as having a high number of inoperable days per year. The model results indicate that wave propagation to this berth is related to waves in the main channel being refracted onto this area: consequently, it is considered that a spur-type structure on either the north or south breakwater is unlikely to be effective in reducing wave energy at Berth 4. On this basis improved conditions could be obtained at this berth by obtained by constructing an open pile platform with absorption beach below, which would reduce reflections although it should be noted that the direct wave action will remain.

c) Sand traps are unlikely to be effective in reducing the channel infill. Tests indicate that the sand transport around the breakwaters is confined to the vicinity of the breakwaters, so that in order to be effective, a sand trap would have to be constructed so close to the breakwater that it may compromise its structural integrity.

d) At this location, net southerly drift was predicted, and this is consistent with the local geomorphology (i.e. the nature of the sand spit on the northern side of the estuary entrance). On this basis there would be a benefit in extending the northern breakwater into deeper water. Any extension over that simulated would have the effect of reducing sediment bypassing and associated infill of the channel.

e) The port sediment infill is summarised broadly from the conclusions stated in Section 2.2.4 and Section 4.8 as follows:

Infill (m^3/year)	**Phase I**		**Phase II**	
	Inner channel and berths	Outer channel	Inner channel and berths	Outer channel
Sand	7,700	45,000-75,000	3,500	240,000-280,000
Mud	115,000	-	540,000	-
Total	**122,700**	**45,000-75,000**	**543,500**	**240,000-280,000**

Sand infill in the inner channel and berth areas could be substantially reduced by extending the dredging area upstream (westwards) to create an effective sand trap.

During the construction phase, bypassing of the breakwaters is significant and there is likely to be high channel sedimentation. Predictions suggest order 336,000m^3 per year.
For Phase I it was noted that sand may pass around the breakwater ends but not be immediately deposited in the channel. In this case the sand may settle close to the channel, creating a ready source for subsequently infill. The volumes associated with this source represent order 50 to 100% of the quoted channel infill.

Storm infill will also give rise to sand bypassing the breakwaters and consequent infill of the channel. Predictions indicate that over a three-hour storm there could be (sand) infill of order 10,000-20,000m^3.

The above figures represent a best estimate at channel sedimentation which is based on the most up-to-date methods and accurate numerical modelling techniques. As stated in Section 4.3, however, it is important to bear in mind that sediment transport is not an exact science and there remains uncertainty in the prediction of sediment transport and associated estimates of sedimentation. There is a wealth of information from research worldwide, some of which has been cited in this document, which confirm and highlight this uncertainty in predictions of sediment transport in the marine environment. Effective measures which could be implemented to improve future predictions of sedimentation include the detailed collection of data relating to infill (bathymetric surveys, dredging records and measurements of seabed and suspended sediment data), so that this information could be applied to develop a calibrated sediment transport model for this site. This would then provide a means of providing more accurate estimates of future sedimentation as the port further develops and expands its facilities.

f) Shore behaviour and the need for coastal protection should follow construction of the port breakwaters so that an appropriate methodology can be implemented as necessary. It should be noted that the relatively balanced sediment drift to both north and south should give a lower coastal impact than that if the drift was dominated either to north or south, because there is likely to be a period of recovery following each of the main NE/SW monsoon periods. Hence the approach of monitor and future action is appropriate. The most appropriate estimate of the volumes of material which may be required as re-nourishment of the coast would be that predicted to infill the channel as highlighted in the table in Section 4.8. This is on the basis that under existing conditions sediment passes across the bar system at the entrance to the estuary (possibly being stored on the bar for periods of time) and naturally feeds the coast downdrift. Trapping this volume sediment in the approach channel could lead to a comparable reduction in supply to the downdrift coast.

Contents

Contents continued

Tables

Figures

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1. Introduction

1.1 BACKGROUND

Howe (India) Pvt Ltd are presently undertaking engineering design and impact studies on behalf of Krishnapatnam Port Company Ltd and requested the provision of mathematical modelling studies to assess elements of these studies for the proposed new bulk handling terminal at Krishnapatnam.

HR Wallingford was well placed to carry out the required studies having specific experience of modelling this site and the proposed bulk handling terminal as described in the outline design studies carried out on behalf of Beckett Rankine Partnership and described in HR Wallingford report EX4847 (Reference 1). As part of this earlier study a site visit was undertaken which included a boat trip from which a good understanding of the processes operating at the site was obtained.

1.2 SCOPE OF WORK

The original terms of reference for the mathematical model studies were prescribed by Howe India as follows:

Part-I (Phase-1)

A) Tidal Flow Model

To simulate tidal flows for the following conditions:

- To be tested for spring tides (f ood and ebb).
- To establish the tidal flow scenario incorporating direction and velocity of currents inside of the port giving due consideration to the presence of Khandaleru River, Buckingham Canal as well as Khandaleru Creek. However, an upstream dam blocks sediment transport by Khandaleru River.
- To establish the siltation pattern inside the port and channel with quantification of siltation.

B) Wave Tranquility Model

To assess the wave agitation within the Port area for the following conditions

- To be tested at MSL.
- To be tested for waves from NE, E & SE directions.
- Wave heights outside the port for each of the above directions to be 6m, 3m & 2m.
- Wave Period : 10 Sec
- Wave heights at different relevant locations inside the port and ship manoeuvring areas to be identified.

C) Moving Bed Model to Assess Adequacy of Sand Trap and the requirement of Shore Protection on North of the North Breakwater

To simulate sediment transport, including moving bed for the following conditions:

- To be tested at MSL (wave spectrum to be identified by the testing agency along with its offer).
- To be tested for waves from ESE & SE directions, representing SW monsoon (June – September), and from NE & ENE directions representing NE monsoon.
- Representative wave heights and test duration to be assessed and identified by the testing agency, in its offer.

- Available Information on bed samples can be made available to the successful contender.
- The test must definitively establish the location and the size of the sand trap to arrest effectively the northwards littoral drift which occurs during the SW monsoon. (June to September).
- The test must identify the extent of erosion north of the north breakwater and recommend the means as well as extent of shore protection measures viz, groynes/spurs, their spacings, lengths, elevations, etc., gabion mattress protection etc.
- Shore protection south of the south breakwater if required during NE monsoon is also to be quantified and protection measures recommended.
- Test must identify the effect on erosion of the shore under partial construction (say half the length) of the breakwaters.
- Recommend the relative sequence of construction of north and south breakwaters including maximum lag in the placement of different layers (amour layer, under layer and core).

Part-II (Phase-2)

Repeat (A) and (B) above for deepened & widened entrance channel, turning basin, berthing area including in addition to the crude & POL jetty, the LNG jetty also. (Refer Drawing Nos. I-413/L-001/Rev.E and I-413/C3-L-002/Rev.E).

On the basis of these terms of reference HR Wallingford provided Howe India with a proposal with appropriate scope of work. Following further revision of the scope of work HR Wallingford were commissioned to carry out the studies, the results of which are described herein.

1.3 REPORT STRUCTURE

The remainder of this report is structured as follows. Chapter 2 covers item A of the Terms of Reference, in respect of tidal flow modelling and sedimentation. Chapter 3 described the wave tranquility studies (Item B) and Chapter 4 summarises the tasks under item C - wave-generated (littoral) drift and sand trap optimisation studies, and coastal impact assessment. Finally, the conclusions from these studies are presented in Chapter 5.

2. *Tidal Flow and Sedimentation Modelling*

2.1 TIDAL FLOW MODELLING

2.1.1 Approach

The approach for this item of the studies was to retrieve the previously established tidal flow model from archive, modify the numerical model mesh in order to be able to resolve the new Port structures, and to simulate spring and neap tide conditions for analysis and for input to sediment transport models. As a consequence of this approach, and the fact that in the earlier study the model had been shown to be calibrated, the basis of the present scope of work was that it was assumed that no further calibration of the model was necessary.

2.1.2 Model setup

Tidal flow modelling was carried out using the HR Wallingford depth-averaged flow model, TELEMAC-2D. TELEMAC-2D is a state-of-the-art finite element flow model, originally developed by LNHE Paris, which uses a completely unstructured grid which has the advantage of allowing fine resolution in specified areas, and also enabling the accurate simulation of water movement in complex-shaped areas. Further details of TELEMAC are provided in Appendix 1.

The Krishnapatnam TELEMAC-2D flow model previously established for Krishnapatnam Port Company Ltd (January 2004) was re-commissioned for this study. For details of set-up and the calibration, please refer to this HR Wallingford Report EX4847. Since the model bathymetry and boundary conditions were unchanged since the previous study, no further calibration of the model was carried out during this study but for reference Figure 2.1 shows the earlier model calibration in which the key parameters (model friction and eddy viscosity) were determined.

For these studies the model mesh was adjusted for modelling Phase I and Phase II scenarios of the proposed development. Bathymetry was interpolated from the existing bathymetry set for the area and from AUTOCAD drawings of proposed works provided by Howe India.

The same grid system was adopted as in the previous study.

The following hydrodynamic data was utilised during this study:

Mean High Water Spring	1.2m
Mean High Water Neap	1.0m
Mean Sea Level	0.8m
Mean Low Water Neap	0.7m
Mean Low Water Spring	0.5m

2.1.3 Spring and neap tidal flow conditions for Phase I

The Phase I model bathymetry (Figure 2.2) was generated with the following changes to the existing model:

- A short Northern and longer Southern breakwater were included.
- A Multipurpose berth construction dredged to a depth of -13.8mCD and an associated small area of reclamation or the lighthouse Island.
- A turning circle dredged to -13.8mCD in the port entrance.
- An approach channel of depth -13.8mCD, that runs approximately East Northeast, dredged to -14.4mCD, just under 10km in length and 160m wide.
- A conceptual sand trap at -14mCD to the south of the Southern Breakwater was also included into the bathymetry. Note that the ultimate configuration for the sand trap is defined from Item C (Chapter 4).

Bathymetry outside of the Port development and further into the Creeks remained unchanged and identical to the existing scenario.

Figures 2.3 and 2.4 show the peak flood and ebb flow vectors for the spring tide simulation in the vicinity of the development. The speeds are greatest at the western end of the Multipurpose berth, where the bathymetry shallows quickly to undredged levels, and this has the effect of accelerating the flood tide as water enters the estuary. On the ebb tide, water flows over this relatively shallow area at speed and slows when it encounters the deepened area to the east. Peak ebb velocities rise to a maximum of 0.87m/s along the western end of the new dredged berth, whilst in the same area, the maximum flood velocities of 0.84m/s are seen. It should be noted that these current magnitudes are sufficient to mobilise sediment: a degree of bed level adjustment should be anticipated as a consequence.

Neap tide peak ebb and flood flow vectors can be seen in Figures 2.5 and 2.6. This distribution is similar to the spring tide currents, but the magnitude is smaller. Peak ebb speeds of 0.48m/s and flood speeds of 0.47m/s are seen in the undredged areas to the west of the berth. Again, it should be noted that these currents are sufficiently high to mobilise sediment and that consequently, a degree of seabed adjustment should be anticipated.

2.1.4 *Spring and neap tide conditions for Phase II*

The Phase II (Figure 2.7) model was set up using the existing bathymetry and drawings, provided by Howe India and comprised (in addition to changes made in Phase I):

- Berths at a depth of -19.8mCD along the entrance and main channel of the Port.
- The addition of an extra dock to the south of the Port and berths of -19.8mCD along the Southern Island.
- A -20.7mCD turning circle, replacing the shallower turning circle in Phase I.
- A large scale dredging and reclamation plan to redirect Khandaleru Creek (including berths for shallow draft vessels and a turning circle of -14mCD).
- Berths and reclamation further east in the Port (-19.8mCD and -13.2mCD) and a turning circle dredged to -19.8mCD.
- The approach channel extended to just under 14km, at a depth of -21.6mCD and 250m wide.

Figures 2.8 and 2.9 depict the peak ebb and flood speeds for the spring tide. Due to the degree of deepening the average speeds are of order 0.05m/s throughout the Port area, increasing to 0.1m/s between the breakwaters and 0.2m/s in the narrower reach at the Multipurpose Berth. Peak speeds of 0.8m/s are seen in the undredged areas to the west during the ebb and 0.7m/s during the flood. At peak flood, speeds or 0.25m/s are recorded at the Multipurpose Berth and 0.2m/s between the breakwaters. In the dredged areas, these speeds are typically below the threshold for motion of sediment, which would suggest that there will be minimal erosion in these areas, and moreover, there will be a tendency for any sediment reaching these areas to settle out.

During the neap tide (Figure 2.10: ebb, Figure 2.11: flood), peak speeds reach 0.32m/s (ebb) and 0.5m/s (flood) in the undredged areas whereas in the dredged zones the speeds are again very low. The speed at the Multipurpose Berths reach 0.15m/s. As under spring tide conditions, the low currents in the dredged areas would suggest a tendency for sediment to settle out.

Output from the two TELEMAC-2D flow models (Phases I and II) were used as input to the cohesive and non-cohesive sediment transport modelling described in the following sections.

2.2 TIDALLY INDUCED SEDIMENTATION

2.2.1 *Introduction*

Having established the tidal flow conditions for spring and neap tides for both phases of the port development, the flow files were used as input to sediment transport models representing the transport and deposition of sand and mud. This approach was consistent with the earlier modelling studies.

It is important to stress at this point that whilst the techniques employed are state-of-the-art, and in fact the sediment transport methods used in the model are the most up to date and acknowledged and used worldwide, there remains uncertainty in sediment transport predictions due to the very nature of the physical processes and limitations in the science of this field. In this respect it is acknowledged that the uncertainty in the transport rate and associated sedimentation means that predictions are only accurate to within a factor of 2 to 5 in coastal scenarios (without local calibration). Further information on calibration targets can be found in Soulsby (1997).

The above accuracy factor of 2 to 5 is appropriate for a sandy environment which is appropriate for the main channel outside the port areas, whereas in the berths there may be significant infill of fine silts and muds. The magnitude of mud infill is critically dependent on the levels of suspended sediment concentration (and other factors including its erodibility). In the absence of any detailed information relating to suspended sediment concentrations, the mud transport model was run with typical parameters representing the various physical processes. Accordingly, as in the case for the sand transport, it should be borne in mind that whereas the model will provide useful information in respect of the distribution of sediment in the port areas and access channel, the actual volumes of infill will depend strongly on the ambient (background) concentration fields. Consequently, volume of channel and berth infill will be subject to a degree of uncertainty and for the purposes of this study it is suggested that a similar level of agreement (i.e. a factor 2 to 5) is applied to the predictions of mud infill.

2.2.2 *Non-cohesive sediment (sand) transport modelling*

Model setup

To evaluate the sand transport pathways under tidal action the HR Wallingford SANDFLOW model was applied. SANDFLOW is a 2D sand transport model developed by HR Wallingford (see Appendix 1) which covers the same area as that set up for the TELEMAC model, and uses the output from TELEMAC to simulate transport patterns over the same model mesh. For this model study SANDFLOW was run using a median grain diameter, D50 of 250 microns and run over three tides. Data from the second tide was used to produce the results.

Spring and neap sand transport for Phase I

The net tidal sediment transport pathways for the spring tide can be seen in Figure 2.12, with the deposition over the tide being presented in Figure 2.13. The distribution of sand transport patterns is consistent with the tidal current patterns, with erosion and transport in the shallower (undredged) areas immediately upstream of the berths. The reduced tidal flow speeds in the dredged areas tends to give rise to sedimentation in the dredged channel during the ebb tide. There is also an area of active redistribution of the seabed in the area to the north of the turning circle.

On the basis of these results it is concluded that there is likely to be some degree of sand infill in the main berth areas, and on the northern side of the turning circle, as the seabed close to the dredged areas adjusts following the construction. The degree of infill is therefore likely to reduce in time as the seabed finds a new equilibrium. However, it is also recommended that the dredged berth area be extended further west (upstream) past the Phase I berths in order to provide a sand trap thereby reducing the risk of infill directly at the berths. By reference to Figure 2.13 it can be seen that the zone of high sedimentation (shown in red) is relatively short, so that extension of the dredged area upstream by a length of order 200m (with width the same as the dredged berth, and to the same depth) would relocate this area of anticipated high sedimentation to be sited a similar distance upstream, and importantly away from the Phase I berth.

Corresponding figures showing the neap tide patterns can be seen in Figures 2.14 (net tidal sediment flux) and Figures 2.15 (net tidal deposition). The same pattern or erosion and deposition can be seen at the western end of the dredged berth and on the northern side of the turning circle, although the magnitude of sedimentation is lower.

In terms of quantities of infill, the model predictions shown in Figure 2.13 suggest a rate of up to 100mm per tide in the upstream (western) end of the berths. Closer inspection of the results indicates that this figure is up to 35mm per tide. Clearly, this rate of infill would not continue for long before natural bed levels are restored, and this would suggest that the area could rapidly lose depth. Again, extension of the channel to the west would provide a suitable trap to attract sediment and reduce infill at the berths.

Spring and neap sand transport for Phase II

With the additional dredging and deepening of the Upputeru River, sand sediment transport in the port area is diminished considerably. Figures 2.16 and 2.17 show the net tidal flux and deposition, respectively, for a spring tide. Deposition and erosion are limited to the edge of the dredged zone in the western end of the port, and this is again due to the relatively high currents in the undredged areas mobilising sand which is then deposited in the deepened areas. As recommended for Phase I, extension of the dredged area upstream by a length of order 200m (with width the same as the dredged berth, and to the same depth) would relocate this area of anticipated high sedimentation to be sited a similar distance upstream, and importantly away from berths which may be sited in this area.

Figures 2.18 and 2.19 are corresponding images for the neap tide; here comparable patterns can be seen in the same areas. Little sand transport and associated deposition is seen within the port area itself.

2.2.3 *Cohesive sediment (mud) transport*

Model setup

To evaluate the deposition in the Port resulting from mud transport a SUBIEF model of the study area was set up. SUBIEF is a 2D mud transport model developed by LNHE as part of the TELEMAC suite and also runs on the same model mesh using currents directly from TELEMAC. Further details of SUBIEF are provided in Appendix 1.

The SUBIEF model was run for two tides for both Phase I and Phase II, with results taken from the second tide. The model was set up with a constant upstream concentration boundary condition of 100mg/l and a constant offshore boundary condition of 100mg/l. The offshore boundary conditions had little influence on concentrations inside the estuary, since there is adequate distance for the model to adjust accordingly before reaching the study area. Increased fine sediment load in the river will, however, lead to increased siltation in the Port areas.

In the absence of site specific information the parameters used in the simulation were based on prior experience of similar studies carried out at HR Wallingford and from advice in Dynamics of Estuarine Muds (2000) as follows:

Critical shear stress for deposition, τ_d	$= 0.1 N/m^2$
Critical shear stress for erosion, τ_e	$= 0.3 N/m^2$
Erosion constant, M_e	$= 0.0002 m^{-1}s$
Settling velocity, w_s	= 1 mm/s

Spring and neap mud transport for Phase I

Figures 2.20 and 2.21 represent the mud deposition patterns for a spring and neap tide respectively, and it is noted that these patterns are broadly consistent with the findings in the earlier study, with deposition being predicted in the deepened areas. During the spring tide, peak deposition of 0.65mm is noted on the southern side of the newly dredged channel. Deposition within the turning circle reaches approximately 0.4mm. During the neap tide, deposition is also seen within the existing deepened part of the Port, reaching levels of up to 0.3mm.

Spring and neap mud transport for Phase II

Figures 2.22 and 2.23 show the net deposition of mud over a spring and neap tide for the Phase II scenario. The pattern of infill in the main channel and Phase I berth areas is similar to that predicted for the Phase I scenario but greater rates of infill are predicted to occur in the western areas in Phase II.

During spring tide conditions, deposition of up to 4mm is predicted in the western areas of the port development whereas deposition near to the Multi-purpose berth is predicted to be lower at order 0.02mm/tide, with 0.01mm/tide predicted in the turning circle.

Under neap tide conditions the pattern of sedimentation is similar to that during springs, except that the accumulation of sediment is predicted to be concentrated in the more upstream areas of the port. Deposition of up to 4mm is seen in the western areas of the port with less than 0.01mm in the turning circle and at the Multi-purpose berth.

2.2.4 Tidal sedimentation assessment

The infill predictions described above were processed further to provide an estimate of the initial rate of sedimentation due to tidal processes only. The volumes of infill in the dredged areas from the various simulations area presented in the table below.

	Sand (m^3/tide)		Mud (m^3/tide)	
	Spring	Neap	Spring	Neap
Phase I	22	negligible	240	90
Phase II	10	negligible	975	563

Scaling these figures for the mud infill (assuming order 350 spring tides and 350 neap tides per year) yields totals of 115,000m^3/year in Phase I and 540,000m^3/year in Phase II. Since these values represent tidal processes only, there is no variation through the year. These volumes will be sensitive to the ambient levels of suspended sediment concentration and as highlighted in the earlier study, the sediment load in the river upstream will influence the volumes of siltation experienced in the Port areas.

Applying the same scaling to the sand infill yields 7,700m^3/year in Phase I and 3,500m^3/year in Phase II. However, given the nature of the sand infill (which occurs adjacent to the deep cuts at the western end of the dredged zone and to the north of the turning circle) it is considered that this infill is an over-estimate of the longer-term rate because there will be adjustment to the seabed in the areas where the sand transport is greatest, and this will reduce the sand infill over time. Note that this is not expected to be the case for infill due to silts and muds which will continue to infill the channel. In addition, as highlighted in Section 2.2.2, it is recommended that the dredged zone be extended approximately 200m upstream (west) beyond the berths (with width the same as the dredged berth, and to the same depth) and this will also reduce the amount of maintenance dredging in the berth areas.

In terms of the distribution of the sand infill Figure 2.13 highlights that the sand infill is likely to occur at the berths in Phase I, as well as there being a risk of some sedimentation on the northern side of the turning circle. In Phase II Figure 2.17 indicates that the areas prone to sand infill are in the SW areas of the port. Under tidal processes alone, 100% of the quoted volume of infill is predicted to occur in these areas (northern side of turning circle and in the inner berths): tidal currents alone are insufficient to mobilise sand and cause infill in the outer channel. The volumes of infill quoted above include the large rate of deposition shown at the edge of the dredged areas in Figure 2.13 (Phase I) and Figure 2.17 (Phase II). Figure 2.13 highlights, however, that along the main berth in Phase I typical infill is in the band 0.1 to 1.0mm per tide on spring tides and this equates to a loss of depth (ignoring ship motion which will tend to redistribute the infill) of up to 0.3m per year (using the upper value of infill). Figure 2.13 highlights that loss of depth at the berths is minimal (sedimentation occurring away from the berths).

In respect of the distribution of mud infill Figures 2.20 and 2.21 indicate that in Phase I the distribution of muddier infill will tend to accumulate over the entire deepened area relatively evenly (especially when it is considered that ship motion will tend to redistribute some of the infill). Loss of depth in the berth areas is up to 0.5mm per tide on both springs and neaps and this equates to order 0.3m per year although it should be borne in mind that ship motion, and the density of the settled mud could alter this depth of infill. In Phase II it is concluded from Figures 2.22 and 2.23 that the mud infill will be concentrated in the inner berths to the west of the port, with approximately 80% of the annual volume quoted above occurring in these areas: the remainder (20%) settling out relatively evenly in the inner channel area and turning circle. Loss of depth in the berth areas is shown to be up to approximately 2mm (especially in the inner berths as shown in Figures 2.22 and 2.23) on both spring and neap tides and this equates to order 1.5m per year although it should be borne in mind that ship motion, and the density of the settled mud could alter this depth of infill.

It was concluded in the earlier study that suspended sediment concentrations offshore are likely to be relatively low because the currents speeds experienced are low. Hence siltation is considered to be generally limited to the inner channel and port areas with only low rates of siltation in the outer channel.

It should also be borne in mind that in addition to tidal processes, wave action will also give rise to sedimentation, particularly in the access channel, and this aspect is considered as part of the sand trap assessment (Chapter 4).

3. *Wave Tranquility Studies*

3.1 OFFSHORE WAVE DATA

The offshore wave climate was obtained from the UK Met Office Global Wave model. This model is run as part of the operational wave forecasting system and is then re-run in hindcast mode, incorporating measured data from satellites and instruments. Data was extracted from a combination of two points (14.6N 80.6E and 14.7N 80.4E) for the period November 1994 to October 2006. Data derived from this model has been used at HR Wallingford on numerous projects worldwide, and the total data set available (covering 12 years) was adequate for determining the more frequent wave climate information: for the more extreme (cyclone-induced) waves alternative data sources were used (see below).

The offshore wave climate is presented as Table 3.1a in terms of a scatter table of wave height versus wave direction, and in Table 3.1b in terms of wave height versus mean wave period, and as a wave rose in Figure 3.1. The largest waves approach from approximately the east whereas the most frequent waves approach from the south east.

Extreme offshore wave conditions from given return periods were derived from the waves climate accounting for combined wind waves and swell. The 50:1 year return period was derived by counting back within the climate for each direction sector. 1:1, 1:50 and 1:100 year return periods were derived by fitting Weibull probability distributions. For the more extreme waves, however, the influence of cyclones must be taken into account: these are not resolved by the Met Office model.

Cyclone wave conditions were adopted from a previous HR Wallingford study (HR Report: EX4847-Krishnapatnam Port Sedimentation Study, 2004); these conditions were derived from Young's formula based on extreme cyclone wind speeds.

The following Table presents the offshore wave conditions where the 50:1 and 1:1 year conditions are derived from the UK Met Office model climate and the 1:50 and 1:100 year conditions are due to cyclonic storms. Peak wave period was calculated assuming a JONSWAP spectrum for the waves for which Tz=0.781Tp applies.

Extreme offshore wave conditions at the site

Return period (years)	Wave direction (^{0}N)	Hs (m)	Tz (sec)	Tp (sec)
50:1	60	1.2	4.6	5.9
50:1	90	1.2	4.6	5.9
50:1	135	1.4	4.9	6.3
1:1	60	2.4	6.5	8.3
1:1	90	2.4	6.0	7.7
1:1	135	1.85	5.9	7.6
1:5	60	2.85	6.5	8.3
1:5	90	3.41	7.4	9.5
1:5	135	2.16	6.2	8.0
1:10	60	3.06	7.5	9.6
1:10	90	3.89	7.6	9.7
1:10	135	2.4	6.3	8.1
1:50 cyclone	any	14.2	12.4	15.1 – 16.6
1:100 cyclone	any	16.2	12.7	15.8 – 16.7

3.2 THE TOMAWAC WAVE TRANSFORMATION MODEL

In order to transform the offshore waves to nearshore locations near the port entrance, a TOMAWAC wave transformation model was set up and run. TOMAWAC is a 3rd generation finite-element spectral wave model which simulates the transformation of random directional waves considering the following processes:

- Wave shoaling
- Wave refraction
- Depth-induced breaking, bottom friction and whitecapping
- Wave growth due to the wind
- Wave blocking

It was developed by the National Hydraulics Laboratory (LNH) of the Research and Development Division of the French Electricity Board (EDF-DER) as part of the TELEMAC finite element hydraulic modelling system.

The model extended out to deep water and included the proposed dredged channel for the Phase I layout (see Figure 3.2). As agreed in the scope of work, waves from East (90°N) and Southeast (135°N) were run in the model. It is clear from the wave climate (Table 3.1) that waves from the Northeast are fairly rare and less directly incident, therefore waves from 60°N were tested instead of 45°N. For each wave direction waves of return period 50:1, 1:1 and 1:100 years were modelled. Separate wave conditions were derived for each direction sector for the 50:1 and 1:1 year conditions as shown in the Table in Section 3.1. Conditions from each of these directions are expected to occur within the relevant return period. For the 100 year cyclone waves, however, the direction is uncertain, so, although each wave direction was considered, only one of these would be expected within the 100 year return period.

The model was run at a fixed water level of Mean Sea Level. Figures 3.3 to 3.11 show results from the TOMAWAC model as colour contour plots of significant wave height. The results show that the channel partially reflects wave energy and also causes a divergence of wave energy away from the line of the channel due to refraction. It should be noted that the TOMAWAC model does not include the processes of wave diffraction around the breakwaters or wave reflections from these or other structures. Therefore, in order to investigate waves within the port area a separate local ARTEMIS wave disturbance model needed to be patched in (See Section 3.3 below). Consequently within the areas of the breakwaters, results from the ARTEMIS model (Figures 3.13 to 3.21) should be taken instead of results from the TOMAWAC model (Figures 3.3 to 3.11). Figures 3.3 to 3.11 show a curved boundary of points near the harbour entrance. Wave conditions were extracted from the TOMAWAC model results at these locations in order to provide spatially varying boundary conditions for the ARTEMIS model.

Figures 3.9 to 3.11 show that the longer period 100 year cyclone wave conditions are heavily affected by refraction and depth limited by breaking before reaching the harbour breakwaters. Therefore, although different offshore directions were tested, the wave heights and directions at the harbour breakwaters were remarkably similar.

3.3 LOCAL ARTEMIS WAVE DISTURBANCE MODEL

Inside the harbour, the effects of wave diffraction around the breakwaters and wave reflections from the breakwaters, quay walls and other structures will become important. It was therefore necessary to use a local ARTEMIS wave disturbance model of the harbour area. The ARTEMIS model is based on the finite element solution of the Mild Slope Equation. It was developed by the National Hydraulics Laboratory (LNH) of the Research and Development Division of the French Electricity Board (EDF-DER) as part of the TELEMAC finite element hydraulic modelling system.

The ARTEMIS model represents the transformation of random waves including the following effects:

- Wave shoaling
- Wave refraction
- Partial reflections from breakwaters and other coastal structures
- Wave diffraction.
- Energy dissipation due to depth-limited wave breaking and seabed friction.
- Wave resonance effects

3.3.1 Modelling of the Phase I layout

The model area and bathymetry for the Phase I layout is shown in Figure 3.12 together with locations of analysis points. In the inter-tidal areas where waves will be absorbed, the depths were set as a minimum of 2m in order to avoid the need for extremely fine model resolution. Waves in these areas were absorbed by the boundaries. The relatively low reflection coefficients of other natural boundaries were set based on the slope of the bathymetry. The armoured breakwaters were specified to have a reflection coefficient of 0.5 whereas the vertical quay walls at the berths were specified with a reflection coefficient of 0.95

Spatially varying wave conditions were applied at the seaward boundary of the model from the results of the TOMAWAC model. The directional spreading of the waves was represented by using 9 components. The model was run for the same 9 wave conditions as the TOMAWAC model. Results are presented in Figures 3.13 to 3.21 as colour contour plots of wave height within the harbour area. In these plots the area outside the curved ARTEMIS model boundary was patched with results from the TOMAWAC model.

In addition, wave conditions are tabulated in Table 3.2 at the six locations shown in Figure 3.12. Locations 1 to 3 are at the centres of the proposed berths and locations 4 to 6 are along the centreline of the channel. Waves at each of the berths are small. It is clear from the plots that the dredged channel causes the wave energy to diverge into the shallow areas to the north and south of the channel.

Downtime at the berths will clearly depend on the types of vessels and operations being considered. However, these results clearly show that the wave energy reaching the berths from offshore is very low. The wind blowing within the harbour will create surface chop which may be higher than these wave heights but, being of very short period will not affect the vessels.

Under 100 year cyclone conditions the worst waves at the entrance are predicted to be 2.1m Hs but even these waves do no not give significant wave disturbance at the berths however downtime would probably be caused due to the direct effect of the wind alone.

3.3.2 Modelling of the Phase II layout

The ARTEMIS model was then set up to represent the Phase II layout as shown in Figure 3.22. The TOMAWAC model was also re-run with the deeper Phase II dredged channel to provide boundary conditions to the model. The ARTEMIS model was run in the same way as for Phase I and results are presented in Figures 3.23 to 3.31. In Phase II there are many more vertical quays so, whereas in Phase I the waves were predicted to diverge from the deep channel and be dissipated on the undeveloped areas of the harbour, in Phase II much of this wave energy is reflected back into the harbour so wave heights are generally higher.

The model results have been analysed to extract the maximum value of the significant wave height along each of the berths/quays and in the channel as shown in Figure 3.22. These wave heights are tabulated in Table 3.3. It is clear that the quay wall at Berth 4, directly in line with the entrance is generally the most exposed. For waves from northeast and east there will be refraction of wave energy into the basin near position 11with significant wave heights of up to 0.6m. Waves shoal up onto the shallow area inside the south breakwater behind the Crude and P.O.L Chemical Cargo berths. Under cyclone conditions, these berths (Positions 9 and 10) are expected to experience swell waves of 1.0m Hs.

3.3.3 Assessment of the number of operable days

At the clients request, the number of operable days at the various berths was required to be assessed based on the simulations carried out. For this assessment, the following permissible wave height thresholds were provided by Howe India PVT Ltd.

i)	Container berths (location 11 to15)	0.65 m
ii)	Multipurpose berths (1, 20, 19, 18, 17, 16, 7&6)	0.80 m
iii)	Dry bulk a) Coal (3 to 5) b) Iron ore (2)	 0.80 m 1.00 m
iv)	Tankers a) Tankers - Liquid Cargo / POL products. (8, 10) b) Gas tanker (9)	 1.00 m As per International Standard based on your experience

Applying the permissible wave height thresholds quoted above, the downtime due to waves at each of the berths in Phase I and Phase II is likely to be less than one day a year except at Berth 4 in Phase II. Based on using the model runs that have been carried out to interpolate the nearshore climate to waves at the berth, accounting for each of the dominant wave direction sectors, it is estimated that waves could cause downtime at Berth 4 for between 10% and 15% of the time (876-1315 hours). However the downtime will not be in continuous chunks, and an assumption of an average storm duration (above the threshold) lasting about 12 hours was applied which means that the number of separate days affected doubles to 100 days a year, hence the operable days would be less than 320 in a year at Berth 4. Using the same methodology a 1.0m threshold at Berth 4 (instead of 0.8m) gives downtime for 2% - 6% of the time, which by the same argument affects about 30-40 separate days a year, however the resolution with only a few wave conditions is rather coarse to be precise.

The above analysis only considers downtime due to longer period waves from offshore: it does not take account of any downtime due to wind or equipment problems. It is also assumed that the very short period 'choppy' waves that would be generated locally within the harbour would not contribute to the downtime thresholds since these short period waves would be unlikely to move the large vessels.

Waves at Berth 4 are relatively high since the waves pass though the harbour entrance along the channel and then diverge due to refraction towards the sides of the channel. This affects both Berth 4 and the area between Berths 13 and 14 (see Figure 3.22).

The effect of wave concentration at Berth 4 occurs with waves from 135°N as well as from 90°N due to the fact that, by the time they reach the harbour entrance the waves have refracted so that they enter directly into the port area. They therefore still propagate down the entrance channel and especially toward the Berth 4 side of the channel as seen in Figure 3.28. Given this direction of approach of the waves which give rise to the high wave energy at Berth 4, it is concluded that a spur structure on the north or south breakwater is unlikely to be very effective in reducing wave energy at Berth 4.

Regarding the wave directions quoted in Table 3.2 for Phase I: Inside the harbour the waves have a number of directional components due to reflections: mean direction is shown. At Location 3 the direction quoted is affected by reflections from the quay. At Location 6 (Figure 3.12), there is a divergence of waves from the channel leading to the change in direction. In Phase II there are many more reflective quays so the pattern of waves becomes more confused with standing waves in some places. Hence it is not appropriate to quote single wave directions because the waves at any location may be a combination of waves from various directions.

4. Sand Trap Optimisation and Coastal Impact Studies

4.1 INTRODUCTION

The original specification for this element of the study required simulations to be carried out using representative waves for littoral drift in order to establish the location and size of a sand trap "to arrest effectively the northwards littoral drift which occurs in the SW monsoon", together with an assessment of the potential for coastal impact and associated recommendations for remedial measures.

During the course of the negotiations for the studies HR Wallingford also advised that it would be prudent to consider the effects of changes in the coastline as a consequence of build up against the breakwaters when assessing the sand trap configuration. This was based on the fact that the original drawings provided by Howe India with suggested location for the sand trap in relatively deep water which would be unlikely to experience infill and therefore be effective in the period immediately post construction. Accordingly, in addition to the simulations based on the existing bathymetry with the proposed breakwater structures imposed, simulations were also carried out with the coastline and nearshore bathymetry modified to represent a future scenario when the seabed had adjusted around the Port structures.

4.2 METHODOLOGY

4.2.1 Modelling approach

Simulations were carried out using the HR Wallingford coastal area modelling framework, PISCES.

PISCES is a state-of-the-art, fully-interactive coastal area modelling framework, capable of simulating the various processes of wave propagation, current distribution, and the resulting sediment transport in complex coastal areas.

