January 2024

Assessment of Impact on the Maritime Usage Report – Volume 4

Navigation Maintenance Dredging 2026-2033

On behalf of

Port of Waterford

MALONE O'REGAN

MALONE O'REGAN ENVIRONMENTAL

QUALITY
I.S. EN ISO 9001:2015
NSAI Certified

Form ES - 04

MALONE O'REGAN
ENVIRONMENTAL

[redacted]

Title: Assessment of Impact on the Maritime Usage Report – Volume 4, Navigation Maintenance Dredging 2026-2033, Port of Waterford

Job Number: E2042

Prepared By: [redacted] **Signed:** [redacted] __________

Checked By: **Signed:** __________

Approved By: **Signed:** __________

Revision Record

Issue No.	Date	Description	Remark	Prepared	Checked	Approved
01	26/01/24	ER Report – Vol 4	FINAL	AK	KOR	KOR

Assessment of Impact on the Maritime Usage Report – Volume 4

Navigation Maintenance Dredging 2026-2033

Port of Waterford

Contents

APPENDICES

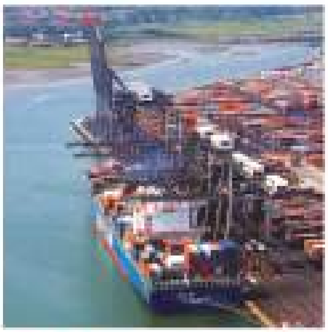
APPENDIX G-1

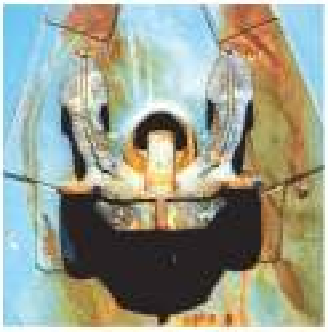
Port of Waterford

Port of Waterford: Dredge Disposal

Numerical modelling of disposal plumes

December 2023

Innovative Thinking - Sustainable Solutions

Page intentionally left blank

Port of Waterford: Dredge Disposal

Numerical modelling of disposal plumes

December 2023

Document Information

Document History and Authorisation		
Title	Port of Waterford: Dredge Disposal	
	Numerical modelling of disposal plumes	
Commissioned by	Port of Waterford	
Issue date	December 2023	
Document ref	R.4322	
Project no	R/5257/02	
Date	**Version**	**Revision Details**
15/08/2023	0.1	Working document for client comment
08/09/2023	1	Issue for client review
10/11/2023	2	Issued for client use - Comments addressed
08/12/2023	3	Issued for client use – Table amendment

Prepared	Approved	Authorised
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]

Suggested Citation

ABPmer, (2023). Port of Waterford: Dredge Disposal, Numerical modelling of disposal plumes, ABPmer Report No. R.4322. A report produced by ABPmer for Port of Waterford, December 2023.

ABPmer

[redacted]

Contents

Appendices

Tables

Figures

1 Introduction

The Port of Waterford (PoW) is considering the future options for improving efficiency (technical and financial) of existing dredging operations. To complement and inform this scope of works, the PoW has previously commissioned ABPmer to develop detailed estuary wide numerical hydrodynamic and sediment transport models. These models are capable of replicating the present environmental conditions, in order to assess the physical effects of on-going port operations, including maintenance dredging and disposal.

The previous modelling studies have been supported by the development of an estuary (conceptual) understanding. This creates the baseline information related to the on-going estuary processes, trends, and physical characteristics, and has aided the subsequent interpretation of the field survey measurements and modelling results, in the context of the natural physical environment and client objectives. The estuary (conceptual) understanding has been documented previously, in ABPmer 2017a. The model build, and calibration, has also been supported by an extensive survey campaign, which is described, along with presentation of the results, in ABPmer 2017b.

The numerical models have been built using the Danish Hydraulic Institute (DHI) software package MIKE3FM (Flexible Mesh), which was developed by DHI for complex applications within oceanographic, coastal and estuarine environments. MIKE3FM simulates the water level variation and three-dimensional flows in the area of interest. Additional modules have been implemented to assess dredge plume tracking and sediment transport processes throughout the estuary and the immediate offshore region. The model development, calibration and validation are the subject of ABPmer 2017c.

This report focusses on the characterisation of the dispersion of deposited dredged sediment at the licensed disposal ground situated at the entrance to Waterford Estuary within the Port of Waterford limits; see Figure 1 for location.

The dredging and disposal operations within the Waterford Estuary have previously been assessed through numerical modelling by Deltares (Eysink *et al*., 2000 and Eysink *et al*., 2001). These studies applied a series of numerical hydrodynamic modelling tools, assessing the hydrodynamics, waves, sediment transport and longer-term morphology of the wider study area. Analysis of the range of activities associated with dredging and disposal works was assessed, over a range of tidal and (storm) wave conditions and for the range of *in situ* sedimentary conditions (ranging from silts to sands) at each dredge location. The assessments investigated the fate of increased suspended sediments during dredging and disposal operations and the longer-term evolution of a disposal mound under a range of wave conditions (calm, moderate and rough).

The present study considers a series of full-dredge disposal operations, investigating the potential impacts on short-term suspended sediment concentrations and associated settling/ deposition. The modelling tools applied include the driving hydrodynamics and wave conditions associated with a defined storm event. The modelled sediment disposal includes the range of sediment components from the dredge sites (ranging from silts to sands), with disposal operations over both spring and neap tidal periods. Further detail on the assessment approach is provided in the following sections.

1.1 Modelling objective

The aim of this current study is to assess contemporary dredge disposal volumes from three locations within the estuary and review their potential impact on sensitive receptors in the vicinity of the disposal site (see Figure 1). The three areas from which dredge material is sourced are:

- Belview Quay (BV);
- Cheekpoint Lower Bar (CPLB); and
- Duncannon Bar (DC)

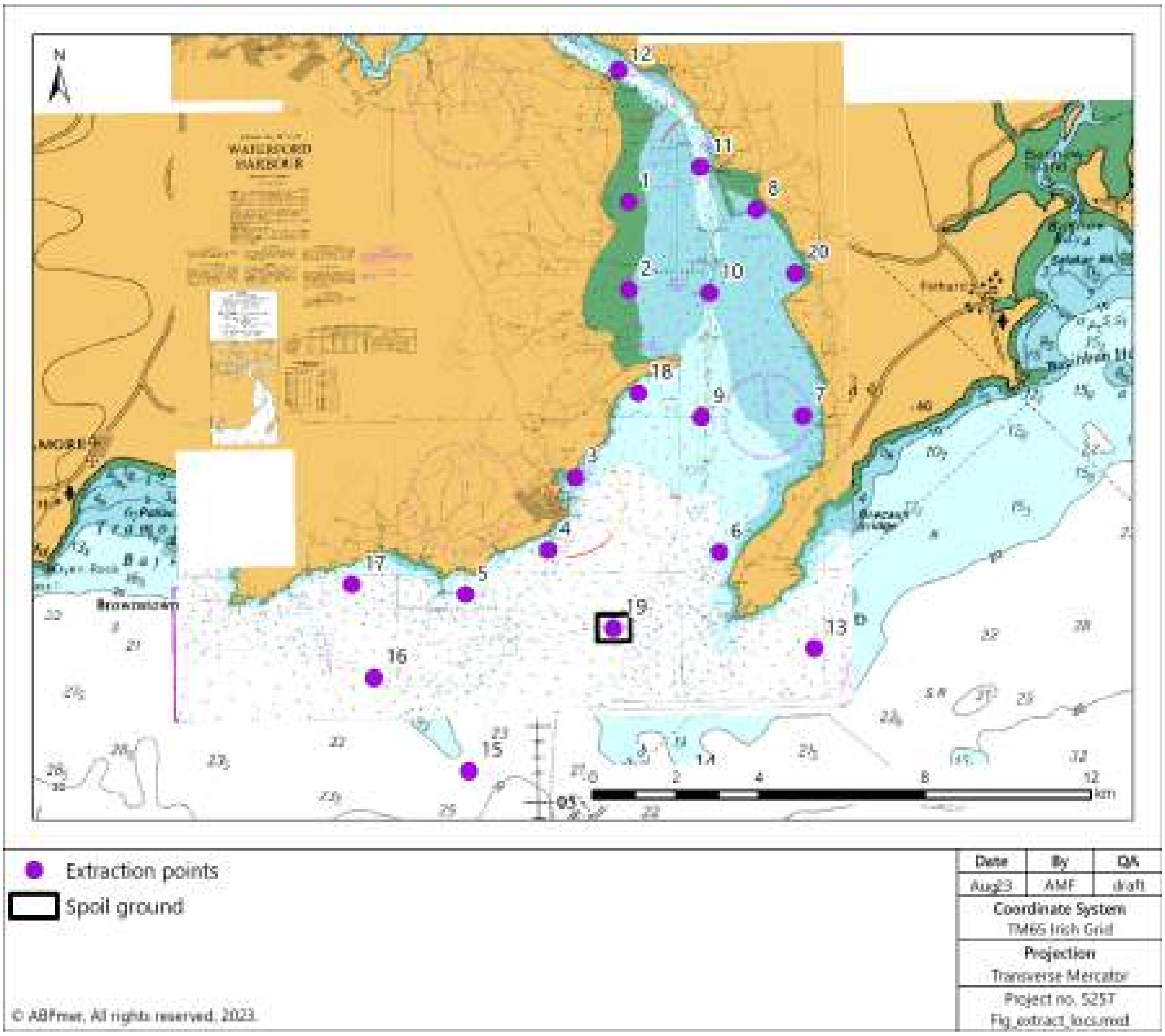


Figure 1. Disposal site and timeseries extraction locations

1.2 Model updates

The present study provides a modelling assessment of the dredge disposal site, the dredge material sources listed above and the existing layout of channels and structures within the wider Waterford Estuary.

Simulations of dredge disposal plumes have been assessed with current estimates of dredge quantities and a comprehensive set of sensitive receptors (provided by PoW and shown in Figure 1). Additionally, assessed storm conditions have also been updated with an indicative moderate storm generating a wave height of 3.5 m at the disposal site. Both these updates are discussed in greater detail in Sections 4.3 and 4.2.1 respectively.

2 Disposal Site Location

As shown on Figure 1, the existing disposal site covers an area of 800 m x 650 m (52 ha), in the centre of the entrance to the Waterford Estuary. The site is located at depths between 18 m and 21 m below Ordnance Datum Dublin (ODD), north to south, with isolated depths that shallow to 15.8 m below ODD. This could be the result of a hard outcrop, or the deposit in the past of hard material, although this is unknown.

Tidal flows within the disposal site are of the order of 0.5 m/s throughout the tide (ABPmer, 2017b), and it is exposed to significant wave activity, particularly during storms. These characteristics are important in determining the dispersion characteristics of the disposal site.

The field measurements (ABPmer, 2017b), and the subsequent flow patterns from the calibrated hydrodynamic flow model (ABPmer, 2017c), indicate that the tidal flow characteristics are typically uniform over the site. Based on this assessment it is considered that the dispersion characteristics of the site can be established through modelling dispersion from the centre of the disposal site alone.

3 Dredge Sediment Characteristics

As the bed sediment is dredged by Trailing Suction Hopper Dredger (TSHD), the material has the potential to 'break down' into its component particulate form as it passes through centrifugal pumps into the dredger hopper. Little or no overflow occurs to bulk the load as this is relatively unproductive for the predominantly fine-grained material dredged, particularly from CPLB. Although some consolidation would occur in the base of the hopper during transit to the disposal site, this is unlikely to 'bind' the material together to any significant degree. At the disposal site, once the material is released, it will quickly settle to the bed beneath the keel of the dredger. Sediment will be dispersed into the water column from the edges of the passive plume as it falls, due to flow advection and disturbance from the vessel propellers.

As a worst case for dispersion, the material in this assessment is considered to be the size of the individual particles; however, some flocculation or aggregation of particles may also occur. The vast majority of material will, however, pass directly to the bed within the passive plume stage. Most of the dispersion will start near to the bed. The proportion of sediment that is released to the water column, as the passive plume descends, will be highly variable between individual deposits; therefore, the actual contribution to the dispersion is unknown.

3.1 Particle size

To determine the particle size composition of the deposited material, an analysis of sediment size grading curves (particle size distributions) of bed samples, collected in the vicinity of three main dredge locations (Belview Quay, CPLB and Duncannon Bar), has been provided by PoW.

A synthesis of these data indicates that the particle sizes representing the average d15, d50 and d85, from samples in the vicinity of each dredge area, would generally characterise the variation in bed sediments from each location. These sizes, and the proportion of the sediment matrix they represent (along with the particle settling velocity used in the model), are given in Table 1.

Table 1. Composition of released material dredged from Belview, CPLB and Duncannon

Source / Parameter		Representative grain size (µm)	Representative material type	Distribution in release (%)	Settling velocity ($x10^{-3}$ m/s)
Belview Quay (BV)	d15	28	Silt	30	0.6
	d50	255	Medium sand	40	35.4
	d85	654	Coarse sand	30	88.5
Cheekpoint Lower Bar (CPLB)	d15	8	Silt	30	0.1
	d50	42	Silt	45	1.4
	d85	127	Fine sand	25	11.7
Duncannon Bar (DC)	d15	87	Very fine sand	20	5.8
	d50	137	Fine sand	70	13.4
	d85	224	Fine sand	10	29.6

4 Modelling

The disposal site dispersion characterisation has been undertaken using the MIKE3FM Mud Transport (MT) module, using the hydrodynamics from the calibrated MIKE3FM HD model (ABPmer, 2017c and introduced above). As seen in Section 3.1, the material deposited is predominantly relatively fine grained with a significant proportion of silt (*circa* 20 to 50 %). The material is, therefore, likely to have some cohesive properties, hence it is more appropriate for a mud model simulation as opposed to sand transport modelling.

During a typical campaign, dredging occurs 'around the clock' at Duncannon Bar and Belview (with nighttime limits on dredging activity at Cheekpoint Lower Bar). Therefore deposits, in theory, could be made at any state of the tide and would potentially be undertaken on both spring and neap tides. The model run scenarios have therefore been designed to determine the most probable worst-case dispersion, particularly with respect to the potential for recirculation of the sediment back into the Estuary.

4.1 Model simulation scenarios

Modelled disposal scenario runs are defined to provide a comprehensive understanding of the dispersion characteristics of the existing disposal site at the entrance to the Waterford Estuary from each of the three source locations (BV, CPLB and DC). These scenario model runs were derived by assessing the field and modelled flow characteristics through the tide in the vicinity of the disposal site. The aim of the runs was to determine the worst-case extent and magnitude of dispersion of the dredged material associated with sediment releases, and to determine the potential for sediment recirculation back into the estuary. The individual model run scenarios are summarised in Table 2.

Model scenarios have been undertaken with deposits across the range of both spring and neap tides. The analysis of the flows showed there was little difference in the pattern of flow directions throughout the neap tide except that flow speeds were approximately halved. The maximum dispersion potential would therefore occur on spring tides. On neap tides more material could be expected to accumulate at/near the disposal site that would have the potential to be dispersed on the following spring tides, or during the subsequent arrival of the peak storm wave. Consequently, whilst storm waves can be expected to enhance resuspension of bed material, the spring tidal flows are considered the primary mechanism for tidal dispersion of the deposited dredge material across the wider study area.

As noted earlier, the flows across the disposal site are similar throughout the area; hence all model scenario runs have the sediment from the dredge disposal input to the model at the centre of the existing disposal site.

Belview Quay, CPLB and Duncannon Bar are the main areas dredged, where the sediment composition is slightly different (see Section 3).

All model runs also have a time-varying wave condition imposed over the model domain, which increases the potential for sediment disturbance, hence increases the dispersion potential. The reasoning for this is that the disposal site is in an exposed location and wave measurements in the vicinity of Duncannon Bar (ABPmer, 2017b) show that there is, for the most part, some wave activity occurring at all times, which would be larger at the disposal site. The wave event included in the model has been agreed with PoW and is selected to represent a typical 'storm' condition. These specific conditions are set out in Table 3, which provides the quantitative input information for the scenario runs.

4.2 Wave conditions

As discussed above, a selected wave event has been applied within the disposal site model scenario runs, in order to include the potential for increased, wave-induced, dispersal of material. The derivation of the storm wave is provided below.

The model run scenarios include a build-up of wave conditions across the start of the model run, with the peak of the storm wave timed to occur just after (4 hours) the last dredge disposal event. In this way, the full assessed dredge campaign (from each source location) is completed just prior to the storm peak, meaning the full disposal volume is potentially impacted by the storm wave. This is agreed with PoW and considered to represent a realistic worst-case scenario, accounting for (e.g.) operational limits on the dredging and disposal activities.

4.2.1 Storm Conditions

Storm conditions at the disposal site were reviewed using ABPmer’s inhouse SEASTATES simulated 43-year hindcast wave conditions at the estuary mouth. Figure 2 indicates that the majority of waves originate between 165°N and 225°N. Wave heights exceed 2.5 m approximately 4.5% of the time and exceed 3.5 m approximately 2.8% of the time. These larger wave events are shown to only originate from southerly / south-westerly direction sectors.

OffshoreWaterford - Hs Dirm Scatter Table - All Data - Percentage (occurences as proportion of all data)

Wave Direction (Deg) From

Significant Wave Height (m)

Lower (>=)		355	5	15	25	35	45	55	65	75	85	95	105	115	125	135	145	155	165
	Upper (<)	5	15	25	35	45	55	65	75	85	95	105	115	125	135	145	155	165	175
8.5	9.0																		
8.0	8.5																		
7.5	8.0																		0.00
7.0	7.5																		0.00
6.5	7.0																		0.00
6.0	6.5																		0.00
5.5	6.0																	0.00	0.01
5.0	5.5																0.00	0.00	0.01
4.5	5.0															0.00	0.00	0.01	0.02
4.0	4.5															0.00	0.01	0.02	0.03
3.5	4.0															0.01	0.02	0.04	0.05
3.0	3.5													0.00	0.00	0.03	0.04	0.08	0.11
2.5	3.0												0.00	0.00	0.02	0.04	0.08	0.12	0.19
2.0	2.5		0.00	0.00	0.00	0.00		0.00				0.00	0.01	0.03	0.05	0.10	0.16	0.21	0.30
1.5	2.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.07	0.12	0.14	0.20	0.26	0.36	0.49
1.0	1.5	0.02	0.01	0.01	0.01	0.01	0.02	0.02	0.04	0.07	0.09	0.15	0.20	0.21	0.35	0.46	0.59	0.72	0.86
0.5	1.0	0.14	0.10	0.11	0.09	0.11	0.14	0.21	0.31	0.42	0.47	0.53	0.60	0.74	0.83	0.82	0.89	1.02	1.15
0.0	0.5	0.14	0.12	0.12	0.13	0.13	0.14	0.17	0.23	0.27	0.30	0.28	0.26	0.26	0.26	0.23	0.20	0.24	0.23
Sum		0.31	0.24	0.24	0.24	0.25	0.30	0.40	0.59	0.76	0.87	0.98	1.14	1.36	1.65	1.89	2.27	2.81	3.44

Lower (>=)		175	185	195	205	215	225	235	245	255	265	275	285	295	305	315	325	335	345		Cum.	
	Upper (<)	185	195	205	215	225	235	245	255	265	275	285	295	305	315	325	335	345	355	Sum	Sum	Exced.
8.5	9.0																				100.00	0.00
8.0	8.5			0.00																0.00	100.00	0.00
7.5	8.0			0.00																0.00	100.00	0.00
7.0	7.5	0.00	0.00	0.01	0.00															0.01	100.00	0.00
6.5	7.0	0.00	0.01	0.01	0.01															0.03	99.99	0.01
6.0	6.5	0.01	0.01	0.02	0.01															0.06	99.96	0.04
5.5	6.0	0.01	0.02	0.04	0.01	0.00														0.10	99.90	0.10
5.0	5.5	0.02	0.04	0.07	0.04	0.00														0.19	99.80	0.20
4.5	5.0	0.03	0.08	0.14	0.08	0.00														0.37	99.61	0.39
4.0	4.5	0.07	0.14	0.21	0.16	0.02														0.67	99.25	0.75
3.5	4.0	0.12	0.26	0.45	0.33	0.08	0.00													1.37	98.57	1.43
3.0	3.5	0.19	0.44	0.75	0.58	0.22	0.02	0.00												2.47	97.21	2.79
2.5	3.0	0.35	0.70	1.26	1.13	0.57	0.09	0.01		0.00	0.00		0.00		0.00					4.57	94.73	5.27
2.0	2.5	0.49	1.03	2.07	1.84	1.06	0.30	0.06	0.01	0.01	0.00	0.00	0.00	0.00	0.00					7.74	90.16	9.84
1.5	2.0	0.77	1.46	2.94	3.12	2.00	0.80	0.28	0.07	0.03	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.00	0.00	13.23	82.42	17.58
1.0	1.5	1.14	1.95	3.75	5.03	4.08	1.65	0.71	0.32	0.17	0.11	0.07	0.04	0.03	0.03	0.03	0.03	0.02	0.02	23.03	69.19	30.81
0.5	1.0	1.42	1.74	2.59	4.29	5.19	4.03	2.35	1.44	0.99	0.58	0.39	0.29	0.27	0.25	0.21	0.17	0.17	0.17	35.23	46.16	53.84
0.0	0.5	0.21	0.29	0.35	0.56	0.83	0.63	0.41	0.39	0.41	0.46	0.50	0.42	0.40	0.36	0.33	0.26	0.22	0.19	10.93	10.93	89.07
Sum		4.84	8.18	14.66	17.21	14.07	7.52	3.81	2.23	1.60	1.17	0.97	0.76	0.71	0.65	0.57	0.47	0.42	0.38	100.00		

Figure 2. SEASTATES hindcast wave conditions

Table 2. Model disposal site scenario runs

Run ID	Tide for simulation	Deposit Location within Disposal site	Source of Material	Wave Condition	Comment
1a	Spring/ Neap Cycle (full dredge campaign)	Centre	Belview Quay (BV)	Timing of peak wave event to occur coincident with mean NEAP tide	Simulation of effect from the peak of the storm event occurring just after disposal cycle has completed.
1b				Timing of peak wave event to occur coincident with mean SPRING tide	
2a	Spring/ Neap Cycle (full dredge campaign)	Centre	Cheekpoint Lower Bar (CPLB)	Timing of peak wave event to occur coincident with mean NEAP tide	Simulation of effect from the peak of the storm event occurring just after disposal cycle has completed.
2b				Timing of peak wave event to occur coincident with mean SPRING tide	
3a	Spring/ Neap Cycle (full dredge campaign)	Centre	Duncannon Bar (DC)	Timing of peak wave event to occur coincident with mean NEAP tide	Simulation of effect from the peak of the storm event occurring just after disposal cycle has completed.
3b				Timing of peak wave event to occur coincident with mean SPRING tide	

4.3 Definition of model dredge disposal inputs

The dredge disposal operations have been implemented within the model scenario runs using information provided by PoW, relating to past dredging/disposal campaigns. For the present study, a series of 'full campaign' disposal scenarios have been assessed, aimed at investigating the realistic worst-case from disposal of a full dredge from each of the source locations.

Model input parameters, as agreed with PoW, are provided in Table 3. Maximum disposal rates, as applied to the modelling tools, are from the Duncannon location at 42,994 m^3/day (or 68,791 wet tonnes/day).

Table 3. Model input parameters – full campaign release

Representative Campaign	CPLB	DC	BV
Frequency (hrs)	2.88	1.75	4.07
Assumed Max Dredger in Waterford (hopper m^3)	5,500	5,500	5,500
Hopper draft (m)	7	7	7
Load Factor	0.51	0.57	0.42
Number of Trips	30	52	7
In situ density (t/m^3)	1.5	1.6	1.5

Accordingly, the 'full dredge' campaign scenarios take the total number of loads (per site), coupled with the total combined time to load, turn, transit, dump and return transit, to provide a timeseries of release events into the model. Deposits at the disposal site therefore occur for between 28 hours (from BV) up to *circa* 4 days (for a full dredge disposal from DC). Model test runs are defined so that the disposal campaigns complete towards the peak of both spring and neap tides; therefore any potential variation in the subsequent storm wave coinciding with the typical tidal ranges can be considered. The remainder of the model run period, after disposal stops, provides information on how the plumes develop and subsequently start to (or completely) decay back to background levels.

As can be seen from Table 3, the actual dredge requirement varies considerably between campaign locations, particularly for the relatively low volumes disposed of from BV. This variation may need to be accounted for in interpreting the model results.

4.3.1 Wave disturbance conditions

Figure 3 shows a selected timeseries of wave conditions from the ABPmer SEASTATES modelled hindcast dataset. In considering the 'worst case' for resuspension of disposal material, waves from the southerly / south-westerly sector are the most likely to recirculate sediment, since these pass through the spoil ground and progress into the outer Waterford Estuary.

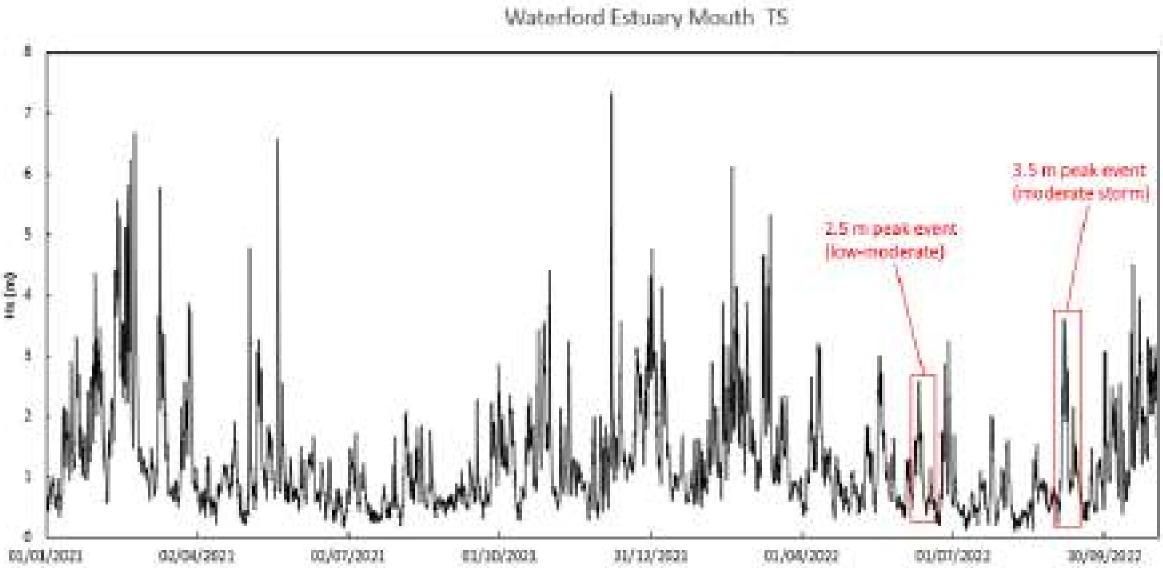


Figure 3. Agreed storm wave condition representing a 'moderate energy' storm (~ 12 storms per year)

Table 4 shows the wave conditions that have been applied to the disposal model runs as indicated in Table 2.

Table 4. Summary of timeseries wave conditions applied as input to the disposal scenarios

Wave type	Peak of Significant Wave Height Hs (m)	Peak Wave Period Tp (s)	Wave Direction of peak event (°N)
Moderate storm event	3.5	7.8	200 - 230

These wave conditions are applied to the mud transport model as a time-varying but spatially constant wave event, hence there is no representation of shallow water wave effects (shoaling, refraction, sheltering) within the model. In this way, given the wave conditions have been derived from the hindcast data at Duncannon, the model is considered to properly reflect the relevant wave influences at the disposal site and across the outer estuary. Upstream of Passage East, and also within the sheltered areas (behind Creadan Head, for example), the wave conditions applied to the model are likely to represent an overestimation of the actual wave climate, providing a 'worst-case' for bed agitation and resuspension as a result of wave activity.

5 Method of Results Presentation

Sediment dispersal run model results have been extracted to show the extent of dispersion for both suspended sediment concentration (SSC) (excess concentration, above background) and the associated change in bed thickness, showing where accumulation of sediment (both temporary and permanent) is likely to occur.

Two forms of output are provided to illustrate the modelled sedimentary dispersion effects of the individual proposed schemes. These are:

- Plan (map plots); and
- Timeseries plots.

Together, these forms of output present the spatial and temporal effects from each of the disposal scenario runs. The plan plots firstly indicate the overall extent of dispersal from the deposit ground and indicate the locations and magnitude where the maximum concentrations within the water column, along with accumulations on the bed, occur. Further plots are produced of the actual modelled distribution at specific times following the end of the relevant release campaign. These indicate how the sediment pattern evolves with successive tides and indicates the effects of sediment re-erosion or permanent accumulation.

Timeseries plots have also been extracted, which illustrate the movement of sediment and the time 'signal' of the plume evolution and bed thickness, at the agreed sensitive locations. The extracted timeseries data reflect the evolution of the plume and its overall extent, with reference to specific strategic locations. These individual extraction locations are shown in Figure 1, and on the various 'maximum extent' map plots.

6 Plume Dispersion Modelling Results

The model outputs for the listed scenarios are provided in the following Figures:

Figure 4: Maximum SSC and maximum bed thickness for full dredge campaign from **Belview Quay (BV)**, with peak of the storm wave coincident with a **mean NEAP** tidal range;

Figure 5: Maximum SSC and maximum bed thickness for full dredge campaign from **Belview Quay (BV)**, with peak of the storm wave coincident with a **mean SPRING** tidal range;

Figure 6: Maximum SSC and maximum bed thickness for full dredge campaign from **Cheekpoint Lower Bar (CPLB)**, with peak of the storm wave coincident with a **mean NEAP** tidal range;

Figure 7: Maximum SSC and maximum bed thickness for full dredge campaign from **Cheekpoint Lower Bar (CPLB)**, with peak of the storm wave coincident with a **mean SPRING** tidal range;

Figure 8: Maximum SSC and maximum bed thickness for full dredge campaign from **Duncannon Bar (DC)**, with peak of the storm wave coincident with a **mean NEAP** tidal range; and

Figure 9: Maximum SSC and maximum bed thickness for full dredge campaign from **Duncannon Bar (DC)**, with peak of the storm wave coincident with a **mean SPRING** tidal range.

Figure 10: Instantaneous SSC and bed thickness at selected time periods between 2 hours and 36 hours after completion of the disposal campaign from **Duncannon Bar (DC)**, with peak of the storm wave coincident with a **mean SPRING** tidal range.

In addition to the map plots listed above, timeseries outputs of excess depth-averaged SSC and bed thickness are also provided at Appendix A and B, respectively.

Disposal Scenario 1a: Full dredge campaign from BV; storm wave coincides with NEAP tide

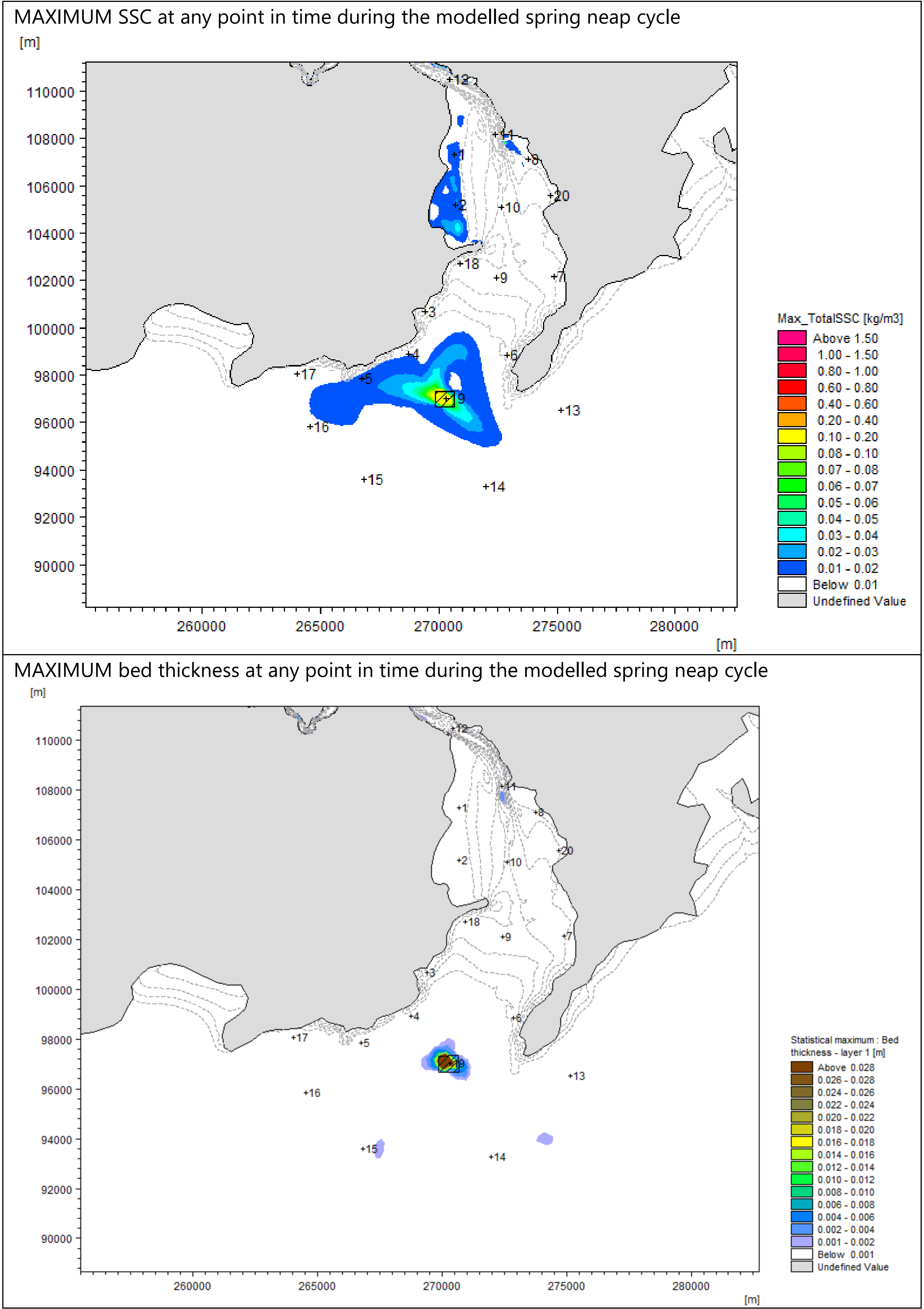


Figure 4. Maximum SSC and maximum bed thickness – BV (Neap)

Disposal Scenario 1b: Full dredge campaign from BV; storm wave coincides with SPRING tide

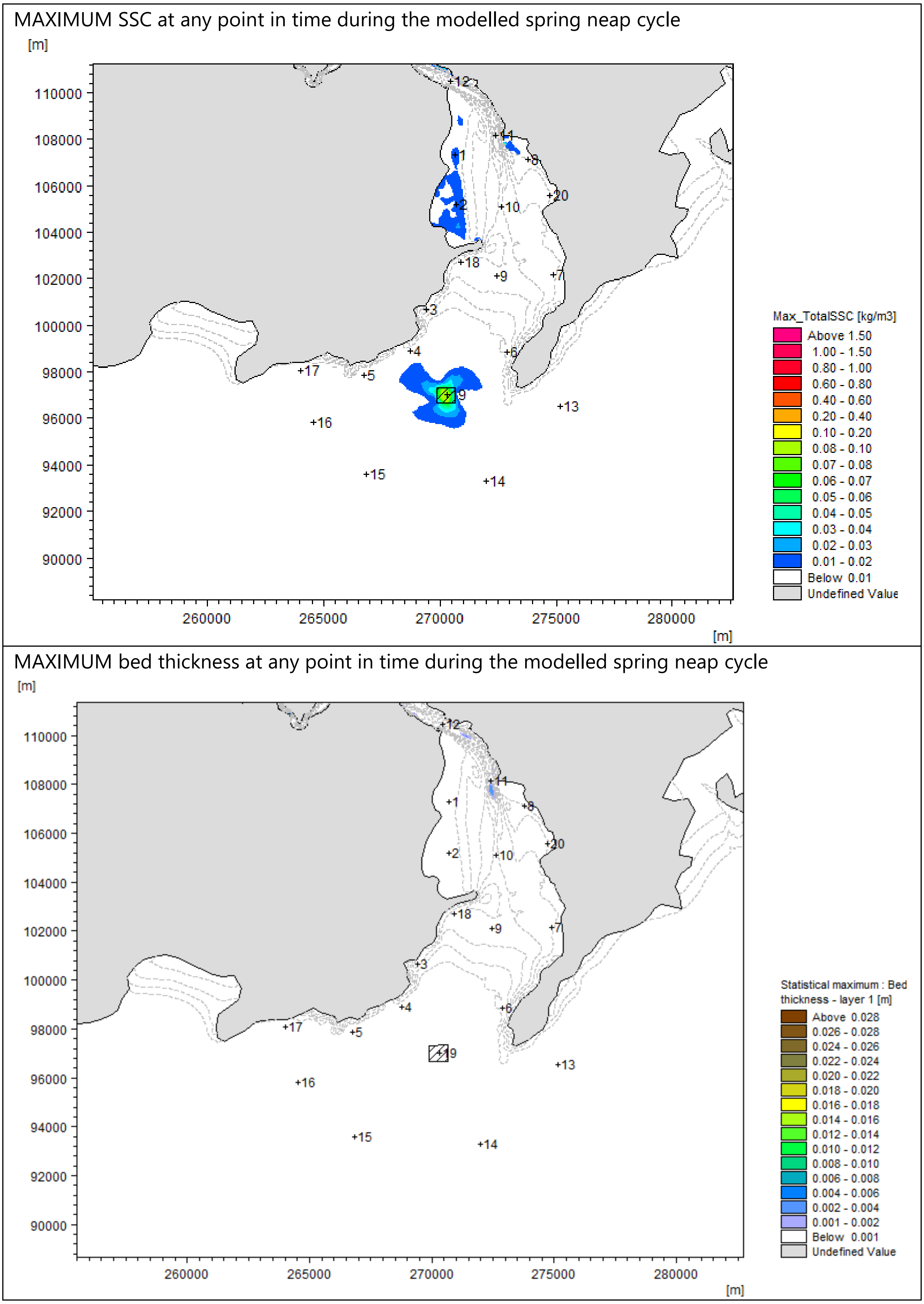


Figure 5. Maximum SSC and maximum bed thickness – BV (Spring)

Disposal Scenario 2a: Full dredge campaign from CPLB; storm wave coincides with NEAP tide

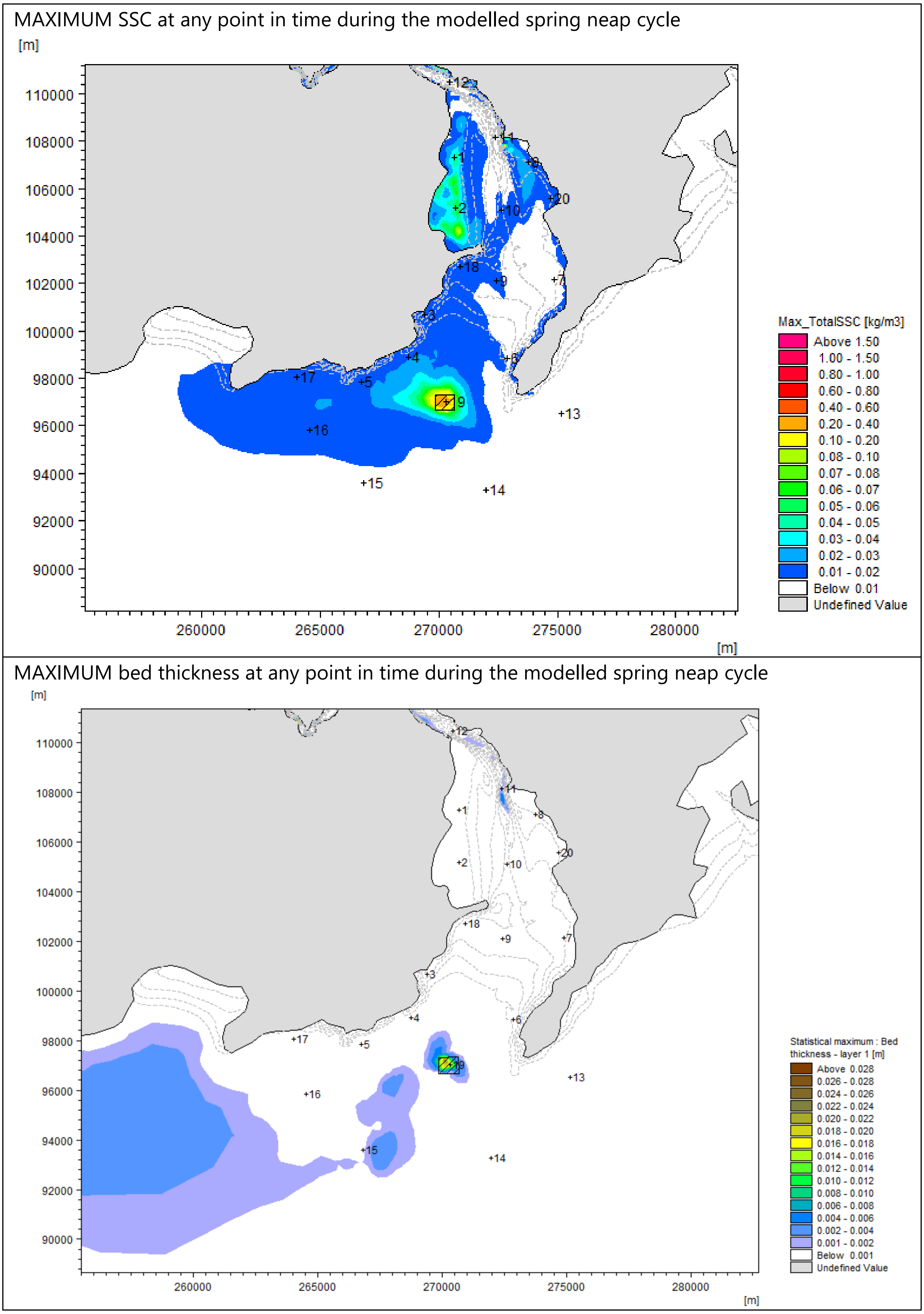


Figure 6. **Maximum SSC and maximum bed thickness – CPLB (Neap)**

Disposal Scenario 2b: Full dredge campaign from CPLB; storm wave coincides with SPRING tide

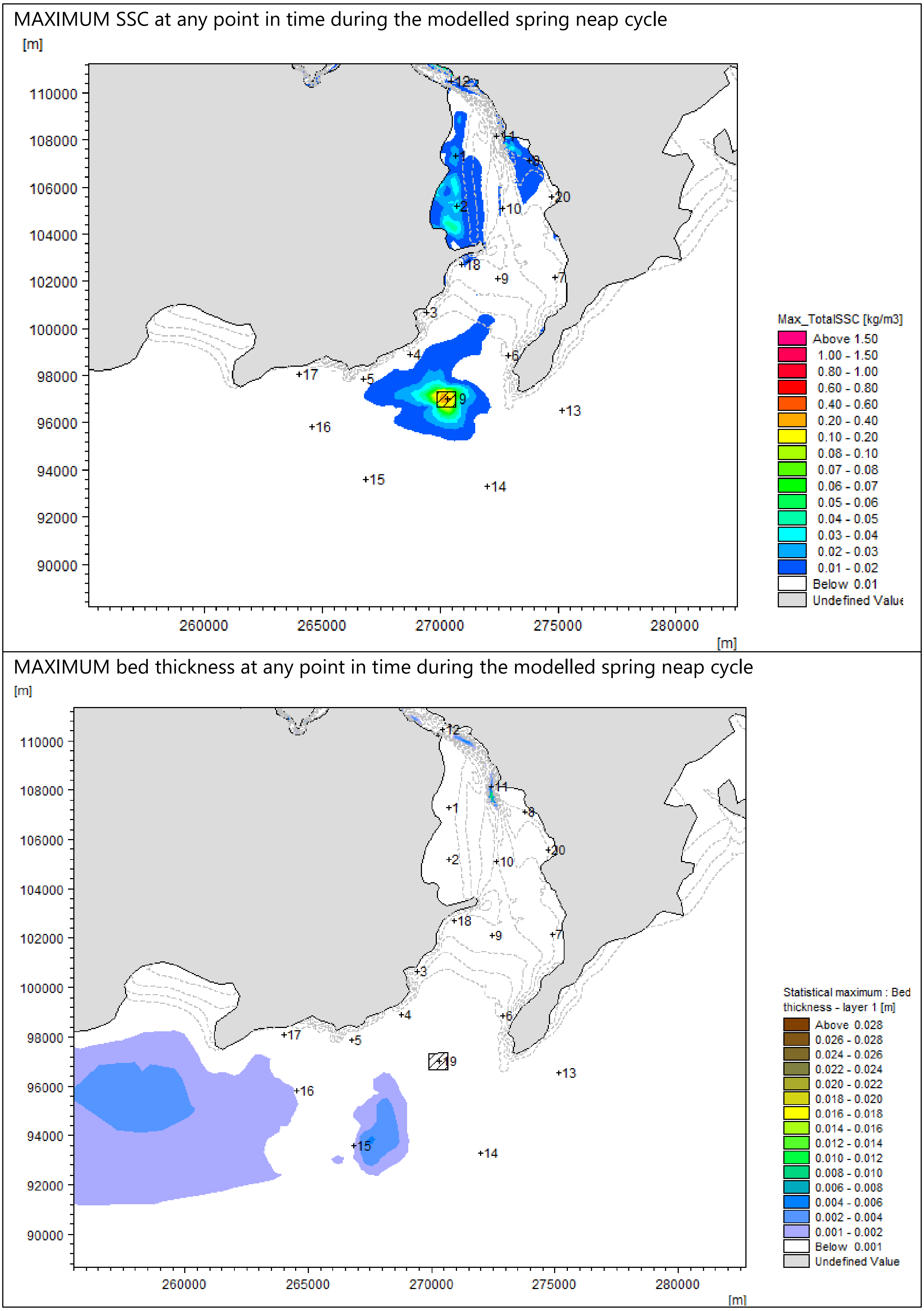
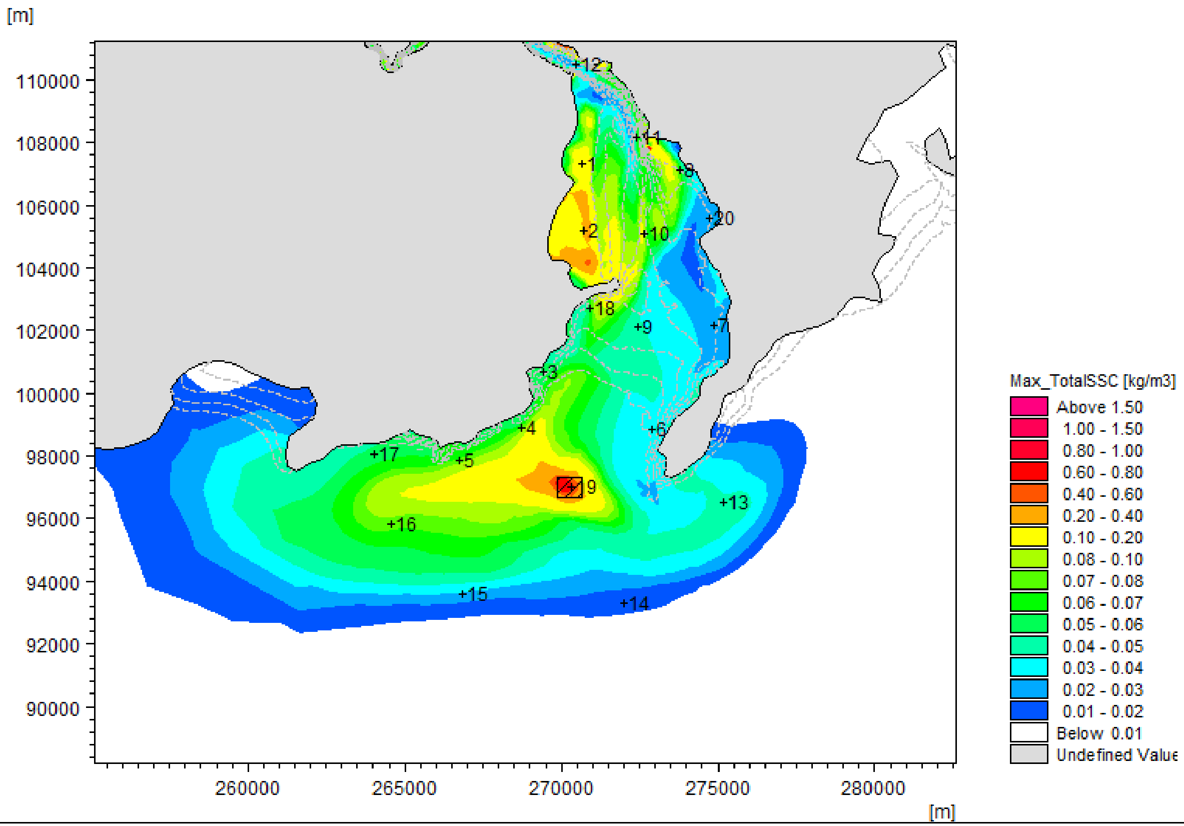


Figure 7. Maximum SSC and maximum bed thickness – CPLB (Spring)

Disposal Scenario 3a: Full dredge campaign from DC; storm wave coincides with NEAP tide

MAXIMUM SSC at any point in time during the modelled spring neap cycle



MAXIMUM bed thickness at any point in time during the modelled spring neap cycle

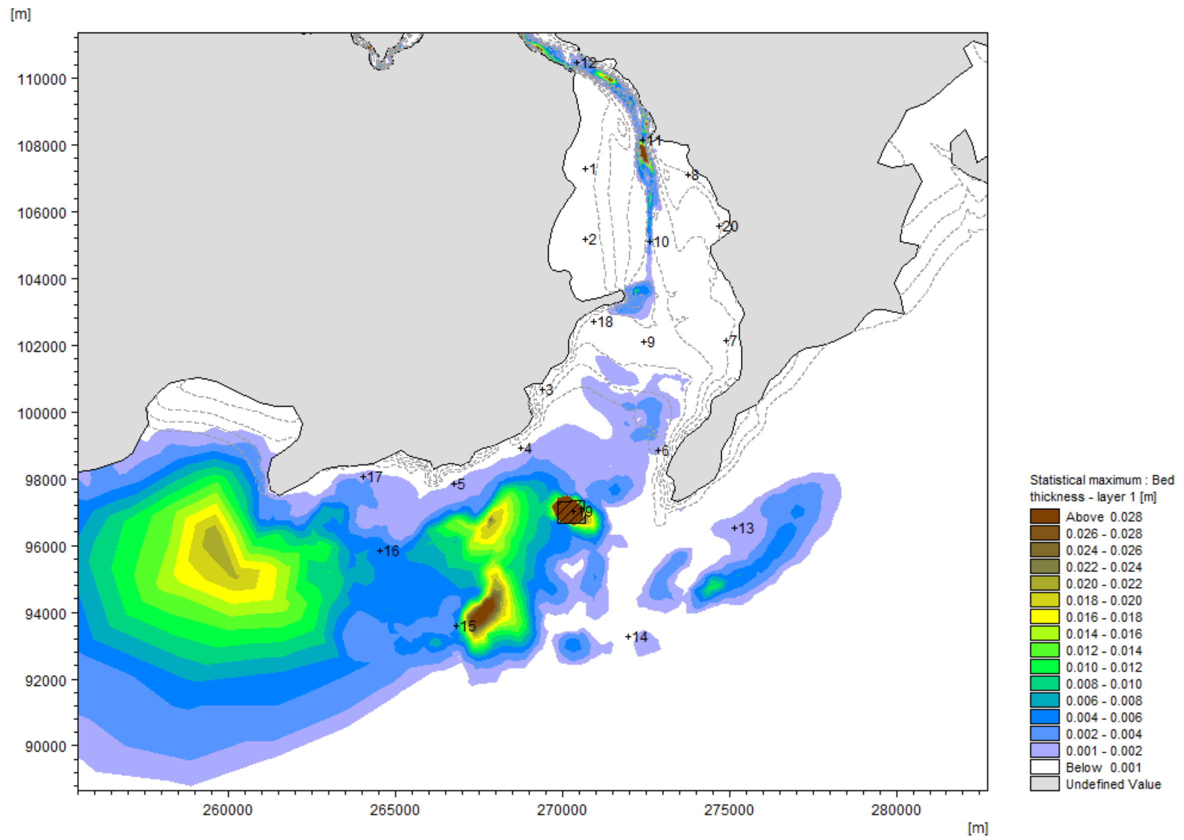


Figure 8. Maximum SSC and maximum bed thickness – DC (Neap)

Disposal Scenario 3b: Full dredge campaign from DC; storm wave coincides with SPRING tide

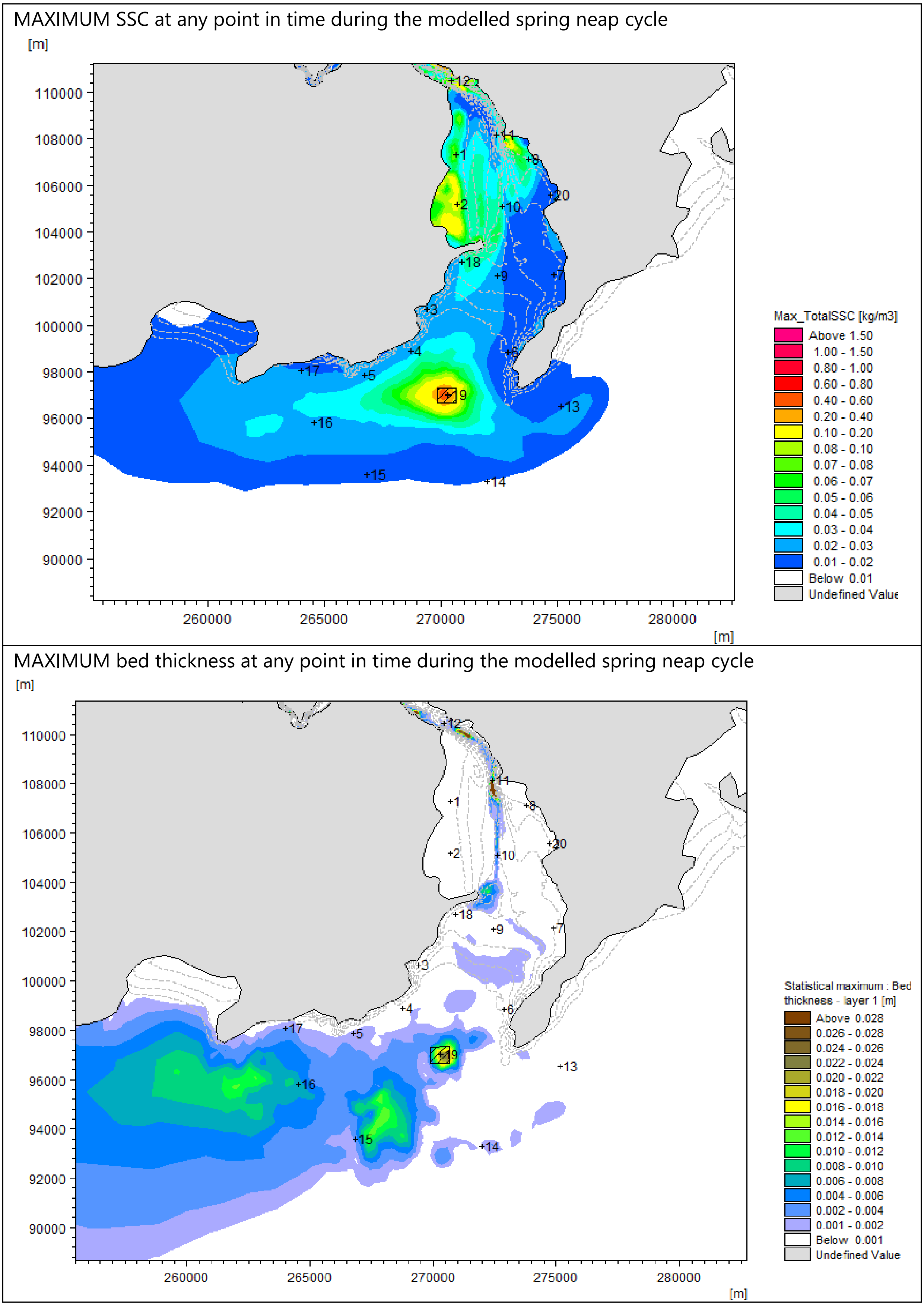


Figure 9. **Maximum SSC and maximum bed thickness – DC (Spring)**

6.1 Full campaign from Belview Quay

Results from the modelling shown in Figure 4 (peak storm wave coincides with mean neap tide) indicate peak excess SSC values of around 100 to 200 mg/l within the disposal site. Further afield, peak excess SSC values reduce with distance, with predicted values of around 20 to 30 mg/l in the outer Estuary, reducing to around 10 mg/l within a distance of up to 5 km to the east and west of the disposal site. Maximum excess SSC values of around 30 mg/l are predicted in the lee of Creadan Head.

Associated changes to bed thickness indicate relatively little effect (noting the total disposal volume from Belview is relatively small (and of short duration) as compared to those from CPLB and Duncannon Bar. Maximum accretion of around 3 to 4 cm is predicted across the spoil ground, but the subsequent dispersal of material leads to accretion levels of less than 1 mm across the surrounding regions.

Where the peak of the storm wave coincides with a mean spring tide (Figure 5), the larger tidal range (and faster tidal flows) result in a higher overall dispersion and lower relative maximum concentrations (when compared to the neap tide conditions). Peak concentrations at the disposal site are around 80 to 100 mg/l (associated with the release events), but the magnitude and extent of the sediment plume across the wider region is more limited to the area around the disposal site and the outer parts of the estuary. Peak increases in SSC of up to 10 to 20 mg/l are predicted to extend around 2 km east and west of the disposal site, whilst peak concentrations in behind Creadan Head reach around 20 mg/l.

Due to the generally higher flow conditions, material associated with the disposal plume from Belview is generally maintained in suspension, with little predicted bed accretion across the study area. Small areas of siltation of up to 2 mm are predicted towards the northern end of the main Duncannon Channel (off of Duncannon Strand) and further north towards Passage East. Across the remainder of the outer estuary and approaches, the deposit material from the Belview campaign results in maximum siltation of less than 1 mm.