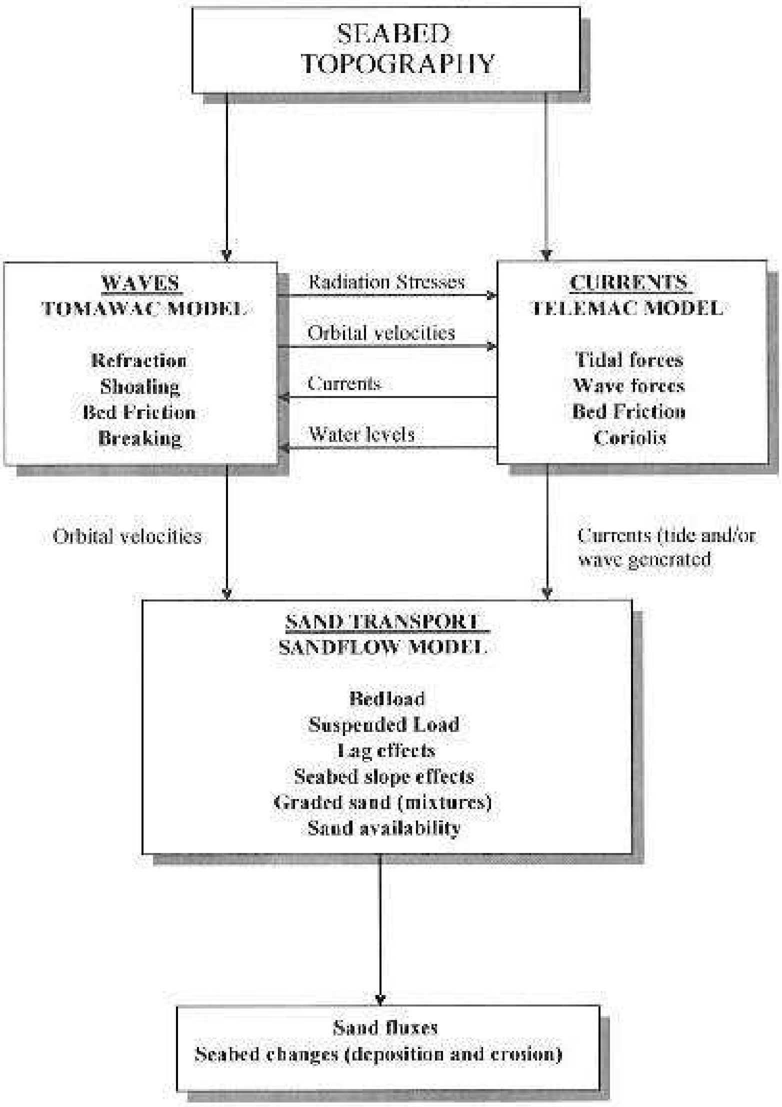
For this study PISCES will comprise the wave propagation model, TOMOWAC in combination with the finite element flow model TELEMAC and the SANDFLOW sand transport model. All models work on the same TELEMAC unstructured mesh.

TOMAWAC is a 2nd generation finite-element spectral wave model which simulates the transformation of random directionally spread waves considering the following processes:

- Wave shoaling
- Wave refraction by the seabed and by currents
- Depth-induced breaking, bottom friction and whitecapping
- Wave growth due to the wind
- Wave blocking.

The TOMAWAC model was developed by the National Hydraulics Laboratory (LNH) of the Research and Development Division of the French Electricity Board (EDF-DER) as part of the TELEMAC finite element hydraulic modelling system. The model also links directly with the TELEMAC flow model so that in principle flow fields from TELEMAC can be used to consider current refraction of the waves, and wave radiation stress fields from the TOMAWAC model can be used to generate wave-induced currents to be modelled by TELEMAC.

TELEMAC is the flow model that solves the shallow water equations including the terms that represent generation of wave driven currents due to wave breaking. Output from TELEMAC (in the form of (wave-generated) currents and TOMAWAC (in the form of wave orbital velocities) are input to SANDFLOW to simulate sediment transport in both the offshore and nearshore (wave breaker) zones. By this means sediment transport due to waves and wave-induced currents is simulated, shown schematically in the figure below.



PISCES model structure

Further details of TOMAWAC, TELEMAC and SANDFLOW are presented in Appendix 1.

Typical application of PISCES comprises setting up a bathymetric database, selection of specific input wave conditions for simulation, calculating the corresponding currents and sand transport pathways and analysis of the results. A consequence of detailed model resolution and sophistication of the models means that it is not usually possible to model all wave conditions in a particular climate. Accordingly, PISCES is used to model representative patterns of drift for selected representative wave conditions and the results are integrated to yield the gross and net longshore drift. Through research and application of PISCES to a number of case studies, HR Wallingford has developed reliable techniques to determine representative input wave conditions as described in Section 4.2.4.

4.2.2 *PISCES track record*

The track record for PISCES is long, with PISCES being successfully used in the following recent relevant projects.

- Haifa Marina, Israel. PISCES was used to assess the impact of the proposed Haifa Marina on the adjacent coastline and nearshore areas.
- Ashdod Breakwater, Israel. PISCES was used specifically to calculate the degree of sediment bypassing around the main breakwater, as part of additional coastline evolution modelling studies required for the proposed port development and main breakwater extension.
- Ashdod sediment bypassing, Israel. As part of the consent process for the port development including main breakwater extension, studies were required to consider the practicalities of carrying out sediment bypassing. PISCES results were re-interpreted to aid in the development of a bypassing strategy.
- Portobello, UK. PISCES was used to assess the degree of bypassing around a new reclamation housing a waste water treatment works, with the aim of optimising the reclamation design to minimise the coastal impact.
- Kilkeel, UK. PISCES was used to assess the sediment transport around a harbour complex under combined tide and wave action. A variety of new harbour designs were tested as a means of optimising the harbour layout.
- Mowe Baii, Namibia. PISCES was used to assess the feasibility of siting a new port on the Skeleton Coast at Mowe Baii, an area of particularly high littoral drift.
- Qua Iboe Nigeria. PISCES was used to model the strong littoral drift around the Qua Iboe river mouth during wet and dry season conditions. The feasibility of maintaining a channel through the bar at the mouth was investigated.
- Great Yarmouth, UK. PISCES was used in this large study to simulate combined waves and tides to predict the impact of a proposed new harbour on the east coast of the UK.
- Harwich, UK. PISCES was used to assess the impact of the placement of sand on the coast as part of a nourishment project.
- Kuwait Waterfront V PISCES was used to assess the annual average loss of sediment out of an artificial pocket beach on the Kuwait Corniche. The PISCES results were used as input to the design.
- SASME research project. PISCES was used to simulate the growth of offshore bars in a wave-driven sediment regime.
- Happisburgh to Winterton research project, UK. PISCES was used to simulate the impact of offshore reefs constructed on the East Anglian coastline. The modelling successfully reproduced the reduction in sediment supply to the downdrift coast.
- Hai Phong, Vietnam. PISCES was used to simulate the sediment transport patterns at the marine entrance to the proposed new access channel to the Port of Hai Phong.
- East Head, UK. PISCES was used to investigate the tide and wave-generated sediment transport field in the vicinity of East Head, as a means of establishing the regime of this complex system at the entrance to Chichester Harbour.

- Walton Backwaters, UK. PISCES was used to simulate combined wave and tidal flows and sediment transport patterns at the entrance to Walton Backwaters.
- Poole Bay, UK. PISCES was used to simulate the sediment transport pathways due to combined tides and storm waves within Poole Bay as part of a coastal strategy study for this area.
- Southern North Sea Sediment Transport Study II, UK. PISCES was used to simulate combined tide and sediment transport patterns at Winterton on the E coast of the UK in order to establish sediment transport pathways between the Ness and the offshore sand banks.
- La Union, El Salvador. PISCES was used to simulate sediment transport under tides with wave stirring as part of the Port rehabilitation project. Sedimentation in the proposed dredged channel was predicted.
- Saemangeum, Korea. PISCES was used to simulate sediment transport fields in the region of the Saemangeum tidal wetland project. Scenarios modelling included the long-term evolution of the seabed following closure of the seadike.
- Poole Bridge, UK. PISCES studies were undertaken to assess the impact of proposed bridge piers on the channel connecting Holes Bay with Poole Bay.
- Akko Marina, Israel. PISCES was applied to assess the potential impact of a proposed marina on the coast at Akko in Israel. In addition, PISCES was also applied to specifically consider the degree of beach loss in a proposed bathing area, and in this same bathing area, PISCES was used to assess the wave-generated currents for input to a safe bathing assessment.

4.2.3 Simulations performed

An overview of the simulations performed for optimisation of the sand trap is given in the table below. All simulations were carried out with the water level set at Mean Sea Level conditions with no tidal currents. Local current conditions are thus due to the effects of wave breaking and the resulting wave-induced current patterns and the wave orbital velocities were used as input to the sand transport model for each of the listed conditions. The cases with existing seabed represent the simulations whereby the Port structures, breakwaters and channel were imported directly into the seabed, whereas tests with an evolved seabed represent a future scenario whereby the coastline and nearshore has evolved and built up against the breakwaters. This evolution and prediction of the future bathymetry was based on the results for the existing bed and also drawing on experience of coastal change in the lee of structures at other sites around the world. The aim of this approach using an evolved seabed was to provide a more thorough assessment of the effectiveness of the sand traps taking into consideration that following construction there will be a period of adjustment which may have a bearing on the optimum configuration of the sand trap.

The model results for each of the schematisations are discussed in the following sections.

Overview of simulations

Phase	Sand trap	Seabed configuration	Wave conditions
Existing case	-	Initial	5 representative wave conditions: 30°, 60°, 90°, 120° and 150°N
Construction	-	Initial	5 representative wave conditions: 30°, 60°, 90°, 120° and 150°N
Phase I	1 (south b/w)	Initial	5 representative wave conditions: 30°, 60°, 90°, 120° and 150°N
	1	Future	2 representative wave conditions: 30°N and 150°N
	2 (north b/w)	Future	2 representative wave conditions: 30°N and 150°N
	3 (north b/w)	Future	2 representative wave conditions: 30°N and 150°N
	2	Initial	Storm wave conditions: 90°N
	3	Initial	Storm wave conditions: 90°N
Phase II	2	Initial	5 representative wave conditions: 30°, 60°, 90°, 120° and 150°N
	3	Initial	5 representative wave conditions: 30°, 60°, 90°, 120° and 150°N

4.2.4 *Determination of representative wave conditions*

As described in Section 4.2.1, due to the requirement to model a very large area, and to resolve the approach channel and other key areas around the port breakwaters with a fine mesh, the runtimes for simulations were relatively long. This approach of exploiting the computational power to define very fine meshes is not unusual, and results in the requirement to reduce the number of input conditions simulated to a representative subset.

In this case it was required to reduce the offshore wave climate (shown in Tables 3.1a and 3.1b) into a small set of conditions that were representative of the longshore drift. The routine to determine these conditions is described in Appendix 2, and resulted in the following representative wave conditions whereby each condition in a given directional sector is representative of the littoral drift of all waves in that directional sector. The probability (frequency of occurrence) of each wave conditions is therefore determined according to the relative frequency of waves from each directional sector as shown in Table 3.1a.

No.	Direction (°N)	Hs (m)	Tp (s)	Probability (%)
1	30	1.25	4.5	0.93
2	60	1.27	4.5	9.75
3	90	1.12	4.0	14.47
4	120	0.96	4.0	9.65
5	150	0.97	4.0	43.81

4.3 ACCURACY CONSIDERATIONS

Prior to presenting the results of the sand transport simulations and assessment of the sand trap, it is appropriate to discuss accuracy considerations.

As highlighted in the proposal for these studies, it is widely acknowledged in the scientific community that in the coastal environment sediment transport predictions are only accurate to within a factor of order 2 to 5. It should further be noted that this degree of accuracy represents the agreement between predicted and observed sediment transport rates when the hydrodynamic conditions are defined. This finding was borne out of research studies whereby candidate organisations who are recognised as leaders in the field of sediment transport performed blind sediment transport tests (i.e. without the possibility of adjusting the model parameters). Further details of such studies can be found in Reference 2, and the conclusions arising in respect of accuracy are summarised in Soulsby 1997 (Reference 3). Similar degrees of accuracy are reported in other sources, such as the US Army Corps of Engineers (see for example, Reference 4) and in the Journal of Coastal Research (see for example, Reference 5). In this latter reference it is noted that accuracy to within a factor of 10 to 100 is not uncommon.

The above uncertainty is essentially due to the fact that sediment transport is not a precise science, and as a consequence, sediment transport formulae tend to be based on empirical or semi-empirical methods which are also subject to degrees of error. Hence whilst the best approaches and methods are employed to predict sediment transport it is clear that the application of any specific sediment transport algorithm will give rise to predictions that are subject to a degree of uncertainty.

In addition to the uncertainty related to the sediment transport algorithms described above, it should also be borne in mind that there will also be error associated with the predictions of sand transport due to the natural variability in the physical conditions and processes. At this site, whilst the data coverage is adequate to setup and perform modelling simulations, it is important to appreciate that there will be variability in the sand transport rates due to natural variability in various fields, including:

- Changes in the nearshore bathymetry;
- Changes in the offshore waves;
- Variability in the seabed sediment characteristics (sediment grain size, grain shape, effects of fine sediment (mud) on sand)
- Freshwater effects
- Additional (general circulation) current streams (other than tides and waves)

The conclusion arising from the above discussion is that the sediment transport predictions carried out in this (or any) study should be considered as being representative but will also be subject to uncertainty. It should also be noted, however, that despite the apparent uncertainty using numerical models they still provide a valuable means of assessing the performance of a scheme and in this case, a useful means of assessing the relative pros and cons of scheme (sand trap) alternatives.

Taking into consideration the above factors, it is concluded that without specific local calibration it is not unreasonable to assume that the uncertainty in the sand transport predictions (and associated predictions of channel infill) will remain of the order of a factor 2 to 5.

4.4 SIMULATION OF EXISTING CONDITIONS

Simulations were initially carried out for the case with the existing scenario, using the natural seabed as shown (in the vicinity of the proposed Port) in Figure 4.1. PISCES simulations were performed with a tidal level set at Mean Water Level (no tidal influence), for each of the five representative wave conditions summarised in the table in Section 4.2.4.

Tests were carried out with a median grain diameter of 0.1mm, which corresponds to the finer fraction considered in the earlier HR Wallingford study and was considered to be more appropriate in this sedimentation study since it is the finer sand fractions that will more readily bypass the port breakwaters and infill the approach channel.

Wave heights and directions for each input wave condition are shown in Figure 4.2 and Figure 4.3 shows the corresponding wave-generated currents which are induced by the wave breaking. Figure 4.4 shows the associated sand transport rates for each wave condition and Figure 4.5 summarises the weighted overall sediment transport rate after combining the individual results according to their frequencies of occurrence and scaling up to yield average annual transport values.

4.4.1 Discussion

The average annual net sand drift in the study area is predominantly southerly, and whilst this pattern accords with the spit formation which extends from the north side of the estuary entrance and is also consistent with the southerly deviation in river mouths nearby to the north (see earth.google.com at location 14° 19'16"N, 80° 9'21"E), these results do contrast with other findings and further discussion on this finding is appropriate.

Other sources of information suggest that the net drift in this region is northerly, and this is also the generally accepted pattern of distribution over much of the east coast of India. The earlier study carried out by Frederick Harris (Reference 5) concluded that the net drift is northerly and the earlier HR Wallingford study using a simpler profile model also showed net northerly transport (although this net transport was small compared to the high gross transport rates to both south and north). Further analysis of these earlier studies, however, indicated that in the Frederick Harris study, an additional "swell" condition was included with a very high weighting factor, whereas the other representative wave conditions applied were relatively similar to those applied in the present study. Since the wave climate used in the present (and the Frederick Harris) study includes the swell wave activity it is not appropriate to apply an additional wave condition to represent this process: the effects of swell activity should be incorporated into the filtering mechanism used to determine the representative wave conditions. This is the case for the HR Wallingford method used in the present study, and it is concluded that this additional "swell" condition was applied to artificially create net northerly drift.

That the present HR Wallingford findings contrast with the earlier HR Wallingford study, despite using comparable wave data sets is attributed to the fact that the profile model used in the earlier study assumes complete longshore uniformity in all fields whereas it is clear from the information provided in Figures 4.2 to 4.4 that the hydraulic fields around the estuary entrance and over the delta area are not longshore uniform. Further, the curvature of the coastline to the north of the Port tends to induce southerly transport even for waves from due east. This information highlights the benefit of applying the two-dimensional area model at this site.

Hence it is concluded that the average annual net longshore sand transport field determined by the PISCES model is credible and consistent with the local geomorphology.

4.5 SIMULATION OF CONSTRUCTION PHASE

Simulations were carried out to consider the sand transport patterns and potential channel infill during the construction phase when the breakwaters would be partially constructed (and approach channel dredged to 6m). The specific dimensions of the breakwaters for this scenario were provided by Howe India Ltd.

Figure 4.6 shows the model bathymetry in the vicinity of the Port area. Figures 4.7, 4.8 and 4.9 show the fields of wave height and direction, wave-generated currents, and sand transport patterns respectively. Figure 4.10 shows the pattern of integrated sand transport scaled up to give annual transport rates.

Under these conditions, sand bypassing of both the south and north breakwaters occurs so that there is limited protection of the approach channel to infill.

It should be noted that for this scenario, and the following scenarios including the port breakwaters, that high transport rates are predicted on the sides of the breakwaters (which are resolved in the model mesh) since the model assumes that sand is able to be transported along these rock structures. In practise, the transport rates on these structures will be lower since the availability of sand in these areas is low so that the model predictions immediately adjacent to the breakwaters should be interpreted with care.

The integrated volume of channel infill under this scenario amounted to $336{,}000m^3$/year.

4.6 SIMULATION OF PHASE I LAYOUT

4.6.1 *Assessment of sand trap configuration 1*

Simulations of the Phase I layout were initially carried out with the sand trap configuration as suggested in the drawings provided by Howe India Ltd, as shown in Figure 4.11, with a volume of order $600{,}000m^3$. The approach channel is dredged to -14.4mCD.

Figures 4.12, 4.13 and 4.14 show the fields of wave height and direction, wave-generated currents, and sand transport patterns respectively. Figure 4.15 shows the pattern of integrated sand transport scaled up to give annual transport rates.

These simulations highlight interesting features in the hydraulic fields. In particular, the refraction of the waves by the nearshore bathymetry, and the varying angle of incidence of wave attack on the breakwaters give rise to complex wave-generated currents and corresponding sand transport patterns.

Figure 4.15 shows the weighted potential sand flux and these results indicate the following important findings:

- due to the southerly dominance in the littoral drift there is a greater tendency for sand bypassing around the shorter northern breakwater than around the southern breakwater;
- Sand transport into the sand trap is minimal because it is in relatively deep water (outside the breaker zone and too far from the breakwater to catch the drift induced by wave breaking on the breakwater;
- Sedimentation occurs in the approach channel;
- In addition to the material falling into the channel, in Phase I sand will pass around the breakwater heads and settling adjacent to the channel, with the potential of being subsequently swept in.

The integrated volume of channel infill under this scenario amounted to 62,000m^3/year. Material bypassing the breakwater heads and thereby acting as a source for further, subsequent potential infill is 73,000m^3/year. Infill in the sand trap is calculated to be 25,300m^3/year.

Simulations following bed evolution
The cases with an evolved seabed represent a future scenario whereby the coastline and nearshore has evolved and built up against the breakwaters. This evolution and prediction of the future bathymetry was based on the results for static bed and also drawing on experience of coastal change in the lee of structures at other sites around the world. The aim of this approach using an evolved seabed was to provide a more thorough assessment of the effectiveness of the sand traps taking into consideration that following construction there will be a period of adjustment which may have a bearing on the optimum configuration of the sand trap.

Figure 4.16 shows the model bathymetry used for the evolved bed cases for Phase I with sand trap configuration 1. Simulations were performed for two of the phase representative waves, from 30°N and 150°N as waves approaching the coastline under these angles are likely to produce the highest drift rates, and the hydraulic fields generated (wave heights, wave-generated currents and sand transport patterns are presented in Figures 4.17, 4.18 and 4.19).

With the evolved bathymetry the integrated volume of channel infill under this scenario amounted was estimated by calculating the infill for the two wave conditions simulated and rescaling the infill induced by the other three wave conditions for the cases without the bed evolution. On this basis the annual channel infill amounted to 49,000m^3/year and the infill in the sand trap was calculated to be 13,900m^3/year. Material bypassing the breakwater heads and thereby acting as a source for further potential infill is 56,700m^3/year.

Hence, despite evolving the seabed contours adjacent to the breakwater which could thereby allow greater bypassing of the port breakwaters, greater channel infill does not occur. This is considered to be due to the fact that the re-orientated coastline is more in equilibrium with the predominant wave conditions so that the littoral drift is reduced.

4.6.2 *Assessment of sand trap configuration 2*

On the basis that the simulations with the sand trap configuration 1 showed little effectiveness of the sand trap at this location, and also considering the net southerly drift at this location and the shorter northern breakwater, it was considered that a sand trap adjacent to the north breakwater could be effective. Simulations were carried out with sand trap with dimensions 120m by 70m and 7m deep (capital volume including side slopes of order 79,000m^3) and with the evolved seabed as shown in Figure 4.20.

Wave heights, wave-generated currents and sand transport patterns for the waves from 30°N and 150°N are shown in Figures 4.21 to 4.23. With this sand trap configuration the integrated volume of channel infill under this scenario amounted to 75,000m^3/year. Material bypassing the breakwater heads and thereby acting as a source for further potential infill is 44,000m^3/year. Infill in the sand trap was calculated to be 25,900m^3/year.

These tests indicate that placing the sand trap at this location, and with this configuration increases the channel infill to a quantity which is comparable to that predicted for the initial seabed. Comparison of Figures 4.23 and 4.19 suggest that as well as trapping sediment, the sand traps also focus the wave activity and this can also have the detrimental effect of enhancing the sand transport around the (north) breakwater.

4.6.3 Assessment of sand trap configuration 3

In order to make sand trap 2 more effective, its shape was modified making it longer (160m) and narrower (50m), as shown in Figure 4.24. The capital volume including side slopes is of order 75,000m^3.

Wave heights, wave-generated currents and sand transport patterns for the waves from 30°N and 150°N are shown in Figures 4.25 to 4.27. With this sand trap configuration the integrated volume of channel infill under this scenario amounted to 46,000m^3/year. Material bypassing the breakwater heads and thereby acting as a source for further potential infill is 28,000m^3/year. Infill in the sand trap was calculated to be 17,500m^3/year.

These tests indicate that relative to the predictions with sand trap 2, the channel infill is reduced but that this is not due to increased trapping by sand trap 3. It is considered that the more significant effect of the sand trap is in modifying the propagation of the waves as the pass over the trap toward the breakwater, and altering the breakwater bypassing.

4.6.4 Assessment of Phase I under storm wave conditions

Further Phase I simulations were carried out to assess the degree of channel (and sand trap) infill during storm wave conditions. Accordingly to the scope of work tests were required to be carried out for "up to 6m" wave heights and yet the wave climate suggested maximum recorded wave heights in the band 4 to 4.5m. On this basis offshore wave conditions of 4.25m and 10.5s from direction 90°N were selected.

Tests were carried out on the existing bathymetry with sand trap configurations 2 and 3 (even though the scope of work was limited to one sand trap configuration).

Figure 4.28 shows the model bathymetry with sand trap 2 and Figures 4.29 and 4.30 show the wave heights, wave-generated currents, sand transport patterns and seabed changes over a three hour period. This period of three hours was considered appropriate on the basis that the offshore wave climate is determined according to three hourly sampling and registered only one single event of this magnitude storm condition. These tests show that under storm conditions the width of the sand transporting zone is large and there is considerable transport bypassing the port breakwaters. Infill in the channel is 12,600m^3 and in the sand trap is 3,800m^3 in the three hour period.

Figure 4.31 shows the model bathymetry with sand trap 3 and Figures 4.32 and 4.33 show the wave heights, wave-generated currents, sand transport patterns and seabed changes over a three hour period. Infill in the channel is 20,700m^3 and in the sand trap is 2,800m^3 in the three hour period.

4.6.5 *Consideration of the sequence of construction*

The construction phase tests indicate that infill of the channel will be significant in this phase. Accordingly, if the construction programme and all necessary construction procedures allow, it would be prudent to construct the relevant breakwater prior to the coming season – i.e. construct the southern breakwater prior to the SW monsoon, and the northern breakwater prior to the NE monsoon.

4.7 SIMULATION OF PHASE II LAYOUT

The performance of the sand trap and the degree of channel infill was assessed for the Phase II Port layout. These tests were carried out using the existing bathymetry with Phase II layout structures as specified by Howe India imposed. Tests were carried out with the sand trap 2 and sand trap 3 configuration (even though the scope of work was limited to one sand trap configuration).

4.7.1 *Assessment of sand trap configuration 2*

Figure 4.34 shows the model bathymetry at the port entrance, with sand trap 2. The approach channel is dredged to -20.7mCD.

Figures 4.35, 4.36 and 4.37 show the fields of wave height and direction, wave-generated currents, and sand transport patterns respectively. Figure 4.38 shows the pattern of integrated sand transport scaled up to give annual transport rates.

The integrated volume of channel infill under this scenario amounted to 286,000m^3/year. Infill in the sand trap is calculated to be 142,300m^3/year which is greater than the capital volume by a factor of order two, implying that it will infill relatively quickly. The greater volume of channel infill is mainly due to the fact that the channel is deeper and therefore wider (at the top) than in Phase I, and is thereby subject to greater infill. The channel also has a marked effect on the wave propagation, which also alters the pattern of transport around the breakwaters, leading to higher rates of infill of the sand trap.

4.7.2 *Assessment of sand trap configuration 3*

Figure 4.39 shows the model bathymetry at the port entrance, with sand trap 3.

Figures 4.40, 4.41 and 4.42 show the fields of wave height and direction, wave-generated currents, and sand transport patterns respectively. Figure 4.43 shows the pattern of integrated sand transport scaled up to give annual transport rates.

The integrated volume of channel infill under this scenario amounted to 241,000m^3/year. Infill in the sand trap is calculated to be 136,800m^3/year which is greater than the capital volume by a factor of order two, implying that it will infill relatively quickly. The greater volume of channel infill is mainly due to the fact that the channel is deeper and therefore wider than in Phase I, and is thereby subject to greater infill. The channel also has a marked effect on the wave propagation, which also alters the pattern of transport around the breakwaters, leading to higher rates of infill of the sand trap.

4.8 CHANNEL SEDIMENTATION AND SAND TRAP CONCLUSIONS

The table below summarises the channel sedimentation due to wave effects as assessed in this study.

Annual infill			
Phase	Sand trap	Seabed configuration	Channel infill (m^3/year)
Construction	-		336,000
Phase I	1 (south b/w)	Initial	62,000*
	1	Future	49,000*
	2 (north b/w)	Future	75,000*
	3 (north b/w)	Future	46,000*
Phase II	2	Initial	286,000
	3	Initial	241,000
Storm infill			
Phase	Sand trap	Seabed configuration	Channel infill (m^3/3hr storm)
Phase I	2	Initial	12,600
	3	Initial	20,700

* Note as highlighted in Section 4.6 that in addition to the material falling into the channel, in Phase I sand will pass around the breakwater heads and settling adjacent to the channel, with the potential of being subsequently swept in. These additional volumes are typically 50 to 100% of the channel infill.

These results indicate that the location and configuration of the sand trap does have an effect on the magnitude of the channel infill. What is also evident from the model output figures, however, is that the principal effect of the sand trap is not in intercepting the main stream of sediment around the breakwaters as it was intended, but rather to modify the local wave propagation and resulting currents and sediment transport pathways. The sediment transport pathways around the breakwaters are complex, and the relatively small wave conditions and depths of water involved give rise to a stream of sediment which passes very close to the breakwaters: closer than a sand trap should be sited (since it could compromise the integrity of the breakwater structures). Recent physical model studies at HR Wallingford for another project on the east coast of India indicated that the proposed sand trap had a significant detrimental impact on the breakwater stability, because the pit caused the waves to shoal and break directly onto the breakwater structure.

All tests were performed with sand traps. Based on the findings stated above it is recommended that the degree of channel infill for the case without sand traps is estimated from the average of the values obtained. For Phase I this amounts to 57,000m^3/year (plus additional potential infill as highlighted in the footnote to the table above), and for Phase II this amounts to 264,000m^3/year.

On the basis of the information obtained it is concluded that the performance of the sand trap is inconclusive, and in order to make it more effect by placing it closer to the breakwaters may be detrimental to their integrity. The breakwaters extend far offshore, outside the breaker zone for most wave conditions, and thereby have a significant effect in reducing the channel infill (for example, compare the infill for the construction phase with any of the Phase I predictions). Furthermore, the simulations with an evolved seabed also indicate that rather than there being significantly higher infill after the seabed has built up on either side of the structures, because the breakwaters are so long, the re-orientation of the coastline limits the amount of potential bypassing. Hence there is little evidence (within the limits of accuracy of the predictions) to indicate that after a period of evolution, that the channel infill will increase significantly.

The storm wave infill studies also indicate that under these conditions, whilst the sand traps accumulate sediment, the volume of infill in the trap is small compared to the channel infill, suggesting that a sand trap would only be marginally effective under storm conditions.

The conclusion arising from this study, therefore, is that there is little apparent benefit in construction of a sand trap to limit channel sedimentation at this site. Furthermore, there is evidence to suggest that as the coastline adjusts to the port structures the risk of a substantial increase in channel sedimentation is small. On this basis it is recommended that there is no sand trap constructed at this site, but that seabed monitoring is undertaken following construction of the breakwaters so that further information can be gathered to aid in the interpretation of the morphological changes. For example, in the event that there is sufficient build up of sand adjacent to the breakwaters which would enable a sand trap to be constructed in the main sediment transport stream which was effective and yet not detrimental to the breakwater stability.

The distribution of sand infill is as follows:

- In the outer channel the infill will be confined to the entrance to the port, in the vicinity of the breakwater tips. The simulations show that this infill is due to bypassing of the breakwaters, so that any accumulation will be relatively localised and in the vicinity of the breakwater tips.
- In the inner channel the simulations show that the infill is restricted to the zone between the port entrance (ie the breakwater tips) and the turning circle.

The storm wave simulations highlight the tendency for potentially rapid loss of depth where infill of up to 0.35m in a period of three hours could occur. For a storm of long duration (e.g. 12 hours) it is possible, therefore that within a relatively narrow zone at entrance to the port (see Figure 4.33) there could be loss of depth of over 1m.

Infill will occur in areas further inside the port due to tidal processes as described in Section 2.2.

4.9 COASTAL PROTECTION MEASURES

In this section the various possible options for shore protection are summarised, drawing on the results of the littoral drift assessment described in Section 4.6, the effects of the proposed Port structures on this drift, and based on past experience of experts at HR Wallingford.

Options for coastal protection against erosion at this (and any other) site are as follows:

- Do nothing;
- Removal of the cause of the erosion;

- Nourishment of the area with sediment;
- Reduce the sediment transport rate;
- Increase the strength of the coast (by hard measures).

Of the above options, only the second (removal of the cause of the erosion) is not possible at this location. However, regardless of the postulated likely impact arising as a consequence of the littoral drift predictions and degree of interception of any scheme, it would be prudent to design an appropriate coast protection scheme only after sufficient site-specific information has been obtained such that appropriate and timely design can be applied.

At this location, prior to the present study it was envisaged that the site is characterised by net northward drift, because the earlier study using a simplified model suggested this and also because in general terms the drift on the eastern coast of India is considered to be net northward. The results of this study, however, have concluded that the net drift (based on the long-term wave climate used) is southerly, and it has also been shown that there is evidence from satellite imagery (see for example earth.google.com) of net southerly drift nearby (e.g. see for example the river mouth entrance which is deviated southwards at 14° 19'16"N, 80° 9'21"E) as well as at the river entrance at Krishnapatnam itself, which also shows a spit feature extending from the northern shore.

Hence it is concluded that whilst the gross drift is likely to be quite high in both directions (southerly and northerly) the net drift is small compared to the gross drift, and a small reduction in the gross southerly drift could give rise to net northerly at this location.

In any event, with relatively strong drift to the north and south it is anticipated that the coastline and nearshore tendency following construction will be to accrete and build out in the immediate vicinity of both of the breakwaters, with erosion possible further to the north of the northerly breakwater and further to the south of the southerly breakwater. The coastal evolution may exhibit a strong seasonal signal, with erosion of the coast on one side of the port during one season followed by a period of recovery in the following season.

Considering the options for coastal protection above, these fall into two broad categories:

1. Soft measures (nourishment and bypassing);
2. Hard measures (structures).

Soft measures include nourishment of the areas of erosion directly using sediment from elsewhere. Given the amount of material to be excavated during the capital dredging programme, if this is not all to be used to raise the level of the land at the Port, it would be prudent to consider utilising some of this material either prior to construction, or following construction (necessarily storing it temporarily nearby). Bypassing could be undertaken whereby sediment is passed around the Port breakwaters, in effect making the structures open to the littoral drift. However, given the relatively balanced littoral drift at this location (i.e. strong gross drift to north and south, and small net drift) this option is not considered to be appropriate.

Hard measures include seawalls, training walls, groynes, offshore breakwaters. Satellite imagery shows rock groynes to the north of the port of Chennai, which is a well documented case of strong northerly drift (so that these groynes were likely to have been placed to offset coastal erosion). It is also noted that there are no groynes apparent to the north of the port at Ennore. Of these options, seawalls are more typically constructed to protect the rear of the beach against storm wave action which gives rise to strong cross-shore sediment transport. They are also relatively expensive, and accordingly this option is not considered to be the most effective at Krishnapatnam. Similarly, training walls are also expensive and not appropriate at this location. Therefore, the two remaining options for coastal protection would be groynes (rock or timber) or offshore breakwaters (usually rock). Groynes would run perpendicular to the coastline (as at Chennai), or offshore breakwaters would be placed parallel to the shoreline. The construction methods would be more likely to influence the ultimate choice of method, since groynes could be placed from the landside whereas the offshore breakwaters would normally be placed by barge.

Given the natural variability in the longshore drift, the likely seasonal variation in the erosion and the possibility that some of the capital dredged material could also be used to nourish the beaches to either side of the Port it is recommended that a programme of coastal monitoring is put in place following construction of the port structures, in order that appropriate coverage of shore protection is instated as required. Ultimately, if groynes or offshore breakwaters are constructed, these should extend to beyond the breaker zone (so that the longshore drift is substantially reduced) and spacing should typically be order 200-500m over the areas concerned.

5. Conclusions and recommendations

Conclusions and recommendations arising from this study are as follows:

5.1 TIDALLY INDUCED SEDIMENTATION

Infill of the channel and port areas was assessed by simulating spring and neap tidal conditions, and calculating the transport of both sand and mud. There is abundant source of sand in the outer estuary and coast, and despite the dam upstream in the river, fine material is also abundant in the water column, hence both sand infill and siltation should be anticipated.

The mud infill prediction yields totals of 115,000m^3/year in Phase I and 540,000m^3/year in Phase II, and this infill is relatively evenly distributed over the deepened areas. Applying the same scaling to the sand infill yields 7,700m^3/year in Phase I and 3,500m^3/year in Phase II. Given the nature of the sand infill (which occurs adjacent to the deep cuts at the western end of the dredged zone and to the north of the turning circle) it is considered that this infill is an over-estimate of the longer-term rate. This is because there will be adjustment to the seabed in the areas where the sand transport is greatest, and this will reduce the sand infill over time. Note that this is not expected to be the case for infill due to silts and muds which will continue to infill the channel. In addition, as highlighted in Section 2.2.2, it is recommended that the dredged zone be extended approximately 200m upstream (west) beyond the berths (with width the same as the dredged berth, and to the same depth) as this will also reduce the amount of maintenance dredging in the berth areas.

In terms of the distribution of the sand infill, Figure 2.13 highlights that the sand infill is likely to occur at the berths in Phase I, as well as there being a risk of some sedimentation on the northern side of the turning circle. In Phase II Figure 2.17 indicates that the areas prone to sand infill are in the SW areas of the port. Under tidal processes alone, 100% of the quoted volume of infill is predicted to occur in these areas (northern side of turning circle and in the inner berths): tidal currents alone are insufficient to mobilise sand and cause infill in the outer channel.