6.2 Full campaign from Cheekpoint Lower Bar

Results from the modelling shown in Figure 6 (peak storm wave coincides with mean neap tide) indicate peak excess SSC values of around 200 to 300 mg/l in and around the disposal site. Further afield, peak excess SSC values reduce with distance, with predicted values of around 20 to 30 mg/l in the outer Estuary and up to 10 mg/l within a distance of around 10 km to the west and 2 km to the east of the disposal site. Maximum excess SSC values of around 80 mg/l are predicted in the lee of Creadan Head.

Associated changes to bed thickness indicate relatively little effect (noting the material dredged from CPLB has a generally higher fines content as compared to those from Belview and Duncannon Bar and, consequently, is more easily maintained in suspension (rather than settling to the bed). Maximum accretion of around 2 to 3 cm is predicted across the spoil ground, indicating the existing tidal flows are typically sufficient to mobilise the newly deposited material. Across the wider study area, subsequent dispersal of material leads to accretion levels of generally less than 1 mm across the surrounding regions, with an area of maximum accretion of around 2 to 3 mm predicted to the west, offshore of Rinnashark Harbour.

Where the peak of the storm wave coincides with a mean spring tide (Figure 7), the larger tidal range (and faster tidal flows) result in a higher overall dispersion and lower relative maximum concentrations (when compared to the neap tide conditions). Peak concentrations at the disposal site are around 200 mg/l (associated with the release events), whilst the magnitude and extent of the sediment plume across the wider region is more limited to the area around the disposal site and the outer parts of the estuary. Peak increases in SSC of up to 20 to 30 mg/l are predicted to extend around 2 km west of the disposal site, whilst peak concentrations in behind Creadan Head reach up to around 40 mg/l.

As with the disposal from Belview (above), the generally higher flow conditions lead to material associated with the disposal plume from CPLB being generally maintained in suspension, with little predicted bed accretion across the study area. This is further influenced by the higher proportion of fine sediment in the dredge material from CPLB, which is slower to settle, and more easily retained within the water column. Under the spring tidal conditions, small areas of siltation of up to 2 mm are predicted to the west and southwest of the disposal site, whilst the upper part of the outer estuary (within the main channel around Duncannon Strand) shows predicted maximum sedimentation of around 8 to 10 mm. Further north in the channel, towards Passage East, maximum siltation of around 4 mm is predicted. Across the remainder of the outer estuary and approaches, the deposit material from the CPLB campaign results in maximum siltation of less than 1 mm.

6.3 Full campaign from Duncannon Bar

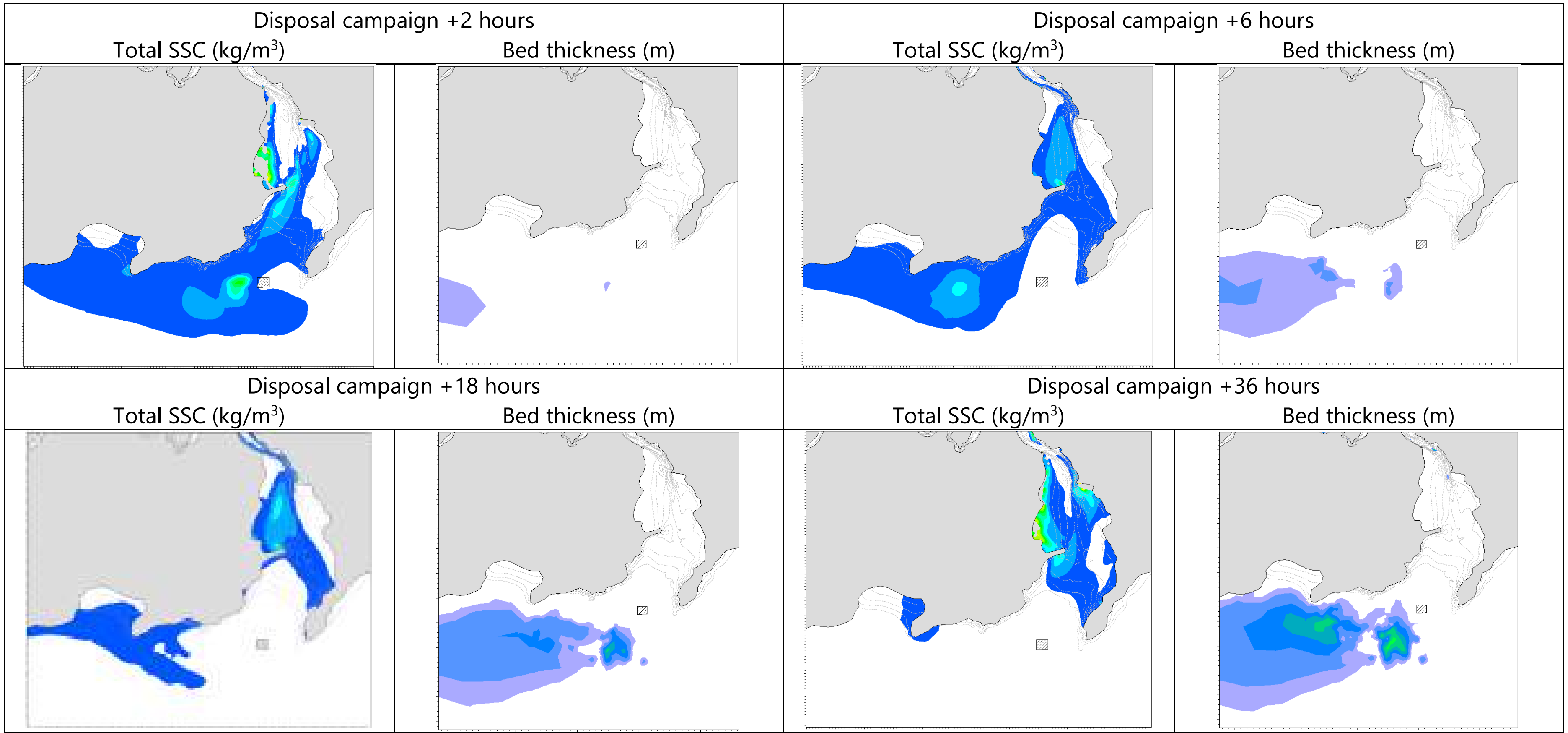
The full dredge campaign disposal from Duncannon Bar gives the greatest predicted impact on SSC and accretion.

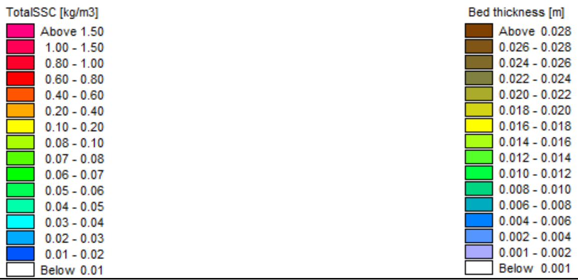
Results from the modelling shown in Figure 8 (peak storm wave coincides with mean neap tide) indicate peak excess SSC values in excess of 400 mg/l in and around the disposal site. Further afield, peak excess SSC values reduce with distance, with predicted values of around 100 to 200 mg/l in the outer Estuary and up to 5 km to the west of the disposal site. Maximum excess SSC values of around 300 mg/l are predicted in the lee of Creadan Head.

Associated changes to bed thickness indicate relatively little effect within the estuary itself, outside of the main approach channel through Duncannon Bar (where maximum accretion of 2 to 3 cm is predicted. Maximum accretion of up to 0.3 m is predicted across the spoil ground, and an area of predicted accretion up to 3 cm is shown around 4 km to the southwest. Offshore of Rinnashark Harbour, an area of accretion up to 2 cm is predicted but the wider dispersal of material leads to accretion levels of less than 1 mm across most of the outer estuary and the surrounding regions to the east.

Where the peak of the storm wave coincides with a mean spring tide (Figure 9), the larger tidal range (and faster tidal flows, as noted above) result in a higher overall dispersion and lower relative maximum concentrations (when compared to the neap tide conditions). Peak concentrations at the disposal site are around 300 mg/l (associated with the larger volume of material assessed from Duncannon and, by association, more release events; see Table 3), but the magnitude and extent of the sediment plume across the wider region is more limited than that predicted under neap tide conditions. Peak increases in SSC of up to 20 mg/l are predicted to extend around 10 km west and around 3 km southeast of the disposal site, whilst peak concentrations in behind Creadan Head reach around 100 mg/l.

The generally higher flow conditions under spring tides (compared with neaps) result in less material associated with the disposal plume from Duncannon settling to the bed across the study area. Maximum siltation at the disposal site is predicted to reach around 2 to 2.5 cm, whilst limited areas of siltation of up to 1 cm are predicted to the west and southwest of the spoil ground. Towards the northern end of the main Duncannon Channel (off of Duncannon Strand) and further north towards Passage East, maximum siltation of up to 2.5 cm is predicted. Across the remainder of the outer estuary and approaches, the deposit material from the Duncannon campaign results in maximum siltation of less than 1 mm.





Disposal release scenario 3b:

- Full disposal campaign from Duncannon
- Peak storm event coincides with spring tide

Figure 10. Selected timesteps showing development of SSC and bed thickness following full campaign from Duncannon (Scenario 3b)

7 Discussion

The model run scenarios described above have been designed to determine the most probable worst-case dispersion of material from the disposal site, particularly with respect to the potential for recirculation of the sediment back into the Estuary. The application of an extreme storm condition also provides a worst-case impact on deposition and dispersion of material across the wider study area. As noted above, wave heights typically exceed 2.5 m approximately 4.5% of the time and exceed 3.5 m (the magnitude of the event modelled for this study) approximately 2.8% of the time.

The selected timestep plots provided in Figure 10 show the instantaneous predicted increased SSC and bed sedimentation at a range of time periods after the end of the Duncannon disposal campaign. Rather than the overall maximum values provided in Figure 4 to Figure 9, these plots show how the disposal plume is predicted to develop, in response to the driving tidal and wave forcing conditions. Only the plume development from Duncannon is shown as the smaller disposal volume from Belview and the larger dispersion of the finer material from Cheekpoint Lower Bar results in overall lower instantaneous concentrations from these campaigns.

The results of the instantaneous plume development indicate a peak concentrations of around 60 to 70 mg/l in and around the disposal site. Across the wider region, plume concentrations above 10 mg/l are predicted to extend west to Rinnashark Harbour and east to Hook Head. In addition, a sediment plume with concentrations of up to 30 to 40 mg/l (above baseline) extends into the outer estuary, past Dunmore East and, for disposal campaigns from Duncannon, this plume extends further north, past Creadan Head and on towards Duncannon Strand.

Associated instantaneous sedimentation plots are also provided in Figure 10. As discussed above, the relatively low volume of disposal material from Belview and the relatively higher fine sediment content of material dredged from CPLB result in generally limited siltation from these campaigns. Where material does settle to the bed (under slack water conditions around high and low tide), the subsequent peak flows are sufficient to remobilise the material and put it back into suspension for further dispersion. The influence of the storm event is also a contributing factor, providing added energy to the system and resulting in wave-induced bed shear stress, which further limits the sedimentation potential for the material in suspension.

With a greater volume of deposited material, the results of the modelling for the Duncannon campaign (Figure 10) do reveal some settling of material to the bed. Initially (around 2 hours after the end of the disposal campaign), as the storm event builds towards its peak, bed accretion is generally limited. With greater time passing from the end of the campaign, and as the peak of the storm event passes and calmer conditions return (from both lower wave heights and with the tide moving away from the peak of the spring towards neap conditions), more settling of material is predicted. By 36 hours after the end of disposal, accretion of up to around 1 cm is predicted to the southwest of the disposal site and of around 0.7 cm further west towards Brazen Head. However, as is shown throughout the range of modelling scenarios undertaken, the peak flows associated with spring tidal conditions are sufficient to remobilise this material, indicating that the settling shown in Figure 10 will only be temporary until the next spring tide or until further storm conditions return.

The temporal nature of the peak SSC and sedimentation values are also shown in the timeseries plots, at the sensitive locations, provided in Appendices A and B. These plots show the peaks in excess SSC values, which 'spike' for a short period of time as the plume passes the location, before dropping off as the plume moves away. This cycle continues as the disposal events are underway (and as the flood and ebb tides move material back and forth across the site). Once the disposals cease, the material in suspension becomes continuously more dispersed and concentrations drop back to existing (baseline) levels.

A similar pattern is revealed in the bed sedimentation timeseries (Appendix B), with peak siltation under slack water conditions whilst the plume remains active. The deposits are then periodically removed as the peak of the next tide resuspends the settled material. With ongoing dispersion across the subsequent tides (and following the end of disposal operations), the accretion typically drops to baseline levels. At all locations, the levels of peak siltation are predicted to be very small (typically <0.5 mm).

8 References

ABPmer, (2017a). Waterford Estuary: Estuary Understanding, ABPmer Report No. R.2826.

ABPmer, (2017b). Waterford Estuary: Hydrographic Survey Programme- Report, ABPmer Report No. R.2839.

ABPmer, (2017c). Waterford Estuary, Model Calibration and Validation, ABPmer Report No. R.2894, for Port of Waterford, December 2017.

Eysink, W.D., de Graaff, R.F. and Bos, K.J., (2000). Dredging of Duncannon Bar: Environmental impact of dredging and spoil dumping. Report produced by Deltares for New Ross Port Company. September 2000.

Eysink, W.D., de Graaff, R.F. and Bos, K.J., (2001). Dredging of Suir and Barrow Rivers: Environmental impact of annual spoil dumping at sea off Hook Head. Report produced by Deltares for New Ross Port Company. March 2001.

9 Abbreviations/Acronyms

BSS	Bed Shear Stress
CPLB	Cheekpoint Lower Bar
Hs	Significant Wave Height
ODD	Ordnance Datum Dublin
SSC	Suspended Sediment Concentrations
TSHD	Trailing Suction Hopper Dredger
Tp	Peak wave Period
Tz	Zero Crossing Period

Cardinal points/directions are used unless otherwise stated.

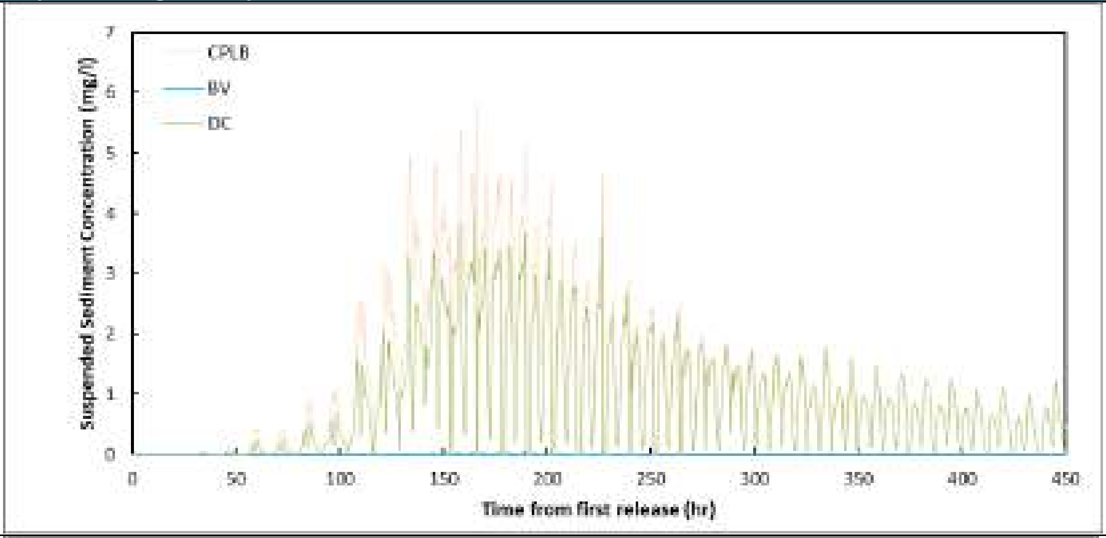
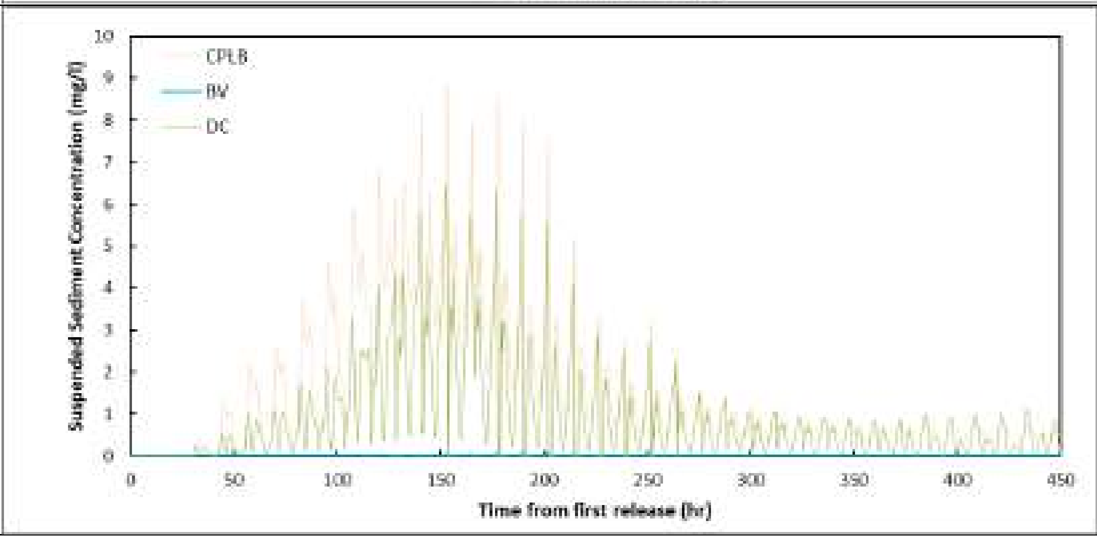
SI units are used unless otherwise stated.

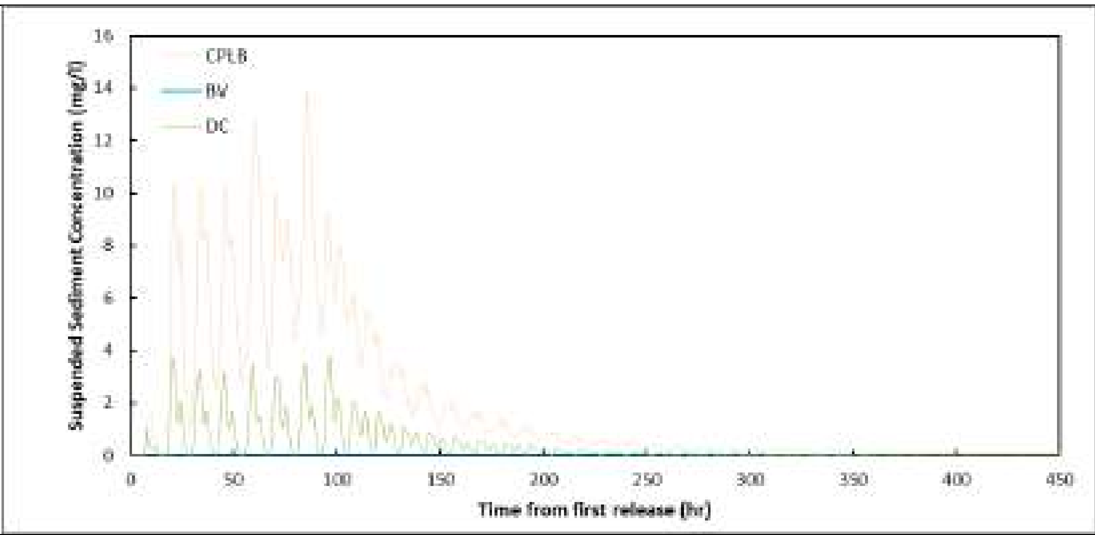
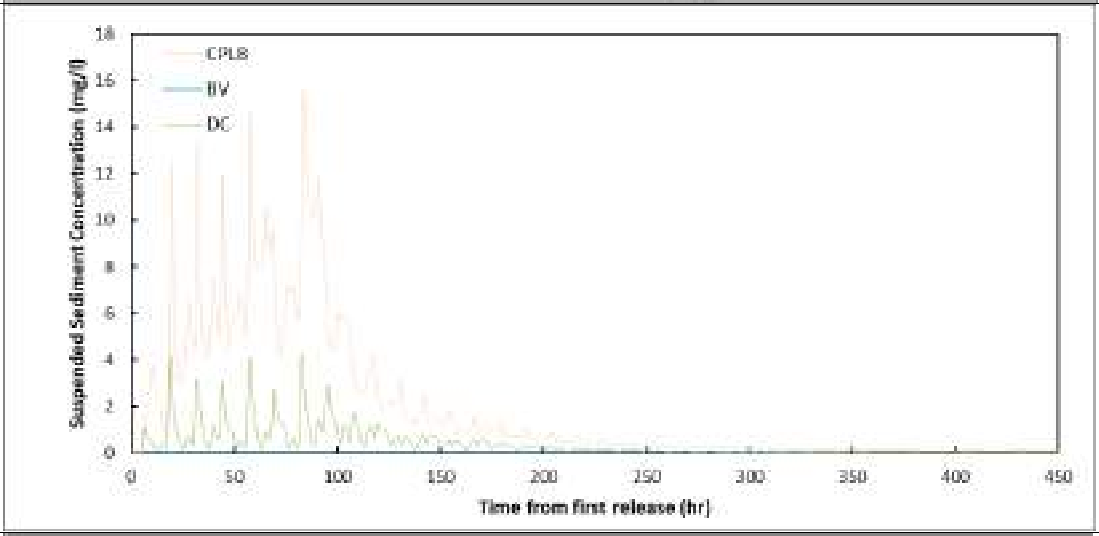
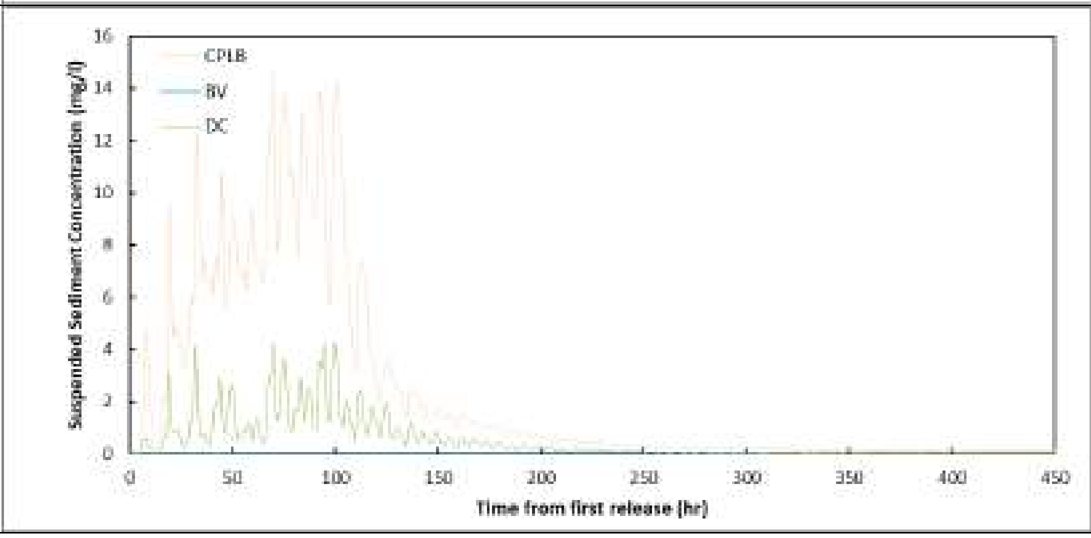
Appendices

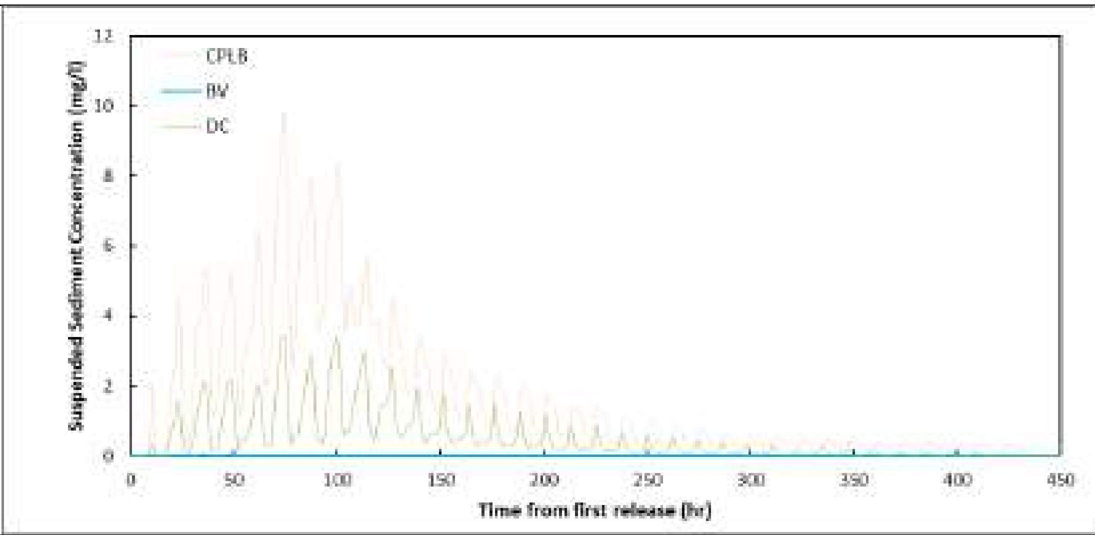
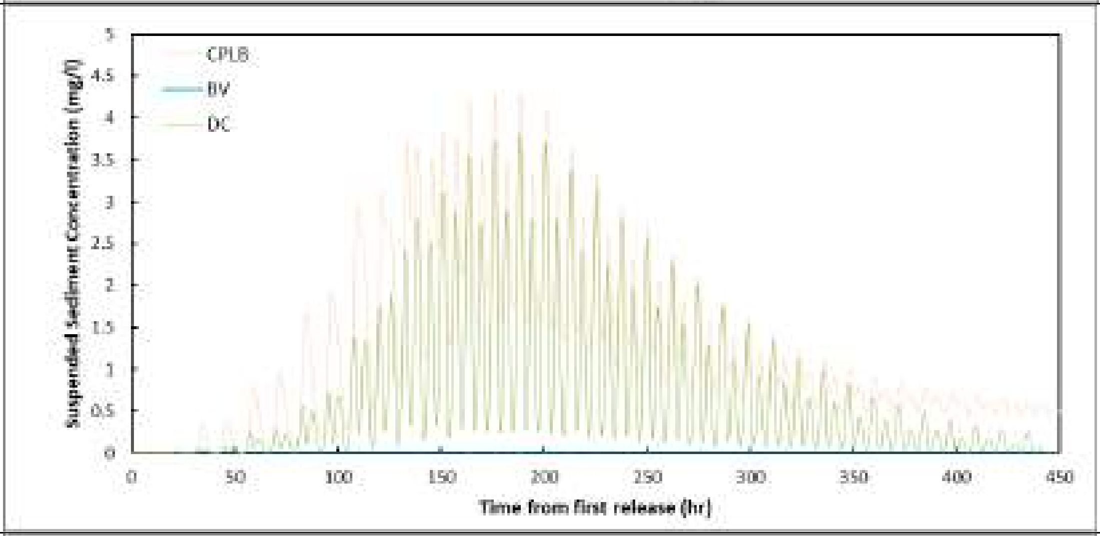
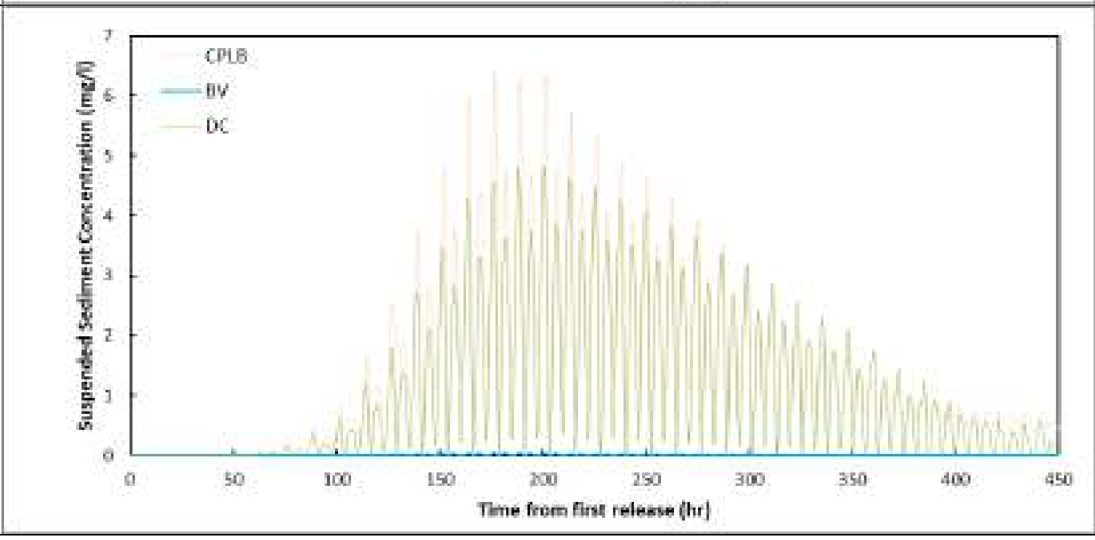
Innovative Thinking - Sustainable Solutions

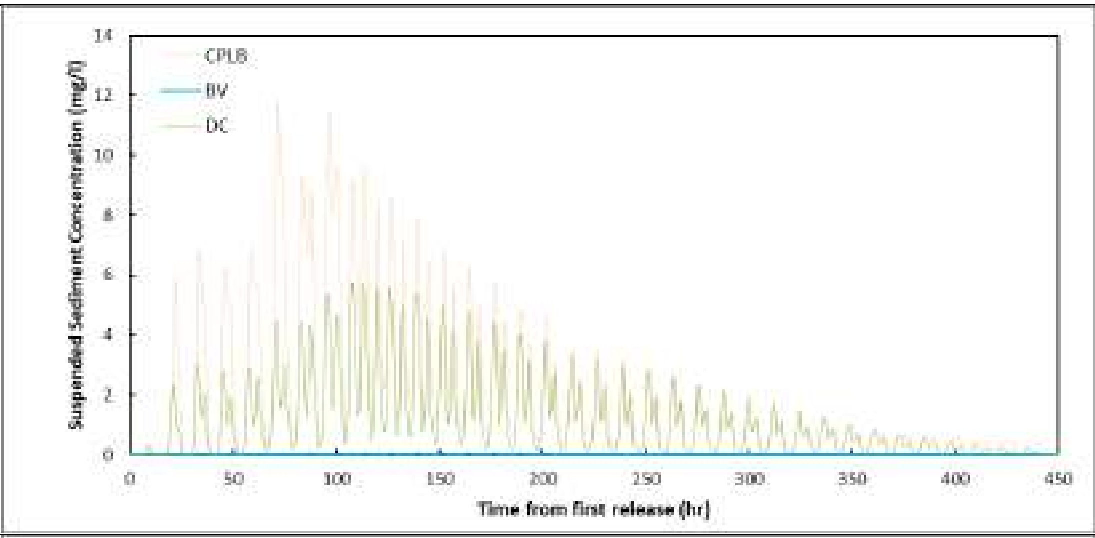
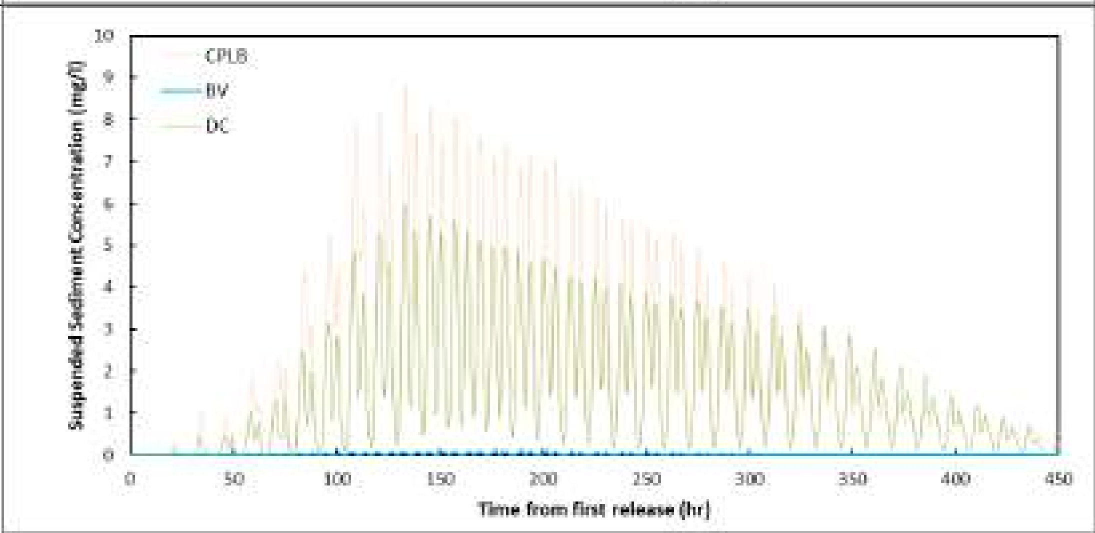
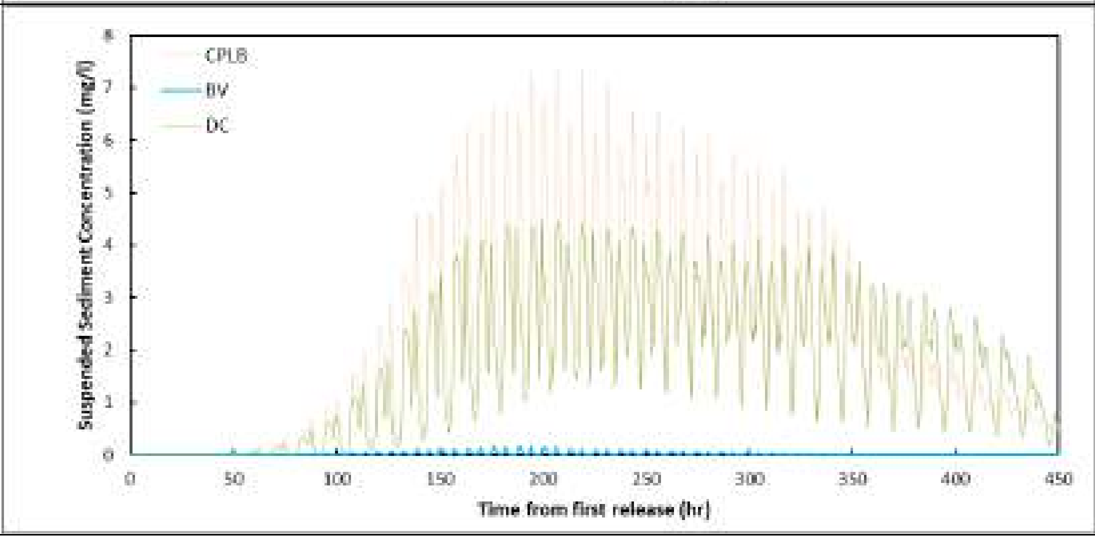
ABP mer

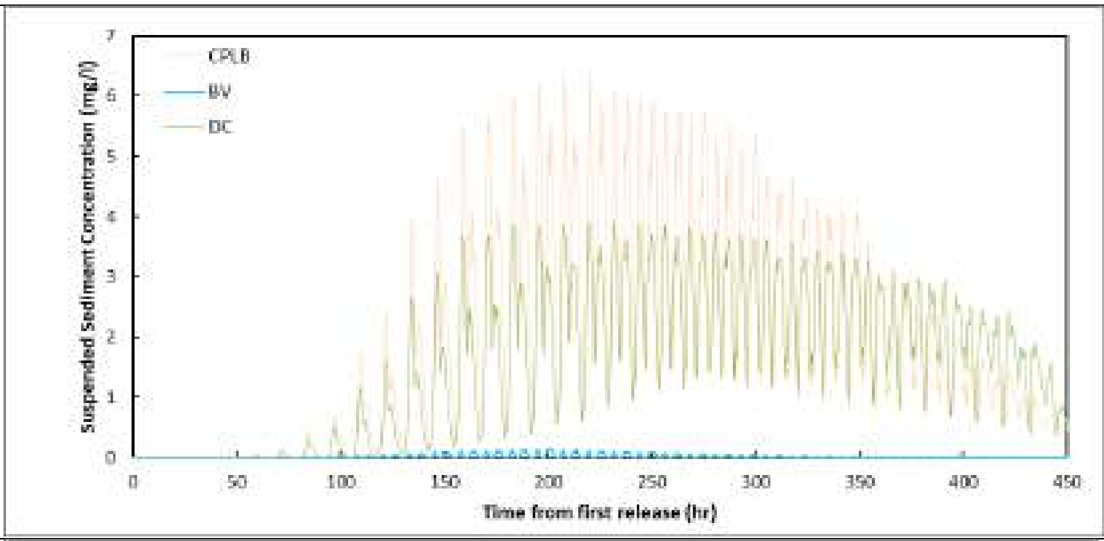
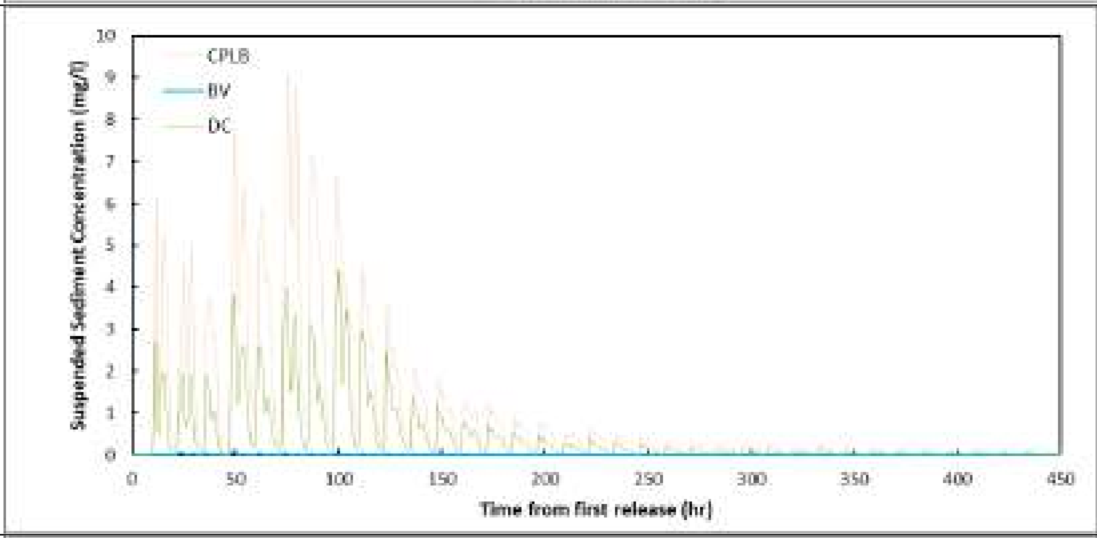
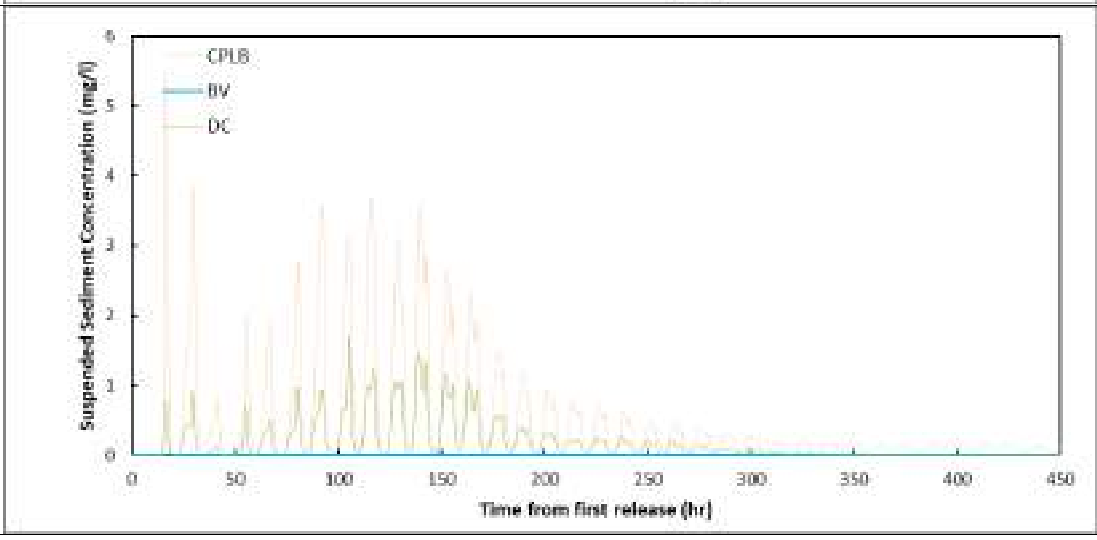
A Appendix A: Timeseries of Depth-Averaged SSC at Extraction Sites

ID	Depth-averaged suspended sediment concentrations (SSC)
1	
2	

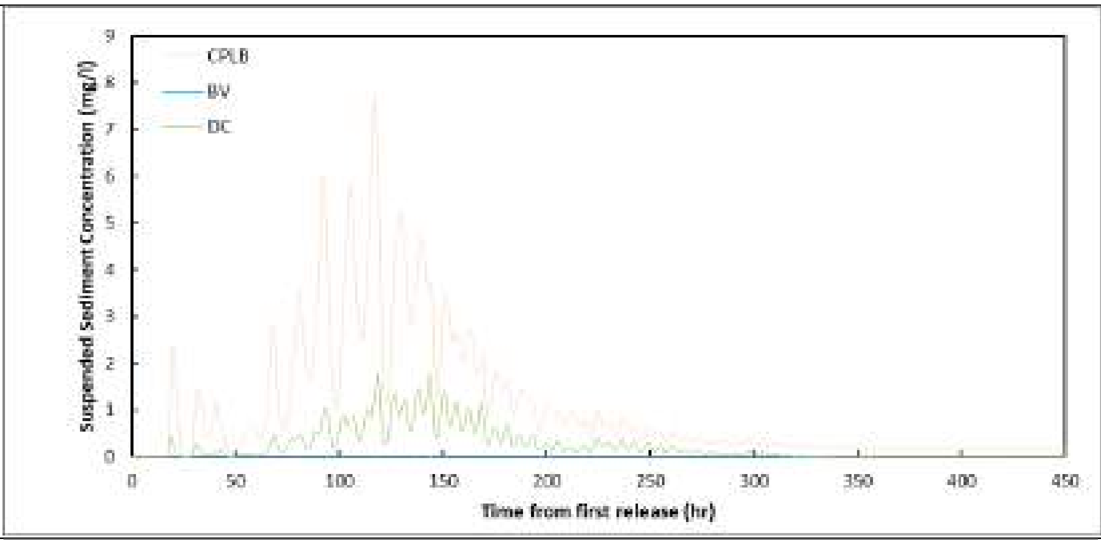
3	CPLB BV DC Suspended Sediment Concentration (mg/l) Time from first release (hr)
4	CPLB BV DC Suspended Sediment Concentration (mg/l) Time from first release (hr)
5	CPLB BV DC Suspended Sediment Concentration (mg/l) Time from first release (hr)

6	CPLB BV DC Suspended Sediment Concentration (mg/l) Time from first release (hr)
7	CPLB BV DC Suspended sediment Concentration (mg/l) Time from first release (hr)
8	CPLB BV DC Suspended Sediment Concentration (mg/l) Time from first release (hr)

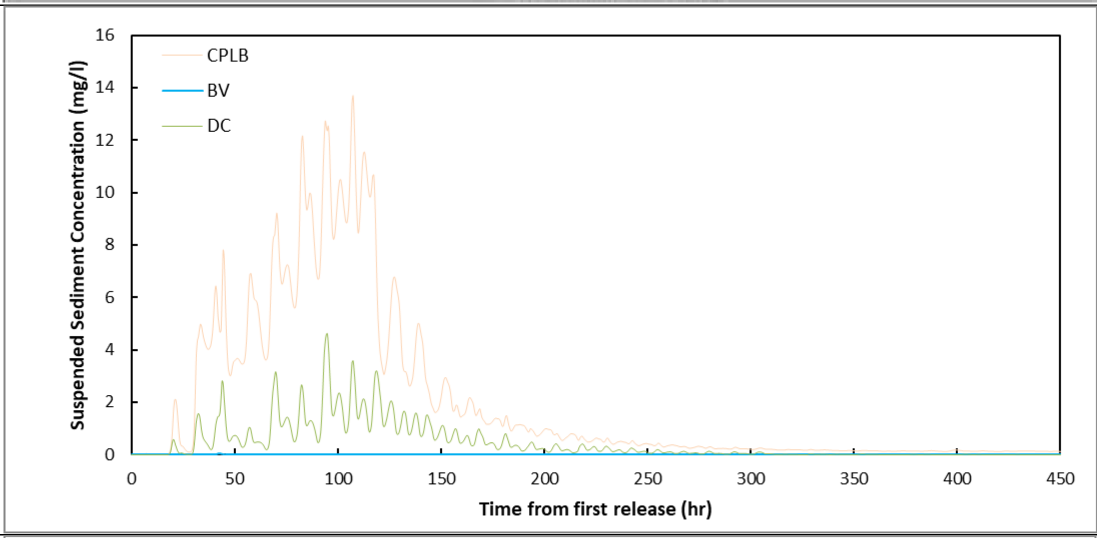
9	CPLB BV DC Suspended Sediment Concentration (mg/l) 0 2 4 6 8 10 12 14 0 50 100 150 200 250 300 350 400 450 Time from first release (hr)
10	CPLB BV DC Suspended Sediment Concentration (mg/l) 0 1 2 3 4 5 6 7 8 9 10 0 50 100 150 200 250 300 350 400 450 Time from first release (hr)
11	CPLB BV DC Suspended Sediment Concentration (mg/l) 0 1 2 3 4 5 6 7 8 0 50 100 150 200 250 300 350 400 450 Time from first release (hr)

12		CPLB BV DC Suspended Sediment Concentration (mg/l) 0 1 2 3 4 5 6 7 0 50 100 150 200 250 300 350 400 450 Time from first release (hr)
13		CPLB BV DC Suspended Sediment Concentration (mg/l) 0 1 2 3 4 5 6 7 8 9 10 0 50 100 150 200 250 300 350 400 450 Time from first release (hr)
14		CPLB BV DC Suspended Sediment Concentration (mg/l) 0 1 2 3 4 5 6 0 50 100 150 200 250 300 350 400 450 Time from first release (hr)

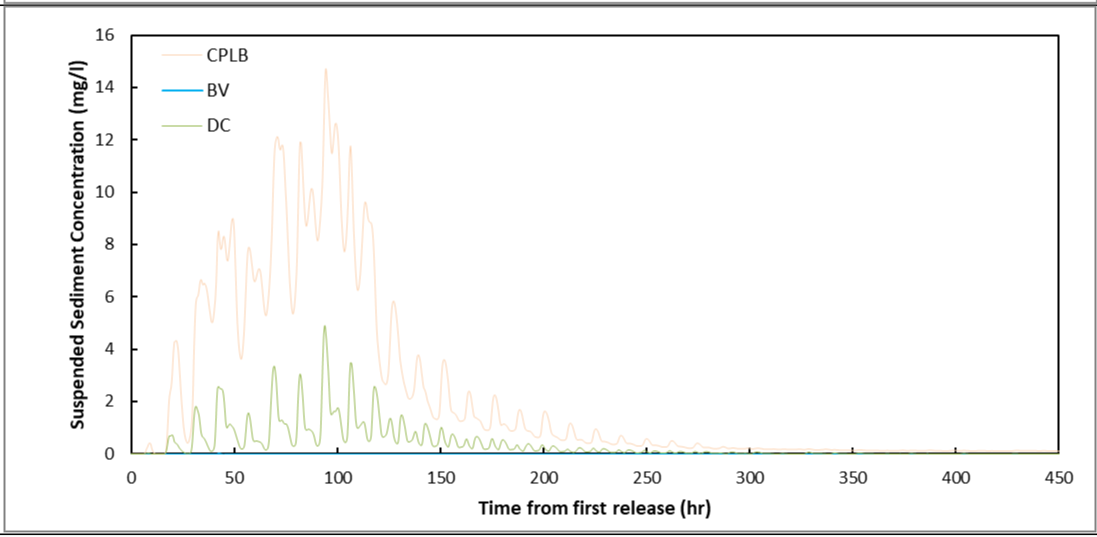
15

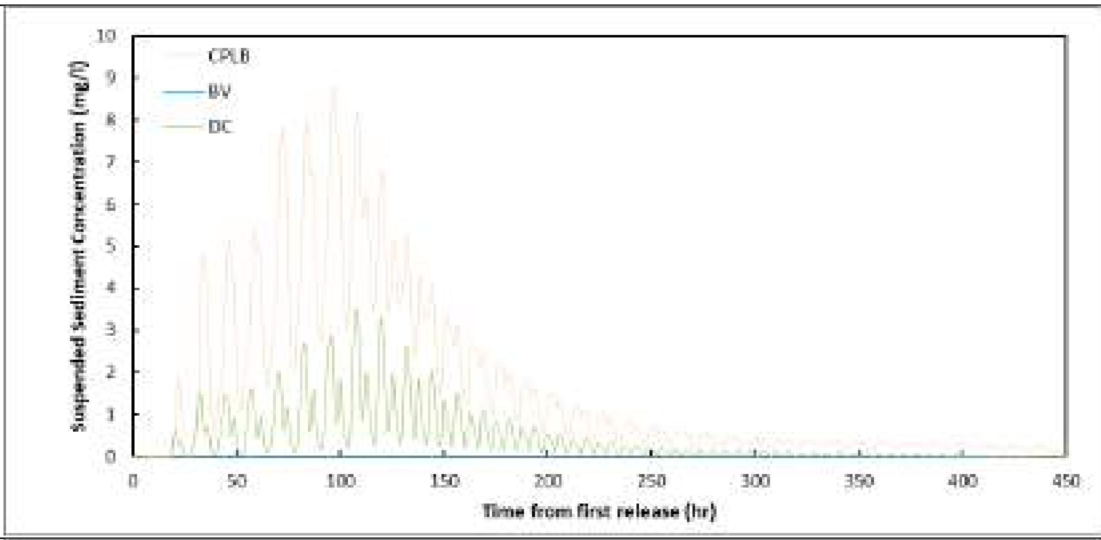
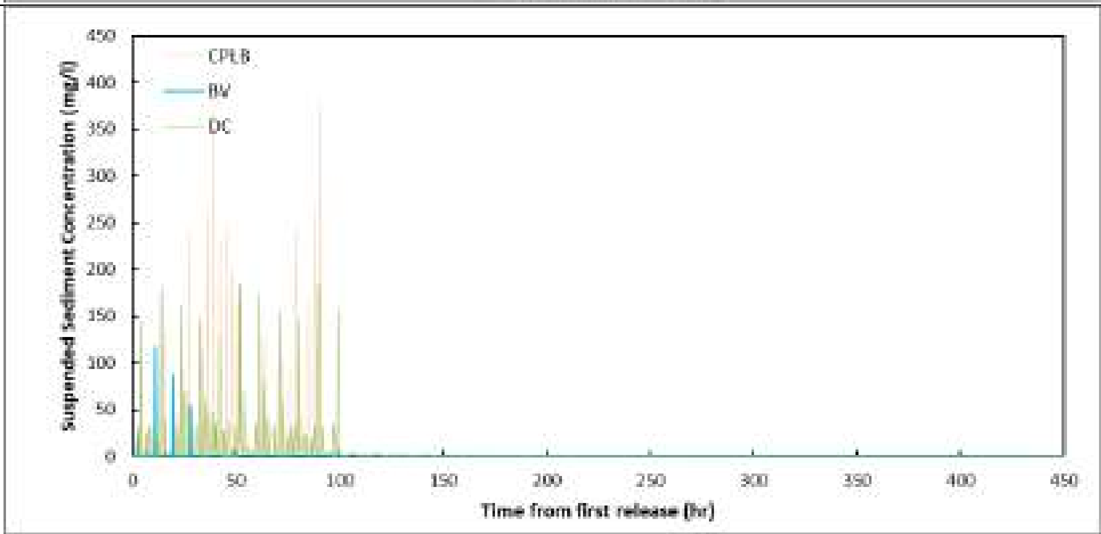
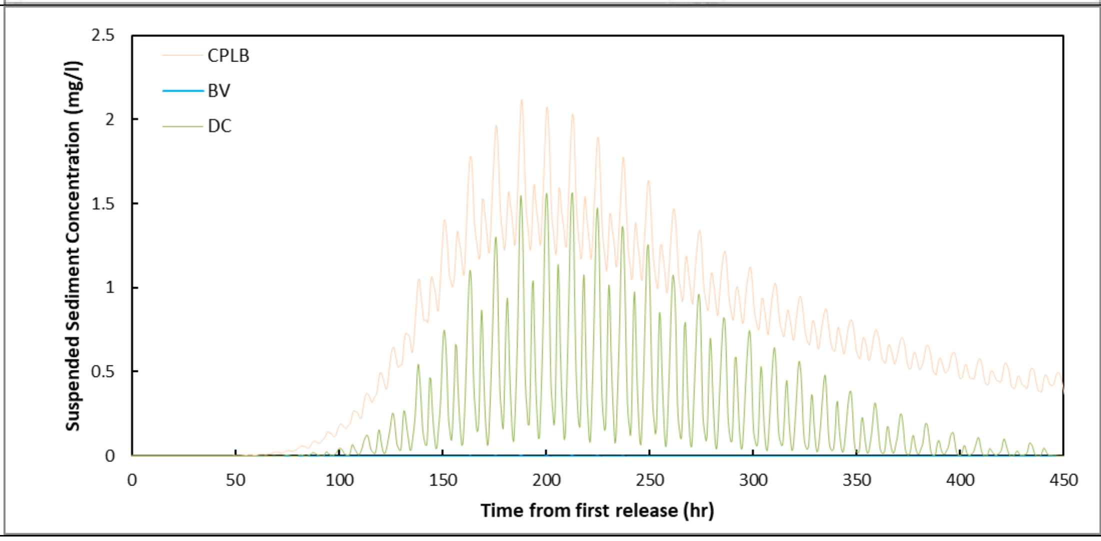

CPLB
BV
DC
Suspended Sediment Concentration (mg/l)
0
1
2
3
4
5
6
7
8
9
0
50
100
150
200
250
300
350
400
450
Time from first release (hr)

16

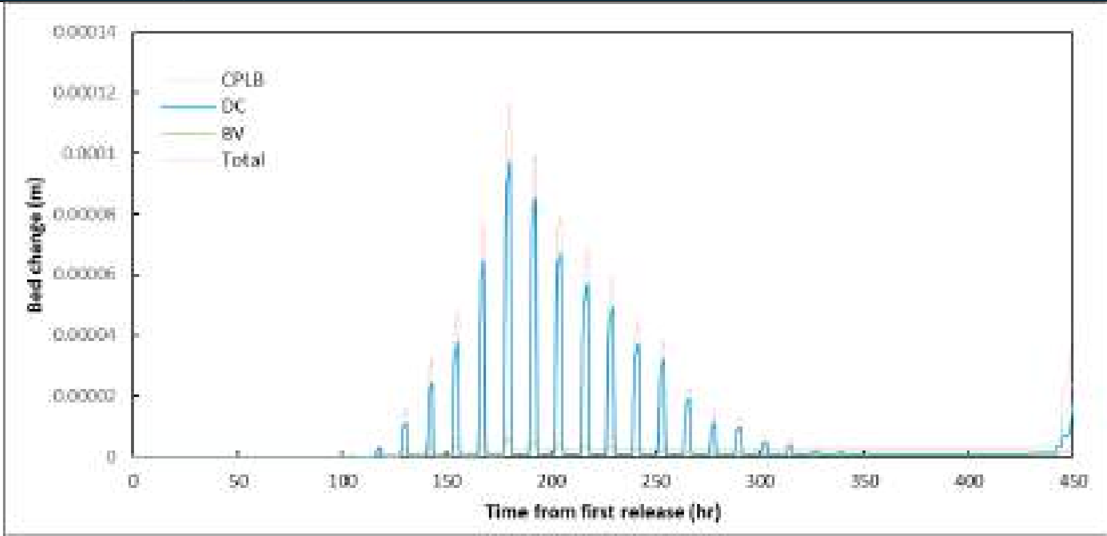
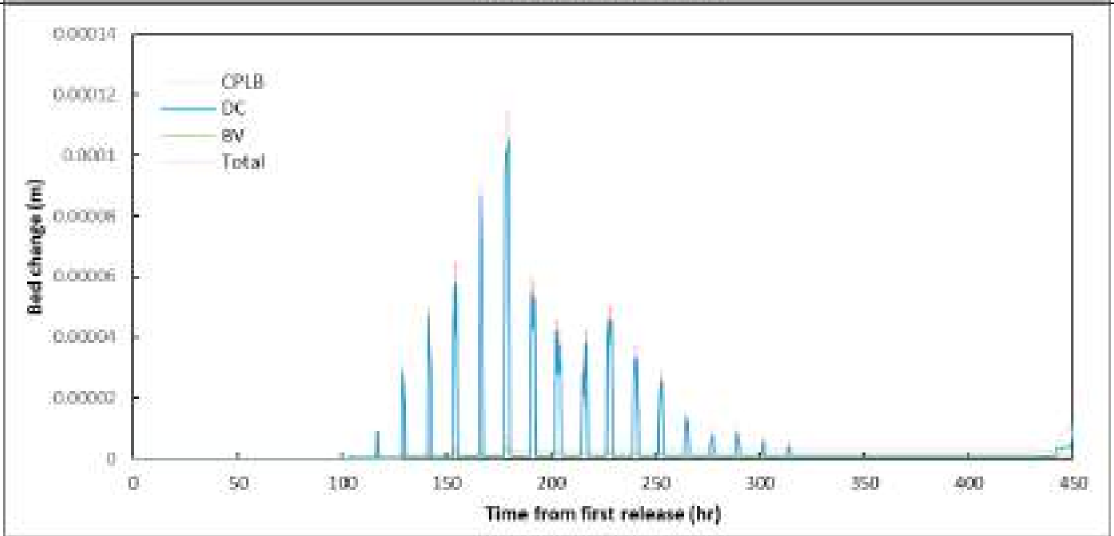
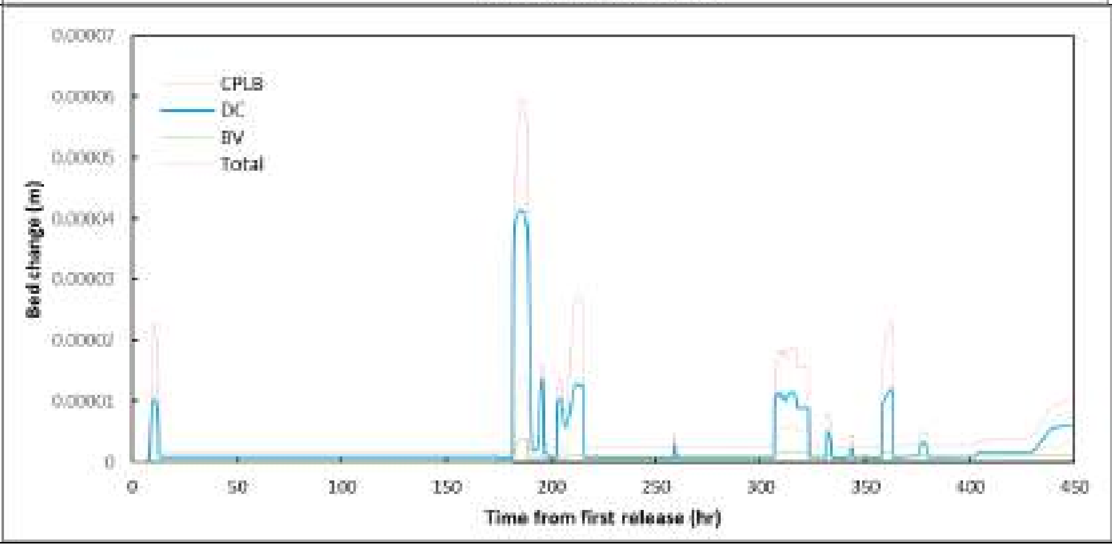

CPLB
BV
DC
Suspended Sediment Concentration (mg/l)
0
2
4
6
8
10
12
14
16
0
50
100
150
200
250
300
350
400
450
Time from first release (hr)

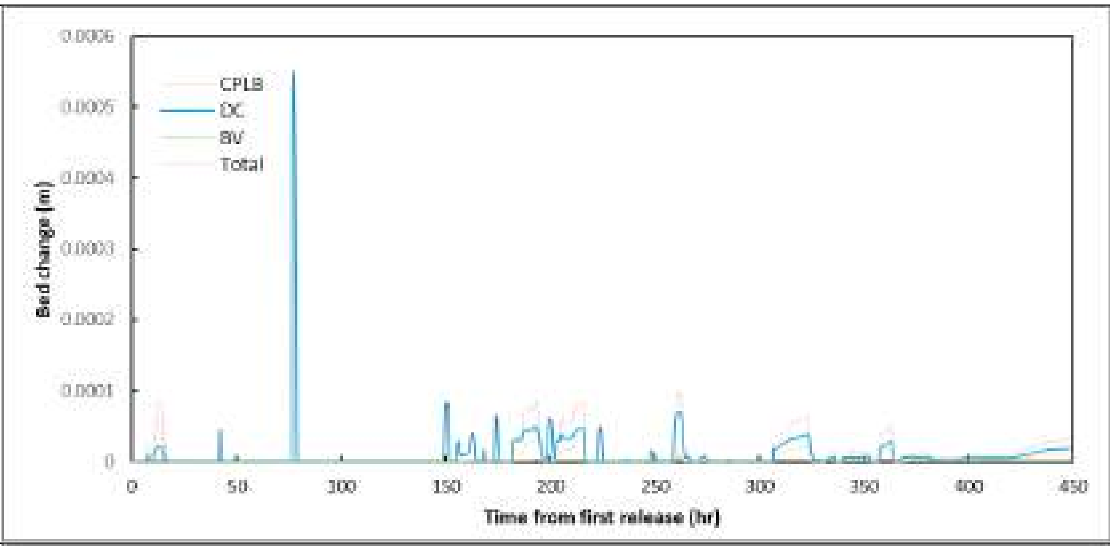
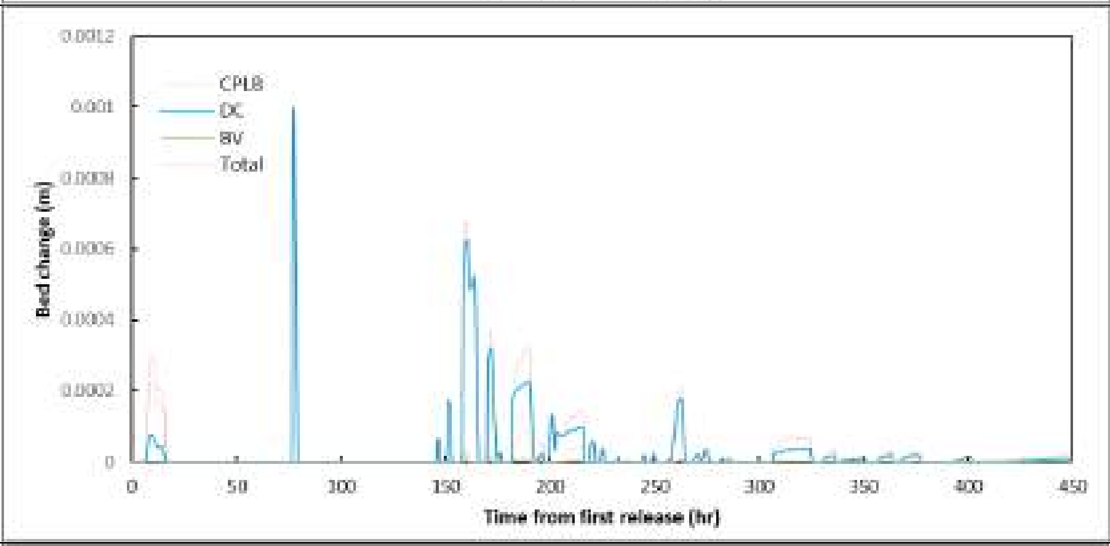
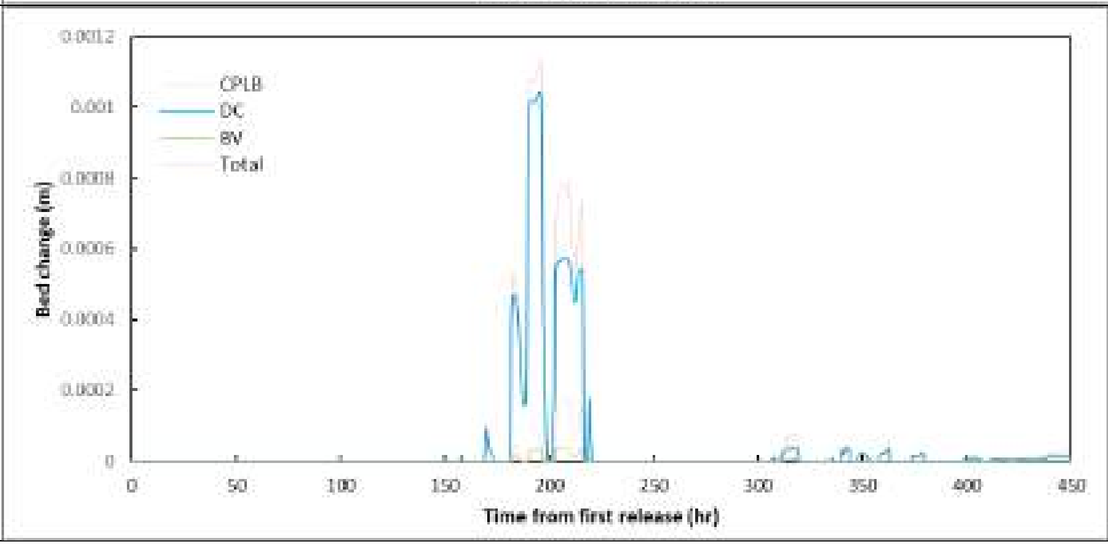
17


CPLB
BV
DC
Suspended Sediment Concentration (mg/l)
0
2
4
6
8
10
12
14
16
0
50
100
150
200
250
300
350
400
450
Time from first release (hr)

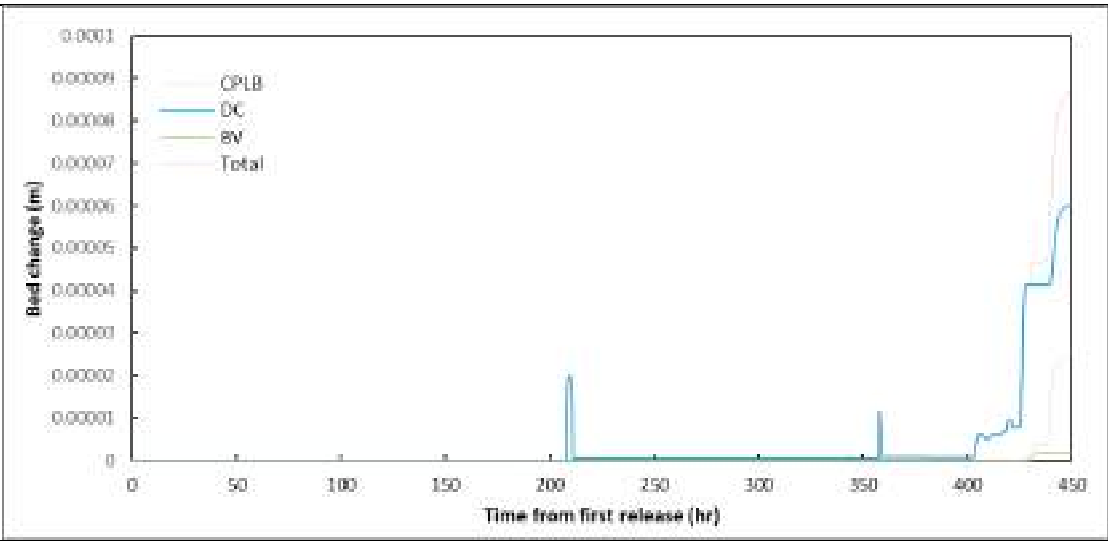
18	 CPLB BV DC Suspended Sediment Concentration (mg/l) Time from first release (hr) 0 1 2 3 4 5 6 7 8 9 10 0 50 100 150 200 250 300 350 400 450
19	 CPLB BV DC Suspended Sediment Concentration (mg/l) Time from first release (hr) 0 50 100 150 200 250 300 350 400 450 0 50 100 150 200 250 300 350 400 450
20	 CPLB BV DC Suspended Sediment Concentration (mg/l) Time from first release (hr) 0 0.5 1 1.5 2 2.5 0 50 100 150 200 250 300 350 400 450

B Appendix B: Timeseries of Bed Level Change at Extraction Sites

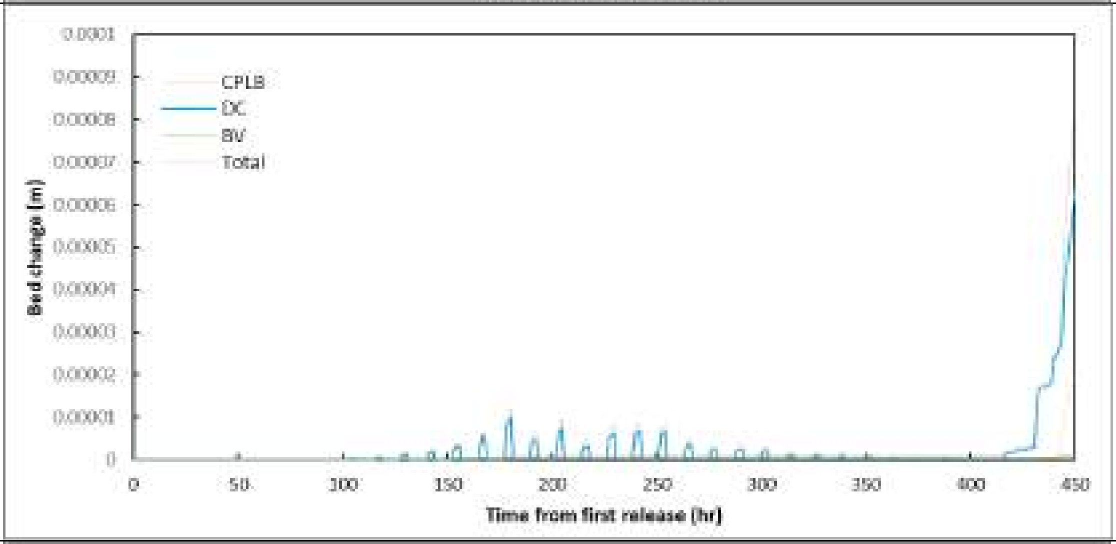
<table>
<tr><th>ID</th><th>Bed level change</th></tr>
<tr><td>1</td><td>
</td></tr>
<tr><td>2</td><td>
</td></tr>
<tr><td>3</td><td>
</td></tr>
</table>

4	CPLB DC BV Total Bed change (m) 0.0006 0.0005 0.0004 0.0003 0.0002 0.0001 0 0 50 100 150 200 250 300 350 400 450 Time from first release (hr)
5	CPLB DC BV Total Bed change (m) 0.0012 0.001 0.0008 0.0006 0.0004 0.0002 0 0 50 100 150 200 250 300 350 400 450 Time from first release (hr)
6	CPLB DC BV Total Bed change (m) 0.0012 0.001 0.0008 0.0006 0.0004 0.0002 0 0 50 100 150 200 250 300 350 400 450 Time from first release (hr)

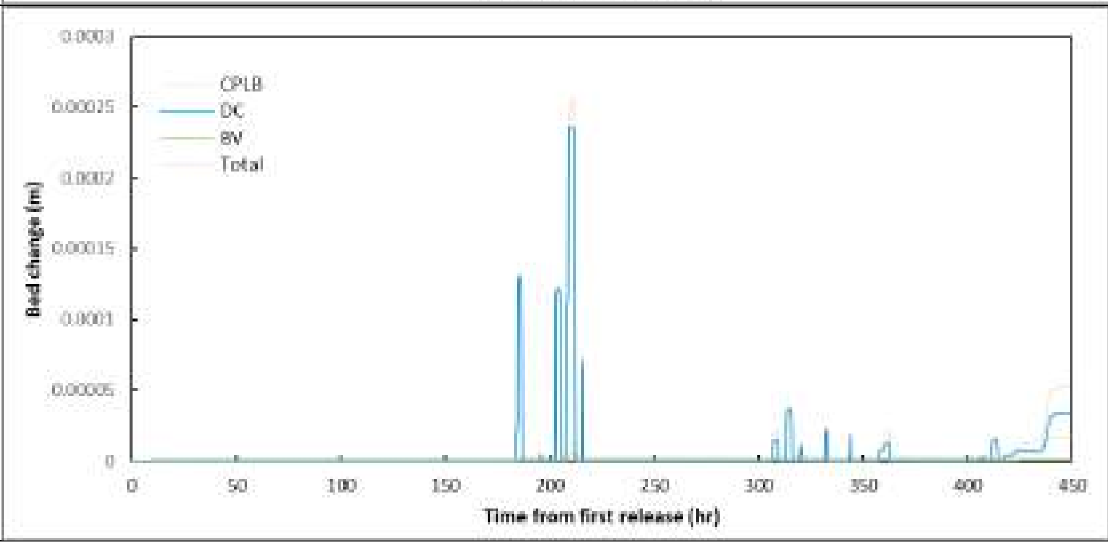
7

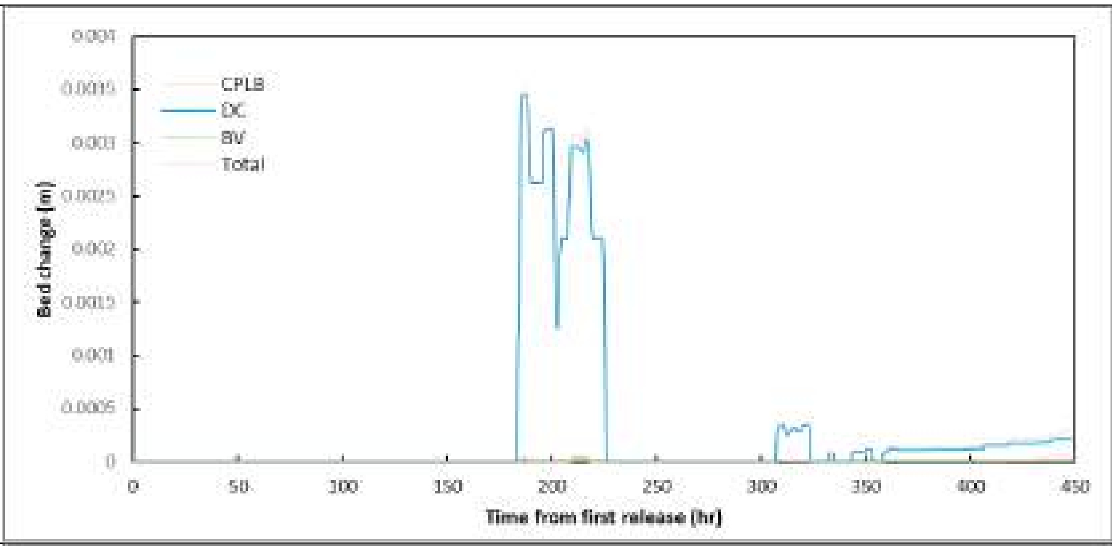
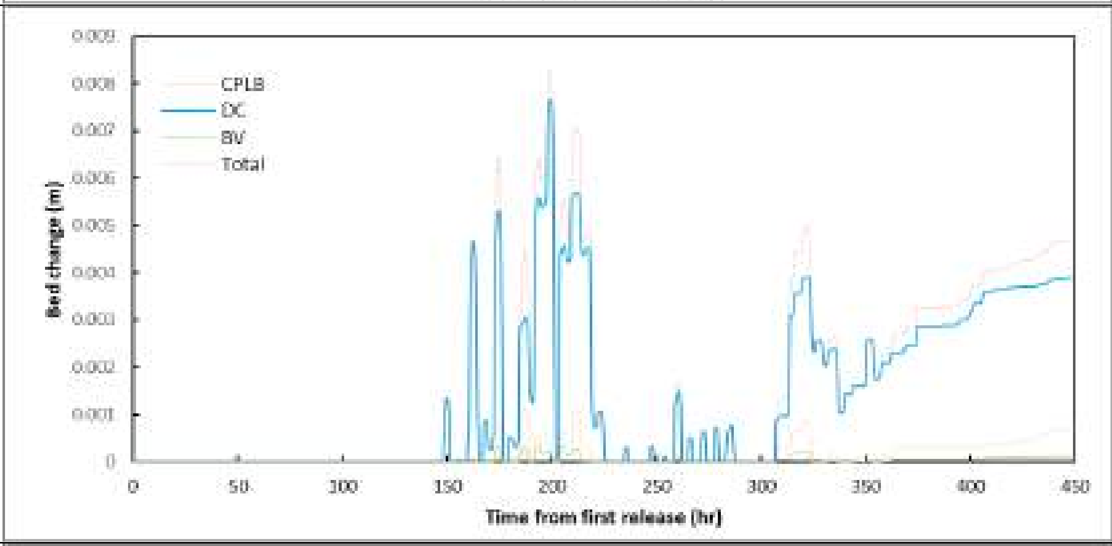
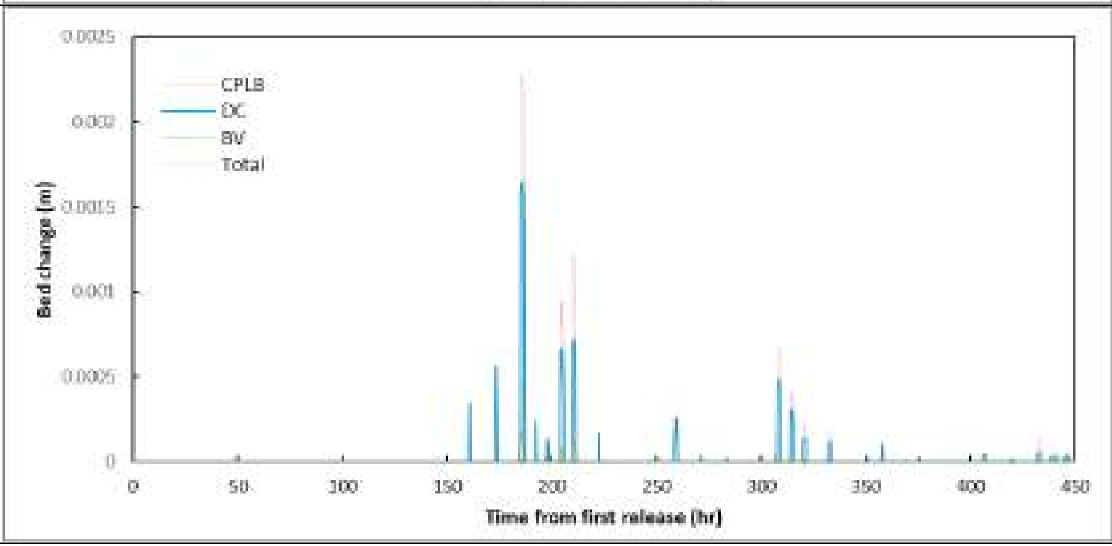

Bed change (m)
0.0001
0.00009
0.00008
0.00007
0.00006
0.00005
0.00004
0.00003
0.00002
0.00001
0
CPLB
DC
BV
Total
0
50
100
150
200
250
300
350
400
450
Time from first release (hr)

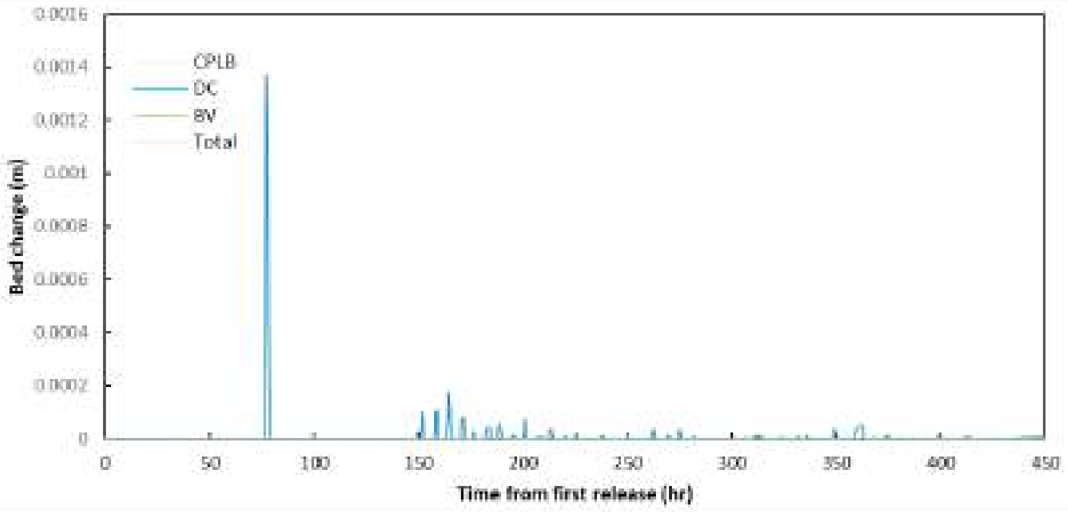
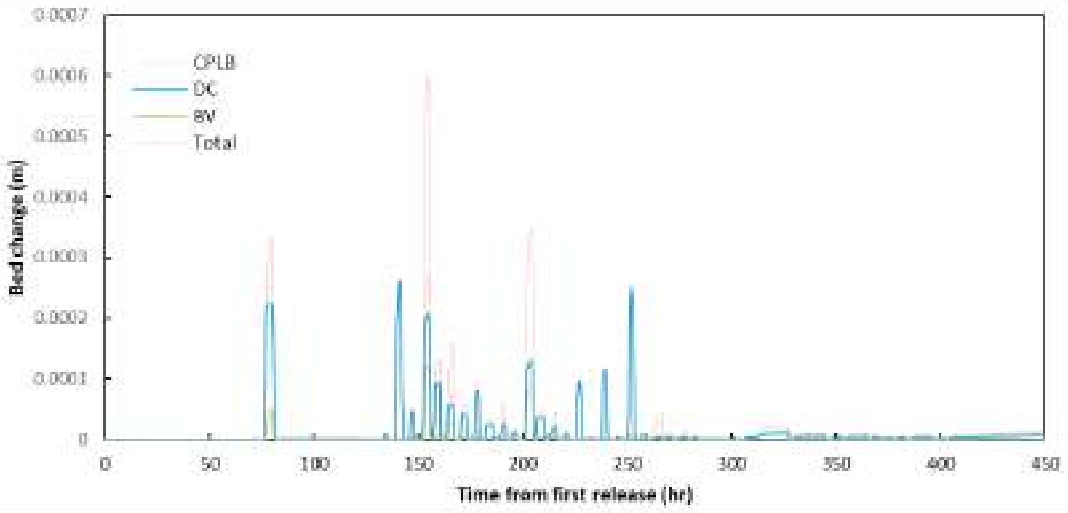
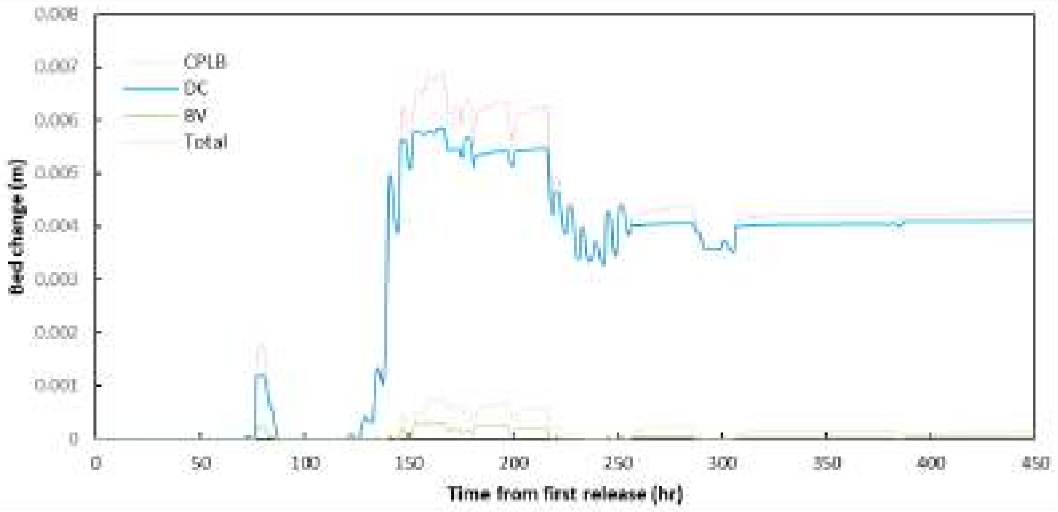
8

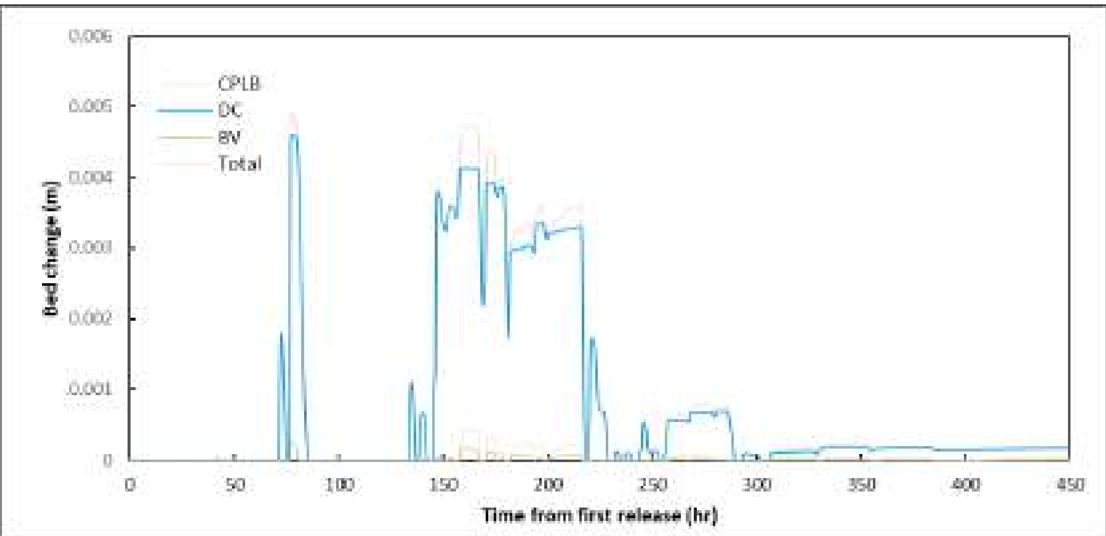
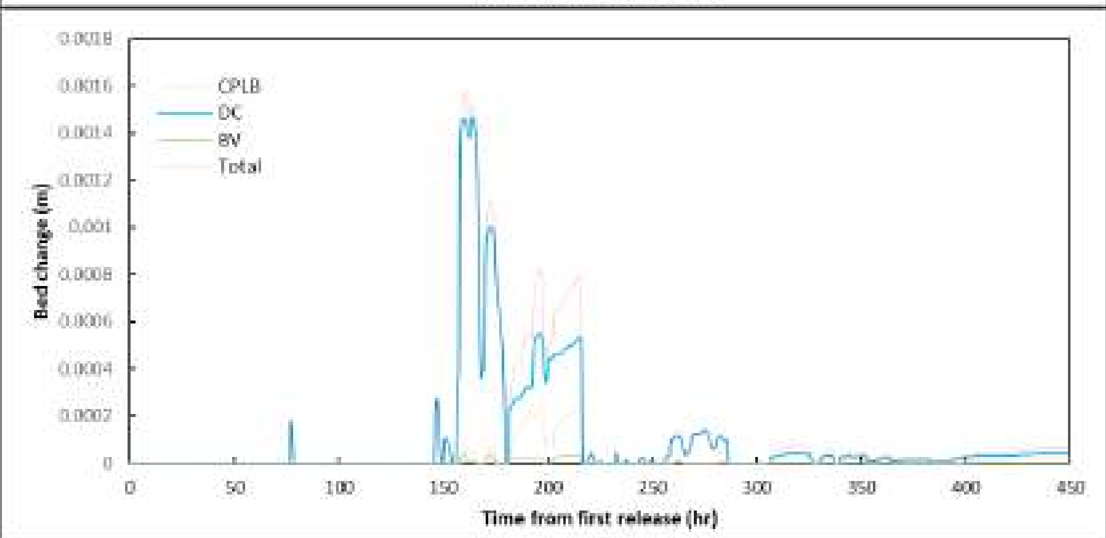
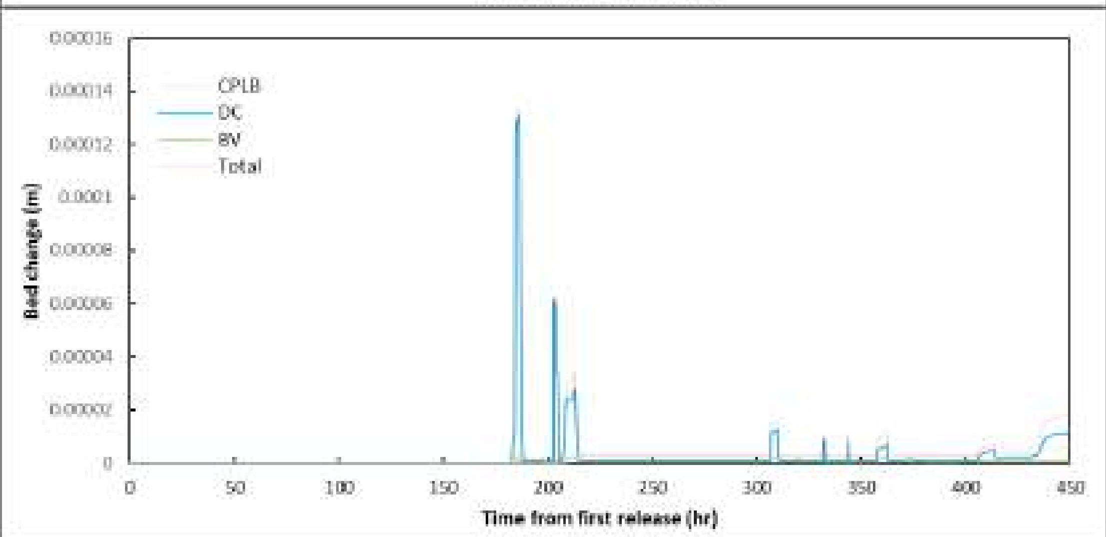

Bed change (m)
0.0001
0.00009
0.00008
0.00007
0.00006
0.00005
0.00004
0.00003
0.00002
0.00001
0
CPLB
DC
BV
Total
0
50
100
150
200
250
300
350
400
450
Time from first release (hr)

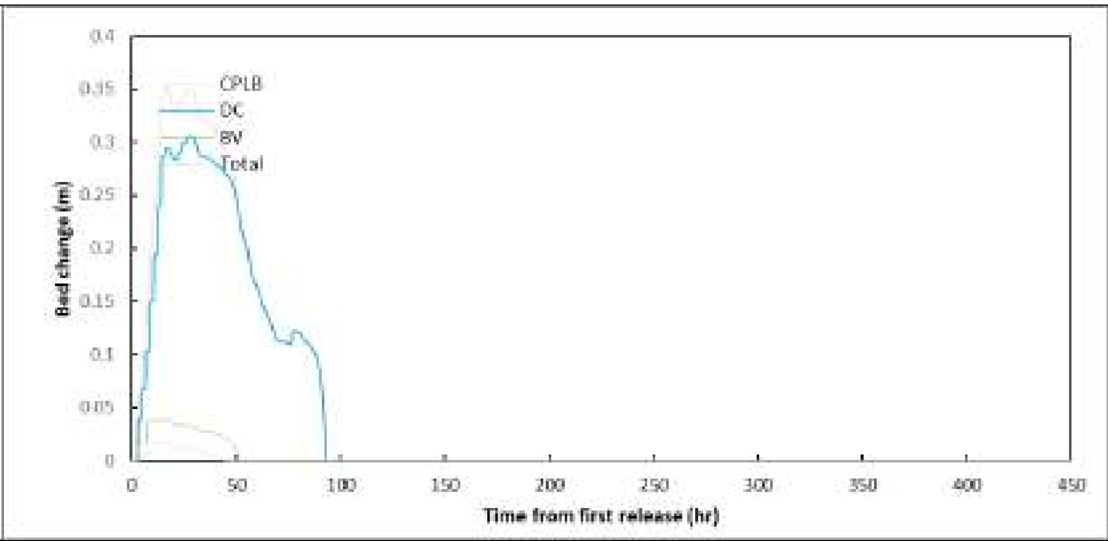
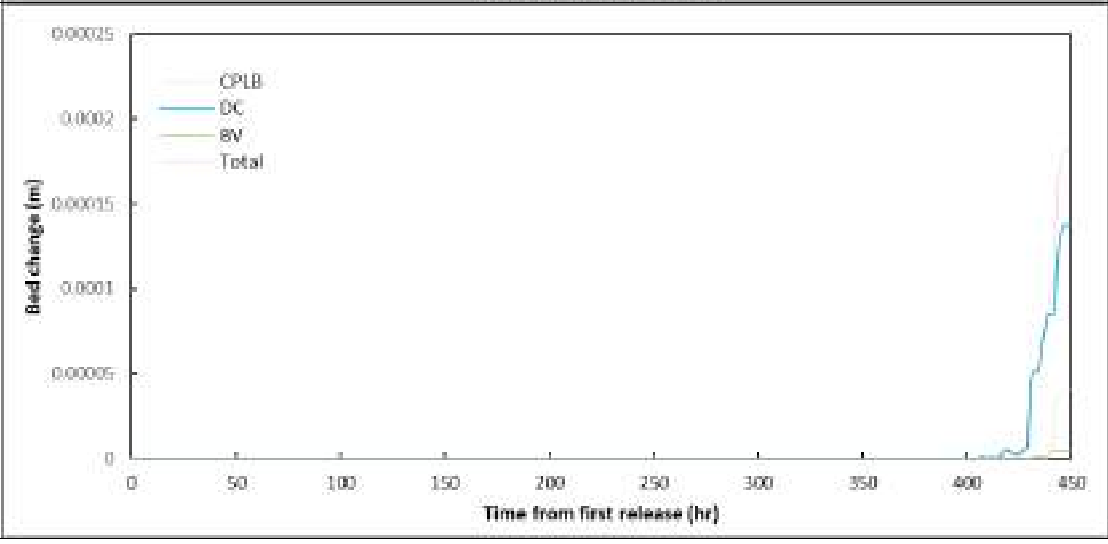
9


Bed change (m)
0.0003
0.00025
0.0002
0.00015
0.0001
0.00005
0
CPLB
DC
BV
Total
0
50
100
150
200
250
300
350
400
450
Time from first release (hr)

10	CPLB DC BV Total Bed change (m) Time from first release (hr)
11	CPLB DC BV Total Bed change (m) Time from first release (hr)
12	CPLB DC BV Total Bed change (m) Time from first release (hr)

13	 0.0016 0.0014 0.0012 0.001 0.0008 0.0006 0.0004 0.0002 0 Bed change (m) CPLB DC BV Total 0 50 100 150 200 250 300 350 400 450 Time from first release (hr)
14	 0.0007 0.0006 0.0005 0.0004 0.0003 0.0002 0.0001 0 Bed change (m) CPLB DC BV Total 0 50 100 150 200 250 300 350 400 450 Time from first release (hr)
15	 0.008 0.007 0.006 0.005 0.004 0.003 0.002 0.001 0 Bed change (m) CPLB DC BV Total 0 50 100 150 200 250 300 350 400 450 Time from first release (hr)

16	CPLB DC BV Total Bed change (m) Time from first release (hr) 0.006 0.005 0.004 0.003 0.002 0.001 0 0 50 100 150 200 250 300 350 400 450
17	CPLB DC BV Total Bed change (m) Time from first release (hr) 0.0018 0.0016 0.0014 0.0012 0.001 0.0008 0.0006 0.0004 0.0002 0 0 50 100 150 200 250 300 350 400 450
18	CPLB DC BV Total Bed change (m) Time from first release (hr) 0.00016 0.00014 0.00012 0.0001 0.00008 0.00006 0.00004 0.00002 0 0 50 100 150 200 250 300 350 400 450

19	 CPLB DC BV Total Bed change (m) 0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0 50 100 150 200 250 300 350 400 450 Time from first release (hr)
20	 CPLB DC BV Total Bed change (m) 0 0.00005 0.0001 0.00015 0.0002 0.00025 0 50 100 150 200 250 300 350 400 450 Time from first release (hr)

[redacted]

ABP mer

APPENDIX G-2

Port of Waterford

Waterford Estuary

Plough Assessment

November 2017





Innovative Thinking - Sustainable Solutions

ABP mer

Page intentionally left blank

Waterford Estuary

Plough Assessment

November 2017

1D2O1846 Photo: © Peter Barrow Photography 3rd June 2011 Tel: 0872-559638

Document Information

Document History and Authorisation		
Title	Waterford Estuary	
	Plough Assessment	
Commissioned by	Port of Waterford	
Issue date	November 2017	
Document ref	R.2899TN	
Project no	R/4506/02	
Date	**Version**	**Revision Details**
27/10/2017	1	Draft for client review
01/11/2017	2	Issued for client use - with minor client comment

Prepared (PM)	Approved (QM)	Authorised (PD)
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]

Suggested Citation

ABPmer, (2017). Waterford Estuary, Plough Assessment, ABPmer Report No. R.2899TN.
A report produced by ABPmer for Port of Waterford, November 2017.

ABPmer
[redacted]

Contents

Table

Figures

1 Introduction

ABPmer has developed detailed, estuary-wide numerical hydrodynamic and sediment transport models for the Port of Waterford (PoW) to aid their Master Planning Programme and current marine operational requirements. These models replicate the present environmental conditions within the estuary and can be used to determine any changes and effects on the marine environment resulting from future development and dredging operations. The numerical model has been built using the Danish Hydraulic Institute (DHI) software package MIKE3 FM (Flexible Mesh). The setup, calibration and validation of these modelling tools are reported separately (ABPmer, 2017).

In order to maintain access for vessels to the berths at Belview and the independent O'Briens wharves (and also, onward to Waterford), PoW routinely require to carry out dredging and ploughing operations over Cheekpoint Lower Bar, near the confluence of the Rivers Barrow and Suir. This area is presently subject to siltation, which requires active intervention to maintain sufficient underkeel clearance for visiting vessels. As part of the PoW Master Planning Programme, schemes are being considered to help alleviate the siltation and thus reduce dredging commitment on PoW. The current maintenance practice is to dredge with a Trailing Suction Hopper Dredger (TSHD), nominally three times per year (February/March, June and September/October). The sediment is deposited at a licenced disposal site just off the entrance to the Waterford Estuary. Between dredge campaigns ploughing/bed levelling is carried out to maintain the least available depth (LAD).

Renewal of the dredge licence is required and the regulator has requested that an assessment of the dispersion of the sediment from the plough activity be assessed. This technical note provides the results and assessment of dispersion modelling of a typical plough campaign.

This report is structured as follows:

Section 2: Background to the PoW ploughing campaign and derivation of model input parameters;

Section 3: Model setup for the ploughing assessment;

Section 4: Results of the plough assessment; and

Section 5: Discussion of results.

2 Background

To maintain the LAD of the channel for as long as possible between bulk sediment removal from TSHD campaigns PoW have introduced ploughing/ bed levelling operations over Cheekpoint Lower Bar. This bed levelling helps maintain sufficient depths for safe vessel access to the Belview berths and upstream parts of the Waterford Estuary. For renewal of the dredge licence the regulators (Environmental Protection Agency (EPA) and Department of Housing, Planning, Communications & Local Government (DHPLG)) have requested an assessment of the dispersion of sediment throughout the estuary from the ploughing activity.

Information from recent ploughing campaigns at Cheekpoint Lower Bar has been analysed to determine a set of 'realistic' bed disturbance parameters from the plough operations, which can then be used within the numerical modelling to assess the dispersion effects. This analysis indicates the plough effect is highly variable between campaigns. The model input parameters have been derived to represent a realistic worst case with respect to potential for dispersion.

The following sub-sections describe the normal plough operation, the sediment composition that is dispersed and determination of a realistic rate of plough induced sediment disturbance.

2.1 Ploughing activity

The current ploughing activity is undertaken by 'dragging' a 10 m wide bed levelling ('box') over the bed along the axis of the maintained channel and to either side. On each track the box will disturb an average of *circa* 0.3 m of bed sediment to the lower levels of the water column where it is dispersed by the prevailing tidal flows. The bed levelling is a near continuous process for the time period of operation with the 'box' dragged at a speed of *circa* 1.5 knots, (0.77 m/s) over the ground, with and against the tide on alternate tracks. The track design is planned to cover the complete area to be maintained over each campaign.

The current plough regime for each campaign is to undertake bed levelling on four consecutive days on spring tides (only), although a neap tide campaign was carried out in 2017 as an 'emergency' when weather conditions prevented the scheduled spring tide campaign. The vessel works for 10.5 hours, between approximately 0745 hours and 1815 hours, on each day; therefore the bed sediment disturbance will occur at different parts of the tidal cycle, on both the flood and ebb tide, as well as slack water periods. No disturbance occurs over the night time hours.

Sedimentation is generally greatest to the south side of the river, outside the defined channel. About 35% of the plough time is concentrated in this area at the start of each campaign, with the rest of the time in the main channel and to the north. Figure 1 shows a plot of the track coverage for a typical plough dredge campaign undertaken in July 2017. As a result of this typical plough operation the sediment will disperse to different locations in the estuary, with the finest particles travelling furthest before resettling to the bed. Depending on the location of settlement and the material characteristics relative to the bed shear stresses created by the tidal flows it will either be re-eroded for further dispersion or will accumulate on the bed. This process is likely to create differential sorting of the disturbed sediment. It is this dispersion from a representation of the plough operation that the numerical model has simulated.

2.2 Sediment composition

As the bed sediment is disturbed by the plough the material has the potential to 'break down' into its component particulate form as it is suspended into the water column. Some of the finer material (silt/clay) may remain cohesive and move as larger particles. For the purpose of modelling it is however assumed that fine particles will occur i.e. the material disturbed will be broken down to its constituent parts. Any modelling will therefore tend to overestimate the overall extent of dispersion within the estuary as the proportion of fines is likely to be over-represented.

To determine the particle size composition of the disturbed material an analysis of sediment size grading curves (particle size distributions) of bed samples collected at the following locations (in and around the plough maintained areas), was undertaken:

- Main navigation channel;
- Main sedimentation area to the south of the channel;
- Intertidal mud areas;
- Kilmokea Point (Power Station Berth); and
- Mid channel immediately up and down estuary of the ploughed area.

A synthesis of these data indicated that three particle sizes would characterise the bed sediments that will be disturbed. These sizes, and the proportion of the sediment matrix they represent, are given in Table 1.

Table 1. Composition of released material for plough operation assessment

Representative Grain Size (µm)	Representative Material Type	Distribution in Release (%)	Settling Velocity ($x10^{-3}$ m/s)
16	Silt	30	0.16
62	Silt/Sand	45	2.42
129	Sand	25	10.04

Data from 1989 and 2017 were used in this analysis, and showed that there has been little change in the sediment composition over time.

2.3 Sediment disturbance rate

For modelling of the dispersion from the plough dredging it is necessary to calculate a disturbance rate (kg/s dry solid) to be input to the model during the plough operation. For this analysis the effects of plough campaigns undertaken in January and February 2017 (on spring tides) and July 2017 (on a neap tide), were analysed along with siltation rates calculated between surveys when no ploughing was occurring from 2016.

From these records the spring and neap tide average accumulation rates in the area limits of the plough campaigns were 1,371 m^3/day and 580 m^3/day, respectively. The results of the ploughing in volumetric terms was, however, highly variable between campaigns. This is due to the on-going sedimentation rate at the time, the actual tidal range, weather conditions prior to and during the ploughing and the proportion of time at various flow rates and tide directions during the operation. These will all differ between individual campaigns.

Analysis of the various available volumetric evidence suggest that, allowing for potential sedimentation that would have occurred during the period of plough disturbance, a realistic rate of disturbance would be in the range of about 1,100-1,700 tonnes dry solid per day. Based on a continuous working time of 10.5 hours per day, this equates to a disturbance rate of 29-44 kg/s.

For the modelling to provide a realistic worst case of the dispersal effect of the ploughing, the higher rate of 44 kg/s has been used as input to the model simulation along the plough track.

3 Plough Model Setup

The plough disturbance model simulation has been undertaken by using the data from the calibrated MIKE3 FM hydrodynamic model to run the MIKE3 MT (Mud Transport) model, in de-coupled mode. Within this model, the background suspended sediment concentrations were not included; therefore all results presented are in the form of 'above background' (concentrations) or 'in addition to background' for change to the bed thickness. In this mode the effects attributable to the plough are directly determined, although interactive effects with the background sediments in the system are not accounted for.

3.1 Plough track release location

Track plots from the recent ploughing campaign (July 2017) have been provided by PoW, and are shown in Figure 1. These tracks show the coverage of the ploughing activity over four consecutive days between 14 and 17 July 2017. The general extent of each day's activity has been defined in the model by a series of 'plough boxes', which combine to provide a representation of the overall extent of ploughing activity for the July 2017 campaign. This campaign area is typical of the current working practice.

The combined extent has then been used to define the input locations for the release of disturbed material within the model. In Figure 1, the purple lines define the northern and southern limits of the ploughing activity, with two further tracks defined at equidistant points in between. These four 'Plough assessment tracks' have then been used as input coordinates for the plough assessment model, providing sediment disturbance inputs covering the full lateral extent from which sediment dispersion occurs. The inputs also represent the varying flow conditions across the estuary and at the up- and down-estuary ends of the ploughed area.

In the vertical plane, the disturbed material is released into the water column at a constant height of 1 m above the bed. This level has been defined by the type of ploughing equipment utilised, and the associated expected release height of the disturbed sediment.

3.2 Release duration

As discussed, the current plough operation for each campaign is based on a 12 hour daytime shift. Allowing for transit time to and from the Cheekpoint Lower Bar area this results in the working window of 0745 through to 1815 each day (totalling 10.5 hours of continuous ploughing activity per day). This work pattern is planned usually over four consecutive days of a spring tide each campaign.

In the model this is simulated for the exact times for four consecutive spring tides, with tidal ranges varying between 3.8 and 3.9 m, close to the mean spring tide range of 4.0 m at Cheekpoint. No disturbance is input to the model outside these times. On each day, sediment is released into the model as a moving input, back and forth along each of the tracks shown in purple on Figure 1, and at a nominal speed of 1.5 knots. The southern track is run on Day 1, with the track moving northwards on successive days. On each day the track starts in the west and takes 20 minutes to pass through the length of channel before returning on the same alignment. On completion of the simulation of the ploughing activity the model is then allowed to run-on for a further 8 days of simulation time, to assess the subsequent fate of the disturbed material as it settles, and is then allowed to be re-suspended (should flow induced bed shear stresses be sufficient at the individual locations), on subsequent tides.

3.3 Release rate

Section 2.3 details the calculation of the sediment release likely attributable to the plough activity. As noted, this is likely to be highly variable. For the purpose of modelling, the higher rate calculated (representing a 'realistic worse case') has been used, in order to model the likely highest sediment dispersion in the estuary. Consequently, a constant sediment release rate of 44 kg/s has been used throughout the period of ploughing activity, inserted into the model 1 m above the bed. In reality the rate will vary considerably.

3.4 Composition of released material

Table 1 shows the particle sizes that are considered to characterise the sediments likely to be ploughed at Cheekpoint Lower Bar (as defined in Section 2.2). The sediment disturbed in the model is simulated by the three sediment fractions, their respective proportional contributions within the sediment matrix, and the calculated settling velocities of individual particles (without consideration of flocculation processes).

3.5 Deposition and erosion

Within the numerical model, controls on the rate of deposition and erosion are provided by setting a series of bed shear stress (BSS) thresholds, as described below.

When BSS is *below* the threshold for deposition, material in suspension is able to settle to the bed (at the rate defined in Table 1, above), increasing the thickness of material on the bed. The model is not run in morphological mode; therefore there is no feedback provided to estuary hydrodynamics. However, the small amount of sediment released in the model, and the resultant change in bed level due to settlement, will be small compared to the depths in the estuary; therefore any error due to this simplification will be negligible. As sediment settles to the bed local suspended sediment concentrations (SSC) will be reduced. Conversely, under conditions where the BSS is *above* the defined deposition threshold, material is maintained in suspension and transported around the estuary in accordance with the variation in the hydrodynamic flows.

When BSS is *above* the threshold for erosion, material on the bed is able to become re-suspended, and entrained back into the water column, increasing the SSC. Under conditions where the BSS is *below* the erosion threshold, settled material is maintained on the bed.

There is a range of recommended values for these thresholds (derived from both theoretical and practical experiments). Ultimately, the choice of deposition and erosion thresholds is one of the primary calibration parameters.

Within the present study, the sediment is considered to be freshly laid-down, cohesive mud with little time for consolidation. On this basis a low bed shear stress for erosion of 0.3 N/m^2 has been used in the model. In reality this value will also vary between locations and with the particular sediment composition. This value, however, is considered a realistic average figure. The threshold at which settling from flowing water occurs has been set to 0.1 N/m^2, which the literature indicates to be not unreasonable for generally fine-grained, cohesive material. At BSS values between the defined thresholds, the sediment remains in the water column (as SSC), without transfer to or from the bed.

3.6 Initial conditions

Within the plough assessment model, initial conditions of SSC and bed thickness are both set to zero (i.e. there is no material within the model at the start of the simulation, and the only material released is that representing the ploughing operations).

In this way, the results of the assessment provide a prediction of the fate of the ploughed material only. Model outputs of SSC are showing values above background (rather than total SSC), whilst model outputs of bed thickness show only the settling of the ploughed material (without taking account of any sediment transport processes affecting bed material from the rest of the model domain).

The initial extent of the dispersion is also maximised by undertaking the plough simulation over the spring tides.

The modelling assumption is that this settled material is then mobilised by the ploughing activity, to return the bed level to the maintained depth. The model simulation has also assumed a bed wet density of 1,300 kg/m^3 (and equivalent to a dry density of 448.46 kg/m^3) for the calculation of the thickness of the settled layer on the sea bed.

4 Plough Model Results

Timeseries of the modelled outputs for SSC and sedimentation have been extracted at a number of interest locations; defined by areas predicted to be accretionary, along with strategic locations of interest. The extraction locations are shown in Figure 2.

These timeseries, for each of the 16 locations, are shown in Figure 3 to Figure 18. Within each figure, the tidal signal from Cheekpoint is provided, in order to illustrate the tidal state related to the plume information. Separate plots are then provided for SSC, sedimentation and bed shear stress. Each plot starts at the beginning of Day 1 of ploughing operations, and runs on to the end of the simulation period, approximately 8 days after the cessation of ploughing operations on Day 4.

These timeseries plots illustrate the peak values of SSC and sedimentation, at each location, and also provide information on the duration over which these peak values can be expected to occur.

In addition to the timeseries plots at selected locations of interest, a series of map plots are also provided, showing the spatial extent and magnitude of predicted SSC and sedimentation over the days following the ploughing campaign. These results are shown in Figure 19 to Figure 23, and cover the period from 'Plough +0 days' (Figure 19, immediately after the end of ploughing on Day 4 of operations), with daily results provided on each subsequent figure, up to 'Plough +4 days'.

The map plots show how the spatial extent, and magnitude, of sedimentation and SSC varies over the days immediately following the plough campaign, as the estuary approaches neap tidal conditions. Each figure shows the predicted peak sedimentation over slack water (generally on or around HW and LW tidal conditions) and the peak SSC (above background) during the intervening ebb and flood tide.

A detailed discussion is provided in Section 5, but in general, the following observations can be made about the plough assessment results:

- Peak SSC values are observed in the immediate vicinity of the ploughing operations;
- Ploughing operations begin during a flood tide, resulting in material being transported, in suspension, up-estuary towards Little Island;
- Relatively little material is transported into the River Barrow;
- During slack-water periods, material settles out to the bed, before some is resuspended during subsequent ebb/flood tides;
- Ploughed material is generally pulsed through the system, over an area between Little Island and the deep channel just downstream of Cheek Point;
- Relatively small amounts of material are transported upstream or downstream of these limits;
- The intertidal areas between the groynes on the southern bank act as a sink for ploughed material;
- Following cessation of ploughing operations, the level of intermittent peak SSC through the wider Cheekpoint area reduces to a level of less than 10 mg/l within a period of around 4 days; and
- Material deposited to the bed is subject to resuspension during spring tides, but not on neap tides.

The results of the plough assessment are discussed further in the following section.

5 Discussion

The discussion of the plough assessment outputs initially describes the general extent of dispersion, along with indicative magnitudes of effect. Subsequently, a more detailed description of the results (and the influencing processes) is provided for sub-sections of the estuary.

5.1 General extent of dispersion

Numerical modelling of the dispersion of sediment from a plough campaign (representative of a 'realistic worst case' scenario, with respect to dispersion of sediment around the estuary) has been undertaken. Outputs have been selected to show the change in distribution with time, at daily intervals for four days following completion of the plough campaign (Figure 19 to Figure 23). After this period ('Plough +5 days' onwards), suspended sediment concentrations throughout the estuary (and attributable to the plough campaign) are reduced to below 10 mg/l above background; therefore outputs from this period have not been presented.

These map plots of SSC distribution show a 'snap-shot' in time; different distributions will result for different times within the tide. To account for this variability and to make the plots comparable (to enable an assessment of the decay in effect from the plough operations to be undertaken), the following distribution plots are presented at daily intervals:

- Sedimentation (thickness change on the bed) over slack water on HW;
- Sedimentation over slack water on LW;
- Peak SSC during the ebb tide (generally taken at, or around, HW +2); and
- Peak SSC during the flood tide (generally taken at, or around, HW -4).

The sedimentation plots represent the maximum bed accumulations (and lowest suspended sediment concentrations within the water column), whereas the SSC plots are shown at the times of high flood and ebb flows (and therefore representative of the maximum SSC in the water column).

The maximum extent from all plots indicates that sediment is dispersed throughout the estuary system. The vast majority of this material moves in an up-estuary direction, within the areas predominantly between Cheek Point and Little Island. The down-estuary extent of main effects is predominantly carried to the area up-estuary of Buttermilk Point, and particularly within the deep off Cheek Point itself. The results indicate that the majority of the disturbed sediment is retained/incorporated into the background within these areas and available for resettlement back into siltation areas over a longer timeframe.

5.1.1 Effect immediately after plough disturbance

The greatest extent of effect is observed immediately following the completion of the plough campaign. Figure 19 (at the end of the plough disturbance), shows that:

- Near-bed SSC values are almost everywhere higher on the flood tide, compared to the ebb;
- Focal points are evident, where the disturbed sediment is concentrated by the flows, 'collects', and is then re-eroded (i.e. temporary stores), and others which continually accrete (i.e. 'sinks');
- Temporary store locations include:

- The deep pocket around Cheek Point, particularly towards the western edge; and extending across the slope from Cheekpoint Lower Bar, in the direction of Drumdowney Point. This 'extension' of the main area is immediately at the edge of the area that has accreted as a result of the construction of the groynes in the 1990's.

  Figure 19 shows concentrations through this area in excess of 1,000 mg/l on peak flood flows, but which are considerably less on ebb flows. Sediment from the plough disturbance is also shown to deposit with depths of up to 0.04 m over LW in this area and, to a lesser extent, within the deep channel through Carters Patch. It is possible that this, in reality, would be a layer of fluid mud in the base of the pocket.

  This accumulation is shown to be re-eroded during the flood tide, to the extent that it is completely removed at HW. The deep pocket therefore acts as a temporary store of sediment. The flood tide erosion of this material will add to the SSC that is being transported through the area from down-estuary on the flood tide;

- Two locations on the edge of the deeper channel both to the north and south of the Cheekpoint Upper Bar, which join together across the estuary opposite the northeast end of Belview Quay.

  Peak flood tide concentrations, as a result of the plough disturbance, are generally up to 1,000 mg/l, but are considerably lower on the ebb. Around these locations, sedimentation of up to 0.02 m is evident across the width of the estuary at LW. During the flood tide, the sediment through the centre of the reach is re-eroded but accumulations remain over the shallows on either side of the estuary;

- A further area where sediment appears to concentrate is the confluence of Queen's Channel and King's Channel, around Little Island. Here, the concentrations are highest on the ebb tide at the exit of Queen's Channel.

  Accumulations of sediment on the bed are evident during the HW and LW slack period, particularly over the 'bar' at the entrance of the King's Channel at HW, whilst the Queen's Channel has been flushed of sediment (except over the shallow intertidal at the edges).