In respect of the distribution of mud infill Figures 2.20 and 2.21 indicate that in Phase I the distribution of muddier infill will tend to accumulate over the entire deepened area relatively evenly (especially when it is considered that ship motion will tend to redistribute some of the infill). In Phase II it is concluded from Figures 2.22 and 2.23 that the mud infill will be concentrated in the inner berths to the west of the port, with approximately 80% of the annual volume quoted above occurring in these areas: the remainder (20%) settling out relatively evenly in the inner channel area and turning circle.

5.2 WAVE TRANQUILITY

Wave tranquility was assessed under various input wave conditions including relatively frequent events and extreme events. Results, in the form of wave heights, were tabulated a specific locations near the berths and in the channel. It is clear from the results that the dredged channel causes the wave energy to diverge into the shallow areas to the north and south of the channel.

Downtime at the berths will clearly depend on the types of vessels and operations being considered. These results clearly show that the wave energy reaching the berths from offshore is very low. The wind blowing within the harbour will create surface chop which may be higher than these wave heights but, being of very short period will not significantly affect the vessels.

Under 100 year cyclone conditions the worst waves at the entrance are predicted to be 2.1m Hs in Phase I but even these waves do no not give significant wave disturbance at the berths however downtime would probably be caused due to the direct effect of the wind alone.

In Phase II there are many more vertical quays so, whereas in Phase I the waves were predicted to diverge from the deep channel and be dissipated on the undeveloped areas of the harbour, in Phase II much of this wave energy is reflected back into the harbour so wave heights are generally higher.

It is clear that the quay wall at Position 4, directly in line with the entrance is generally the most exposed. For waves from northeast and east there will be refraction of wave energy into the basin near Position 11 with significant wave heights of up to 0.6m. Waves shoal up onto the shallow area inside the south breakwater behind the Crude and P.O.L Chemical Cargo berths. Under cyclone conditions, these berths (Positions 9 and 10) are expected to experience swell waves of 1.0m Hs.

Applying permissible wave height thresholds provided by Howe India Pvt Ltd, the downtime due to waves at each of the berths in Phase I and Phase II is likely to be less than one day a year except at Berth 4 in Phase II where it is estimated that waves could cause downtime for between 10% and 15% of the time (with a 0.8m threshold). Allowing for typical storm durations it is estimated that this would affect about 100 days a year, hence the operable days would be less than 320 in a year at Berth 4. Using the same methodology a 1.0m threshold at Berth 4 (instead of 0.8m) gives downtime for 2% - 6% of the time, which by the same argument affects about 30-40 separate days a year, however the resolution with only a few wave conditions is rather coarse to be precise.

Waves at Berth 4 are relatively high since the waves pass though the harbour entrance along the channel and then diverge due to refraction towards the sides of the channel. This affects both Berth 4 and the area between Berths 13 and 14.

The effect of wave concentration at Berth 4 occurs with waves from 135°N as well as from 90°N due to the fact that, by the time they reach the harbour entrance the waves have refracted so that they enter directly into the port area. Given this direction of approach of the waves which give rise to the high wave energy at Berth 4, it is concluded that a spur structure on the north or south breakwater is unlikely to be very effective in reducing wave energy at Berth 4.

5.3 WAVE-GENERATED INFILL, SAND TRAP ASSESSMENT AND COASTAL PROTECTION

Sediment transport due to waves and wave-generated currents was assessed for the Phase I construction phase and for Phase I and Phase II with various sand trap arrangements. Tests were performed to predict the average annual sedimentation in the port and channel and in the sand traps, and also to assess the infill during storms.

Simulations of the littoral drift under existing conditions yielded net southerly drift which is in contrast to earlier findings and previous studies. On further analysis, however, it is concluded that this southerly net drift is consistent with local geomorphology. The net transport rate is small compared to the gross transport in each direction.

Channel sedimentation was assessed for all scenarios tested. During the construction phase, and post-construction under storm wave conditions sediment bypassing of the structures takes place and there is consequent channel infill. Otherwise, in typical conditions the port breakwaters extend beyond the breaker zone so that the amount of sand bypassing is small and limited to the immediate vicinity of the breakwaters. As a consequence of this finding, it was concluded that there is little direct benefit in constructing a sand trap on either the north or the south breakwater. In order to effectively trap the main stream of sediment, such a trap would be required to placed very close to the breakwater(s) which could compromise their integrity. In the tests simulated, the sand traps accumulate sediment, but not necessarily to the benefit of the channel, which continues to infill.

In order to fully assess the potential benefits of the sand traps, and recognising that the coastline is likely to evolve following construction, further tests were carried out with an evolved seabed, in order to see if bypassing of the structures would increase in the future. Tests suggested that this was not the case, and this is largely due to the length of the breakwaters: the coastline evolution will continue until the beach re-orientates itself into a position of zero net drift, and since the breakwaters extend such a long way offshore, the realignment of the beach/nearshore is such that sediment the transport pathways are not increased. Accordingly, there is no significant evidence to suggest that the sand traps would be more effective in the future when the seabed has evolved.

Infill in the channel and the sand traps tested was assessed, to yield estimates of the annual volume of infill, and infill during storm conditions.

All tests were performed with sand traps. Based on the findings stated above it is recommended that the degree of channel infill for the case without sand traps is estimated from the average of the values obtained. For Phase I this amounts to 57,000m^3/year (plus additional potential infill as highlighted in the footnote to the table in Section 4.8), and for Phase II this amounts to 264,000m^3/year.

Accuracy considerations have been thoroughly discussed. As highlighted in the original proposal for this study, there is uncertainty in all sediment transport predictions due to natural variability in the various inputs, and also due to the algorithms applied. Based on the best available advice, uncertainty in the predicted volumes of channel and sand trap infill is considered to be a factor 2 to 5.

Options for coastal protection have been discussed. Whereas the coastline is expected to build up immediately adjacent to the port breakwaters, there may be erosion to the north and south as a consequence of the blockage to the littoral drift. Given the relatively high gross northerly and southerly sediment transport and small net transport, and seasonal nature in the longshore drift, it is considered that the site may be characterised by erosion on one side of the port during part of the year, followed by recovery in the second part of the year. Hence rather than large scale erosion on one side of the port and accretion on the other side, as would occur at a site with high net transport to either north or south, the potential erosion of the coast and nearshore may recover each year without intervention. In any event, it is recommended that following construction, regular monitoring of the coastline to either side of the port is carried out in order that intervention could take place if required. Options for coastal defence have been reviewed, and these could be soft measures or hard measures. Soft measures could include re-nourishing simply moving material along the coast to the areas of erosion. The most appropriate estimate of the volumes of material which may be required as re-nourishment of the coast would be that predicted to infill the channel as highlighted in the table in Section 4.8. This is on the basis that under existing conditions sediment passes across the bar system at the entrance to the estuary (possibly being stored on the bar for periods of time) and naturally feeds the coast downdrift. Trapping this volume sediment in the approach channel could lead to a comparable reduction in supply to the downdrift coast.

The studies have shown in during the construction phase, order 330,000m^3/year is predicted to infill the channel, although Figures 4.9 and 4.10 indicate that this infill is due to re-working of the delta system rather than a measure of the sediment bypassing the existing river entrance. The tests for Phase II provide channel infill estimates of order 240,000-280,000m^3/year which arises out of sediment bypassing the breakwaters. Smaller volumes infill the channel in Phase I but the amount of sediment bypassing the breakwaters will be comparable to these figures (240,000-280,000m^3/year) (with the remaining amount settling outside the channel) as described in the footnote to the table in Section 4.8. Hence whilst there will be build up of the coastline immediately adjacent to each breakwater, this volume of 240,000-280,000m^3/year will be trapped in the channel which would otherwise have passed onto the delta and nourished the beaches to either side. On this basis this is the estimated volume of material which may need to be considered in a nourishment programme.

Of the hard measures available, these would most appropriately be either groynes or shore-detached breakwaters. The post-construction monitoring would provide the most useful information to aid in the location and design (length, spacing) of such structures.

5.4 OVERALL FINDINGS AND CHANNEL AND PORT INFILL SUMMARY

Results of the studies described herein are summarised briefly as follows:

a) Tidally-induced sedimentation is limited to the inner channel and port berth areas. Sand infill will tend to occur in the western (upstream) areas close to the limit of extent of dredging, and extending the dredging a relatively small distance (order 200m with width the same as the dredged berth, and to the same depth) will promote sedimentation in these areas rather than at the berths. Mud infill will, however, tend to occur over much of the inner channel and port areas. Vessel movements will tend to re-distribute the finer bed deposits, potentially spreading the infill into other port areas.

b) Wave tranquility in the port areas is relatively low, with only Berth 4 in Phase II being highlighted as having a high number of inoperable days per year. The model results indicate that wave propagation to this berth is related to waves in the main channel being refracted onto this area: consequently, it is considered that a spur-type structure on either the north or south breakwater is unlikely to be effective in reducing wave energy at Berth 4. On this basis improved conditions could be obtained at this berth by obtained by constructing an open pile platform with absorption beach below, which would reduce reflections although it should be noted that the direct wave action will remain.

c) Sand traps are unlikely to be effective in reducing the channel infill. Tests indicate that the sand transport around the breakwaters is confined to the vicinity of the breakwaters, so that in order to be effective, a sand trap would have to be constructed so close to the breakwater that it may compromise its structural integrity.

d) At this location, net southerly drift was predicted, and this is consistent with the local geomorphology (i.e. the nature of the sand spit on the northern side of the estuary entrance). On this basis there would be a benefit in extending the northern breakwater into deeper water. Any extension over that simulated would have the effect of reducing sediment bypassing and associated infill of the channel.

e) The port sediment infill is summarised broadly from the conclusions stated in Section 2.2.4 and Section 4.8 as follows:

Infill (m^3/year)	**Phase I**		**Phase II**	
	Inner channel and berths	Outer channel	Inner channel and berths	Outer channel
Sand	7,700	45,000-75,000	3,500	240,000-280,000
Mud	115,000	-	540,000	-
Total	**122,700**	**45,000-75,000**	**543,500**	**240,000-280,000**

Infill in the outer channel is determined primarily by the wave action and associated littoral drift around the breakwaters, so that sedimentation takes place at the entrance to the port over a relatively narrow zone (order 1000m) between the breakwater tips and the turning basin.

Sand infill due to tidal action in the inner channel and berth areas could be substantially reduced by extending the dredging area upstream (westwards) to create an effective sand trap.

During the construction phase, bypassing of the breakwaters is significant and there is likely to be high channel sedimentation. Predictions suggest order 336,000m^3 per year.

For Phase I it was noted that sand may pass around the breakwater ends but not be immediately deposited in the channel. In this case the sand may settle close to the channel, creating a ready source for subsequently infill. The volumes associated with this source represent order 50 to 100% of the quoted channel infill.

Storm infill will also give rise to sand bypassing the breakwaters and consequent infill of the channel. Predictions indicate that over a three-hour storm there could be (sand) infill of order 10,000-20,000m^3.

The above figures represent a best estimate at channel sedimentation which is based on the most up-to-date methods and accurate numerical modelling techniques. As stated in Section 4.3, however, it is important to bear in mind that sediment transport is not an exact science and there remains uncertainty in the prediction of sediment transport and associated estimates of sedimentation. There is a wealth of information from research worldwide, some of which has been cited in this document, which confirm and highlight this uncertainty in predictions of sediment transport in the marine environment. Effective measures which could be implemented to improve future predictions of sedimentation would include the detailed collection of data relating to infill (bathymetric surveys, dredging records and measurements of seabed and suspended sediment data), so that this information could be applied to develop a calibrated sediment transport model for this site. This would then provide a means of providing more accurate estimates of future sedimentation as the port further develops and expands its facilities.

f) Shore behaviour and the need for coastal protection should follow construction of the port breakwaters so that an appropriate methodology can be implemented as necessary. It should be noted that the relatively balanced sediment drift to both north and south should give a lower coastal impact than that if the drift was dominated either to north or south, because there is likely to be a period of recovery following each of the main NE/SW monsoon periods. Hence the approach of monitor and future action is appropriate. The most appropriate estimate of the volumes of material which may be required as re-nourishment of the coast would be that predicted to infill the channel as highlighted in the table in Section 4.8. This is on the basis that under existing conditions sediment passes across the bar system at the entrance to the estuary (possibly being stored on the bar for periods of time) and naturally feeds the coast downdrift. Trapping this volume sediment in the approach channel could lead to a comparable reduction in supply to the downdrift coast. The tests for Phase II provide channel infill estimates of order 240,000-280,000m^3/year which arises out of sediment bypassing the breakwaters. Smaller volumes infill the channel in Phase I but the amount of sediment bypassing the breakwaters will be comparable to these figures (240,000-280,000m^3/year) (with the remaining amount settling outside the channel) as described in the footnote to the table in Section 4.8. Hence whilst there will be build up of the coastline immediately adjacent to each breakwater, this volume of 240,000-280,000m^3/year will be trapped in the channel which would otherwise have passed onto the delta and nourished the beaches to either side. On this basis this is the estimated volume of material which may need to be considered in a nourishment programme.

6. References

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Tables

Table 3.1a Offshore wave climate from UK Met Office model – Hs vs Direction

FREQUENCIES FOR WAVE MODEL DATA AT 14.6N 80.6E, 14.7N 80.4E PERIOD OF DATA: 11/1994 TO 10/2006

MONTHS: JANUARY TO DECEMBER

DIRECTION OF HIGHER OF SEA OR SWELL HEIGHT (DEGREES TRUE)

LOWER LIMIT / UPPER LIMIT / RESULTANT WAVE HEIGHT (METRES)	IND.	346–015	016–045	046–075	076–105	106–135	136–165	166–195	196–225	226–255	256–285	286–315	316–345	TOTAL
0.0 TO 0.5	..	1	10	22	96	94	534	101	8	10	22	16	10	924
0.6 TO 1.0	..	18	87	853	1695	1222	5256	701	143	300	665	379	55	11374
1.1 TO 1.5	..	2	44	576	533	299	1548	254	68	142	378	239	7	4090
1.6 TO 2.0	..	3	13	159	68	4	23	9	3	9	28	22	..	361
2.1 TO 2.5	..	..	3	23	10	2	..	..	..	..	..	..	..	38
2.6 TO 3.0	..	..	..	5	4	1	..	..	..	..	..	..	..	10
3.1 TO 3.5	..	..	..	..	3	..	..	..	..	..	..	..	..	3
3.6 TO 4.0	..	..	..	1	1	..	..	..	..	..	..	..	..	2
4.1 TO 4.5	..	..	..	..	1	..	..	..	..	..	..	..	..	1
4.6 TO 5.0	..	..	..	..	..	..	..	..	..	..	..	..	..	..
5.1 TO 5.5	..	..	..	..	..	..	..	..	..	..	..	..	..	..
5.6 TO 6.0	..	..	..	..	..	..	..	..	..	..	..	..	..	..
6.1 TO 6.5	..	..	..	..	..	..	..	..	..	..	..	..	..	..
6.6 TO 7.0	..	..	..	..	..	..	..	..	..	..	..	..	..	..
7.1 TO 7.5	..	..	..	..	..	..	..	..	..	..	..	..	..	..
7.6 TO 8.0	..	..	..	..	..	..	..	..	..	..	..	..	..	..
8.1 TO 8.5	..	..	..	..	..	..	..	..	..	..	..	..	..	..
8.6 TO 9.0	..	..	..	..	..	..	..	..	..	..	..	..	..	..
9.1 TO 9.5	..	..	..	..	..	..	..	..	..	..	..	..	..	..
9.6 TO 10.0	..	..	..	..	..	..	..	..	..	..	..	..	..	..
10.1 TO 10.5	..	..	..	..	..	..	..	..	..	..	..	..	..	..
10.6 TO 11.0	..	..	..	..	..	..	..	..	..	..	..	..	..	..
11.1 TO 11.5	..	..	..	..	..	..	..	..	..	..	..	..	..	..
11.6 TO 12.0	..	..	..	..	..	..	..	..	..	..	..	..	..	..
12.1 TO 12.5	..	..	..	..	..	..	..	..	..	..	..	..	..	..
12.6 OR MORE	..	..	..	..	..	..	..	..	..	..	..	..	..	..
TOTAL	..	24	157	1639	2131	1622	7361	1065	222	461	1093	656	72	16803

Table 3.1b Offshore wave climate from UK Met Office model (Hs v Tm)

FREQUENCIES FOR WAVE MODEL DATA AT 11.8N 80.8E, 14.7N 80.4E   PERIOD OF DATA: 11/1994 TO 10/2006

MONTHS: JANUARY TO DECEMBER

RESULTANT WAVE PERIOD (SECONDS)

LOWER LIMIT / UPPER LIMIT / RESULTANT WAVE HEIGHT (METRES)	0.0 / 1.0	1.1 / 2.0	2.1 / 3.0	3.1 / 4.0	4.1 / 5.0	5.1 / 6.0	6.1 / 7.0	7.1 / 8.0	8.1 / 9.0	9.1 / 10.0	10.1 / 11.0	11.1 / 12.0	12.1 / 13.0	13.1 / 14.0	14.1 / 15.0	15.1 / 16.0	16.1 / 17.0	17.1 / 18.0	18.1 /	TOTAL
0.0 TO 0.5	..	..	..	257	393	183	66	14	3	1	..	..	..	..	..	..	..	..	..	921
0.6 TO 1.0	..	..	..	1625	7983	1411	261	73	16	5	1	1	..	..	..	..	..	..	..	11370
1.1 TO 1.5	..	..	..	709	2913	932	152	11	8	..	..	1	..	..	..	..	..	..	..	4330
1.6 TO 2.0	..	..	..	..	92	235	25	6	3	..	..	..	..	..	..	..	..	..	..	363
2.1 TO 2.5	..	..	..	..	1	14	15	8	..	..	..	..	..	..	..	..	..	..	..	38
2.6 TO 3.0	..	..	..	..	..	1	9	..	..	..	..	..	..	..	..	..	..	..	..	10
3.1 TO 3.5	..	..	..	..	..	..	..	3	..	..	..	..	..	..	..	..	..	..	..	3
3.6 TO 4.0	..	..	..	..	..	..	..	2	..	..	..	..	..	..	..	..	..	..	..	2
4.1 TO 4.5	..	..	..	..	..	..	..	1	..	..	..	..	..	..	..	..	..	..	..	1
4.6 TO 5.0	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
5.1 TO 5.5	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
5.6 TO 6.0	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
6.1 TO 6.5	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
6.6 TO 7.0	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
7.1 TO 7.5	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
7.6 TO 8.0	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
8.1 TO 8.5	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
8.6 TO 9.0	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
9.1 TO 9.5	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
9.6 TO 10.0	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
10.1 TO 10.5	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
10.6 TO 11.0	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
11.1 TO 11.5	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
11.6 TO 12.0	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
12.1 OR MORE	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..	..
TOTAL	..	..	..	1891	11370	2766	526	113	41	9	7	4	..	..	..	..	..	..	..	16803

NOTE:- .. INDICATES ZERO FREQUENCY

Table 3.2 Wave conditions from the ARTEMIS model of Phase I at output locations (shown on Figure 3.12) at the berths and along the channel

Offshore waves	Nearshore wave conditions				
	Points	Hs (m)	Tm (sec.)	direction (⁰N)	Total water depth (m)
50-in-1-60⁰N	1	0.1	5.6	71	-14
	2	0.1	5.6	73	-14
	3	0.1	5.6	55	-14
	4	0.4	5.6	74	-15.2
	5	0.5	5.6	101	-15.2
	6	0.8	5.6	105	-15.2
50-in-1-90⁰N	1	0.1	5.6	69	-14
	2	0.1	5.6	79	-14
	3	0.1	5.6	83	-14
	4	0.3	5.6	110	-15.2
	5	0.5	5.6	95	-15.2
	6	0.8	5.6	91	-15.2
50-in-1-135⁰N	1	0.1	7.2	71	-14
	2	0.1	7.2	91	-14
	3	0.1	7.2	58	-14
	4	0.3	7.2	87	-15.2
	5	0.4	7.2	91	-15.2
	6	0.9	7.2	65	-15.2
1in1-60⁰N	1	0.1	7.9	73	-14
	2	0.1	7.9	88	-14
	3	0.1	7.9	45	-14
	4	0.3	7.9	92	-15.2
	5	0.6	7.9	96	-15.2
	6	1.0	7.9	101	-15.2
1in1-90⁰N	1	0.1	7.3	72	-14
	2	0.1	7.3	72	-14
	3	0.1	7.3	62	-14
	4	0.4	7.3	94	-15.2
	5	0.7	7.3	94	-15.2
	6	1.1	7.3	89	-15.2
1in1-135⁰N	1	0.1	7.2	71	-14
	2	0.1	7.2	90	-14
	3	0.1	7.2	60	-14
	4	0.4	7.2	90	-15.2
	5	0.5	7.2	91	-15.2
	6	1.0	7.2	67	-15.2
1in100-60⁰N	1	0.1	15.5	109	-14
	2	0.1	15.5	100	-14
	3	0.1	15.5	112	-14
	4	0.1	15.5	200	-15.2
	5	0.7	15.5	84	-15.2
	6	2.1	15.5	87	-15.2

Table 3.2 Wave conditions from the ARTEMIS model of Phase I at output locations (shown on Figure 3.12) at the berths and along the channel (continued)

Offshore waves	Nearshore wave conditions				
	Points	Hs (m)	Tm (sec.)	direction (^{0}N)	Total water depth (m)
1in100-90^{0}N	1	0.1	15.5	110	-14
	2	0.2	15.5	99	-14
	3	0.1	15.5	113	-14
	4	0.1	15.5	199	-15.2
	5	0.6	15.5	84	-15.2
	6	2.0	15.5	86	-15.2
1in100-135^{0}N	1	0.1	15.5	110	-14
	2	0.1	15.5	101	-14
	3	0.1	15.5	112	-14
	4	0.1	15.5	191	-15.2
	5	0.6	15.5	83	-15.2
	6	1.9	15.5	90	-15.2

Table 3.3 Wave conditions from the ARTEMIS model of Phase II at output locations (shown on Figure 3.22) at the berths and quays

Location as in Figure 3.22	Run								
	50:1 60° Tm=5.6 (s)	50:1 90° Tm=5.6 (s)	50:1 135° Tm=7.2 (s)	1:1 60° Tm=7.9 (s)	1:1 90° Tm=7.3 (s)	1:1 135° Tm=7.2 (s)	1:100 60° Tm=15.5 (s)	1:100 90° Tm=15.5 (s)	1:100 135° Tm=15.5 (s)
1	0.5	0.4	0.3	0.4	0.4	0.3	0.5	0.5	0.5
2	0.4	0.4	0.4	0.4	0.3	0.4	0.4	0.5	0.5
3	0.6	0.6	0.3	0.3	0.4	0.3	0.8	0.8	0.8
4	0.7	0.8	1.1	0.8	1.1	1.4	1.3	1.3	1.2
5	0.5	0.7	0.3	0.5	0.4	0.3	0.9	0.9	0.9
6	0.3	0.4	0.2	0.2	0.2	0.2	0.5	0.5	0.5
7	0.5	0.6	0.3	0.4	0.5	0.3	0.8	0.8	0.7
8	0.2	0.3	0.2	0.2	0.2	0.3	0.6	0.5	0.5
9	0.4	0.4	0.2	0.4	0.4	0.2	1.0	1.0	0.9
10	0.4	0.3	0.2	0.3	0.4	0.3	0.9	0.8	0.8
11	0.6	0.6	0.4	0.4	0.5	0.5	0.6	0.6	0.5
12	0.4	0.4	0.2	0.3	0.2	0.2	0.6	0.5	0.5
13	0.5	0.5	0.3	0.4	0.5	0.5	0.5	0.5	0.5
14	0.4	0.5	0.3	0.3	0.4	0.4	0.6	0.6	0.6
15	0.4	0.4	0.3	0.3	0.2	0.4	0.9	0.9	0.7
16	0.4	0.5	0.2	0.2	0.3	0.3	0.4	0.5	0.4
17	0.4	0.5	0.2	0.2	0.3	0.3	0.5	0.5	0.4
18	0.4	0.4	0.2	0.3	0.2	0.3	0.5	0.5	0.5
19	0.4	0.5	0.1	0.3	0.2	0.2	0.4	0.5	0.4
20	0.5	0.5	0.3	0.3	0.5	0.4	0.7	0.7	0.4
21	0.5	0.5	0.5	0.5	0.6	0.7	0.8	0.8	0.8
22	0.7	0.8	0.6	0.7	0.8	0.8	1.4	1.5	1.5
23	0.8	0.9	1.0	0.8	1.1	1.1	2.0	2.2	2.3

Figures

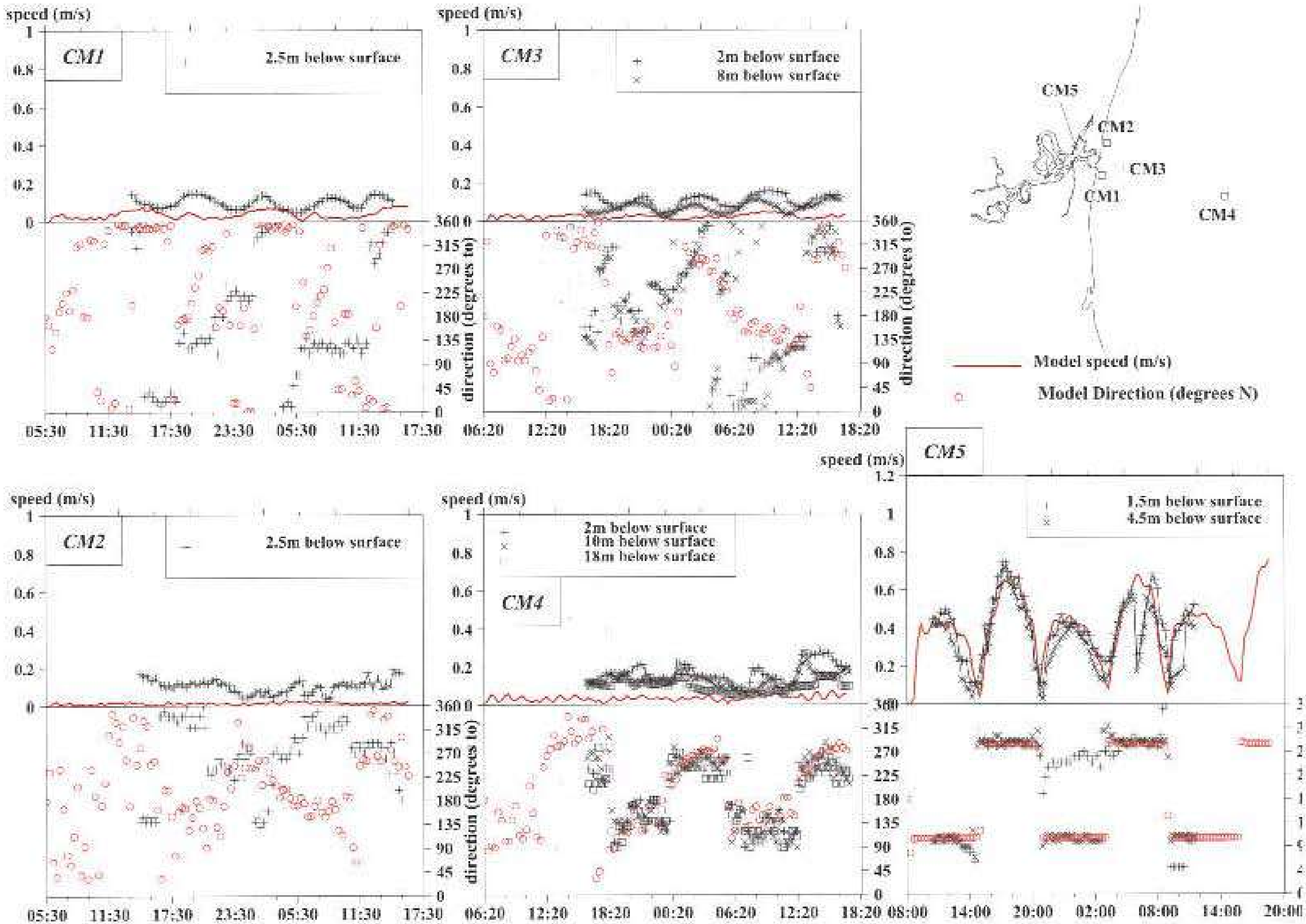
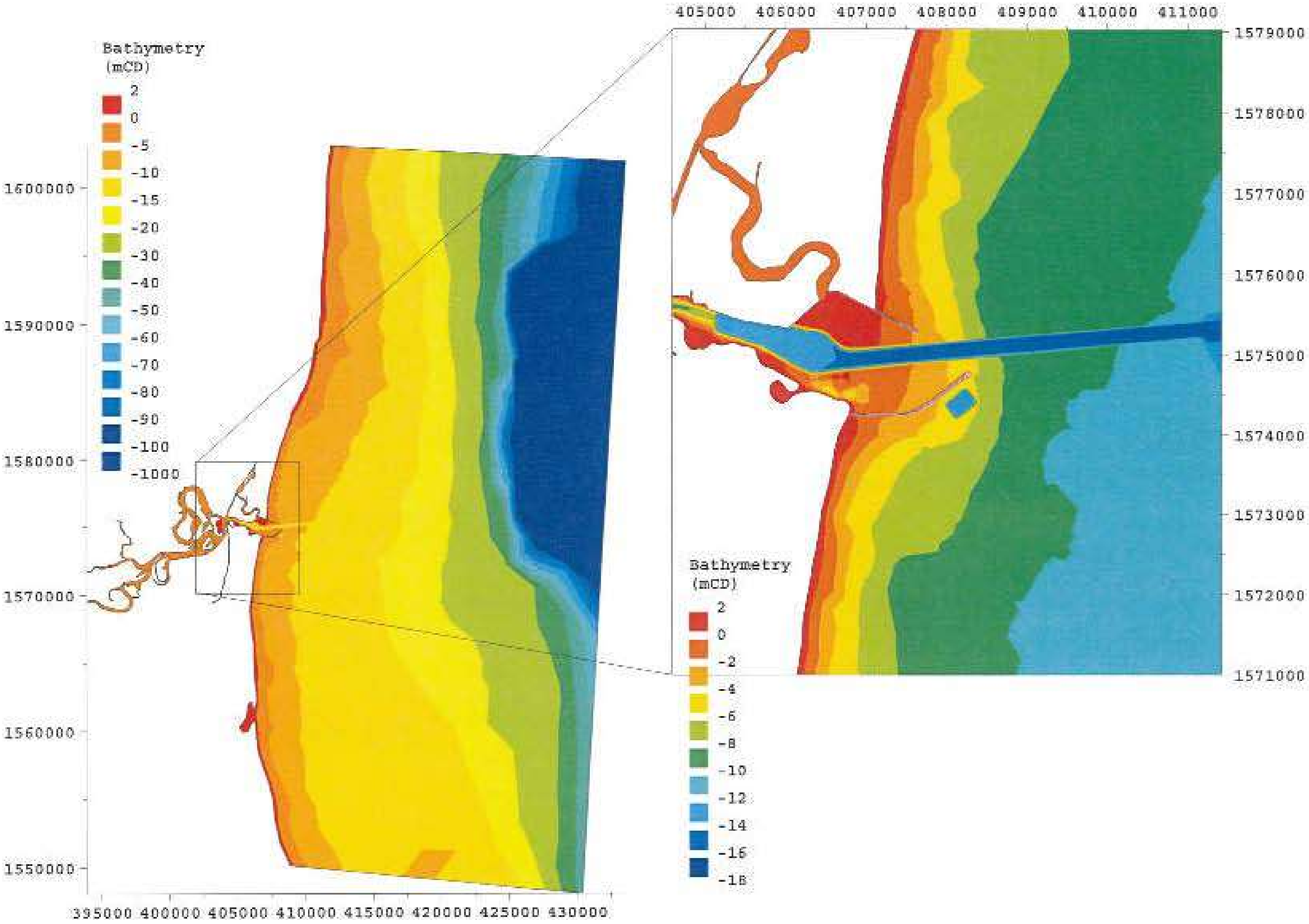


Figure 2.1 Previous model calibration

Figure 2.2 Phase I tidal flow model layout and bathymetry



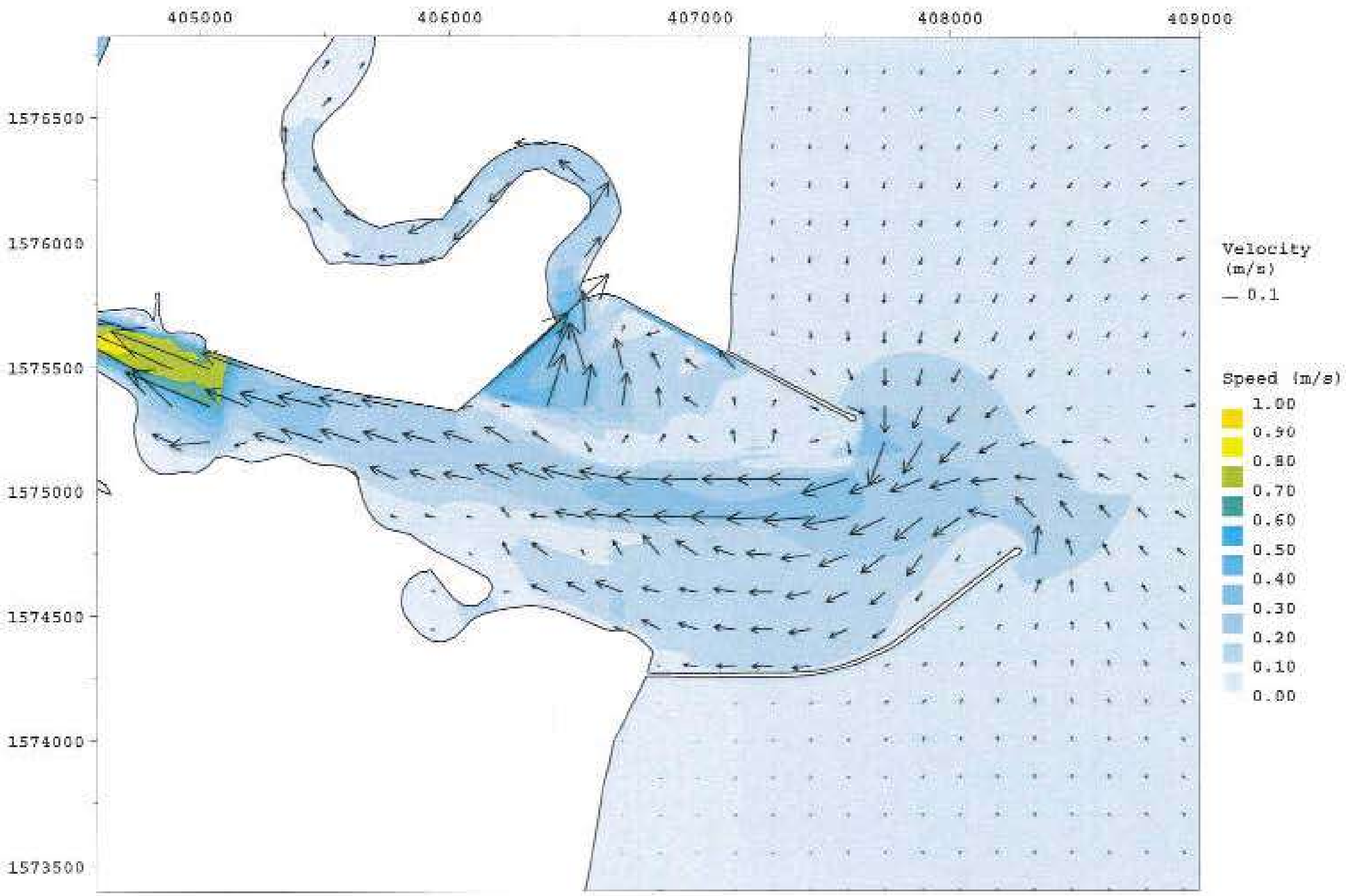


Figure 2.3 Spring tide peak flood currents, Phase 1

Figure 2.4 Spring tide peak ebb currents, Phase I

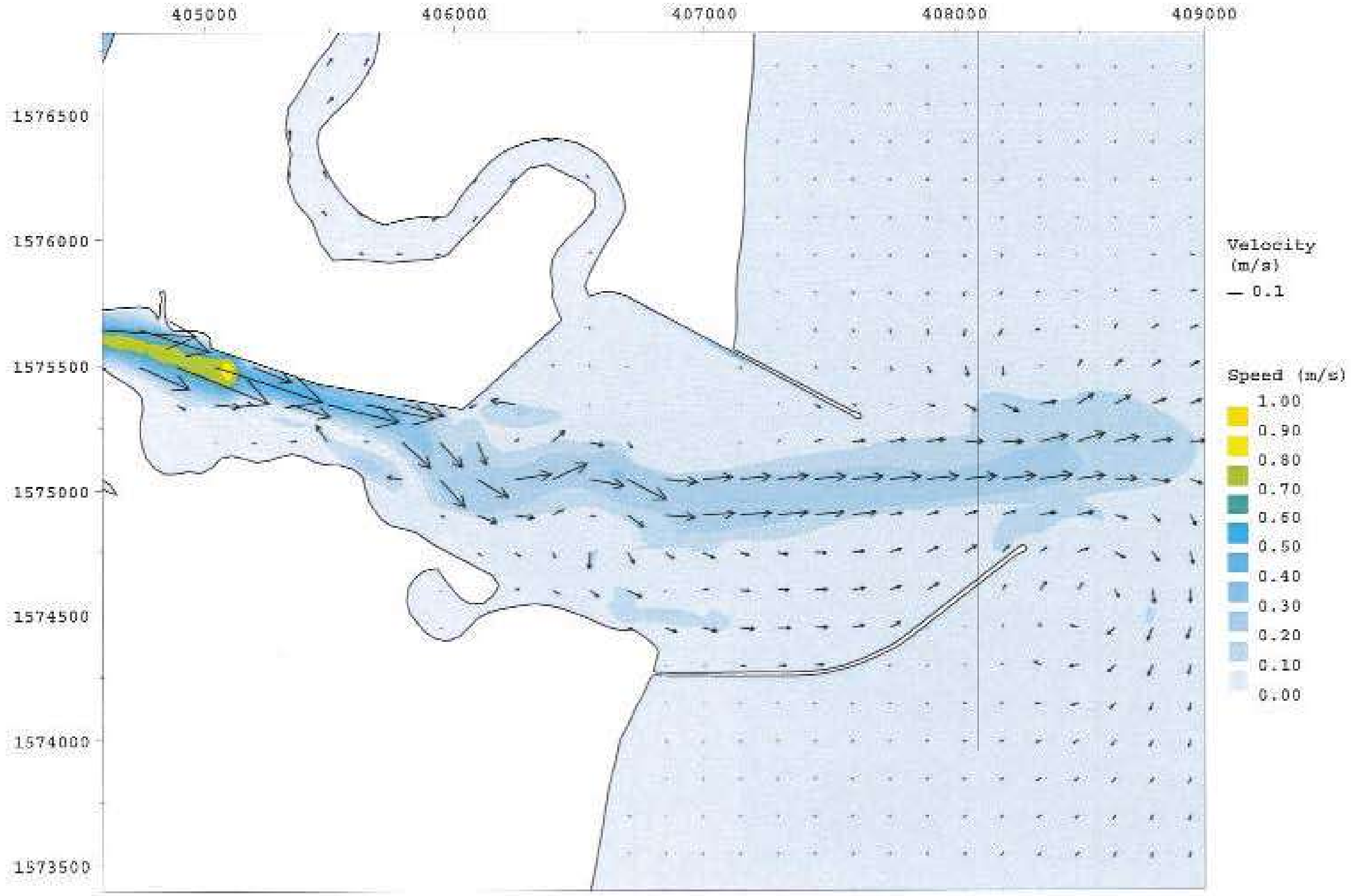


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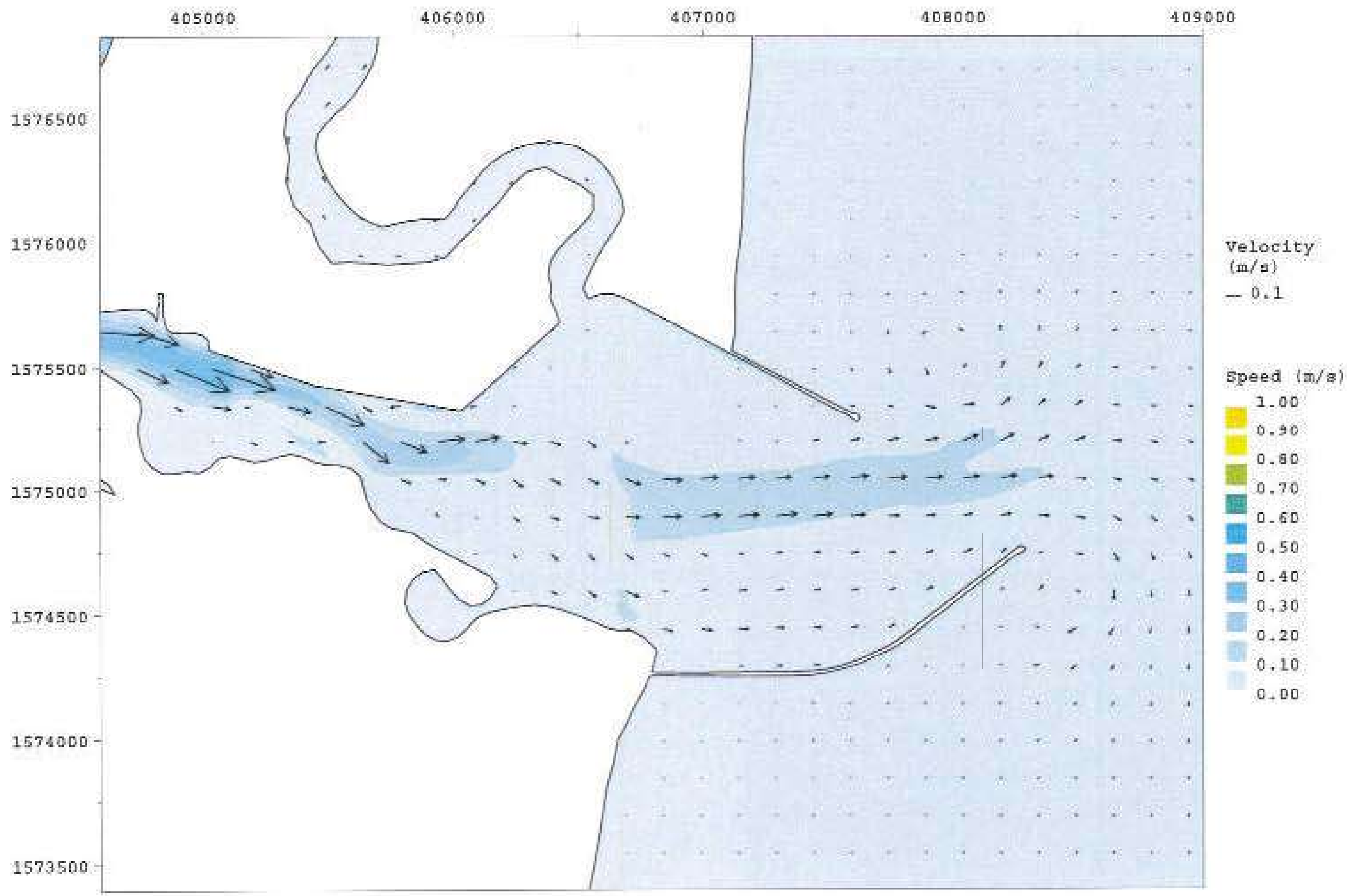
Figure 2.5 Neap tide peak ebb currents, Phase 1



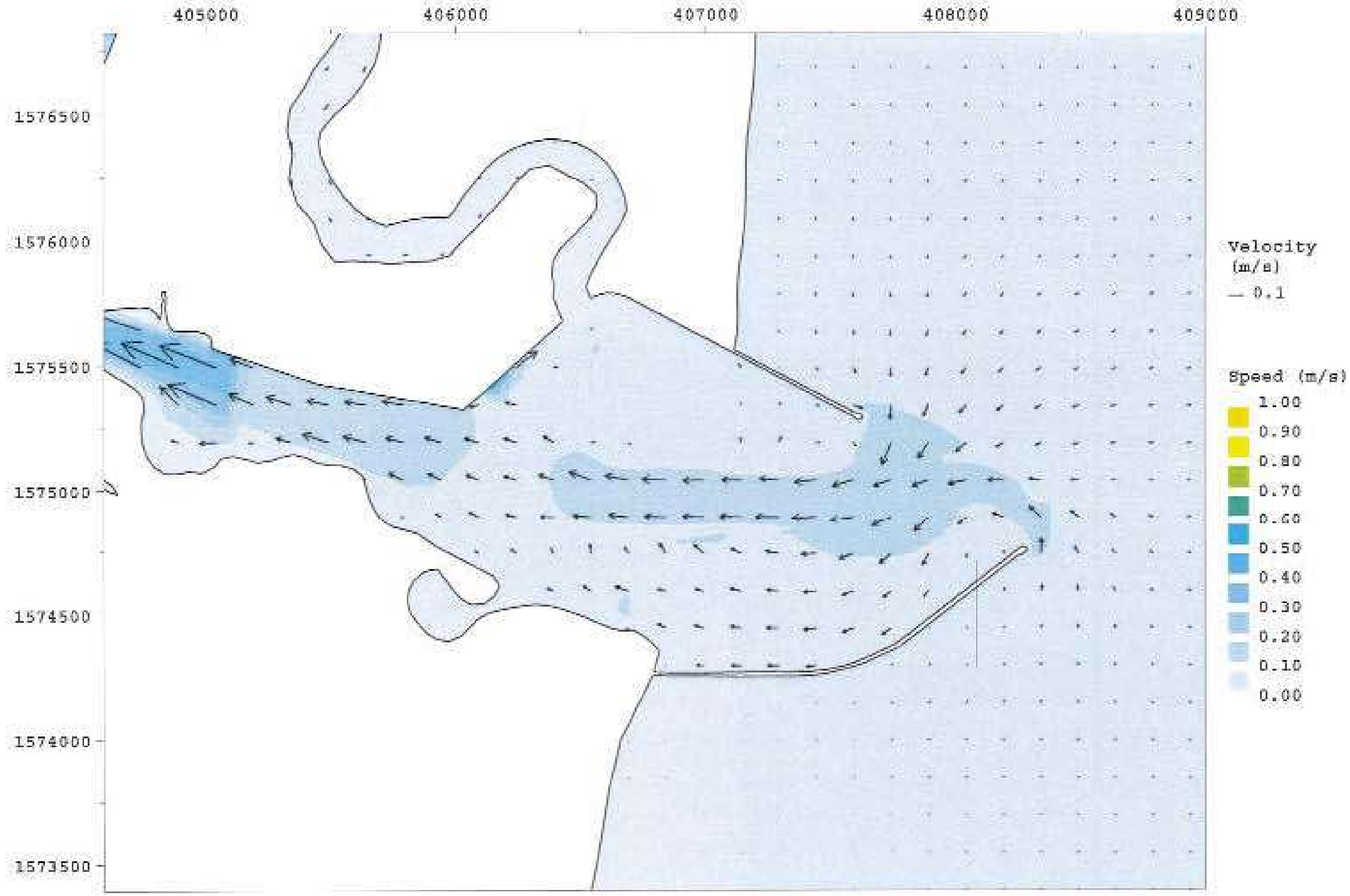


Figure 2.6 Neap tide peak flood currents, Phase 1

Figure 2.7 Phase II tidal flow model layout and bathymetry

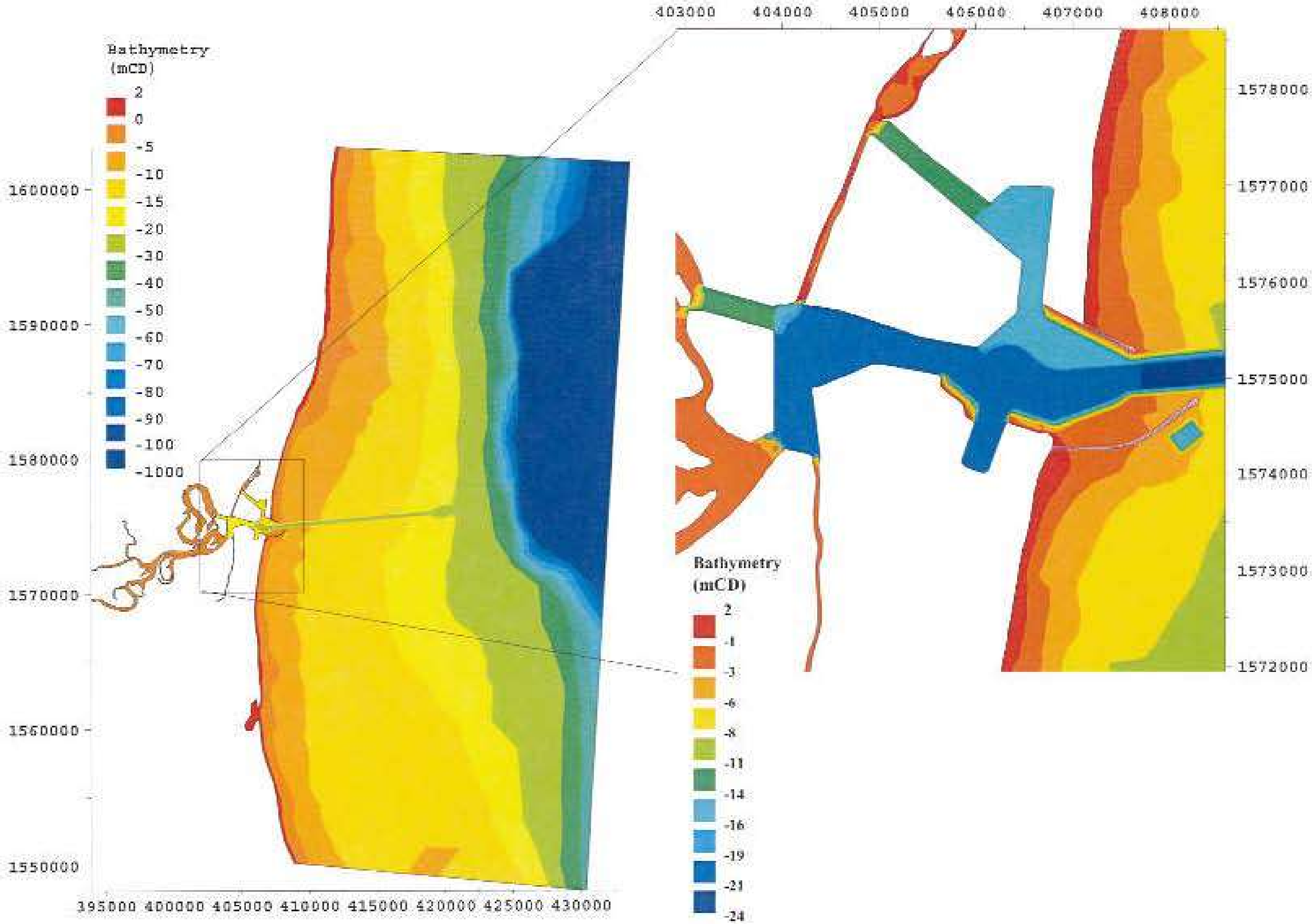
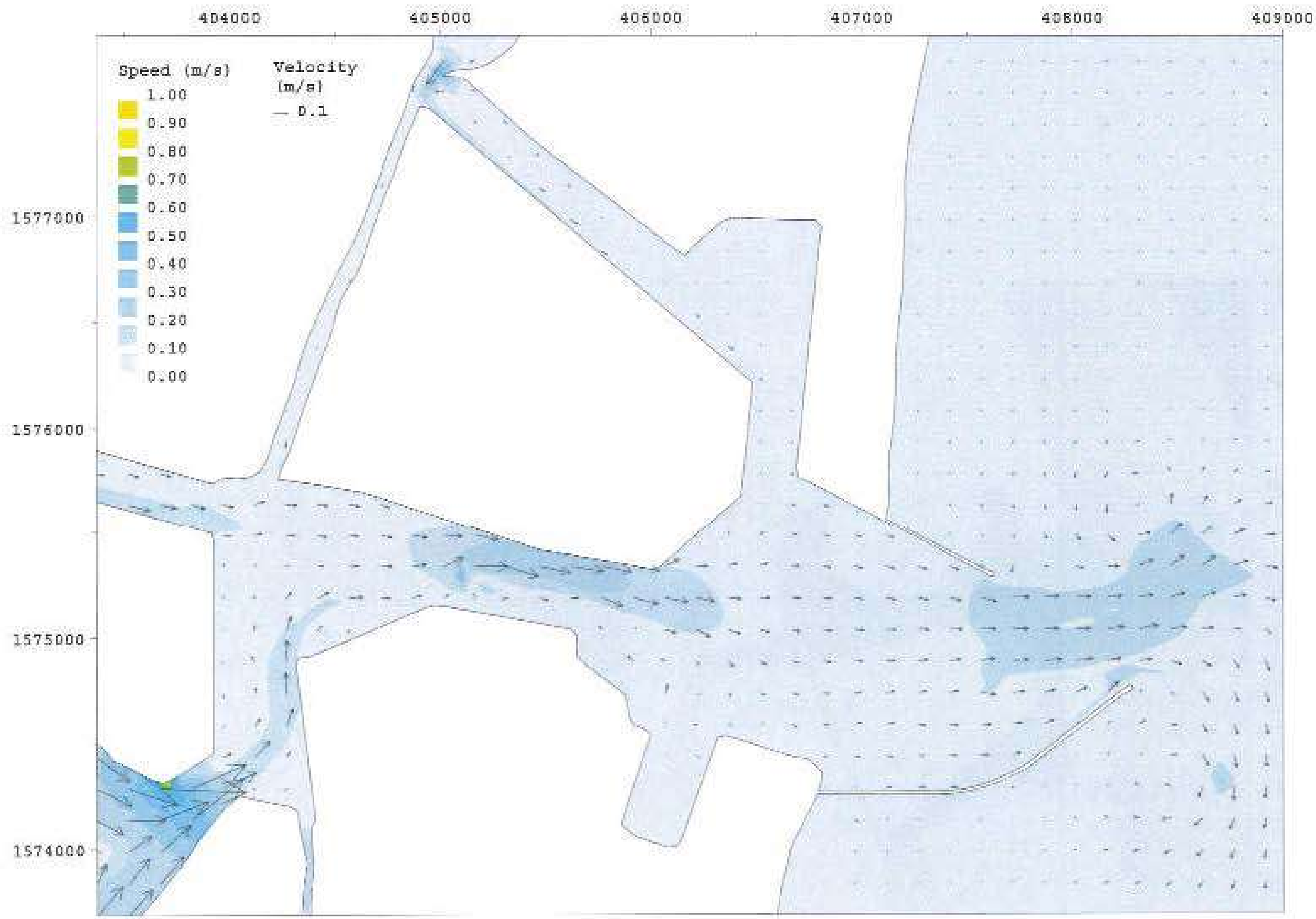


Figure 2.8 Spring tide peak ebb currents, Phase II



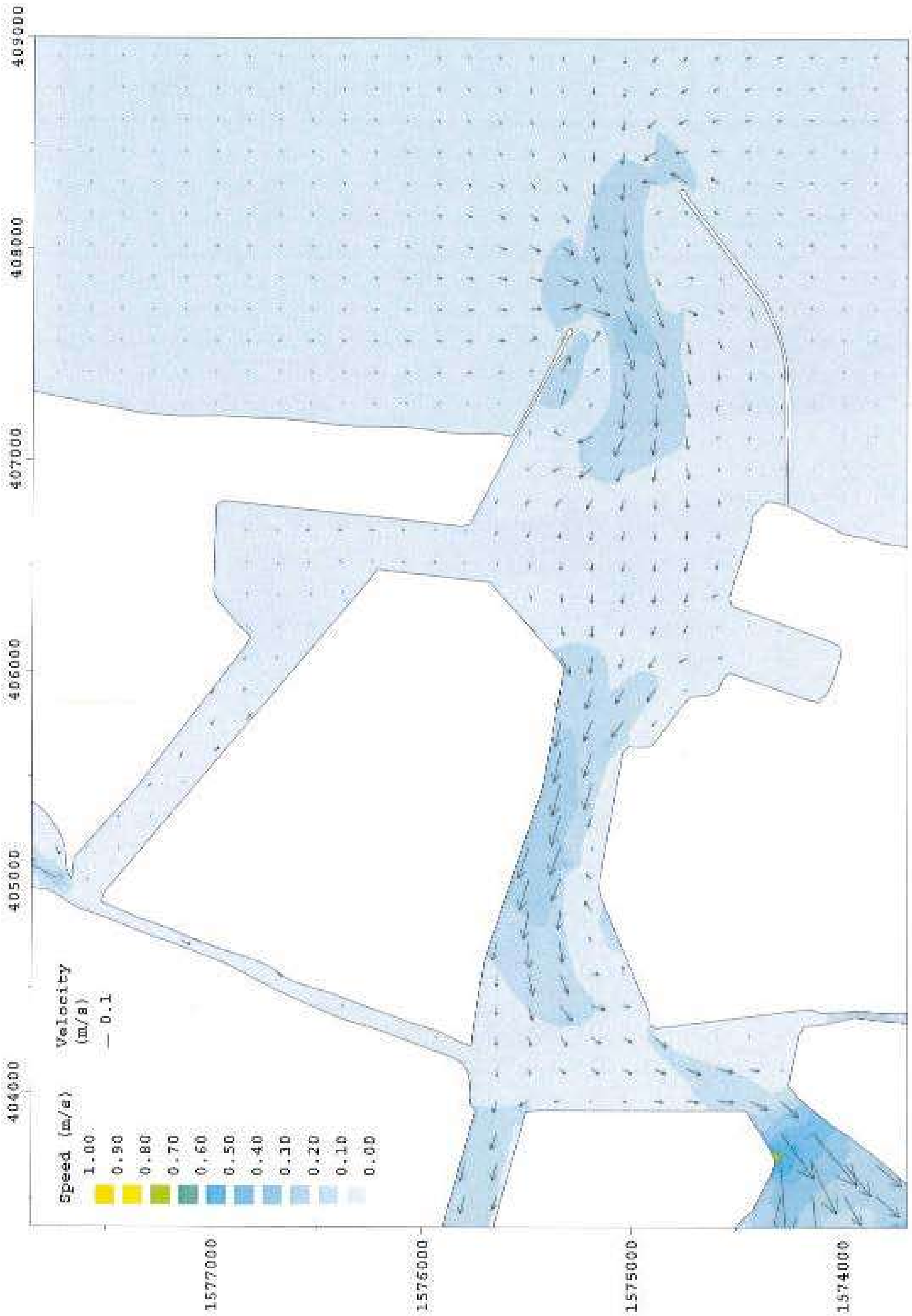


Figure 2.9 Spring tide peak flood currents, Phase II

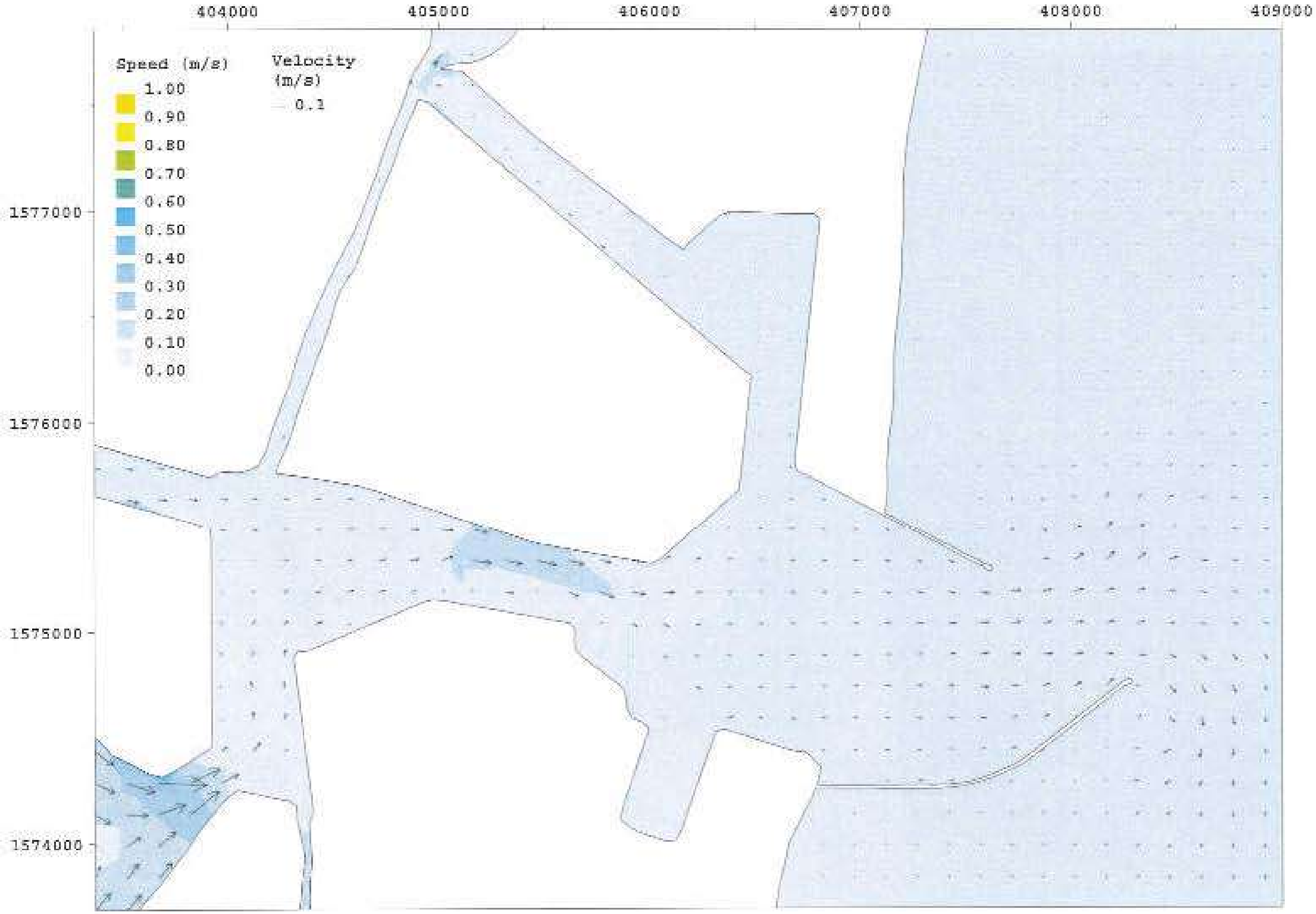


Figure 2.10 Neap tide peak ebb currents, Phase II

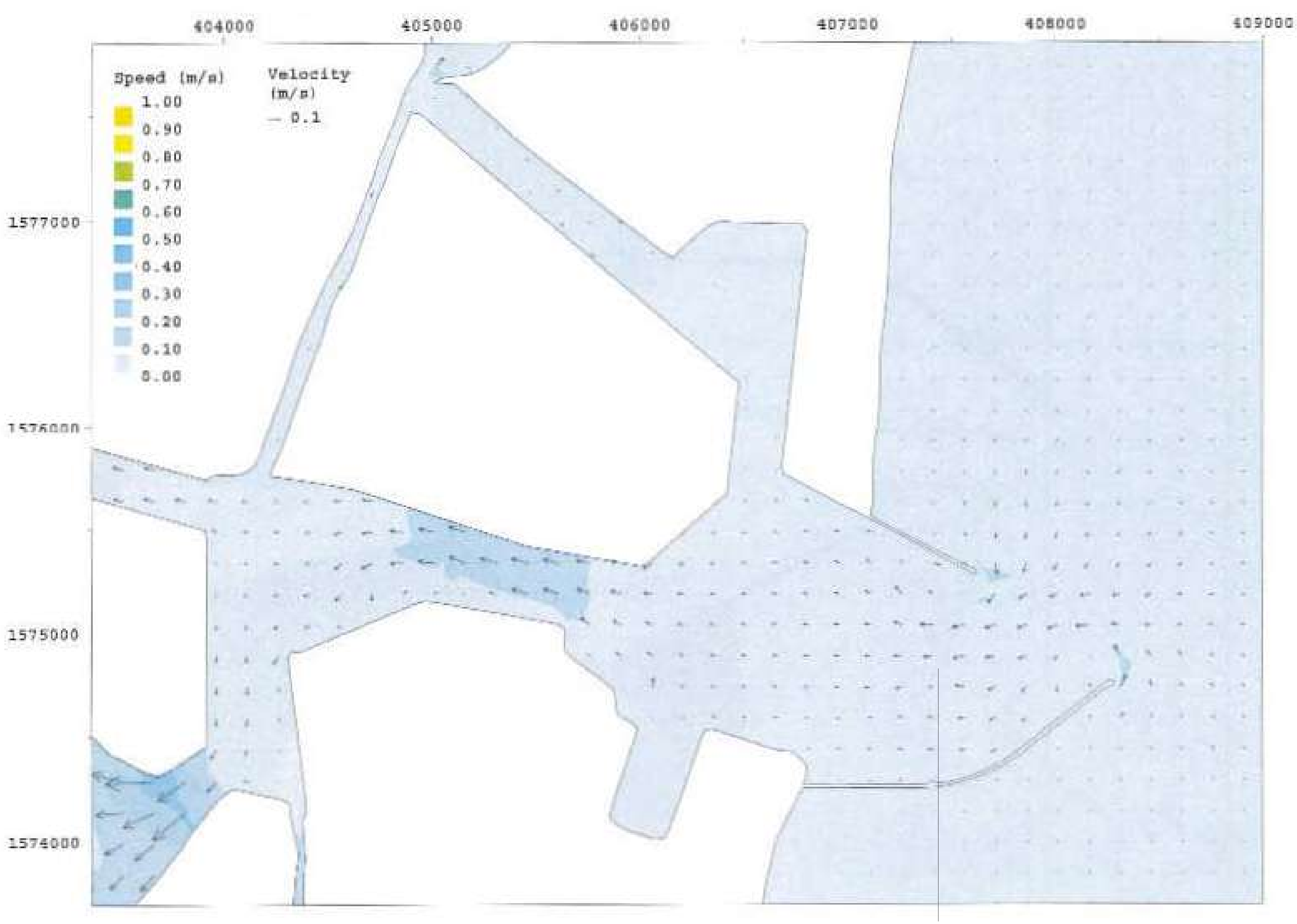


Figure 2.11 Neap tide peak flood currents, Phase II

Figure 2.12 Spring tide net tidal sediment transport patterns, Phase I

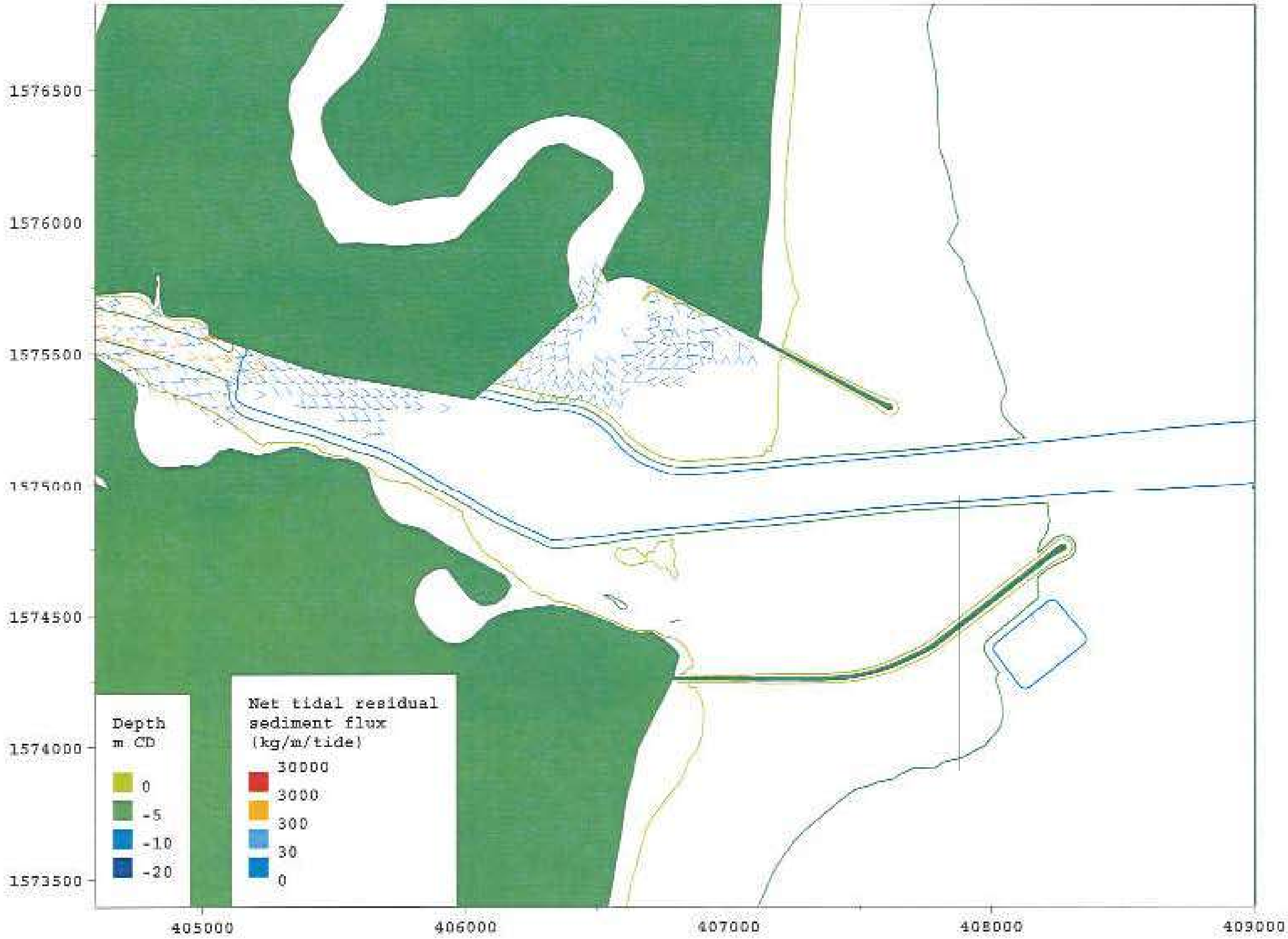


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Figure 2.13 Spring tide net tidal patterns of sedimentation, Phase I