- Sink locations (i.e. areas of net accretion) include:
  - Around the edge of the intertidal and shallow intertidal to the south of the channel at Cheekpoint, particularly the channel edge outside the entrance to Cheekpoint Harbour. This is primarily the area of siltation from natural flows;
  - The shallower areas either side of the estuary, along the Cheekpoint Upper Bar channel, and particularly the down-estuary end of the Belview Quay;
  - The east side of the estuary opposite the Belview Quays; and
  - The intertidal areas near the confluence with King's and Queen's Channel, especially the entrance to Woodland Pill, up-estuary of O'Briens Wharf, and in the lee of the training wall from Little Island.

In these areas, accumulations of up to 0.1 m generally build up quickly, whilst plough disturbance is being undertaken, and then increase more slowly with time. Little change is seen to occur between 3 and 4 days following the dredge, when sediment concentrations in the water column, as a result of the plough disturbance, have significantly reduced. This is illustrated by the small differences in the comparative plots presented in Figure 22 and Figure 23.

5.2 Effect across estuary sections

The results of the plough assessment identify three general sections of the estuary, where effects are observed. These areas (defined by the influencing process, the relative magnitudes and extents of predicted effect) are described further in subsequent sections of this report, and are broadly defined as:

- Down-estuary of Cheek Point to Buttermilk Point;
- The confluence area, between Cheekpoint Harbour, Barrow Bridge and Snowhill Point; and
- Up-estuary of Snowhill Point to Little Island.

Outside of these areas (downstream of Buttermilk Point, upstream of Barrow Bridge and upstream of Little Island) the predicted effects of the plough are considered negligible. Example results for these areas are shown in the timeseries plots at River Barrow (Figure 11) and Passage East (Figure 15).

Upstream of Barrow Bridge (Figure 11), peak SSC values are less than 130 mg/l (above background), and, more generally, are less than 50 mg/l. Peak values persist for a very short period of time (around 10-20 minutes) during the flood tide, as (some limited) material from the plough disturbance is carried upstream into the River Barrow. SSC levels have dropped to less than 10 mg/l (above background) within 3 days of the end of plough disturbance. Levels of sedimentation, as a result of the plough disturbance, are considerably less than 0.001 m.

At Passage East (Figure 15), peak SSC values of up to 60 mg/l (above background) are predicted around LW conditions, resulting from material being brought downstream, from the plough disturbance, on the ebbing spring tide. Peak SSC values are only evident in single spikes (i.e. for a period of 10 minutes), before the turning tide moves the material back upstream towards Cheekpoint. Outside of the peak spikes (associated with erosion of settled material on the early flood tide), SSC values at Passage East are generally less than 20 mg/l, reducing with time to less than 10 mg/l within 3 days of the end of plough disturbance. Associated levels of sedimentation at Passage East, as a result of the plough disturbance, are considerably less than 0.001 m.

As a result of the negligible magnitude of effect, these areas are not considered further within this discussion.

5.2.1 Cheek Point to Buttermilk Point

Within this area, the map plots (Figure 19 to Figure 23) show the greatest effects of the plough disturbance occur in the deep pocket off of Cheek Point, but smaller changes are evident elsewhere in the reach. These effects have been considered using timeseries analysis at four locations.

Carters Patch

Locations 14 and 15 (Figure 16 and Figure 17) show the variation in effects between the main flood channel and the adjacent bank at Carters Patch (see Figure 2 for locations). Locations 7 and 16 (Figure 9 and Figure 18, respectively) are representative of the conditions in the vicinity of the shellfish beds to the west and east of the reach.

Over the shallow area of Carters Patch (Figure 16), it is clear that suspended sediment from the plough disturbance passes up- and down-estuary, through this location. The level of SSC is seen to increase as the ploughing proceeds, but is immediately shown to reduce once ploughing ceases. Peak concentrations of *circa* 100 mg/l occur as the tide approaches (and just after) LW. However, these concentrations are only achieved for less than an hour per tide (total). For the most part, concentrations are 50 mg/l, or less, at the bed. Within two days of the end of ploughing operations, the average concentrations (above background) are less than 10 mg/l.

Over LW, the higher concentrations that build up just before LW, deposit over the slack, to be re-eroded on the flood. Such changes in bed thickness are, however, negligible (maximum less than 0.001 m). Ebb shear stresses at this location are greater than on the flood, but both are high enough (on spring tides) for erosion to occur, should sediment have deposited. Predominantly, flows will transport material through the area. On neap tides, flows are just high enough to transport the sediment through the area, except around HW and LW, when accretion occurs. Conversely to spring tides, neap flows are not sufficient to cause re-erosion of deposited material.

In the adjacent navigation channel (Figure 17), the plough disturbance causes elevated concentrations of up to 50 mg/l, but with isolated patches reaching 150 mg/l, near to LW on the flood tide. These concentrations are 'pulses' which last for no more than 20 minutes, as the ebb tide approaches LW. Sedimentation (up to 0.004 m) is re-suspended on the following flood tide.

The site characteristics can be seen to respond to the plough activity, as the elevated SSC and temporary bed sediment accumulations reduce soon after the ploughing ceases, and within 2 days concentrations reduce to less than 10 mg/l (above background).

Adjacent shellfish areas

A feature of this general area is the negligible BSS on the ebb tide. A similar pattern of BSS is seen in the shellfish area to the west side of the channel (Location 7, Figure 9). Here the SSC resulting from the plough disturbance is higher, with peaks (lasting generally less than 20 minutes) of the order of 200 mg/l, although isolated pulses of over 600 mg/l are predicted at the time of peak flood flows, towards the end of ploughing. The average elevated concentration throughout the tide is around 50 mg/l. This is reduced to below 10 mg/l, 2-3 days following completion of the ploughing.

During the ebb, when flows/BSS are low, sedimentation of up to 0.015 m is indicated, although for the most part, this is less than 0.01 m and is present for up to six hours, before being eroded by the spring tide flood flows.

On the east side (in the channel) at the edge of the Shelburne Bay shellfish area (Location 16; Figure 18), the area is one of sedimentation on the flood tide and transport, without erosion, on the ebb. Any sediment reaching this area from the plough activity, will deposit from flood tide flows. For the 'realistic worst case' plough disturbance scenario assessed, about 0.014 m of sediment was predicted to settle to the bed. As a result, suspended sediment concentrations within the water column, are generally predicted to be low (less than 30 mg/l, with isolated peaks of up to 80 mg/l). As with all sites, the SSC decayed quickly following the end of the ploughing; however, the settled material was retained at the location of analysis.

5.2.2 Confluence between Cheekpoint Harbour, Barrow Bridge and Snowhill Point

The main area of effect is within, and adjacent to, the plough disturbance area.

Plough disturbance area

Maximum SSC values, within the bottom layer of the water column, are shown to be in the order of 2,500 mg/l at the point of plough disturbance, at the time of peak flood flows, and around 1,500 mg/l at times of slower/slack flows. This is illustrated in Figure 6, which presents the timeseries of SSC on Plough Track 4 (with simulated working on 12 April 2017). This plot also indicates that:

- Over LW periods, some settlement (up to 0.08 m) occurs, showing not all of the disturbed settlement clears the area of the channel over LW (but is subsequently re-eroded on the next flood tide, putting additional SSC into the water column, as a direct result of the plough);
- The dispersal from the plough is initially in a narrow plume;
- SSC values at this site, related to the sediment disturbance from the previous days tracks, are lower (peak SSC values generally reducing to <100 - 500 mg/l), with increasing distance of the track, to the south;
- Natural erosion at the site occurs on the upper half of the flood tide on spring tides, but not on neaps;
- Conversely, on the ebb tide an accretionary trend almost permanently occurs, and is particularly evident on neap tides;
- Within one day of completion of the plough disturbance, the peak near-bed SSC (above background) are reduced by over an order of magnitude (to *circa* 250 mg/l), further decaying to background levels within four days (on reducing-range spring tides). The peak SSC values also only last for less than an hour, at the time of peak flows. For the rest of the tide, the highest concentrations are well below 100 mg/l, and reduce with time.

Southern intertidal / shallow subtidal and Cheekpoint Harbour Channel

Timeseries Location 3, 5 and 6 (Figure 5, Figure 7 and Figure 8), represent the sedimentary conditions around the siltation area on the south side of the channel. These are locations of sedimentation sinks, identified from the map plots of sediment distribution (discussed above).

The timeseries plots for each of the three locations show sediment accumulation of about 0.1 m, 0.4 m and 0.08 m, respectively as a result of the plough disturbance. Locations 5 and 6 (Figure 7 and Figure 8), to the east, show the sediment accumulates during both the flood and ebb flows, but not at HW and LW. This reveals that sediment is being passed into the area from both upstream and downstream directions, but at these locations, the flows are so low that sedimentation occurs. No accumulation occurs over HW or LW as no sediment is transported into the area under these conditions. This is shown by the fact that SSC values are negligible (<10 mg/l) during these periods.

In both cases, the rates of sedimentation begin to increase after about 2 days of ploughing. This suggests that this is the timescale for the dispersed material (probably the coarser material) to be moved up- and down-estuary, before returning to the general location.

Peak SSC values rarely exceed 150 mg/l, and then only as isolated peaks of no more that 10-20 minutes duration. For the most part, the elevated SSC is in the range 20-50 mg/l during the ploughing, reducing to generally less than 10 mg/l after 2 days (and not discernible from background after about 4 days, on reducing spring tides).

Location 3 (Figure 5) is to the west, on the edge of the deep at Snowhill Point. Here, the ploughing causes SSC of over 500 mg/l for around 3 hours during the flood tide peak flows, building to isolated peaks of around 2,000 mg/l. During the ebb, however, the SSC is shown to rarely increase to 50 mg/l. Again, there is an indication that the majority of disturbed material takes around two days to return to the area, causing the significant increase in SSC towards the end of the plough disturbance. At this site, the direct effect of the plough disturbance, is elevated SSC of around 500 mg/l.

Sedimentation is also seen to occur at the site during the first part of the flood tide, as sediment is supplied to the area from down-estuary. The flows in the deep bathymetry fall quickly, causing the sedimentation; however, later in the tide, flow speeds rise as sediment supply to the area reduces, and some erosion occurs before flows slacken over HW. Sedimentation then continues throughout the ebb, although concentrations in the water column are not high. This suggests sediment is transported to the area and immediately deposits.

This pattern is maintained whilst ploughing continues, but then reduces *circa* one day following the end of ploughing. With the supply of sediment stopped, small-scale net erosion occurs, followed by some accretion as the tidal range falls. On neap tides, flows are too slow to erode the bed, or to move sediment into the area; hence the depth of sedimentation stabilises at a predicted accretion of about 0.1 m.

North bank to Barrow Bridge

A timeseries location was extracted at Kilmokea Point Jetty (Location 12; Figure 14). This shows the ploughing gives rise to elevated concentrations of around 200 mg/l on peak flood flows. In general, however, the SSC is not elevated to more than about 50 mg/l for longer than 2-3 hours, and during the tides on the latter 2 days of the plough disturbance. Outside of these periods, the SSC is not elevated by more than about 10 mg/l.

Accumulations of up to 0.001 m could occur over LW, but are eroded on the following flood tide.

5.2.3 Snowhill Point to Little Island

The effects of the plough disturbance on the area between Snowhill Point and Little Island are described is in the following sections, at the Belview Terminal and Little island confluence.

Belview Terminal

Two locations for timeseries analysis have been extracted in the Belview area. Location 8 (Figure 10) was chosen to illustrate whether the ploughing was affecting siltation within the berths, and the second site (Location 2; Figure 4), is in the area identified as a sediment sink at the down-estuary end of the Quay.

During the second half of the plough campaign, high sediment concentrations are shown to pass through the berth areas on the flood tide, with concentrations of over 2,000 mg/l for up to 30 minutes around the mid-tide level; reducing to around 500 mg/l, later in the flood tide. Similar 'pulses' of sediment with concentrations of up to 600 mg/l, are also predicted towards the end of the ebb tide. These elevated levels are only shown to last for five consecutive tides, before decaying to background levels within four days of the end of plough disturbance.

During the periods of high SSC, depth changes of up to 0.003 m are predicted to settle over LW and the early flood tide, before being re-eroded later in the tide. It is noted that some sediment continues to be moved to the area over the following neap tides, to accumulate in the berth; however, this is of negligible magnitude for this plough disturbance scenario.

At the downstream end of the Quay (Location 2; Figure 4), a similar pattern of SSC values is evident. Here, however, sediment accumulates throughout the ebb, and most of the flood, before a short period of high flows erodes the accumulations. Whilst high spring tides continue, the accumulated material reduces on each tide, but sediment continues to move in to the area. As the tidal range falls, the erosion ceases. The area is still supplied with sediment on the flood and ebb, but at reduced rates;

this sediment accumulates at the site until neap tides are not strong enough to supply further material. The model predicts an accretion thickness of around 0.025 m, above any background sedimentation, at this site.

Little Island confluence

Timeseries Location 1 (Figure 3) is located in a sediment 'sink', identified in the lee of the training wall to Little Island (see Figure 2 for location).

Similar to other locations, the highest concentrations occur on the flood tide, towards the end of the plough disturbance. Elevated concentrations reach about 900 mg/l and are high for over two hours of the flood tide. By comparison, ebb concentrations are negligible. Again, once the ploughing stops, the SSC signal decays quickly to background levels.

The pattern of sedimentation is interesting as it reflects the ploughing operation (working during daylight hours, with no disturbance overnight). At Location 1, this intermittent disturbance is reflected in alternating higher and lower bed accumulations during the plough activity. The sediment accumulates after each plough track, and then falls away when ploughing ceases and the area is only supplied by sediment already moving around the system. As the tidal range falls, the area accretes around HW, until either the source of material to the area reduces to insignificant levels, or neap flows are unable to transport any sediment to further supply the site. Such accumulations, however, are small, *circa* 0.004 m.

5.3 Effect in context of background measurement

The predicted levels of increased SSC can be put into context against the background levels, as measured during the survey campaign at River Barrow, Carters Patch and Duncannon (and shown in Figure 24 to Figure 26).

The results of the survey campaign show higher SSC values during spring tides, compared to neap tides, and also indicate the influence of storm events in increasing further the natural levels of sediment within the water column.

Within the River Barrow, the survey campaign recorded peak SSC values of up to around 600 mg/l on a spring tide, with levels generally recorded at around 200 mg/l. The concentrations reduce over neap tides to less than 50 mg/l as material settles to the bed under weak flow conditions. A similar pattern is observed at Carters Patch, with peak spring values of up to 350 mg/l, reducing to around 50 mg/l on neaps. At Duncannon, spring peaks are generally less than 200 mg/l reducing to less than 10 mg/l on neaps. At these latter sites, a storm event, recorded at the end of April 2017, elevated the spring tide levels to around 1,000 mg/l at Duncannon, and around 600 mg/l at Carters Patch.

The increased SSC (above background), as predicted by the modelled plough assessment, indicate levels that are generally similar to those observed naturally in the system. Peak values arising from the plough campaign are predicted to be up to 1,000 to 2,000 mg/l, and limited in duration (less than 30 minutes) to isolated peaks around the times of the highest flows. These values compare against the peak measured concentrations during the observed storm event, with values of up to 1,000 mg/l.

Outside of the peak values, the average increase in SSC as a result of the plough campaign is generally around 50 mg/l. As discussed, these values quickly fall away after cessation of plough operations, to less than 10 mg/l within four days. These values compare against the background spring tide values of between 200 and 600 mg/l (increasing in and up-estuary direction).

5.4 Concluding remarks

Numerical dispersion modelling has been undertaken, simulating a typical plough/bed levelling operation at Cheekpoint Lower Bar. Track plot information, bed sample analysis and a synthesis of accretion rates and plough disturbance production rates have been used to define the modelling scenario to be simulated. The sediment disturbance release rates for the model simulation were chosen to represent a 'realistic worst case' scenario.

The results of the modelling indicate that:

- Dispersed sediment moves throughout the estuary;
- The vast majority moves up-estuary, but is generally confined between Buttermilk Point and Little Island;
- The greatest effects are seen throughout the estuary at the end of the plough disturbance scenario. These effects decay to background levels within about four days following cessation of ploughing on falling spring tides;
- Most material is moved (transported and eroded) on the flood tide and during spring tides;
- Neap tides are predominantly accretional;
- The modelling has identified locations of temporary sediment storage (later eroded) as well as sediment 'sinks', where accretion is more permanent, notably the southern edge of the Cheekpoint section, adjacent to the maintained channel;
- Maximum sediment concentrations (above background) at the point of disturbance are around 2,500 mg/l near-bed at the time of peak flows, and 1,500 mg/l during slack flows;
- One day following completion of plough disturbance, peak SSC are reduced by over an order of magnitude at the disturbance site;
- Maximum concentrations away from the disturbance location, for the most part, occur on peak flood flows as 'pulses' that rarely last for longer than 30 minutes per tide. Individual spikes can reach 1,000 mg/l at some locations;
- Elevated SSC that last for several hours are generally in the range 150-250 mg/l, depending on location, on spring flood tides, and lower on ebb tides. Average elevated concentrations are rarely above 50 mg/l;
- These values compare against the measured background SSC level, which were recorded between 350 and 600 mg/l between Carters Patch and the River Barrow, on a typical spring tide, increasing to up to 1,000 mg/l during an observed storm event;
- Sedimentation as a result of the plough disturbance is for the most part temporary, accumulating during periods of slack water, or in areas of eddy circulation. With the exception of identified 'sink' areas, accumulations are small, a few millimetres to 1 to 2 centimetres. Most accumulations are re-eroded on the following peak flows (predominantly on the flood);
- In the shellfish areas around Carters Patch sedimentation of up to 1.5 cm was present for a maximum period of 6 hours before being re-eroded; and
- In all cases, sedimentation rates and SSC levels increase after *circa* 2 days of ploughing. This indicates that this is the timescale for disturbed material (probably the coarser fraction) to move up- and down-estuary, before returning through the Cheekpoint area.

6 Reference

ABPmer, 2017. Waterford Estuary: Model Calibration and Validation. ABPmer, Report No. R.2894.

7 Abbreviations/Acronyms

AWAC	Acoustic Wave And Current Profiler
BSS	Bed Shear Stress
DHI	Danish Hydraulics Institute
DHPLG	Department of Housing, Planning, Communications & Local Government
EPA	Environmental Protection Agency
FM	Flexible Mesh
HW	High Water
LAD	Least Available Depth
LW	Low Water
MT	Mud Transport
PoW	Port of Waterford
SSC	Suspended Sediment Concentration
TSHD	Trailing Suction Hopper Dredger

Cardinal points/directions are used unless otherwise stated.

SI units are used unless otherwise stated.

Figures

Innovative Thinking - Sustainable Solutions

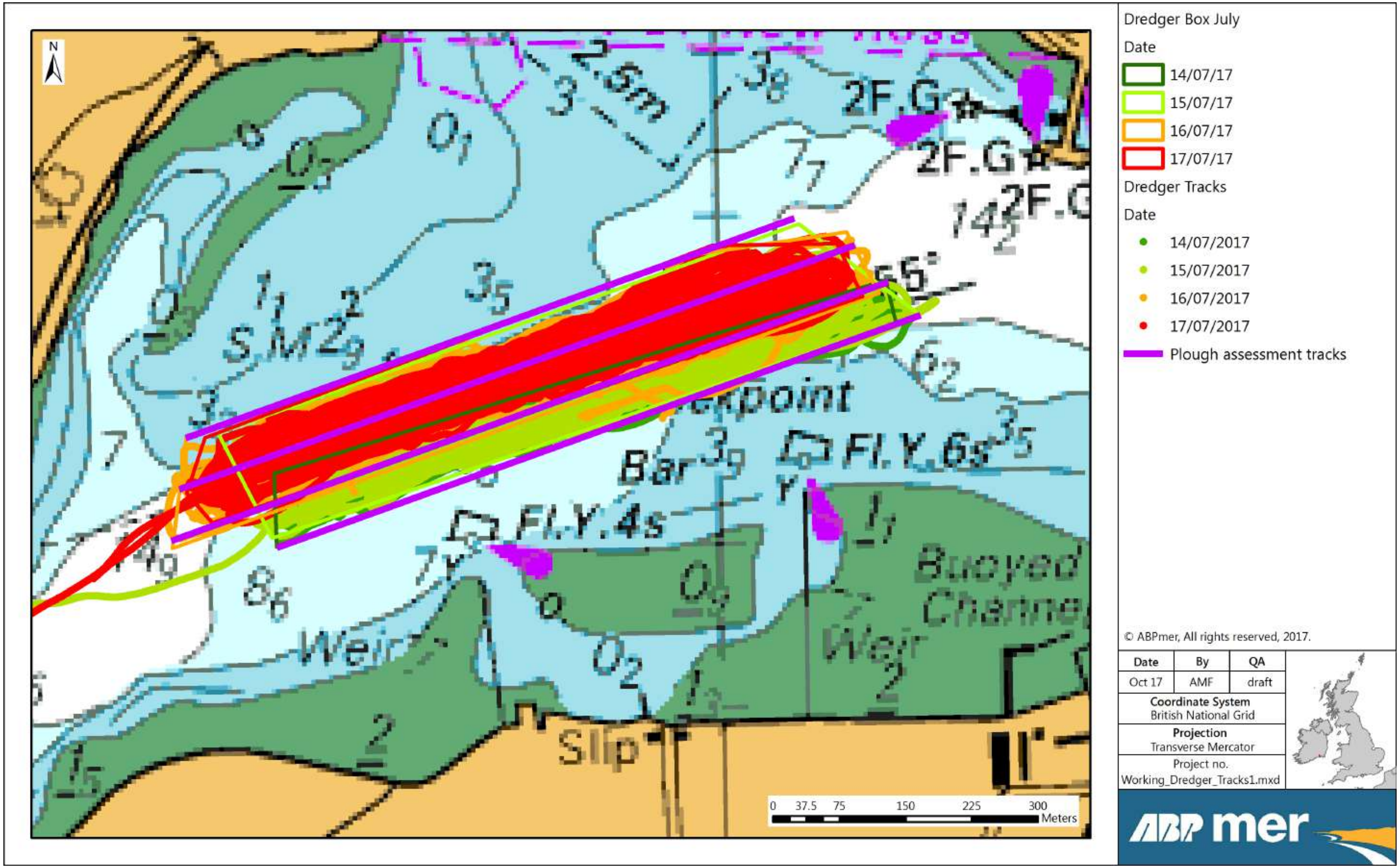


Figure 1. Plough tracks from July 2017 campaign with tracks used in present assessment

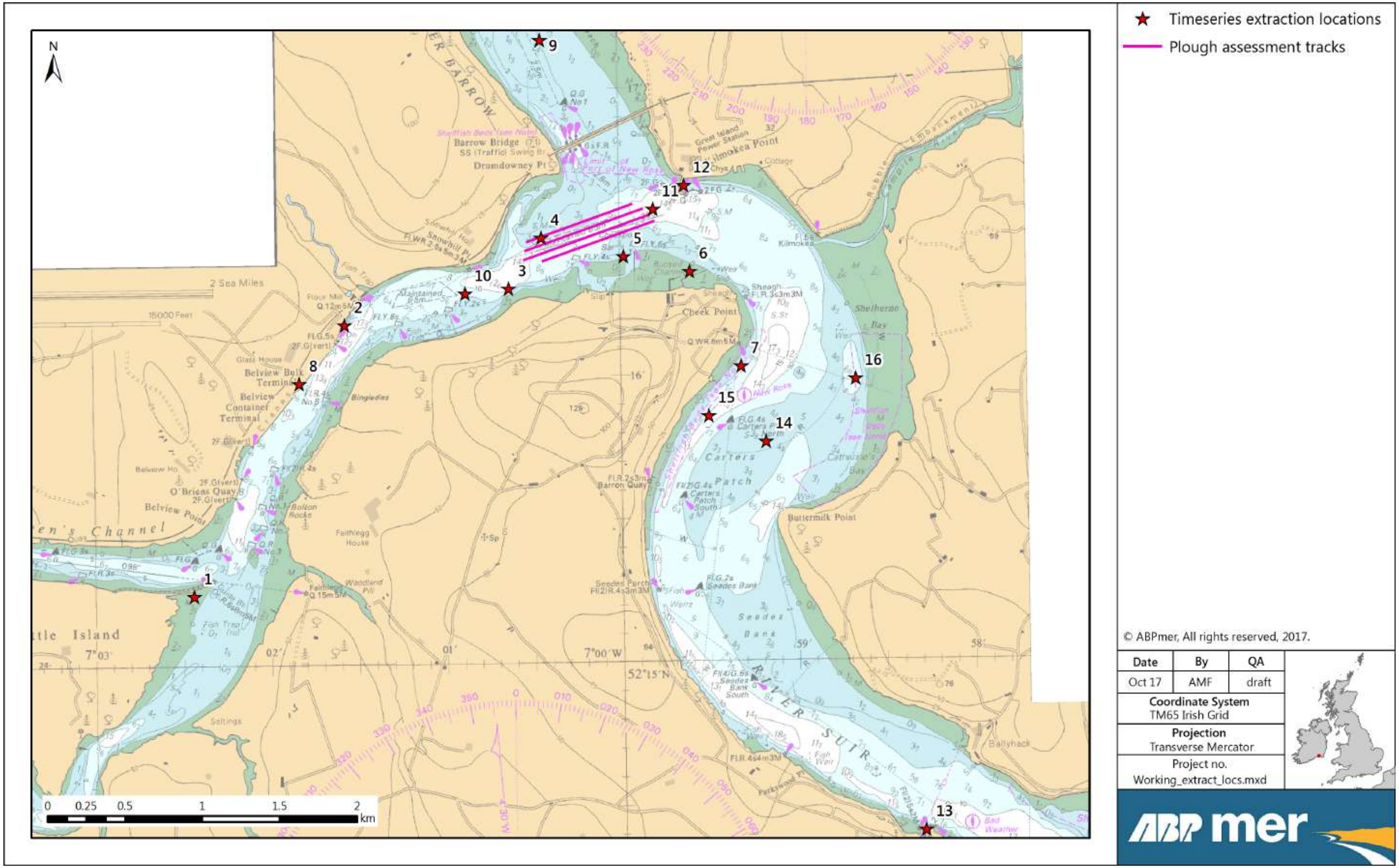


Figure 2. Extraction location for timeseries plots

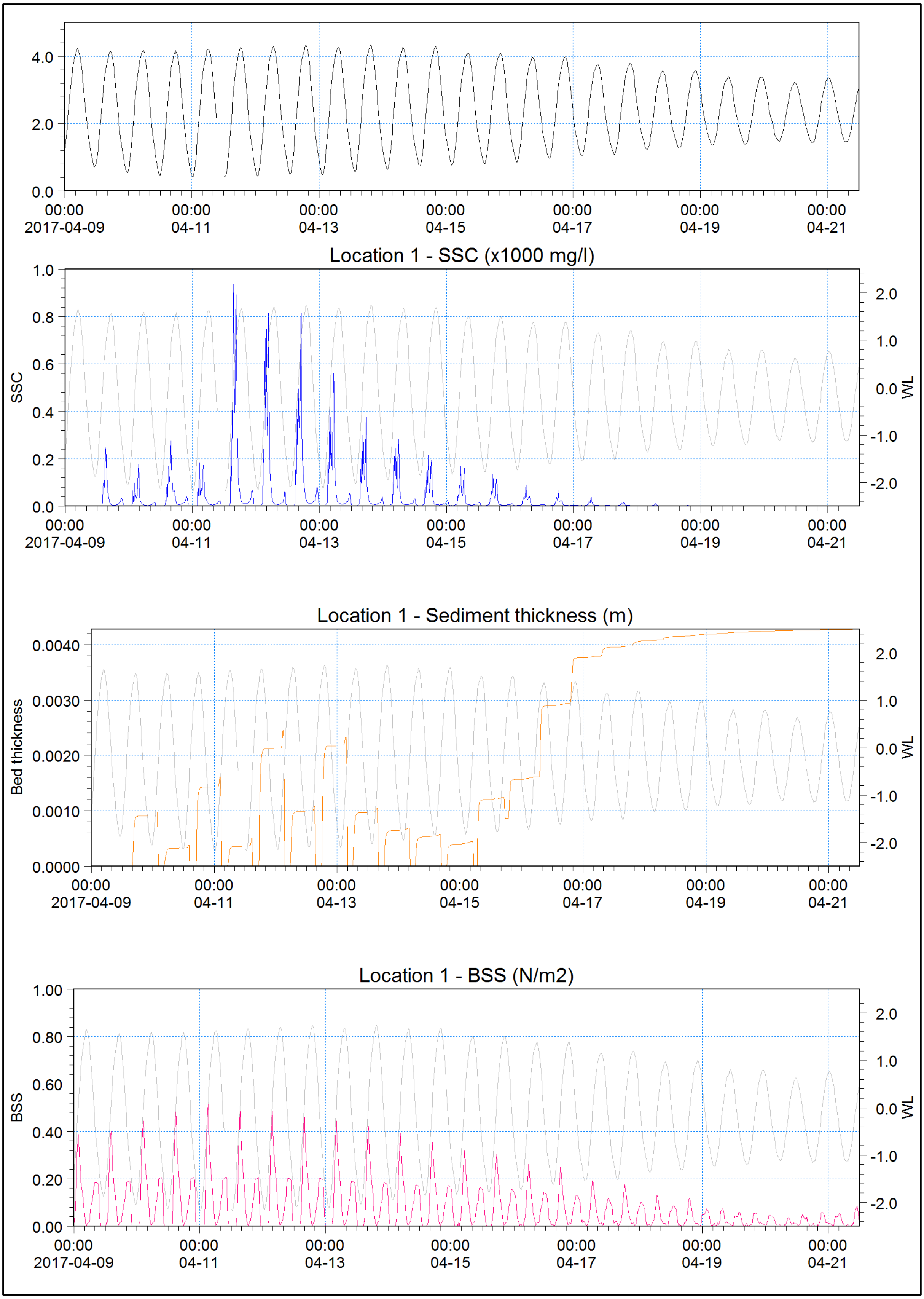


Figure 3. Timeseries of SSC, bed thickness and BSS - Location 1 (Little Island)

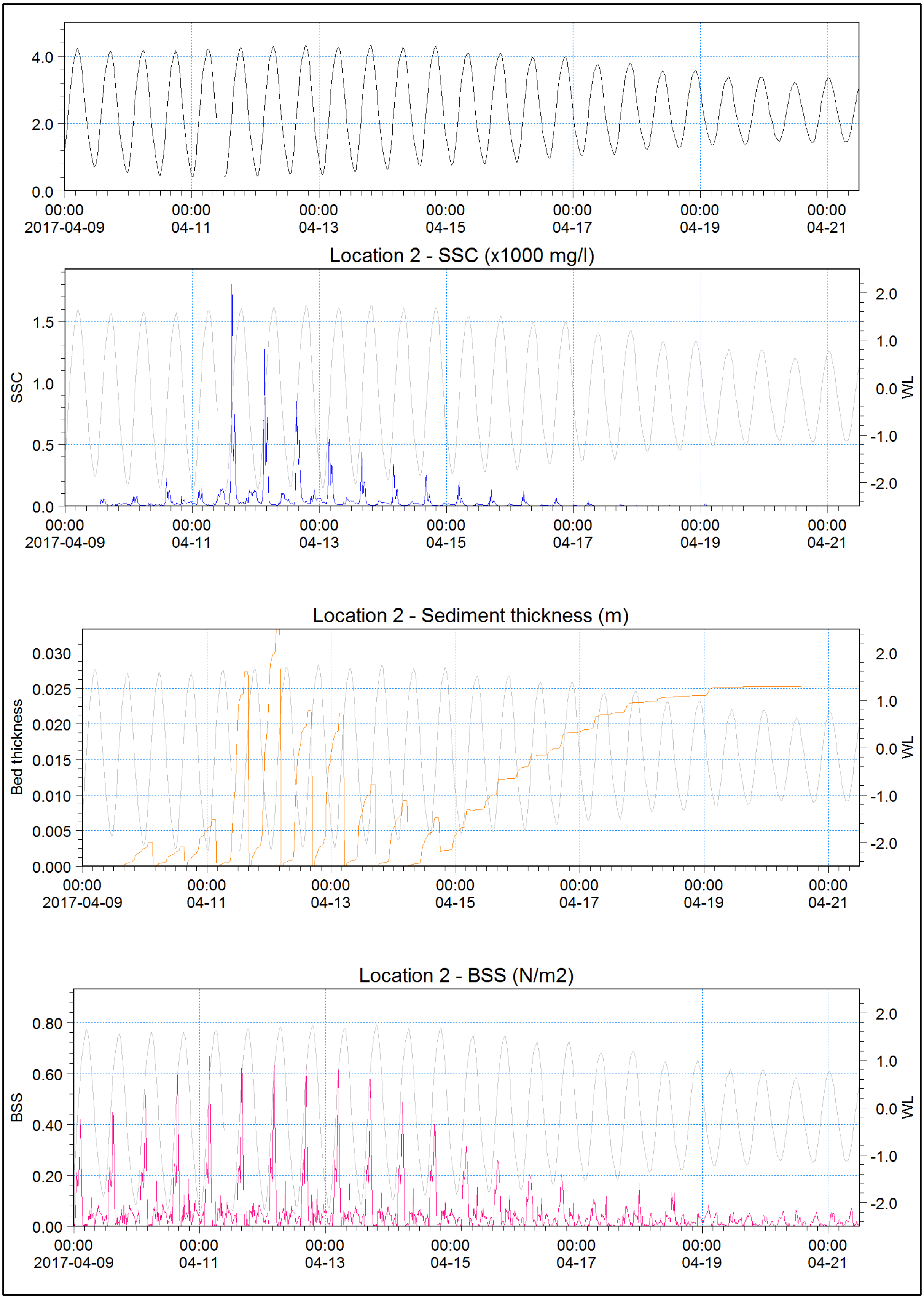


Figure 4. Timeseries of SSC, bed thickness and BSS - Location 2 (Upper Belview wharf)

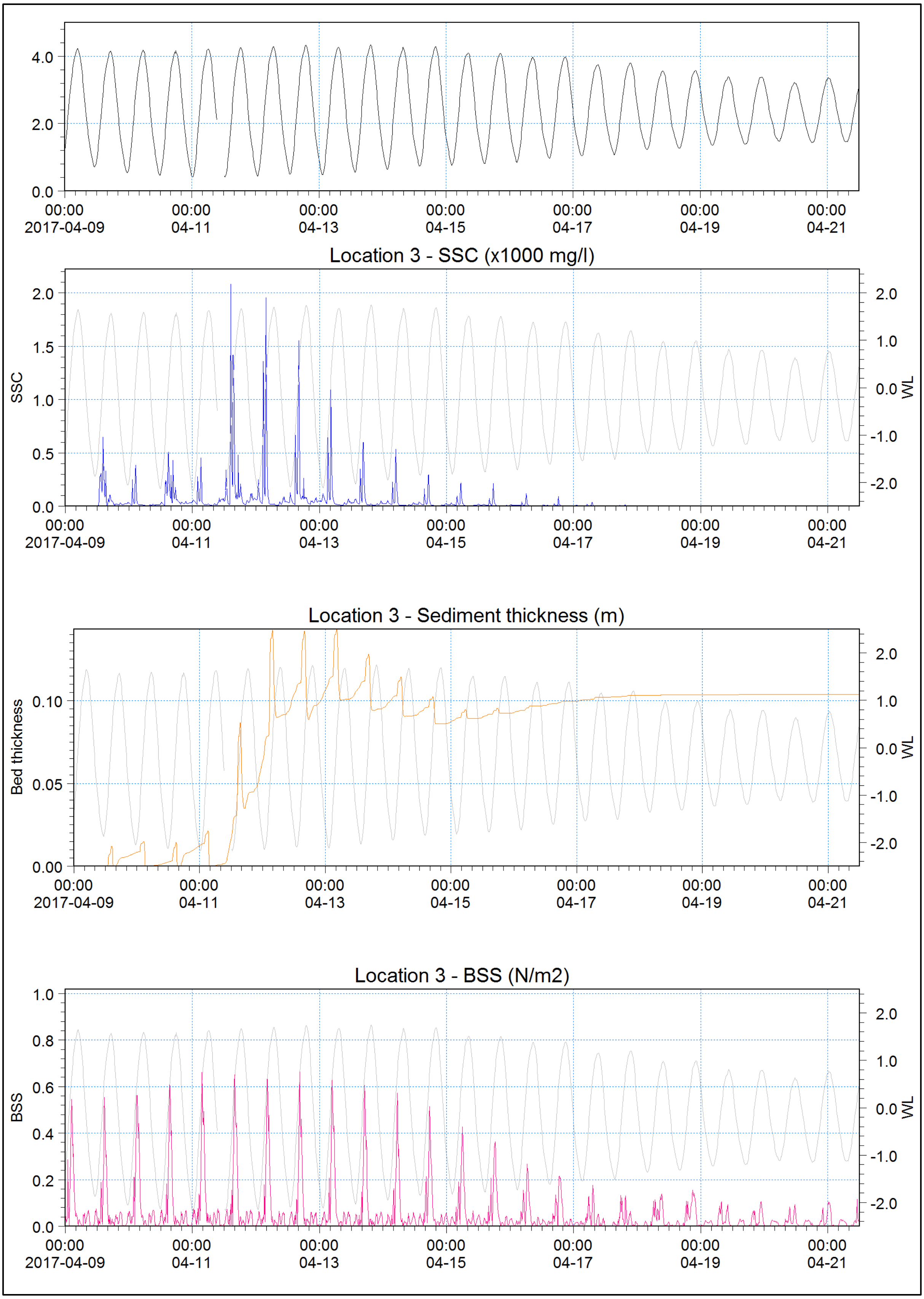


Figure 5. **Timeseries of SSC, bed thickness and BSS - Location 3 (opposite Snowhill Point)**

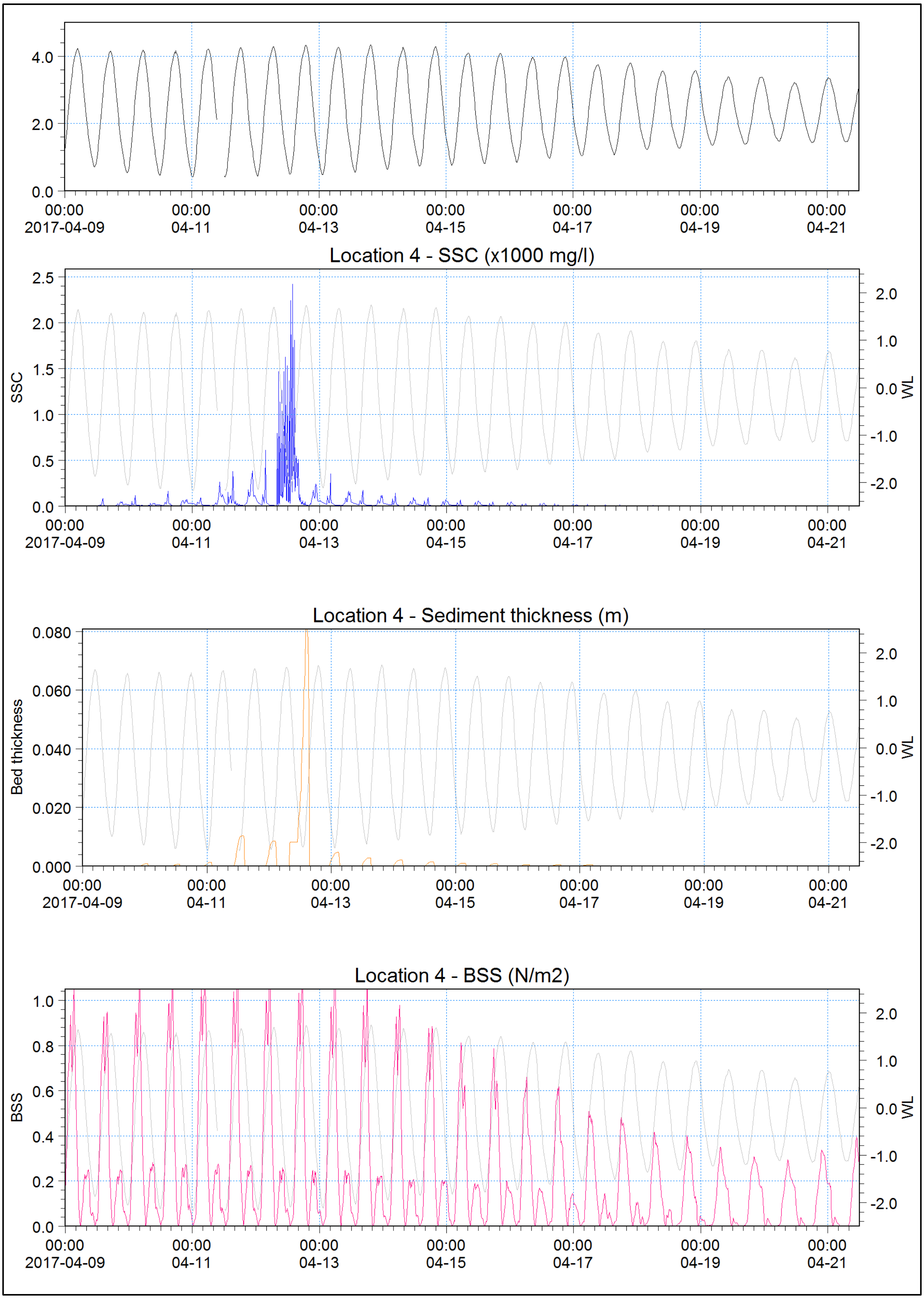


Figure 6. Timeseries of SSC, bed thickness and BSS - Location 4 (Plough Track 4)

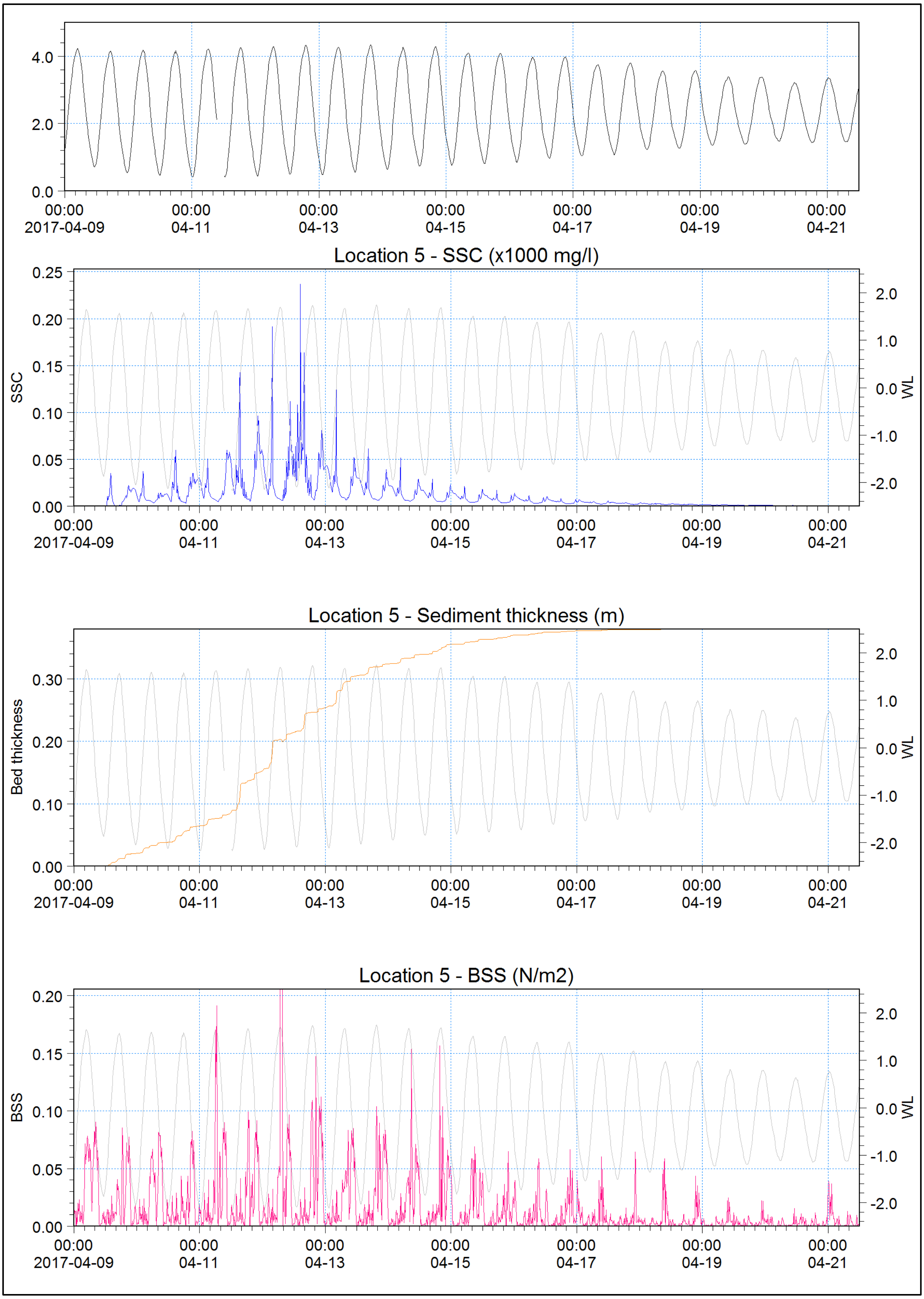


Figure 7. Timeseries of SSC, bed thickness and BSS - Location 5 (offshore longest groyne)

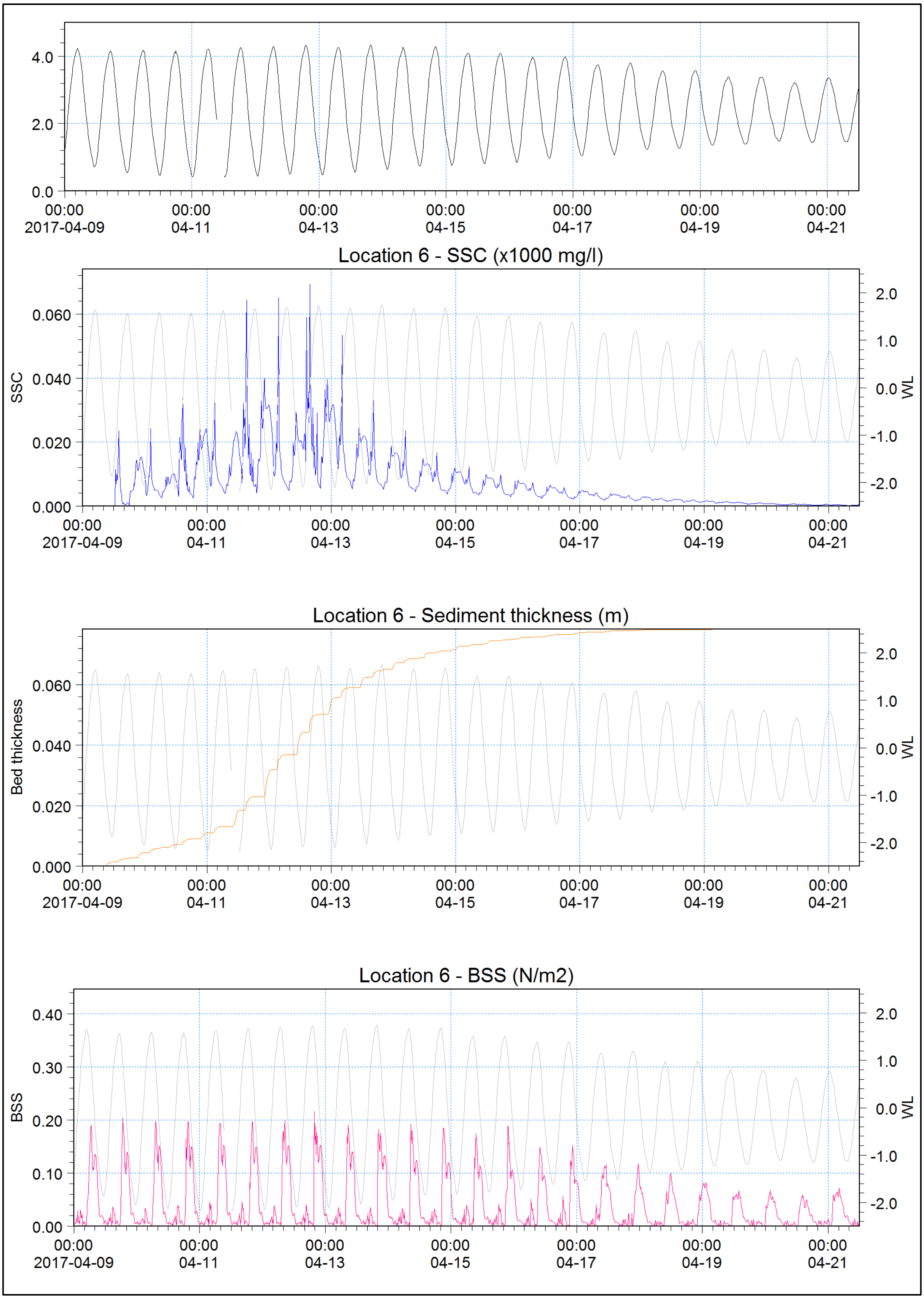


Figure 8. Timeseries of SSC, bed thickness and BSS - Location 6 (Cheekpoint Harbour Channel)

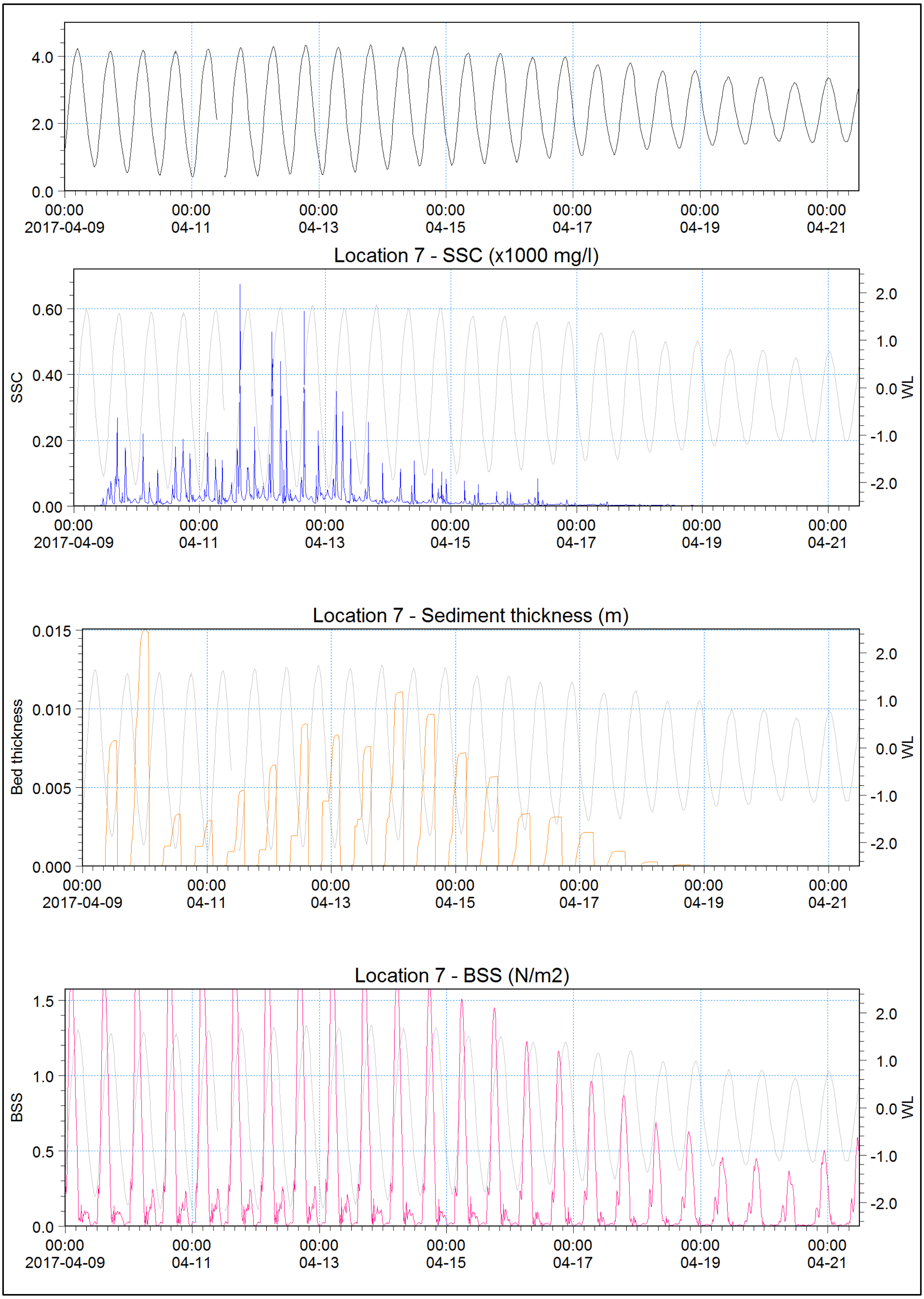


Figure 9. **Timeseries of SSC, bed thickness and BSS - Location 7 (downstream Cheek Point)**

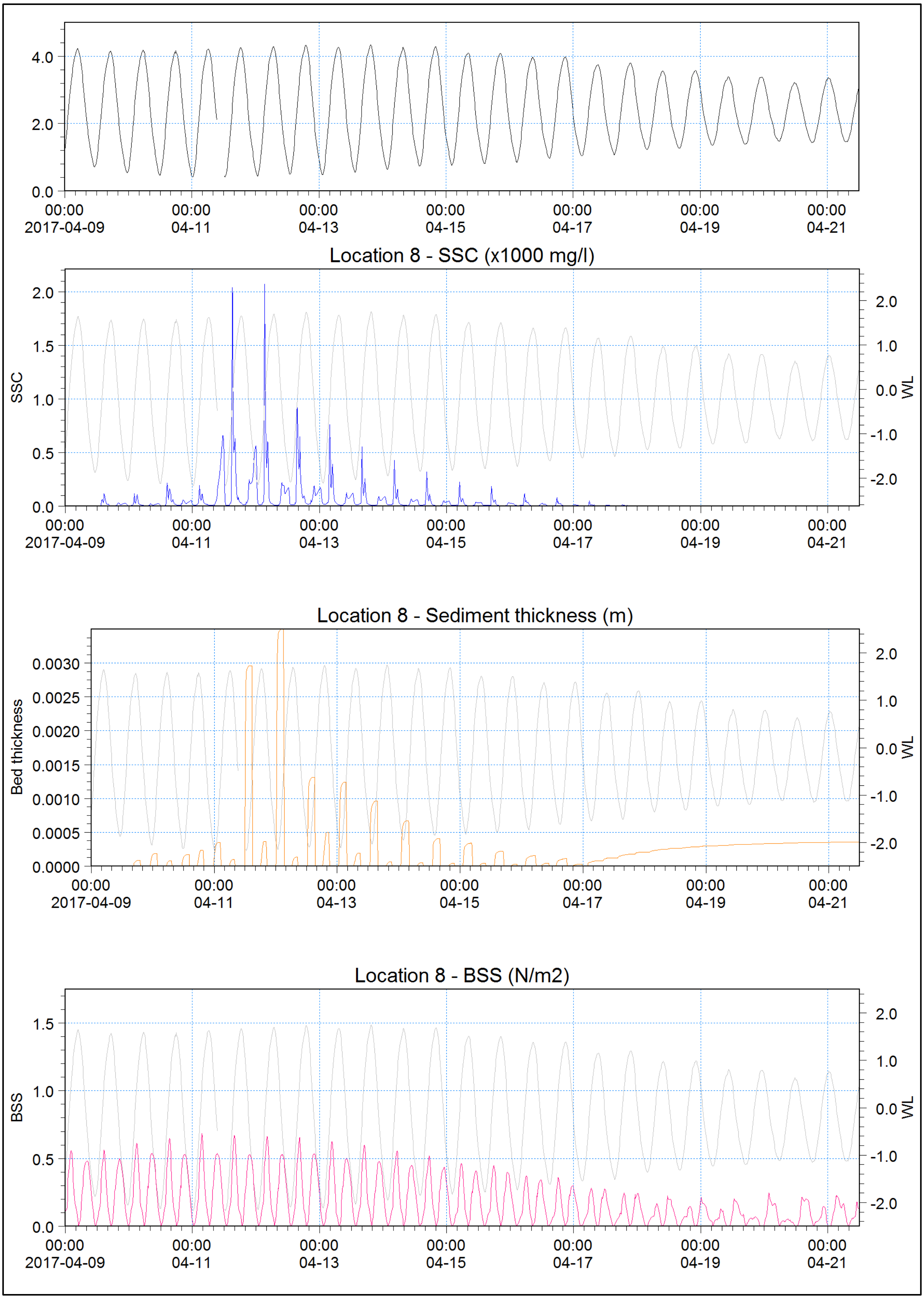


Figure 10. Timeseries of SSC, bed thickness and BSS - Location 8 (Belview central wharf)