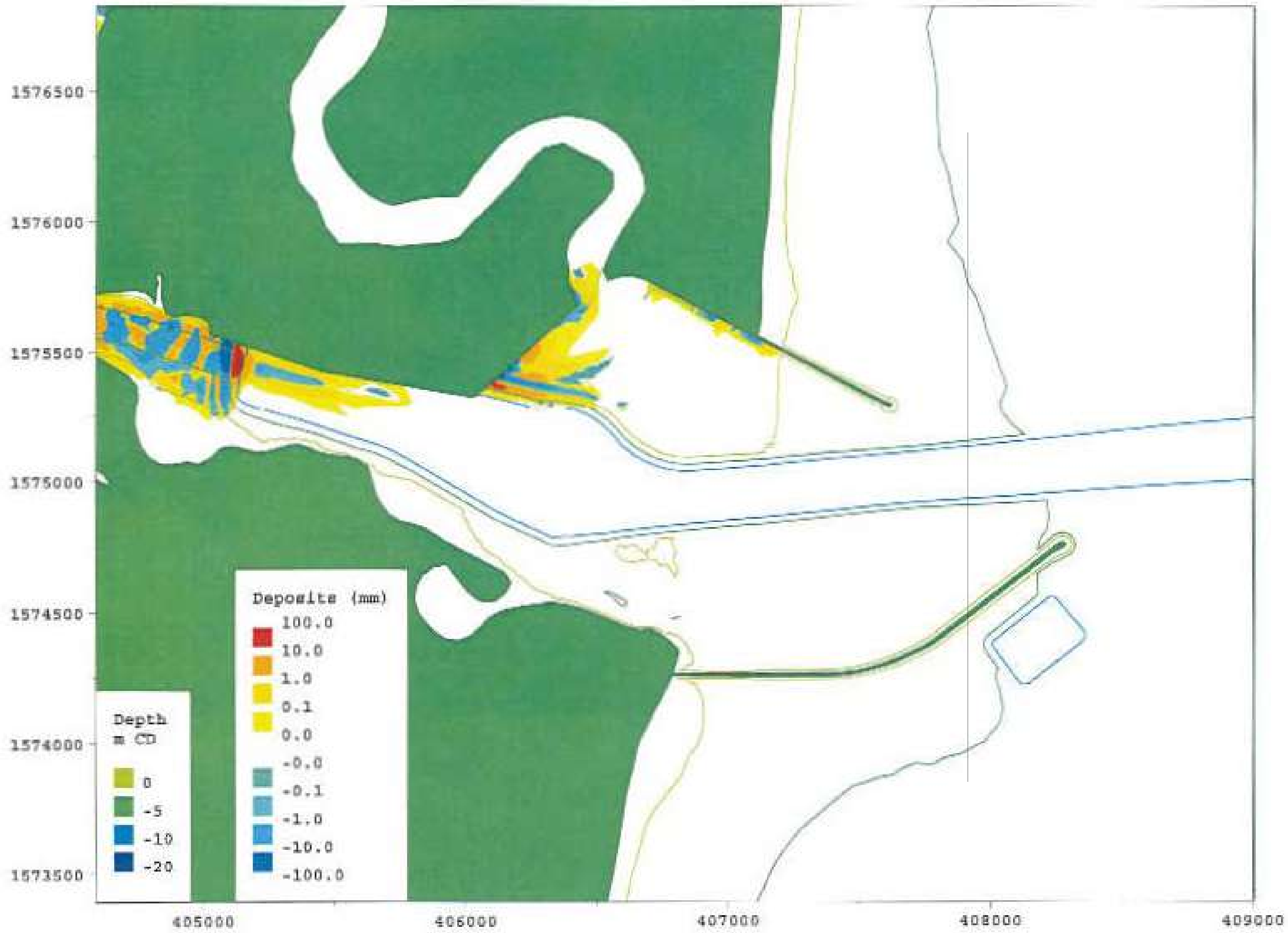

Figure 2.14 Neap tide net tidal sediment transport patterns, Phase I

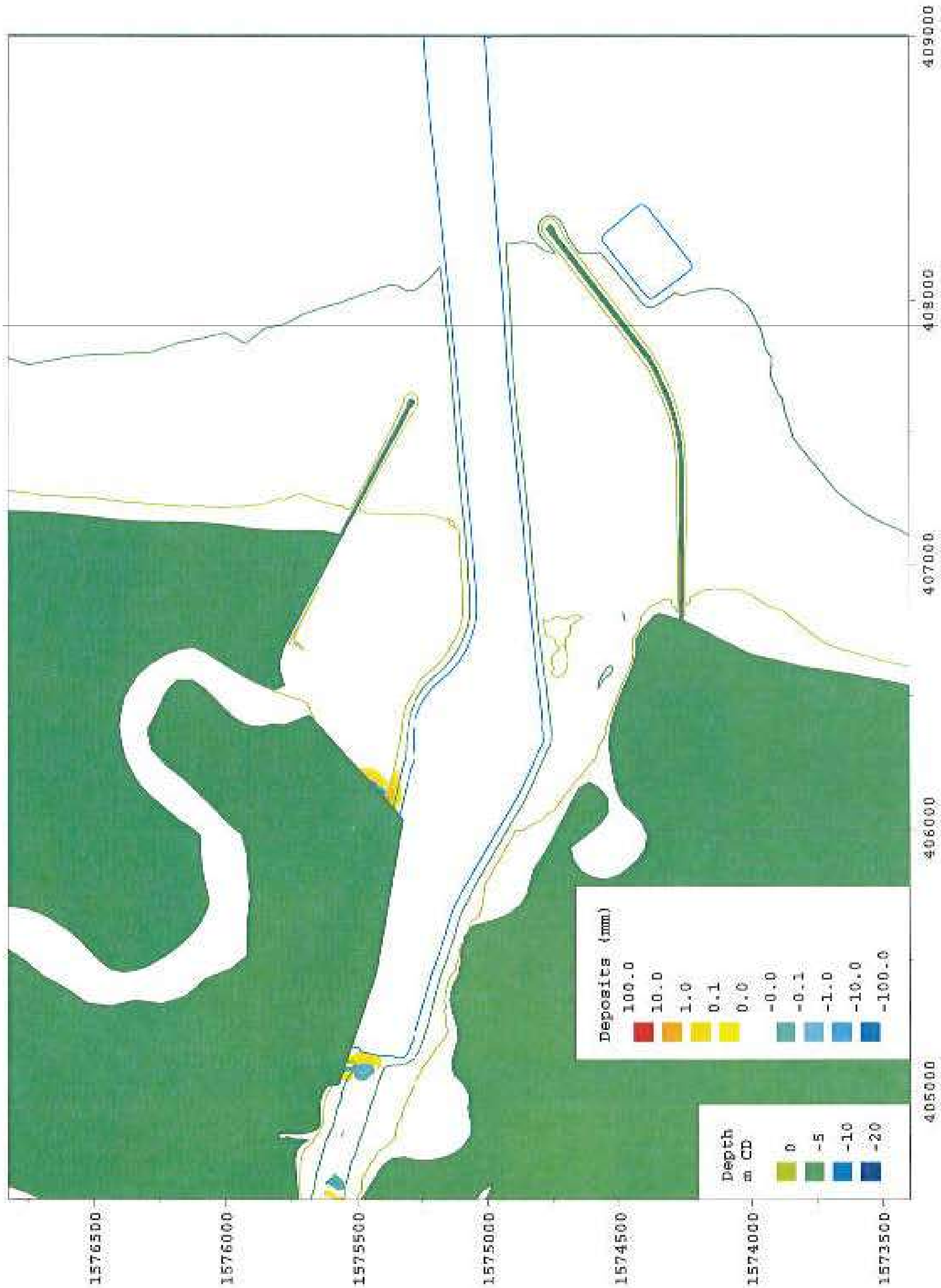

Figure 2.15 Neap tide net tidal patterns of sedimentation, Phase 1

Figure 2.16 Spring tide net tidal sediment transport patterns, Phase II

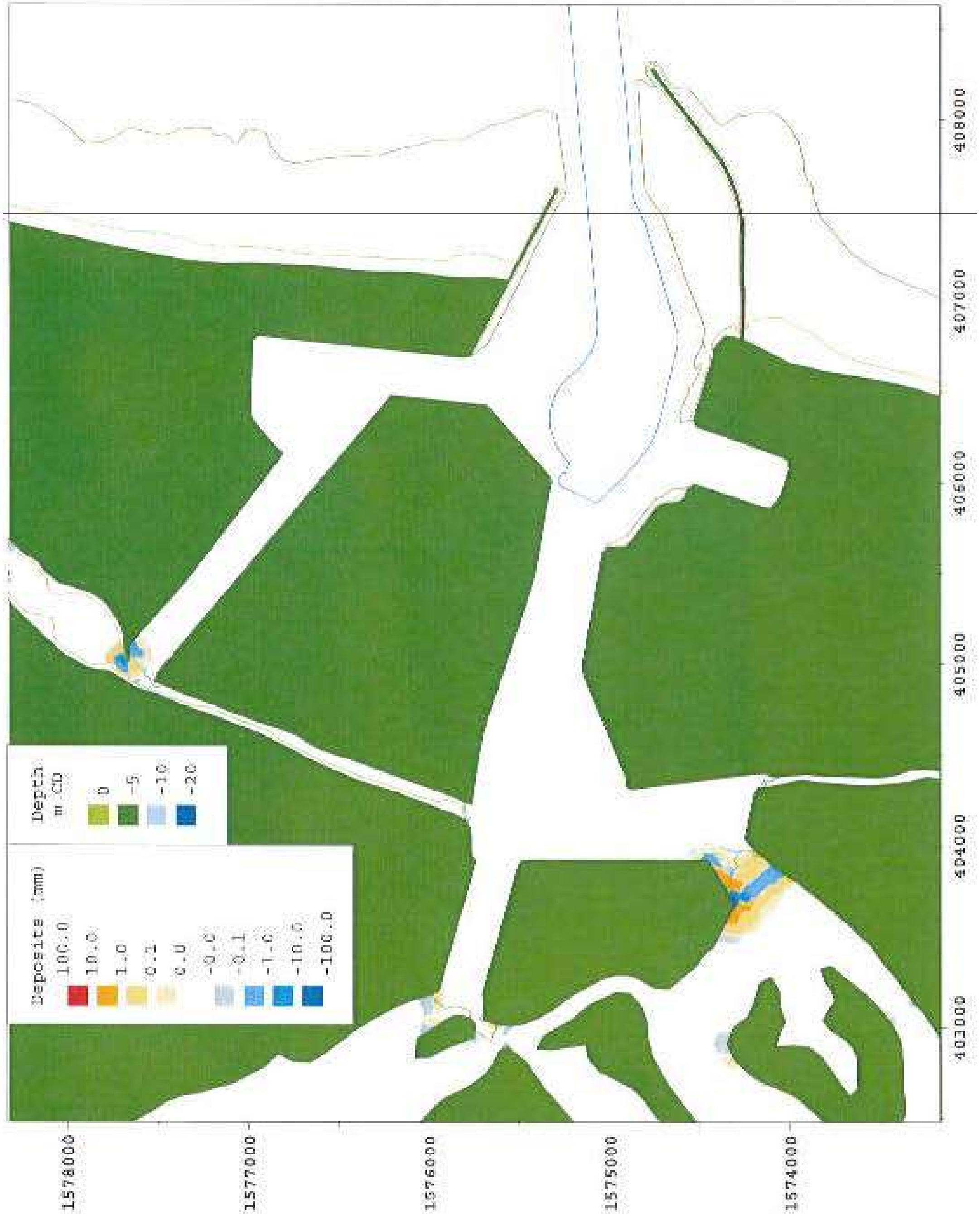

Figure 2.17 Spring tide net tidal patterns of sedimentation, Phase II

Figure 2.18 Neap tide net tidal sediment transport patterns, Phase II

Figure 2.19 Neap tide net tidal patterns of sedimentation, Phase II

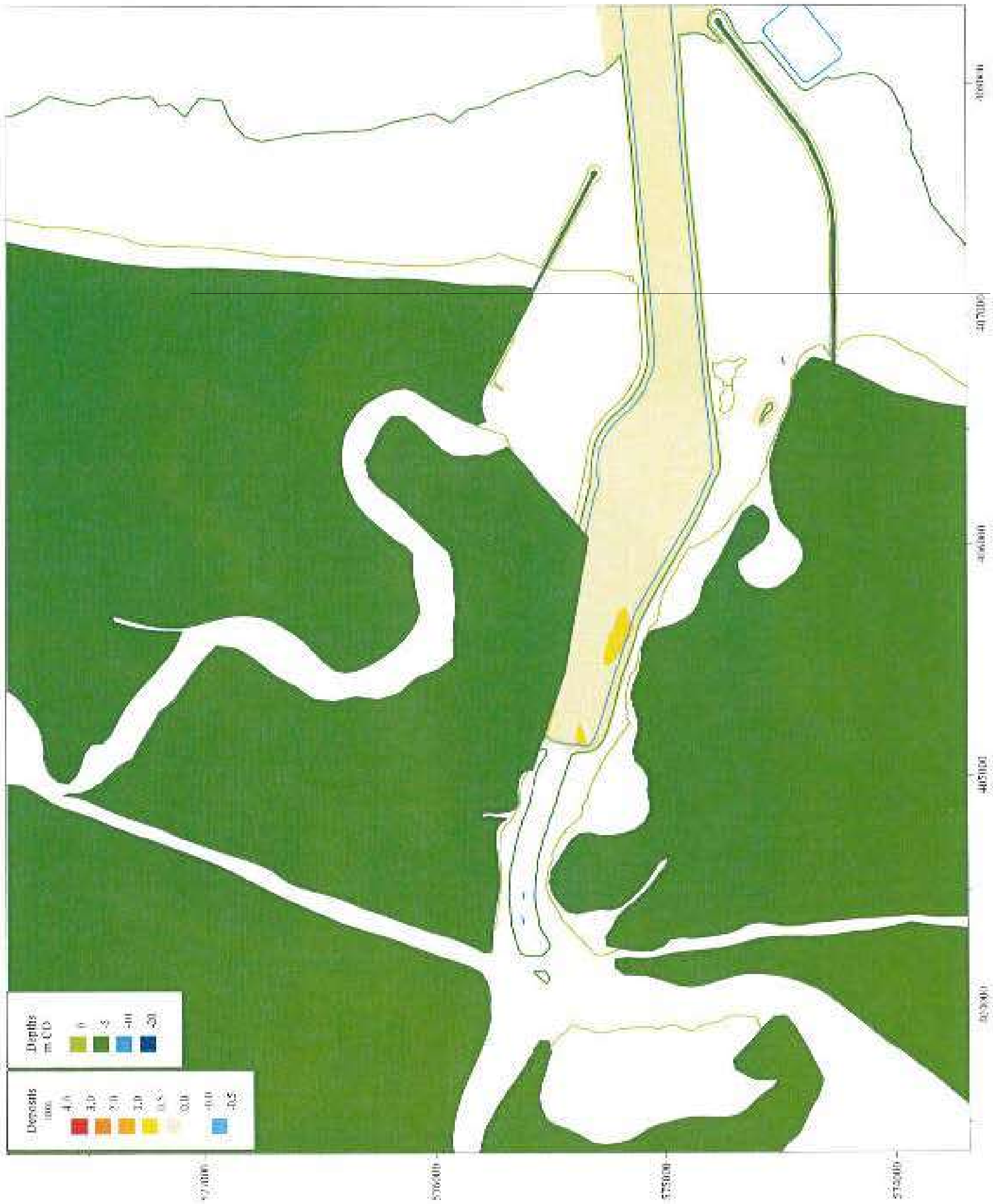

Figure 2.20 Spring tide patterns of mud deposition, Phase 1

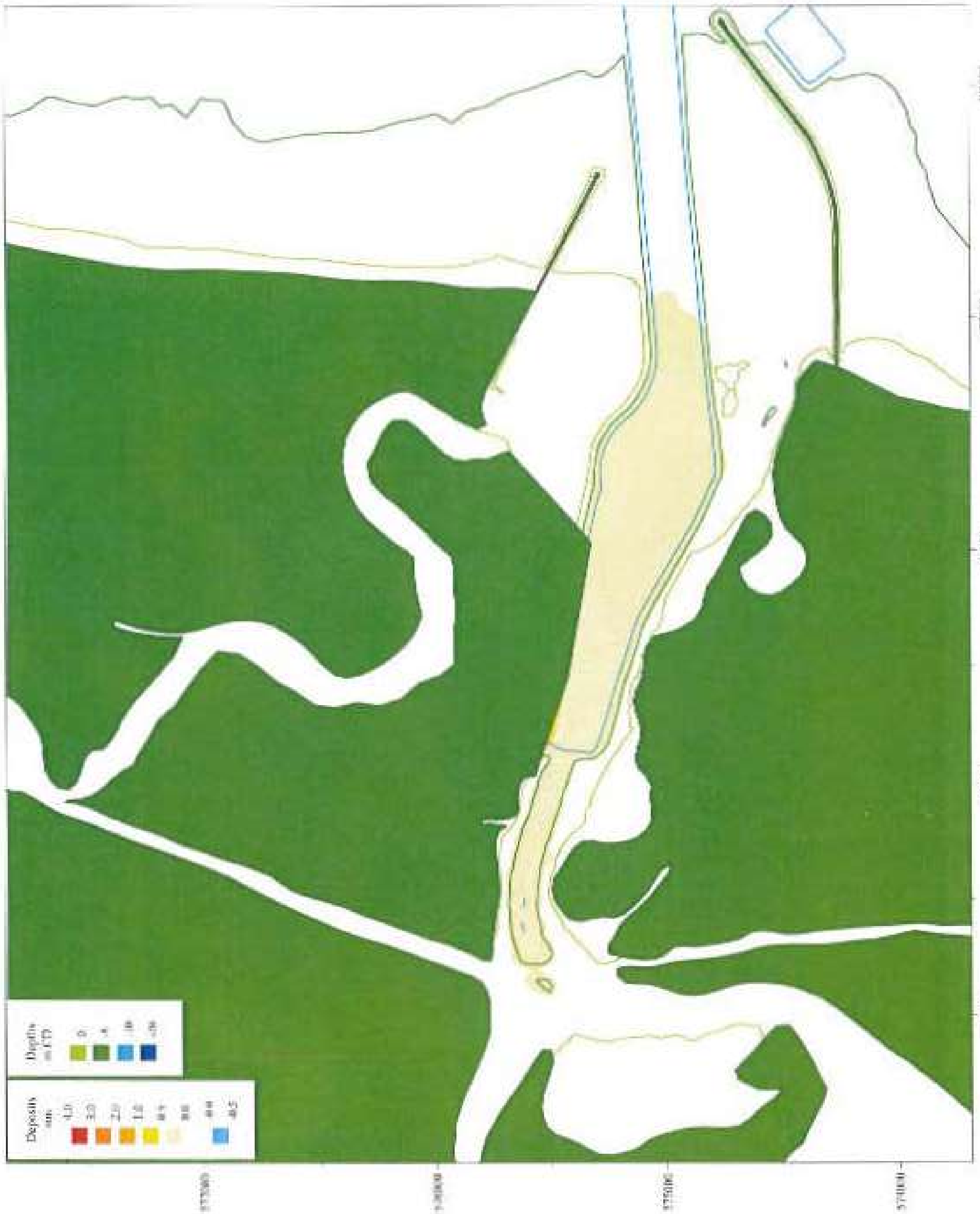

Figure 2.21 Neap tide patterns of mud deposition, Phase I

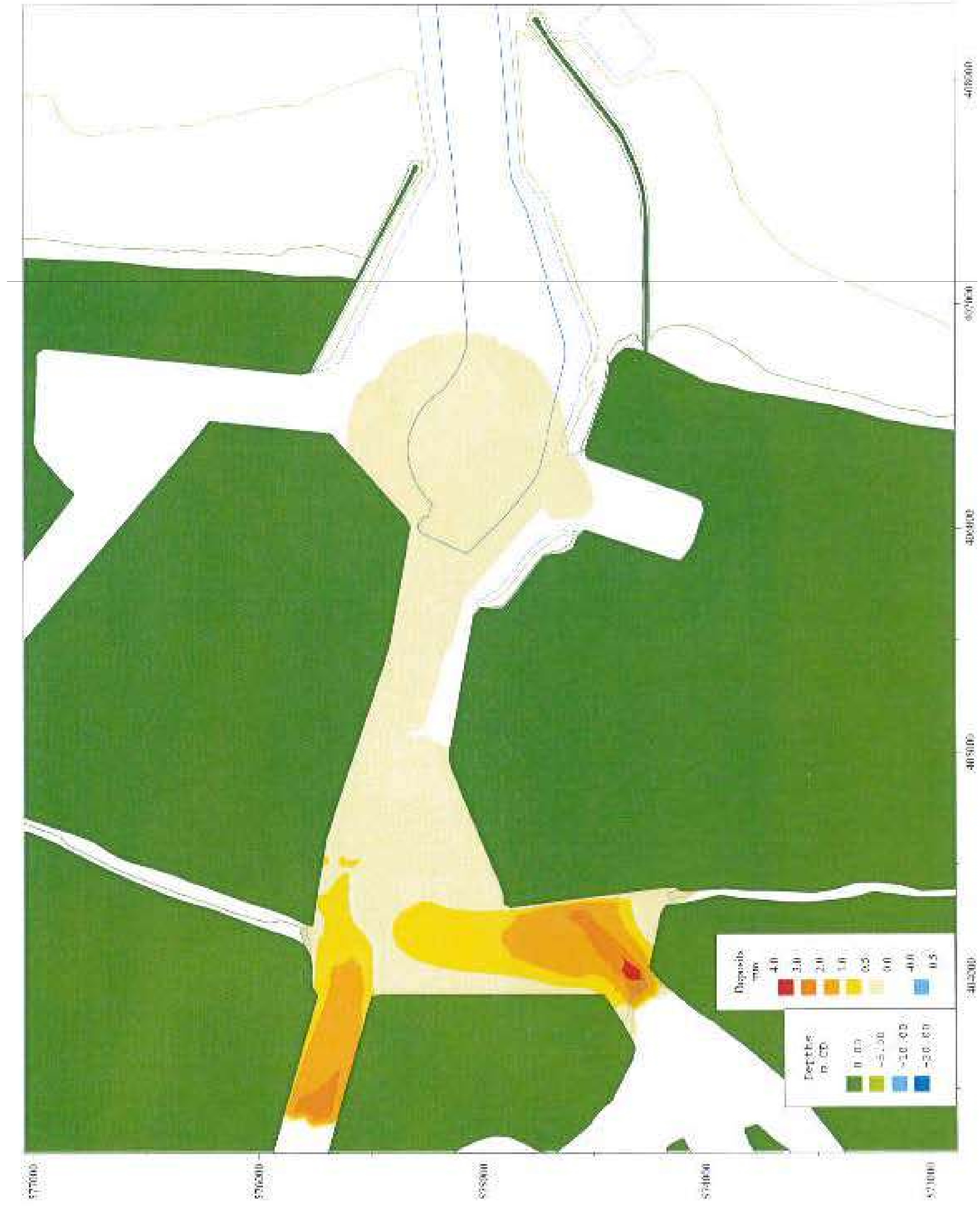

Figure 2.22 Spring tide patterns of mud deposition, Phase II

Figure 2.23 Neap tide patterns of mud deposition, Phase II

Offshore wave rose

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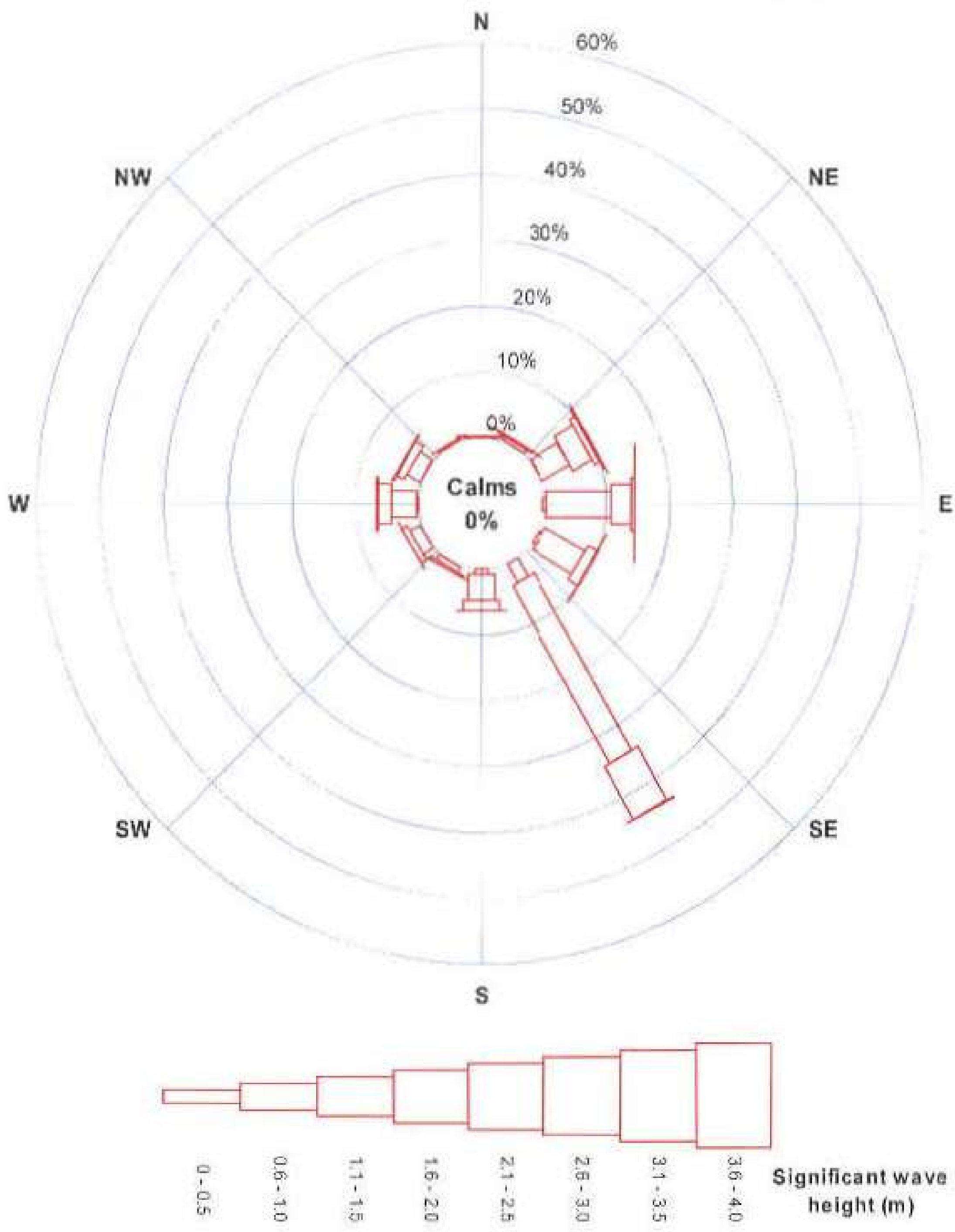

Figure 3.1 **Offshore wave rose from UK Met Office Global Wave model Points 14.6N, 80.6E and 14.7N, 80.4E**

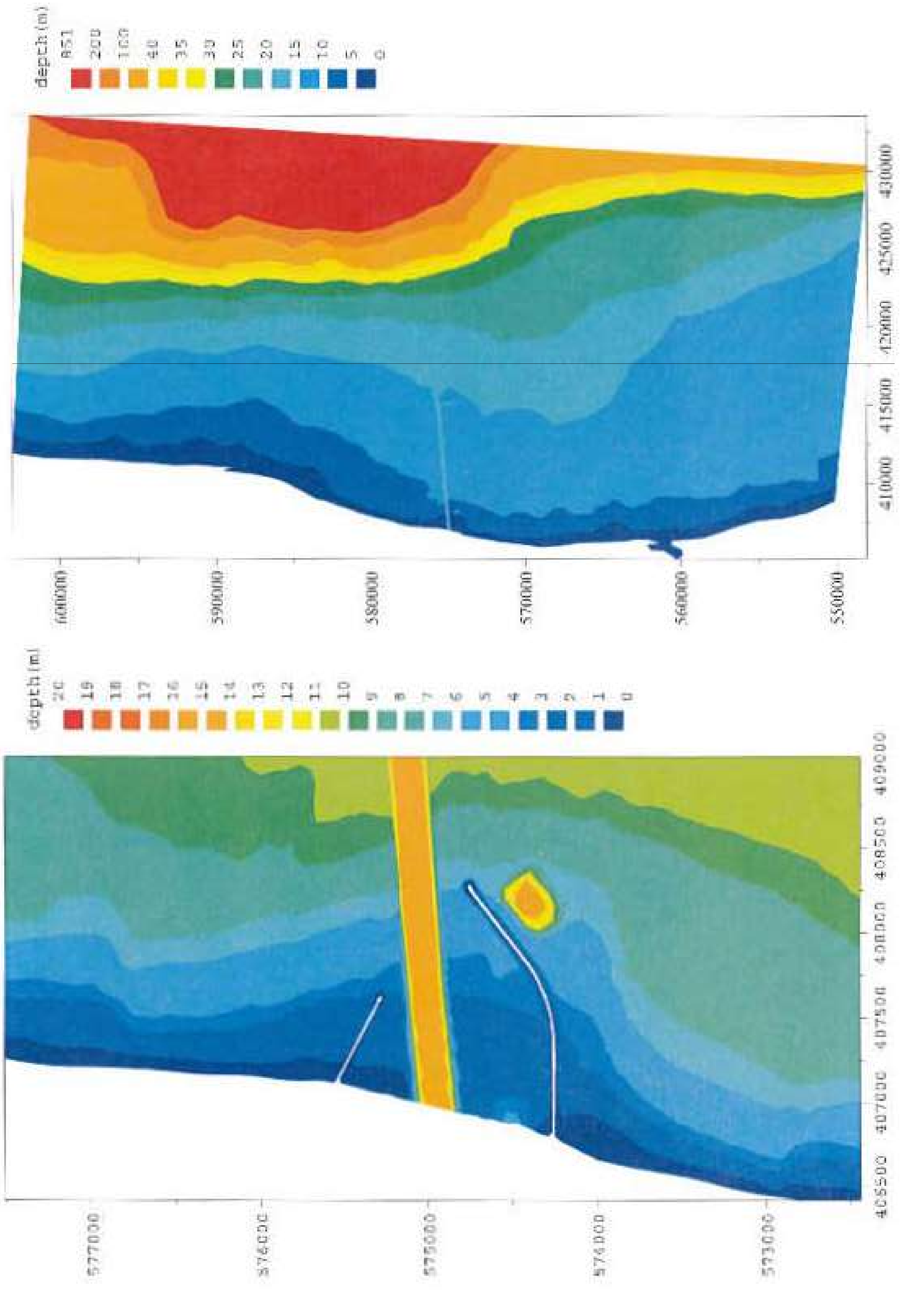

Figure 3.2 TOMAWAC model depths (at MSL=0.8mCD)

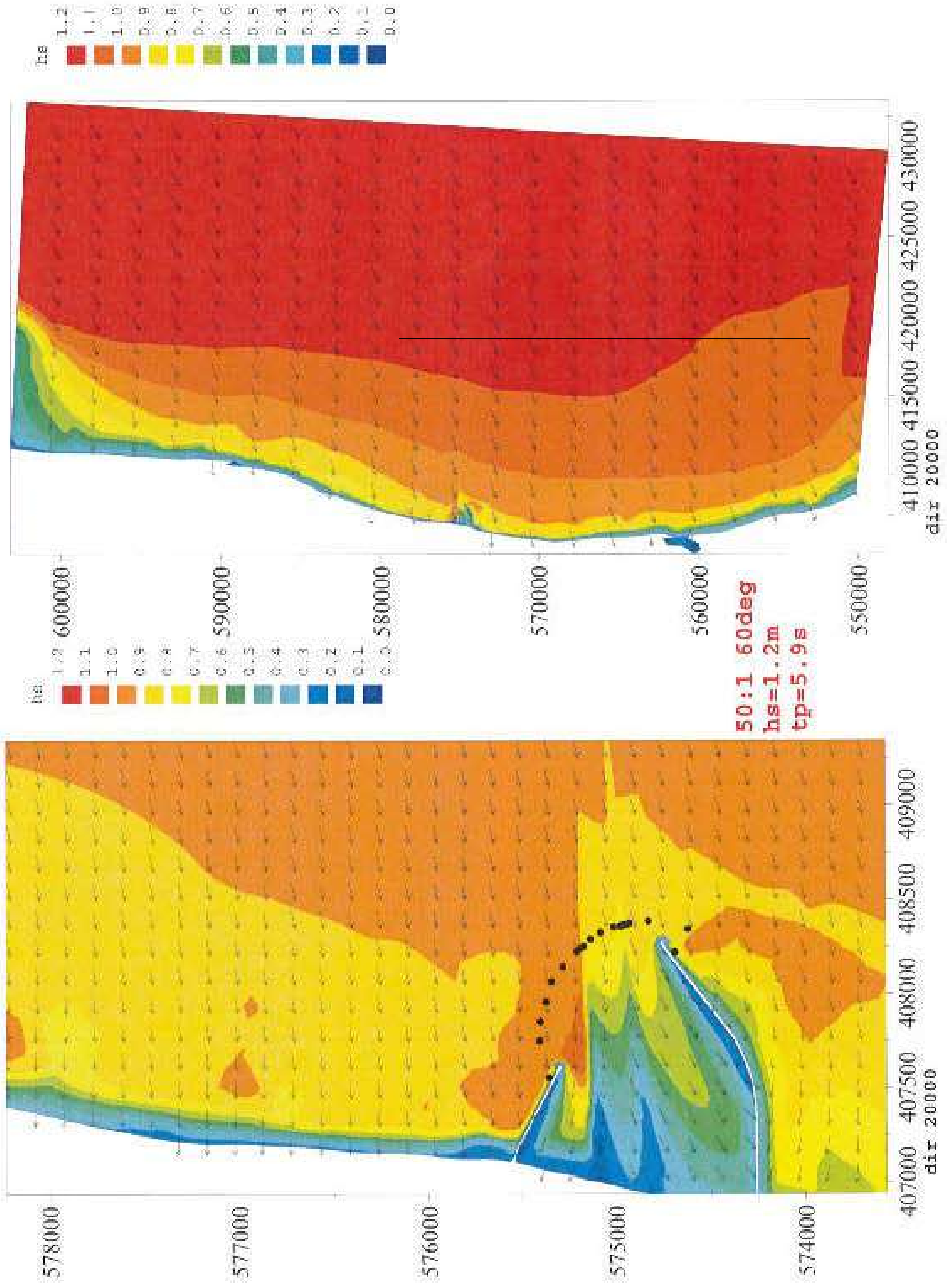

Figure 3.3 Significant wave height and direction from Tomawac 50 in 1, Hs_0=1.2m, tp_0=5.9s, dir=60^0N

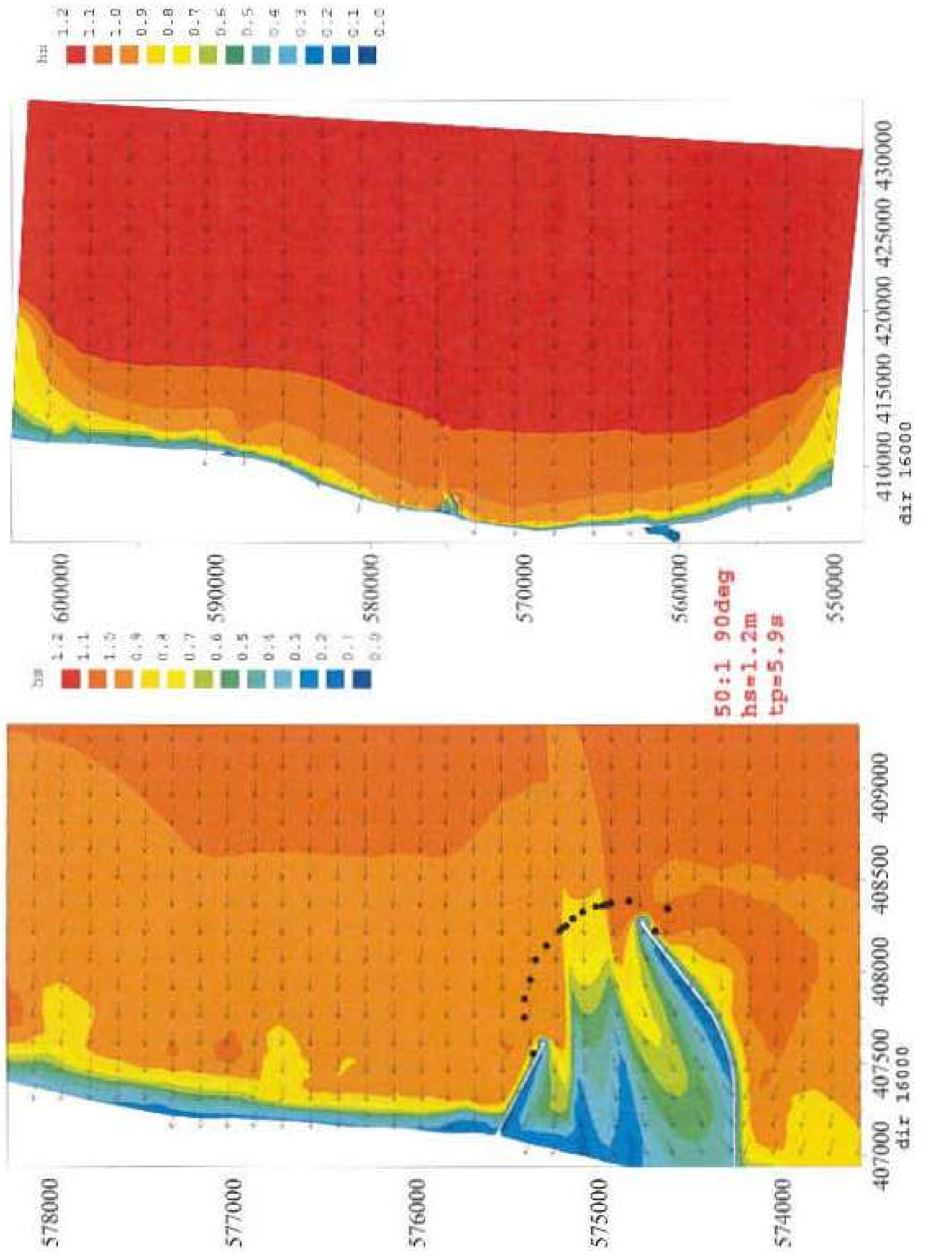

Figure 3.4 Significant wave height and direction from Tomawac 50 in 1, Hs_0=1.2m, tp_0=5.9s, dir=90^0N