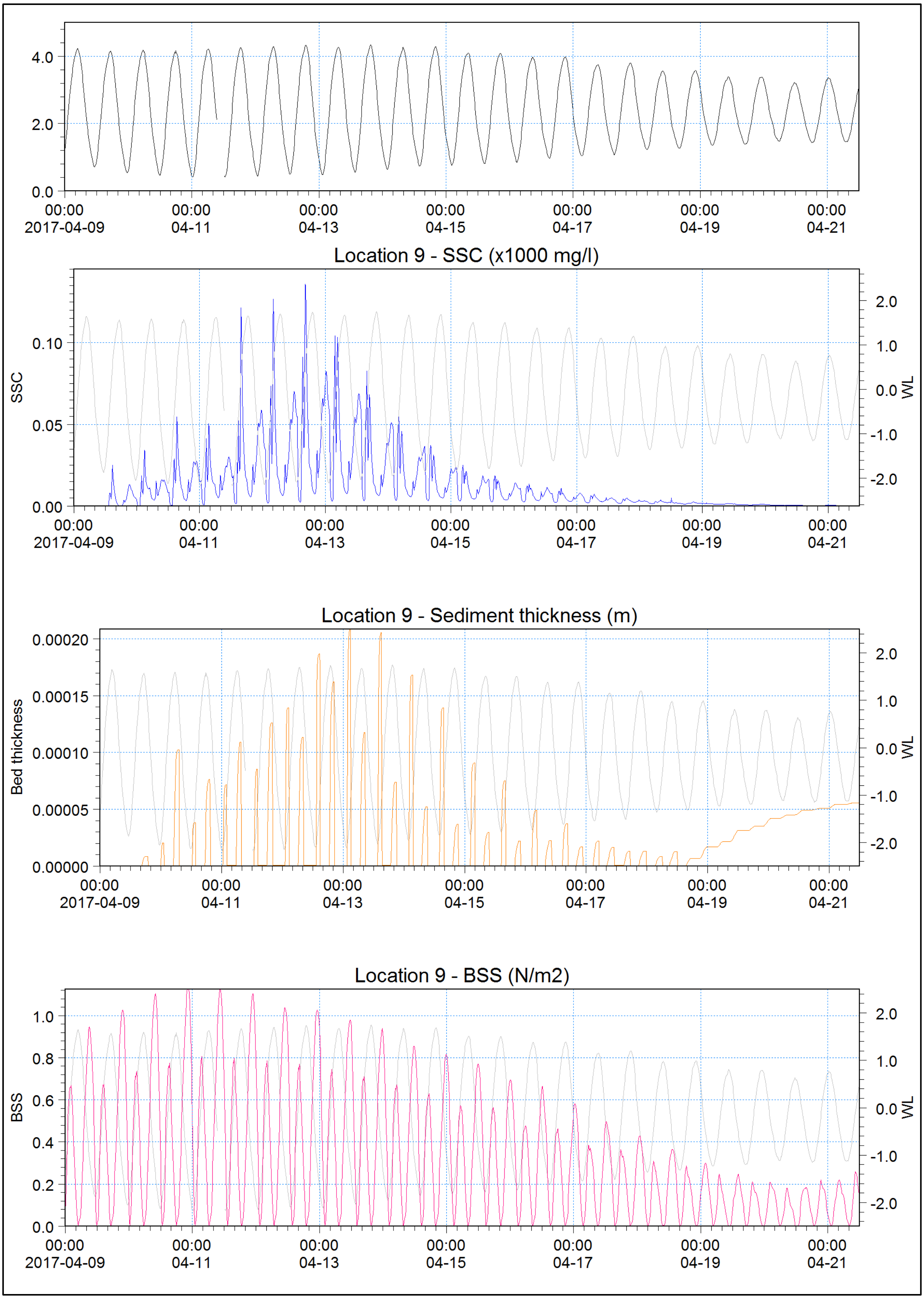


Figure 11. Timeseries of SSC, bed thickness and BSS - Location 9 (upstream Barrow Bridge)

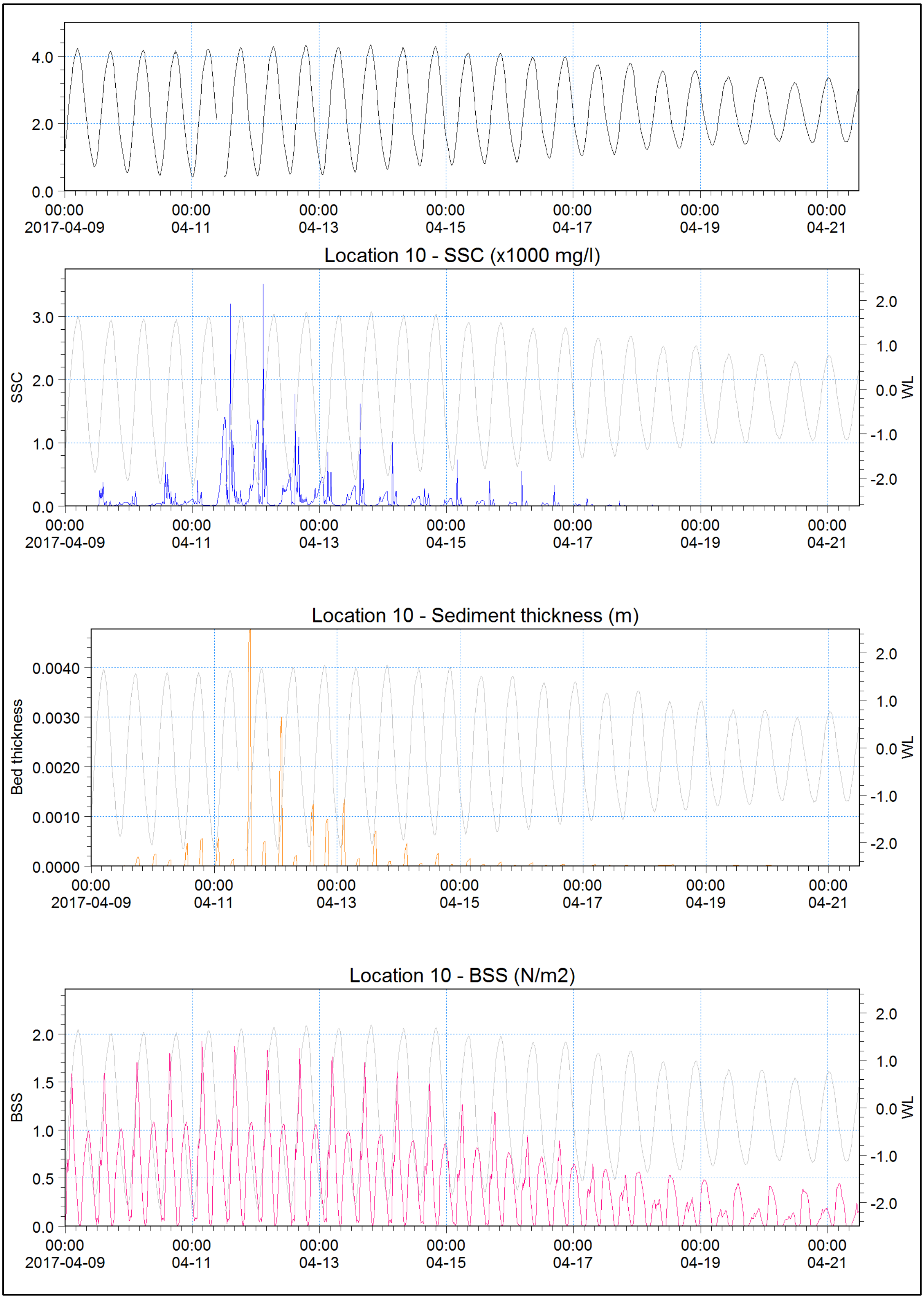


Figure 12. **Timeseries of SSC, bed thickness and BSS - Location 10 (upstream plough campaign area)**

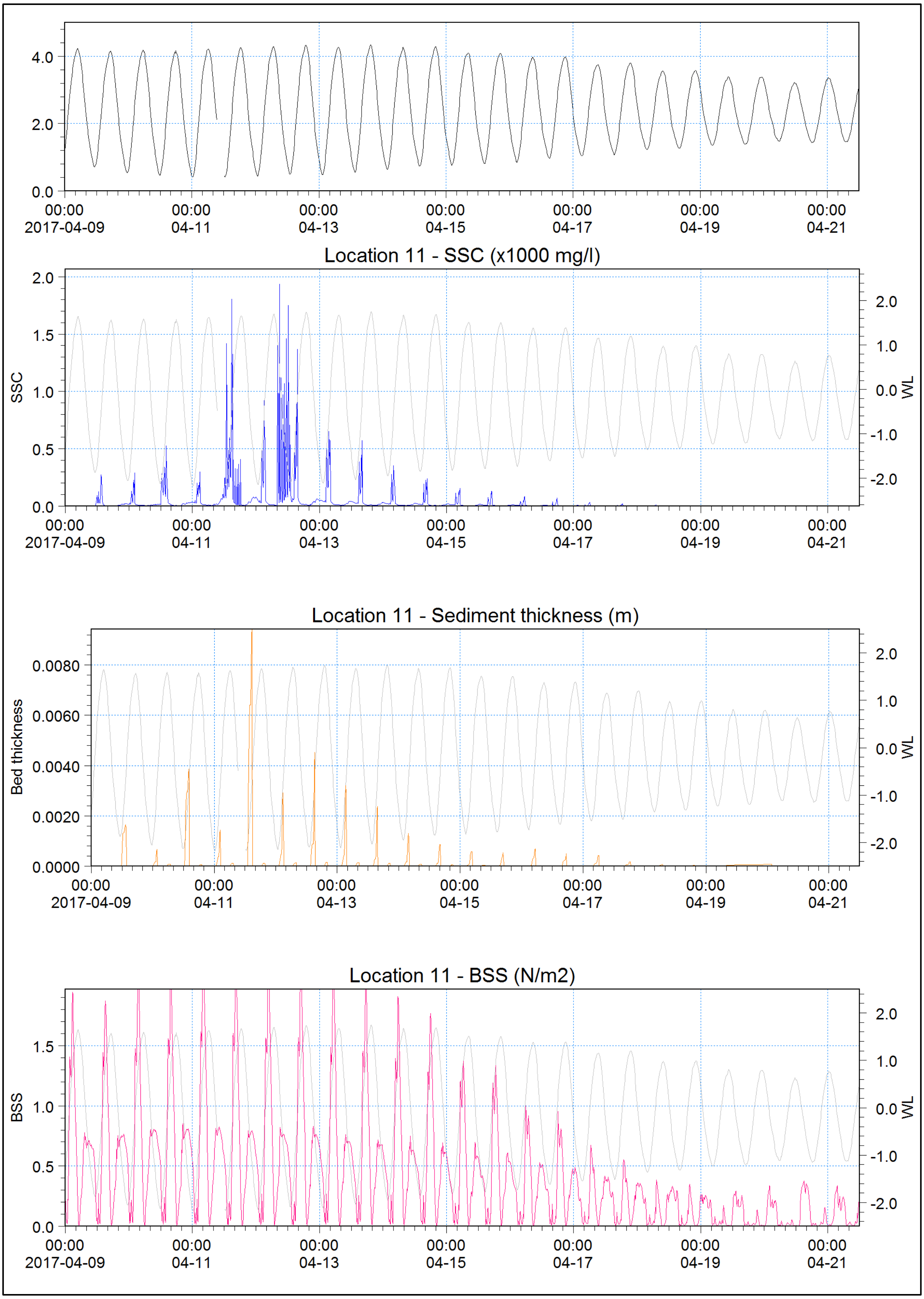


Figure 13. Timeseries of SSC, bed thickness and BSS - Location 11 (downstream plough campaign area)

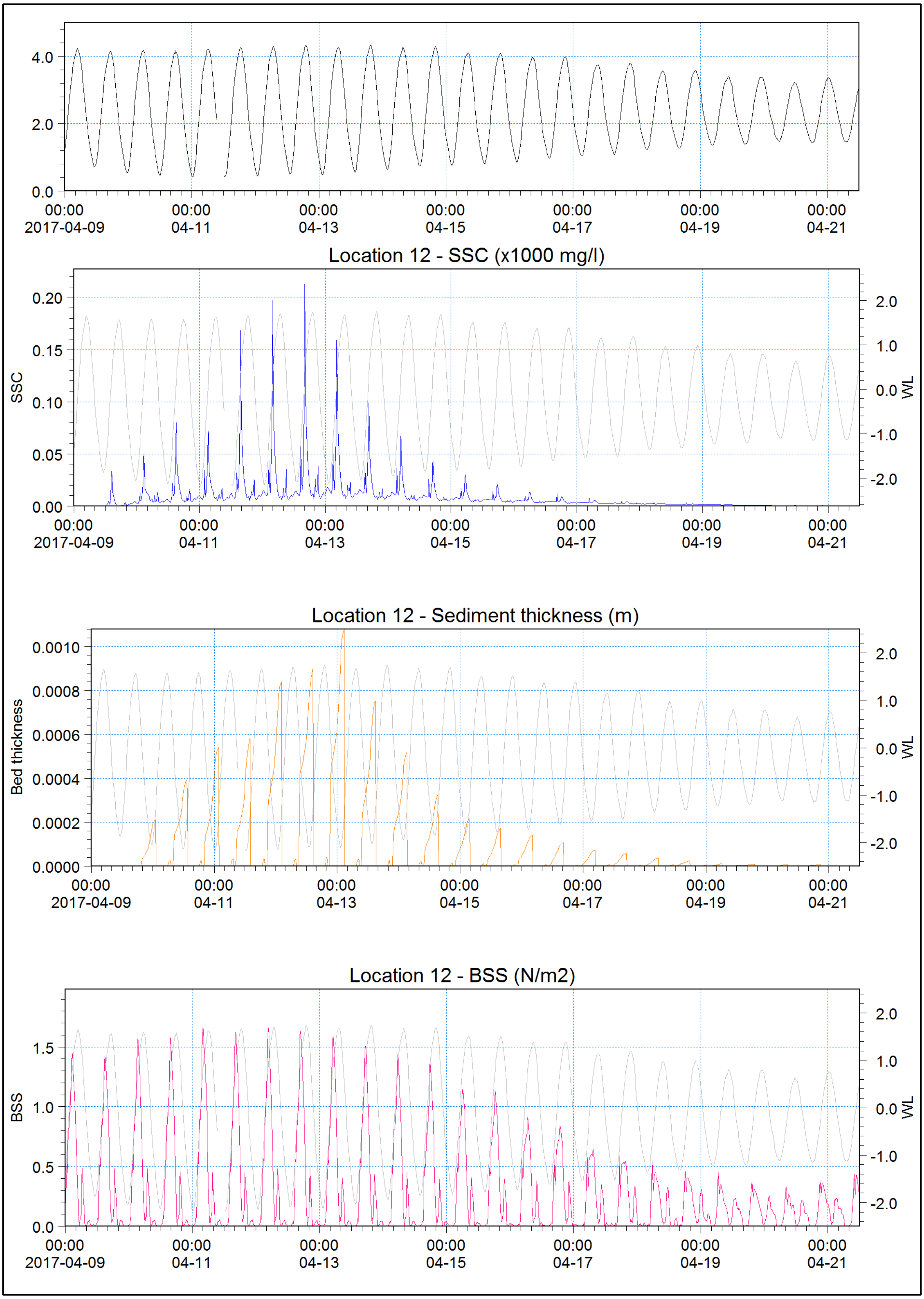


Figure 14. **Timeseries of SSC, bed thickness and BSS - Location 12 (Kilmokea Point Jetty)**

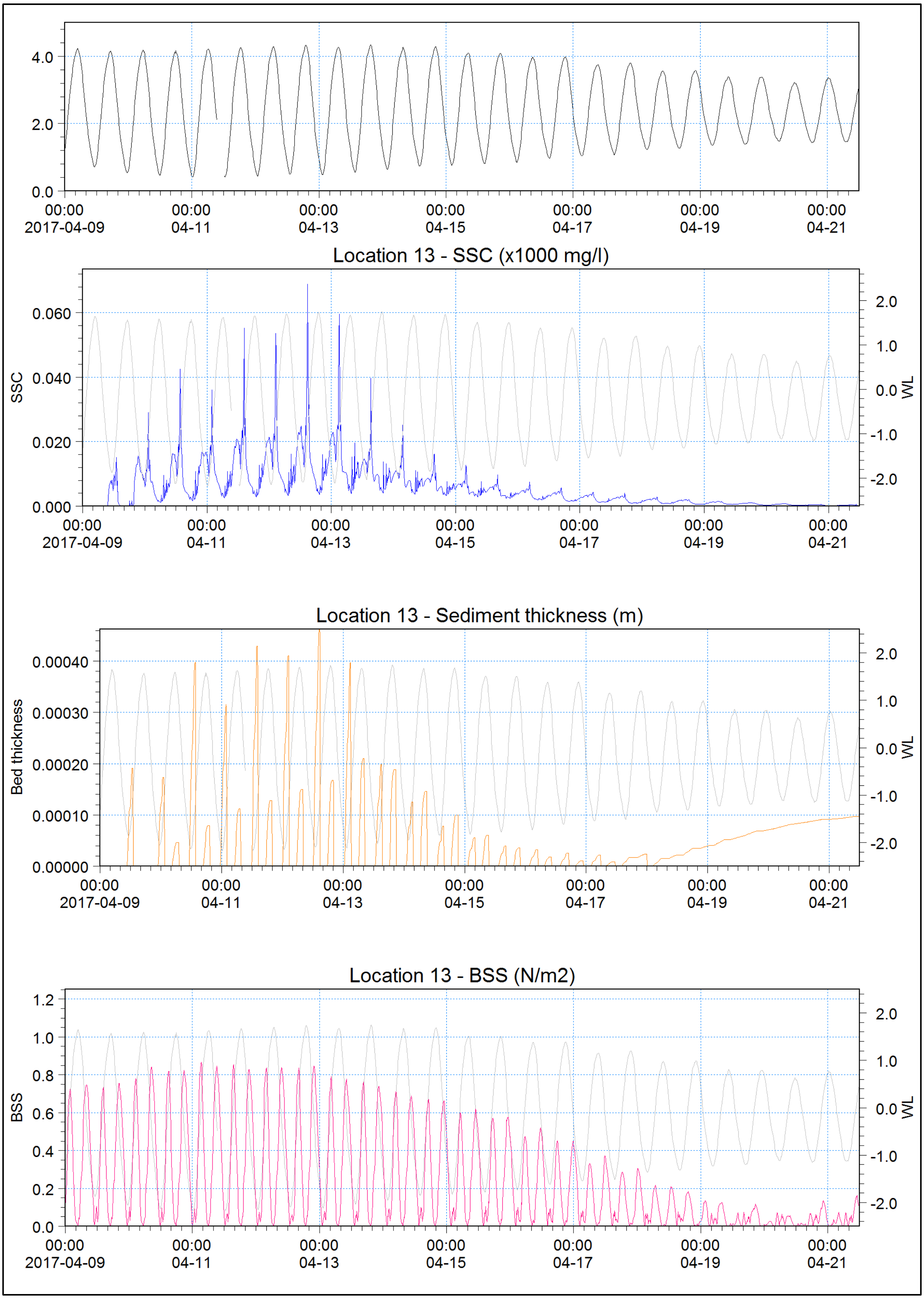


Figure 15. Timeseries of SSC, bed thickness and BSS - Location 13 (Passage East)

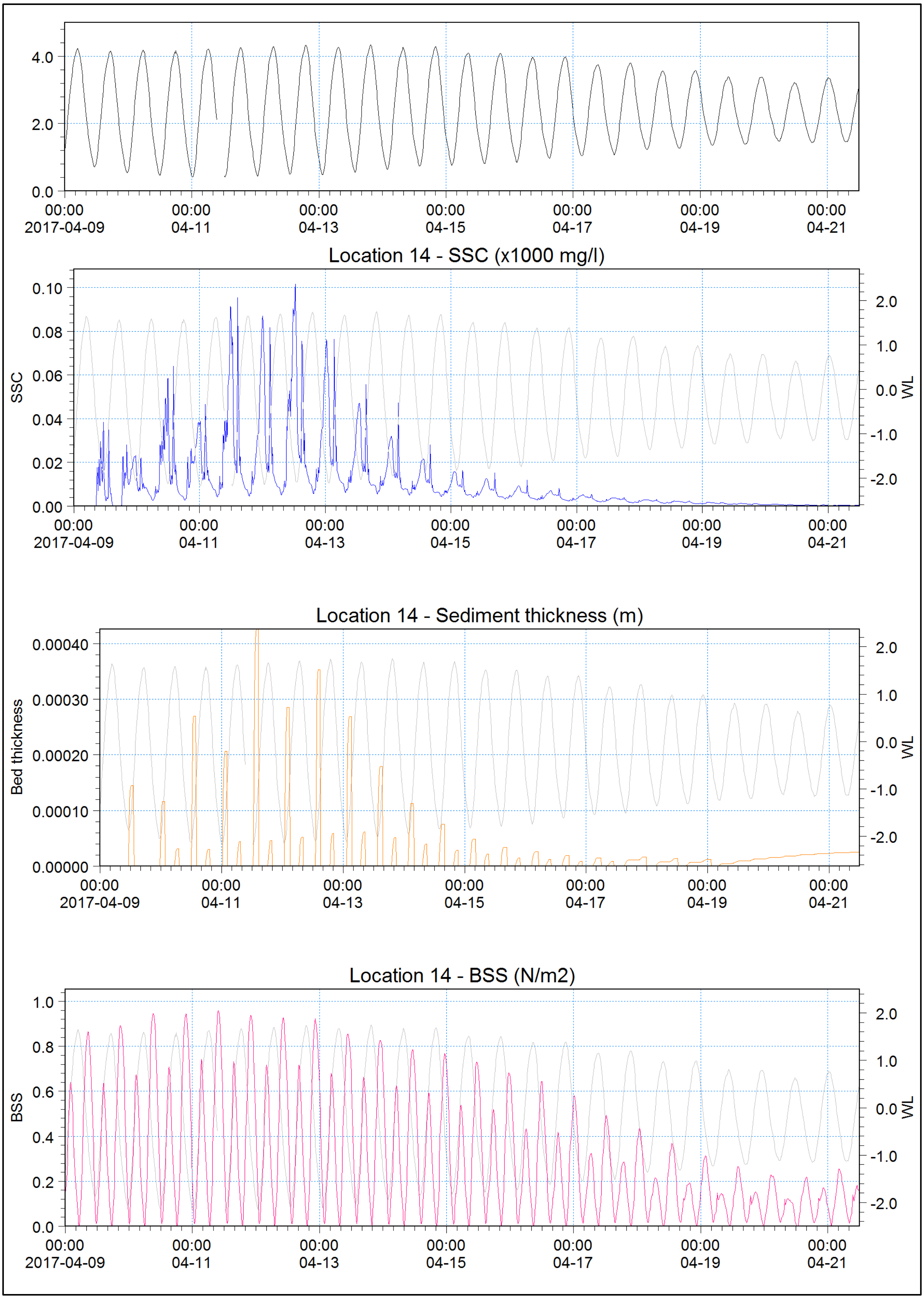


Figure 16. Timeseries of SSC, bed thickness and BSS - Location 14 (Carters Patch bank)

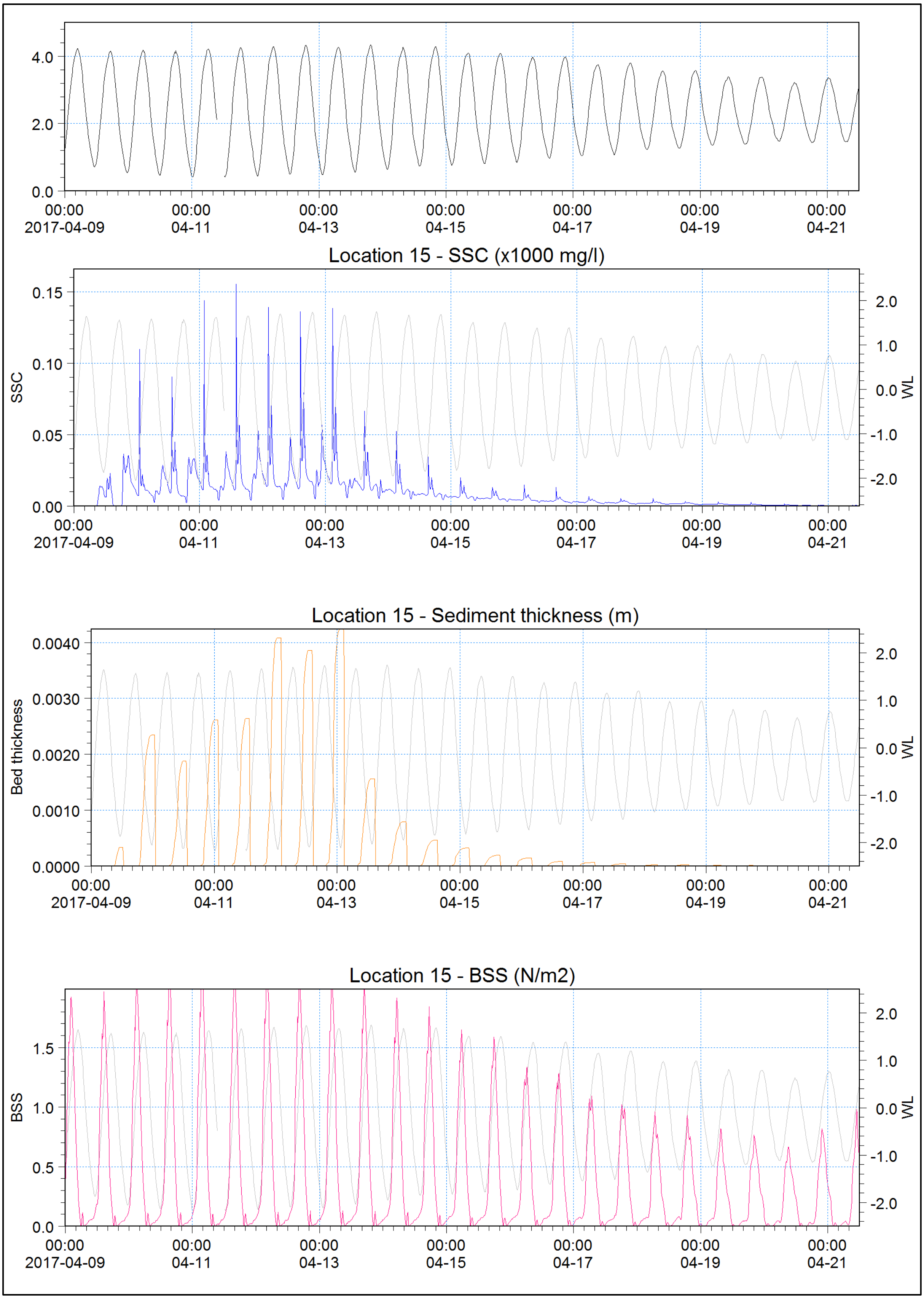


Figure 17. Timeseries of SSC, bed thickness and BSS - Location 15 (Carters Patch channel)

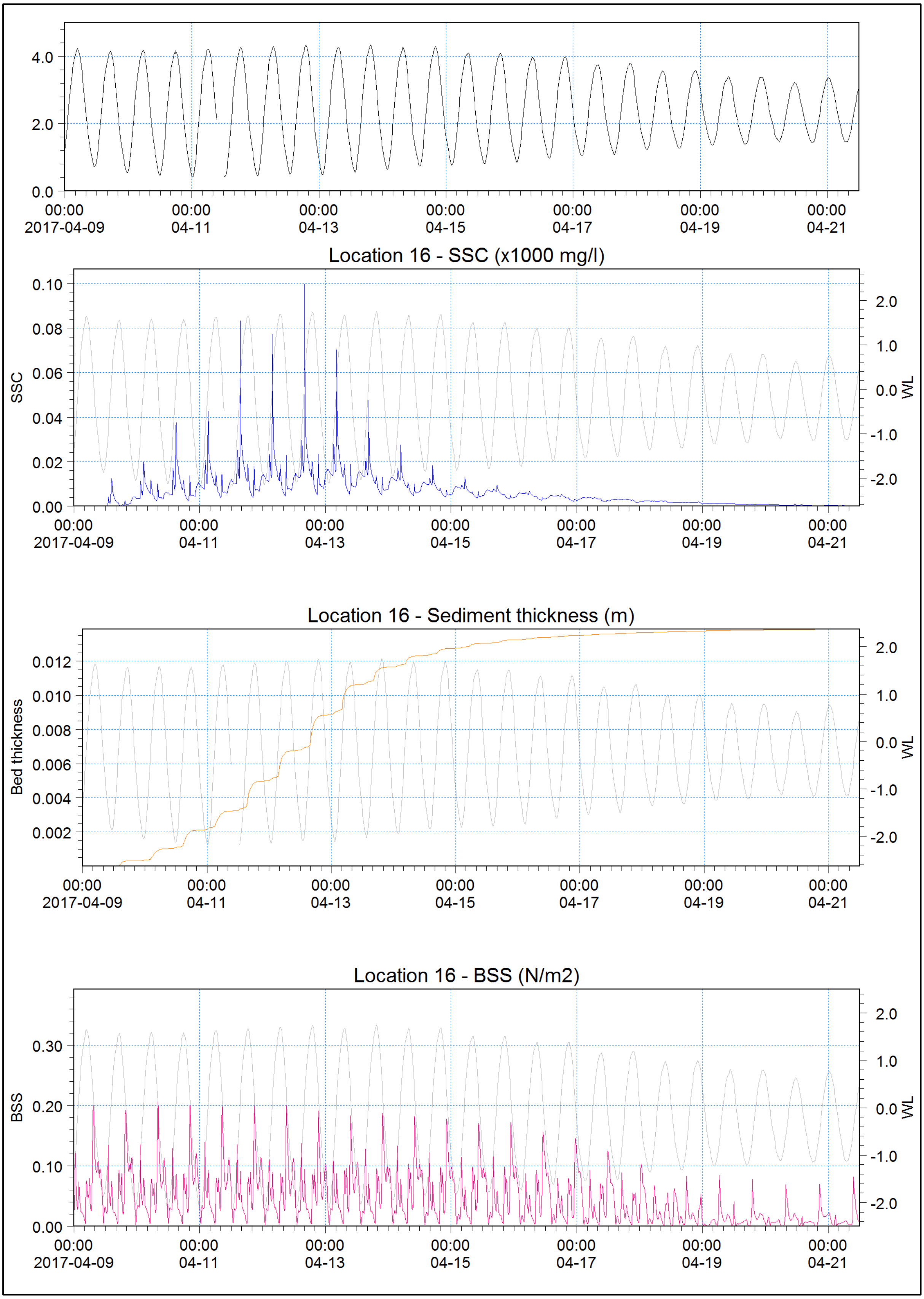


Figure 18. Timeseries of SSC, bed thickness and BSS - Location 16 (Shelburne Bay)

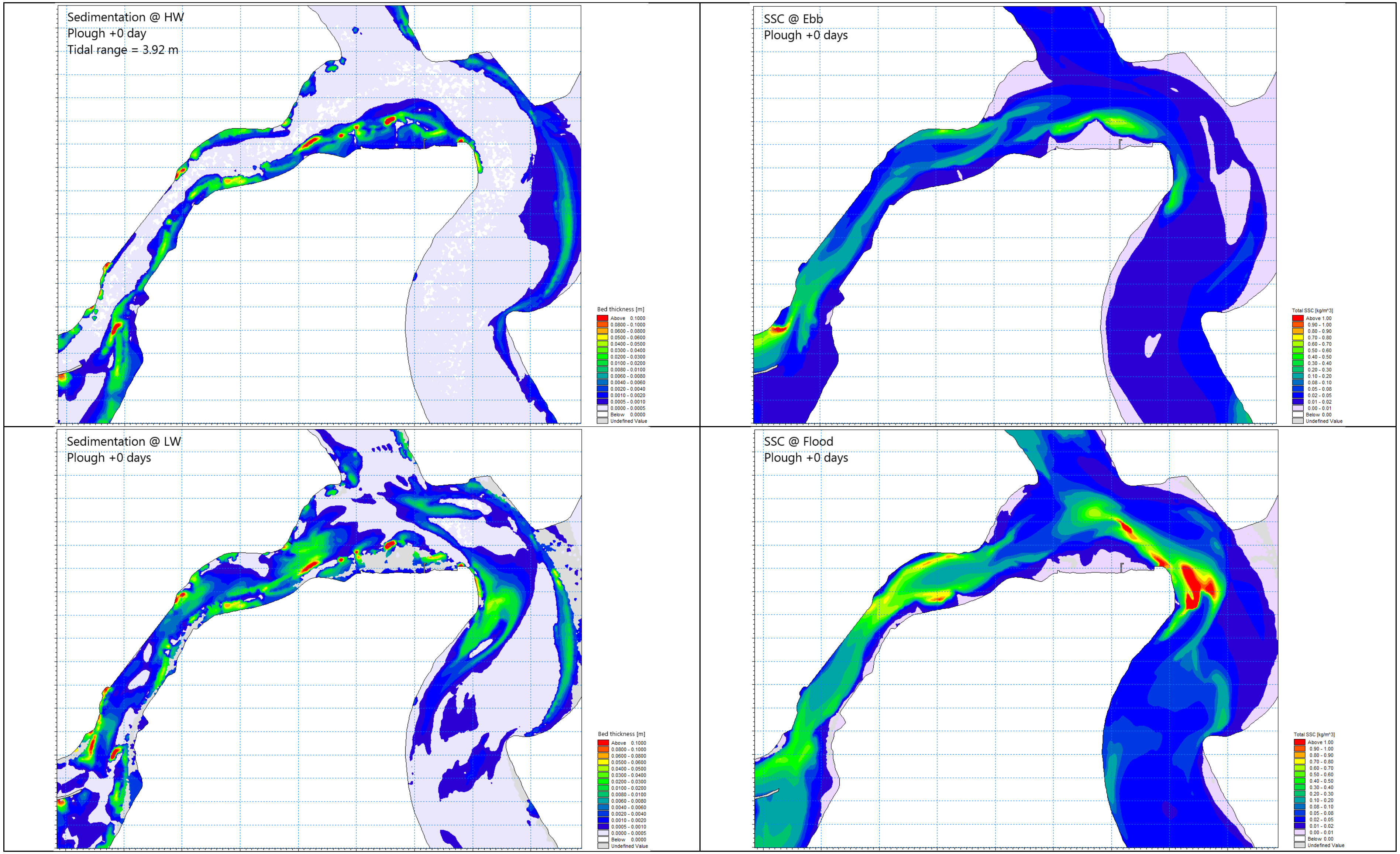


Figure 19. Map plots of sedimentation (left) and SSC (right) through a tidal cycle - 0 days after ploughing

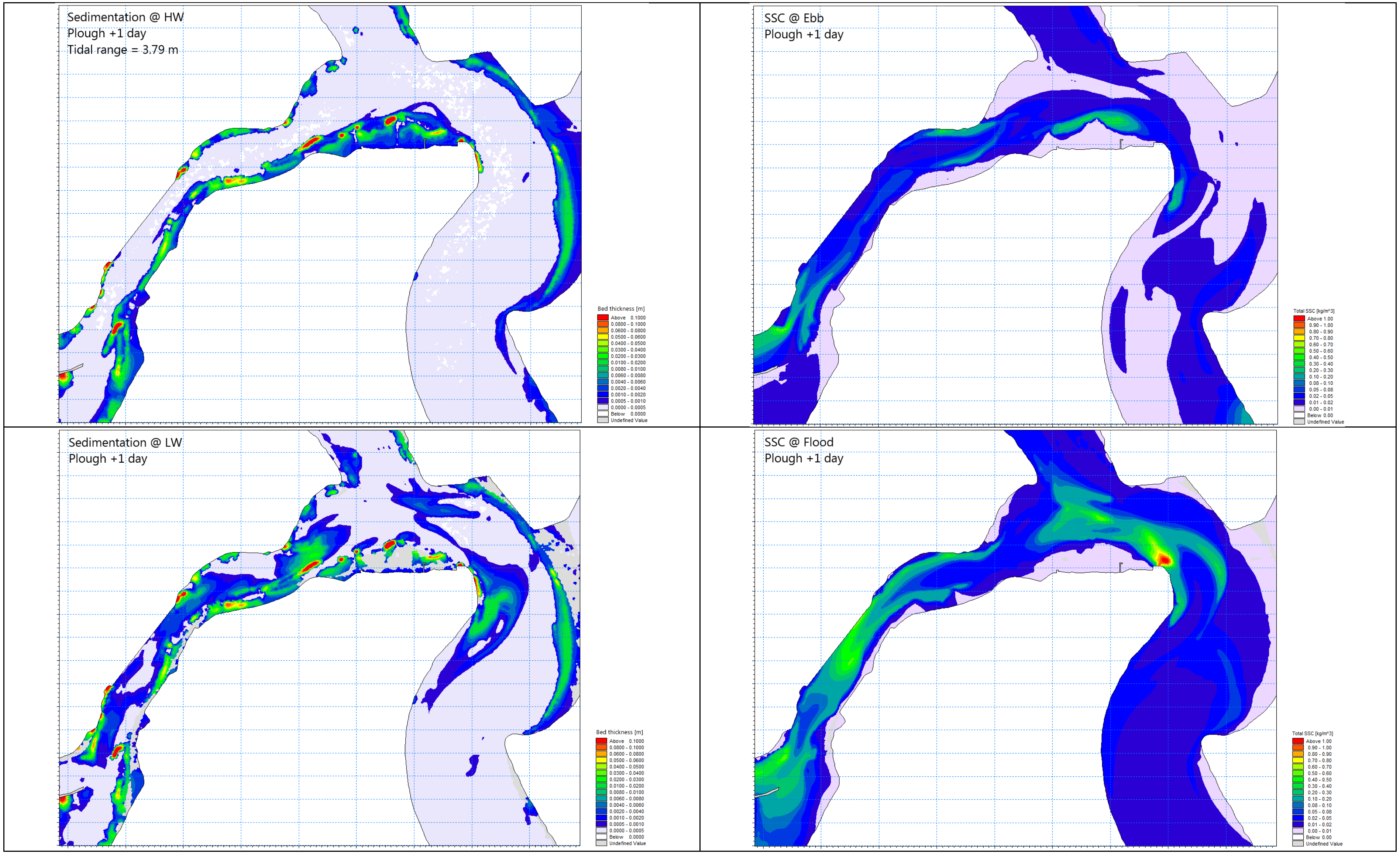


Figure 20. Map plots of sedimentation (left) and SSC (right) through a tidal cycle - 1 day after ploughing

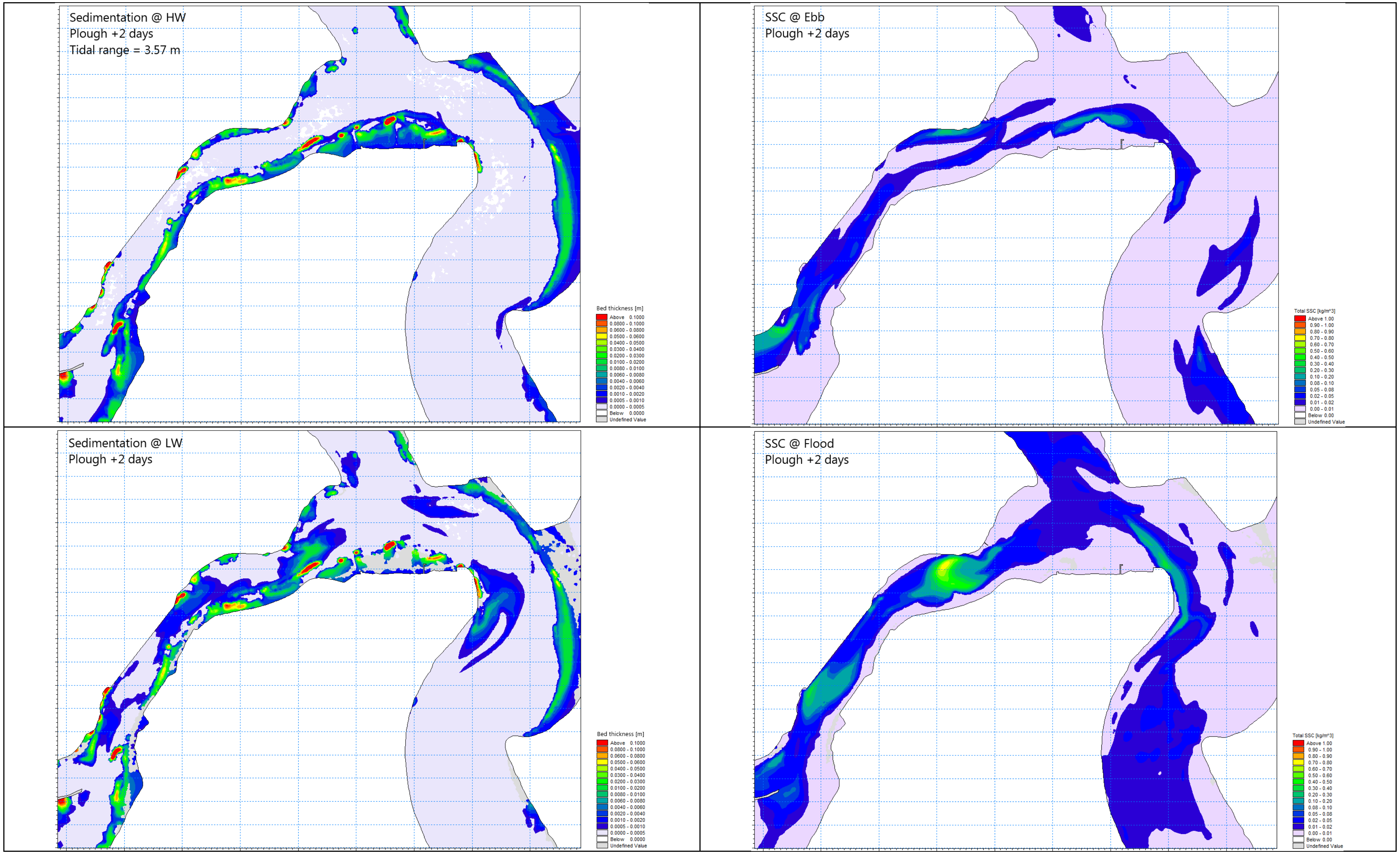


Figure 21. Map plots of sedimentation (left) and SSC (right) through a tidal cycle - 2 days after ploughing

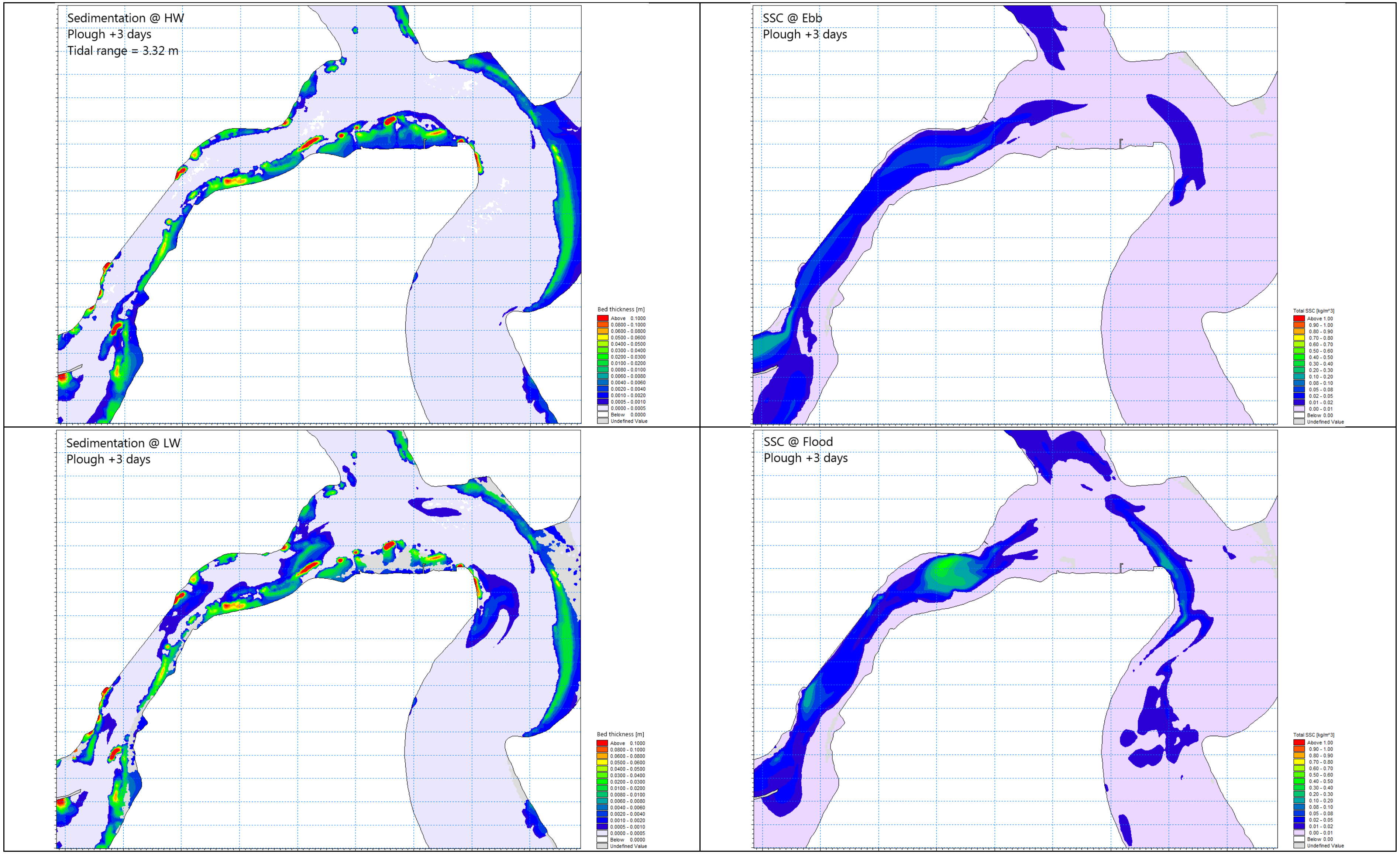


Figure 22. Map plots of sedimentation (left) and SSC (right) through a tidal cycle - 3 days after ploughing

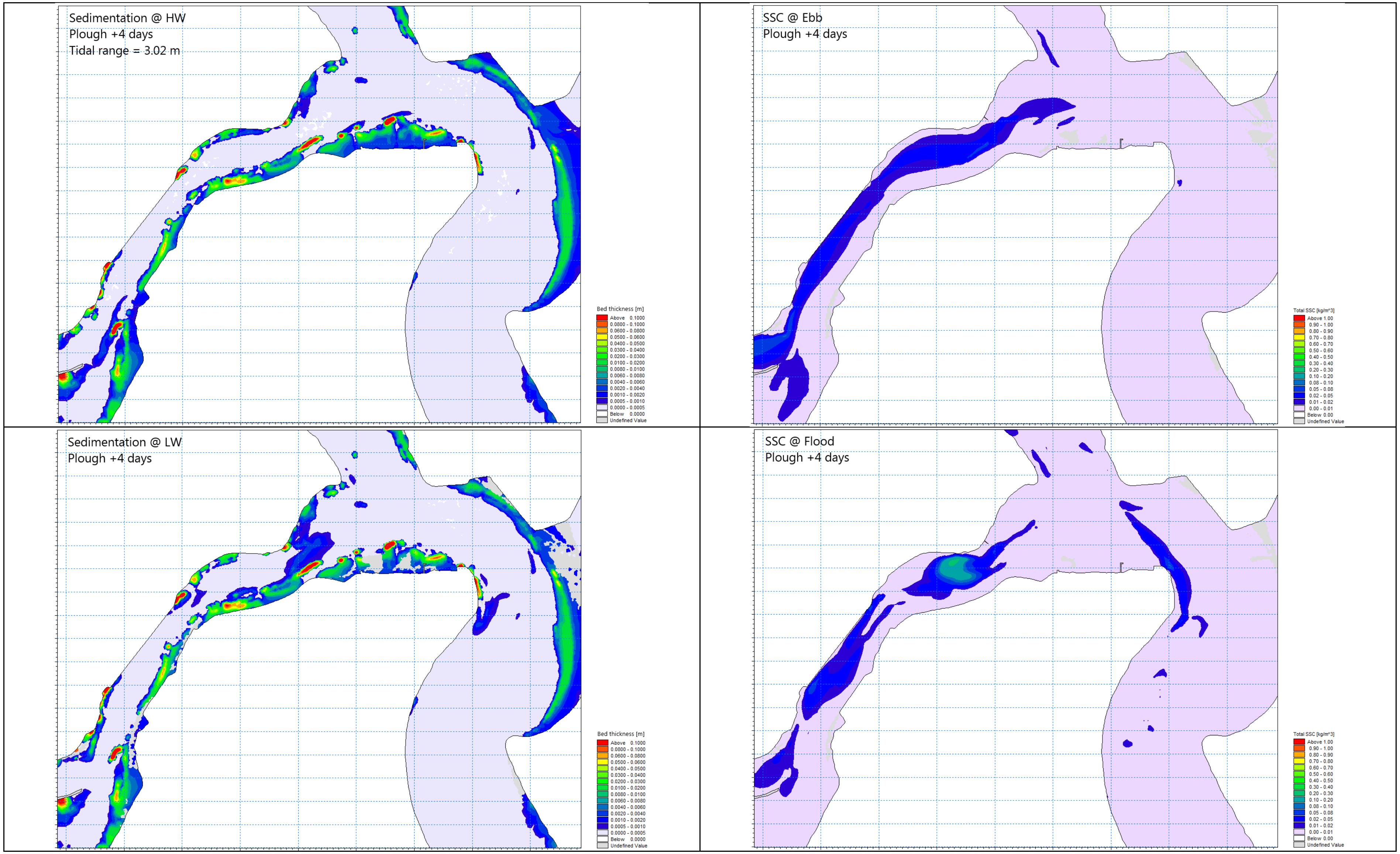


Figure 23. Map plots of sedimentation (left) and SSC (right) through a tidal cycle - 4 days after ploughing

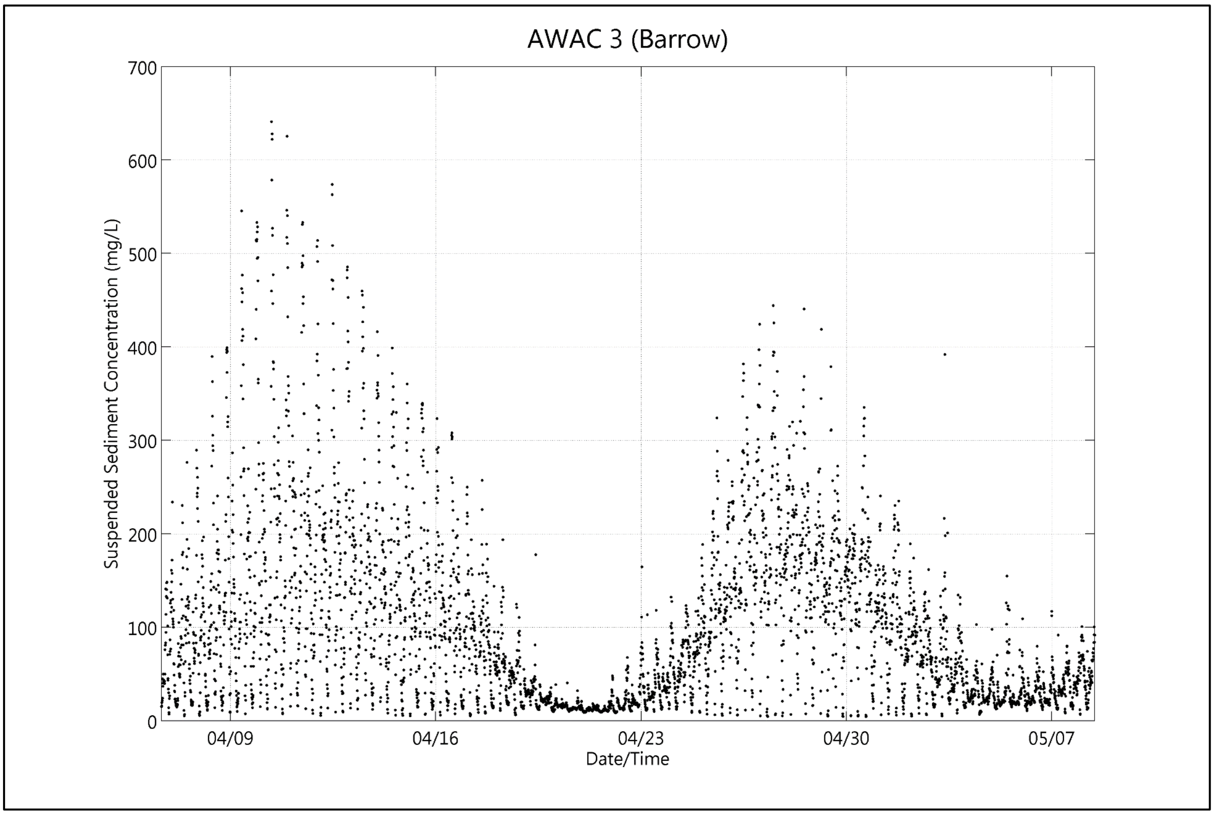


Figure 24. Measured SSC from AWAC 3 (Barrow)

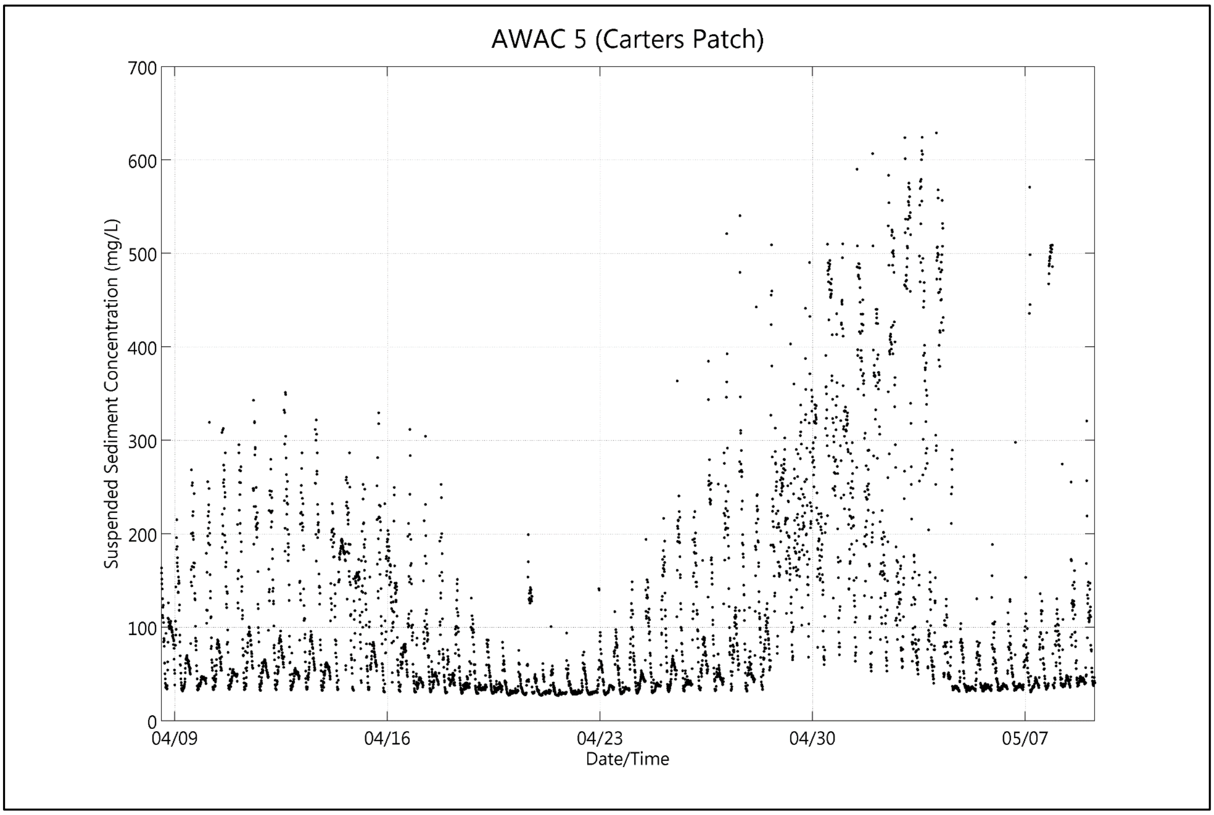


Figure 25. Measured SSC from AWAC 5 (Carters Patch)

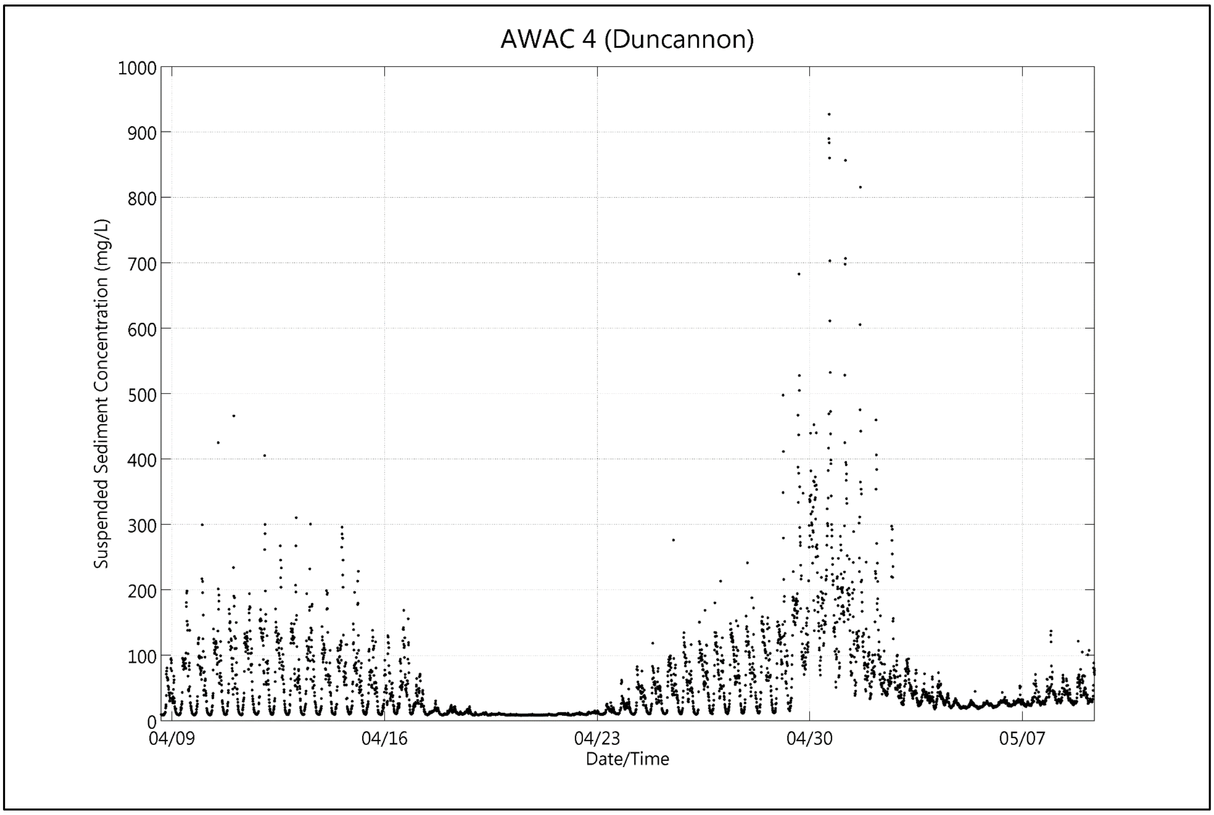


Figure 26. Measured SSC from AWAC 4 (Duncannon)

Contact Us

ABPmer
[redacted]
www.abpmer.co.uk

APPENDIX G-3

Dredging of Duncannon Bar

Environmental impact of dredging and spoil dumping

[redacted]

WL | delft hydraulics

Contents

List of References

List of Tables

4 Sand dispersion at the dump site

4.1 General

The purpose of the sand dispersion study is to determine the long term spreading of the dump. For this purpose the dump has been schematised into a heap of sand on the sea bed. To study the spreading of the sand a morphological model has been made based on the DELFT3D model system. This model system includes the tidal flow model as discussed in Chapter 3. A 2-dimensional wave propagation model has been added to provide the wave conditions over the area. Based on the results of the flow and wave model the sediment transports and the bottom changes were determined using the morphological model DELFT3D-MOR. This is an integrated model system combining the effects of flow, waves, sediment transports and bottom changes. The model has been run for a simulation period of 10 years to compute the morpho-dynamic behaviour of the heap of sand.

In this chapter first the study approach and input parameters are described. Hereafter the results are presented and discussed.

4.2 Approach and input parameters

In an ideal situation, the simulations for the spreading of the sand heap should be carried out covering all possibilities of water levels, current velocities, wave heights and directions related to their possibilities of occurrence. This approach however would result in an unrealistic number of simulations to be carried out. Therefore, the hydraulic conditions are schematised into a few conditions which are representative for the total flow and wave climate.

For the tidal conditions a morphological tide has been selected based on a weighting procedure considering sediment transport rates related to the tidal range. This approach has proven to be reliable in similar projects carried out in the past. The selected tide has been shown in Figure 4.1 and covers 25 hours.

The wave climate is an important input parameter for the transport capacities in the study area. Due to the wave activity, sediment is stirred up after which it can be transported by the tidal flow. The wave climate has been derived from our previous study for Belview Quay (Eysink et al., 1996). The probability of occurrence of the wave conditions at the 20 m depth contour near Waterford are presented in Table 4.1 and 4.2. This wave climate is based on ships observation data in the period between 1949 and 1994 which were derived from the British Met Office.

According to the 1996 study, the wave climate has been schematised into three wave conditions (calm, moderate and rough). The schematisation was carried out in such a way that the representative wave conditions, together with their corresponding durations, give more or less the same annual transport rates in the area of interest as the total wave climate. The representative wave conditions are shown in Table 4.3.

Condition		H_s (m)	T_p (s)	duration (%)	duration (days/year)
1	calm	0.0	-	50	182.5
2	moderate	1.5	6.6	40	146.0
3	rough	3.0	9.0	10	36.5

Table 4.3 Schematised wave climate for morphodynamic computations

For a more detailed description of the wave climate reference is made to Eysink et al., 1996.

For the morphological computations the wave pattern has been computed at the high waters of the morphological tide and at the low waters (see Figure 4.1). For the intermediate water levels the wave parameters are obtained by interpolation between the wave patterns at HW and LW. The wave pattern at LW for condition 3 (H_s = 3.0 m) are presented in Figures 4.2 (without the sand heap) and 4.3 (with the sand heap) for the open sea area at the dump site. These figures indicate that the influence of the sand heap on the wave pattern is only minor.

The total amount of dredged material is estimated at 335,000 - 425,000 m^3. Based on the dimensions of the dump site, the resulting sand heap at this location has a height of approximately 0.8 - 1.0 m. For the assessment of the dispersion of the sand the maximum value of 1.0 m has been selected to take the maximum disturbance into account in the model simulations. This means that the depth reduces from approximately 21 m to about 20 m.

Sieve curves of the bottom material were provided by the client. Analysis of these curves indicated that the bottom material at the dredging site is finer than the bottom material at the dump site. However, it can be expected that during dredging the percentage of fine material will reduce during the overflow of the hopper. Furthermore, part of the finer material will be washed out during dumping. Assuming that 50 % of the material less than 63 μm will be washed out, it can be concluded that the dump material at the bottom of the dump site will be comparable to the original material at the sea bed of the dump site. For this material the following sediment characteristics have been selected:

D_{50} 100 μm
D_{90} 300 μm
fall velocity0.008 m/s

The sand transport rates in the area were computed using the Bijker formula which includes the transport contributions of both waves and currents. The transports were computed over the morphological tide in discrete steps of 15 minutes (which means a total of 100 steps) taking into account the variation of the wave field during the tide. Hereafter the average transport over the morphological tide was computed. Based on this average transport the bottom changes were determined.

The bottom changes were computed by morphodynamic computations. This means that the interaction between the variation of the water depth due to sedimentation and erosion and the hydraulic conditions has been taken into account. After computing the bottom changes in a certain period of time the hydraulic conditions were updated by new flow, wave and transport computations, and so on.

The sediment transports and bottom changes in the existing situation were computed as well. These bottom changes were subtracted from the bottom changes in the situation with the spoil dump assuming that the bottom changes in the existing situation can be dealt with as noise. Finally, this gives the resulting effect of the spoil dump on the morphological developments at the dump site.

4.3 Results

Firstly, the cumulative bottom changes due to the various conditions were computed in the first year after the dumping of the sand. The bottom changes after respectively conditions 1, conditions 1 and 2, and after all three conditions are shown in Figures 4.4, 4.5 and 4.6.

From these first computations it can be concluded that the contribution of the calm condition on the morphology can be neglected. During this condition no significant bottom changes occurred. The bottom changes due to the moderate and rough sea states indicate that the height of the sand heap tends to reduce. The sand from this heap is deposited in the direct vicinity of the dump site at the north-western and at the south-eastern side. Due to this process the height of the sand heap is reduced while it is spread out over a larger area.

As the calm conditions have a negligible influence on the sand dispersion, these conditions can be neglected in the long term prediction of the sand dispersion. Therefore, only the moderate and rough conditions are taken into account in the simulations from 1 year to 10 years. The resulting bottom changes are presented in Figures 4.7 to 4.11 showing the results after 2, 3, 4, 5 and 10 years. These results show a progressive dispersion of sand in time. However the process of dispersion reduces in time due to the reduced disturbance of the spoil dump. After 10 years the dispersion of sand is still limited to a distance of about 1.5 km from the centre of the spoil dump. The maximum erosion of the sand heap then is equal to -0.8 m while the maximum sedimentation appeared to be 0.35 m at the north-western site of the dump location.

5 Effect of dredging on silt dispersion in Suir River estuary

5.1 Approach

Predictions on the impact of dredging activities at Duncannon Bar on spreading of suspended sediment in the estuary of the Suir river requires a tool that adequately describes the physical processes in the area. These physical processes include:

(i) Hydrodynamics as governed by tidal forcing, river discharges and wave forcing and
(ii) Suspended sediment transport processes as determined by the hydrodynamics and the exchange fluxes with the bed (erosion and deposition).

In order to meet the objectives of the study the software package DELFT3D was used. DELFT3D has been developed by Delft Hydraulics and includes different modules on hydrodynamics, waves, sediment transport, morphology and water quality processes. Between the various modules there is an off-line coupling, which means that computed quantities by a specific module are stored on an intermediate file (communication file) and subsequently used by another module. In the case of suspended sediment transport modelling discharges, water levels and bed shear stresses of the FLOW module and bed shear stresses of the WAVE module are used by the suspended sediment module. Together with appropriate values for the input parameters of the sediment module predictions are made on suspended sediment transport. Because the two-dimensional, depth-averaged, version of DELFT3D is used, values for the dispersion coefficient have to be defined. This coefficient determines the magnitude of the dispersive transport, resulting from the depth-averaging in the model. The sum of dispersive and advective transport, the latter resulting from the flow velocities, gives the total transport of suspended sediment.

The horizontal transport of suspended sediment in the model is calibrated by comparing the suspended sediment concentration in a number of locations in the estuary and adjusting the model parameters, so that an optimum agreement between measurements and model results is achieved. The calibration procedure is described in detail in the next section.

5.2 Mathematical representation of physical processes

The horizontal transport of suspended sediment in a two-dimensional, depth-averaged, model is given by the advection-diffusion equation:

$$\frac{\partial c}{\partial t}+\frac{\partial}{\partial x}(uc)+\frac{\partial}{\partial y}(vc)-\frac{\partial}{\partial x}\left(D_x\frac{\partial c}{\partial x}\right)-\frac{\partial}{\partial y}\left(D_y\frac{\partial c}{\partial y}\right)=E-D$$

with:

c	suspended sediment concentration [mg/l],
u	depth-averaged velocity in x-direction [m/s],
v	depth-averaged velocity in y-direction [m/s],
t	time [s],
D_x	dispersion coefficent in x-direction [m^2/s],
D_y	dispersion coefficent in y-direction [m^2/s],

and where the erosion flux E is given by:

$$E = M(\frac{\tau_b}{\tau_e} - 1) \qquad \text{for } \tau_b > \tau_e$$

$$E = 0 \qquad \text{for } \tau_b \leq \tau_e$$

with:

M	erosion parameter [kg/(m^2.s)],
τ_b	bed shear stress [Pa],
τ_e	critical erosion shear stress [Pa].

and the sedimentation flux is given by:

$$D = w_s c\left(1 - \frac{\tau_b}{\tau_d}\right) \qquad \text{for } \tau_b < \tau_d$$

$$D = 0 \qquad \text{for } \tau_b \geq \tau_d$$

with:

w_s	settling velocity [m/s],
τ_d	critical deposition shear stress [Pa].

5.3 Field measurements

Field data for the calibration and validation of the suspended sediment model are taken from two different references:

- Measurements that were carried out as part of the hydraulic studies for Cheekpoint upper and lower bar as carried out by Delft Hydraulics (Rijn, 1990a);
- Measurements that were carried out by HSL in 1999 specifically for this study.

It is noted that since the measurements of 1989 and 1990 the hydrodynamics in the upper estuary have changed due to the construction of Belview Quay and groynes in the vicinity of Cheekpoint. This will introduce uncertainties in that area when comparing the measurements of 1989/1990 and the results of the simulations, because in the latter case the present geometry and bathymetry is taken into account. This holds for Station A on the River Suir and in particular for Station E near Cheekpoint harbour. Because Station E is located close to the present construction works (see Figure 3.1) the results of the measurements in this station have not been taken into account in the present study.

The selected locations for calibration and validation are listed in Table 5.1. The time frames of the measurements and the hydrodynamic conditions during these measurements have also been indicated in the table.

Location name	Time frame	Tide	Tidal range[1])	Used for:
Station A	1989-12-29	Spring	3.4 m	calibration
Station B	1989-12-30	Spring	3.5 m	calibration
Station G	1990-01-01/02	Spring	3.3 m	calibration
Duncannon Bar (DB)	1999-06-12	Spring	3.5 m	calibration
Disposal Site (DS)	1999-06-11	Spring	3.1 m	calibration
Duncannon Bar (DB)	1999-06-22	Neap	2.4 m	validation
Disposal Site (DS)	1999-06-23	Neap	2.4 m	validation

[1]) from the model

Table 5.1 Measurement locations for calibration and validation

In most cases the measurements have been performed during a complete tidal cycle of 12.5 hours, apart from Station G where the measurements prolonged for only 10 hours. During the 1989/1990 survey measurements were done at five levels, i.e.: 0.15 m, 0.65 m, 1.65 m and 4.65 m from the bed and 1 m below the water surface. In 1999, samples were taken at three depths, i.e.: near the bed, at mid-depth and near the surface. From these measurements a depth-averaged concentration is computed for comparison with the model simulations. It is noted that for the 1989/1990 measurements the two positions at 0.15 m and 0.65 m from the bed contribute only for 10% to the depth-averaged concentration. The measurements during the spring tides are used for calibration of the model, whereas the measurements during the neap tides are used for validation.

Suspended sediment concentration

The 1989/1990 measurements in Stations A, B, E and G (see Figure 3.1) on suspended sediment concentration of the fraction smaller than 63 μm (denoted as mud) show a dynamic variation during the tide, with maximum concentrations at 0 to 2 hours after maximum ebb and flood currents and minimum concentrations at 0 to 2 hours following slack water. Concentrations vary between 50 and 500 mg/l in Stations A and B. In Station G the maximum concentration reaches values of more than 1000 mg/l, whereas in Station E concentrations are always less than 150 mg/l. Variations in concentration may be caused by local bed exchange processes (erosion and deposition) and advection. In the latter case a water body carrying sediment with a different sediment concentration results in a decrease or increase of the concentration when passing through the survey station. A first estimate of the settling velocity is obtained by assuming uniform conditions and thus neglecting advection. This settling velocity is then used as input for the model simulations. Because the model takes into account advective transport of the sediment, the settling velocity may be modified during calibration in order to obtain an optimum agreement between measured and computed suspended sediment concentration.

First estimates of the settling velocity are obtained in two ways:

1. From the complete emptying of the concentration profile the settling velocity follows from:

$$w_s = \frac{h}{T_{sed}}$$

with:

h water depth [m],
T_{sed} sedimentation period [s].

For Stations A, B and G the characteristic water depth is 10 m and the concentration decreases over a period of 1 to 3 hours. This results in a settling velocity of 1 to 3 mm/s.

2. During maximum ebb and maximum flood the concentration profiles can be approximated with Rouse profiles from which the settling velocity follows.This assumes steady state conditions with fully adapted concentration profiles. The time T_{adapt} required to obtain these profiles is given by:

$$T_{adapt} = \frac{h^2}{\varepsilon_z}$$

with the vertical mixing coefficient given by:

$$\varepsilon_z = \frac{1}{6} h u_*$$

where:

u_* shear stress velocity [m/s]

The shear stress velocity follows from the depth-averaged velocity and the roughness parameter:

$$u_* = u\sqrt{g}\frac{n}{h^{1/6}}$$

With u_* = 0.02 m/s and n = 0.026 the adaptation time becomes approximately 1 hour indicating that during flood and ebb there is sufficient time to arrive at fully adapted concentration profiles.

The Rouse concentration profiles are described by:

$$\frac{c}{c_a} = \left(\frac{h-z}{z} \frac{a}{h-a} \right)^{\frac{w_s}{\kappa u_*}}$$

with:

c_a reference concentration at height a above the bed [mg/l],
z height above the bed [m],
κ von Karman constant (= 0.4).

Figures 5.1a and 5.1b present the measured and computed concentration profiles during ebb and flood for Stations A, B, E and G respectively. The reference concentration is the measured concentration at a height 0.15 m above the bed. The results indicate that the resulting settling velocities vary between 1 and 4 mm/s (or even 7 mm/s when in Station G the concentrations at 18:00 hrs are used), see Table 5.2. Values between brackets indicate that probably no steady state condition is reached with respect to the horizontal flow velocity or the vertical sediment concentration distribution, so that values for the settling velocity may be biased.

Location	Maximum ebb	Maximum flood
Station A	2.8	3.3
Station B	(1.1)	(0.8)
Station E	3.8	3.8
Station G	1.0	(4.0)

( ) no steady state reached

Table 5.2 Settling velocity from fitted Rouse concentration profiles

The settling velocities as derived above are significantly larger than those presented in report H1118 (Rijn, 1990a). The latter have been obtained from a device employed in the field (Field Pipette Withdrawal Tube) giving median settling velocities between 0.03 and 2 mm/s. It is well-known that there is discrepancy between settling velocities from these kind of tubes and those obtained by e.g. in-situ video camera systems (see e.g. van Leussen, 1994). The sampling of a water-sediment mixture probably destroys the fragile flocs that contribute most to the median settling velocity.

The 1999 measurements did not give any reason for a different approach.

Bed composition

In 1989 bed samples were taken in the area enclosed by Stations A, B and G. The grain size distributions of these samples show that the mud fraction (%<63 μm) can be more than 40%. Highest mud fractions were encountered along the sides of the estuary and lowest in the channel. The sand is mostly fine, i.e. between 63 and 200 μm. From these measurements it is concluded that there is availability of mud over the whole area between Stations A, B and G.

In 1999 additional information became available about the composition of the sea bed in front of the Suir estuary showing a more sandy bed.

5.4 Calibration

5.4.1 General approach

A calibrated suspended sediment transport model requires a calibrated model on hydrodynamics and proper values for the parameters that are needed for the formulations representing the sediment exchange fluxes with the bed. The flow model has been calibrated on tidal propagation, water levels and discharges as described in Chapter 3. The sediment transport model is then calibrated by adjusting the parameters that follow from the sediment properties and by imposing correct boundary conditions for the suspended sediment concentrations. The procedure to arrive at the proper parameter values is done by means of sensitivity runs with the model, taking into account the available data on sediment properties. Those parameters that can not be deduced from the available data are varied within a realistic range, as set by data from literature and consultant's experience. Following calibration the suspended sediment transport model is validated. In that case model predictions are compared with independent data that have not been used during calibration and representing conditions that are different from those for calibration. During validation the model parameters are not changed.

5.4.2 Parameter settings

The objective of the calibration of the model is to determine the parameters of the erosion and sedimentation fluxes and the longitudinal dispersion coefficients in such a way that the computed sediment concentrations and the measured values show similar variation. The following parameters are investigated to arrive at an optimum reproduction:

- Settling velocity w_s;
- Critical shear stress for sedimentation τ_d;
- Erosion parameter M;
- Critical shear stress for erosion τ_e;
- Longitudinal dispersion coefficients D_x and D_y.

During calibration the longitudinal dispersion coefficients D_x and D_y are kept equal. At the sea and river boundaries concentrations of 10 mg/l are imposed. The exact values of these concentrations are not important as the suspended sediment transport in the estuary is mainly governed by the erosion and sedimentation processes. The calibration run assumes a mud bed all over the estuary, rivers and adjoining sea. In reality this is not true for the outer estuary and sea, but if no erosion takes place the presence of mud in the model in these areas will not affect the calibration results.

Results of the hydrodynamic simulations are written to the communication file with a time step of 10 minutes. The computations with the sediment module are performed with a integration time step of 10 minutes. An implicit, unconditionally stable, numerical scheme is used for the discretisation of the equations.

A number of combinations of the aforementioned parameters has been investigated. The best result is obtained with the parameter settings as indicated in Table 5.3.

Parameter	Value
Settling velocity	3 mm/s
Critical shear stress for sedimentation	0.5 Pa
Erosion parameter	$3.47\ 10^{-5}$ kg/(m^2.s)
Critical shear stress for erosion:	0.5 Pa
Dispersion coefficient:	20 m^2/s

Table 5.3 **Parameter setting after calibration**

The selected settling velocity of 3 mm/s is in the range as estimated directly from the field measurements. Further, it should be realised that in the prototype the sedimentation flux is given by:

$$S_{prototype} = w_s c_b$$

whereas in the model the flux to the bed follows from:

$$S_{model} = w_s c_{avg}$$

Because c_b is larger than c_{avg} the settling velocity in the model should be increased in order to arrive at the correct sedimentation flux.

The critical shear stress for deposition is somewhat larger than normally found for homogeneous mud mixtures in laboratory flumes (0.1-0.2 Pa). A higher value seems reasonable considering the amount of silt in suspension.

The erosion parameter can vary various orders of magnitude and thus this parameter is used to arrive at the correct average concentration level. The value is varied within the range as found in literature (see e.g. Winterwerp, 1989): 10^{-3} - 10^{-5} kg/(m^2.s).

A critical shear stress for erosion equal to 0.5 Pa is realistic for loosely deposited cohesive sediment. The consequence of τ_d being equal to τ_e is that with increasing bed shear stress following slack water a decreasing deposition rate is immediately followed by an increasing erosion rate. This appeared to be necessary to reproduce the strongly varying suspended sediment concentrations during the tidal cycle.

Also the rate of the dispersion coefficient has been varied within realistic limits during calibration. Ultimately the settings as presented in Table 5.3 are selected for the silt dispersion computations.

5.4.3 Results

Results of the calibration run are shown in Figure 5.2 for Station A, in Figure 5.3 for Station B and in Figure 5.4 for Station G. Station E has been eliminated from the analysis, because it is located very close to the present training works near Cheekpoint; these training works were not present during the survey of 1989/1990. In Figure 5.5 and Figure 5.6 the model results at Duncannon Bar (DB) and at the Disposal Site (DS) respectively are compared with the measurements. The measured concentrations at five depths for the 1989/1990 survey and at three depths for the 1999 measurements have been converted to depth-averaged concentrations. For each cross-section the model results are presented in three or four locations (for example denoted as A4, A5, A6 and A7 for Station A) to check for concentration differences in lateral direction. The x- and y-coordinates of the outermost observation locations in the cross-sections are given below.

Location	x	y	Location	x	y	Width [m]
A4	265962	112592	A7	265844	112635	126
B3	267250	116174	B5	267139	116108	129
G3	269449	111467	G8	268932	111353	529
DB3	272540	105300	DB7	272686	105280	147
DS3	270153	97112	DS7	270415	97072	265

From the simulation results in these locations it is concluded that in the model the suspended sediment is rather homogeneously distributed in lateral direction. Thus, for comparison with field data the choice for a location in a specific cross-section does not significantly affect the reproduction quality of the model.

In Stations A and to a larger extent in Station B magnitude and variation of the suspended sediment concentration are reproduced by the model. However, a phase lag appears between measurements and model results with the model results shifted forward in time. The same applies to Station G. The high concentration of 300 mg/l is not reproduced by the model and may be caused by meteorological effects as it was quite stormy on the day of the measurements (Rijn, 1990a). At Duncannon Bar (DB) the peak concentration preceding low water slack is reproduced, although the concentration is two times larger in the model. The peak concentration is attributed to the outflow of water from the estuary loaded with sediment. Although, after the turning of the tide, during flood, the velocities are comparable with those during ebb, no increase in sediment concentration is found. This is due to the inflow of sea water which carries almost no sediment. At the Disposal Site no noticeable concentration is computed, which compares with the measurements. From these results it is concluded that the dynamic variation of the suspended sediment due to the tidal flow and the large scale distribution of the concentration field is fairly well reproduced by the model.

The phase lag of the suspended sediment concentration may be explained to some extent by the hydrodynamics in the model. The water level in Station A is approximately 1 hour later in the model as compared with the measurements, possibly resulting from the new groynes at Cheekpoint.

Finally, model results are compared qualitatively with satellite images. Figure 5.7 shows the computed silt-concentration pattern during spring tide conditions. This pattern quantitatively agrees rather well with the spot image presented on Figure 5.8.

5.5 Validation

The model is validated against measurements at Duncannon Bar and at the Disposal Site during neap tide. Results are presented in Figure 5.9 and Figure 5.10 respectively. The maximum sediment concentration at Duncannon Bar has reduced in the model to 30% of its maximum value during spring tide. This still is approximately 100% larger than according to the neap tide measurements. At the Disposal Site no significant increase in concentration is found, which is in accordance with the measurements. In spite of these differences it is concluded that the effect of different hydrodynamic conditions (spring tide versus neap tide) on suspended sediment concentrations is described satisfactorily by the model.

5.6 Simulations on dredging and disposal

5.6.1 Input of sediment load due to dredging activities

General

The maintenance dredging involves two major dredging areas:

- Duncannon Bar, halfway the mouth of the estuary;
- Cheekpoint Lower Bar, more upstream, near the river junction.

The disposal area is at sea just in front of the mouth of the estuary.

With regard to turbidity caused by the dredging activities factors of importance are:

- The composition of the bottom in the dredging area (dredged material);
- The dredging and disposal technique and working method used;
- The hydrodynamics (and water quality) in the dredging area.

The dredging and disposal actions and the hydrodynamic circumstances (flow, wave climate, water depth and scale) determine the source value of turbidity generated by the maintenance dredging. The dispersive processes in the near field water area will be predicted by numerical simulation.

The dredging is executed by the 'Lesse', a trailing suction hopper dredge (TSHD) with a hopper of 1538 m^3. Loading of the 'Lesse' on the site takes on average 1 hour and 10 minutes, whereas overflow of the hopper already starts after 10 minutes. Overflow continues throughout the rest of the loading time. The fully laden draught of the dredge is approximately 5 m. Unloading at the disposal area takes place by opening the bottom valves and takes on average 5 to 7 minutes.

Analysis and evaluation of the material to be dredged

From the geotechnical information from the grab samples it can be concluded that the (top) layer to be dredged at Duncannon Bar largely consists of silt and fine sand (D_{50} approx. 63 μm).

The geotechnical information from the Cheekpoint Lower Bar area is more ambiguous. In 'deeper' areas the fine sand content is predominant (D_{50} > 63 μm: 80 - 90 %), whereas in the shallow areas the silt content prevails (D_{50} < 63 μm: 50 - 65 %). No information was found about the organic matter content. No indication was found about the occurrence of coarse debris.

Turbidity generated by the dredging activity

The amount of dredged material would be a total of 525,000 in-situ m^3. The sailing distance from Duncannon Bar to the disposal area is 8 km; from Cheekpoint to the disposal area 20 km.

The turbidity production is analysed in an absolute sense. In an evaluation the turbidity generated by the dredge must be weighed against the turbidity which results from natural causes (e.g. storm surges) and the background turbidity (e.g. navigation) that occurs in the dredging area before, during and after the dredging activity.

Turbidity generation during the trailing suction hopper dredging process occurs during the following stages:

- The trailing involves the movement of the suction head(s) and suction pipe(s) through the water at a velocity in the order of 2 to 4 knots (1 - 2 m/s). This causes turbidity close to the bottom.
- With low keel clearance the return flow under and along the dredge is a possible source of turbidity.
- During the manoeuvring of the dredge, propeller wash will cause erosion and turbidity. During trailing significantly less erosion is caused by the propeller wash.
- Lean mixture discharge overboard (LMOB).
- Hopper overflow during the loading process.
- Dredged material degassing and gas release from the river bed (here probably not an issue).
- Leakage from the hopper bottom valves.
- Deblocking of the suction head(s) in the event of coarse material stuck in the suction system.

It should be noted that, apart from overflow and hopper leakage, the turbidity production is confined to the lower part of the water depth. This is an advantage.

From literature it can be concluded that the amount of dredged material brought into suspension by a medium size trailing suction hopper dredge is about 10 to 12 kg dry solids per cubic meter removed sediment (or in this case 3.7 kg dry solids per second) using LMOB but no overflow. Overflow results in a considerable contribution of the additional turbidity which then becomes about ten times as much as without overflow and is estimated to be 37 kg dry solids per second. The overflow effluent not only contains more silt but it is also introduced high in the water column. A major part of the resuspended material settles in the direct vicinity of the dredge.

At a distance of about 50 m around a dredging TSHD the additional turbidity on top of the background turbidity, will be caused by an additional, resuspended silt concentration of about 250 to 300 mg/liter.

Turbidity generated by disposal of the dredged material

The spoil will be dumped by opening of the bottom valves/doors of the hopper of the dredge. When the contents of the hopper drops into the water and sinks to the bottom part of the dredged material gets into suspension by segregation of the perimetry and turbulent exchange. The amount of suspension depends on the type of dredged material, the granular composition and the consistency. The discharge will take only a few minutes. The impact of the spoil on the sea bed will result in erosion and resuspension of bed material and can even create craters of several meters. This becomes more severe if the discharge takes place on earler discharges. Also density currents will occur up to several hundreds of metres. In relation with silt loss during loading and the geotechnical information it is estimated that the dumping process of the hopper can cause additional turbidity by a silt source of about 12 kg dry solids of silt per second during dumping. The plume will develop for a major part low in the water column. The averaged silt concentration is estimated to be 20 to 40 mg/liter at a radius of 50 m from the disposal site.

5.6.2 Run scenarios, simulation periods and dredging-dump cycle

Scenarios

The effect of dredging and disposal on the suspended silt concentration is studied for spring as well as neap tidal conditions, both, with and without waves. The parameter setting as obtained from the calibration and validation of the model has been applied.

Basically, a mud bed is present all over the model area. The silt mass per computational cell was set at $1\ 10^{20}$ grams, which guarantees an unlimited supply of silt during the simulation period. In these cases with a mud bed, the discharged silt will form part of the existing bed after deposition. When it is subsequently resuspended, there will be no difference with the reference situation (i.e. without discharges) and thus the effect of dredging and disposal is reduced to the small part of the additional silt load that has not settled yet during the first slack tide.
In addition, simulations have been performed starting with a fixed bottom. In these cases the discharged silt due to dredging and dumping can be followed as a tracer throughout the estuary. Silt that is resuspended due to dredging and dumping will be transported by the tide and settle around slack water. After slack water, the silt is eroded again if the local velocity

becomes higher than the critical velocity for erosion and in this way the sediment gradually disperses in the estuary. This scenario describes the behaviour of a loosely deposited sediment on a fixed bed.
The scenarios with and without an initial mud bed can be considered as extreme cases of the actual situation where mud is not present everywhere.

The tidal difference at Duncannon Bar is 3.6 m during spring and 2.1 m during neap tide. For the simulations with waves a wave height of 1.5 m is prescribed at the sea boundary of the WAVE-module. The wave heights are computed for a mean water level. Wave heights decrease from 1.5 m at the entrance of the estuary (Hook Head) to 0.5 m at Duncannon Bar and 0.3 m at the Upper Bar (see Figure 5.11).

The model simulations performed to determine the impact of dredging and dumping are presented in Table 5.4 and labelled with their run numbers.

	With fixed bed			
	No waves		With waves	
	No dredging	With dredging	No dredging	With dredging
Spring	-	Run 40	-	-
Neap	-	Run 41	-	-
	With mud bed			
Spring	Run 42a	Run 42b	Run 51a	Run 51b
Neap	Run 43a	Run 43b	Run 52a	Run 52b

Table 5.4 Run programme

Simulation periods

The simulation times are given in Table 5.5. They refer to arbitrary dates in 1999. Times for spring and neap tide are similar.

Process	Start simulation period	End simulation period
Hydrodynamics	1999-01-01 00:00	1999-01-05 04:00
Results to communication file	1999-01-04 03:00	1999-01-05 04:00
Silt transport	1999-01-04 03:00	1999-01-07 06:00

Table 5.5 Simulation periods

During the simulations on silt transport the same hydrodynamic results are used from the communication file for each period of 25 hours.

Dredging operation cycle

The cycle of operation during dredging and disposal is based in information supplied by the Client. It consists of:

1. Dredging at Duncannon Bar (1 hr and 30 min);
2. Sailing from Duncannon Bar to the Disposal Site (30 min);
3. Dumping at the Disposal Site (5 min);
4. Sailing from the Disposal Site to Duncannon Bar (30 min);
5. Dredging at Duncannon Bar;
6. Sailing from Duncannon Bar to the Disposal Site;
7. Dumping at the Disposal Site;
8. Sailing from the Disposal Site to the Upper/Lower Bar near Cheekpoint (1 hr and 15 min);
9. Dredging at the Upper/Lower Bar (1 hour and 20 min);
10. Sailing from the Upper?Lower Bar to the Disposal Site (1 hr and 15 min);
11. Dumping at the Disposal Site;
12. Sailing from the Disposal Site to Duncannon Bar;
13. etc.

A complete cycle as described above takes a total time of 9 hrs and 5 min. For the simulations the times have been slightly adapted so that 3 dredging-disposal cycles fit in a cyclic simulation period of 25 hours. Table 5.6 gives in detail the times and loads as used during the simulations. It is further noted that during dredging and loading of the dredger the first 10 minutes are without overflow and thus the sediment input is reduced.

The dredging and dumping cycle is graphically depicted in Figure 5.12.

The co-ordinates of the dredging and dump locations are:

Duncannon Bar:	x = 272586	y = 104004
Upper/Lower Bar:	x = 267142	y = 113757
Disposal Site:	x = 270300	y = 97098

Dr./dump	Act. no.	Activity	Start time	Duration	Load DB	Load LB	Load DS
Cycle			[m-d-yy h:min]	[h:min]	gram/s	gram/s	gram/s
1	1	Dredging DB-filling	1-6-99 5:00	0:10	2500	0	0
1	2	Dredging DB-overflow	1-6-99 5:10	1:15	37000	0	0
1	3	Sailing DB-DS	1-6-99 6:25	00:25	0	0	0
1	4	Dumping DS	1-6-99 6:50	00:10	0	0	12000
1	5	Sailing DS-DB	1-6-99 7:00	00:25	0	0	0
1	6	Dredging DB-filling	1-6-99 7:25	0:10	2500	0	0
1	7	Dredging DB-overflow	1-6-99 7:35	1:15	37000	0	0
1	8	Sailing DB-DS	1-6-99 8:50	00:25	0	0	0
1	9	Dumping DS	1-6-99 9:15	00:10	0	0	12000
1	10	Sailing DS-LB	1-6-99 9:25	01:05	0	0	0
1	11	Dredging LB-filling	1-6-99 10:30	00:10	0	2500	0
1	12	Dredging LB-overflow	1-6-99 10:40	01:00	0	37000	0
1	13	Sailing LB-DS	1-6-99 11:40	01:05	0	0	0
1	14	Dumping DS	1-6-99 12:45	00:10	0	0	12000
1	15	Sailing DS-DB	1-6-99 12:55	00:25	0	0	0
2	1	Dredging DB-filling	1-6-99 13:20	0:10	2500	0	0
2	2	Dredging DB-overflow	1-6-99 13:30	1:15	37000	0	0
2	3	Sailing DB-DS	1-6-99 14:45	00:25	0	0	0
2	4	Dumping DS	1-6-99 15:10	00:10	0	0	12000
2	5	Sailing DS-DB	1-6-99 15:20	00:25	0	0	0
2	6	Dredging DB-filling	1-6-99 15:45	0:10	2500	0	0
2	7	Dredging DB-overflow	1-6-99 15:55	1:15	37000	0	0
2	8	Sailing DB-DS	1-6-99 17:10	00:25	0	0	0
2	9	Dumping DS	1-6-99 17:35	00:10	0	0	12000
2	10	Sailing DS-LB	1-6-99 17:45	01:05	0	0	0
2	11	Dredging LB-filling	1-6-99 18:50	00:10	0	2500	0
2	12	Dredging LB-overflow	1-6-99 19:00	01:00	0	37000	0
2	13	Sailing LB-DS	1-6-99 20:00	01:05	0	0	0
2	14	Dumping DS	1-6-99 21:05	00:10	0	0	12000
2	15	Sailing DS-DB	1-6-99 21:15	00:25	0	0	0
3	1	Dredging DB-filling	1-6-99 21:40	0:10	2500	0	0
3	2	Dredging DB-overflow	1-6-99 21:50	1:15	37000	0	0
3	3	Sailing DB-DS	1-6-99 23:05	00:25	0	0	0
3	4	Dumping DS	1-6-99 23:30	00:10	0	0	12000
3	5	Sailing DS-DB	1-6-99 23:40	00:25	0	0	0
3	6	Dredging DB-filling	1-7-99 0:05	0:10	2500	0	0
3	7	Dredging DB-overflow	1-7-99 0:15	1:15	37000	0	0
3	8	Sailing DB-DS	1-7-99 1:30	00:25	0	0	0
3	9	Dumping DS	1-7-99 1:55	00:10	0	0	12000
3	10	Sailing DS-LB	1-7-99 2:05	01:05	0	0	0
3	11	Dredging LB-filling	1-7-99 3:10	00:10	0	2500	0
3	12	Dredging LB-overflow	1-7-99 3:20	01:00	0	37000	0
3	13	Sailing LB-DS	1-7-99 4:20	01:05	0	0	0
3	14	Dumping DS	1-7-99 5:25	00:10	0	0	12000
3	15	Sailing DS-DB	1-7-99 5:35	00:25	0	0	0
4	1	Dredging DB-filling	1-7-99 6:00	0:10	2500	0	0

Start of cycle time: 1-6-99 5:00
DB: Duncannon Bar
LB: Lower Bar
DS: Disposal Site

Table 5.6 Dredging and dumping cycle and loads

5.6.3 Results of computations

The results of the computations with the different scenarios are presented as follows:

- Time histories of silt concentration at 16 monitoring stations, the two dredging locations and the disposal site.
- Contour plots of silt concentration distributions in the estuary and at sea at various time intervals.

For the simulations with a mud bed the *differences* in silt concentrations in the water between the case with silt discharges due to dredging and the reference situation without silt discharges are presented (for locations see Fig. 6.1 in Section 6.1).

Spring tide-fixed bed-no waves (Figs. 5.13-5.30)

The additional depth-averaged sediment concentration generated during dumping at the location of the Disposal Site is less than 6 mg/l due to the large water depth. At the dredging locations the additional concentrations generated during dredging are much higher: up to 120 mg/l at Cheekpoint Lower Bar and 90 mg/l at Duncannon Bar. Results of the computations for this scenario indicate that the rise in suspended sediment concentrations in the monitoring stations in the model due to dredging and dumping rapidly reduces to less than 20 mg/l and is even not noticeable at a larger distance of the additional silt sources.

Contour plots for this situation are presented in Figures 5.18 - 5.30 at intervals of 1 hour for a complete tidal cycle showing the spreading of the suspended sediment. No effects are observed south of Dunmore East.

Neap tide-fixed bed-no waves (Figs. 5.31-5.36)

During neap tide the suspended sediment concentrations due to dredging and dumping in the monitoring stations are comparable with or less than those during spring tide. For comparison the contour plot of 1999-01-06 at 22:00 hour is shown on Figure 5.36.

Spring tide-mud bed-no waves (Figs. 5.37-5.44)

The computational results in the monitoring stations indicate that the effect of dredging and dumping with the mud bed is less than for the same case with a fixed bed. In the former case the discharged silt becomes part of the existing bed after deposition and during erosion there is no difference between the reference situation and the situation with dredging and dumping. In both cases the increase of suspended sediment concentrations due to dredging in the monitoring stations is 20 mg/l or less. The contour plots at three time intervals show that the dredging and dumping activities result in a more local effect if a mud bed is present.

Neap tide-mud bed-no waves (Figs. 5.45-5.49)

During neap tide the effect of dredging and dumping is very local and almost negligible in most of the estuary. Largest differences (up to 20 mg/l) occur in the upstream part of the estuary near the confluence of the River Suir and the River Barrow.

Spring tide-mud bed-with waves (Figs. 5.50-5.57)

In case waves are present differences in sediment concentration due to dredging slightly increase in the monitoring points along the banks in the outer estuary. Sediment is kept in suspension in areas with high waves and is transported to locations with low wave heights. However, the increase in suspended sediment concentrations due to dredging in these monitoring stations still is well below 20 mg/l. In the monitoring stations in the upper part of the estuary the results for the cases with and without waves are the same.

Neap tide-mud bed-with waves (Figs.5.58-5.62)

For neap tide conditions with waves the increase in suspended sediment concentration due to dredging activities is comparable with or less than for sping tide conditions.

5.7 Conclusions

1. The effect of dredging and disposal of sediment results in an increase of the suspended sediment concentration of approximately 100 mg/l in the vicinity (i.e. one grid cell) of the dredging location and less than 10 mg/l near the disposal site.
2. At the locations of the monitoring stations near areas of ecological importance the increase of suspended sediment concentration is 20 mg/l or less.
3. The results of the simulations are not very much affected by the assumption whether a fixed bed or a mud bed is present at the start of the simulations.
4. Differences in suspended sediment concentrations due to dredging and dumping are slightly higher during spring tide conditions.
5. The effect of dredging and dumping is not sensitive to waves; similar results were found under conditions without and with waves of moderate height. It is assumed that dredging will be stopped during rough sea conditions.

6 Ecological impact of dredging and dumping

6.1 Description of the Environment

The Duncannon and Cheekpoint Bars are located in the River Suir, in the Southeast of Ireland, at approximately 52°12'N, 6°56'W.

Activities

The River Suir contains a number of environmental and economically important activities that can potentially be affected by the dredging and dumping operation. The type and locations of these activities are summarised below:

- Herring spawning grounds at locations 1a and 1b at open sea.
- Lobster release areas at locations 5a and 5b near the coasts of Falskirt Rock and Hook Head at open sea.
- Oyster production area at location 9 along Woodstown Strand just inside the estuary behind Creadan Head.
- Mussel beds along the estuary from Passage East up to Snowhill Point (locations 10, 11, 17, 19).
- Fish weirs (white fish, cuttle, salmon and eel) at various locations along the lower estuary (locations 12, 13, 15, 16, 18, 20, 21).

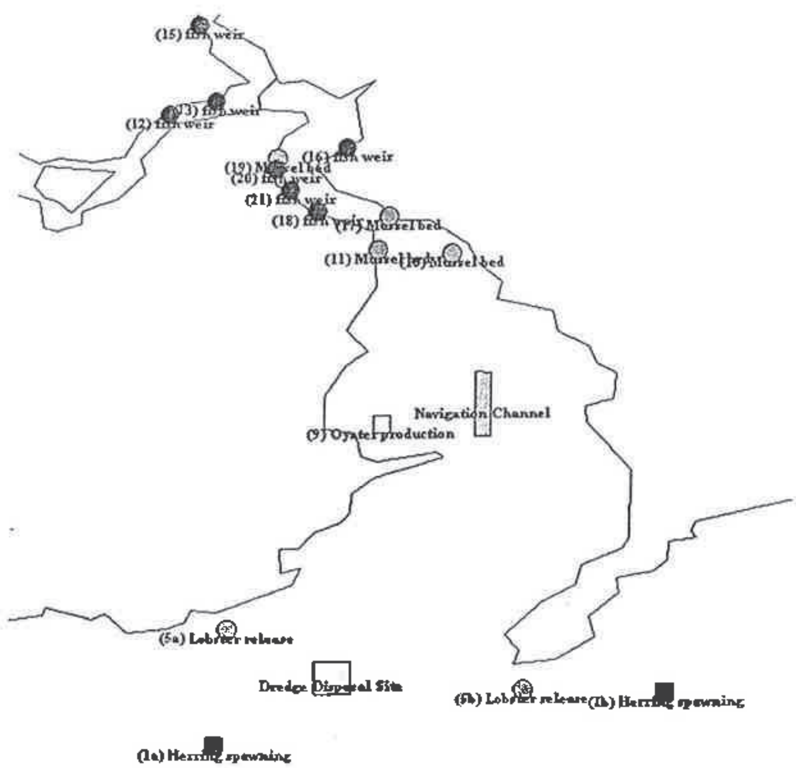


Figure 6.1. Activities in the Suir estuary

Suspended Sediment

Estuaries are naturally turbid systems. Due to the river discharge of suspended particulate matter (SPM) and the salinity gradient, high SPM concentrations do occur.

Commissioned by the Waterford Port Company, Hydrographic Surveys Limited carried out a study of selected environmental parameters, including suspended sediment concentrations. Suspended sediment was measured at two locations, Dredge Disposal Site and Duncannon Bar, during spring as well as neap tides. Suspended sediment concentrations were measured at three depths, at the surface, at the middle and at the bottom of the overlying water column.

At the Disposal Site turbidity, measured as suspended solids, was low. Surface, middle and bottom depth concentrations were approximately 5 mg/l at neap tide. A peak in concentration at the surface (19 and 14 mg/l), found slightly after high water in the neap tide situation, was not reflected at the deeper measurements. The spring tide situation shows some higher concentrations (9, 14 and 19 mg/l) at the middle and bottom depths compared to the neap tide situation.

At Duncannon Bar turbidity was also low at neap tide. Surface, middle and bottom depth concentrations were ranging between 5 and 9 mg/l, with a maximum of 14 mg/l around low water in the evening of 22 June 1999. At spring tide, concentrations of over 100 mg/l were measured near the bottom and in the middle of the water column. A maximum concentration of 28 mg/l was found at the water surface. Notable is that a passing ship visibly was disturbing sediment, resulting in a significant increase in suspended sediment concentrations. Figure 6.2 presents the results of the measurements of suspended solids at Duncannon Bar in a spring tide situation.

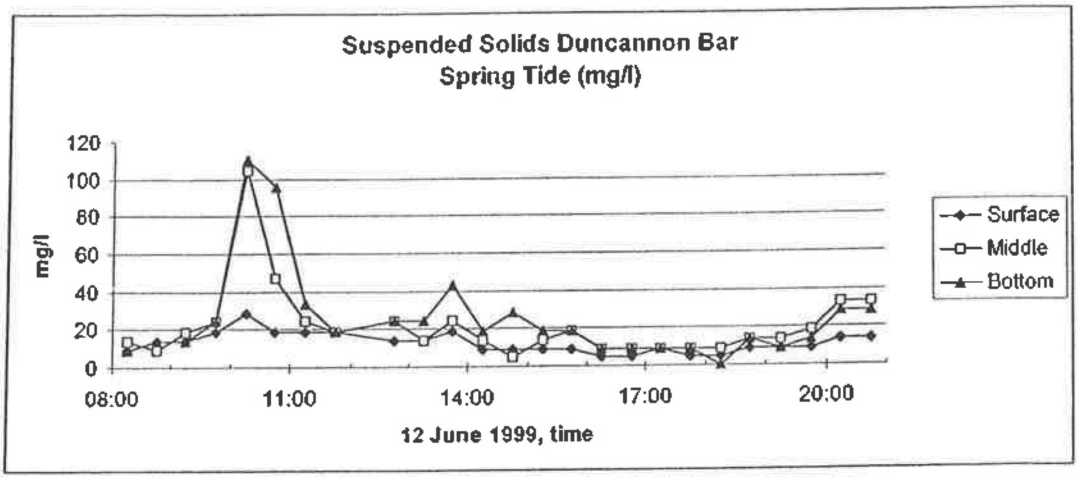


Figure 6.2. Suspended solids concentration at Duncannon Bar in a spring tide situation

In summary, suspended particulate matter concentrations at the Disposal Site are low (5 mg/l). At Duncannon Bar a turbidity maximum occurs, SPM concentrations can reach high levels (>100 mg/l). Highly turbid water may also occur due to ships.

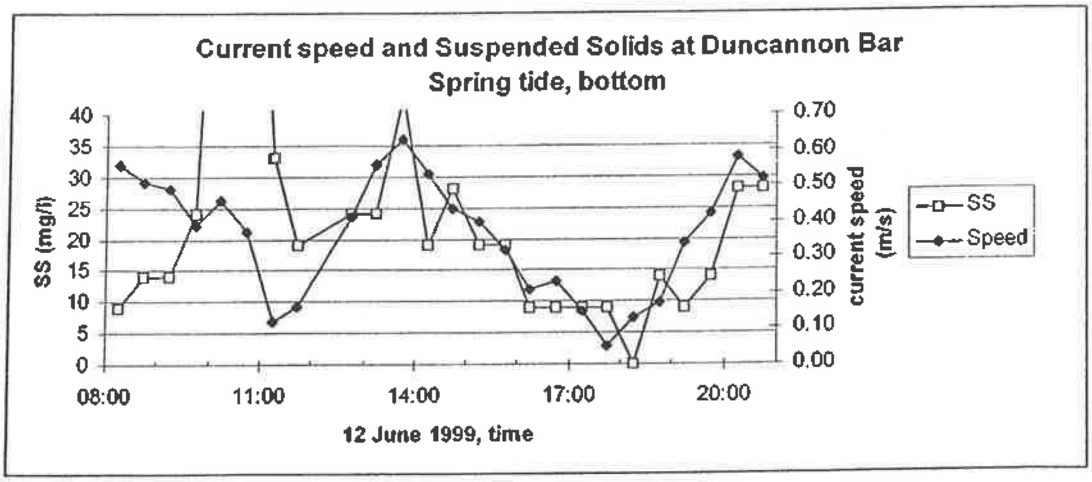


Figure 6.3. Current speed and Suspended Solids concentration at Duncannon Bar at spring tide near the bottom

Figure 6.3 shows the relationship between the current velocity and the suspended solids concentration near the bottom. The gradual decrease and subsequent increase in current velocity around low water correlates very well with the suspended solids concentration near the bottom. Note that the high SS concentrations just before 11:00 and 14:00 h are outliers, caused by the passing of a ship. The correlation between current velocity and suspended solids around high water is not very good.

Bottom Sediment

Commissioned by the Waterford Port Company, Hydrographic Surveys Limited carried out a study of selected environmental parameters, including bottom sediment composition. The bottom sediment was sampled at the Disposal Site, Duncannon Bar, Woodstown Strand, Carters Patch and two offshore sites.

Sediment samples always show a large variance, due to the heterogeneity of sediments. Special emphasis in this analysis is put on the sediment silt content.

The Disposal Site is characterised by a fine brown silty sand, sometimes mixed with (broken) shell and small gravel. The weight percentage of fine silt particles is low, ranging between 0.28% and 13.10%, with a mean of 3.0% silt particles (< 63 µm).

The northern samples of Duncannon Bar are characterised by a fine grey-brown sandy mud with pockets of dark grey organic material. The percentage of fine silt particles is definitely high, ranging between 18.5% and 49.0%, with a mean of 32.2% silt (< 63 µm). The southern samples of Duncannon Bar are characterised by a fine brown silty sand. The percentage of silt is low, ranging between 2.1% and 5.8%, with a mean of 3.7% silt (< 63 µm).

Woodstown Strand is characterised by a fine to medium brown silty sand with a thin layer of silt. The percentage of silt ranges between 0.9% and 18.1% with a mean of 5.8% (< 63 µm).

Carters Patch is characterised by a fine grey-brown sandy mud and fine brown sand. The percentage of silt ranges between 1.4% and 26.4% with a mean of 10.9% silt (<62µm).

The offshore areas are characterised by rock. One grab sample also contained some finer material.

In summary, the Suir estuary shows a wide diversity of grain sizes, ranging from large rocks, gravel and pebbles, primarily in the offshore zone, via silty sand and sandy mud in less exposed areas, to high silt percentages in the sedimentation area of Duncannon Bar.

6.2 Potential Ecosystem Impacts of Dredging and Dumping

6.2.1 Introduction

Generally speaking, short-term, small-scale dredging and dredge spoil disposal projects have less ecological impacts than long-term, large-scale projects (Allen & Hardy, 1980). The most direct, physical effects of the dredging and dumping activities are an increase in the Suspended Particulate Matter (SPM) concentration and a covering of the bottom sediment with disposed material. The increase in SPM can directly and indirectly affect several ecological processes in the water column and in the sediment.

SPM can be classified according to the grain sizes. The larger and heavy fractions will settle easily, while the finer fractions will resuspend and stay in suspension longer. The effects of an increased SPM concentration differ between fractions. The fine fraction of silt and their silt-related processes are very important to the ecological functioning of estuaries. Any change in silt concentrations and silt characteristics may have a potential impact on the ecosystem. In this chapter the ecological functions of silt are briefly addressed, and subsequently, potential ecosystem impacts of the dredging and dumping activities are discussed.

A brief overview of potential effects of suspended material is given in Section 6.2.3. The suspended material may also settle to the bottom. A direct effect may be the burial of benthic species. This is described in Section 6.2.4. Another direct effect is the 'Removal of Benthic Species' at the dredge site (Section 6.2.5). Finally, an indirect effect of the sedimentation of the material may be a change of the sediment composition. This is described in Section 6.2.6.

6.2.2 Ecological Functions of Silt

Silt often is mentioned as an important substance in estuaries. It is clear that silt plays a significant role in chemical, physical and biological processes. Notable aspects of silt related processes are the formation of salt marshes and sedimentation on tidal flats.

To understand the potential ecological effects of the dredging and dumping, this section will provide a synopsis of the ecological functions of silt.

Definitions

In this study *silt* is defined as follows:

- Silt: *that fraction of the sediment that is smaller than 63µm, with or without adsorbed organic (C, P, N) or inorganic material and that is in a floating or (not-consolidated) sedimented condition.* Silt is in a dynamic state: dependent of time, place and physical-chemical-biological surroundings, the quantity of adsorbed organic or inorganic material, shape and size of the resulting complex and the position in the water column, bottom or organism will vary.

Partly overlapping definitions that are often used besides or instead of silt are:

- Particular detritus: All not-living particular organic material, such as pseudofaeces, feacal products, excretion products, dead algae, dead bacteria and other dead organisms.
- Seston: the particulate material that consists of inorganic sediment smaller than 63µm, particulate detritus and living cells of algae and bacteria
- Macroflocs or marine snow: fragile flocs of sediment, organic material, algae and bacteria sizing in between several hundreds µm's to more than a mm.

- Fluid mud: a suspension of silt with a concentration of more than 10 grams per litre. It has a non-Newtonian behaviour and can be transported under certain circumstances with a current velocity of more than a few metres per minute.
- Highly Concentrated Benthic Suspension (HCBS): a suspension of silt with a concentration of several to 10 grams per litre and with a Newtonian behaviour that can be transported with a velocity that is similar to that of non-disturbed water.

Ecological Functions

Silt affects ecological functions, i.e. processes and interactions within and between abiotic and biotic components of the ecosystem that yield a certain product or service. An ecological product is a measurable quantity such as the biomass of mussels or the surface area of salt marshes. An ecological service is a measurable quality such as the buffer against coastal erosion or possibilities for recreation.

Silt affects ecological functions by influencing:

1. Morphology
2. Habitats and substrate
3. Food
4. Water quality

Morphology

Morphological processes that are affected by silt are: floating, transportation, flocculation, sedimentation, consolidation and erosion; the presence and transport as diluted fluid mud and HCBS; the blowing of silt to coastal dunes; the accumulation of silt on flats; the capture, fixation and release - bio(de)stabilisation - by biota such as filterfeeders (Mussels, Cockles, *Ensis, Spisula*), seagrass beds, salt marsh vegetation, cyanobacterial mats and diatom mats.

Habitats and Substrate

Processes related to silt that affect the substrate and habitats for biota are: the presence of gradients in sediment composition that is favourable to certain benthic species; the presence of flocs as substrate for bacteria.

Food

Processes that are affected in relation to food are: the physical-chemical adsorption of organic material and inorganic nutrients; the exchange of adsorbed organic material with dissolved organic material; the sticking of living cells of algae and bacteria; the consumption by detritus eaters, the filtering by suspension feeders, the bacterial decay and subsequent promotion of mineralisation in sediment and water column and the release of nutrients for primary production.

Water Quality

Processes related to the quality of the water are: the extinction of light in the water column, the influence on water purification by suspension feeders, the accelerated sedimentation of dying phytoplankton blooms by sticking and flocculation.

6.2.3 Potential Impacts of Increased SPM Concentration

An increased Suspended Particulate Matter (SPM) concentration is especially harmful to ecological processes in the water column, but it may, directly or indirectly, also affect ecological processes that take place in the intertidal areas.

Primary production (PP) is defined by the growth of phytoplankton and phytobenthos. The primary production of phytoplankton in an estuary is relatively low because of the natural turbidity. Additional turbidity may lead to a decrease in primary production by phytoplankton. When the primary production decreases, less food is available to primary consumers, such as zooplankton and zoobenthos.

The primary production by phytobenthos is less sensitive to turbidity, because these species live on intertidal flats. A burial by sediment, however, may affect the PP of phytobenthos.

Larvae and eggs of fish and shrimp, that are most abundant in shallow areas, are sensitive to increased suspended particulate matter concentrations, more sensitive than adults. An increased SPM may affect the respiration of larvae and the gas-exchange of eggs. SPM concentrations over 100 mg/l may lead to an increased mortality. An increased SPM concentration may also hinder the functioning of the gills of fish. In general pelagic species are more sensitive than bottom fish.

Herring spawning areas are sensitive to increased suspended matter concentrations. Herring preferably spawns on gravel and pebbles, but also on shell and seaweed. The eggs settle to the bottom and stick to these structures. A relative high current velocity (> 1m/s) prevents siltation and supplies oxygen.

Birds and fish that hunt by using their eye-sight can also be sensitive for an increase in turbidity.

As a result of the increased suspended solids concentrations, the food uptake by filter feeders can be negatively affected in two ways. First, the high concentrations of particles can clog the food uptake system and second the food quality (organic to inorganic ratio) may decrease. The extra energy it takes to filter the suspended particulate matter (SPM) out of the water can result in a decrease in the growth rate. The increased turbidity may also lead to a decreased concentration of phytoplankton, what in combination with a hindered food uptake can increase the effect on filter feeders.

The decreased food uptake may lead to a reduced growth of filter feeders. The filtering speed of filter feeders shows an optimum curve with SPM concentrations. Research to the filtering capacity of the Blue Mussel (*Mytilus edulis*) has shown that an average Mussel of 3 centimetres of length will cease filtering at a suspended solids concentration of 250 mg/l. When the SPM concentration is 225 mg/l, the filtering capacity has decreased to about 30% of the maximum filtering speed which is reached at a concentration of 125 mg/l (Widdows et al., 1979).

6.2.4 Potential Impacts of Burial of Benthic Organisms

An increased sedimentation near the dumping site can lead to burial of benthic species by a layer of (mostly anaerobic) sediment. The sensitivity of benthos for burial is dependent on the ability to grow or move upwards.

The potential effects of burial can be subdivided into effects of an incidental, but large, deposition and effects of a continuous, but small, deposition.

Incidental deposition

The potential impact of dredged material disposal on organisms living on or near the bottom can have strong negative impacts if the settling occurs in an area containing sensitive organisms. Areas of concern include coral reefs, seagrass beds, and fish spawning areas. Non-mobile species, such as the Blue Mussel (*Mytilus edulis*), anemones and oysters are also very sensitive to an incidental deposition, resulting in burial of the organism. Other species are more capable of surviving an incidental deposition, either by moving or growing upwards to the sediment surface.

For benthic organisms a 'fatal depth' can be defined, which denotes at what depth of incidental burial the organism will not survive. This fatal depth is species dependent, but also differs with the type of sediment. Essink (1993) provides a literature overview of fatal depths for different organisms and two sediment types, silt and fine sand. In general benthic species are more sensitive to burial by silt than by sand. Furthermore, species of a sandy bottom are more sensitive to burial by silt than species of a silty bottom. Larger species are generally more capable of moving upwards than smaller species. However, the adult *Mya arenaria* is exceptionally large and is not able to move at all.

The fatal depth for incidental deposition of silt for a number of benthic species, selected from Essink (1993), is presented in Table 6.1.

Table 6.1. Fatal depth (cm) for incidental deposition with silt (Essink, 1993 to: Bijkerk, 1988).

Scientific name	Name	Fatal depth (cm)
Mytilus edulis	Blue Mussel	1
Petricola pholadiformis		3
Mya arenaria	Sandgaper	7
Cerastoderma edulis	Cockle	11
Hydrobia ulvae	Mudsnail	18
Macoma balthica	Balthic Tellin	38
Ensis ensis		43
Nephtys hombergii		60

Besides the physical effect of burial, chemical effects of the anaerobic sediment, often together with high sulphide concentrations, play a role. A decreased dissolved oxygen level can amplify the effects of an increased sedimentation. The cleaning of the siphons at an increased sedimentation flux will cost more energy, while at the same time the oxygen levels are lower. The tolerance levels for low oxygen levels and high sulphide levels differ between species. A species such as the Brown Shrimp is a lot more sensitive to anaerobic conditions than species that are used to similar situations.

The exposure time to anaerobic conditions (< 0.2 mg O_2/l) and for high sulphide concentrations (7 mg/l) at a 50% mortality level is presented in Table 6.2.

Table 6.2 Exposure time to anaerobic and sulphide rich conditions at 50% mortality (Essink, 1993; Theede, 1973).