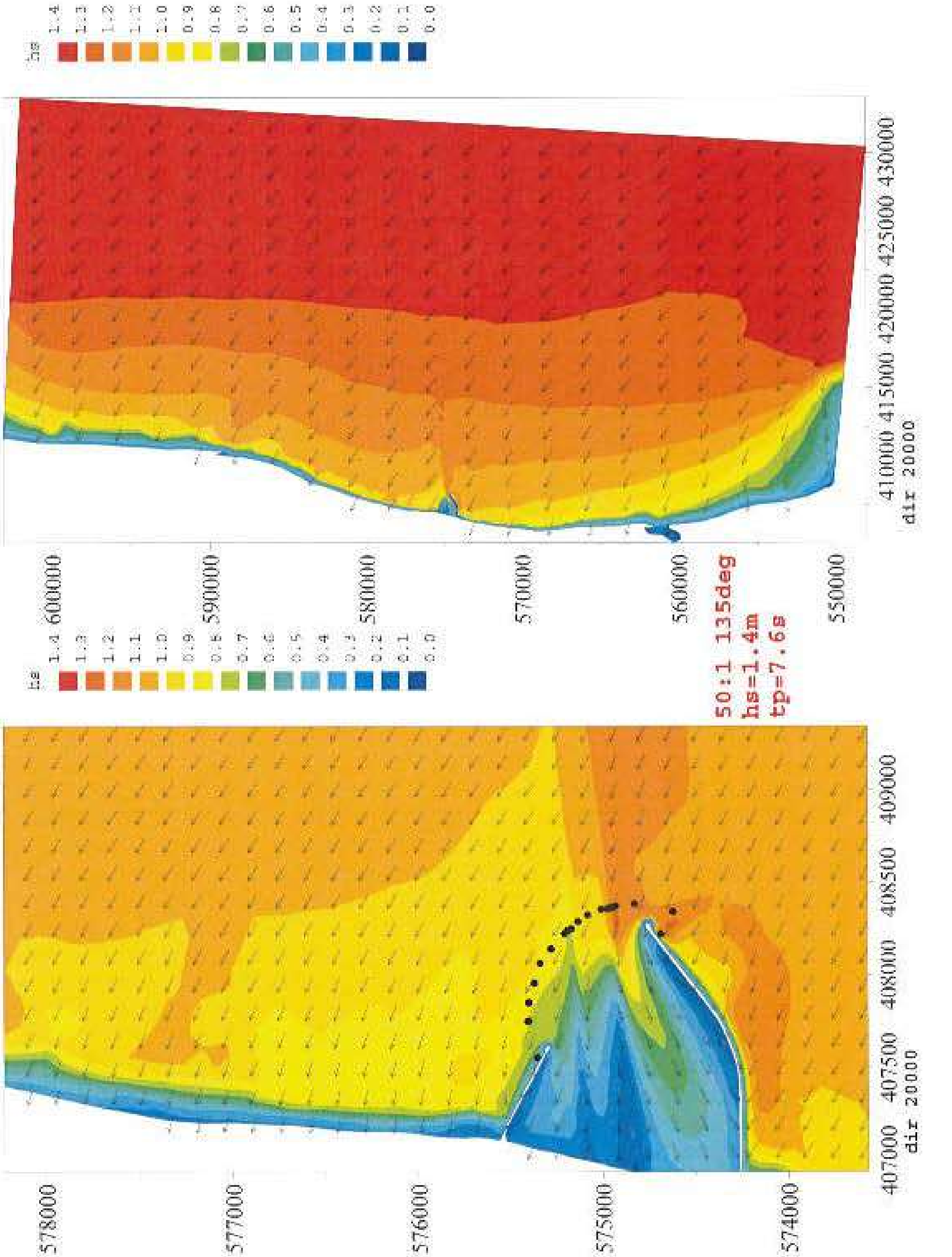

Figure 3.5 Significant wave height and direction from Tomawac 50 in 1, Hs_0=1.4m, tp_0=4.9s, dir=135^0N

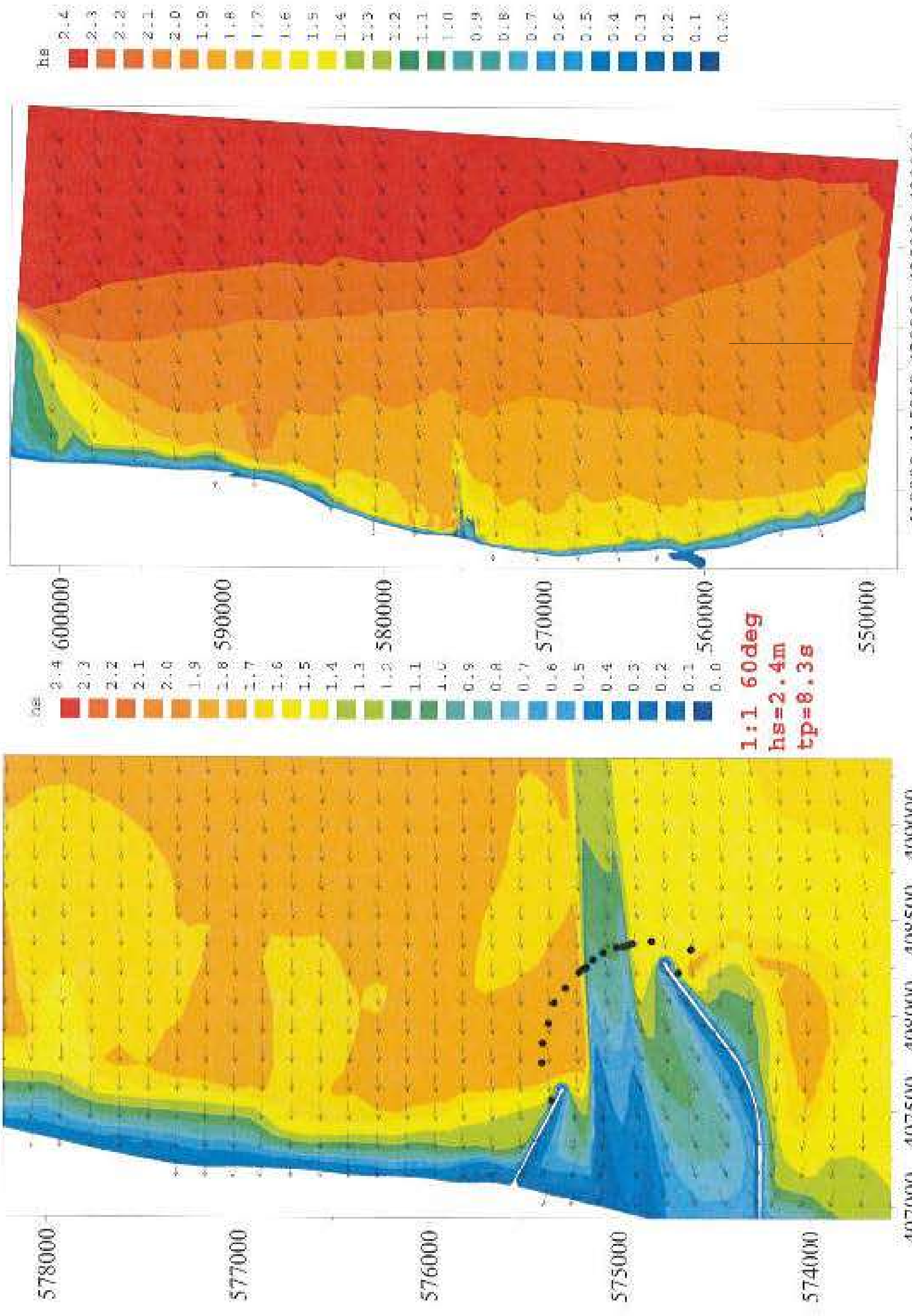

Figure 3.6 Significant wave height and direction from Tomawac 1 in 1, Hs_0=2.4m, tp_0=8.3s, dir=60^{0}N

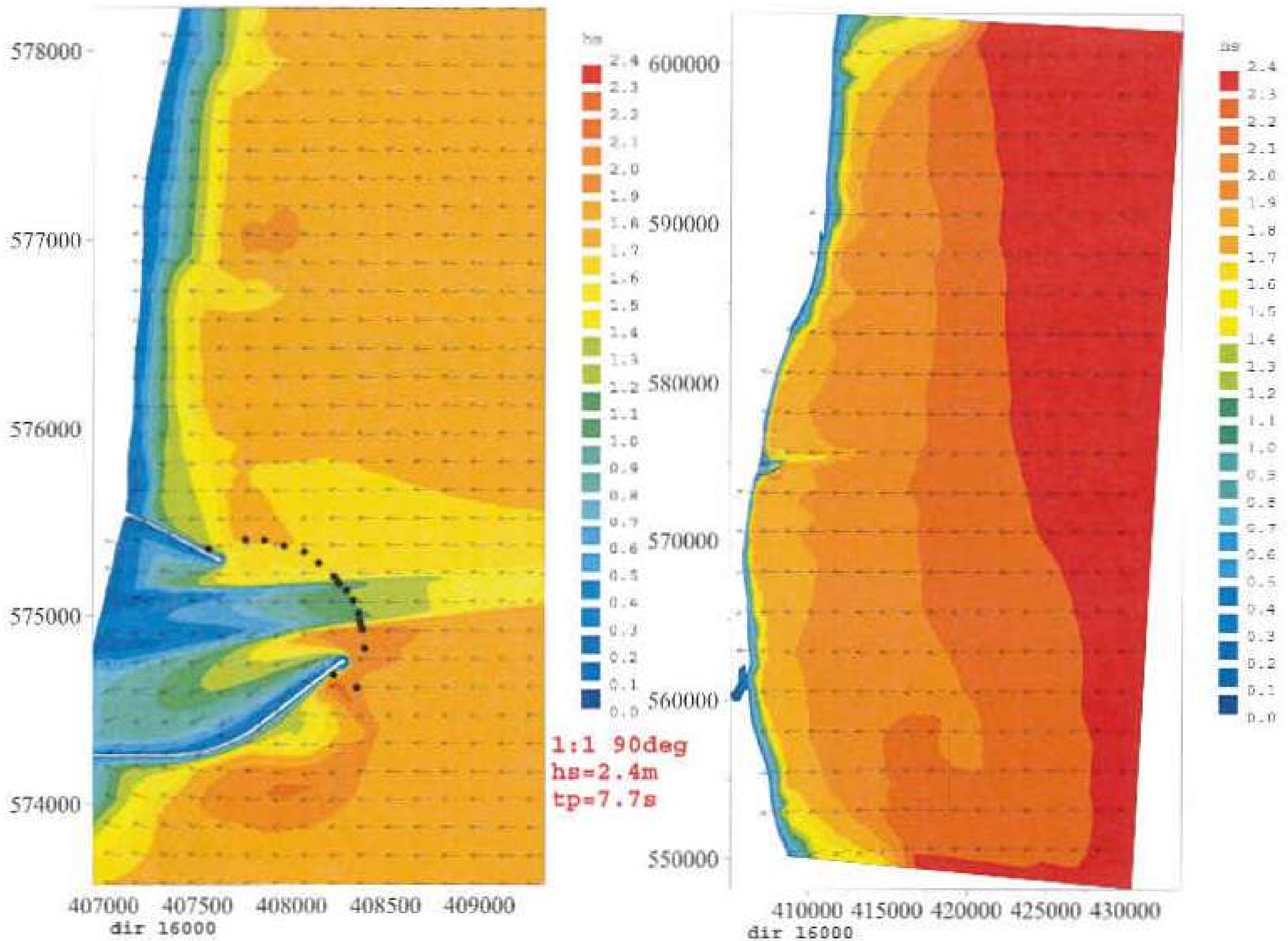

Figure 3.7 Significant wave height and direction from Tomawac 1 in 1, Hs_0=2.4m, tp_0=7.7s, dir=90°N

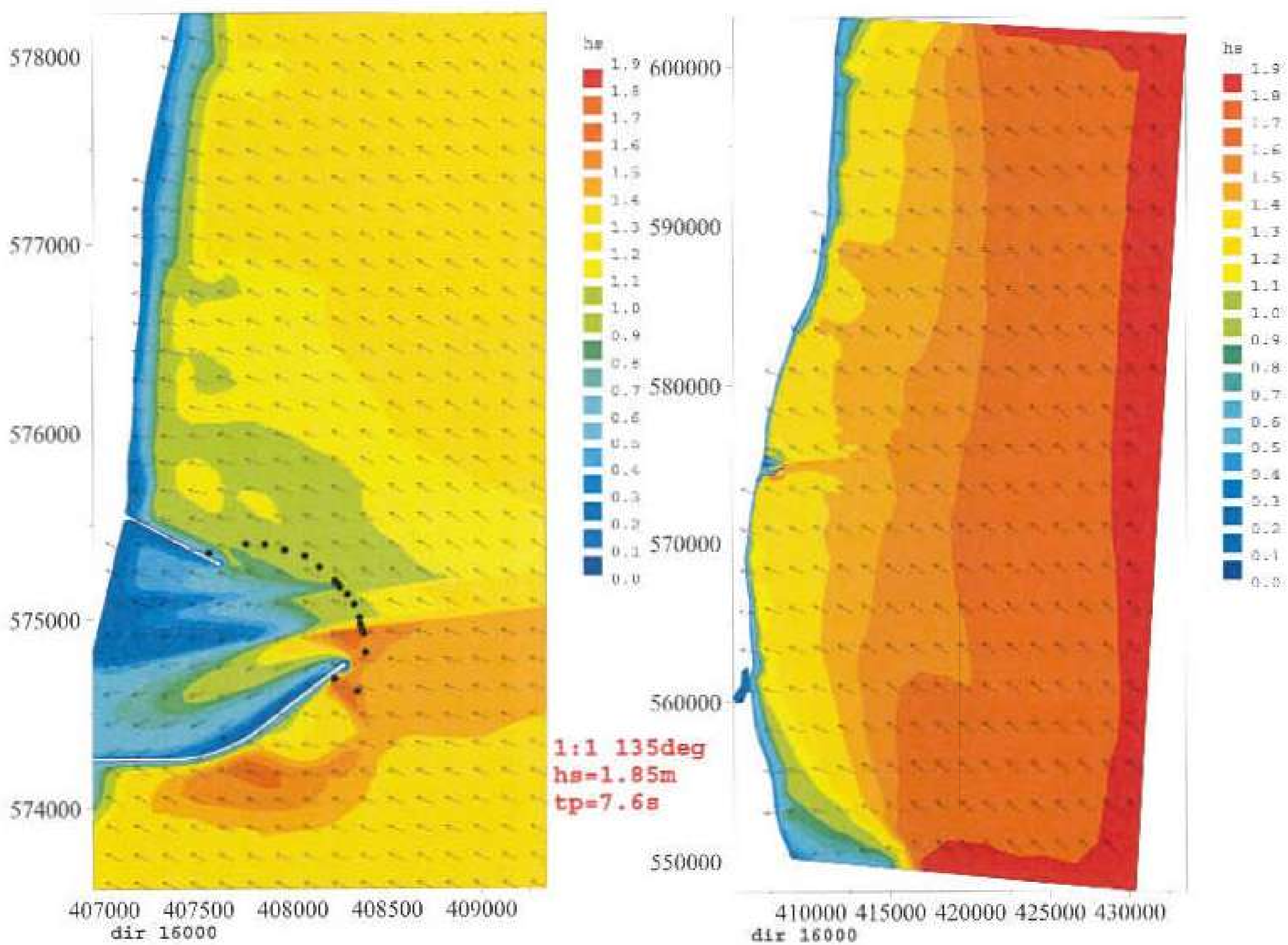

Figure 3.8 Significant wave height and direction from Tomawac 1 in 1, Hs_0=1.85m, tp_0=7.6s, dir=135°N

1675

1788

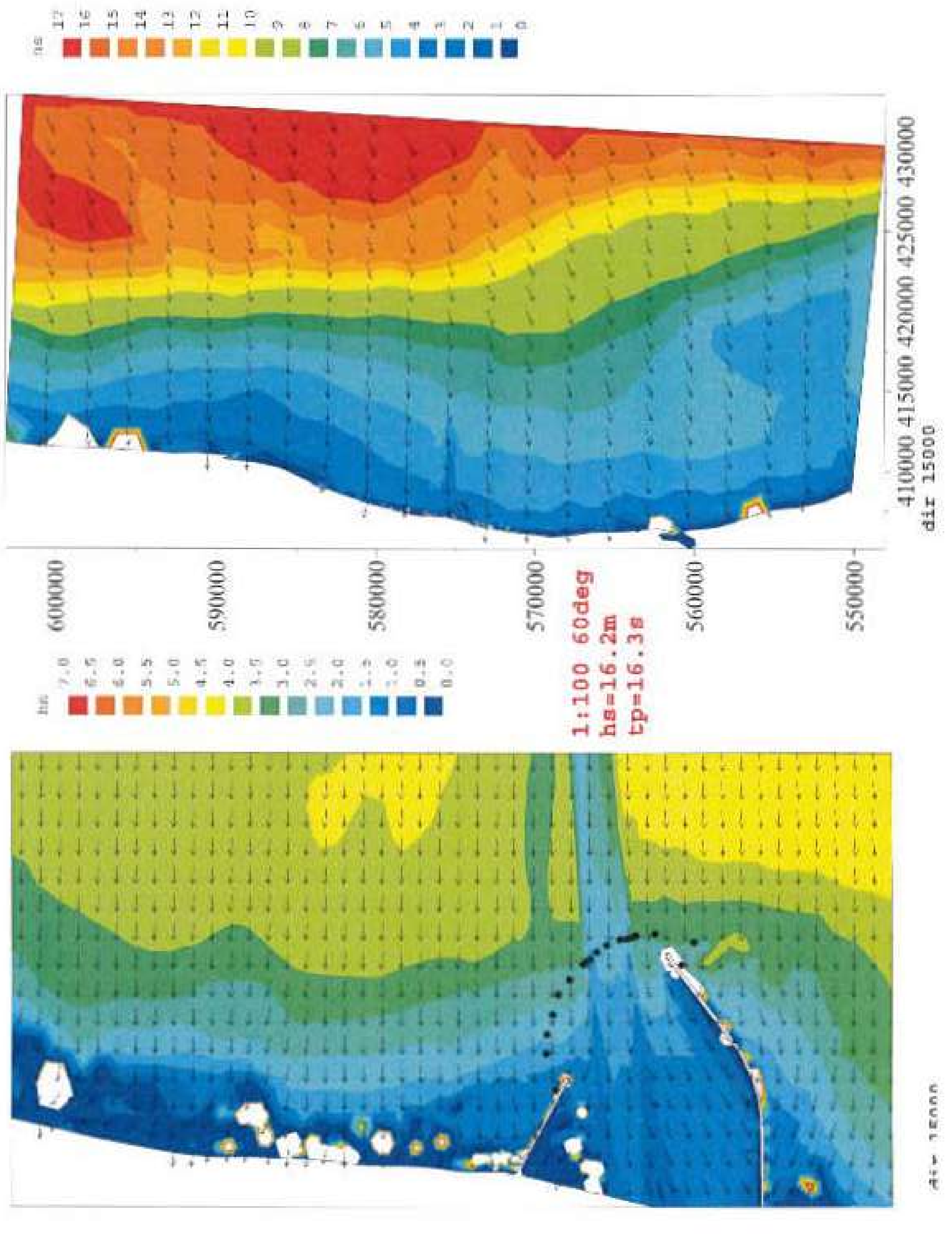

Figure 3.9 **Significant wave height and direction from Tomawac 1 in 100 year, Hs0=16.2m, tp0=16.3s, dir=60°N**

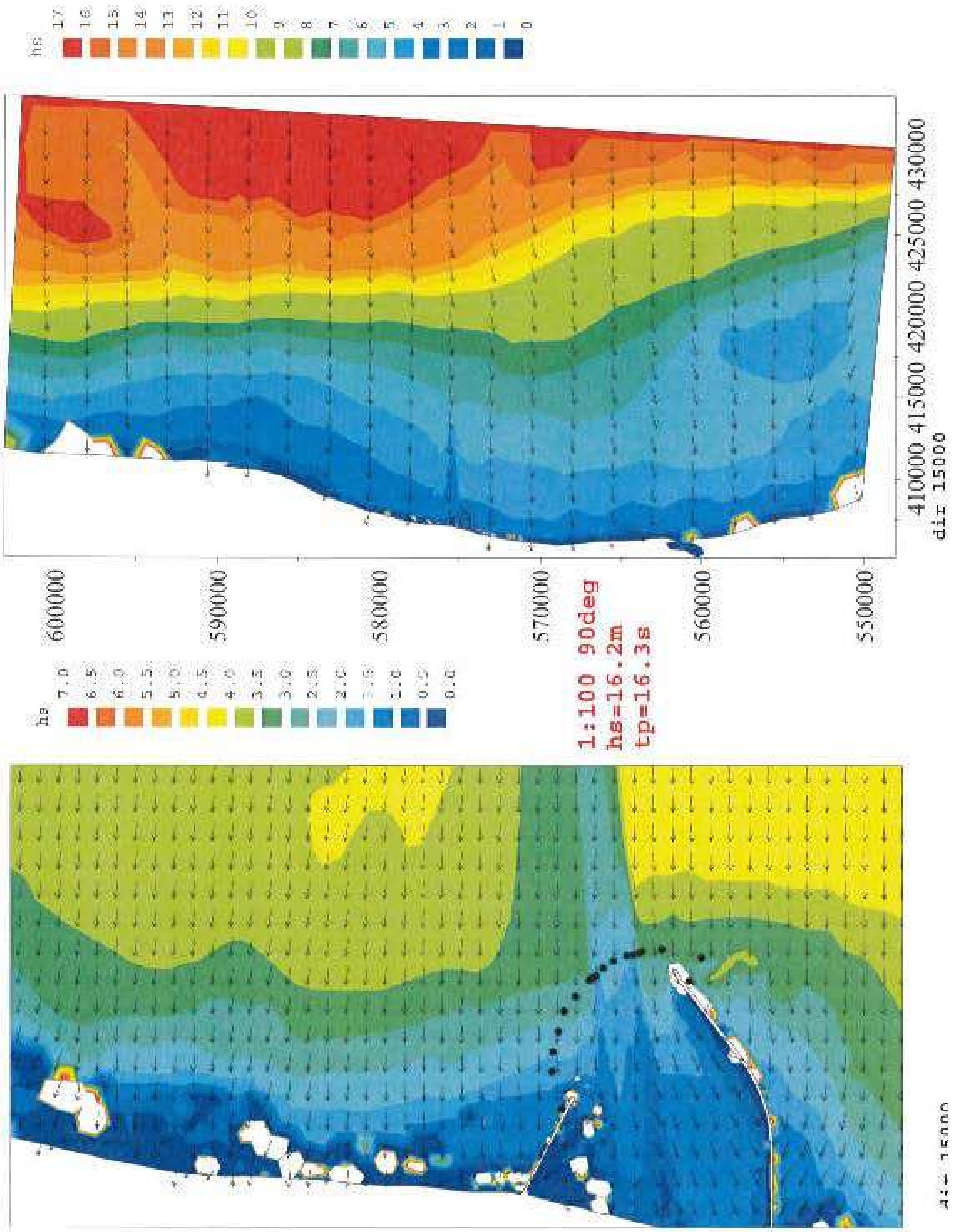

Figure 3.10 Significant wave height and direction from Tomawac 1 in 100 year, Hs0=16.2m, tp0=16.3s, dir=90°N

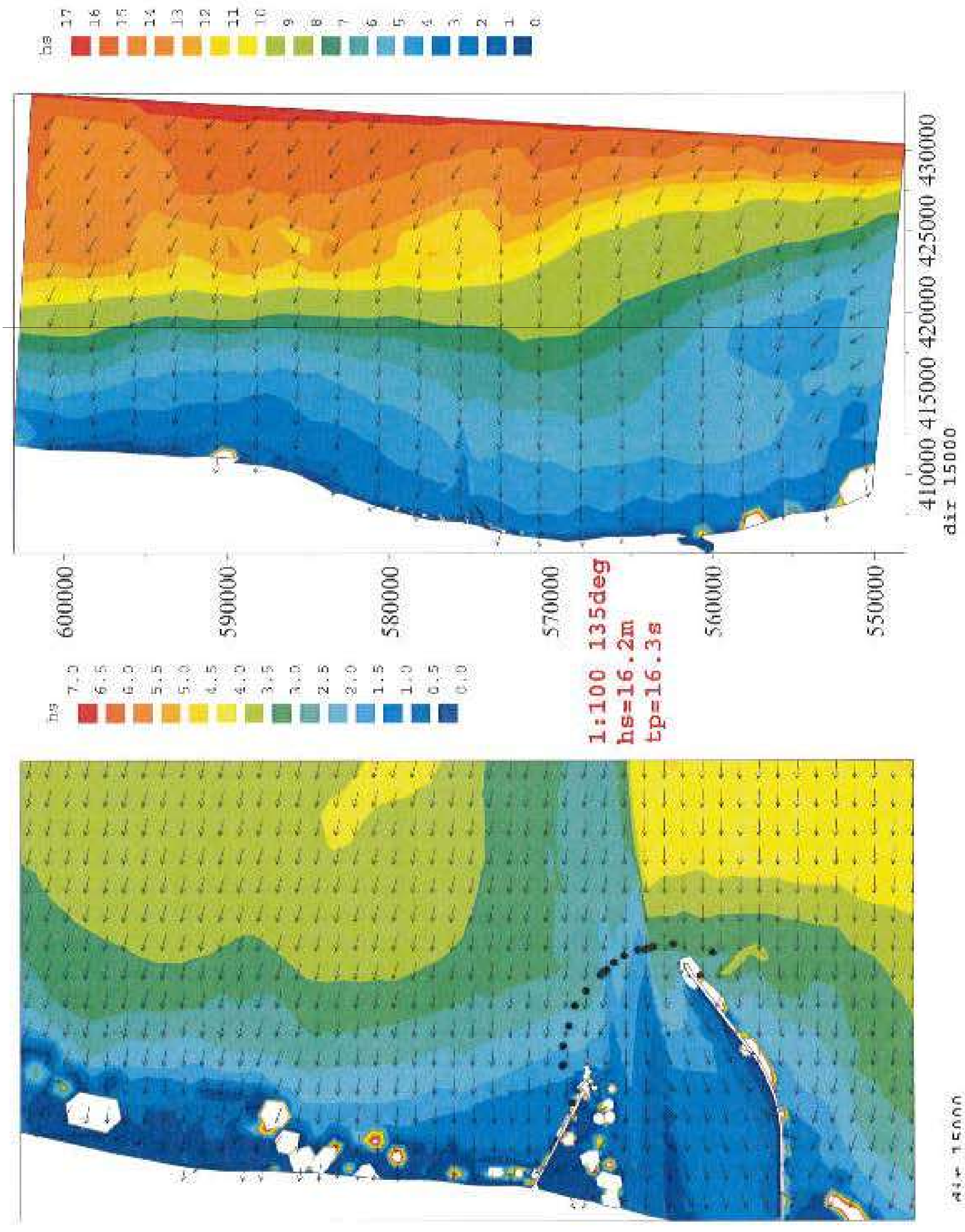

Figure 3.11 Significant wave height and direction from Tomawac 1 in 100 year, Hs0=16.2m, tp0=16.3s, dir=135°N