Scientific name	Name	Exposure time oxygen (hours)	Exposure time sulphide (hours)
Mytilus edulis	Blue Mussel	800	600
Scrobicularia plana		600	500
Mya arenaria	Sandgaper	500	400
Nereis diversicolor	Ragworm	150	100
Cerastoderma edule	Cockle	100	100
Asterias rubens	Common Starfish	90	70
Carcinus maenas	Beach Crab	40	30
Amphiura filiformis	a Brittle Star	25	30
Crangon crangon	Brown Shrimp	2	2

Effects of burial on soft bottom benthic species are temporary. Dependent on the original community structure, recovery may take a couple of years to a decade. Opportunistic species will quickly recolonise the affected site, but long-living bivalve species or some sea urchins do not reproduce each year. In general, soft bottom benthic communities show partial recovery in one year and full recovery in 18 to 24 months. In some cases it will take many years to recover the original species diversity (Allen & Hardy, 1980).

Continuous deposition

A continuous deposition of material to the bottom can have negative effects when the sedimentation rate is higher than the velocity at which the organisms can move or grow upwards. The sensitivity to a long-term continuous deposition again is species dependent and also dependent on the type of sediment. A continuous deposition of silt is in general worse than a deposition of sand. Table 6.3 presents the maximum tolerance for different benthic species for a continuous deposition of silt and fine sand in cm/month.

Table 6.3. Maximum tolerance for continuous deposition of silt and fine sand in cm/month (Essink, 1993; Bijkerk, 1988).

Scientific name	Name	Deposition of silt (cm/month)	Deposition of fine sand (cm/month)
Mya arenaria	Sandgaper	2	5
Cerastoderma edule	Cockle		17
Macoma balthica	Baltic Tellin	15	>17
Arenicola marina	Lugworm	11	>17
Nephtys hombergii		>35	>17
Carcinus maenas	Crab	31	

6.2.5 Potential Impacts of Removal of Benthic Organisms

At the location of the dredging activities, about 75% of the benthic species are removed from the site. Recolonisation of a new channel is often rapid and original biomass is sometimes reached in 2 weeks to 4 months. However, recolonisation is usually by opportunistic species, original species diversity is seldom achieved within the same period (Allen & Hardy, 1980).

A thorough analysis on the effects of dredging in the Lower Columbia River, Washington did not reveal any significant effect on the standing crops of benthic invertebrates. Apparently, benthic invertebrates in the dredged area were able to recolonise quite rapidly after dredging (McCabe et al., 1998).

6.2.6 Potential Impacts of Siltation on Tidal Flats

The substrate composition is important for the benthic communities on intertidal areas. Substrate composition is measured as silt content, median grainsize and organic matter content. The composition is influenced by hydrodynamics and the presence of benthos on the flat which can influence the stabilisation, bioturbation and erodability of the substrate.

As a result of the dredging and dumping a certain amount of suspended material may eventually accumulate on the tidal flats of the estuary. This can result in an increased bottom silt content (siltation). In general, highest densities of benthic species are found in net sedimentation areas, where the deposition of organic material and nutrient concentrations are relatively high. An increase in bottom silt content does not directly have to result in higher densities of benthic species. This is dependent on the suitability of high silt contents for different species. The siltation could result in a change of habitat distribution. Very high bottom silt contents can lead to a decreased suitability for specific species.

6.3 Estimated Impacts of Dredging and Dumping

6.3.1 Estimated Impacts of Increased SPM Concentration

Lobster Release and Herring Spawning Areas

The dumping of dredged material at the Disposal Site will result in a local increase of the Suspended Particulate Matter (SPM) concentration. The increase, however, is very limited in magnitude and size. The fine silt particles will mix and settle relatively fast in the deep water. The additional concentration peak in a radius of 50m from the disposal site is estimated to be 20 to 40 mg/l.

The increased suspended sediment concentrations will hardly reach the locations of the lobster releases or the herring spawning areas. In the model runs a maximum additional SPM concentration of 0.5 mg/l was found at the lobster release areas and 0.25 mg/l at the herring spawning sites. These additional concentrations will not affect the functioning of the lobster release areas or the herring spawning grounds.

Spawning takes place in November-December. A mitigating measure therefore is not to dump the sediment during these months, but considering the low additional SPM concentrations, this is not necessary.

Oyster Production Area and Mussel Beds

The dredging operation of Duncannon Bar will result in an increase of Suspended Particulate Matter concentration (SPM). The increase in SPM concentration has a local and temporary peak of 250 to 300 mg/l at a distance of 50 m around a dredging suction hopper.dredge The plume of suspended matter will be transported with the tidal flow in the Suir estuary. During slack water at the turn of the tide, most of the fine particles will settle to the bottom. Natural SPM concentrations that occur at the Duncannon Bar location, near the oyster production area and mussel beds, reach some tens to 100 mg/l.

The additional effect on the nearby activities, the oyster production area and the mussel beds, is limited. An additional peak increase of 10 mg/l was computed by the water quality model at location (11) (see Fig. 6.1) mussel bed. The other mussel beds, locations (10), (17) and (19), show an additional SPM concentration of 6 mg/l. The oyster production area (9) shows an additional increase of only 3 mg/l.

Concluding, the additional effect of the dredging on turbidity is negligible. Effects of the dredging operation on the oyster grounds and mussel beds in the Suir estuary are also negligible.

Fish Weirs

As a result of the dredging operation at the Cheekpoint Lower Bar, near the fish weirs, a local and temporary increase of suspended particulate matter concentration of 250 to 300 mg/l can occur at a distance of 50 m around a suction hopper dredge. The natural turbidity in the Cheekpoint area is relatively high. Measurements taken in monitoring stations nearby show suspended matter concentrations of over 200 mg/l.

The additional increase in SPM at the locations of the fish weirs is computed with the water quality model. The fish weirs closest to the Cheekpoint lower bar show a temporary increase of 20 mg/l for fish weirs (12) and (13) (see Fig. 6.1). These are typical peak events that take place over a two hour period. All other fish weirs have a peak of maximum 5 mg/l in the worst case situation.

The additional turbidity at the fish weirs is limited to peak events and negligible relative to natural background concentrations. The impact on the functioning of the fish weirs is negligible.

6.3.2 Estimated Impacts of Burial of Benthic Organisms

As discussed in the previous section, the potential effects of burial can be subdivided into effects of an incidental deposition and effects of a continuous deposition.

Incidental Deposition

At the Disposal Site a large amount of dredged material will be dumped. It is to be expected that all benthic species that are present at this site will be covered by a thick layer of sediment and will be buried. Considering the type of sediment (primarily silty sand) and the depth of this location (20m), bivalves species, polychaetes (worms) and brittle stars may be found at this location. Of the species mentioned in the previous section, these may include the Sandgaper (*Mya arenaria*).

The sensitive herring spawning grounds will not be affected by an additional sedimentation due to the disposal of dredged material.

After the dumping, the disposal site will be quickly recolonised by benthic species. At first, opportunistic species such as worms and crabs will search for the dead remains of the original inhabitants, and after a while larvae of bivalve species can settle. After one year, the original biomass may be recovered, but the original species diversity may not be found for a period of a couple of years.

Short-term dissolved oxygen depletion due to the dumping are seldom a problem. At the dump site, reduced oxygen levels are usually found near the bottom at the point of dumping, but are of a short duration. Adverse impacts are most likely to occur in poorly-mixed waters receiving highly organic dredged material, but that is not the case here.

Continuous Deposition

The computations for the continuous resuspension and subsequent sedimentation of disposed sand at the Disposal Site show a very limited area in which sedimentation of sand takes place. Roughly twice the surface area of the Disposal Site shows an additional sedimentation of sand. The net sedimentation rate has a maximum of about 1 cm/month. This rate is sufficiently low for soft bottom benthic species to survive. The additional sedimentation does not reach the locations of the lobster releases and the herring spawning grounds.

6.3.3 Estimated Impacts of Removal of Benthic Organisms

At the Duncannon Bar and Cheekpoint Lower Bar it is to be expected that about 75% of the benthic species are removed. Recolonisation is often rapid and the original biomass is sometimes reached within 2 weeks to 4 months. However, recolonisation usually occurs by opportunistic species. Considering the soft sediments and the natural dynamics of the Suir estuary, it is not expected that there are any very old organisms. The original situation in the dredged channels may be recovered in three years after settling of new bivalve larvae, if maintenance dredging is suspended.

6.3.4 Estimated Impacts of Siltation on Tidal Flats

The increase in concentration of fine matter is very limited compared to the natural background concentrations. A noticeable additional siltation of net sedimentation areas on tidal flats due to dredging is not anticipated.

6.4 Proposed monitoring plan for Suir River and Estuary

6.4.1 The Monitoring Cycle

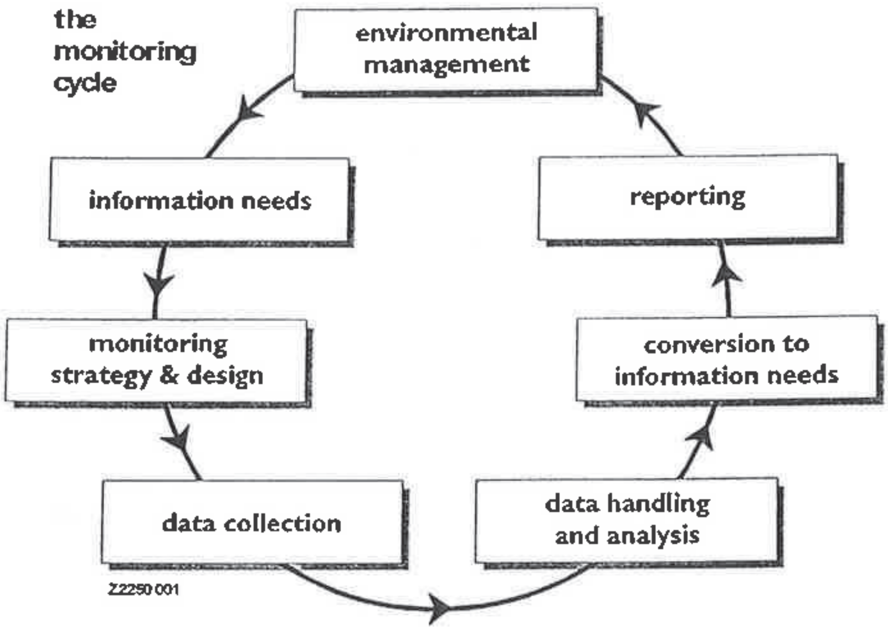


Figure 6.4 The monitoring cycle (after UN/ECE, 1996)

Environmental monitoring can be considered as a series of successive steps which are related to each other in a cyclical fashion. The cycle starts with the identification of priorities in environmental management and definition of information needs, and ends with an information product which can be used by relevant environmental policy makers. A series of 7 steps can be defined which encompass all aspects of environmental monitoring:

1. Environmental Management
2. Information needs
3. Monitoring strategy and design
4. Data Collection
5. Data handling and analysis
6. Conversion of data to information needs
7. Reporting and information dissemination

1. Environmental Management: Identification of Issues

The need for information should be based on the core elements in environmental management, including identified priority issues.

2. Information needs

The most critical and difficult step in developing a successful monitoring programme is the clear definition and specification of information needs and monitoring objectives. Information needs are often based on priority issues, environmental pressures, and consideration of possible management measures. Information needs for monitoring are not stationary, but can and will evolve over time due to developments in environmental management, attaining of targets or changing policies.

3. Monitoring strategy and design

After the specification of information needs, a monitoring strategy and design is required to ensure that the monitoring programme operates to produce the desired information. The strategy and design must 'translate' the information needs into an operational monitoring programme. Design includes the details regarding the selection of variables, selection of sites and sampling frequency and methods.

4. Data collection

Data is collected based on the monitoring strategy and the details specified in the monitoring design.

5 Data handling and analysis

The data collected should be validated and archived in a way that they are accessible for current and future use.

6. Conversion of data to needed information

It is the actual goal of the monitoring programme to convert the collected data into information that will meet the specified information needs. This conversion involves integrated data analysis and interpretation. Applications such as Geographic Information Systems (GIS) and other computer programmes are often efficient ways of producing desired information.

7. Reporting and information dissemination

The reporting of information is the final step in the cycle and links the gathering of information with the information users. To distribute information, reports should be prepared and distributed on regular basis, with a level of detail depending on the use of the information. The evaluation of the obtained information may lead to new or redefined information needs, thus starting a new sequence (cycle) of activities. In this way the monitoring process will be improved.

6.4.2 Information needs

The dredging and dumping of sand that contains silt (<63μm) and clay (<2μm) can potentially cause an additional turbidity in the water column and subsequently an additional sedimentation.

It should be noted that an estuary is by itself a relatively turbid environment. Suspended material from the river is transported to the sea. In the estuary where the salinity increases, a turbidity maximum will occur, partly caused by flocculation. The goal of the monitoring therefore will be to assess the distribution and sedimentation of silt / mud in relation to the natural seasonal dynamics. The question to be answered is whether or not the dredging and dumping will cause a significant additional turbidity and sedimentation.

6.4.3 Monitoring Strategy and Design

The aim of this monitoring plan is to gain maximum insight into the natural functioning of the estuarine system with a minimum of effort and costs.

Most important is to quantify the suspended matter (SPM) concentrations in the river for natural conditions. The SPM concentrations will show a gradient along the axis of the river caused by gradients in salinity and current velocities. This gradient will also show a temporal distribution caused by tidal movements and may show seasonal changes caused by changes in river run-off. Furthermore, the effect of storms and heavy rainfall on turbidity cannot be discarded.

Remote sensing images from the SPOT satellite provide an insight into the seasonal dynamics of the Suir River turbidity. Apparently, in autumn and winter, the plume of suspended matter reaches out further into the sea than in summer. Overall, the shape of the turbid plume is remarkably constant over the year. These pictures can also be used to quantify the concentration of SPM, but that requires excellent pictures, constant atmospheric conditions and constant image operations.

Turbidity Measurements

To get an understanding of the turbidity under natural conditions, turbidity measurements can be carried out over a 12-15 kilometres transect through the river. It is recommended to measure the salinity and turbidity profiles along the river from Belview Quay to Dunmore East during neap and spring tide. Preferably, this should be done around HW and around LW to show the effect of the tidal excursion on the position of the salt wedge and turbidity maximum. The profiles can be determined by measuring e.g. every kilometre just below the water surface, at mid-depth and say 1 m above the bottom. The measuring intervals can be optimised later on when more information is available.

The monitoring programme should consist of a regular site investigations campaign covering a neap and a spring tide in the dry/calm season with low river flow and one in the wet/rough season with high river flow. This could be complemented by one or two incidental site investigations per year after a (severe) storm.

With respect to the dredging operation, measurements are recommended:

1. Prior to dredging, preferably within one week before dredging;
2. and after dredging, preferably not within a week after the dredging has stopped.

Turbidity can be measured with a turbidity meter. An alternative and simple method to measure the suspended matter concentration is to collect a large amount of water in a jerry can (25 litres). Leave the sediment to settle for at least 24 hours and siphon off most of the water. Than filter the sediment (a filter that is used to make coffee is a good choice), and rinse out the sediment with fresh water. After weighing, the SPM concentration in the sample is known. This method is not very useful when sediment concentrations are low, such as at the open sea.

Another possible technique is to make aerial photographs of the turbidity and take a couple of measurements of SPM concentration simultaneously. These measurements can than be used to calibrate the photographs with respect to the spatial distribution of SPM. This is not a simple and straightforward technique, but requires sophisticated modelling.

Note: In aid of the calibration of the computational modelling, several measurements of SPM concentrations over depth will be carried out on the dredging and dumping locations.

Sediment Composition

The increased SPM concentrations and subsequent settling of fine silt particles can potentially result in an increase of silt content on the intertidal flats near the oyster grounds or near the fish weirs. It is recommended to measure the sediment composition with regard to the sand/silt ratio in two transects in the River Suir.

The first transect is located perpendicular to the shoreline in between the fish weirs on Woodstown Strand. Three sampling locations on this transect are recommended. The sediment can be collected using a grab sampler at high water. The percentage of silt in the sample can be obtained by sieving.

The second sampling location is subtidal, near the fish weirs opposite from Seedes Bank (near Buttermilk Point), between Parkswood Point and Barron Quay. Three grab samples are recommended.

Before the grab samples are taken it is worthwhile to take a measurement of the local turbidity, or SPM concentration as well.
It is recommended to take photographs with date indication of the intertidal fish weirs and oyster grounds to establish the base-line situation and to monitor potential siltation in the area.

6.5 Conclusion on Estimated Ecosystem Impacts

The increase in suspended particulate matter concentrations, as a result of the dredging and dumping activities are restricted to a local and temporal effects. The additional increase at various monitoring stations were (ecological) activities take place were computed for different model conditions. Table 6.4 gives an overview of maximum additional SPM concentrations for the monitoring locations. It can be concluded that the additional increase in turbidity will have a negligible effect on the ecological functioning of the Suir.

Monitoring station	Additional SPM concentration (mg/l)
(1a) Herring spawning	0.25
(1b) Herring spawning	0.25
(5a) Lobster release	0.5
(5b) Lobster release	0.5
(9) Oyster production	3
(10) Mussel bed	6
(11) Mussel bed	10
(12) Fish weir	20
(13) Fish weir	20
(15) Fish weir	5
(16) Fish weir	5
(17) Mussel bed	6
(18) Fish weir	5
(19) Mussel bed	6
(20) Fish weir	5
(21) Fish weir	5

Table 6.4. **Maximum additional SPM concentration at the monitoring stations**

The dumping of dredged material will lead to burial of the local soft bottom community at the Disposal Site. This effect will be temporary and a relatively fast recovery of biomass is expected, although the original species diversity may not be found for a period of a couple of years. Effects of burial through continuous resuspension and subsequent sedimentation around the disposal site is negligible.

At the dredging locations about 75% of the benthic species will be removed. The original situation may be recovered in three years, after settling of new bivalve larvae if maintenance dredging is suspended.

Effects of additional siltation of the tidal flats is also negligible.

List of References

Allen, K.O. & J.W. Hardy, 1980. Impacts of navigational dredging on fish and wildlife: a literature review. U.S. Fish and Wildlife Service. Report FWS/OBS-80/07.

Bijkerk, R., 1988. Escaping or staying buried. The effects of an increased sedimentation by dredging on benthic organisms. Literature review. RDD Aquatic Ecosystems, Groningen (in Dutch).

Essink, K, 1993. Ecosystem effects of dredging and dumping in the Ems-Dollard estuary and the Wadden Sea RWS, RIKZ, Report DGW-93.020. Baghwad product 42 (in Dutch).

Eysink, W.D. et al., 1996. Belview Quay Access Channel, Flow modelling, morphology, siltation and economic appraisal of training works, DELFT HYDRAULICS, Report H 2183, December 1996

Gerritsen, H, J.W. de Vries and M.E. Philippart, 1995. The Dutch Continental Shelf Model. pp. 425-467 in: D.R. Lynch and A.M. Davies, eds. Quantitative skill assessment of coastal ocean models.

HSL, 1994. Survey report Duncannon Bar, Hydrographic Surveys Limited, The Cobbles, Crosshaven, county Cork, Ireland, December 1994

HSL, 1994. Survey report Duncannon Bar Dredge Study, Hydrographic Surveys Limited, The Cobbles, Crosshaven, county Cork, Ireland, June 1999

Hydrographer of the Navy, 1968. Irish Coast Pilot, Eleventh edition, Admiralty, London, 1968

Kaaij, Th. van der, and H.F.P. van den Boogaard, 1992. TRIANA and FOUMOD. Tools for the analysis and interpretation of 2D/3D numerical model calculations. DELFT HYDRAULICS, Report Z482.

Leussen, W. van, 1994. Estuarine macroflocks and their role in fine-grained sediment transport, Thesis, University of Utrecht, Faculty of earth science, 7th Febrary, 1994 (ISBN 90-393-0410-6)

McCabe, G.T. Jr., S.A. Hinton & R.L. Emmet, 1998. Benthic Invertebrates and Sediment Characteristics in a Shallow Navigation Channel of the Lower Columbia River, Before and After Dredging. In: Northwest Science, Vol. 72, No. 2, pp. 116-126.

Philippart, M.E. and A. Gebraad, 1997. A new storm surge forecasting system. Proc. First Int. EUROGOOS Conference, The Hague, October 1996.

Rijn, L.C. van, 1990a. Hydraulic studies Cheekpoint upper and lower bar, Waterford, Ireland, DELFT HYDRAULICS, Report H 1118, Annex 2: Field survey, December 1990

Rijn, L.C. van, 1990b. Hydraulic studies Cheekpoint upper and lower bar, Waterford, Ireland, DELFT HYDRAULICS, Report H 1118, Main report, December 1990

Theede, H., 1973. Comparative studies on the influence of oxygen deficiency and hydrogen sulphide om marine bottom invertebrates. Neth. J. Sea Res. 7: 244-252.

UN/ECE, 1996. Guidelines on water quality monitoring and assessment of transboundary rivers. UN/ECE Task Force on Monitoring and Assessment (ISBN 9036945402).

Widdows, J., P. Fieth & C.M. Worral, 1979. Relationship between seston, available food and feeding activity in the common mussel *Mytilus edulis*. Mar. Biol. 50: 195-207

Winterwerp, J.C., 1989, Flow-induced Erosion of Cohesive Beds. WL | Delft Hydraulics, Report 25.

APPENDIX G-4

Prepared for:

Port of Waterford Company

New Ross Port Company

Dredging of Suir and Barrow Rivers

Environmental impact of annual spoil dumping at sea off Hook Head

Report on investigations

March 2001

WL | delft hydraulics

H3822

Prepared for:

Port of Waterford Company
New Ross Port Company

Dredging of Suir and Barrow Rivers

Environmental impact of annual spoil dumping at sea off Hook Head

[redacted]

Report on investigations

WL | delft hydraulics

WL | delft hydraulics

CLIENT:	Port of Waterford Company and New Ross Port Company
TITLE:	Dredging of Suir and Barrow Rivers Environmental impact of annual spoil dumping at sea off Hook Head

ABSTRACT:

The Port of Waterford Company intends to maintain the nautical depth of the access channel to the Port of Waterford at a required level of OD - 6 m or more in the future. This requires annual maintenance dredging at Duncannon and Cheekpoint Bars in this fairway. The permit for the first dredging and dumping was granted by the Minister for the Marine and Natural Resources under specified conditions. One of the conditions was to perform a mathematical model study on the environmental impact of the dredging and dumping activities which was carried out at an earlier stage.
Similarly, New Ross Port Company (NRPC) wishes to maintain minimum nautical depths of OD - 0.3 m in Barrow River. This material also will be disposed of at sea by the NRPC.

This report considers the impact of disposal of dredged material from both the Suir and Barrow Rivers and Waterford Estuary at the disposal site off Hook Head. It considers the impact of a number of consecutive annual dumpings of dredged spoil over a 15 year period.

REFERENCES: Proposal by fax MCI05691/H3822/WE dated 27th November, 2000
Commission of work by fax dated 22nd December, 2000

VER.	ORIGINATOR	DATE	REMARKS	REVIEW	APPROVED BY
0	[redacted]	January 2001	Preliminary	[redacted]	[redacted]
1		February 2001	Draft		
2	[redacted]	March 2001	Final	[redacted]	[redacted]

PROJECT IDENTIFICATION:		H 3822					
KEYWORDS:		Environmental Impact, Sediment transport					
CONTENTS:	TEXT PAGES	14	TABLES	7	FIGURES	16	APPENDICES 0
STATUS:	☐ PRELIMINARY		☐ DRAFT		☒ FINAL		

Contents

List of tables

List of figures

1 Introduction

1.1 Description of the problem

The Port of Waterford Company (PoWC) intends to maintain the nautical depth of the access channel to the Port of Waterford at a required level of OD - 6 m (or more in the future). This requires annual maintenance dredging at Duncannon and Cheekpoint Bars in this fairway (Fig. 1.1). The permit for the first dredging and dumping was granted by the Minister for the Marine and Natural Resources under specified conditions. One of the conditions was to perform a mathematical model study on the environmental impact of the dredging and dumping activities which was carried out at an earlier stage (Eysink et al., 2000). Similarly, New Ross Port Company (NRPC) wishes to maintain minimum nautical depths of OD - 0.3 m in Barrow River. This material also will be disposed of at sea by the NRPC.

This report considers the impact of disposal of dredged material from both the Suir and Barrow Rivers and Waterford Estuary at the disposal site off Hook Head. It considers the impact of a number of consecutive annual dumpings of dredged spoil over a 15 year period.

1.2 Terms of Reference

[redacted] undertook to carry out a study covering the following items in order to further characterise the environmental impact of disposal of dredged spoil:

- The behaviour of the sand dumped at the bottom of the sea at the prescribed dump site will be studied with the sand transport module of our program package DELFT2D.MOR with the same model and procedures as applied in the previous study (Eysink, W.D. et al., 2000). This part of the study will provide the long-term behavior of the sand from 5 consecutive annual spoil dumpings of 300,000 m^3 following the initial spoil dumping which was studied in a previous report (Eysink, W.D. et al., 2000).

Dispersion of silt released into the water due to dredging in the Waterford Estuary and dumping off Hook Head are short-term effects which will only occur during the maintenance dredging operations. The impacts of the temporary additional silt sources due to the dredging and dumping operations have been dealt with in the previous study (Eysink, W.D. et al., 2000).

The required field data for the additional study were already available from the previous studies. The study has been performed by the following team:

[redacted]	Project manager and quality control of sediment dispersion studies. Editor of final report
[redacted]	Sand dispersion study
	Quality control of ecological aspects
	Overall quality control

1.3 Results and conclusions

The additional investigations on the impact of regular dumping of spoil at the approved disposal site at sea have provided with the following results and conclusions:

Behaviour of sand dumped at sea

The behaviour of the sand dumped at the dump site at sea was computed with the sand transport module of DELFT2D.MOR and the validated tidal flow model. Computations were made for an artificial sand heap with an initial height of 1 m on the sea bed at the dump site (representing 425,000 m^3 of spoil) under calm, moderate and rough sea conditions. Bottom changes were computed for 0.5 year (calm sea only), 0.9 year (calm and moderate sea) and 1 year (calm, moderate and rough sea).

After a year the bed level at the dump site was raised again by 0.7 m representing the spoil dumping of the next annual maintenance dredging (300,000 m^3 of sandy spoil) after which the sand dispersion in the following year was computed. This was repeated for a total of six annual spoil dumpings. The subsequent sand dispersion was computed over a period of ten more years.

The simulations indicate that no sand transport will occur at the dump site under calm sea conditions and only little transport under moderate sea conditions. Most of the erosion/sedimentation at the dump site will occur during rough sea conditions.

Computations of the sedimentation/erosion at the dump site over periods of 1 to 15 years show a continuous but slow spreading of the sand heap towards the East and the Northwest in the first 5 years. The spreading towards the East was limited to about 300 m and practically seems to stop after 5 years (see Figures 2.13 and 2.14) whereas the spreading towards the Northwest continued. In the next 10 years the dispersion at the northwestern side gradually extended further but more to the North towards the entrance of the estuary. In this period the sand also started to disperse along the 20 m depth contourline towards the Southeast. After 15 years the dispersion of sand will still be limited to a distance of about 2 km from the spoil dump towards the Northnorthwest and almost 3 km towards the Southeast (Figure 2.12). The total erosion at the centre of the sand heap amounts to 1.0 m at the time of the last dumping, i.e. 5 years after the initial dumping. At the end of the period of 15 years the total erosion at the centre of the disposal site will increase to 2.9 m. The maximum sedimentation appeared to be about 1.6 m at the toe on the northwestern site of the dump location.

The sedimentation rate close to the disposal site will increase in the first 6 years and will then gradually reduce again after the last spoil dumping. The maximum annual sedimentation rate at a distance of 200 m amounts to 20 cm/year and reduces to 11 cm/year at a distance of 400 m. Beyond a distance of 600 m it becomes very low (less than 7 cm/year).

Ecological impact

The ecological study dealt with the possible impacts of burial by sedimentation on different places of ecological interest at sea. This resulted in the following conclusions:

The dumping of dredged material will lead to burial of the local bottom community at the Disposal Site. This effect will be temporary and a relatively fast recovery of biomass is expected after each dumping, although the original species diversity may not be found for a period of a couple of years after termination of the spoil dumpings.

The effects of burial through continuous resuspension and subsequent sedimentation around the disposal site, also in this situation with more than one spoil dumping, is generally believed to be negligible. Some effect may be expected very close to the disposal site after several spoil dumpings.

Due to the general sedimentation pattern indicated by the models (see Figures 2.6 - 2.12), the herring spawning grounds (areas 1a and 1b; see Figure 3.1) at sea and the lobster release areas (areas 5a and 5b) will not be affected at all by the redistribution of the dumped sand.

2 Sand dispersion at the dump site

2.1 General

The purpose of the sand dispersion study is to determine the long term spreading of the dumped sand from the dump location at sea. For this purpose the initial dump has been schematised as a heap of sand on the sea bed. To study the spreading of the sand a morphological model has been made based on the DELFT3D model system. This model system includes the tidal flow model as discussed in Chapter 3 of our previous report (Eysink et al., 2000). A horizontal 2-dimensional wave propagation model has been added to provide the wave conditions over the area. Based on the results of the flow and wave models the sediment transports and the bottom changes were determined using the morphological model DELFT3D-MOR. This is an integrated model system combining the effects of flow, waves, sediment transports and bottom changes. In the previous study the model has been run for a simulation period of 10 years to compute the morpho-dynamic behaviour of the heap of sand of one spoil dumping of 425,000 m^3. In the present study a period of 15 years is simulated with 5 more spoil dumpings of 300,000 m^3 at an annual interval after the initial dumping to determine the total ecological impact in case the dump site is used for a longer period.

In this chapter first the study approach and input parameters are described. Thereafter the results are presented and discussed.

2.2 Approach and input parameters

In an ideal situation, the simulations for the spreading of the sand heap should be carried out covering all water levels, current velocities, wave heights and directions related to their possibilities of occurrence. This approach however would result in an unrealistic number of simulations to be carried out. Therefore, the hydraulic conditions are schematised into a few conditions which are representative for the total flow and wave climate as done in the previous study.

For the tidal conditions a morphological tide has been selected based on a weighting procedure considering sediment transport rates related to the tidal range. This approach has proven to be reliable in similar projects carried out in the past. The selected tide runs from 17:00h on 19th June to 18:00h on 20th June 1999 (Figure 2.1) and covers two tidal cycles in a period of 25 hours.

The wave climate is an important input parameter for the transport capacities in the study area. Due to the wave activity, sediment is stirred up after which it can be transported by the tidal flow. The wave climate has been derived from our previous study for Belview Quay (Eysink et al., 1996). The probability of occurrence of the wave conditions at the 20 m depth contour off the coast at Dunmore East at the mouth of the Suir River are presented in

Table 2.1 and 2.2. This wave climate is based on ships observation data in the period between 1949 and 1994 which were provided by the British Met Office.

According to the 1996 study, the wave climate has been schematised into three wave conditions (calm, moderate and rough). The schematisation was carried out in such a way that the representative wave conditions, tógether with their corresponding durations, give more or less the same annual sediment transport rates in the area of interest as the total wave climate. The representative wave conditions are shown in Table 2.3.

Table 2.3: Schematised wave climate for morphodynamic computations

Condition		H_s (m)	T_p (s)	duration (%)	duration (days/year)
1	calm	0.0	-	50	182.5
2	moderate	1.5	6.6	40	146.0
3	rough	3.0	9.0	10	36.5

For a more detailed description of the wave climate reference is made to Eysink et al., 1996.

For the morphological computations the wave pattern has been computed at the high waters of the morphological tide and at the low waters. For the intermediate water levels the wave parameters are obtained by interpolation between the wave patterns at HW and LW. The wave pattern at LW for condition 3 (H_s = 3.0 m) is presented in Figures 2.2 (without the sand heap) and 2.3 (with the sand heap) for the open sea area at the dump site. These figures indicate that the influence of the sand heap on the regional wave pattern is negligible. The major effect is that the orbital velocity at the sea bed will increase with decreasing water depth over the heap.

The amount of dredged material in the initial dump was estimated at 335,000 - 425,000 m^3 partly consisting of silt. Based on the dimensions of the dump site, the resulting sand heap at this location will have a height of approximately 0.8 - 1.0 m ignoring the part of the fine spoil which will be washed out during dumping. For the assessment of the dispersion of sand the maximum value of 1.0 m has been applied to take the maximum dispersion into account in the model simulations. This means that the depth initially reduces from approximately 21 m to about 20 m. The annual volume of the following dumpings are estimated at 300,000 m^3 which will cause an incremental raise of the bottom at the dump site of 0.7 m after each dumping.

Sieve curves of the bottom material were provided before by the client. Analysis of these curves indicated that the bottom material at the dredging site is finer than the bottom material at the dump site. However, it can be expected that while dredging the percentage of fine material will reduce during the overflow of the hopper. Furthermore, part of the finer material will be washed out during dumping. Assuming that 50 % of the material less than 63 μm will be washed out, it can be concluded that the dumped material at the seabed of the dump site will be comparable to the original bed material at the dump site. For this material the following sediment characteristics have been selected which are applied for all dumpings (Eysink, W.D. et al., 2000):

D_{50}	100 µm
D_{90}	300 µm
fall velocity	0.008 m/s

The sand transport rates in the area were computed using the Bijker formula which includes the transport contributions of both waves and currents. The transports were computed over the morphological tide in discrete steps of 15 minutes (which means a total of 100 steps) taking into account the variation of the wave field during the tide. Hereafter the average transport over the morphological tide was computed. Based on this average transport the bottom changes were determined.

The bottom changes were computed by morphodynamic computations. This means that the interaction between the variation of the water depth due to sedimentation and erosion and the hydraulic conditions has been taken into account. After computing the bottom changes in a certain period of time the hydraulic conditions were updated by new flow, wave and transport computations, and so on.

The sediment transports and bottom changes in the existing situation were computed as well. These bottom changes were subtracted from the bottom changes in the situation with the spoil dump assuming that the bottom changes in the existing situation can be considered as natural changes. The difference gives the impact of the spoil dump on the morphological developments at the dump site.

2.3 Results

Firstly, the cumulative bottom changes due to the various conditions were computed in the first year after the initial dumping of sand. The bottom changes after condition 1 (calm), conditions 1 and 2 (calm and moderate waves), and after all three representative conditions are shown in Figures 2.4, 2.5 and 2.6 respectively.

From these first computations it can be concluded that the impacts of the calm condition on the morphology can be neglected. During this condition no significant bottom changes occurred. The bottom changes due to the moderate and rough sea states indicate that the height of the sand heap tends to reduce. The sand from this heap is deposited in the direct vicinity of the dump site at the north-western and at the south-eastern side. Due to this process the height of the sand heap is reduced while it is spread out over a larger area.

As the calm conditions have a negligible influence on the sand dispersion, these conditions can be neglected in the long term prediction of the sand dispersion. Therefore, only the moderate and rough sea conditions are taken into account in the simulations from 1 year to 15 years. The resulting bottom changes are presented in Figures 2.7 to 2.12 showing the results after 2, 4, 6, 9, 12 and 15 years respectively. The results initially show, as in the previous study, a general tendency of sand dispersion from the disposal area towards the East and particularly towards the Northwest. However, after 5 years the dispersion towards the Northwest is somewhat stronger than in the situation with one dumping whereas also dispersion of sand towards the Southeast starts to develop (Figure 2.9). This is caused by the higher spoil heap due to the repetitive spoil dumpings. This dispersion process continues in the next 10 years; at the Northwest side the sand dispersion gradually turns North towards the estuary mouth and at the Southeast side it further extends along the 20 m depth contourline (Figs. 2.10 - 2.12).

To get a better impression of the developments of the erosion and sedimentation at the disposal site in time, the computed bed devélopment along a cross section running through the sedimentation area at the northwestern side, the disposal area and the sedimentation area at the eastern side is plotted in Figures 2.13 and 2.14. The first figure shows the computed annual development in the period with spoil dumping (increasing bed level in the disposal area), whereas the second figure shows the computed developments during the next ten years after the last spoil dumping.

Note that in Figure 2.13 some irregularities (saw teeth) appear in the bed development at the locations around the toe and the edge of the sand heap where the bed shows a sudden change in bed slope. This is caused by the numerical process of the computations and can be neglected in interpretations of the bed developments. These irregularities in the bed have been smoothed before starting the computations for the period of ten years after implementation of the last spoil dumping (see Figure 2.14).

The results in Figure 2.13 show a progressive erosion of sand in time with the increasing height of the spoil heap. This is caused by the increasing flow velocity and orbital velocity at the bed of the spoil heap with the increasing depth reduction. From these data the minimum annual erosion in the centre of the spoil heap can be approximately derived as a fitted function of the height of the bed level above the original bed at the start of the year:

$$E = 0.071\ \Delta h^{1.32}$$

where:

E = annual erosion depth (m)

Δh = initial height of bed level in centre of the disposal area above the original bed (m)

This relation indicates that in case of continuous annual dumping the erosion becomes equal to the annual dumping height of 0.7 m if the bed level is raised by 5.7 m above the original bed level. This means that, according to the computations, in that case the bed level at the disposal site would always remain below about OD - 15 m.

Figure 2.13 shows a decreasing sedimentation at the east side of the disposal site which remains limited to a distance of about 300 m from that site in the first 5 years. At the northwestern side the sedimentation continues progressively during the first 6 years after the first spoil dumping. In the first two years most of the sand remains within a distance of 400 m from the disposal site. This distance gradually increases to 600 m in the next three years and to about 2 km 15 years after the first spoil dumping. The sedimentation rate close to the disposal site increases in the first 6 years and then gradually reduces again after the last spoil dumping. The maximum annual sedimentation rate at a distance of 200 m amounts to 20 cm and reduces to 11 cm at a distance of 400 m. Beyond a distance of 600 m it becomes very low (less than 7 cm/year).

In ten years after implementation of the last spoil dumping, the sedimentation rate close to the spoil heap reduces in time due to the reducing height of the spoil heap which means less disturbance on the local flow conditions (see Figure 2.14). The total erosion at the centre of the sand heap (total dump height 4.5 m) is equal to 1.0 m five years after the first dumping and has increased to 2.9 m at the end of the total period of 15 years. The maximum sedimentation after 15 years appeared to be approximately 1.6 m at the toe of the dump heap on the northwestern side.

3 Ecological impact of dumping

3.1 Description of the environment

The Duncannon and Cheekpoint Bars are located in the River Suir, in the Southeast of Ireland, at approximately 52°12'N, 6°56'W.

Activities

The River Suir contains a number of environmental and economically important activities that can potentially be affected by the dredging and dumping operation (See Figure 3.1).

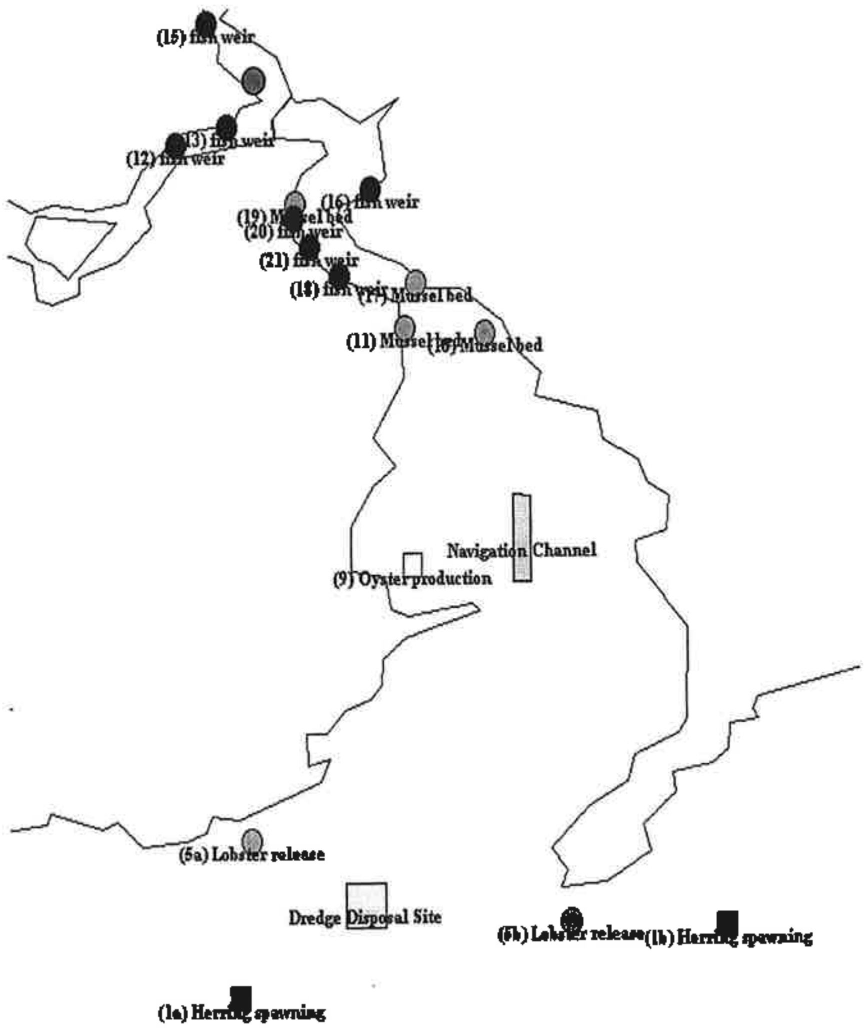


Figure 3.1. Activities in the Waterford estuary.

The type and locations of these activities are summarised below:

- Herring spawning grounds at locations 1a and 1b at open sea,
- Lobster release areas at locations 5a and 5b near the coasts of Falskirt Rock and Hook Head at open sea,
- Oyster production area at location 9 along Woodstown Strand just inside the estuary behind Creadan Head,
- Mussel beds along the estuary from Passage East up to Snowhill Point (locations 10, 11, 17, 19) and at Barrow Bridge,
- Fish weirs (white fish, cuttle, salmon and eel) at various locations along the lower estuary (locations 12, 13, 15, 16, 18, 20, 21). Mussel Bed at Barrow Bridge to be inserted.

For this study only the Herring spawning grounds at locations 1a and 1b and the Lobster release areas at locations 5a and 5b near the coasts of Falskirt Rock and Hook Head at open sea are relevant. Those areas are located in the vicinity of the disposal area and ultimately might be affected by the dispersion of sand from that area.

3.2 Potential ecosystem impacts of dumping

3.2.1 Introduction

Generally speaking, short-term, small-scale dredging and dredge spoil disposal projects have less ecological impacts than long-term, large-scale projects (Allen & Hardy, 1980). The most direct, physical effects of the dredging and dumping activities are an increase in the Suspended Particulate Matter (SPM) concentration and a covering of the bottom sediment with disposed material. The increase in SPM can directly and indirectly affect several ecological processes in the water column and in the sediment.

SPM can be classified according to the grain sizes. The larger and heavy fractions will settle easily, while the finer fractions will resuspend and stay in suspension longer. The effects of an increased SPM concentration differ between fractions. The fine fraction of silt and their silt-related processes are very important to the ecological functioning of estuaries. Any change in silt concentrations and silt characteristics may have a potential impact on the ecosystem. In this chapter the ecological functions of silt are briefly addressed, and subsequently, potential ecosystem impacts of the dredging and dumping activities are discussed.

An overview of potential effects of suspended material, the 'Removal of Benthic Species' at the dredge site and the indirect effect of a change of the sediment composition is described in the previous study (Eysink et al., 2000). These effects will not change due to the repetitive spoil disposal at the dumpsite. The major difference with the previously situation could be the more continuous and increased sand dispersion around the dump site. That aspect is discussed in the next Sections.

3.2.2 Potential impacts of burial of benthic organisms

An increased sedimentation near the dumping site can lead to burial of benthic species by a layer of (mostly anaerobic) sediment. The sensitivity of benthos for burial is dependent on the ability to grow or move upwards.

The potential effects of burial can be subdivided into effects of an incidental, but large, deposition and effects of a continuous, but small, deposition.

Incidental deposition

The potential impact of dredged material disposal on organisms living on or near the bottom can have strong negative impacts if the settling occurs in an area containing sensitive organisms. Areas of concern include coral reefs, seagrass beds, and fish spawning areas. Non-mobile species, such as the Blue Mussel (*Mytilus edulis*), anemones and oysters are also very sensitive to an incidental deposition, resulting in burial of the organism. Other species are more capable of surviving an incidental deposition, either by moving or growing upwards to the sediment surface.

For benthic organisms a 'fatal depth' can be defined, which denotes at what depth of incidental burial the organism will not survive. This fatal depth is species dependent, but also differs with the type of sediment. Essink (1993) provides a literature overview of fatal depths for different organisms and two sediment types, silt and fine sand. In general benthic species are more sensitive to burial by silt than by sand. Furthermore, species of a sandy bottom are more sensitive to burial by silt than species of a silty bottom. Larger species are generally more capable of moving upwards than smaller species. However, the adult *Mya arenaria* is exceptionally large and is not able to move at all.

The fatal depth for incidental deposition of silt for a number of benthic species, selected from Essink (1993), is presented in Table 3.1.

Table 3.1. Fatal depth (cm) for incidental deposition with silt (Essink, 1993 to: Bijkerk, 1988).

Scientific name	Name	Fatal depth (cm)
Mytilus edulis	Blue Mussel	1
Petricola pholadiformis		3
Mya arenaria	Sandgaper	7
Cerastoderma edulis	Cockle	11
Hydrobia ulvae	Mudsnail	18
Macoma balthica	Balthic Tellin	38
Ensis ensis		43
Nephtys hombergii		60

Besides the physical effect of burial, chemical effects of the anaerobic sediment, often together with high sulphide concentrations, play a role. A decreased dissolved oxygen level can amplify the effects of an increased sedimentation. The cleaning of the siphons at an increased sedimentation flux will cost more energy, while at the same time the oxygen levels are lower. The tolerance levels for low oxygen levels and high sulphide levels differ between species. A species such as the Brown Shrimp is a lot more sensitive to anaerobic conditions than species that are used to similar situations.

The exposure time to anaerobic conditions (< 0.2 mg O_2/l) and for high sulphide concentrations (7 mg/l) at a 50% mortality level is presented in Table 3.2.

Table 3.2 Exposure time to anaerobic and sulphide rich conditions at 50% mortality (Essink, 1993; Theede, 1973).

Scientific name	Name	Exposure time oxygen (hours)	Exposure time sulphide (hours)
Mytilus edulis	Blue Mussel	800	600
Scrobicularia plana		600	500
Mya arenaria	Sandgaper	500	400
Nereis diversicolor	Ragworm	150	100
Cerastoderma edule	Cockle	100	100
Asterias rubens	Common Starfish	90	70
Carcinus maenas	Beach Crab	40	30
Amphiura filiformis	a Brittle Star	25	30
Crangon crangon	Brown Shrimp	2	2

Effects of burial on soft bottom benthic species are temporary. Dependent on the original community structure, recovery may take a couple of years to a decade. Opportunistic species will quickly recolonise the affected site, but long-living bivalve species or some sea urchins do not reproduce each year. In general, soft bottom benthic communities show partial recovery in one year and full recovery in 18 to 24 months. In some cases it will take many years to recover the original species diversity (Allen & Hardy, 1980).

Continuous deposition

A continuous deposition of material to the bottom can have negative effects when the sedimentation rate is higher than the velocity at which the organisms can move or grow upwards. The sensitivity to a long-term continuous deposition again is species dependent and also dependent on the type of sediment. A continuous deposition of silt is in general worse than a deposition of sand. Table 3.3 presents the maximum tolerance for different benthic species for a continuous deposition of silt and fine sand in cm/month.

Table 3.3. Maximum tolerance for continuous deposition of silt and fine sand in cm/month (Essink, 1993; Bijkerk, 1988).

Scientific name	Name	Deposition of silt (cm/month)	Deposition of fine sand (cm/month)
Mya arenaria	Sandgaper	2	5
Cerastoderma edule	Cockle		17
Macoma balthica	Baltic Tellin	15	>17
Arenicola marina	Lugworm	11	>17
Nephtys hombergii		>35	>17
Carcinus maenas	Crab	31	

3.3 Estimated impacts of dumping

The main effect of dumping is the impact on benthic organisms due to burial. As discussed in the previous section, the potential effects of burial can be subdivided into effects of an incidental deposition and effects of a continuous deposition.

Incidental deposition

At the Disposal Site a large amount of dredged material will be dumped. It is to be expected that all benthic species that are present at this site will be covered by a thick layer of sediment and will be buried. Considering the type of sediment (primarily silty sand) and the depth of this location (20 m), bivalves species, polychaetes (worms) and brittle stars may be found at this location. Of the species mentioned in the previous section, these may include the Sandgaper (*Mya arenaria*).

The modelling has indicated that sensitive herring spawning grounds will not be affected by an additional sedimentation due to the disposal of dredged material.

After the dumping, the disposal site will be quickly recolonised by benthic species. At first, opportunistic species such as worms and crabs will search for the dead remains of the original inhabitants, and after a while larvae of bivalve species can settle. After one year, the original biomass may be recovered, but the original species diversity may not be found. This process will be repeated after each dumping. Full recovery of the original species diversity will take at least for a period of two years after the last dumping.

Short-term dissolved oxygen depletion due to the dumping is seldom a problem. At the dump site, reduced oxygen levels are usually found near the bottom at the point of dumping, but are of a short duration. Adverse impacts are most likely to occur in poorly-mixed waters receiving highly organic dredged material, but that is not the case here.

Continuous deposition

The computations for the continuous resuspension and subsequent sedimentation of disposed sand at the Disposal Site show a limited area in which noticeable sedimentation of sand takes place. Roughly twice the surface area of the Disposal Site shows a significant additional sedimentation of sand. The net sedimentation rate in this area generally has a maximum of about 1 cm/month. This rate is sufficiently low for soft bottom benthic species to survive. Only in a narrow zone along the disposal site the sedimentation rates are high. At a distance beyond 600 m from the disposal site the sedimentation rate is always less than 5 cm per year.

Due to the general development of the sedimentation pattern indicated by the modelling (see Figures 2.6 - 2.12) the herring spawning grounds (areas 1a and 1b) at sea and the lobster release areas (areas 5a and 5b) will not be affected at all. The model results indicate that the area affected by sedimentation due to spoil dumping generally will remain at a distance of about 1 km from the lobster release areas and more more from the herring spawning grounds.

3.4 Conclusion on estimated ecosystem impacts

At the dredging locations about 75 % of the benthic species will have been removed during the first dredging campaign. The original situation will not be restored under the conditions with annual maintenance dredging.

The increase in suspended particulate matter concentrations, as a result of the dredging and dumping activities are restricted to local and temporal effects. In the previous study (Eysink et al., 2000) the additional increase at various monitoring stations where (ecological) activities take place, were computed for different conditions. Table 3.4 gives an overview of computed maximum additional SPM concentrations for the monitoring locations. It was concluded that the additional increase in turbidity will have a negligible effect on the ecological functioning of the Suir. This holds for each annual dredging campaign at Cheekpoint and Duncannon Bars.

Table 3.4. Computed maximum additional SPM concentration at the monitoring stations.

Monitoring station	Additional SPM concentration (mg/l)
(1a) Herring spawning	0.25
(1b) Herring spawning	0.25
(5a) Lobster release	0.5
(5b) Lobster release	0.5
(9) Oyster production	3
(10) Mussel bed	6
(11) Mussel bed	10
(12) Fish weir	20
(13) Fish weir	20
(15) Fish weir	5
(16) Fish weir	5
(17) Mussel bed	6
(18) Fish weir	5
(19) Mussel bed	6
(20) Fish weir	5
(21) Fish weir	5

Effects of additional siltation on the tidal flats during dredging are also temporary and negligible.

The dumping of dredged material will lead to burial of the local bottom community at the Disposal Site. This effect will be temporary and a relatively fast recovery of biomass is expected, although the original species diversity may not be found for a period of about two years. Hence, between two consecutive dumpings with an interval of (less than) one year no full recovery will occur. Full recovery only can occur after the dump site is abandoned. Even then the species diversity may differ from the original one due to a change of bed composition.

Effects of burial through continuous resuspension and subsequent sedimentation of sand around the disposal site is generally expected to be negligible. Only close to the disposal site high sedimentation rates may cause damage due to burial after several dumpings.

Due to the general sedimentation pattern of the sand eroded from the disposal site as predicted by the models (see Figure 2.12), the herring spawning grounds (areas 1a and 1b) at sea and the lobster release areas (areas 5a and 5b) will not be affected at all.

List of References

Allen, K.O. & J.W. Hardy, 1980. Impacts of navigational dredging on fish and wildlife: a literature review. U.S. Fish and Wildlife Service. Report FWS/OBS-80/07.

Bijkerk, R., 1988. Escaping or staying buried. The effects of an increased sedimentation by dredging on benthic organisms. Literature review. RDD Aquatic Ecosystems, Groningen (in Dutch).

Essink, K, 1993. Ecosystem effects of dredging and dumping in the Ems-Dollard estuary and the Wadden Sea.. RWS, RIKZ, Report DGW-93.020. Baghwad product 42 (in Dutch).

Eysink, W.D. et al., 1996. Belview Quay Access Channel, Flow modelling, morphology, siltation and economic appraisal of training works, WL | Delft Hydraulics, Report H2183, December 1996

Eysink, W.D. et al., 2000. Dredging of Duncannon Bar, Environmental impact of dredging and spoil dumping, WL | Delft Hydraulics, Report H3544, September 2000

Theede, H., 1973. Comparative studies on the influence of oxygen deficiency and hydrogen sulphide on marine bottom invertebrates. Neth. J. Sea Res. 7: 244-252.

Observed Wave Height (m)	Wave Direction (deg.N) -15. . 15.	15. 45.	45.: 75.	75. : 105.	105.: 135.	135.: 165.	165. : 195.	195. : 225.	225 . : 255.	255 . : 285.	285. : 315.	315. : 345.	Total
0 : .25	1.84	2.04	1.33	1.47	.86	.91	1.30	1.37	2.00	2.28	1.35	1.21	17.97
.25: .75	.95	1.37	.93	.96	.44	.62	.90	1.40	2.13	2.16	1.12	.84	13.81
.75: 1.25	1.20	1.34	1.04	.84	.71	.72	1.57	2.18	4.07	4.21	1.58	1.15	20.62
1.25: 1.75	.39	.55	.47	.50	.34	.57	.96	1.56	2.57	2.26	1.10	.61	11.89
1.75: 2.25	.63	.33	.35	.49	.27	.36	.77	1.41	2.67	2.55	.87	.60	11.31
2.25: 2.75	.35	.25	.27	.21	.20	.12	.43	.84	1.79	1.59	.65	.30	7.00
2.75: 3.25	.21	.24	.21	.26	.21	.21	.60	1.33	2.49	2.56	.66	.51	9.50
3.25: 4.25	.05	.17	.11	.11	.03	.11	.28	.64	1.30	1.30	.31	.14	4.56
4.25: 5.25	.05	.02	.07	.03	.05	.02	.13	.27	.29	.49	.22	.07	1.69
5.25: 6.25				.03	.02	.03	.05	.15	.28	.21	.12	.01	.91
6.25: 7.25		.01	.02	.03		.02		.03	.12	.13	.01		.37
7.25: 8.25							.01	.01	.07	.03	.02		.13
8.25: 9.25							.02	.02	.02	.08	.02		.15
9.25:10.25	.01								.01	.01	.03		.06
10.25:11.25							.02		.02				.03
11.25:12.25													
12.25:13.25													
Total	5.68	6.31	4.80	4.93	3.13	3.69	7.05	11.23	19.93	19.87	8.05	5.44	100.00

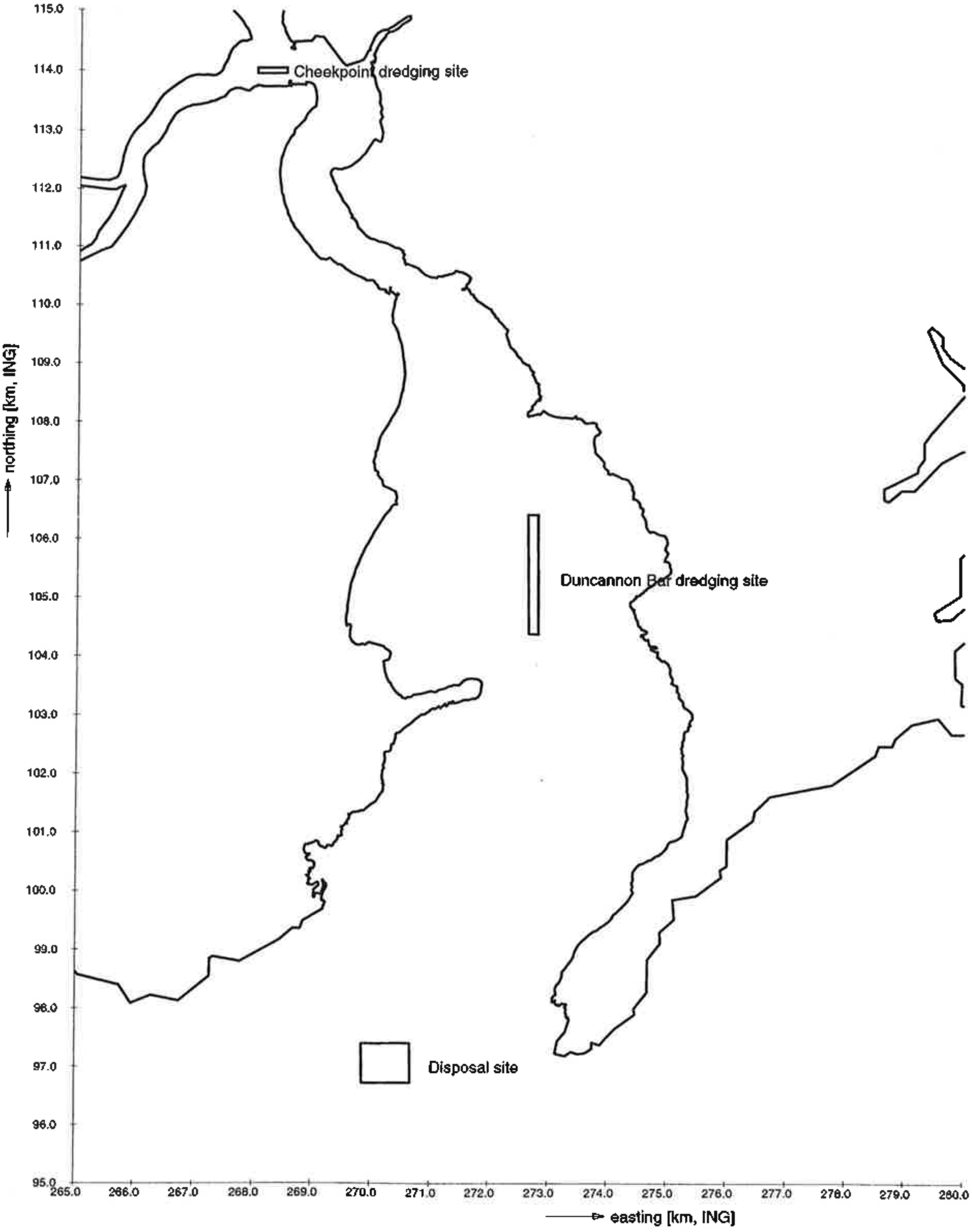
Season All Year
Period 1949 to 1994
Area 354.00 to 352.00 deg. East
50.70 to 52.00 deg. North
No. observations: 11930

Table 2.1 Probability that highest of sea and swell occur in the given height and direction class on open sea near Waterford

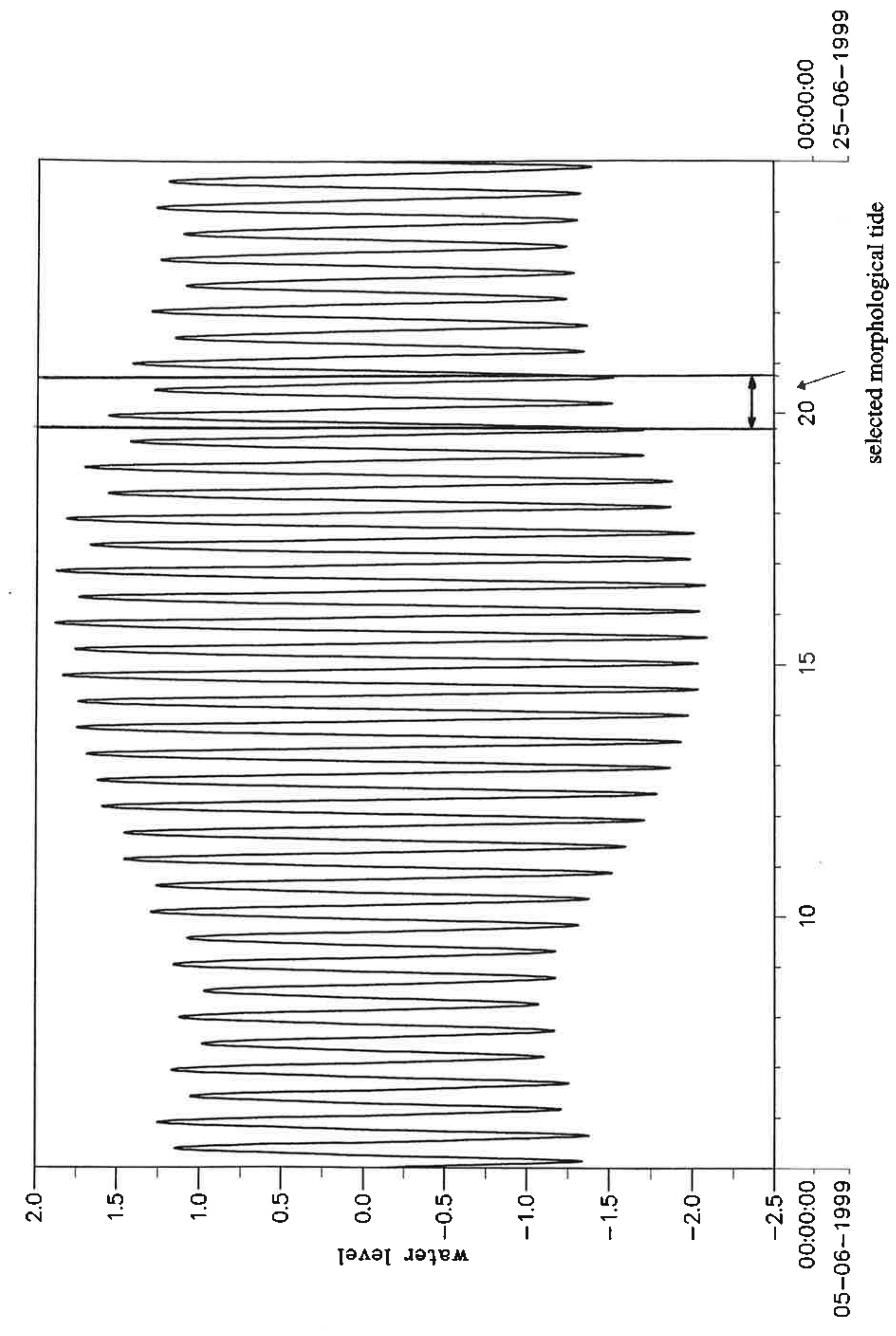
Observed Wave Height (m)	Observed Wave Period (s)										
	< 5.50	5.50: 7.50	7.50: 9.50	9.50: 11.50	11.50: 13.50	13.50: 15.50	15.50: 17.50	17.50: 19.50	19.50: 21.50	>21.50	Total
0 : .25	17.30	.36	.08	.17	.04	.02					17.97
.25: .75	10.94	1.98	.54	.20	.11	.03	.01				13.81
.75: 1.25	11.75	5.57	1.70	.59	.58	.39	.04				20.62
1.25: 1.75	5.21	3.95	1.77	.49	.31	.16					11.89
1.75: 2.25	3.43	4.19	2.41	.75	.38	.15		.01			11.31
2.25: 2.75	1.39	2.87	1.68	.69	.23	.14	.01				7.00
2.75: 3.25	1.04	3.26	2.90	1.54	.54	.18	.02	.01			9.50
3.25: 4.25	.22	1.29	1.35	1.12	.47	.11					4.56
4.25: 5.25	.03	.41	.65	.38	.20	.03					1.69
5.25: 6.25		.13	.29	.31	.13	.04					.91
6.25: 7.25		.04	.11	.08	.11	.01	.02				.37
7.25: 8.25		.01	.06	.03	.03						.13
8.25: 9.25			.07	.06		.01			.02		.15
9.25:10.25			.01	.01	.03	.02					.06
10.25:11.25			.02	.02							.03
11.25:12.25											
12.25:13.25											
Total	51.30	24.06	13.63	6.44	3.16	1.29	.09	.02	.02		100.00

Season: All Year
Period: 1949 to 1994
Area: 354.00 to 352.00 deg. East
50.70 to 52.00 deg. North
No. observations: 11930

Table 2.2 Probability that highest of sea and swell occur in the given height and period class on open sea near Waterford



Situation of dredging and dumping sites	Delft3D-Flow (2DH)	
DELFT HYDRAULICS	H3544	Fig. 1.1



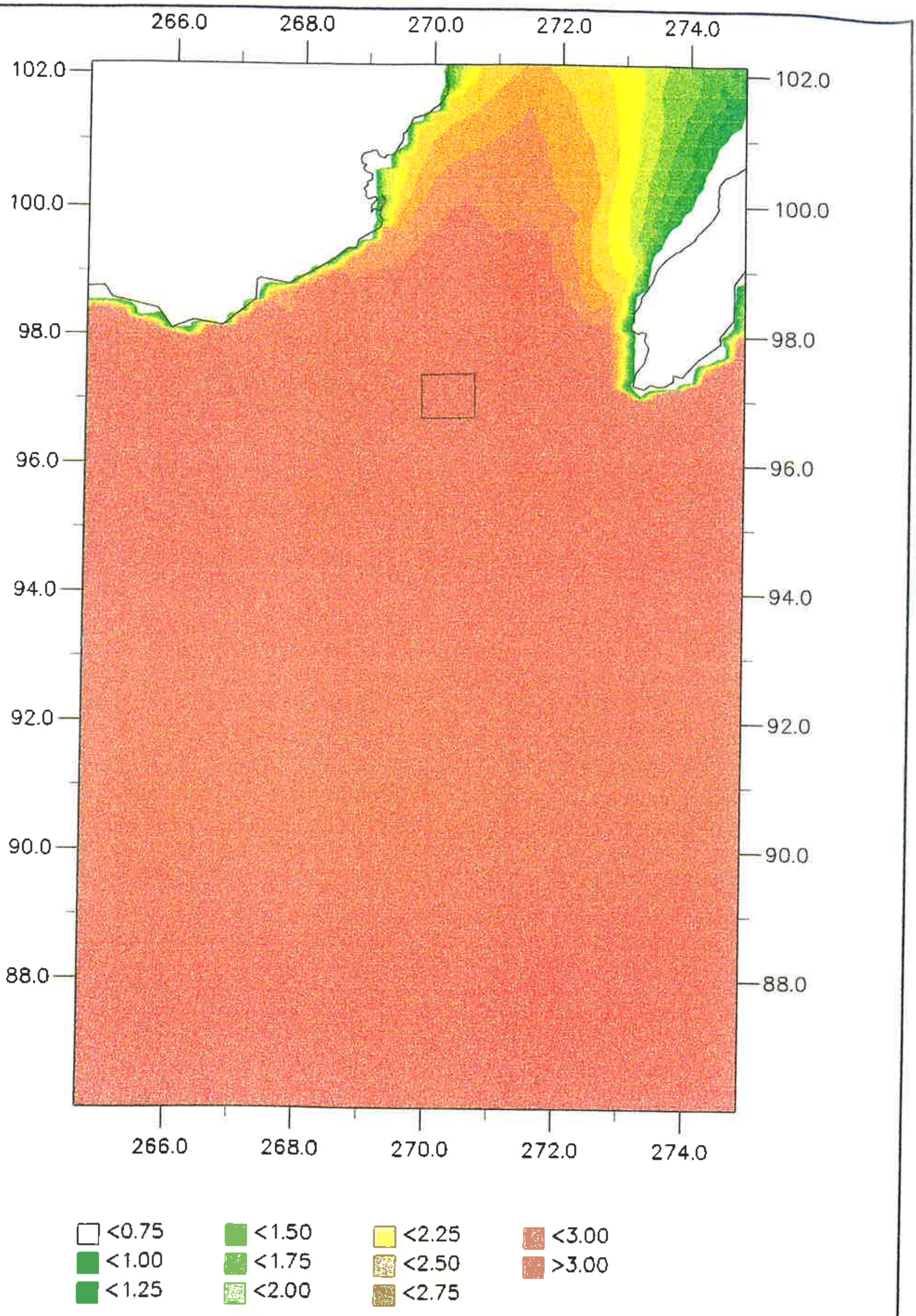
Selected morphological tide
Tidal level at the disposal site

DELFT3D-FLOW

WL | DELFT HYDRAULICS

H3822

Fig. 2.1



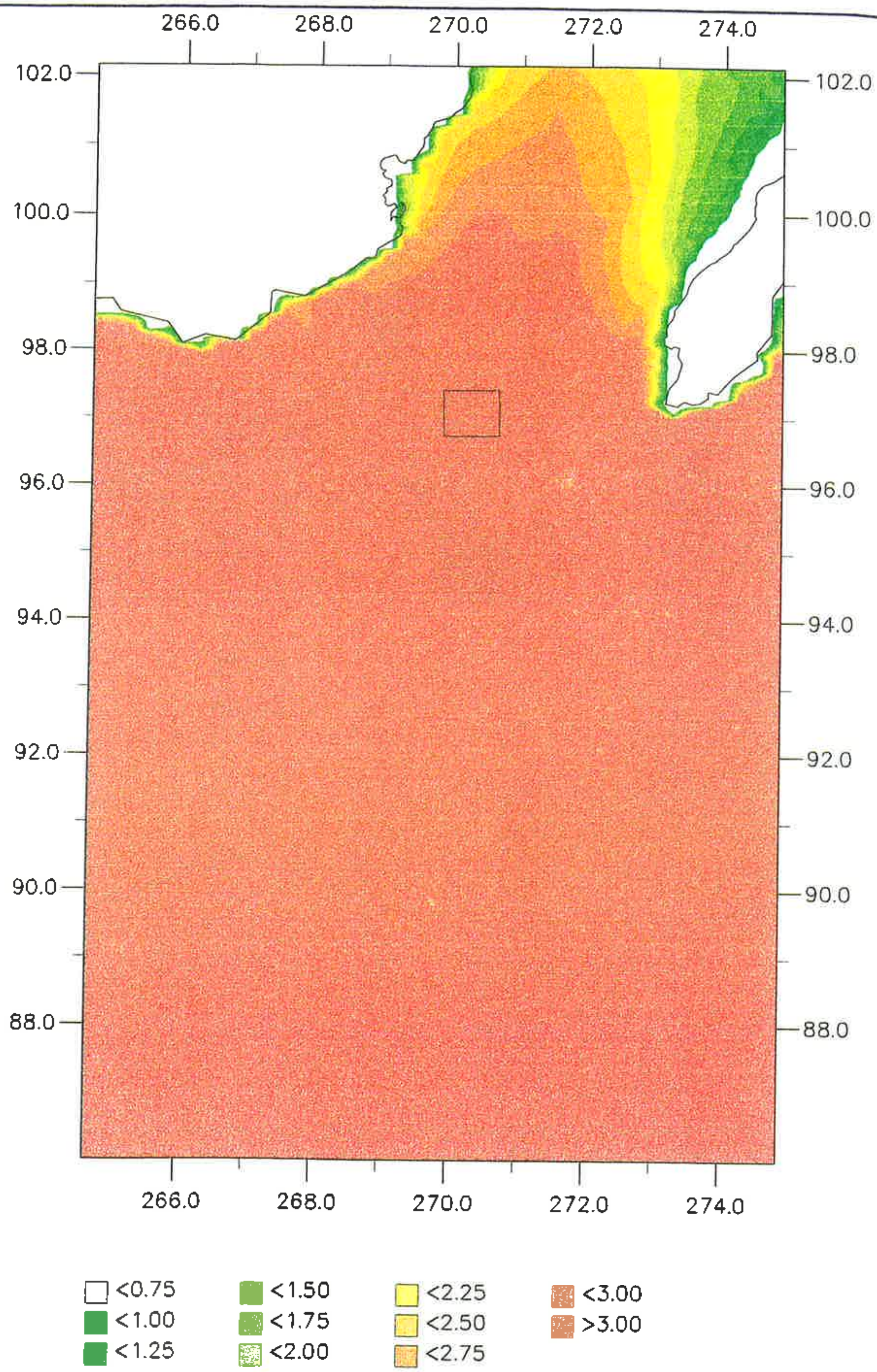
Wave pattern without the spoil dump
Hs = 3.0 m, low tide
(wave height in meters)

DELFT3D-WAVE

WL | DELFT HYDRAULICS

H3822

Fig. 2.2



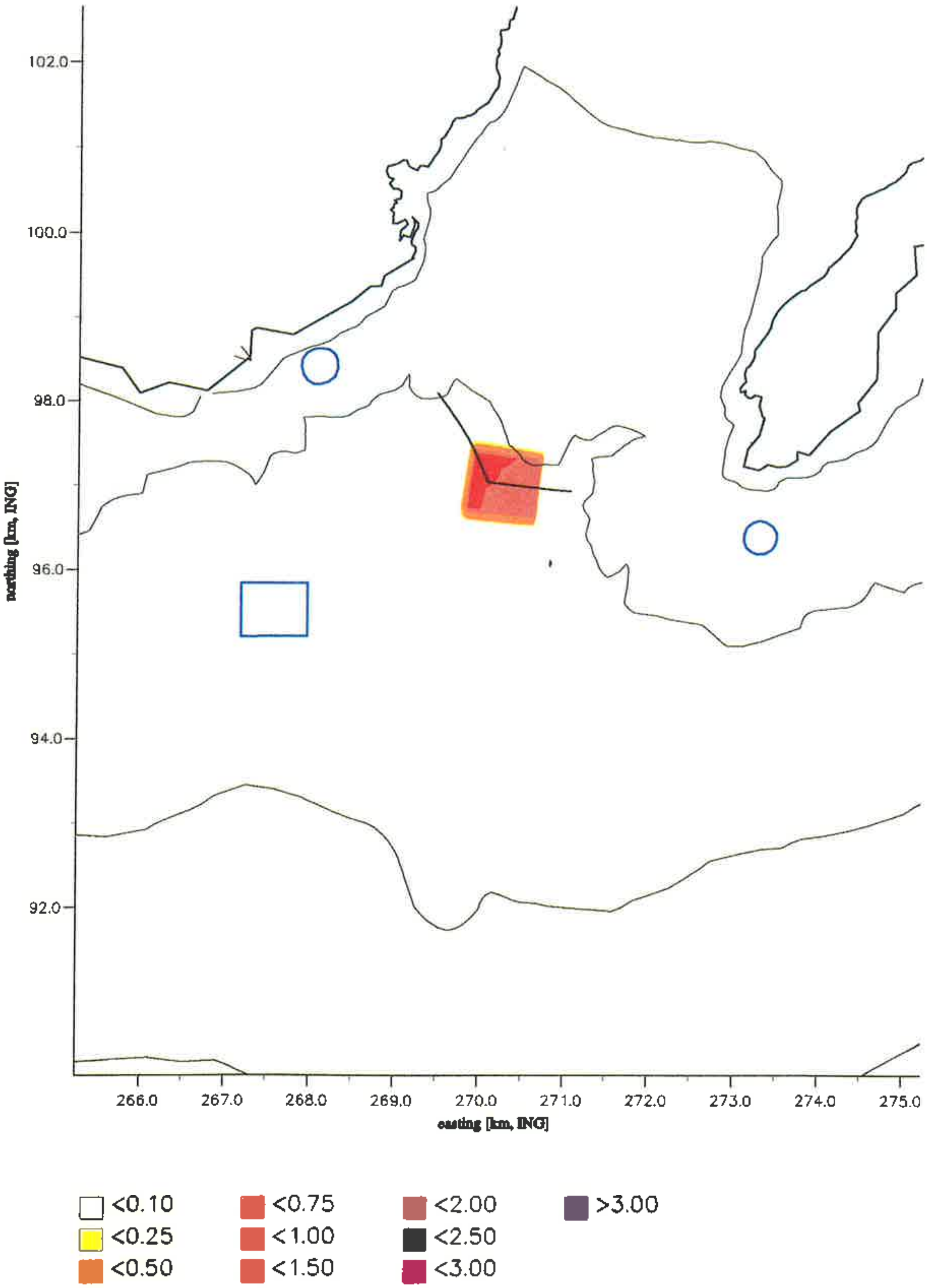
Wave pattern with the spoil dump
Hs = 3.0 m, low tide
(wave height in meters)

DELFT3D-WAVE

WL | DELFT HYDRAULICS

H3822

Fig. 2.3



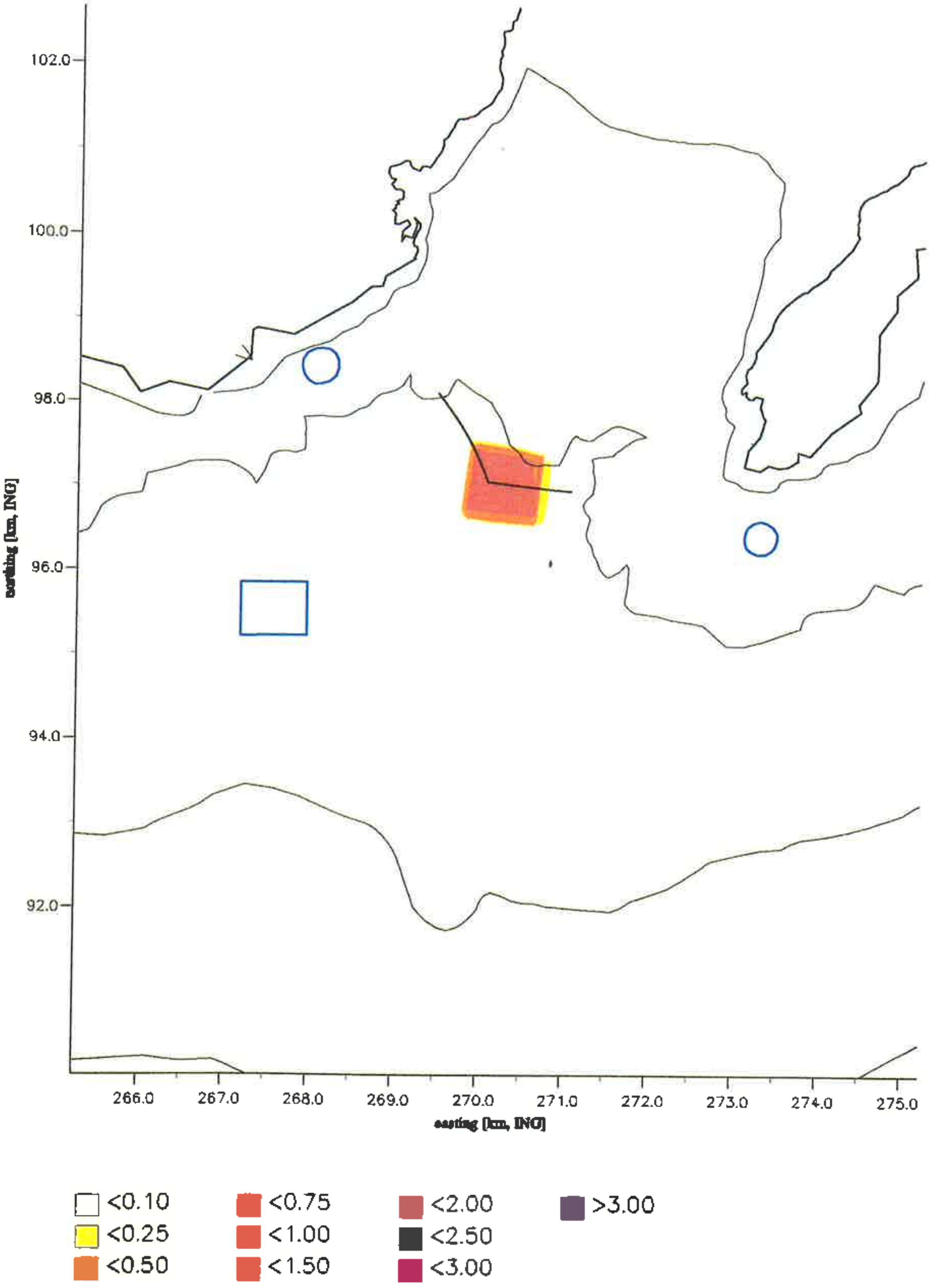
Dispersion of spoil heap, 0.5 year after initial dumping
(legend = sedimentation in metres)
with lobster release (circle) and herring spawning (square) areas

DELFT3D-MOR

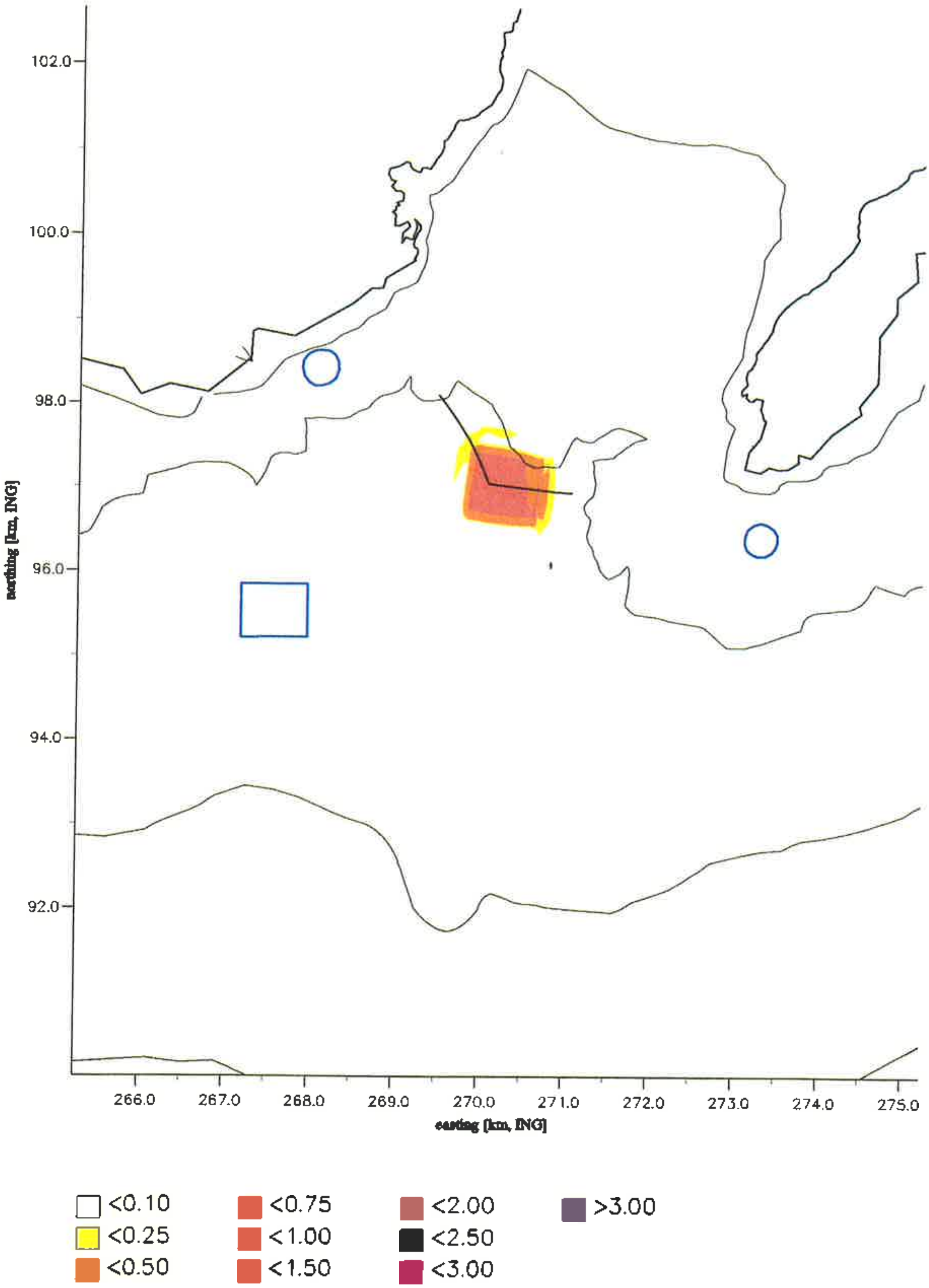
WL | DELFT HYDRAULICS

H3822

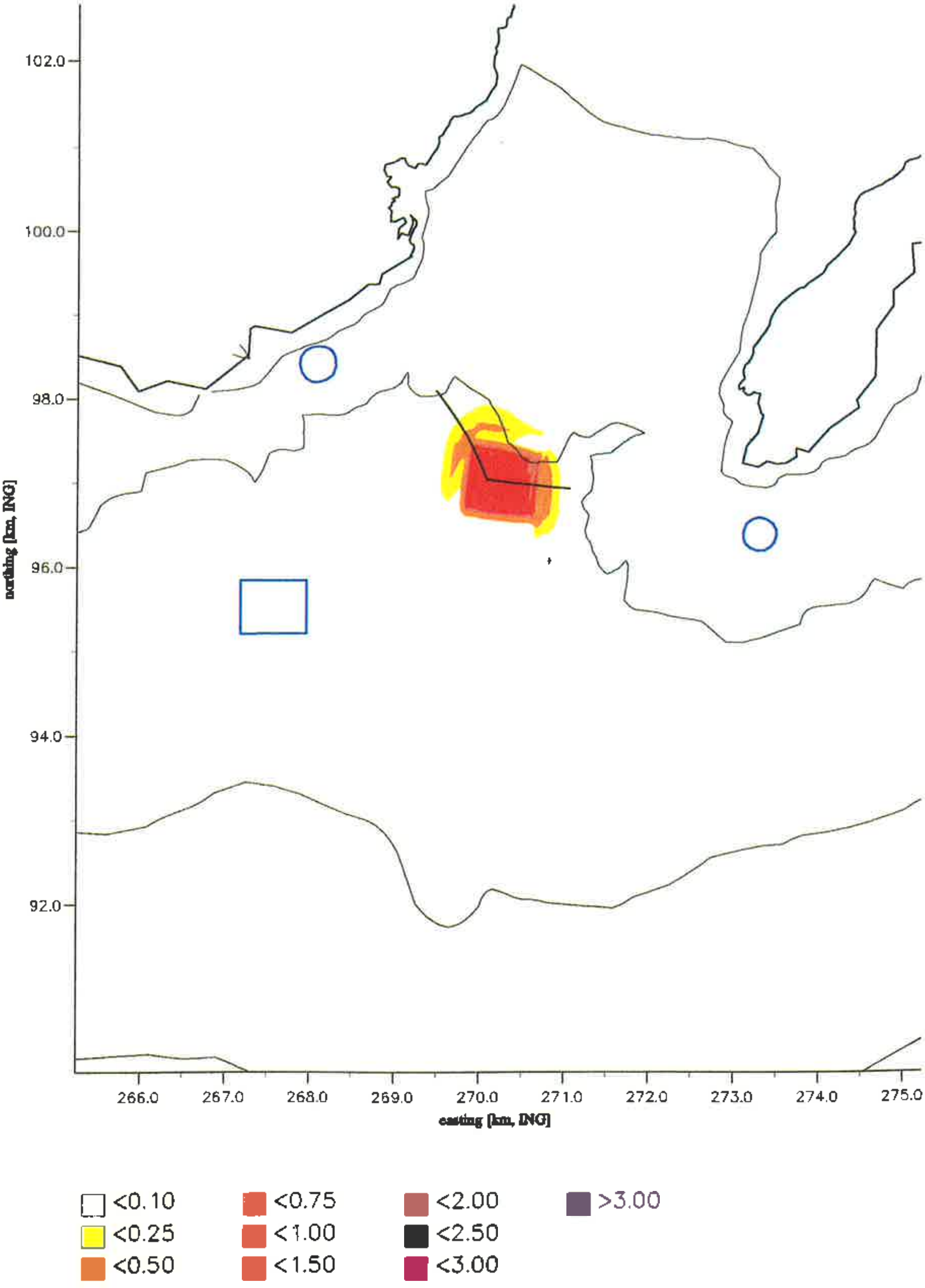
Fig. 2.4



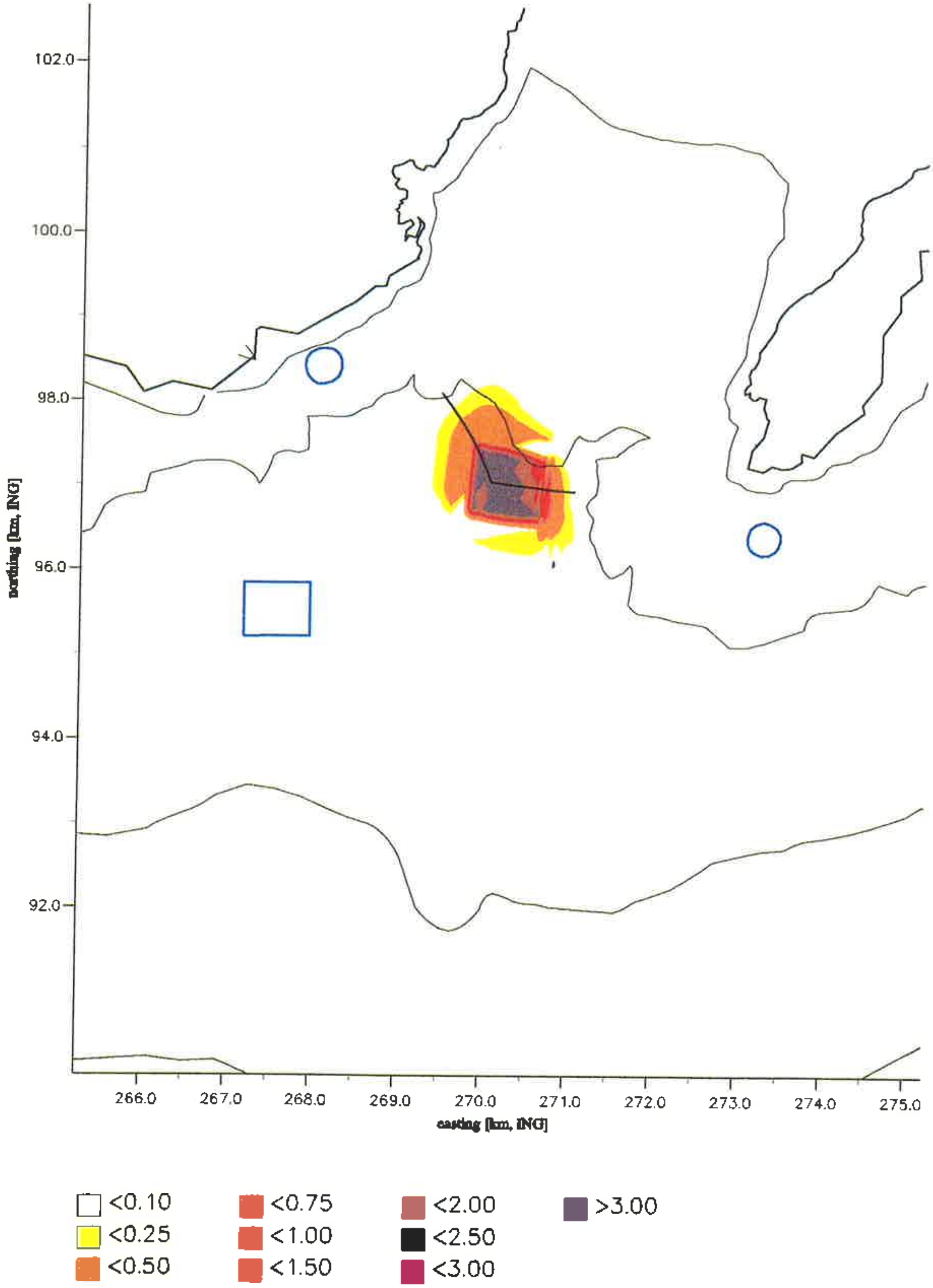
Dispersion of spoil heap, 0.9 year after initial dumping (legend = sedimentation in metres) with lobster release (circle) and herring spawning (square) areas	DELFT3D-MOR	
WL | DELFT HYDRAULICS	H3822	Fig. 2.5



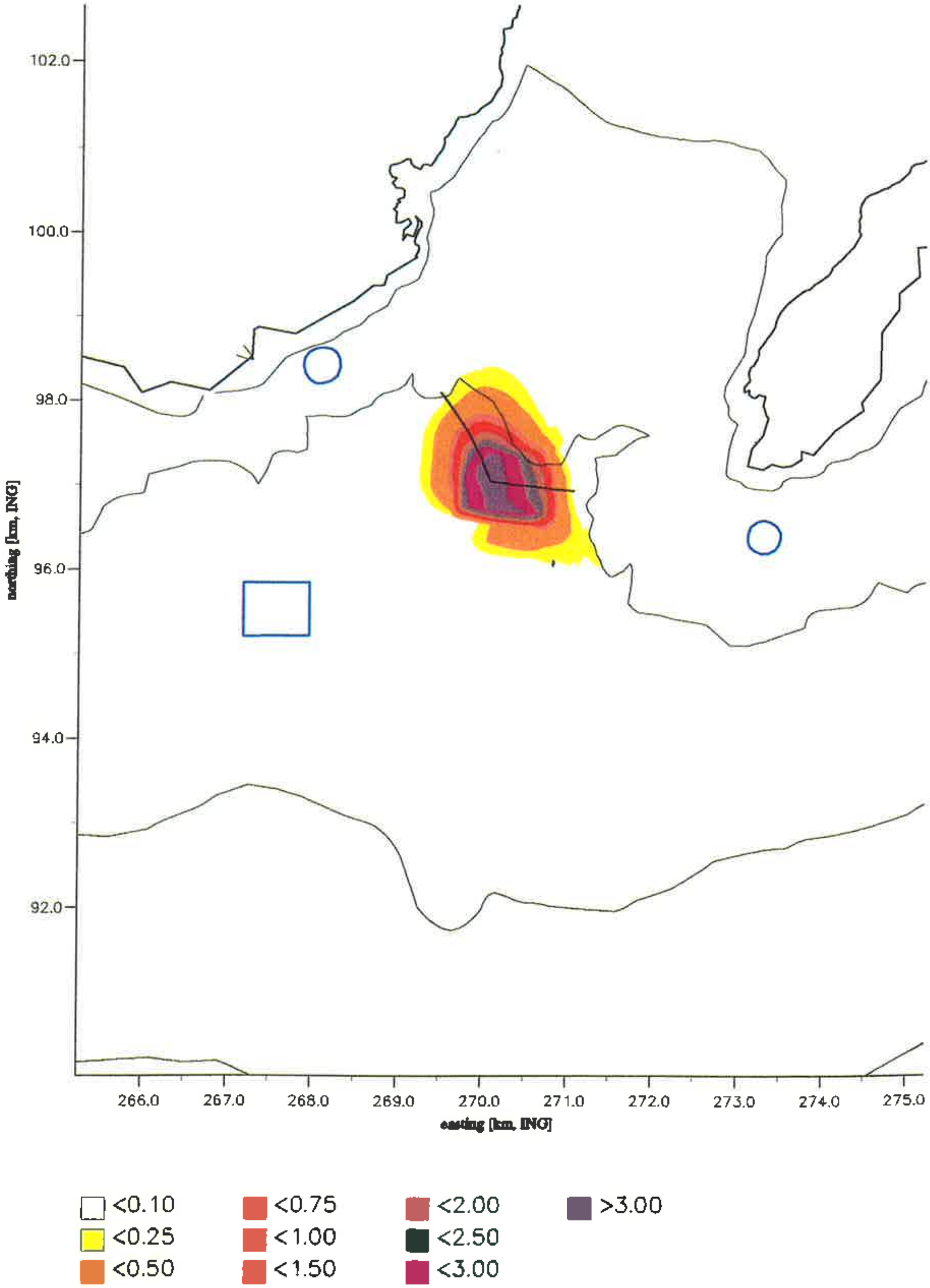
Dispersion of spoil heap, 1 year after initial dumping (before 2nd dumping) (legend = sedimentation in metres) with lobster release (circle) and herring spawning (square) areas	DELFT3D–MOR	
WL | DELFT HYDRAULICS	H3822	Fig. 2.6



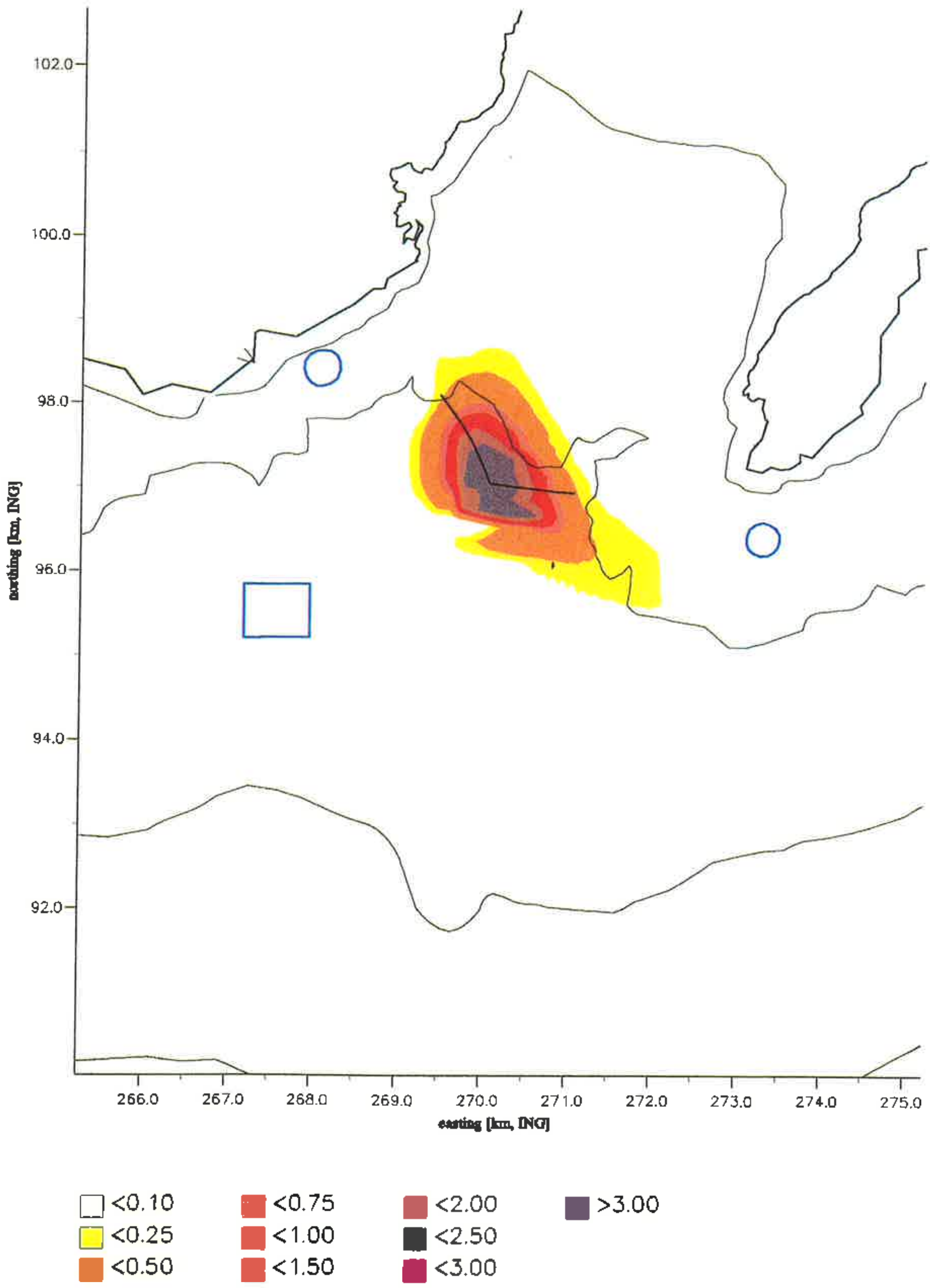
Dispersion of spoil heap, 2 years after initial dumping (before 3rd dumping) (legend = sedimentation in metres) with lobster release (circle) and herring spawning (square) areas	DELFT3D-MOR	
WL | DELFT HYDRAULICS	H3822	Fig. 2.7



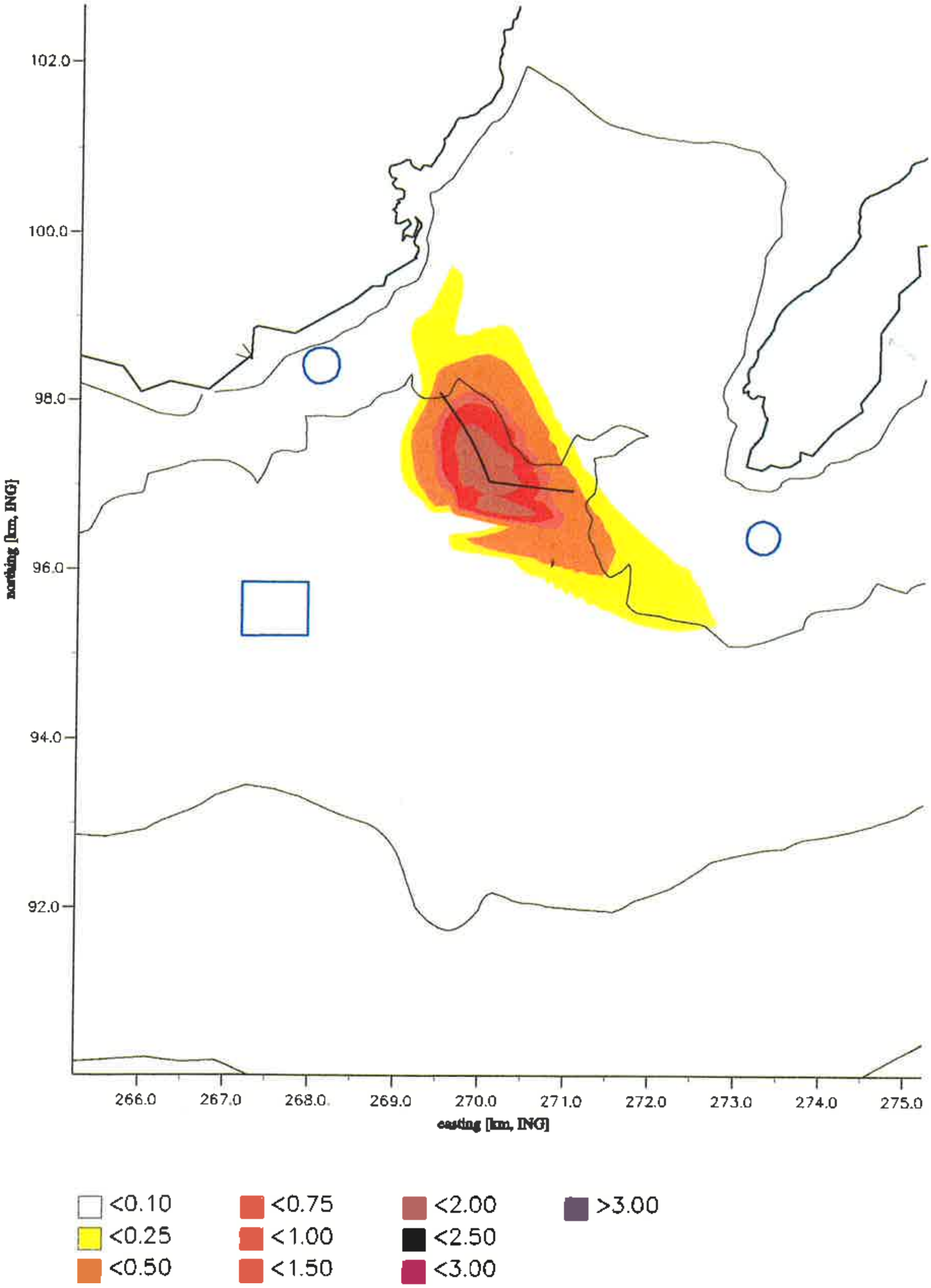
Dispersion of spoil heap, 4 years after initial dumping (before 5th dumping) (legend = sedimentation in metres) with lobster release (circle) and herring spawning (square) areas		
	DELFT3D-MOR	
WL | DELFT HYDRAULICS	H3822	Fig. 2.8



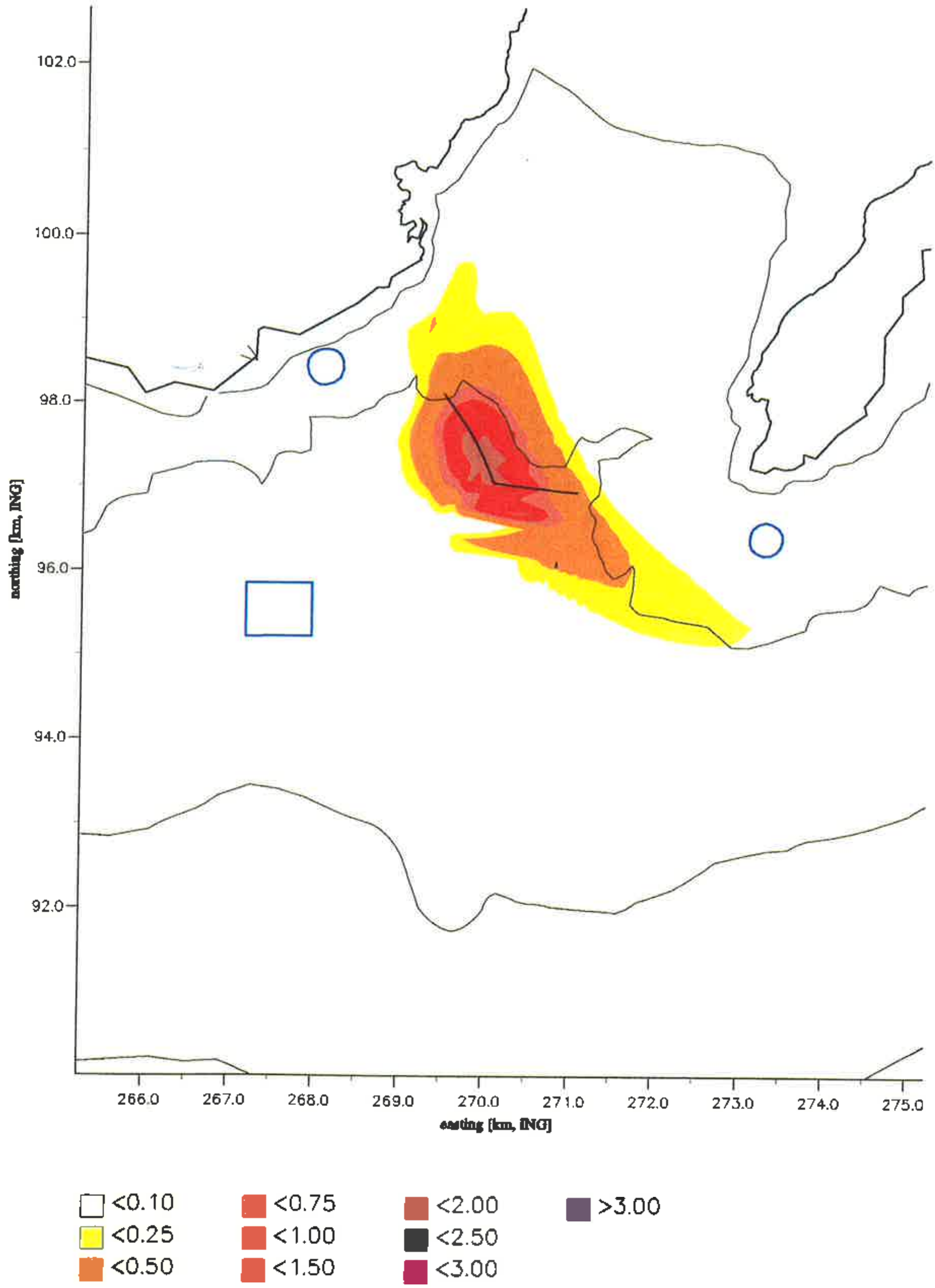
Dispersion of spoil heap, 6 years after initial dumping (legend = sedimentation in metres) with lobster release (circle) and herring spawning (square) areas	DELFT3D-MOR	
WL | DELFT HYDRAULICS	H3822	Fig. 2.9



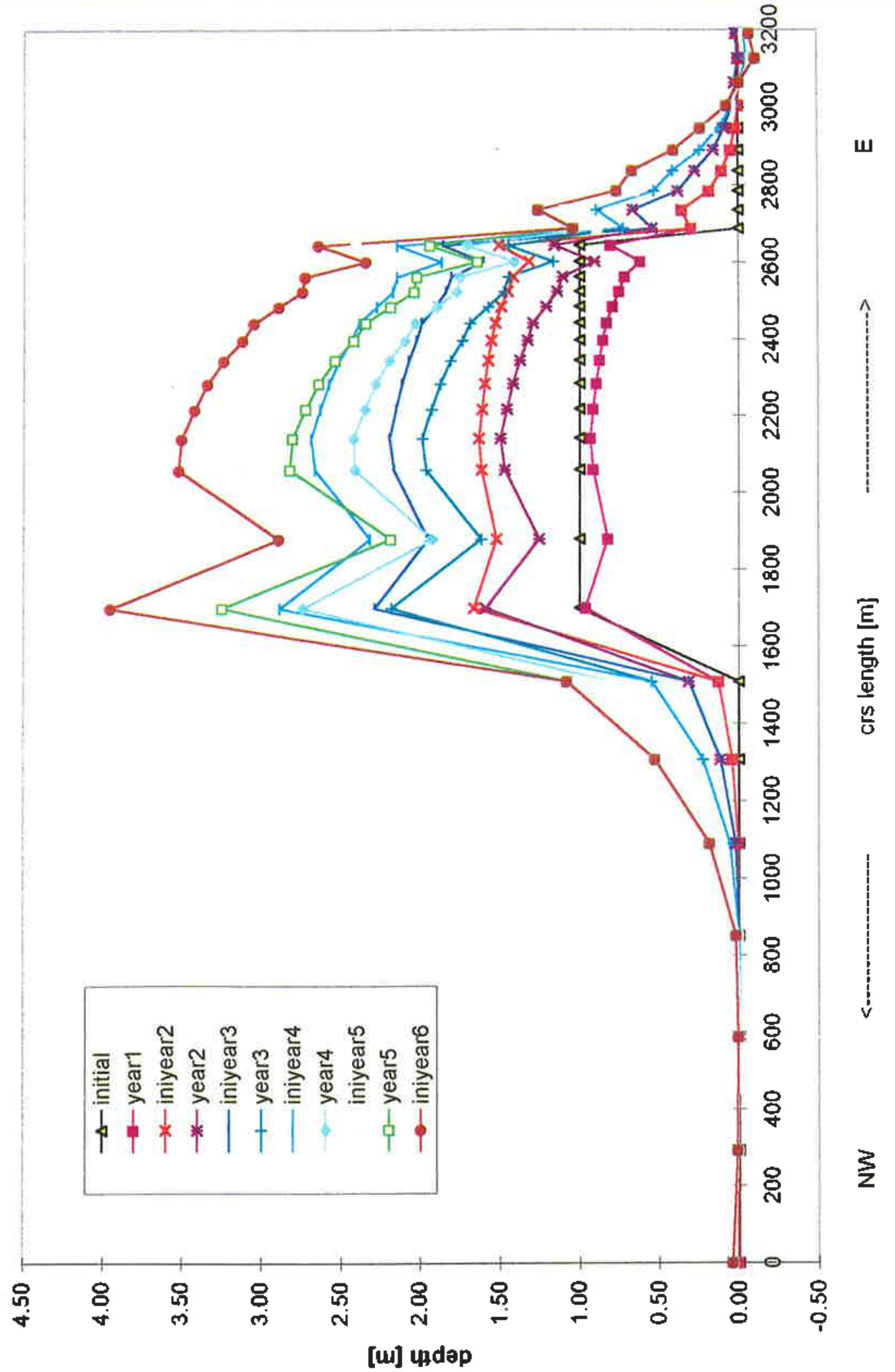
Dispersion of spoil heap, 9 years after initial dumping (legend = sedimentation in metres) with lobster release (circle) and herring spawning (square) areas	DELFT3D-MOR
WL | DELFT HYDRAULICS	H3822 | Fig. 2.10



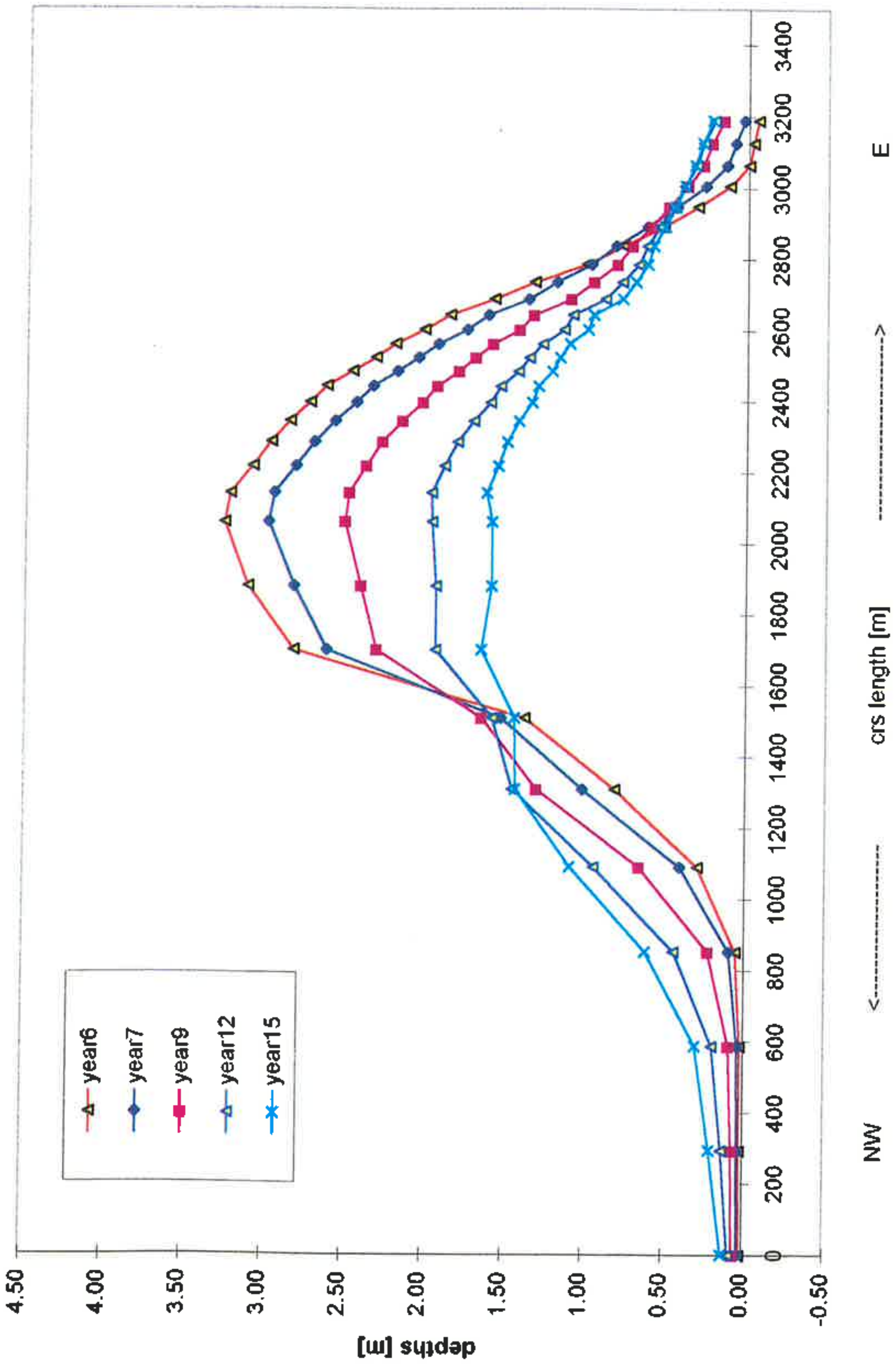
Dispersion of spoil heap, 12 years after initial dumping (legend = sedimentation in metres) with lobster release (circle) and herring spawning (square) areas	DELFT3D-MOR	
WL | DELFT HYDRAULICS	H3822	Fig. 2.11



Dispersion of spoil heap, 15 years after initial dumping (legend = sedimentation in metres) with lobster release (circle) and herring spawning (square) areas	DELFT3D-MOR	
WL | DELFT HYDRAULICS	H3822	Fig. 2.12



Cross section of erosion and sedimentation at the dump site Period: 1-5 years		
	DELFT3D-MOR	
WL | DELFT HYDRAULICS	H3822	Fig. 2.13



Cross section of erosion and sedimentation at the dump site Period: 6-15 years		
	DELFT3D-MOR	
WL | DELFT HYDRAULICS	H3822	Fig. 2.14

WL | Delft Hydraulics

[redacted]