Figure 3.12 ARTEMIS model bathymetry and prediction points: Phase I

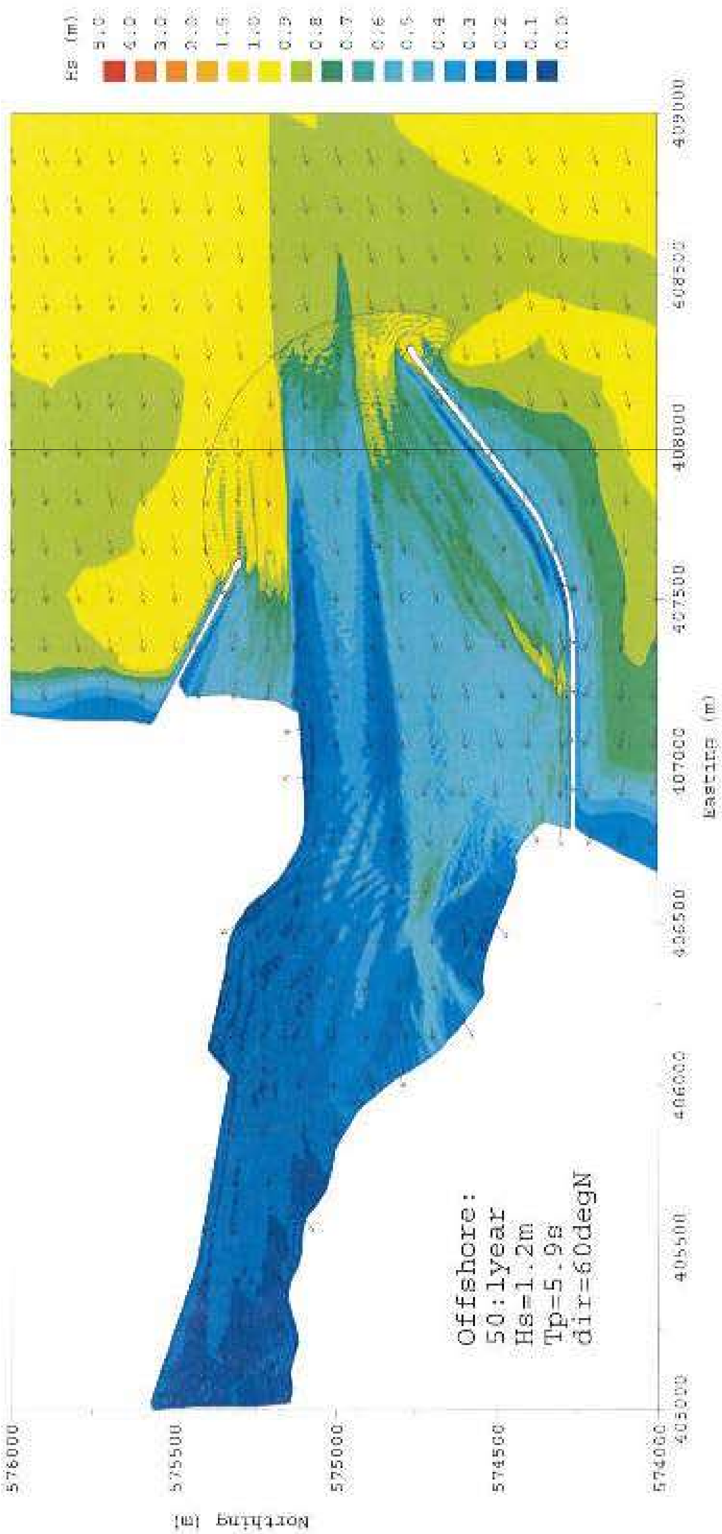

Figure 3.13 Waves for Phase I layout: 50:1 year return period from 60°N

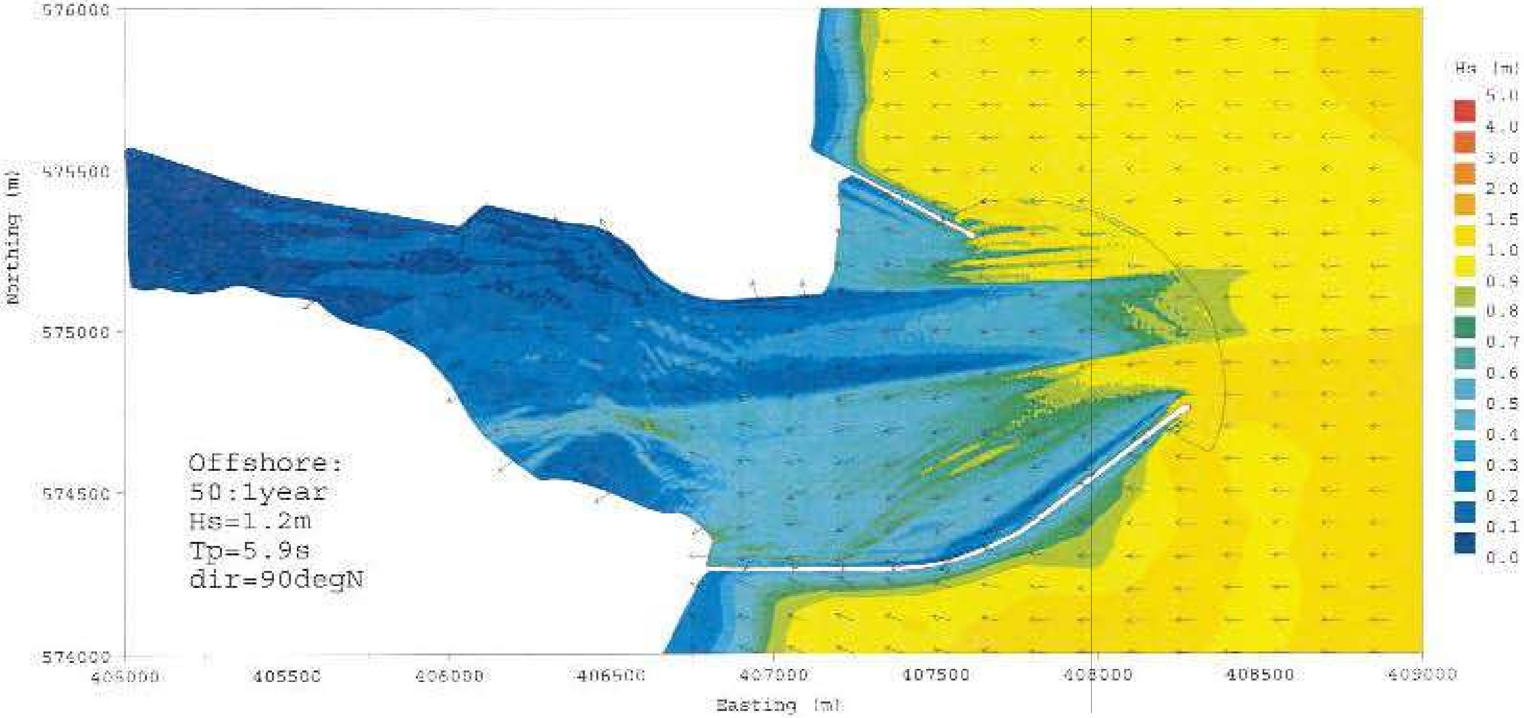

Figure 3.14 Waves for Phase 1 layout: 50:1 year return period from 90°N

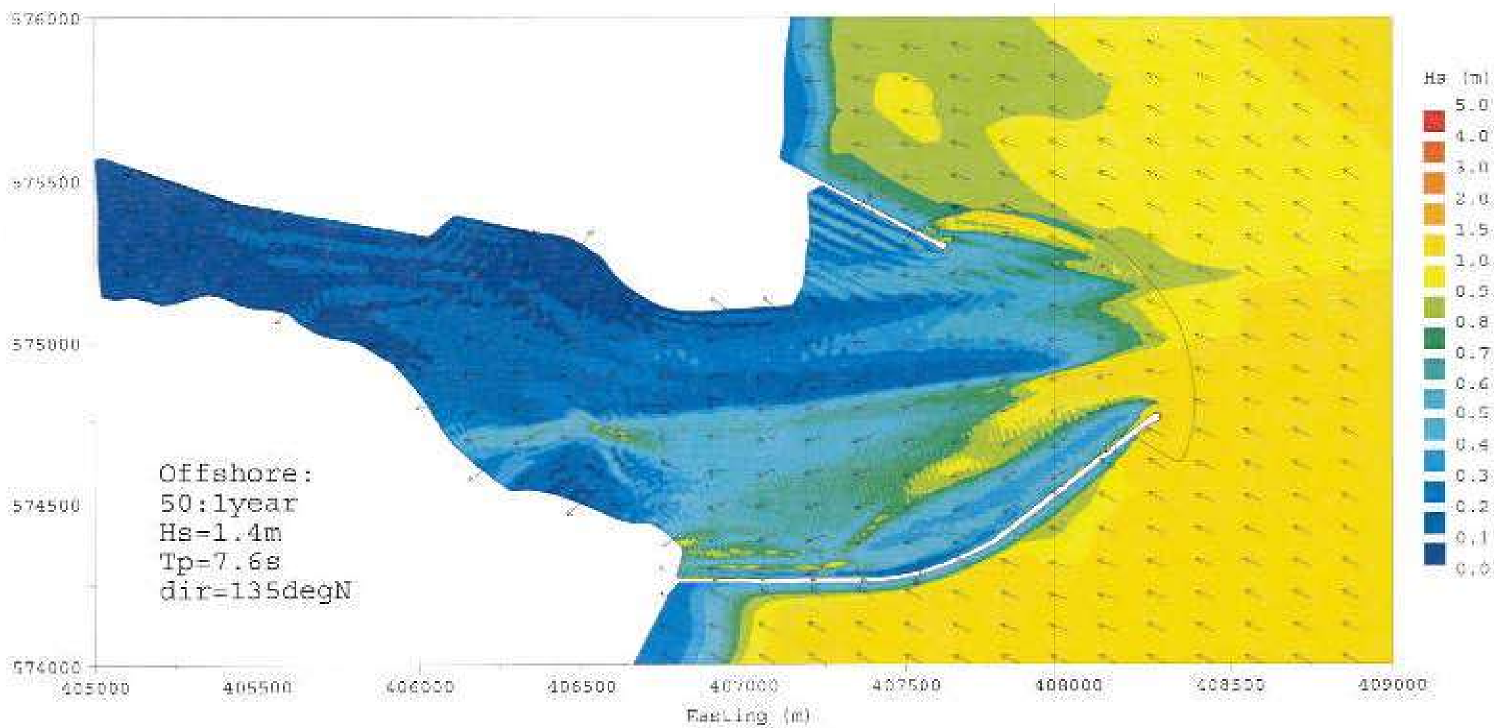

Figure 3.15 Waves for Phase 1 layout: 50:1 year return period from 135°N

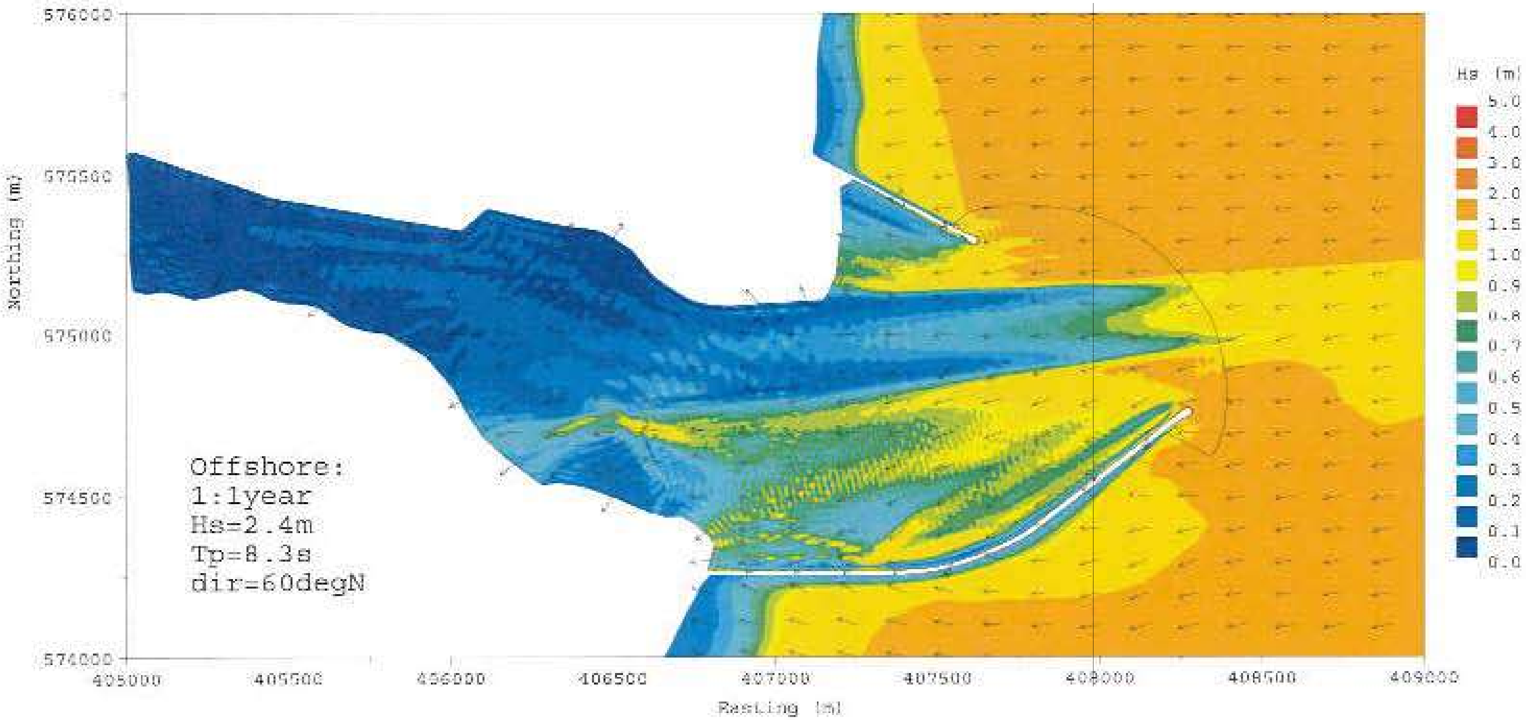

Figure 3.16 Waves for Phase I layout: 1:1 year return period from 60°N

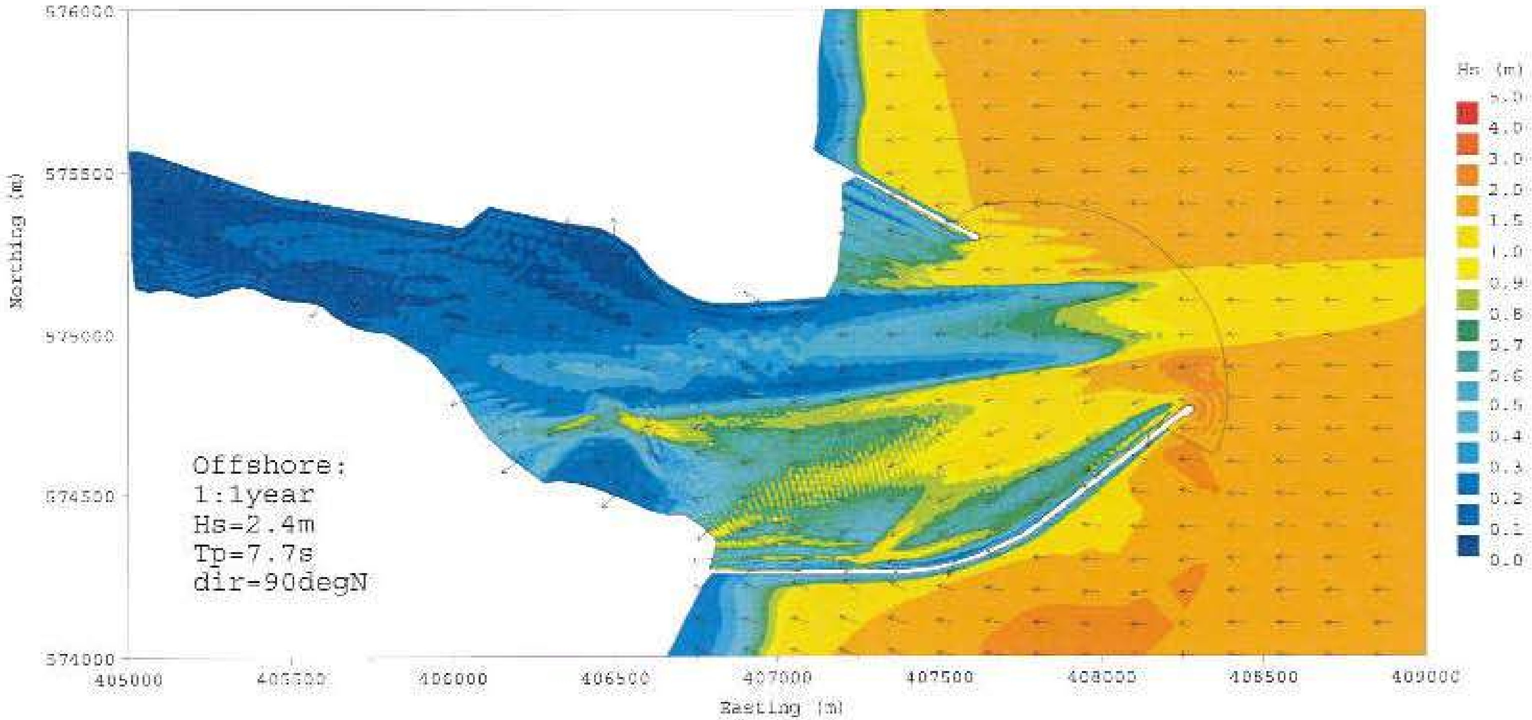

Figure 3.17 Waves for Phase 1 layout: 1:1 year return period from 90°N

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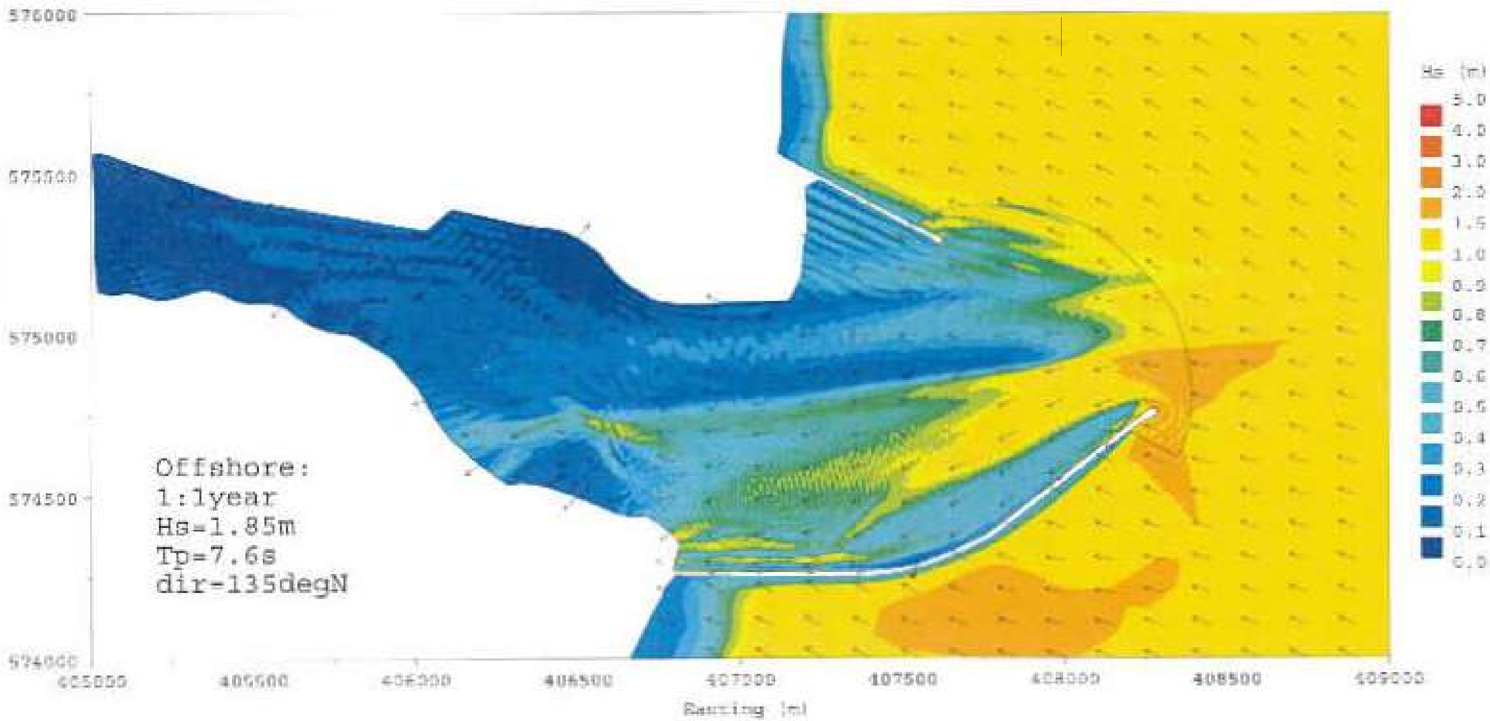

Figure 3.18 Waves for Phase I layout: 1:1 year return period from 135°N

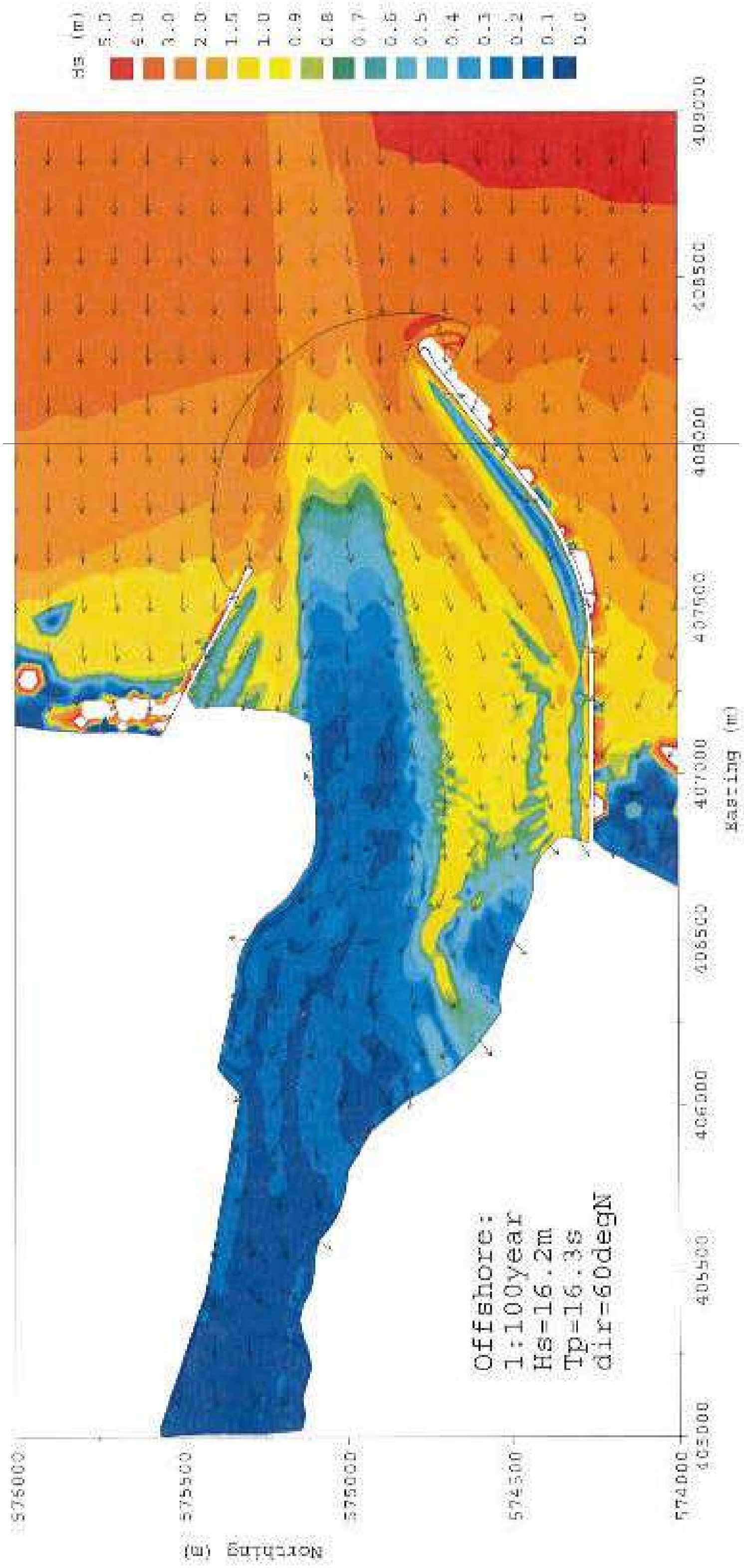

Figure 3.19 Waves for Phase I layout: 1:100 year return period from 60°N

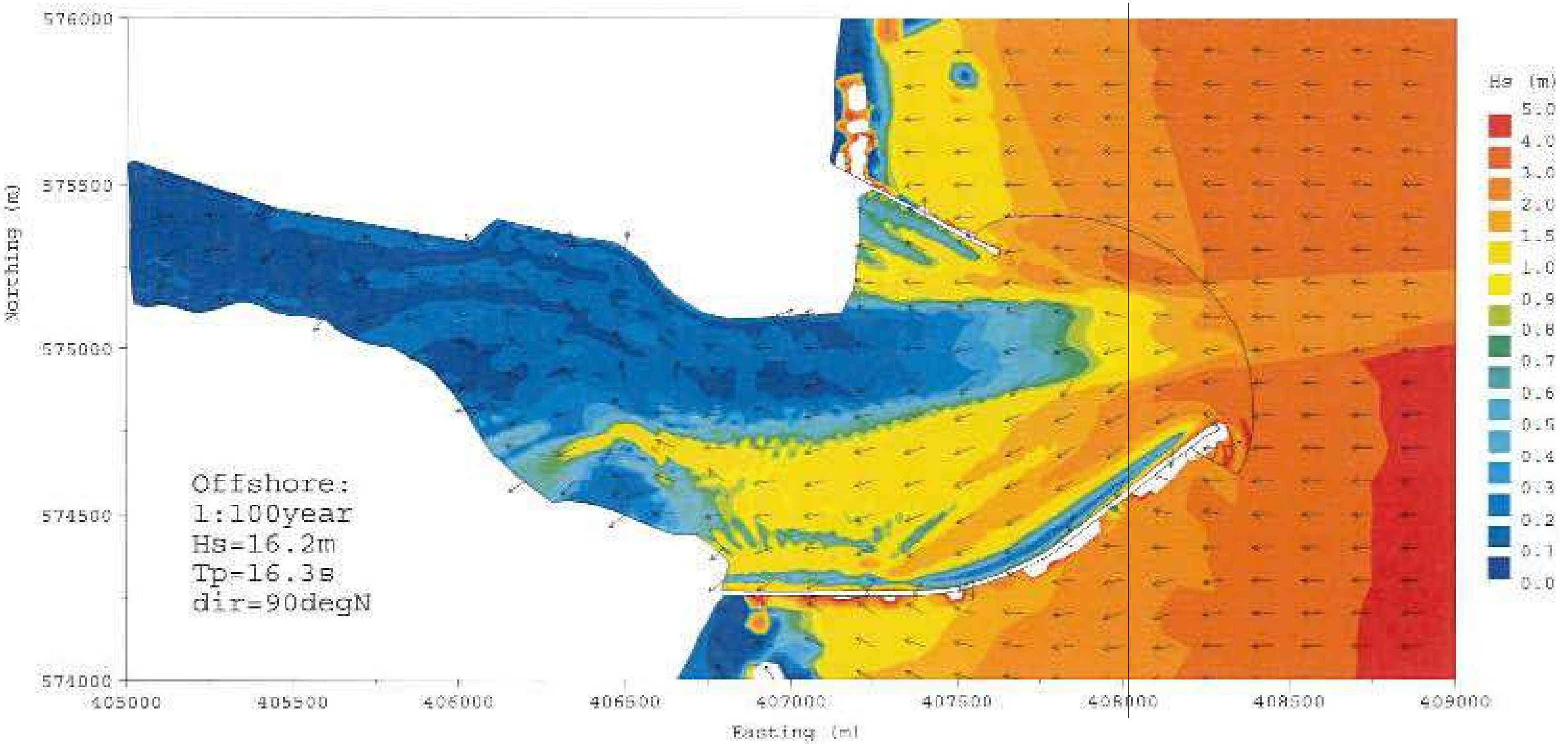

Figure 3.20 Waves for Phase I layout: 1:100 year return period from 90°N

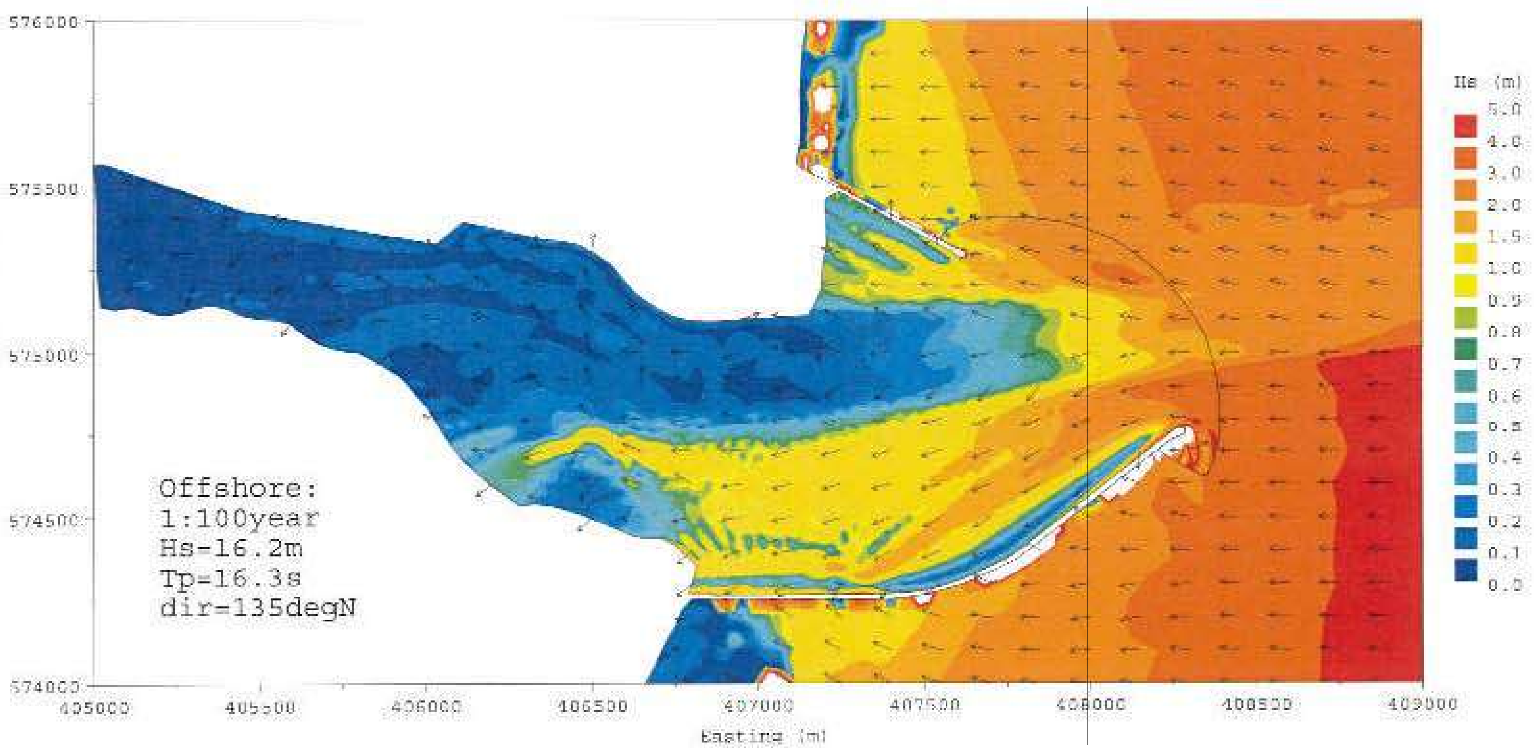

Figure 3.21 Waves for Phase I layout: 1:100 year return period from 135°N

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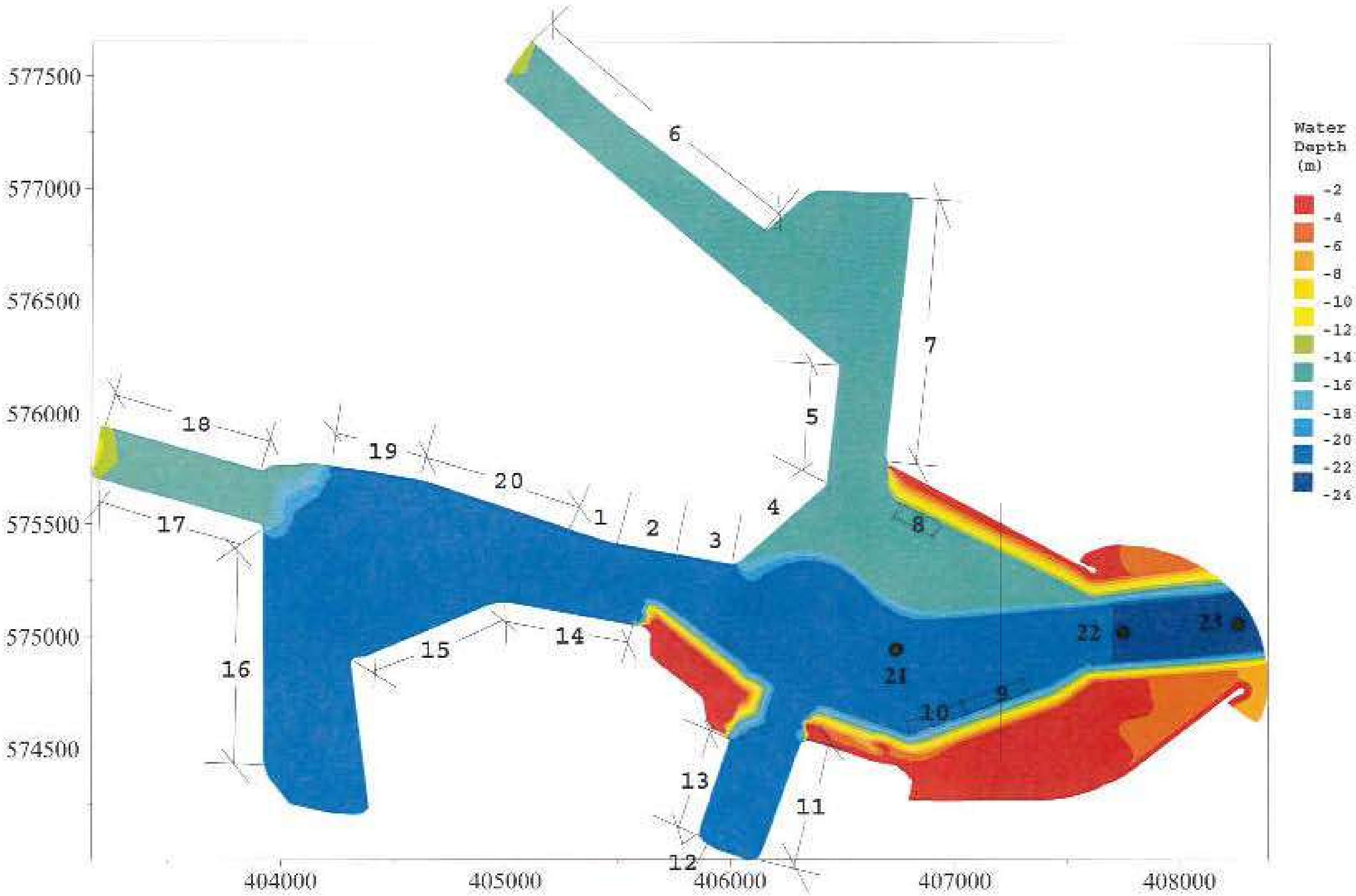


Figure 3.22 ARTEMIS model bathymetry and prediction points: Phase II

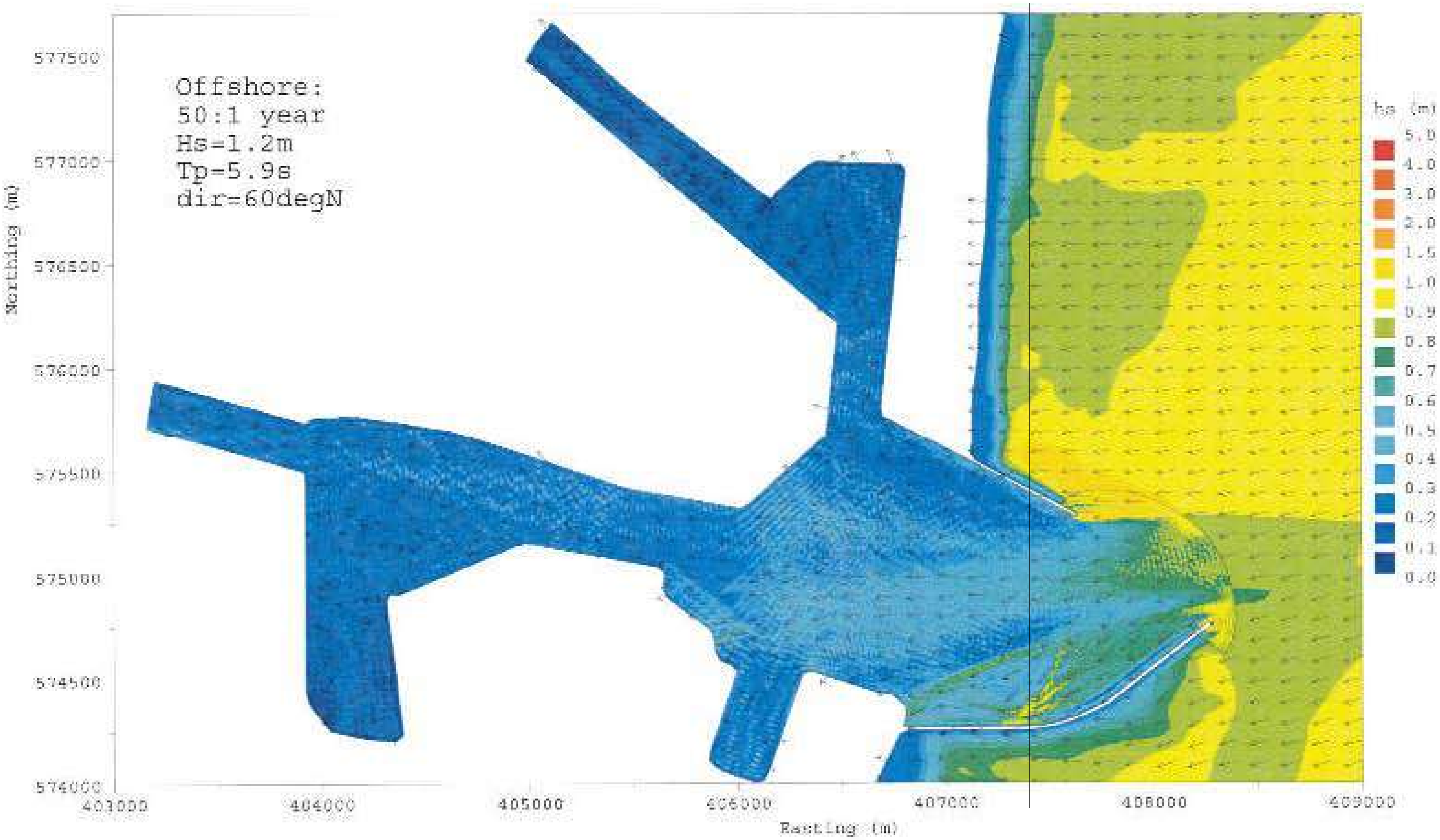


Figure 3.23 Waves for Phase II layout: 50:1 year return period from 60°N

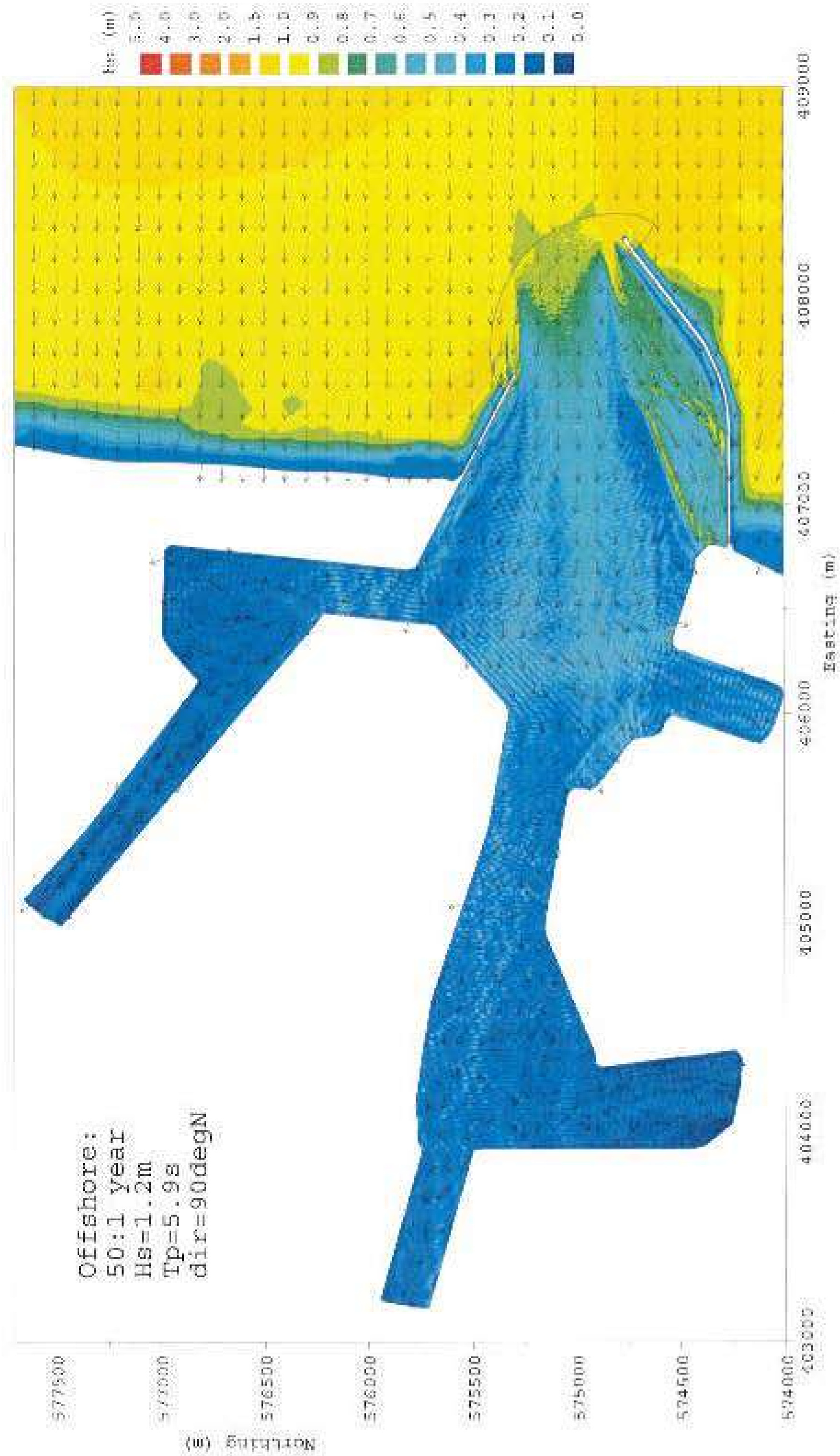


Figure 3.24 Waves for Phase II layout: 50:1 year return period from 90°N

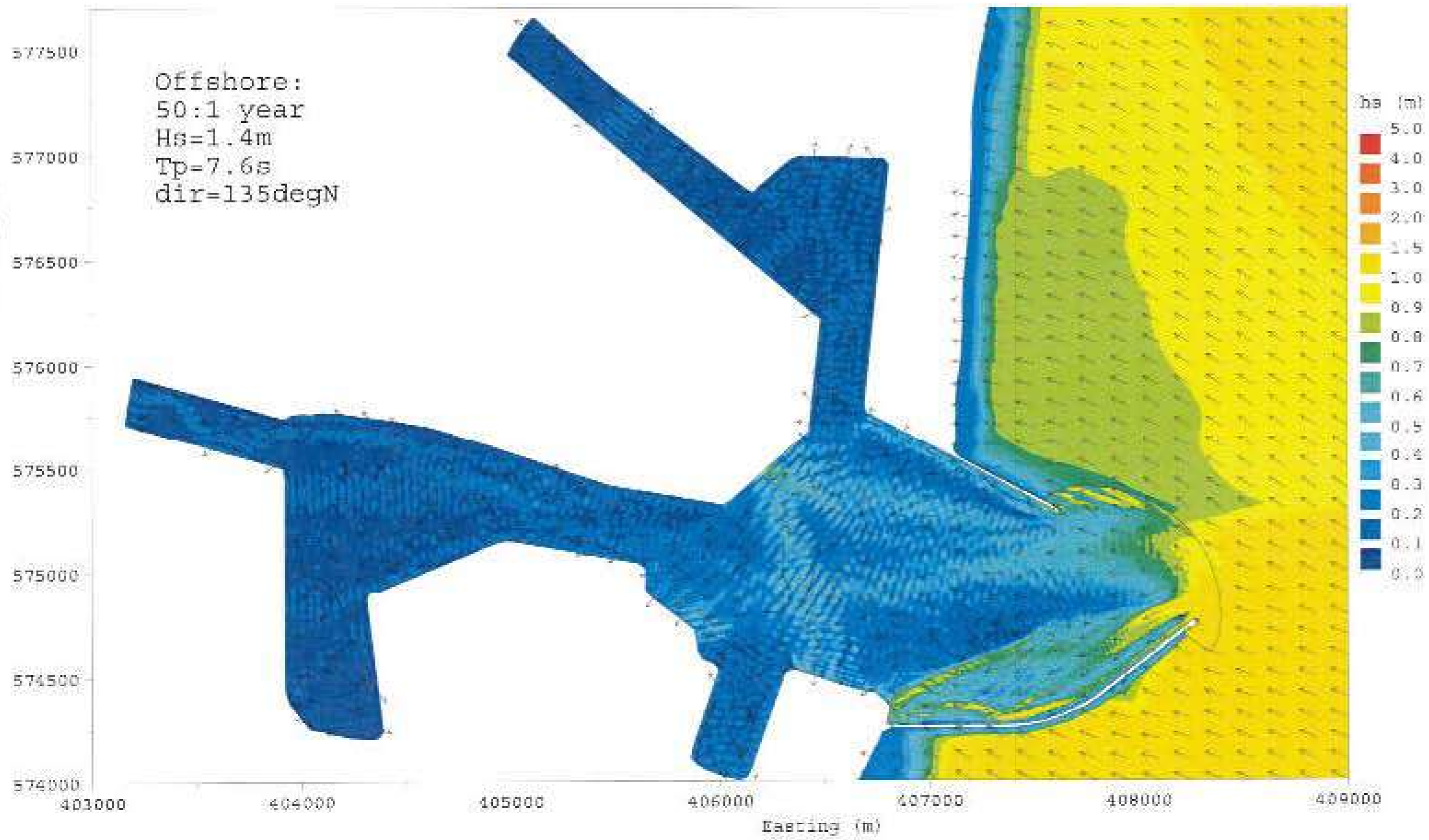


Figure 3.25 Waves for Phase II layout: 50:1 year return period from 135°N

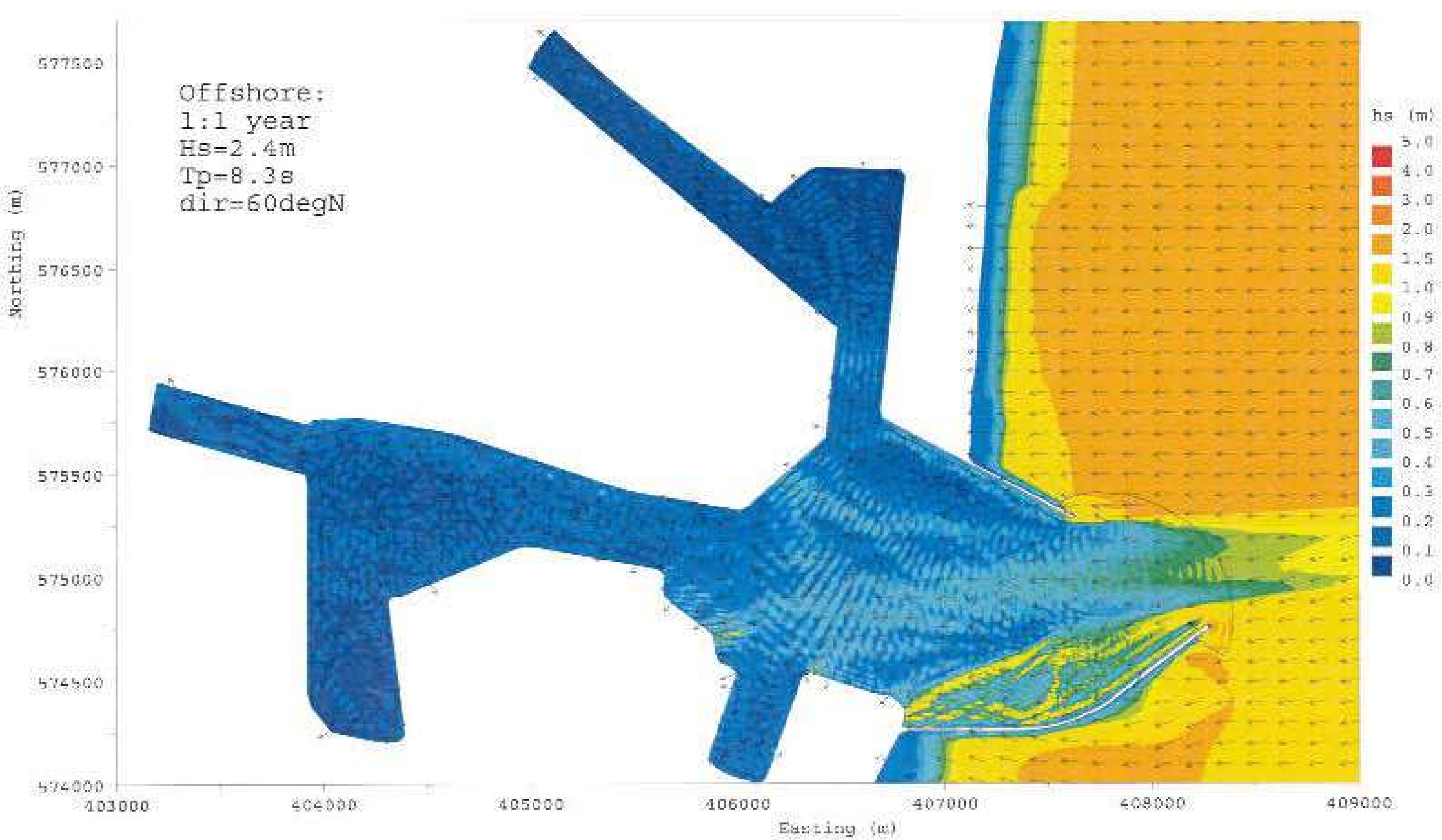


Figure 3.26 Waves for Phase II layout: 1:1 year return period from 60°N

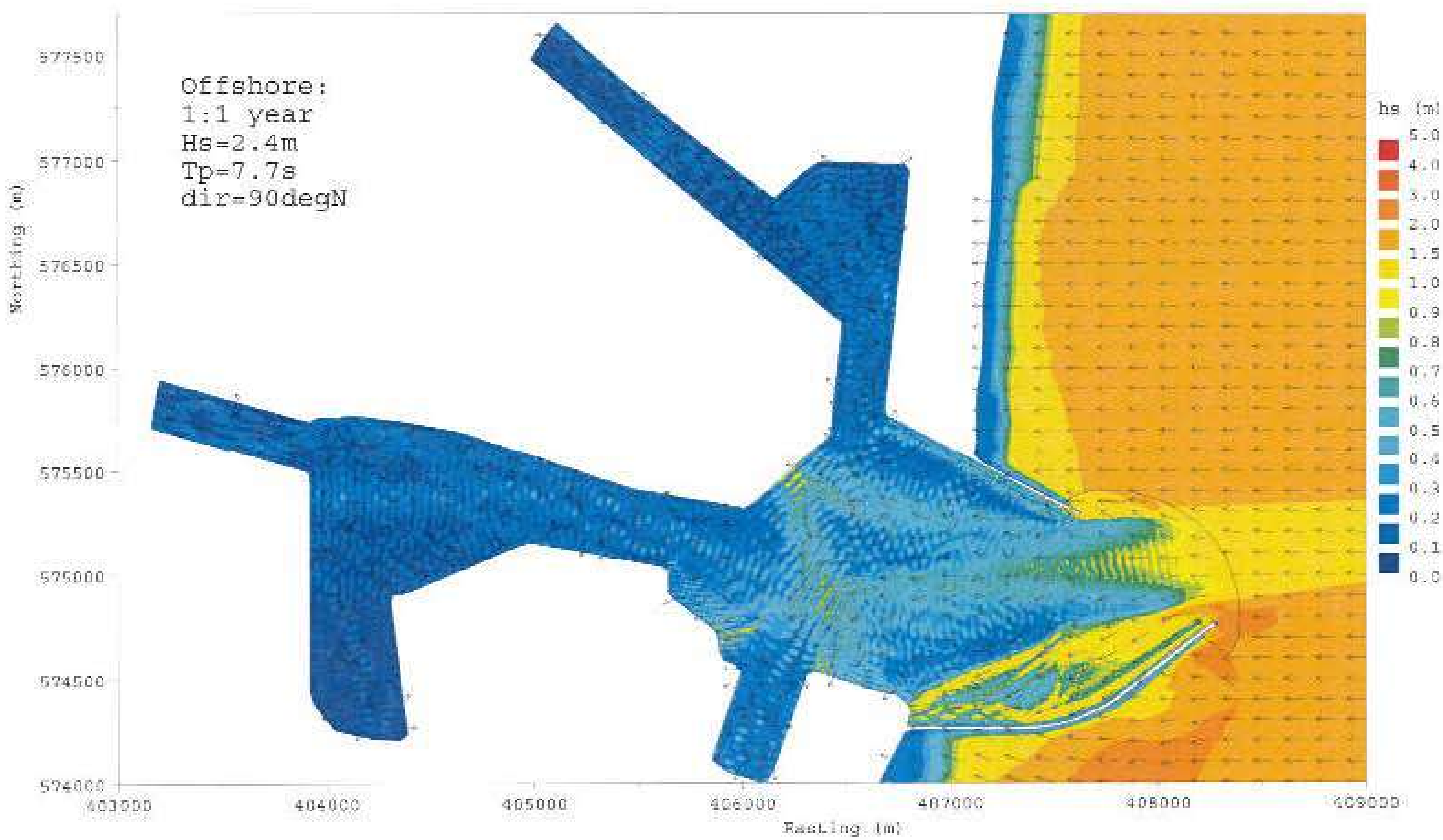


Figure 3.27 Waves for Phase II layout: 1:1 year return period from 90°N

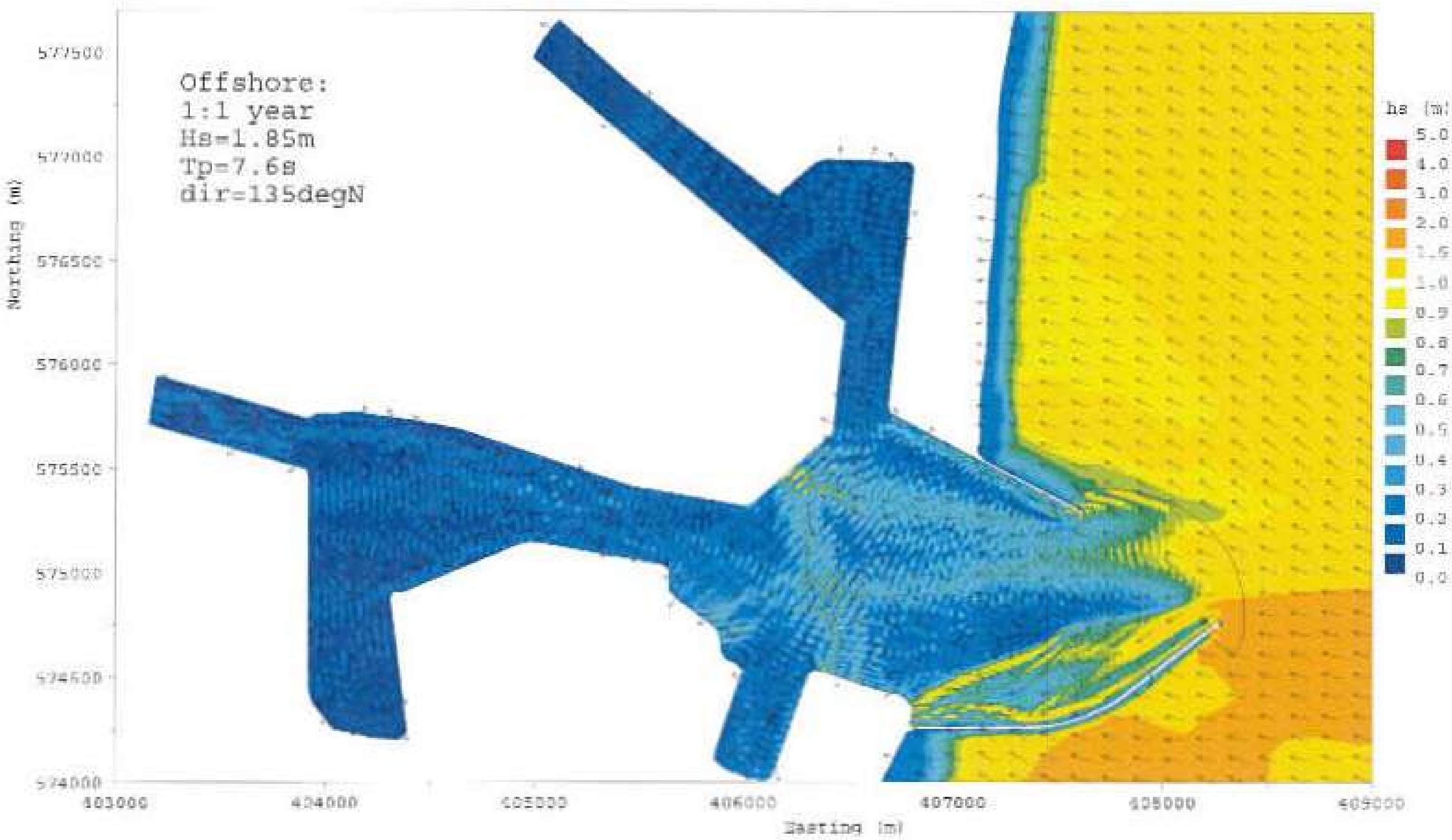


Figure 3.28 Waves for Phase II layout: 1:1 year return period from 135°N

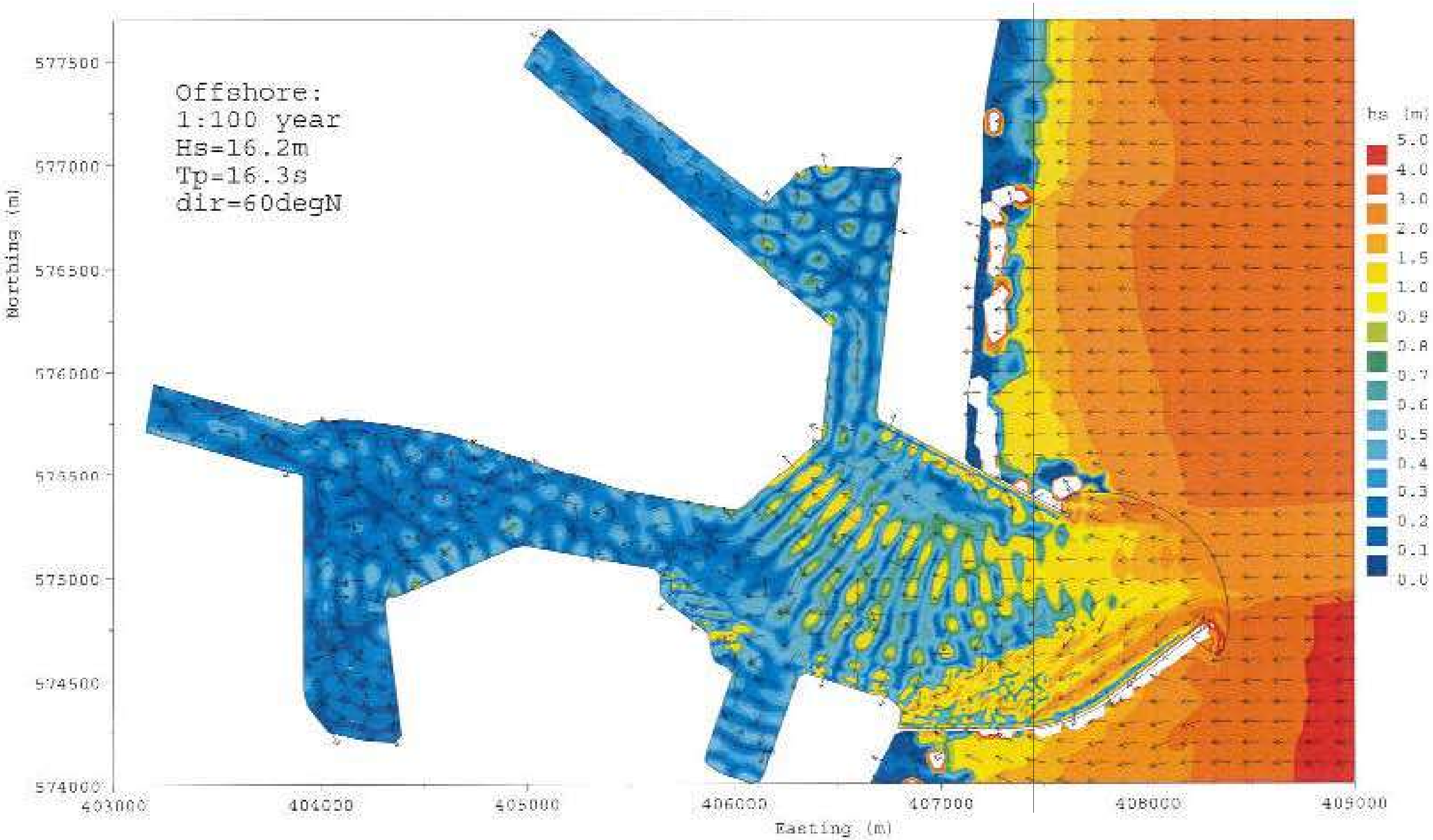


Figure 3.29 Waves for Phase II layout: 1:100 year return period from 60°N

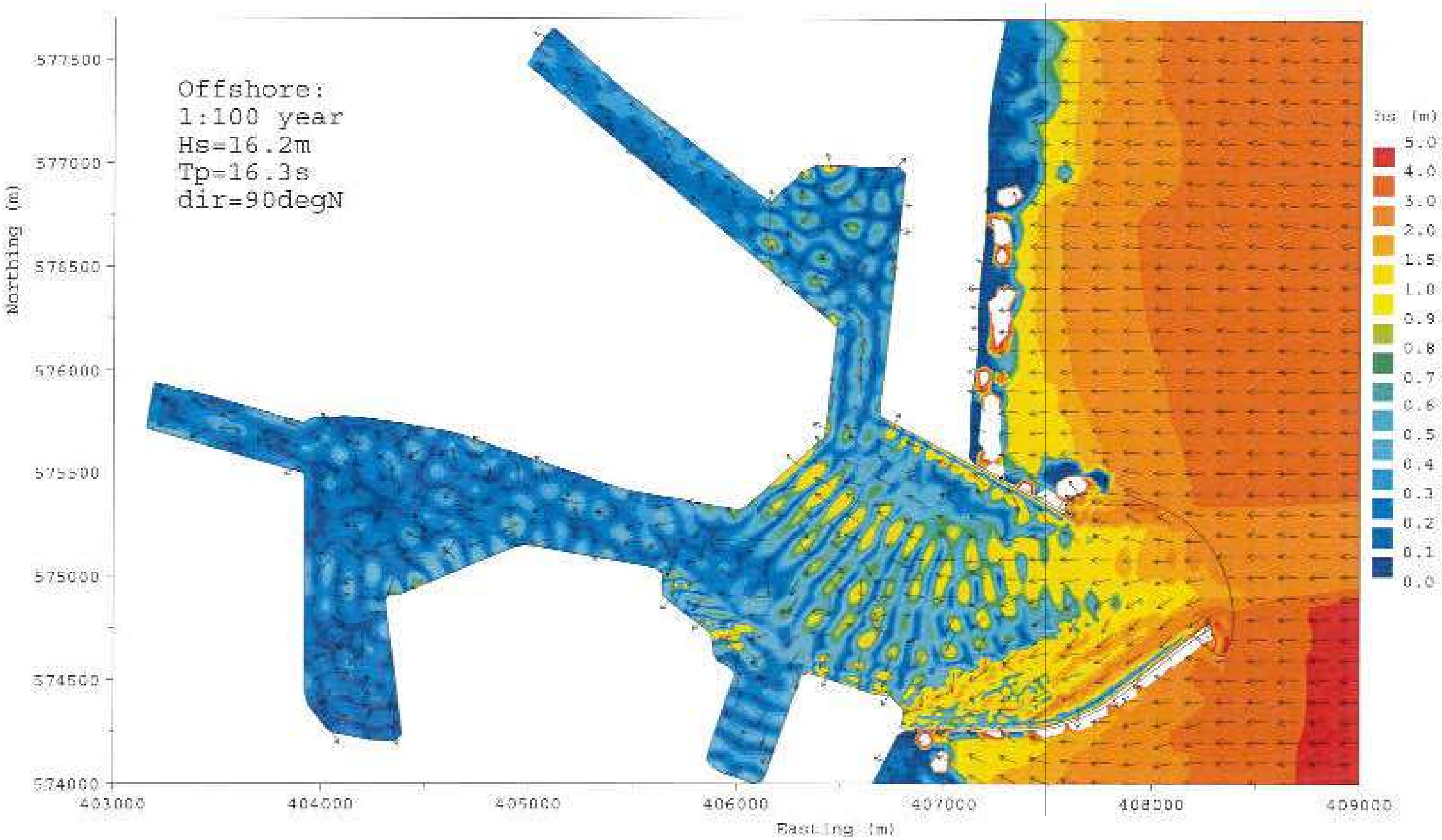


Figure 3.30 Waves for Phase II layout: 1:100 year return period from 90°N

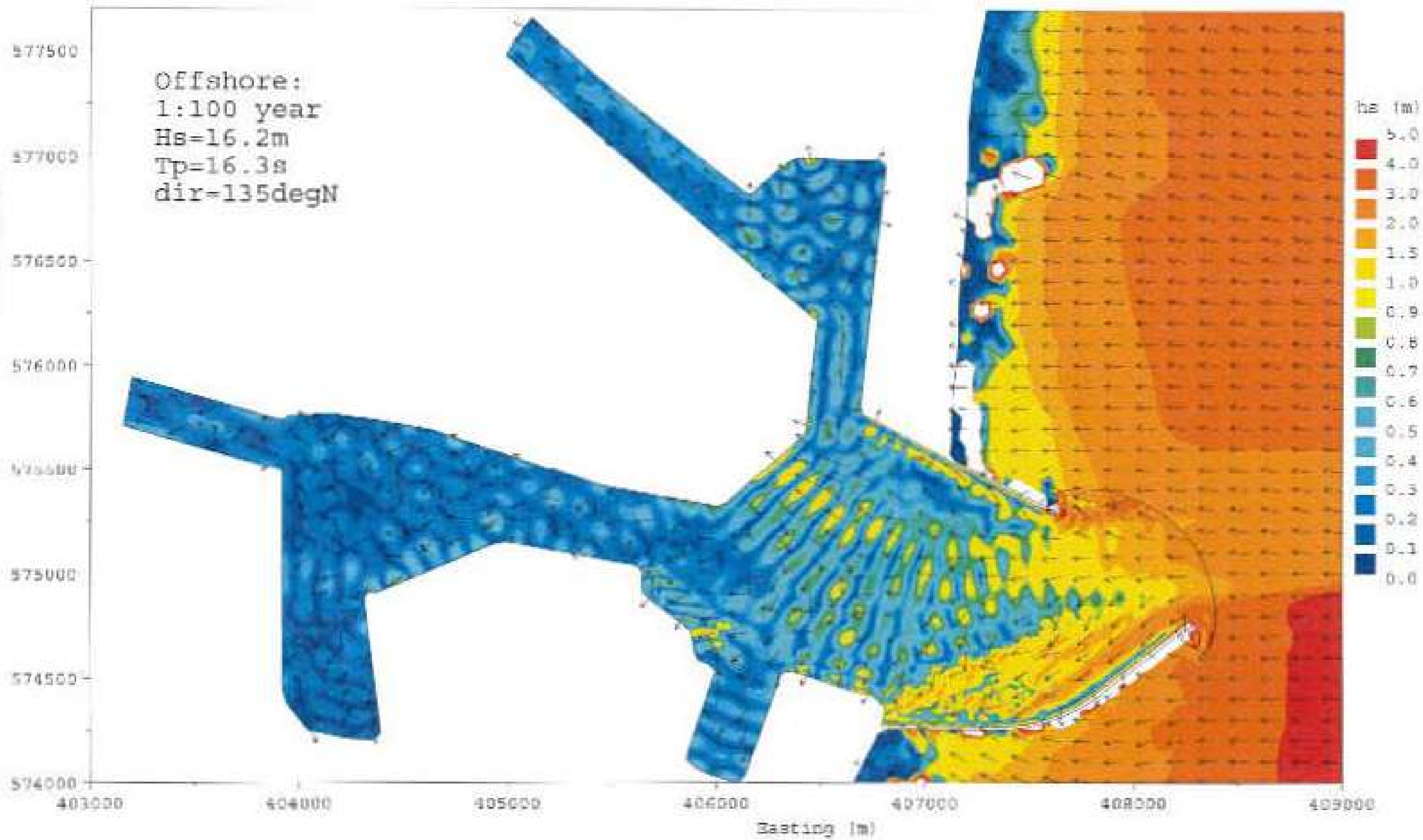
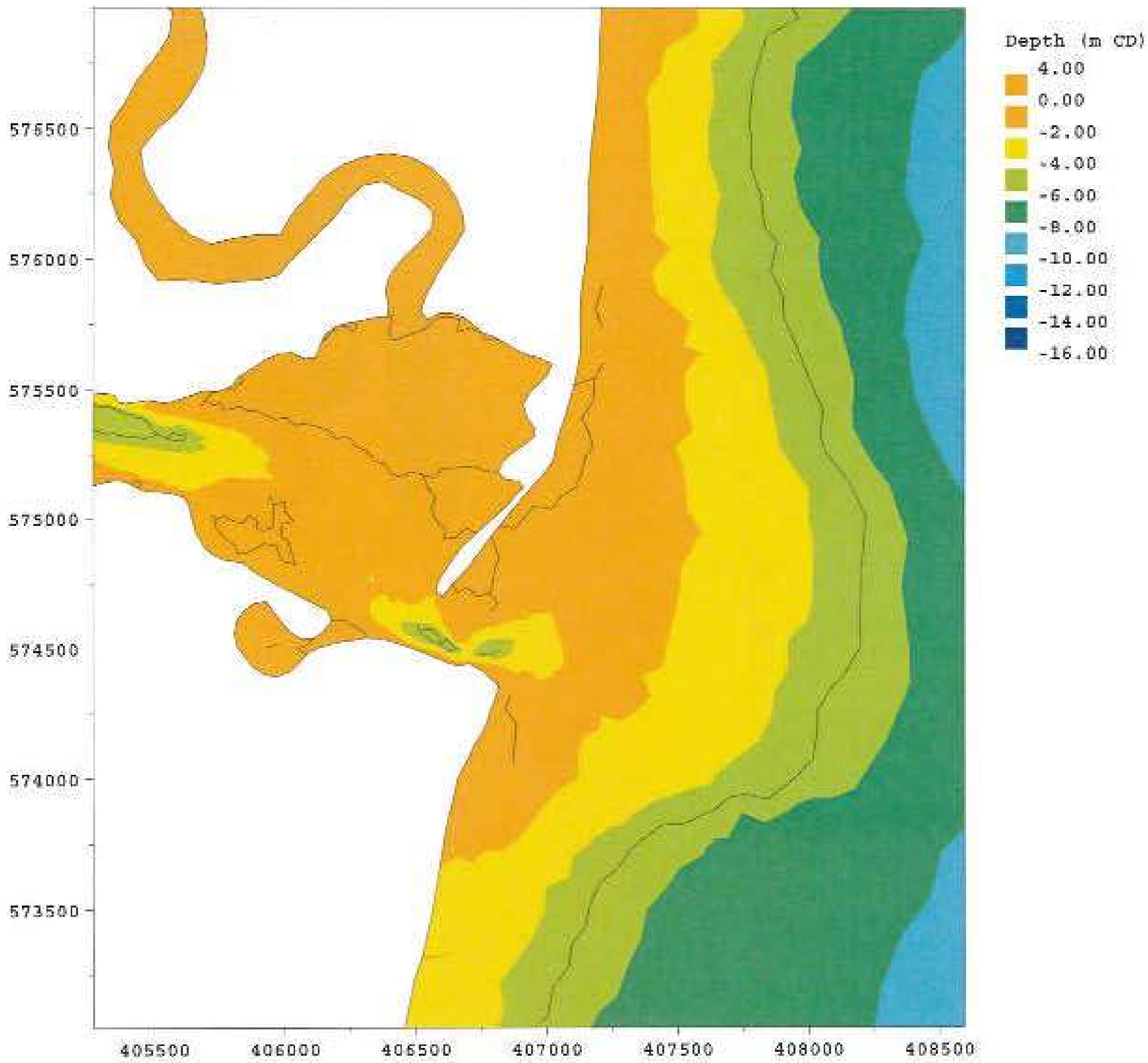


Figure 3.31 Waves for Phase II layout: 1:100 year return period from 135°N

Figure 4.1 PISCES Model bathymetry – Existing scenario



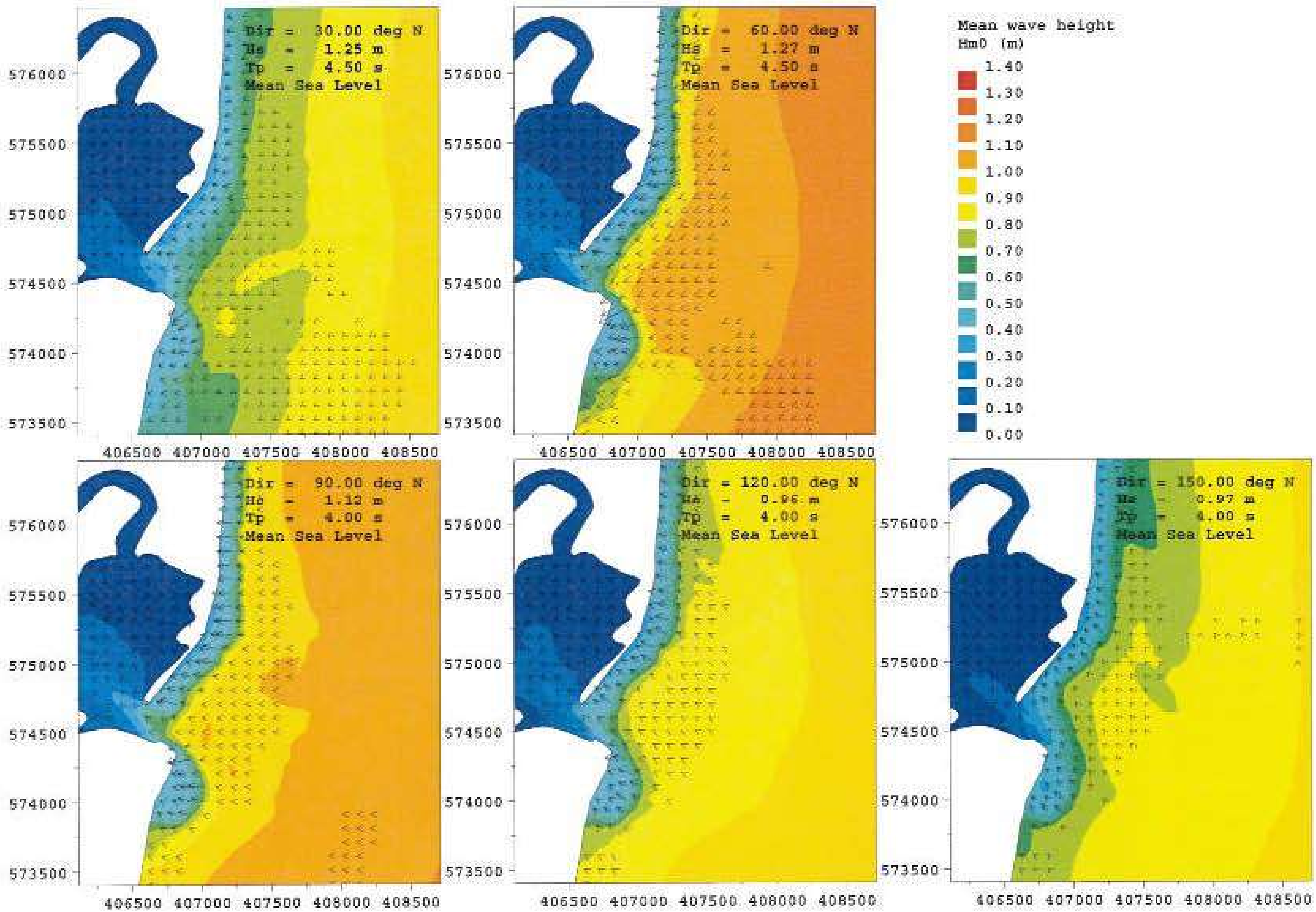


Figure 4.2 Mean wave height for the 5 representative wave conditions – Existing case

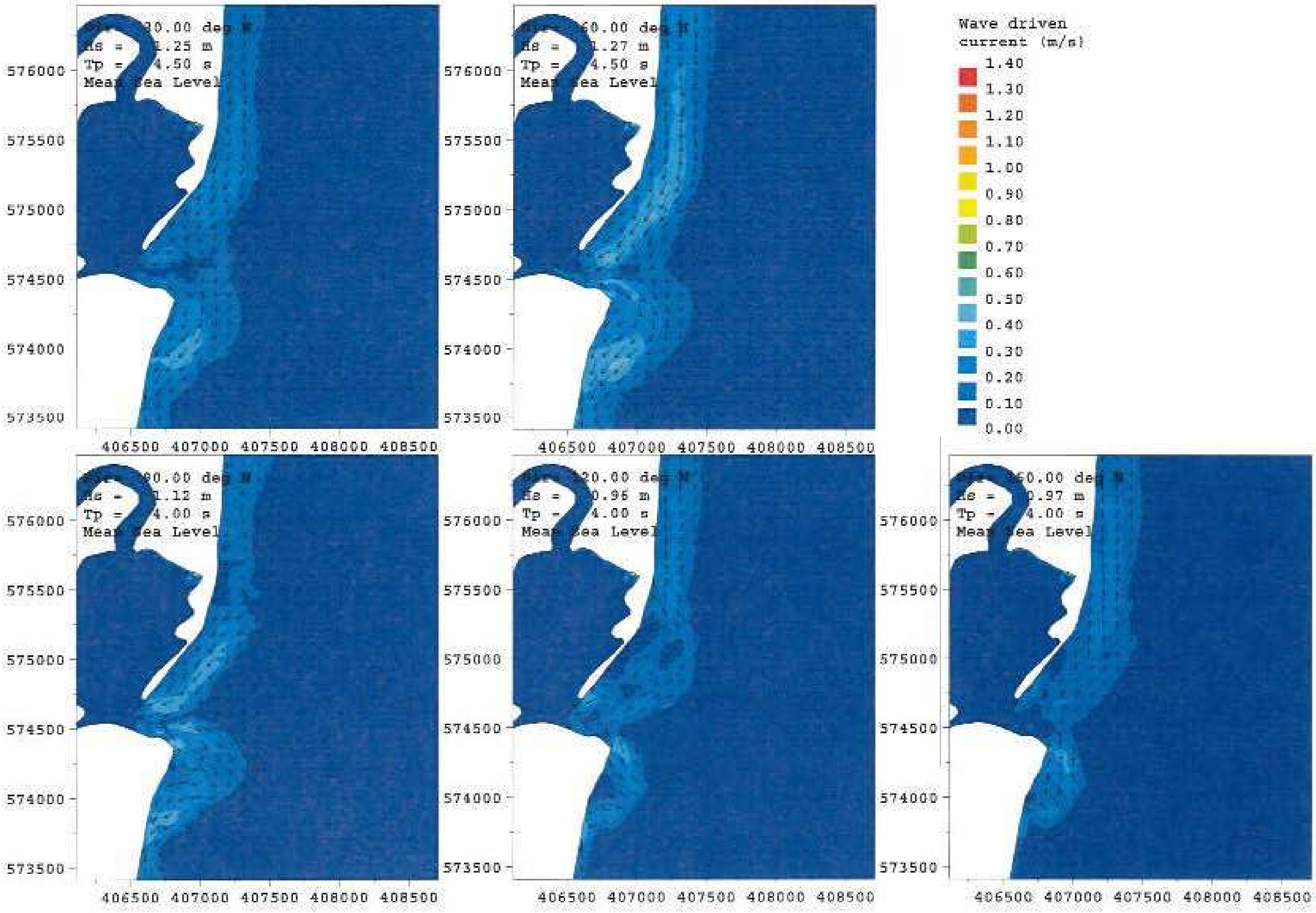


Figure 4.3 Wave-driven currents for the 5 representative wave conditions – Existing case